

Survey announced a major shale gas exploration breakthrough in the WLS in northern Guizhou Province in June 2015, and the northern Guizhou Province become the focus of attention (Wang, 2015). The sedimentary environment controls the thickness and distribution of the organic rich shale. The sedimentary geochemistry records the paleo-environmental properties and evolution information (Zhang et al., 2005; Chen et al., 1996). This work focuses on the shale gas potential of the Wufeng-Longmaxi shale in north Guizhou Province. The objectives are to study the lithofaces and sedimentary environment, to investigate the exploration target and main controls on the accumulation of shale gas, and to provide theoretical support for future shale gas exploration in the Sichuan Basin and in other similar basins.

1 GEOLOGICAL SETTING

The study area is located in Chuandong tectonic belt and Chuannan tectonic belt in the southeast Sichuan Basin, in an area which includes the north Guizhou Province and southeast Chongqing City (Fig.1 A). The Sichuan Basin evolved from a Sinian-Middle Triassic (Z₁-T₂) passive continental margin and

the Jurassic-Quaternary was essentially a foreland basin stage, respectively mainly composed of 4100 m-7000 m thick marine strata and 3500 m-6000 m thick continental strata (Deng et al., 2010; Huang et al., 2009; Mei et al., 2004). Because of regional tectonic activity and the global transgressions, the confined sea was formed, which provided the low energy, anoxia and deep-water conditions in the late Ordovician to early Silurian period (Huang et al., 2011; Chen et al., 2009; Zhang et al., 2005). As sedimentary reaction to the tectonic setting and the global transgressions, a set of fine clastic rocks, primarily black shale, settled in the depositional stage of early Silurian Longmaxi Formation. In the study area, the Wufeng-Longmaxi shale is well developed, with a thickness of 20-200m (Zhu et al., 2010; Su et al., 2007). The shale has a high TOC content and is an important source rock (Liang et al., 2014). The unit consists of black shales in the middle and lower parts, which are rich in organic matter and graptolites, overlain by silty shales above (Fig. 1B). Event deposits (e.g. turbidites) have been recorded (Liang et al., 2016). In general, the gamma value shows spike peak at the black shales in the basal-Silurian, and decreases upward (Fig. 1B).

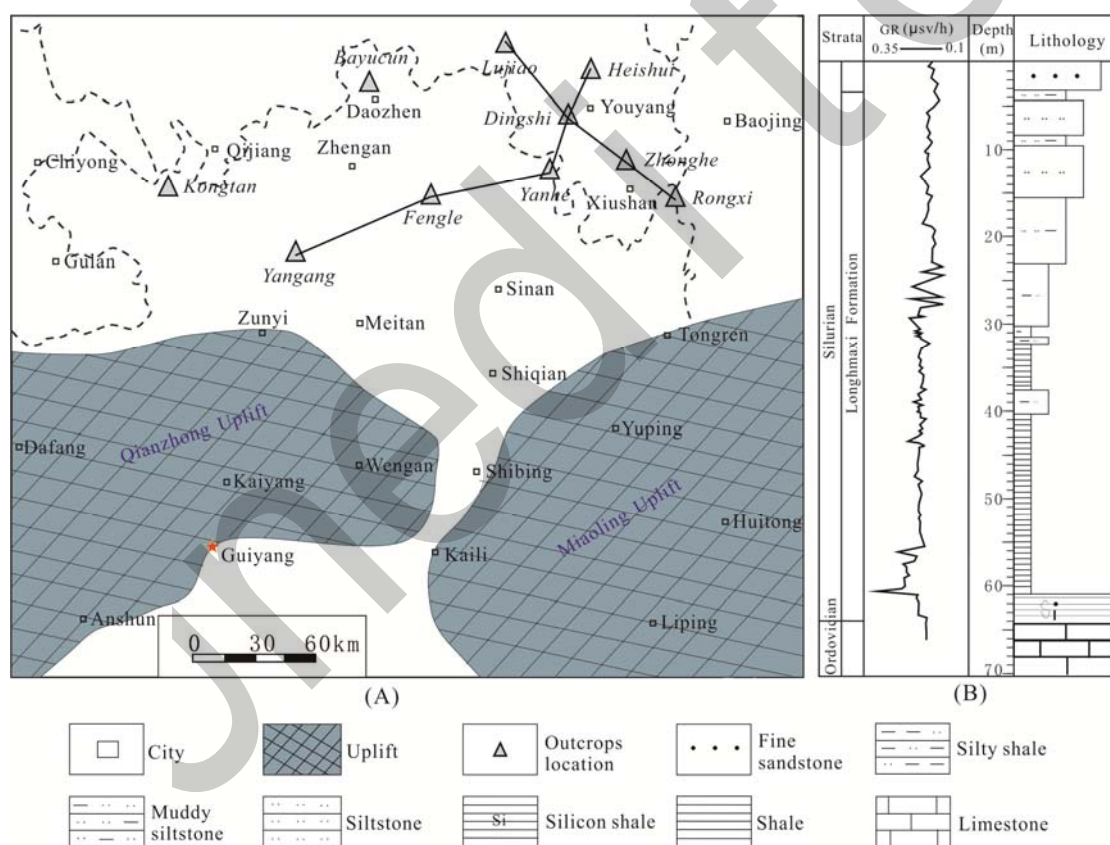


Figure1. Sketch map of study area and samples distribution (A) and the stratigraphy of the Wufeng-Longmaxi shale

2 DATABASE AND METHODOLOGY

In this study, samples were collected from 10 field exposures (locations showed in Figure 1B). The basic data included 670m of total exposure in 10 profiles, thin sections,

mineral composition data by X-ray diffraction, source rock data (vitrinite reflectance, TOC, maceral composition) and element analysis datas from the outcrops, with samples collected at 1.25m intervals in the Lujiao Outcrop. The gamma value of outcrops were collected at 25 cm intervals and constructed by

the portable γ spectrometer (SAIC GR-135). The mineral X-ray diffraction was performed at the experimental data center of the Research Institute of Petroleum Exploration and Development, CNPC. This testing was performed in accordance with standard test method SY/T 6210-1996, "X-ray diffraction quantitative analysis method of clay minerals and common non-clay minerals in sedimentary rocks", using a D/max-2500 TTR. The source rock data (vitrinite reflectance, TOC, maceral composition) were obtained at the Guangzhou Institute of Geochemistry, Chinese Academy of Science, and test technique use the method from Tissot and Welte, 1984. The organic matter maturity and micro-component tests were performed in accordance with standard method SY/T 5124-1995, "Sedimentary rock vitrinite reflectance measurement methods", using a LABORLUX 12POL fluorescence microscope and MPV-3 microscope photometer with a total magnification of 800 times. Because of the absent vitrinite in pre-Devonian sequences, the vitrinite reflectance values were calculated using the formula: $R_o = 0.618BR_o + 0.4$ (Zhang and Zhu, 2006), Where BR_o is bitumen reflectance. The test of organic carbon content was based on test methods GB/T 19145-2003 and GB/T 18602-2001. The test temperature was 27°C, and the testing equipment was a Leco carbon-sulfur analyzer and gas-shows evaluation instrument. The adsorption simulation experiment and the heat-press simulation experiment were performed at Henan Polytechnic University. The adsorbed gas content was determined based on the isothermal adsorption

simulation technique, which measured the adsorbed gas content at a constant temperature and increasing pressure. The lithology of the Wufeng-Longmaxi Formation shale was based on exposure descriptions, thin section observations and mineral composition data. The source rock analysis was primarily based on the vitrinite reflectance, TOC and maceral composition; backscatter (BS) SEM observation was also used.

