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Sedimentary Characteristics and Paleoenvironment of Shale in the Wufeng-Longmaxi Formation, North Guizhou Province, and Its Shale Gas Potential

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ABSTRACT: The Paleozoic Wufeng-Longmaxi shale is one of the main horizons for shale gas exploration in Sichuan Basin. Outcrop, core and thin section observations, X-ray diffraction analysis, trace element geochemistry and other methods have been used to understand the sedimentary characteristics and identify hydrocarbon source rocks in suitable sedimentary paleoenvironments in the Wufeng-Longmaxi shale in northern Guizhou Province. The thickness of the Wufeng-Longmaxi Formation ranges from 20 to 200 m and it was mainly deposited on a deep-water shelf. The TOC content is high, up to 5.75%. The main non-organic minerals are detrital quartz and clay minerals, with a little plagioclase feldspar, potassium feldspar, calcite, dolomite and pyrite. There is also biogenic microcrystalline quartz. Six lithofacies have been identified: siliceous shale, clay shale, calcareous shale, silty shale, carbonaceous shale, and muddy siltstone. Using biological Ba, V/(V+Ni), TOC, V/Cr, B, Sr/Ba and other indicators, we estimate primary productivity, redox conditions and paleosalinity and show that the early stage of Wufeng-Longmaxi deposition occurred under strong anoxic conditions, high paleosalinity and yielded a high TOC content and an excellent potential shale gas source. The anoxic environment was destroyed at the late stages of Wufeng-Longmaxi deposition, the TOC content decreased, so that it is likely to be a high quality source rock. Organic pores acted as the key reservoir space in the shales, and the pores are mainly mesopose, with most pore diameters less than 20 nm. The siliceous shale has high TOC content and brittle mineral (quartz) content making it an important exploration target for shale oil and gas exploration.

KEYWORD: Wufeng-Longmaxi shale, sedimentary characteristics, geochemistry, paleo-environment restoration, shale gas.

0 INTRODUCTION

Shale gas is an unconventional natural gas source in which the shale is both the source and reservoir, and has become a new bright spot for global unconventional oil and gas exploration and exploitation by "fracking" (Zhang, 2010; Jarvie et al., 2007; Zhang et al., 2007; Montgomery et al., 2005). Studies show huge potential for shale gas resources in China, and there has been a major breakthrough in the Fuling district of the Sichuan Basin (Wang, 2015; Zhang et al., 2009). Research on geologic setting, reservoir formation, evaluation parameters and potential resources of shale gas show that the basic geologic conditions for gas formation are favorable in marine, continental and transitional phase basins in China (Hu et al., 2014; Li et al., 2013; Zhang J P et al., 2011; Zhang J C et al., 2008), notably the Early Paleozoic Cambrian Niutitang Formation and lower Silurian Longmali Formation in the Yangzi area (Zhang et al., 2011; Mi et al., 2010; Pu et al., 2010; Zou et al., 2010). Both of these two predominantly shale formations were deposited in hypoxic deep-water environments (Luo et al., 2016). Focus on the Wufeng-Longmaxi shale (WLS), Zou et al. (2010) first discovered nano-pores by utilizing nano-CT technology, initiating study of nanoscale pores in oil and gas reservoirs. Studies suggest that the WLS is dominated by sapropelic deposits, and has high

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hydrocarbon generation potential (Mou et al., 2011; Li et al., 2008; Zhang and Zhu, 2006). The shale porosity is controlled by mineral composition, lithofacies, total organic carbon (TOC) content, organic matter maturity and diagenesis (Liang et al., 2014; Liu et al., 2011).

There is consensus among researchers about organic matter enrichment mechanisms, their environments and main control factors of hydrocarbon source rocks in the Sichuan Basin (Sun and Tang, 2011; Chen et al., 2009; Liang et al., 2009; Wang et al., 2009; Tenger et al., 2006), but there have been few studies of shales in North Guizhou Province. The Chinese Geological Survey announced a major shale gas exploration breakthrough in the WLS of northern Guizhou Province in June 2015, and therefore northern Guizhou Province has become a focus of attention (Wang, 2015). The sedimentary environment controls the thickness and distribution of this organic rich shale and sedimentary geochemistry records its paleo-environmental settings and evolution (Zhang et al., 2005; Chen et al., 1996). The research described here focuses on the shale gas potential of the Wufeng-Longmaxi shale in North Guizhou Province, studying the lithofaces and sedimentary environment, to investigate exploration targets and the main control factors on the accumulation of shale gas, and to provide a theoretical framework for future shale gas exploration in the Sichuan Basin and other similar basins.

1 GEOLOGICAL SETTING

The study area is in the Chuandong tectonic and Chuannan tectonic belts in the southeast Sichuan Basin, in an area lying in northern Guizhou Province and southeastern Chongqing Municipality (Fig. 1a). The Sichuan Basin evolved from a passive continental margin from Sinian to Middle Triassic (Z1-T2) and from Jurassic to Quaternary it was essentially a foreland basin. The Z1-T2 succession is composed of 4 100–7 000 m marine strata followed by 3 500–6 000 m of Jurassic and later continental strata (Deng et al., 2010; Huang, 2009; Mei et al., 2004). In the Late Ordovician to Early Silurian periods a confined sea was formed, which provided low energy, anoxic deep-water conditions because of regional tectonic activity and global transgressions (Huang et al., 2011; Chen et al., 2009; Zhang et al., 2005). A set of fine clastic rocks, primarily black shales, the Wufeng-Longmaxi shale, settled during the depositional stage of the Early Silurian Longmaxi Formation with a thickness of 20–200 m (Zhou et al., 2014; 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 middle and lower parts are rich in organic matter (notably graptolites) overlain by silty shales (Fig. 1b) in which event deposits (e.g., turbidites) have been recorded (Liang et al., 2016). The gamma log shows a spike peak at the black shales of the basal-Silurian, and decreases upward (Fig. 1b).

2 DATABASE AND METHODOLOGY

Samples were collected from 10 exposed field profiles (locations shown in Fig. 1b). The basic data included 670 m of recorded exposures, thin sections, mineral compositions determined by X-ray diffraction, source rock data (vitrinite reflectance, TOC, maceral composition) and element analysis. Samples were collected at 1.25 m intervals across the outcrop of the Lujiao Formation. Gamma ray values at outcrop were collected at 25 cm intervals by a portable γ spectrometer (SAIC GR-135).