3 RESULTS

3.1 Mineralogy

In the study area, the Longmaxi shale is mainly composed by quartz and clay minerals (Fig. 2A), with subordinate feldspar, calcite, pyrite and dolomite. The clay mineral content ranges from 18.5%-53.2%, with an average of 40.6%. The illite and illite-smectite mixed layer are dominated in the clay minerals composition, with relative content being 39%-57% and 29%-53% respectively (Fig. 2B). Quartz content ranges from 25%-73.0%, with an average of 40.8%, which mainly occur as silt grains from terrestrial transportation. In addition, the bio-quartz and diagenesis quartz in the clay minerals can also be found. The bio-quartz is mainly from the diatoms, radiolarians and sponges, and the diagenesis quartz is mainly clay-size grains floated in the clay minerals, from the release of clay minerals illitization. The carbonate minerals mainly occur as fracture fillings and cements. Because of the deep-water reduction environment, the pyrite is relative abundant and mainly occurs as framboidal pyrite.

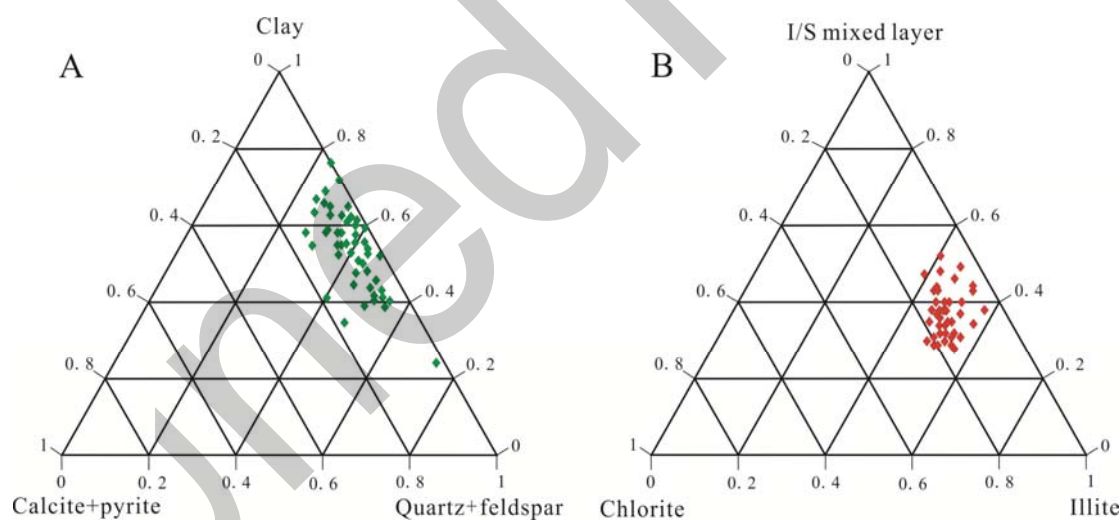


Figure 2. The mineral composition of Wufeng-Longmaxi shale in the study area.

Table 1. The mineral content of different outcrops

Outcrops	Clay /%	Quartz /%	Calcite /%	Dolomite /%	K-feldspar /%	Plagioclase/ %	Pyrite /%
Kongtan	21-58 (40.85)	34-69 (44.35)	0-8 (2.07)	0-7 (1.85)	1-4 (1.62)	1-12 (3.54)	0.2-10 (2.85)
Lujiao	22-44 (33.61)	37-73 (44.14)	0-11 (3.9)	0-10 (2.1)	1-6 (3.67)	2-17 (10.74)	0.1-6 (1.7)
Dingshi	27-59 (45)	30-44 (37.22)	1-10 (4.66)	0-4 (1.67)	0-4 (2.13)	4-13 (8.3)	0.1-3 (1.2)
Zhongxin	23-59 (43.5)	30-44 (40.32)	1-7 (3.37)	1-4 (1.78)	1-4 (2.45)	2-12 (6.3)	0.1-4 (1.16)

3.2 Lithofacies

3.2.1 Siliceous shale

Siliceous shale is characterized by dark-colored and laminated (Fig. 3A), with high TOC content and quartz content (up to 85%). The quartz mainly occur as cryptocrystalline texture siliceous organisms such as radiolaria and sponge (Fig. 4A), which is different from the terrestrial quartz. This lithofacies is mainly developed in the lower Wufeng-Longmaxi shale (Fig. 5).

3.2.2 Clay shale

Clay shale is characterized by dark-color, laminated development and rich in graptolites, with high TOC content and clay minerals (Fig. 3B). Few silt grains float among in the clay (Fig. 4B). This lithofacies is mainly deposited in the deepwater environment with quiet water-body and little terrigenous importation.

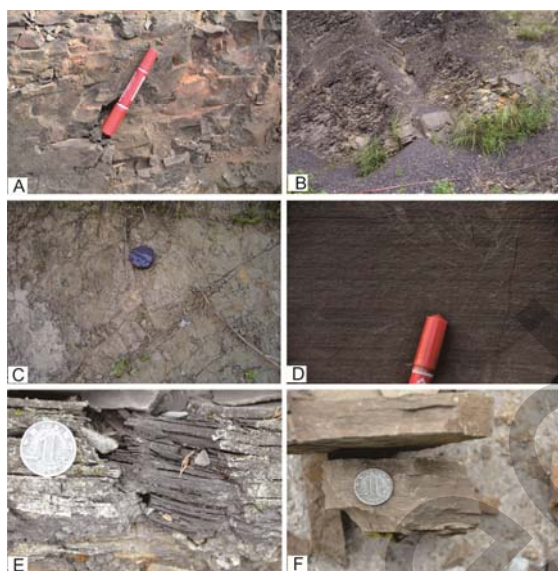


Figure 3. The outcrop characteristics of Wufeng-Longmaxi

shale. A. black siliceous shale with massive bedding and high hardness; B. Black claystone with laminated bedding; C. Gray siltstone; D. Silty shale with horizontal bedding and cross-layer fractures; E. Black carbonaceous shale with horizontal bedding, stained hands and low hardness; F. Gray-green muddy siltstone.

3.2.3 Calcareous shale

Calcareous shale is gray/dark gray colored with horizontal bedding (Fig. 3C). The dark laminae are mainly clay minerals rich in organic matters, and the bright laminae are dominated by calcite (Fig. 4C), with the calcite content accounting about 25% to 50%.

3.2.4 Silty shale

Silty shale is dark gray colored with horizontal bedding (Fig. 3D). The dark laminae are mainly clay minerals mixed with organic matters, and the bright laminae are dominated by silt grains, mainly quartz and feldspar, which account for 25% to 50% floating among clay minerals in the thin section (Fig. 4D).

3.2.5 Carbonaceous shale

Carbonaceous shale is black and gray, stained hands with well-developed laminae in hand specimens (Fig. 3E). The Carbonaceous shale contains a large number of carbonized organic matters, with TOC content ranging from 3% to 15% (Fig. 4E).