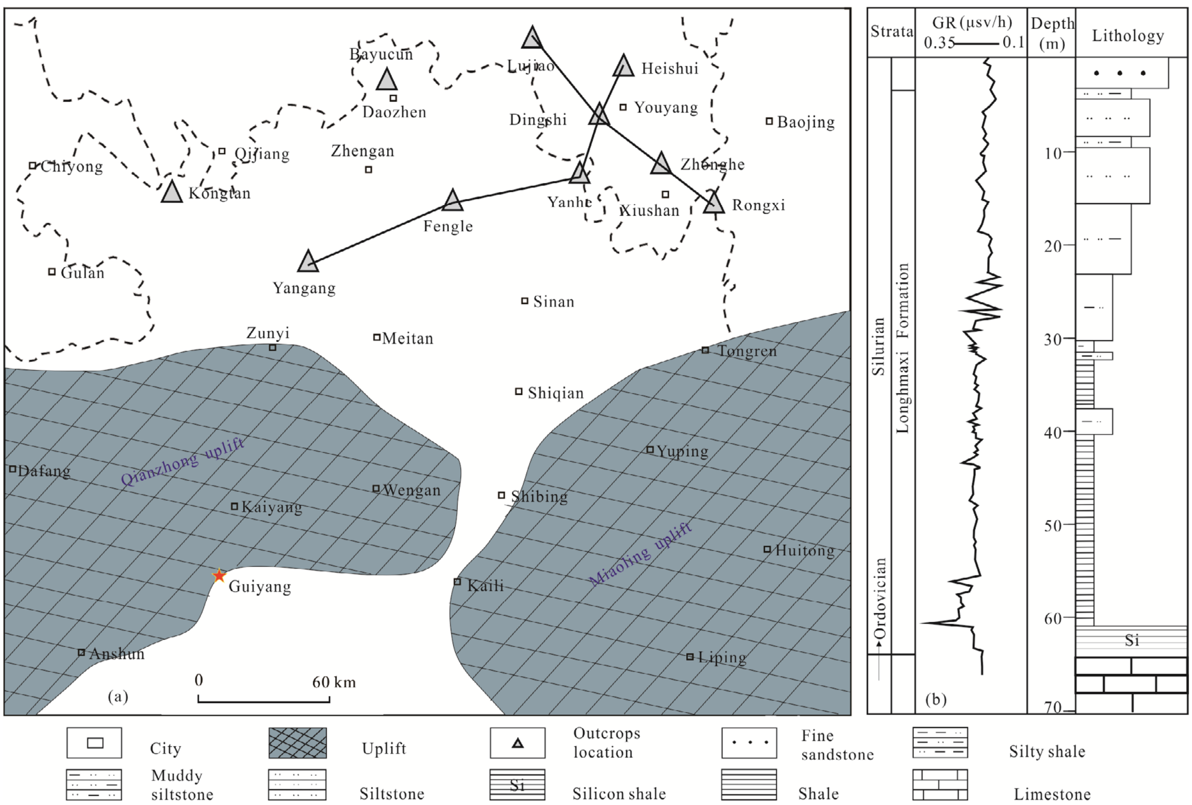

Figure 1. Structural units of the study area, sample distribution and lithologic key (a) to stratigraphic column of the Wufeng-Longmaxi shale (b). Comparative lithofacies logs of profiles joined by firm lines are given in Fig. 11.

Mineral X-ray diffraction was performed at the experimental data center of the Research Institute of Petroleum Exploration and Development, Chinese National Petroleum Company (CNPC) in accordance with standard test method SY/T 6210-1996 (China University of Petroleum (East China), 1996), "X-ray diffraction quantitative analysis method of clay minerals and common non-clay minerals in sedimentary rocks", using a D/max-2500 TTR. Source rock data (vitrinite reflectance, TOC, maceral composition) were obtained at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences using a test technique from Tissot and Welte (1984). Organic matter maturity and micro-component tests were performed in accordance with the standard method SY/T 5124-2012 (National Petroleum and Natural Gas Standardization Technical Committee, 2012), "Sedimentary rock vitrinite reflectance measurement methods", using a LABORLUX 12POL fluorescence microscope and MPV-3 microscope photometer with a total magnification of ×800. Vitrinite reflectance values were calculated using the formula: $Ro=0.618B_{Ro}+0.4$, (B_{Ro} means bitumen reflectance) equivalent to vitrinite reflectance because vitrinite is absent in Pre-Devonian sequences (Zhang and Zhu, 2006). Organic carbon content was determined by test methods GB/T 19145-2003 (Research Institute of Petroleum Processing, 2003) and GB/T 18602-2012 (National Petroleum and Natural Gas Standardization Technical Committee, 2012). The test temperature was 27 °C, and the testing equipment was a Leco carbon-sulfur analyzer and gas-show evaluation instrument. Adsorption simulation experiments and the heat-press simulations were performed at Henan Polytechnic University. The adsorbed gas content was determined by isothermal adsorption simulation, which measured the adsorbed gas content at constant temperature and increasing pressure. The lithology of the Wufeng-Longmaxi Formation shale was determined by exposure descriptions, thin section observations and mineral composition data. Source rock analysis were primarily based on vitrinite reflectance, TOC and maceral compositions; but backscatter (BS) SEM observation was also used.

3 RESULTS

3.1 Mineralogy

In the study area, the Longmaxi shale is mainly composed of 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%. Illite and illite-smectite mixed layers dominate in the clay minerals, with relative contents being 39%–57% and 29%–53% respectively (Fig. 2b). Quartz contents range from 25%–73.0%, with an average of 40.8%, mainly occurring as terrestrial silt grains transported into the basin but bio-quartz and diagenetic quartz can also be found among the clay minerals. The bio-quartz is mainly from diatoms, radiolarians and sponges, and the diagenetic quartz is mainly clay-size grains floated in clay minerals released during clay mineral illitization. The carbonate minerals mainly occur as fracture fillings and cements. Because of the deep-water reduction environment, pyrite is relatively abundant and mainly occurs as framboidal pyrite.