3.2.6 Muddy siltstone

Muddy siltstone is gray, brown or grey-green colored with lenticular bedding, horizontal bedding and cross bedding (Fig. 3F). The debris particles are mainly quartz with subordinate feldspar and mica (Fig. 4F), particles concavo-convex contact. The lithofacies is mainly developed in the upper WSL, indicating that shallower water bodies and increased input of terrestrial debris in the Late Wufeng-Longmaxi period.

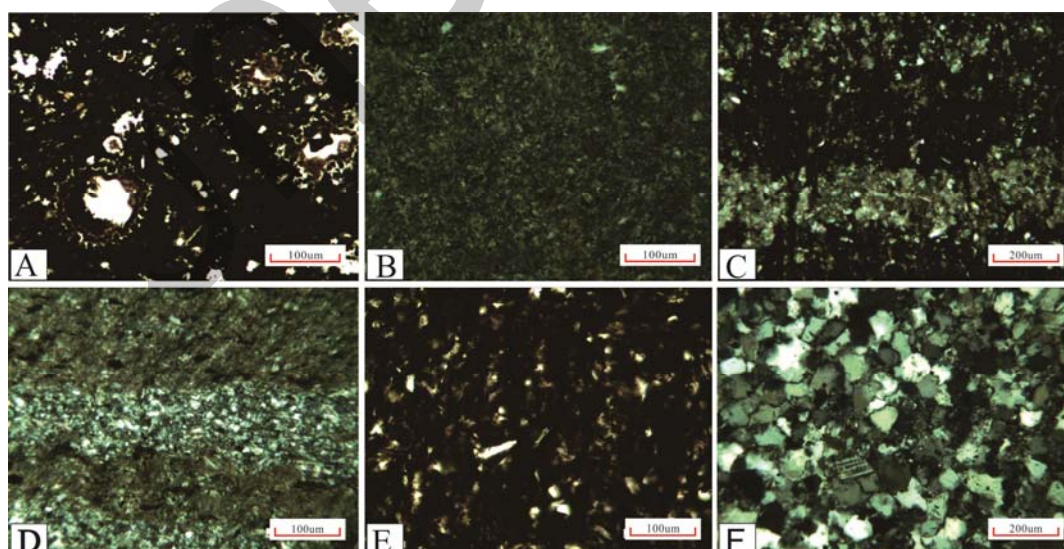


Figure 4. The microscopic features of different lithofacies. A. Black silicon shale with diatoms; B. Black shale with a small amount of quartz floating in the clay minerals; C. Laminated calcareous shale; D. Silty shale with quartz grains floating in the clay

minerals; E. Carbonaceous shale rich in organic matters; F. Gray siltstone with quartz grains lined and concavo-convex intergranular contacts.

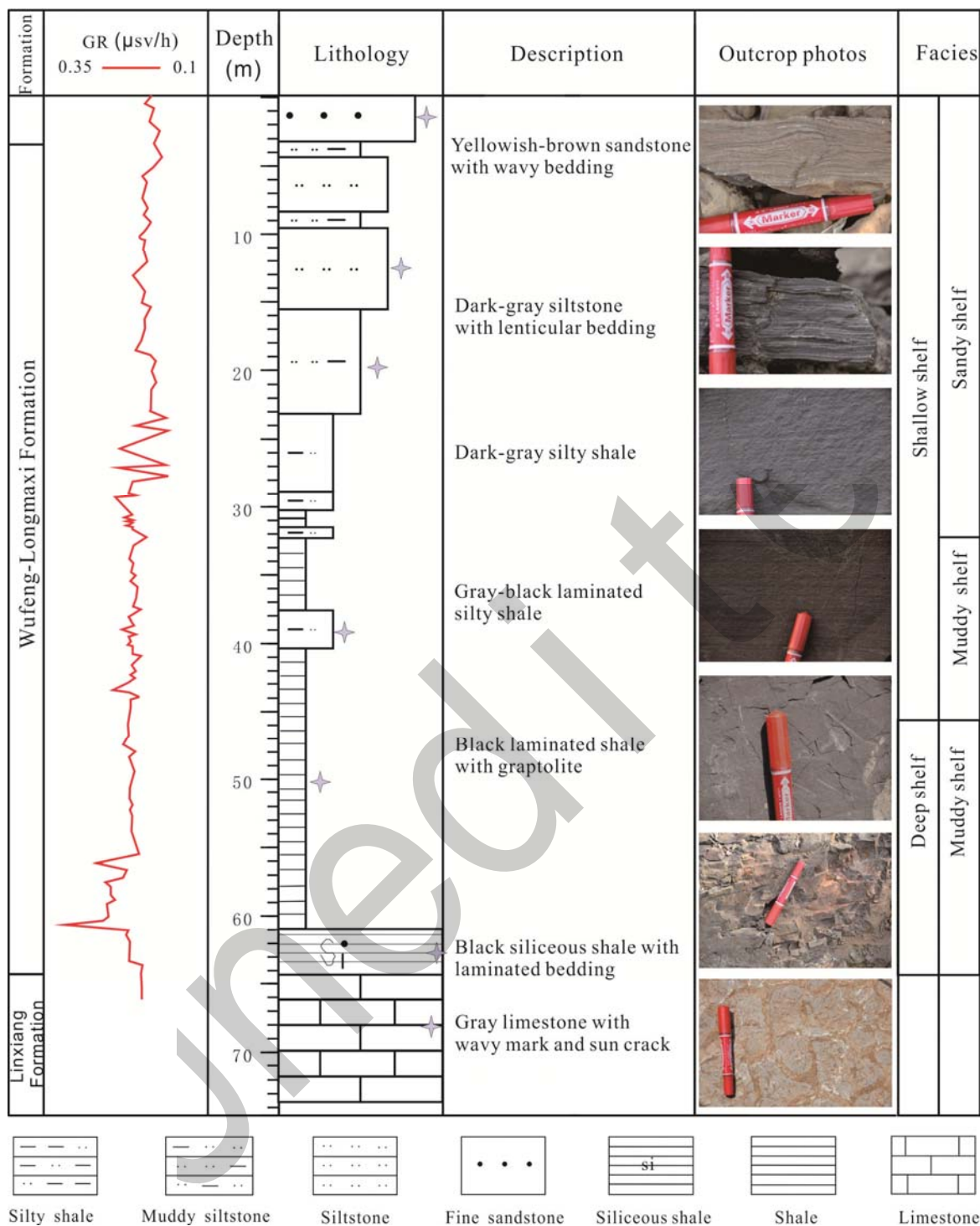


Figure 5. The lithofacies comprehensive column of Lujiao outcrop.

The siliceous shale and clay shale characterized by laminated bedding, rich in organic matter, graptolites and pyrite, indicating a deep-water hypoxic depositional setting, which mainly present in the lower part of the WLS (Fig. 5). Calcareous shale and silty shale are laminated while have relatively low TOC content and high contents of terrigenous materials (quartz and feldspar). They mainly occur in the

Middle WLS (Fig. 5). Muddy siltstone is mainly developed at the Upper WLS (Fig. 5). According to the lithofacies distribution, the terrigenous silt increases and the TOC content decreases from bottom to up. Meanwhile, the GR log has a peak value at the black shales in the basal WLS, and the GR value gradually reduces upward. The vertical stacked relationship of these lithofacies, the TOC content and GR value

show that the water body shallows upward, corresponding to which, the sedimentary facies evolved from deep-water shelf at the Lower WLS, to shallow muddy shelf at the Middle WLS and to shallow sandy shelf at the Upper WLS.