3.2 Lithofacies

The shale is furtherly classified depending on subordinate mineral and biogenetic mineral taking the frequently-used 25% as a limit value. Thus, as calcite content is more than 25%, the lithofacies is named calcareous shale. According to the classification, six lithofacies have been identified.

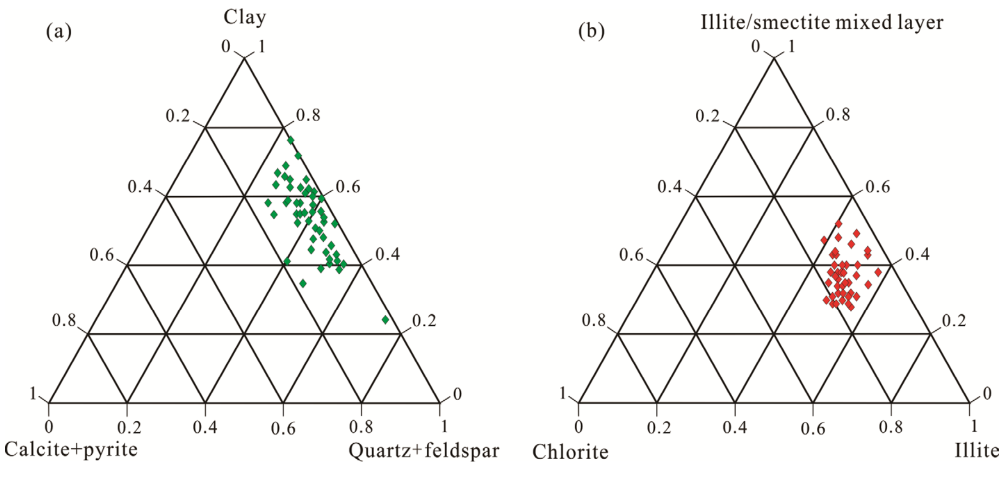

Figure 2. Mineral compositions of Wufeng-Longmaxi shale in the study area.

Table 1 Mineral content of different outcrops. Locations in Fig. 1

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)	0.2–10.0 (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)	0.1–6.0 (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)	0.1–3.0 (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)	0.1–4.0 (1.16)

3.2.1 Siliceous shale

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

3.2.2 Clay shale

Clay shale is characterized by dark-colored laminae rich in graptolites, with high TOC and clay mineral content (Fig. 3b). Few silt grains float among in the clay (Fig. 4b). This lithofacies was mainly deposited in a deep water environment from a quiet water body with little terrigenous input.

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 ranging of 25%–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 lighter laminae are dominated by silt grains, mainly quartz and feldspar, which account for 25% to 50% floating among clay minerals in thin section (Fig. 4d).

3.2.5 Carbonaceous shale

Carbonaceous shale is black and gray with well-developed laminae in hand specimens (Fig. 3e). The Carbonaceous shale contains a large number of carbonized organic matter, 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), with concavo-convex and sutured contacts. The lithofacies is mainly developed in the upper WLS, indicating shallower water bodies and increased input of terrestrial debris in the late Wufeng-Longmaxi period.

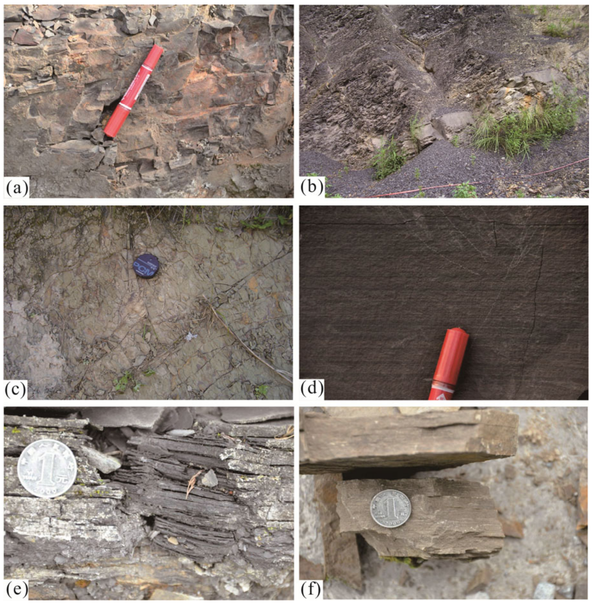

Figure 3. Outcrop characteristics of Wufeng-Longmaxi shale. (a) Black siliceous shale with massive bedding and high hardness; (b) black claystone with laminated bedding; (c) gray siltstone; (d) silty shale with horizontal bedding and cross-layer fractures; (e) black carbonaceous shale with horizontal bedding and low hardness; (f) gray-green muddy siltstone.