3.3 Characteristics of Source Rocks

The organic macerals of the WLS in the study area is mainly asphaltene, most of which are massive and streaky, with few fragmental asphaltene (Fig.6). The organic matter in the shale can produce abundant shale gas as the thermal maturity is enough high. Ro value of outcrop samples of the WLS in the study area ranging from 1.55% to 3.2% with an average of 2.36%, suggesting the shale has reached mature-post mature stage. The Ro value is much higher than the American gas shale, in which Ro is 0.4%~2.0%. The TOC content not only influences the hydrocarbon generation amount of shale, but also the adsorbed gas content (Zhou et al., 2011; Zhang et al., 2009). Higher TOC content indicates higher capacity of hydrocarbon-generation and strong adsorptive capacity for shale gas. Shale gas production in regions with high TOC content is usually higher than that of the regions with low TOC content (Jarvie et al., 2007). The minimum TOC content for gas producing shale in American shale gas is 0.5%, which is chosen as the minimum condition of shale TOC content to produce

industrial shale gas. The TOC content of WLS in the study area is high (Fig. 7). The average TOC content of several outcrops is over than 2%, which has reached the conditions to produce industrial shale gas.

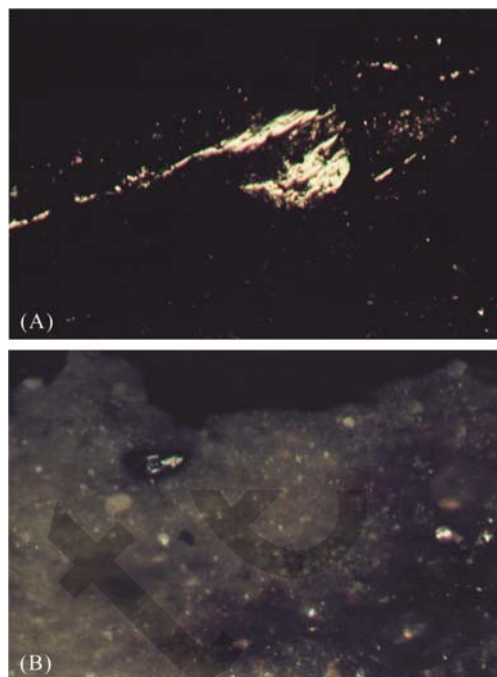


Figure 6. Organic matter morphology of WLS from the Daozhen outcrop (A) and Fengle outcrop (B)

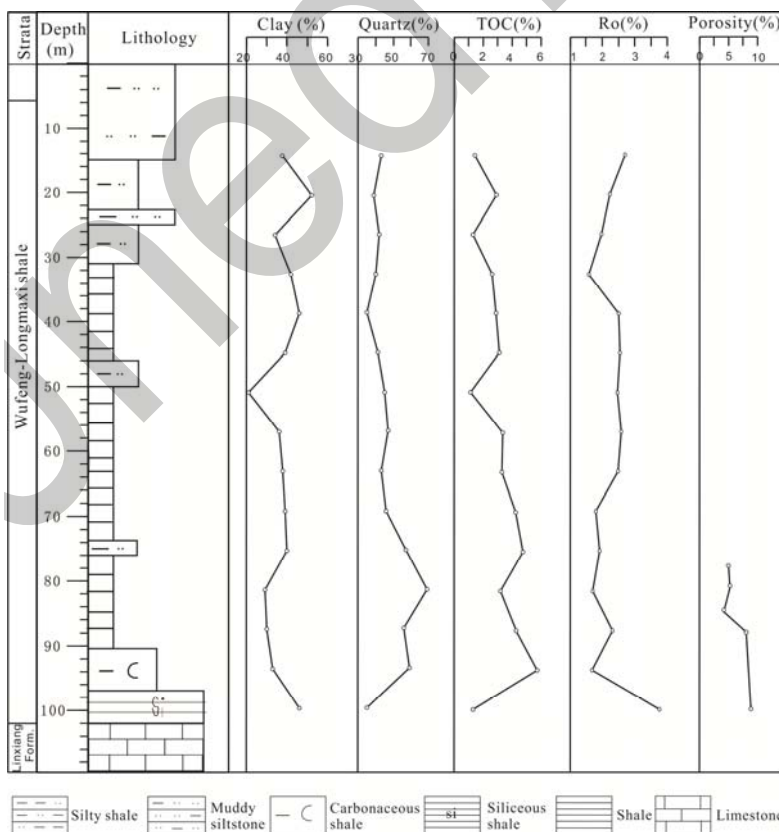


Figure 7. The characteristics of mineral content, TOC, Ro and Porosity of Kongtan Outcrop

4 DISCUSSION

4.1 Element Analysis and Sedimentary Environment

Principal component analysis of the geochemical data complements and reinforces the stratigraphic features shown in Table 2 and Table 3. The geochemical evolution of the sedimentary sequence recorded the WLS in Lujiao Outcrop is illustrated in Fig. 8. In this paper, geochemical elements are used to analyze the sedimentary environment. Bio-Ba and TOC content are used as a proxy for paleoproduction; B, Sr/Ba and B/Ga are used as a proxy for paleosalinity; and the V/Cr, V/(V+Ni) ratios are used as a proxy for anoxic conditions (Ochoa et al., 2013; Algeo and Maynard, 2004; Hetch and Leventhal, 1992).

4.1.1 Palaeo-salinity

In this study, the three parameters B, B/Ga and Sr/Ba are used to analyze palaeosalinity. Studies show that the content of B ranges from 10 $\mu\text{g/g}$ to 120 $\mu\text{g/g}$, with average value of 74.28 $\mu\text{g/g}$. The change trend of B content showed in the Fig. 8 suggesting that the B content decreases upward and peaks at the bottom, with the maximum value being 120 $\mu\text{g/g}$. The value of B of two samples in Wufeng Formation are significantly less

than that of Longmaxi Formation. Because of the difference on element migration ability between B and Ga, the value of B/Ga can be used to analyze palaeosalinity. The results show that the evolution trend of B/Ga and B content are consistent, which reflect that the high palaeosalinity at the bottom and decreases upward. The high Sr/Ba value indicates high salinity, and the Fig.8 shows the Sr/Ba value changes relatively greatly while still decreases upward.

4.1.2 The TOC content

As the important evaluation parameter of source rocks, the TOC content reflects the abundance of organic matter and the oxidizing reduction condition of sedimentary water body to a certain extent. This is the result that organic matter can be preserved well in the strong reducing environment. The TOC content of the WLS in the study area is generally high. The TOC content of Kongtan outcrop decreases upward and ranges from 1.0% to 5.75%, with an average of 3.0 % (Fig.7). The TOC content of Lujiao outcrop ranges from 0.74% to 4.45%, with an average of 1.65 % and decreases upward (Fig.8). The thickness of effective source rock up to 45 m, which suggests that the WLS act as good source rock.