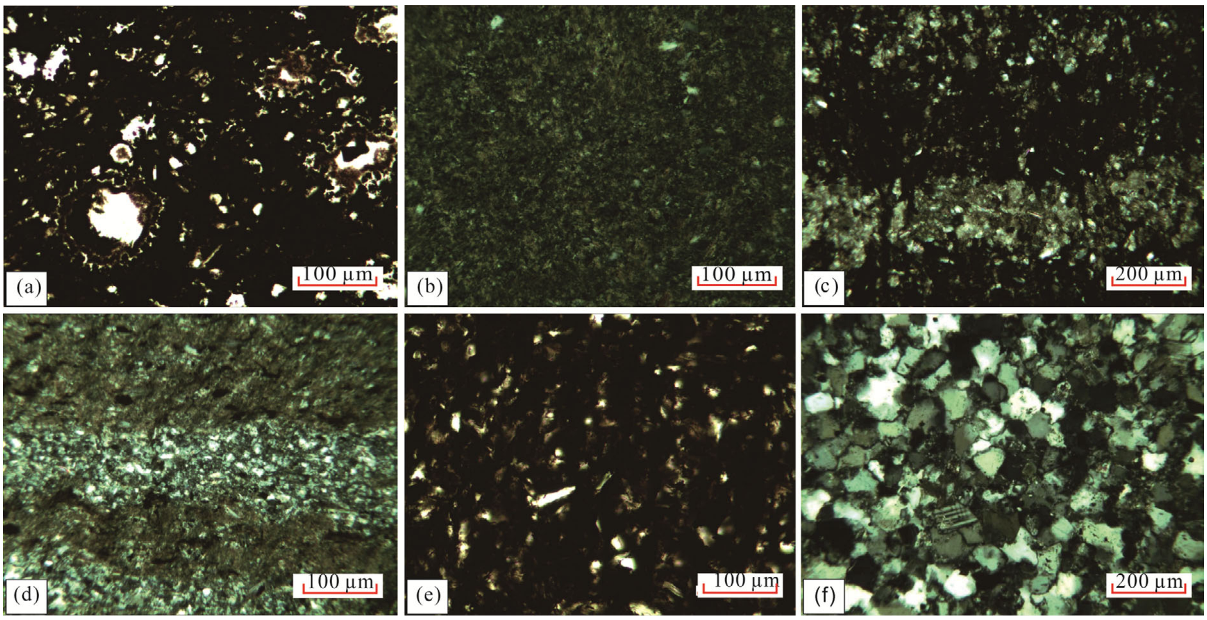

Figure 4. Microscopic features of lithologies from different lithofacies. (a) Black siliceous shale with diatoms, plane polarized light (PPL); (b) black shale with a small amount of quartz floating in clay minerals, cross-polarized light (CPL); (c) laminated calcareous shale (PPL); (d) silty shale with quartz grains floating in the clay minerals interbedded with silt layers (PPL); (e) carbonaceous shale rich in organic matter (PPL); (f) siltstone with quartz and feldspar grains with sutured intergranular contacts (CPL).

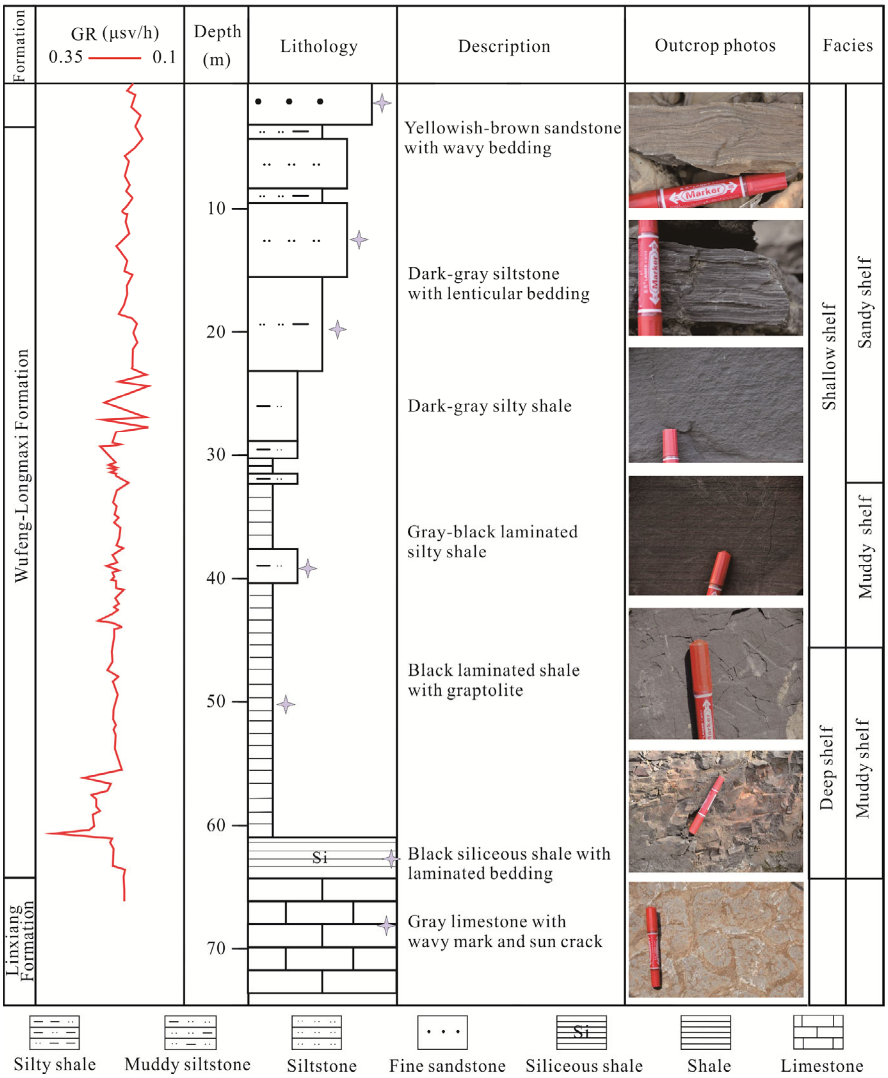

Figure 5. Column section through logged Lujiao Formation outcrops.

The siliceous shale and clay shale are characterized by laminated bedding, abundant organic matter, graptolites and pyrite, indicating a deep-water hypoxic depositional setting, which was mainly present during deposition of the lower part of the WLS (Fig. 5). Calcareous shale and silty shale are laminated with relatively low TOC content and high contents of terrigenous materials such as quartz and feldspar. They mainly occur in the middle WLS (Fig. 5). Muddy siltstone was mainly developed in the upper WLS (Fig. 5).

The lithofacies distribution shows that terrigenous silt increases and the TOC content decreases from bottom to top. The GR log has a peak value in the black shales in the basal WLS, and gradually reduces upward. The vertical depositional relationships of these lithofacies, their TOC content and GR values show that the water body shallowed upwards, while 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. The sutured contacts showed in silty shale and muddy siltstone are suggested to be caused by pressure solution during the late stage of diagenesis, which is consistent with the *R*o value. Strong diagenesis results a great of reduce porosity and permeability of the shales.

3.3 Source Rock Characteristics

The organic macerals in the WLS of the study area is mainly massive streaky asphaltene, with a few fragments of asphaltene (Fig. 6). The organic matter in the shale could produce abundant shale gas because its thermal maturity is high enough. The *R*o value of outcrop samples ranges from 1.55%–3.20% with an average of 2.36% suggesting the shale has reached a mature to post-mature stage. This *R*o value is much higher than that of American gas shale, in which *R*o is 0.4%–2.0%. The TOC content not only influences the amount of potential hydrocarbon generation, but also the adsorbed gas content (Zhou et al., 2011; Zhang et al., 2009). A higher TOC content indicates a higher capacity for hydrocarbon generation and a 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%, chosen as the minimum TOC content to produce industrial shale gas. The TOC content of WLS in the study area is higher than this (Fig. 7). The average TOC content of studied outcrops is over 2%, which has apparently reached the conditions to produce industrial shale gas.

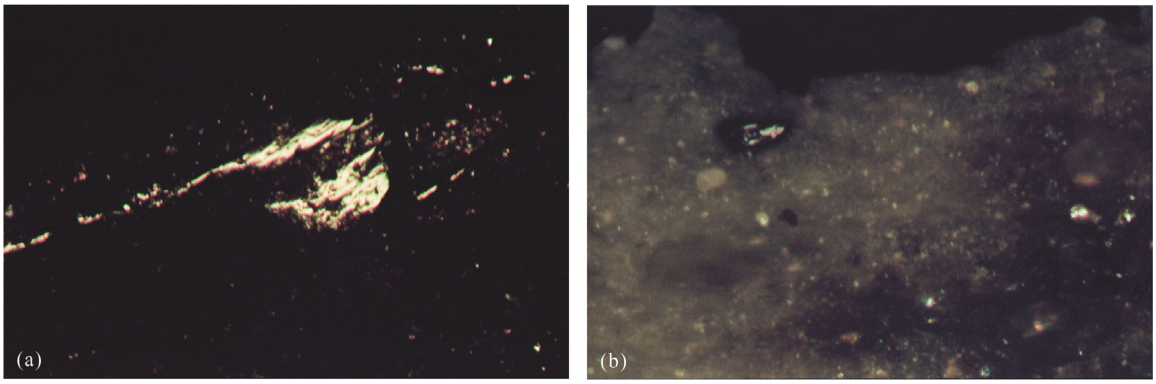

Figure 6. Organic matter morphology of WLS from the Daozhen outcrop (a) and Fengle outcrop (b).

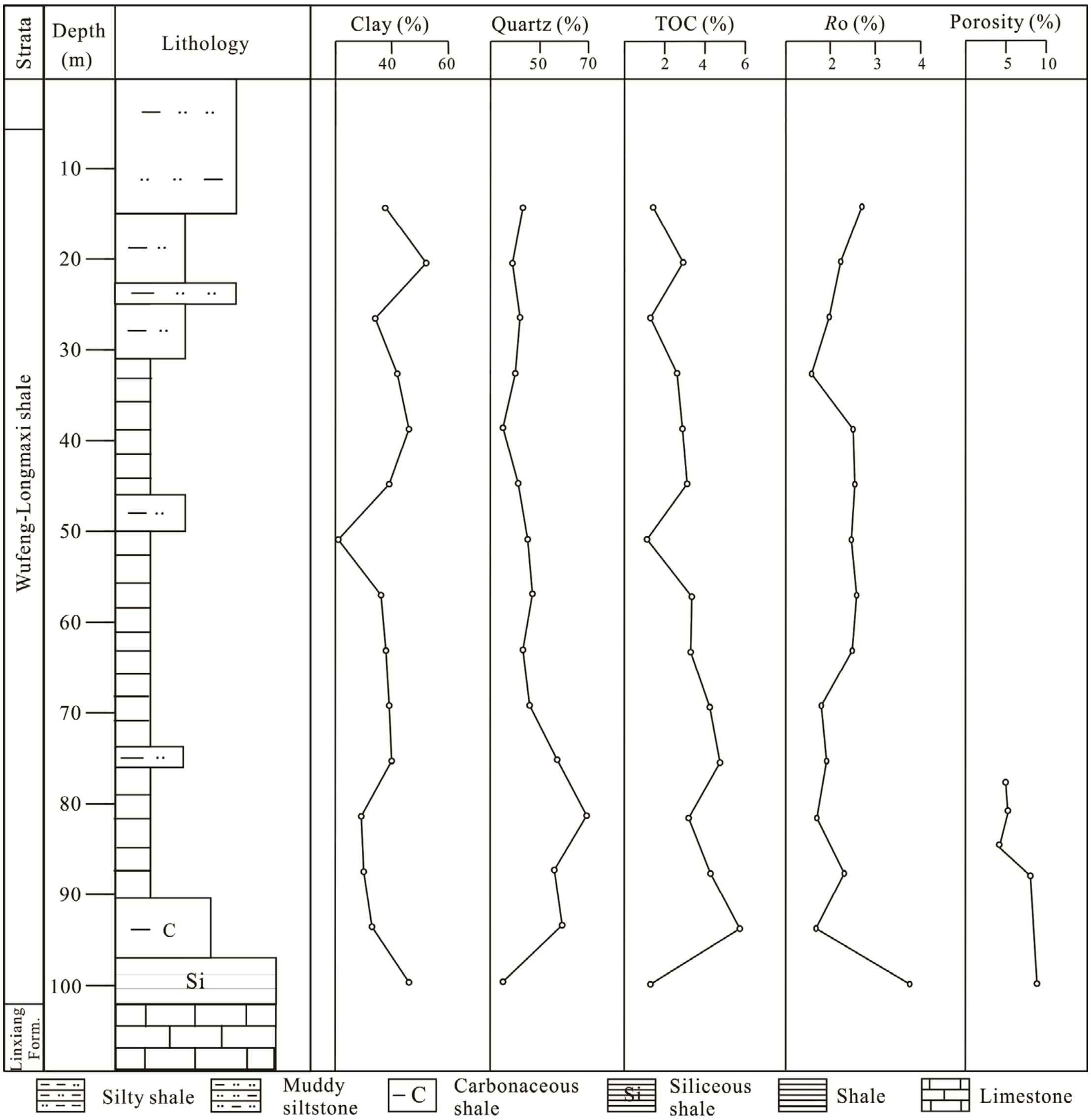

Figure 7. Mineral content, TOC, *R*o and porosity of shale at the Kongtan outcrop.