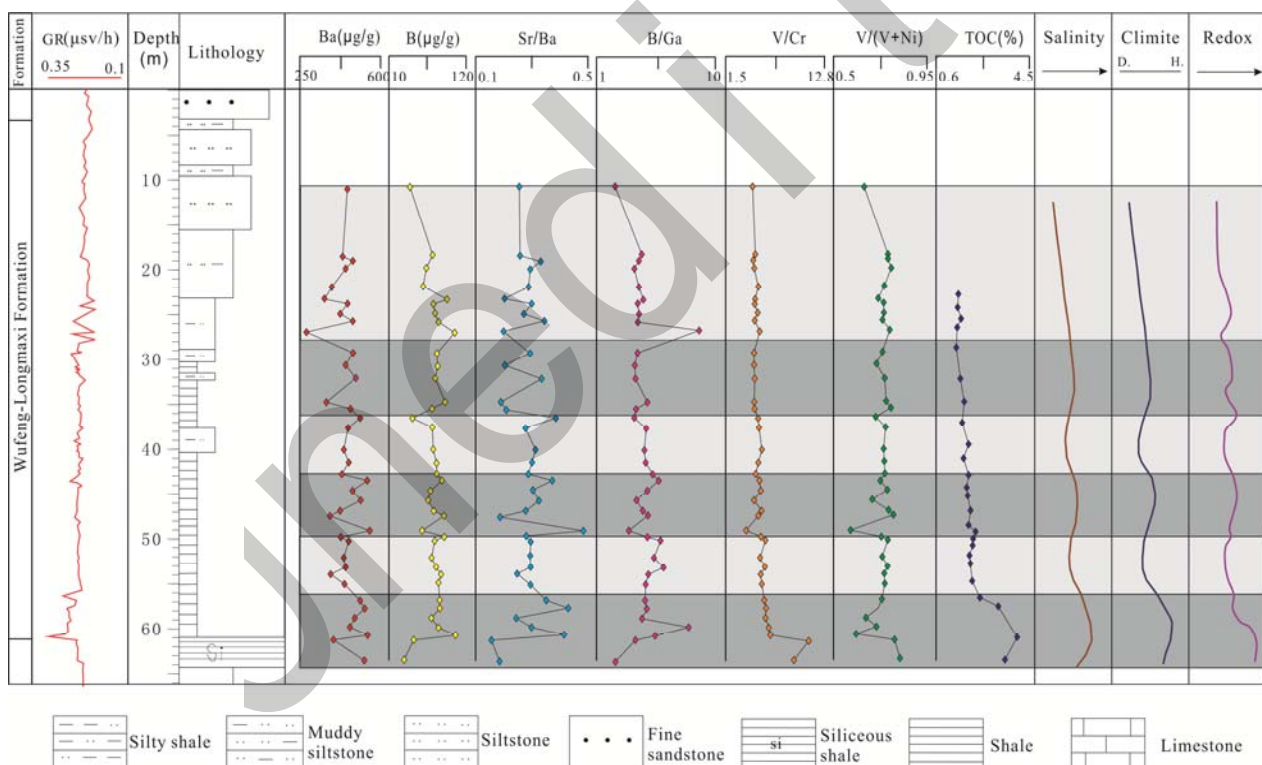


Figure 8. Geochemical analysis of the Lujiao outcrop as an indicator of the sedimentary environment of the WLS.

4.1.3 Primary productivity

Primary productivity is affected by many factors, including chemical conditions of ocean surface water, temperature, climate, ocean currents, etc. The distribution of nutrients in the oceans is controlled by biochemical conditions. And there are obvious differences in responses of different

elements to the primary productivity. Paleoceanographers believe that the biogenic barium can act as a good indicator of primary productivity because of its higher preservation rate and positive correlation with productivity. According to the better correspondence between high primary productivity rate and Ba, Teng et al (2006) built the relationship between productivity

and biogenic barium, indicating the paleocean productivity by using barium abundance, and furthermore characterize the development of quality source rocks.

The abundance of biogenic barium (bio-Ba) cannot be directly tested, which is usually calculated by equation related to total barium, biogenic barium and terrigenous barium. The equation is described as follows:

$$W(\text{bio-Ba}) = W(\text{Ba-Total}) - W(\text{Ti-Total}) \times (W(\text{Ba}):W(\text{Ti}))_{\text{PAAS}}$$

Where $(W(\text{Ba}):W(\text{Ti}))_{\text{PAAS}}$ is the ratio of terrigenous Ba to Ti in the standard shale of the late Archean (PASS), and the number is 0.11. $W(\text{Ti-Total}) \times (W(\text{Ba}):W(\text{Ti}))_{\text{PAAS}}$ represents the content of terrigenous barium in the sediments.

Studies show that the total content of bio-Ba in WLS is overall high, with an average of 420.84 $\mu\text{g/g}$, decreasing upward, suggesting that the productivity is the highest at the bottom and decreases gradually upward.

4.1.4 Redox conditions

Trace elements will be enriched and preserved in the sedimentary record for the effects of redox conditions of water body. Therefore, some elements can be used to characterize the redox conditions during the deposition. These indicators are mainly siderophile and sulfophile elements, including V, Ni, Cr, Mo, Cu, Zn, Cu, U, etc (Teng et al., 2006). Hatch et al (1992) derived that from the study of black shale in North America, high metal (Cd, Mo, V, Zn, etc.) content, high sulfur content, $\text{DOP} \geq 0.67$, and $V/(V+Ni) \geq 0.54$ indicate anoxic environment containing H_2S . It is generally believed that $V/Cr > 2$ indicates anoxic environment, and the V/Cr ratio of Wufeng-Longmaxi formation is mostly larger than 2, consequently showing the anoxic condition. Anoxic reducing environment is a necessary condition of preservation of organic matter, therefore, TOC content, to some extent, reflects the redox condition of the water body.

This paper select three parameters - V/Cr , $V/(V+Ni)$ and

TOC - as the reducing environment discrimination indicators, and thereby analyzed the development environment of quality source rocks (Table 2). Both of the values of V/Cr and $V/(V+Ni)$ show an upward decreasing trend. According to the criterion of Hatch et al (1992), the samples are deposited under the reducing environment with varying degrees of anoxic, which may be related to the regional climate changes. The TOC content is overall large, average being 1.65%. The largest parts are at the bottom of Wufeng-Longmaxi formation, which can be up to 4.45%, decreasing upward.

4.2 The Deposition of Siliceous Shale and Its Significance

The siliceous shale is characterized by high quartz content and TOC content, what's more, numerous silica-rich organisms can be found (Fig. 4A). In addition, the quartz content in the siliceous shale has a positive correlation with the TOC content, suggesting the formation of siliceous shale is closely related to the bio-silica rather than terrestrial source (Liang et al., 2016; Louck et al., 2007). Studies show that the siliceous shale is related to the upwelling, which will bring nutrients to the waterbody and effectively improve siliceous organisms bloom. The geochemistry analysis suggest that the interval of siliceous shale developed is characterized by the palaeo-salinity and reduction increase abruptly (Fig. 8), which can be an important evidence for the upwelling.

The siliceous shale has high TOC content, which means more shale gas generation potential. Organic pores has been suggested to be the key storage space for the gas shale in the WLS. Higher TOC content means more organic pores. In addition, the siliceous shale has high brittle mineral content (quartz) (up to 85%), which is conducive to hydraulic fracturing. The characteristics of source rock, reservoir storage space, porosity, permeability and brittleness suggest that the siliceous shale generated by upwelling acts as the best targets for shale gas exploration in the study.

Table 2. The statistics of TOC, V/Cr , $V/(V+Ni)$ of different outcrops. In the table, 0.26-5.75 (2.54) means Min-Max (Average).

	<i>Kongtan</i>	<i>Lujiao</i>	<i>Dingshi</i>	<i>Daozhen</i>	<i>Rongxi</i>	<i>Fengle</i>	<i>Yanhe</i>
TOC (%)	0.26-5.75 (2.54)	0.74-4.62 (1.65)	0.68-3.85 (1.87)	0.67-6.16 (2.05)	0.59-4.94 (2.6)	0.44-2.54 (1.49)	0.58-4.6 (2.85)
V/Cr	1.2-11.7 (4.63)	1.6-12.2 (2.66)	1.7-3.25 (2.05)	2.4-12.8 (3.48)	1.25-11.2 (3.6)	2.2-10.6 (5.06)	1.5-8 (3.13)
$V/(V+Ni)$	0.69-0.9 (0.77)	0.6-0.96 (0.78)	0.7-0.85 (0.80)	0.58-0.92 (0.76)	0.6-0.89 (0.69)	0.55-0.88 (0.75)	0.64-0.96 (0.82)

4.3 The Shale Gas Enrichment

Nitrogen adsorption experiments suggest that the maximum adsorption gas content of WLS is closely related to the TOC content, and has a positive relationship with the TOC content. As the TOC content is more than 3%, the maximum adsorption gas content of samples can reach 1 m^3/t at 0.5 MP, greater than 2 m^3/t at 2MP~, reach 3.2 m^3/t at 5 MP pressure

(Fig. 9). These datas show the relative high gas content of WLS. Besides of the TOC content, the shale gas content is also affected by the mineral composition and porosity among other factors. Most the pore diameters are less than 20nm, mainly concentrate at about 10nm (Fig.10). Rouquerol (1994) proposed the pore-size classification, micropore: ($D < 2\text{nm}$), mesopore ($2\text{nm} < D < 50\text{nm}$) and macropore ($D > 50\text{nm}$), according to which the pores in the study area is mainly

mesopore, which is consistent with that the organic pore acts as the key reservoir space in the study shale.

Table 3. The element content of the WLS in Lujiao outcrop.

Samples	Element content ($\mu\text{g/g}$)										Element content (%)				
	B	V	Cr	Mn	Ni	Cu	Zn	Ga	Sr	Ba	Na	Mg	K	Ca	Fe
1	10	364	39	20	15	3.1	7.8	6.4	32	285	0.3	0.3	1.77	0.13	0.47
2	34	741	55	36	73	11	87	10	37	478	0.3	0.41	1.88	0.18	1.23
3	114	212	57	422	196	45	316	22	113	268	0.65	1.38	2.62	3.55	4.19
3	82	234	65	251	84	42	101	10	101	378	0.55	1.15	3.03	2.61	3.27
4	68	151	49	164	89	51	107	17	67	347	0.58	1	2.72	2.12	2.43
5	84	182	57	240	61	50	83	19	127	287	0.56	1.29	2.9	4.61	3.37
6	85	202	68	220	57	62	137	20	105	312	0.86	1.75	4.04	3.05	4.4
7	82	174	65	190	40	34	76	19	108	411	0.84	1.46	3.26	2.53	3.62
8	86	140	57	193	33	41	121	19	100	499	0.9	1.41	3.23	1.38	3.48
9	77	155	51	316	30	34	97	13	106	402	0.84	1.54	2.93	3.3	3.56
10	71	135	56	232	36	27	75	14	108	413	0.95	1.4	3	2.37	3.05
11	72	153	50	191	35	37	75	13	100	377	0.83	1.42	3	2.56	3.29
12	74	145	53	168	27	34	77	13	98	383	0.94	1.39	3.15	2.26	3.32
13	94	166	61	208	46	36	95	21	106	435	0.91	1.47	3.22	2.33	3.34
14	51	33	53	155	35	39	106	18	129	251	1.03	1.56	3.88	2.55	2.97
15	91	133	61	89	15	26	55	20	60	503	1.08	1.3	3.31	0.38	3.5
16	73	142	55	294	25	28	82	18	106	437	0.95	1.57	3.06	3.47	3.14
17	63	71	44	194	31	28	70	18	93	307	1.11	1.46	3.32	2.52	2.38
18	67	118	48	176	23	28	65	15	99	360	1.09	1.41	3.2	2.55	3.43
19	88	120	51	190	27	31	75	16	99	268	1.2	1.45	3.29	2.4	3.97
20	80	115	53	214	26	28	83	16	107	425	1.23	1.44	3.24	2.72	3.59
21	78	121	56	189	28	29	73	18	104	385	1.21	1.42	3.17	2.15	3.37
22	72	119	45	229	29	36	97	17	118	413	1.25	1.68	3.8	3.12	4.13
23	70	117	52	191	25	26	73	16	93	388	1.26	1.43	3.09	1.95	3.14
24	33	66	30	237	25	21	70	10	120	311	1.17	1.5	3.09	2.9	2.28
25	69	90	52	64	13	14	36	20	56	374	1.28	1.34	3.44	0.29	3.37
26	94	104	63	77	22	29	80	21	64	526	1.21	1.29	3.2	0.3	3.54
27	75	97	57	209	23	23	71	22	94	296	1.16	1.5	3.06	2.18	3.42
28	81	102	62	327	37	32	85	24	56	405	1.3	1.37	3.25	0.32	3.74
29	79	89	54	186	23	23	64	22	94	357	1.28	1.4	2.98	2.36	3.31
30	163	150	64	115	24	25	85	16	87	649	1.53	1.49	3.75	1.67	3.96
31	76	78	55	200	31	29	67	24	105	354	1.4	1.47	3.18	2.09	2.92
32	80	97	56	243	25	20	80	22	105	375	1.36	1.48	3.09	3.03	3.57
33	79	98	48	247	24	25	100	23	119	359	1.36	1.65	3.05	2.9	3.04
34	75	96	46	184	23	19	63	20	101	436	1.21	1.45	3.08	2.28	3.45
35	73	88	54	210	22	19	63	21	103	358	1.34	1.45	2.92	2.7	3.41
36	72	87	52	210	21	19	68	20	105	391	1.33	1.48	2.95	2.72	3.67
37	99	103	57	330	34	22	96	24	74	537	1.43	1.26	3.14	0.38	3.37
38	52	109	50	216	26	22	85	14	123	489	1.6	1.62	3.46	3.5	2.88

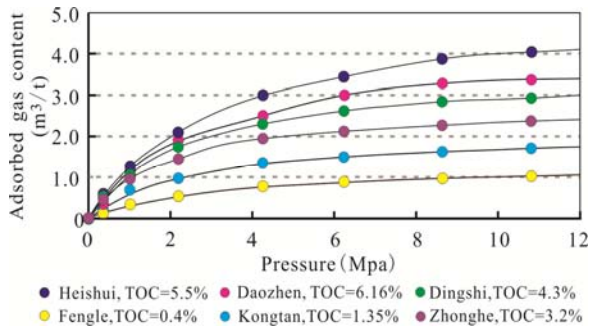


Figure 9. The adsorbed gas content of the WLS.