4 DISCUSSION

4.1 Element Analysis and Sedimentary Environment

Principal component analysis of geochemical data complements and reinforces the stratigraphic features shown in Tables 2, 3. Trace element compositions have been used to analyze the sedimentary environment. Bio-Ba and TOC content were used as proxies for paleoproduction; B, Sr/Ba and B/Ga as proxies for paleosalinity; and V/Cr, V/(V+Ni) ratios as proxies for anoxic conditions (Ochoa et al., 2013; Algeo and Maynard, 2004; Hatch and Leventhal, 1992). The geochemical evolution of the sedimentary sequence recorded the WLS in the Lujiao outcrop is illustrated in Fig. 8.

4.1.1 Paleo-salinity

The three parameters B, B/Ga and Sr/Ba are used to analyze paleosalinity. The B content ranges from 10 to 120 μg/g, with an average value of 74.28 μg/g. The change of B content shown in Fig. 8 suggests that the it decreases upwards and from a peak at the bottom, with a maximum value of 120 μg/g. The B values of two samples in Wufeng Formation are significantly less than that of Longmaxi Formation. the value of B/Ga can also be used to analyze paleosalinity because of the difference in element migration ability between B and Ga. The results show that the evolution trend of B/Ga and B content are consistent, reflecting high paleosalinity at the bottom decreasing upwards. The high Sr/Ba value indicates high salinity, and Fig. 8 shows that Sr/Ba value changes strongly and decreases upwards.

4.1.2 TOC content

The TOC content is an important evaluation parameter of source rocks, reflecting the abundance of organic matter and to a certain extent the redox condition of the water body from which the shale was deposited because organic matter can be preserved well in a strongly reducing environment. The TOC content of the WLS in the study area is generally high. The TOC content of the Kongtan outcrop decreases upwards and ranges from 1.0% to 5.75%, with an average of 3.0% (Fig. 7). The TOC content of the Lujiao outcrop ranges from 0.74% to 4.45%, with an average of 1.65% and decreases upwards (Fig. 8). The thickness of effective source rock is up to 45 m, which suggests that the WLS should act as good source rock.

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 primary productivity. Paleoceanographers believe that biogenic barium can act as a good indicator of primary productivity because of its higher preservation rate and positive correlation with productivity. Due to the correspondence between high primary productivity rate and Ba, Teng et al (2006) proposed a relationship between productivity and biogenic barium, so that paleocean productivity can be estimated by using barium abundance, and indicate the development of quality source rocks.

The abundance of biogenic barium (bio-Ba) cannot be directly tested, but is usually calculated by an equation relating total barium, biogenic barium and terrigenous barium 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(Ba) : W(Ti))PAAS is the ratio of terrigenous Ba to Ti in standard late Archean (PASS) shale with a value of 0.11 while W(Ti-Total)×(W(Ba) : W(Ti))PAAS represents terrigenous barium content of the sediments.

The total content of bio-Ba in WLS is high overall, with an average of 420.84 μg/g decreasing upward, suggesting that productivity is highest at the bottom and decreases gradually upward.

4.1.4 Redox conditions

The preservation and abundance of trace elements in the sedimentary record are affected by redox conditions of the water body and therefore, some elements may be used to characterize the redox conditions during deposition. Such indicators are mainly siderophile and sulfophile elements, including V, Ni, Cr, Mo, Cu, Zn, Cu, U, etc. (Teng et al., 2006; Tenger et al., 2006). Hatch et al. (1992) concluded from study of black shale in North America that high metal (Cd, Mo, V, Zn, etc.) content, high sulfur content, DOP≥0.67, and V/(V+Ni)≥0.54 indicate anoxic environments containing H_2S. It is generally believed that V/Cr>2 indicates an anoxic environment, and the V/Cr ratio of Wufeng-Longmaxi Formation is mostly greater than 2, and consequently shows anoxic conditions. An anoxic reducing environment is a necessary condition for preservation of organic matter and therefore TOC content reflects the redox condition of the water body to some extent.

This paper selects three parameters V/Cr, V/(V+Ni) and TOC as reducing environment discrimination indicators and thereby analyzed environments that should produce quality source rocks (Table 2). Both the values of V/Cr and V/(V+Ni) show an upward decreasing trend so that according to the criteria of Hatch et al. (1992), the samples were deposited under a reducing environment with varying degrees of anoxia, which might be related to regional climate changes. The TOC content is large with an average of 1.65%. The largest values are at the bottom of the Wufeng-Longmaxi Formation, which can be up to 4.45%, decreasing upward.

4.2 Deposition of Siliceous Shale and Its Significance

The WLS siliceous shale is characterized by high quartz content and among the TOC numerous silica-rich organisms have been found (Fig. 4a). The quartz content in the siliceous shale has a positive correlation with the TOC content, suggesting the silica in the shale is bio-silica rather than from a terrestrial source (Liang et al., 2016; Loucks and Ruppel, 2007). Published studies show that siliceous shale is related to upwelling which brings nutrients to the waterbody and encourages blooms of siliceous organisms. The geochemical analysis suggest that the interval where siliceous shale developed is characterized by an abrupt increase in paleo-salinity and reduction (Fig. 8) which is thus important evidence for upwelling.

The siliceous shale has a high TOC content, which means it has shale gas generation potential. Organic pores have been suggested as the key storage space for the shale gas in the WLS. Higher TOC content means more organic pores. Pressure solution fractures (Fig. 4d) might also provide pore spaces. The siliceous shale has a high brittle mineral content (quartz) (up to 85%) which would be conducive to hydraulic fracturing. The characteristics of source rock, reservoir storage space, porosity, permeability and brittleness all suggest that the siliceous shale generated by upwelling provides the best targets for shale gas exploration in the study.

Table 2 Statistics of TOC, V/Cr, V/(V+Ni) of different outcrops

	Kongtan	Lujiao	Dingshi	Daozhen	Rongxi	Fengle	Yanhe
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 (2.60)	0.44–2.54 (1.49)	0.58–4.60 (2.85)
V/Cr	1.20–11.70 (4.63)	1.60–12.20 (2.66)	1.70–3.25 (2.05)	2.40–12.80 (3.48)	1.25–11.20 (3.6)	2.20–10.60 (5.06)	1.50–8.00 (3.13)
V/(V+Ni)	0.69–0.90 (0.77)	0.60–0.96 (0.78)	0.70–0.85 (0.80)	0.58–0.92 (0.76)	0.60–0.89 (0.69)	0.55–0.88 (0.75)	0.64–0.96 (0.82)

Data are shown in range (ave.).