The high TOC content is the key controlling factor for shale gas content and reservoir space development. Therefore, the organic rich lithofacies and intervals are important exploration target. As mentioned above, organic matters enrichment is controlled by the sedimentary environment, and the strong reduction, high paleosalinity and humid climate are favorable conditions. Element analysis suggests that the Lower WLS is favorable interval. The siliceous shale has high TOC content and brittle mineral (quartz) content, and so are easy to fracture. Therefore, siliceous shale can be an important interval for shale oil and gas exploration. According to the lithofacies and sedimentary facies connecting-well profiles (Fig. 11), the northeast is favorable exploration area.

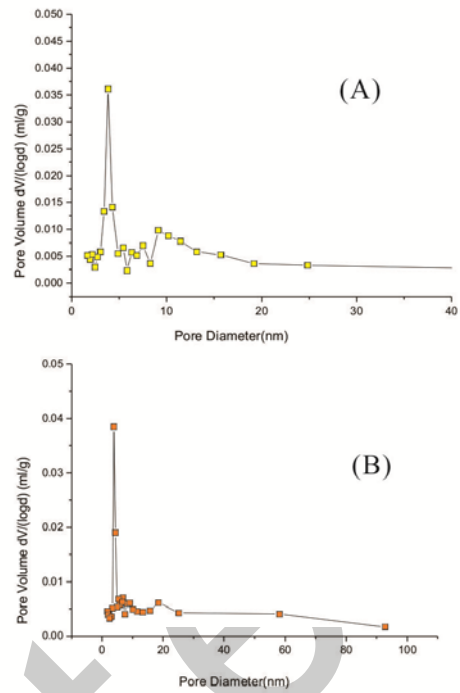


Figure 10. The pore diameter of the WLS.

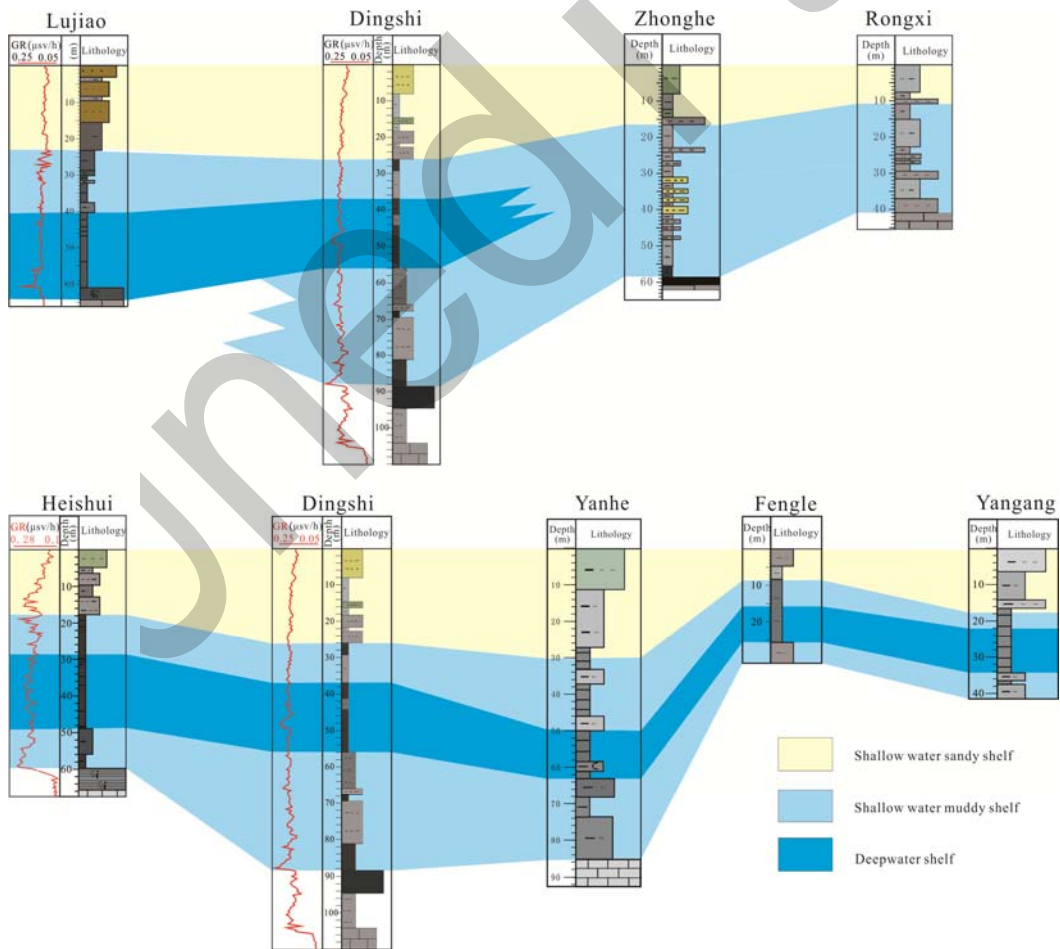


Figure 11. Correlation chart through the study area showing lithofacies distribution.

5 CONCLUSIONS

Paleozoic Wufeng-Longmaxi shale (WLS) is one of the main layers for shale gas exploration in Sichuan Basin. The mineral mainly compose of quartz and clay minerals, also contains a little of plagioclase feldspar, potassium feldspar, calcite, dolomite and pyrite. Six lithofacies have been identified in the WLS: siliceous shale, clay shale, calcareous shale, silty shale, carbonaceous shale and muddy siltstone. Through biological Ba, V/(V+Ni), TOC content, V/Cr, B, Sr/Ba and other indicators, we resume primary productivity, redox conditions and paleosalinity. The results show that early stage of WLS has strong anoxic conditions, high paleosalinity and high organic carbon content. Geochemical index also shows anoxic environment is destroyed at the late of WLS, with the TOC content decreased, is not conducive to generation for good source rock. The organic pore acts as the key reservoir space in the shales, and the pores are mainly mesopore, with most of pore diameters are less than 20nm. The siliceous shale have high TOC content and brittle mineral (quartz) content, which is the important interval for shale oil and gas exploration. The northeast is favorable exploration area.

ACKNOWLEDGMENTS

The work presented in this paper was supported by the Certificate of China Postdoctoral Science Foundation Grant (2015M582165), National Natural Science Foundation of China (No. 41602142, U1262203, No. 41372107), and Fundamental Research Funds for the Central Universities (15CX08001A).

REFERENCES CITED

- Algeo, T. J., Maynard, J. B., 2004. Trace-element behavior and redox facies in core shales of Upper Pennsylvanian Kansas-type cyclothems. *Chemical Geology*, 206, 289-318.
- Chen, H. D., Huang, F. X., Xu, S. L., et al., 2009. Distribution rule and main controlling factors of the marine facies hydrocarbon substances in the middle and upper parts of Yangtze region, China. *Journal of Chengdu University of Technology (Science & Technology Edition)*, 36(6): 569-577.
- Chen, Y. J., Deng, J., Hu, G. X., 1996. The constraint of the environments on content and distribution types of trace element in sediments. *Geology-Geochemistry*, 35(3): 97-105.
- Deng, X., Yang, K. G., Liu, Y. L., et al., 2010. Characteristics and tectonic evolution of Qianzhong Uplift. *Earth Science Frontiers*, 17(3): 79-89.
- Hatch, J. R., Leventhal, J. S., 1992. Relationship between inferred redox potential of the depositional environment and geochemistry of the Upper Pennsylvanian (Missourian) Stark Shale Member of the Dennis Limestone, Wabaunsee County, Kansas, U.S.A. *Chemical Geology*, 99: 65-82.
- Huang, F. X., Chen, H. D., Hou, M. C., et al., 2011. Filling process and evolutionary model of sedimentary sequence of Middle-Upper Yangtze craton in Caledonian (Cambrian-Silurian). *Acta Petrologica Sinica*, 27(8): 2299-2317.
- Huang, J. Z., 2009. The pros and cons of paleohighs for hydrocarbon reservoiring: A case study of the Sichuan basin. *Natural Gas Industry*, 29(2): 12-18.
- Jarvie, D. M., Hill, R. J., Ruble, T. E., et al., 2007. Unconventional shale-gas systems: The Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment. *AAPG Bulletin*, 91(4): 475-499.
- Li, S. J., Xiao K. H., Wo. Y. J., et al., 2008. Developmental controlling factors of Upper Ordovician-Lower Silurian high quality source rocks in marine sequence, South China. *Acta Sedimentologica Sinica*, 26(5): 872-881.
- Liang, C., Jiang, Z. X., Cao, Y. C., et al., 2016. Deep-water depositional mechanisms and significance for unconventional hydrocarbon exploration: A case study from the lower Silurian Longmaxi shale in the southeastern Sichuan Basin. *AAPG Bulletin*, 100 (5): 773-794.
- Liang, C., Jiang, Z. X., Zhang, C. M. et al., 2014. The shale characteristics and shale gas exploration prospects of the Lower Silurian Longmaxi shale, Sichuan Basin, South China: *Journal of Natural Gas Science and Engineering*, 21(12): 636-648.
- Liang, D. G., Guo, T. L., Bian, L. Z., et al., 2009. Controlling factors on the sedimentary facies and development of Palaeozoic marine source rocks. *Marine Origin Petroleum Geology*, 2(14): 1-19.
- Liu, S. G., Ma, W. X., LUBA Jansa, et al., 2011. Characteristics of the shale gas reservoir rocks in the Lower Silurian Longmaxi Formation, East Sichuan basin, China. *Acta Petrologica Sinica*, 27(8): 2239-2253.
- Loucks, R. G., Ruppel, S. C., 2007. Mississippian Barnett shale: Lithofacies and depositional setting of a deep-water shale-gas succession in the Fort Worth basin, Texas. *AAPG Bulletin*, 91(4): 579-601.
- Mei, M. X., Zeng P., Chu, H. M., et al., 2004. Devonian sequence-stratigraphic framework and its paleogeographical background in the Dianqiangui Basin and its adjacent areas. *Journal of Jilin University (Earth Science Edition)*, 34(4): 546-554.
- Mi, H. Y., Hu, M., Feng, Z. D., et al., 2010. Present conditions and exploration prospects of shale gas resource in China. *Complex Hydrocarbon Reservoirs*, 3 (4): 10-13.

- Mou, C. L., Zhou, K. K., Liang, W., et al., 2011. Early Paleozoic sedimentary environment of hydrocarbon source rocks in the Middle-Upper Yangtze Region and petroleum and gas exploration. *Acta Geologica Sinica*, 85(4): 526-531.
- Ochoa, J., Wolak, J., Gardner, M. H., 2013. Recognition criteria for distinguishing between hemipelagic and pelagic mudrocks in the characterization of deep-water reservoir heterogeneity. *AAPG Bulletin*, 97, 1785-1803.
- Pu, B. L., Jiang, Y. L., Wang, Y., et al., 2010. Reservoir-forming conditions and favorable exploration zones of shale gas in Lower Silurian Longmaxi Formation of Sichuan Basin. *Acta Petrolei Sinica*, 31(2): 225-231.
- Montgomery, S. L., Jarvie, D. M., Bowker, K. A., et al., 2005. Missis-sippian Barnett Shale, Fort Worth basin, north-central Texas: Gas-shale play with multi-trillion cubic foot potential. *AAPG Bulletin*, 89(2):155-175.
- Su, W. B., Li, Z. M., Frank, R. E., et al., 2007. Distribution of Black Shale in the Wufeng-Longmaxi Formations (Ordovician-Silurian), South China: Major Controlling Factors and Implications. *Earth Science (Journal of China University of Geosciences)*, 32(6): 819-827.
- Sun, H. C., Tang, D. Z., 2011. Shale gas formation fracture stimulation in the south Sichuan Basin. *Journal of Jilin University(Earth Science Edition)*, 41(1): 34-40.
- Teng, G. E., Liu, W. H., Xu, Y. C., et al., 2006. Comprehensive geochemical identification of highly evolved marine hydrocarbon source rocks: an example from Ordovician Basin. *Science in China*, 36(2): 167-176.
- Wang, Z. G., 2015. Breakthrough of Fuling shale gas exploration and development and its inspiration. *Oil & Gas Geology*, 36(1): 1-6.
- Wang, L. S., Zou, C. Y., Deng, P., et al., 2009. Geochemical evidence of shale gas existed in the Lower Paleozoic Sichuan basin. *Natural Gas Industry*, 29(5):59-62.
- Zhang, D.W., 2010. Strategic concepts of accelerating the survey,exploration and exploitation of shale gas resources in China. *Oil & Gas Geology*, 2(31): 135- 150.
- Zhang, J. C., Jiang, S. L., Tang, X., et al., 2009. Accumulation types and resources characteristics of shale gas in China. *Natural Gas Industry*, 29(12):109-117.
- Zhang, J. C., Xu, B., Nie, H. K., et al., 2008. Exploration potential of shale gas resources in China. *Natural Gas Industry*, 28(6): 136-140.
- Zhang, J. P., Tang, S. H., Guo, D. X., 2011. Shale gas favorable area prediction of the Qiongzhusi Formation and Longmaxi Formation of Lower Palaeozoic in Sichuan Basin, China. *Geological Bulletin of China*, 30(2-3):357-263.
- Zhang, S. C., Zhang, B. M., Bian, L. Z., et al., 2005. Development constraints of marine source rocks in China. *Earth Science Frontiers*, 12(3): 39-48.
- Zhang, S. C., Zhu, G. Y., 2006. Gas accumulation characteristics and exploration potential of marine sediments in Sichuan Basin. *Acta Petrolei Sinica*, 27(5): 1-8.
- Zhang, J. C., Xu, B., Nie, H. K., et al., 2007. Two essential gas accumulations for natural gas exploration in China. *Natural Gas Industry*, 27(11): 1-6.
- Zhou, W., Su, Y., Wang, F. L., et al., 2011. Shale gas pooling conditions and exploration targets in the Mesozoic of Fuxian Block, Ordos Basin. *Natural Gas Industry*, 31(2): 29-36.
- Zhu, Z. J., Chen, H. D., Lin, L. B., et al., 2010. Depositional system evolution characteristics in the framework of sequences of Silurian and prediction of favorable zones in the Northern Guizhou-Southeastern Sichuan. *Acta Sedimentologica Sinica*, 28(2): 243-253.
- Zou, C. N., Dong, D. Z., Wang, S. J., et al., 2010. Geological characteristics, formation mechanism and resource potential of shale gas in China. *Petroleum Exploration and Development*, 37(6):641-654.