Table 3 Trace element contents of the WLS at the Lujiao outcrop

Samples	Element content (μg/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	8	6	32	285	0.30	0.30	1.77	0.13	0.47
2	34	741	55	36	73	11	87	10	37	478	0.30	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	1.00	2.72	2.12	2.43
5	84	182	57	240	61	50	83	19	127	287	0.56	1.29	2.90	4.61	3.37
6	85	202	68	220	57	62	137	20	105	312	0.86	1.75	4.04	3.05	4.40
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	0.90	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	3.30	3.56
10	71	135	56	232	36	27	75	14	108	413	0.95	1.40	3.00	2.37	3.05
11	72	153	50	191	35	37	75	13	100	377	0.83	1.42	3.00	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	1.30	3.31	0.38	3.50
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	3.20	2.55	3.43
19	88	120	51	190	27	31	75	16	99	268	1.20	1.45	3.29	2.40	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	3.80	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	1.50	3.09	2.90	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	3.20	0.30	3.54
27	75	97	57	209	23	23	71	22	94	296	1.16	1.50	3.06	2.18	3.42
28	81	102	62	327	37	32	85	24	56	405	1.30	1.37	3.25	0.32	3.74
29	79	89	54	186	23	23	64	22	94	357	1.28	1.40	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	1.40	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	2.90	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	2.70	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	1.60	1.62	3.46	3.50	2.88

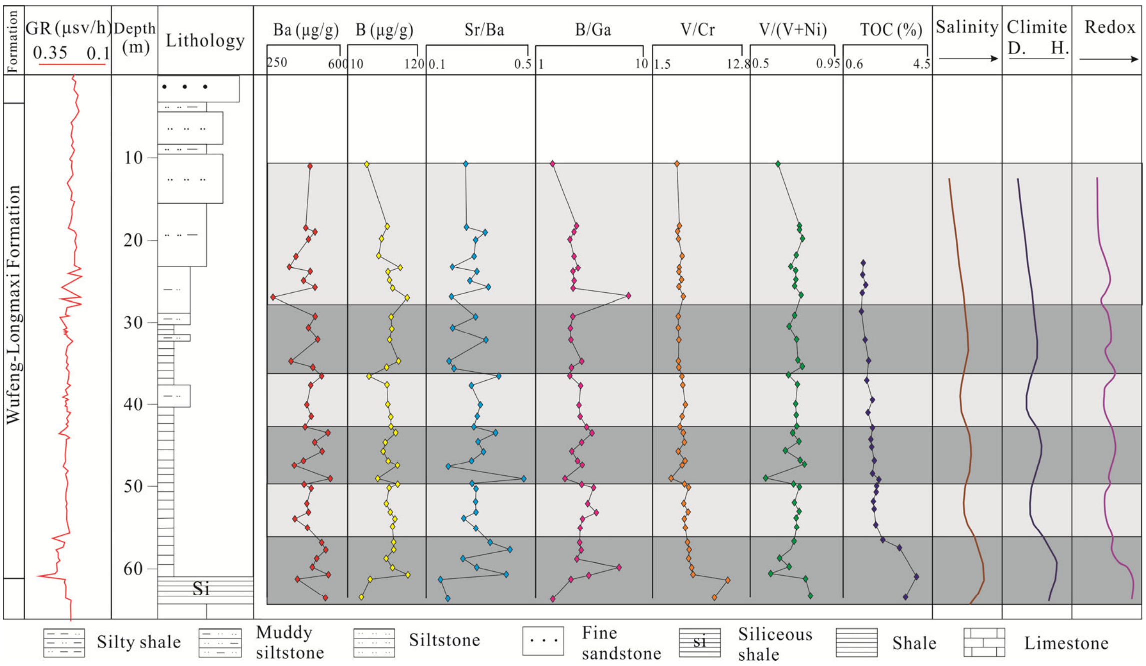

Figure 8. Geochemical analysis of the Lujiao outcrop as an indicator of the sedimentary environment of the WLS.

4.3 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 could reach 1 m^3/t at 0.5 MP, >2 m^3/t at 2 MP, up to 3.2 m^3/t at 5 MP pressure (Fig. 9). These data show potentially relative high gas content. Besides the TOC content, the shale gas content is also affected by the mineral composition and porosity. Most pore diameters are less than 20 nm, mainly concentrated at about 10 nm (Fig. 10). Rouquerol et al. (1994) proposed the following pore-size classification: micropore (D<2 nm), mesopore (2 nm<D<50 nm) and macropore (D>50 nm), according to which the pores in the study area are mainly mesopores, consistent with the organic pores acting as key reservoir spaces in the studied shale. A high TOC content is the key controlling factor for shale gas content and reservoir space development and therefore organic rich lithofacies and intervals are important exploration targets (Jiang et al., 2015).

As mentioned above, organic matter enrichment is controlled by the sedimentary environment and strong reduction, high paleosalinity and humid climate are favorable conditions. Trace element analysis suggests that the Lower WLS is a favorable interval. The siliceous shale has high TOC content and brittle mineral (quartz) content, and so should be easy to fracture. Thus, siliceous shale should be an important interval for shale oil and gas exploration. According to the lithofacies and sedimentary facies shown in connected well profiles (Fig. 11), the northeast is the most favorable exploration area.

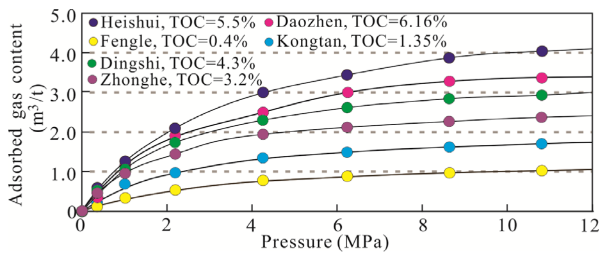

Figure 9. Adsorbed gas content of the WLS.

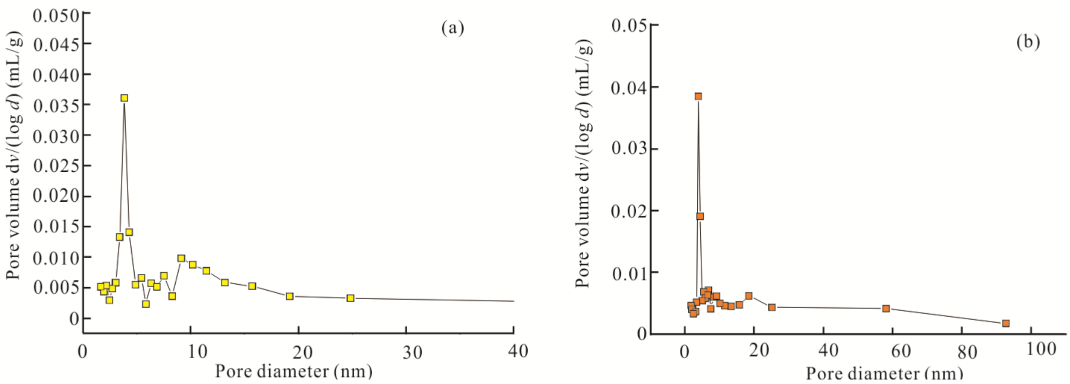

Figure 10. Pore diameters of the WLS.

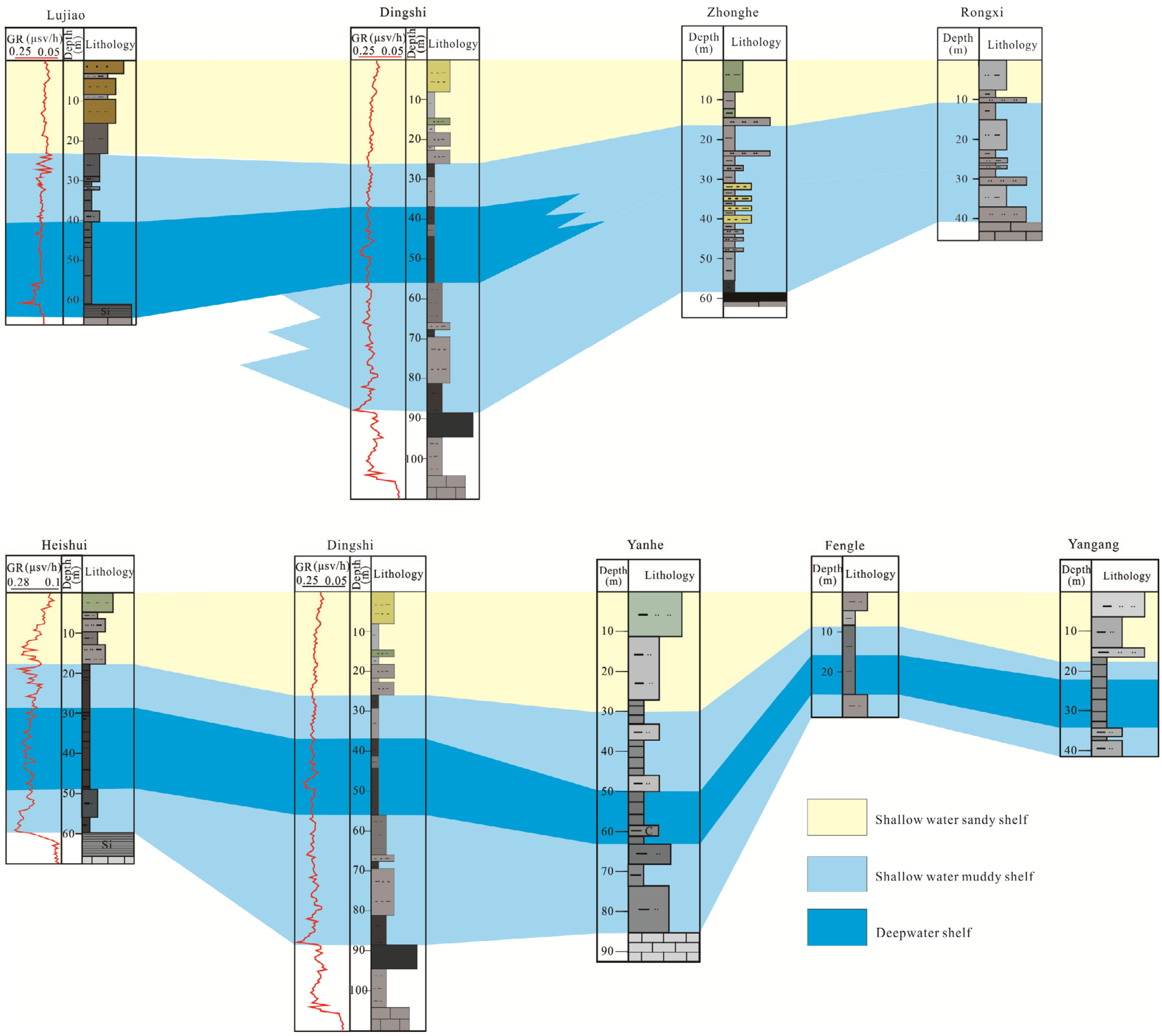

Figure 11. Profile correlation chart through the study area showing lithofacies distribution.

5 CONCLUSIONS

The Paleozoic Wufeng-Longmaxi shale (WLS) is one of the main horizons for shale gas exploration in the Sichuan Basin. The non-organic minerals are quartz and clay minerals, along with a little 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. Using biological Ba, V/(V+Ni), TOC content, V/Cr, B, Sr/Ba and other indicators, we have estimated primary productivity, redox conditions and paleosalinity. The results show that the early stage of deposition of the WLS had strong anoxic conditions, high paleosalinity and high organic carbon content. Geochemical indices also show that the anoxic environment was destroyed late in the deposition of WLS and the TOC content decreased, so it is not conducive to shale gas generation as a good source rock. The organic pores act as a key reservoir space in the shales, and the pores are mainly mesopores with most pore diameters less than 20 nm. The siliceous shale has high TOC content and brittle mineral (quartz) content, important parameters for shale oil and gas exploration. The northeast is the most favorable exploration area.

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