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Depositional Model and Controlling Factors of High-Quality Shales of the Wufeng and Longmaxi Formations in Western Chongqing, Sichuan Basin, China

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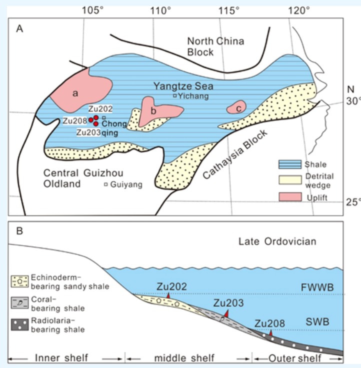

ABSTRACT: The enrichment of organic matter is the foundation for a high-quality shale deposition. It is generally believed that high productivity and persistent anoxic conditions facilitate the preservation and enrichment of organic matter. However, there is a lack of investigation into how the dynamic combination of productivity and anoxia affects organic matter enrichment. Here, the black shales of the Wufeng Formation and Longmaxi Formation in the western Chongqing area were selected, where oceanic anoxia and high productivity evolved as a function of the water depth. The main findings were as follows: (1) the distribution of high-quality shales in the Upper Ordovician Wufeng Formation and the Lower Silurian Longmaxi Formation is closely related to the oxygen minimum zone (OMZ), indicating that the physicochemical conditions within the OMZ zone facilitated the development of high-quality shale; (2) in the late period of the Wufeng Formation, intense ocean upwelling in the middle shelf and outer shelf regions caused high productivity where thick-bedded high-quality shales were deposited; and (3) in the early period of the Longmaxi Formation, ocean upwelling weakened, accompanied by the expansion of the OMZ to shallow water regions, and high-quality shales were widely distributed. Based on the above findings, two depositional models were proposed to account for the formation of high-quality shales, and it is suggested that intense ocean upwelling during the late period of the Wufeng Formation and OMZ expansion during the early period of the Longmaxi Formation played crucial roles in facilitating the formation of high-quality shales. These two models present the spatial and temporal variability of high-quality shale development for the first time and can guide shale gas exploration and development strategies.

1. INTRODUCTION

The Sichuan Basin is located in South China and is rich in marine shale gas resources. It is estimated that[1] the total amount of shale gas in the Sichuan Basin is 57.27×10^{12} m^3 with the Wufeng and Longmaxi shale possessing a high reserve of 2.0×10^{12} m^3. Several national shale gas demonstration zones have been established in the Luzhou, Weiyuan, and Fuling districts[2,3] where shale gas production remained high, reflecting the great potential and benefits of shale gas resources in the Sichuan Basin.

Deep-buried shale in the Sichuan Basin, over 4500 m beneath the surface, is the future target in which over 60% of shale gas is trapped.[4,5] However, it is a great challenge to explore the deeply buried shale, due to the created complex distribution of geostresses in deep-buried depth[6] and the uncertain distributions of high-quality shales in different tectonic zones,[7] the latter of which are the key to exploration of deep shale gas. To address this issue, previous researchers have conducted numerous studies and the development of high-quality shales has been attributed to several factors such as redox conditions, marine primary productivity, terrestrial clastic input, tectonic evolution, and sea level fluctuations; these factors complicate the prediction of high-quality shales of the Longmaxi Formation (Yan et al.)[8] and control the transformation of redox conditions (Dong et al.; Lu et al.).[9,10] At the microscale, size and morphology of micropores have a significant effect on the gas state and content of trapped gas within shale reservoirs (Gao et al.),[11] and the structure of micropores in different lithofacies displays distinct gas storage capacity of organic matter (Lin et al.).[12] These studies provide basic theoretical guidance for shale gas exploration and development in the Sichuan Basin but with several controversies: discrepancies lie between the interpretations of the depositional environment of the lowermost Longmaxi Formation as being sulfidic[13,14] versus oxic[15] as well as between high productivity[16] and low productivity.[13,17] The contradictions resulted from (1) a lack of standard classification of marine shale, making it difficult to perform comparisons of

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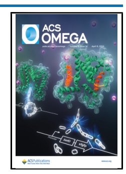

shale among different regions and (2) a lack of a continuous transect from shallow water to deep water that can reveal spatial and temporal heterogeneity of marine shales. Therefore, it is necessary to trace controlling factors of high-quality shale along a continuous transect based on high-resolution bathymetry and geochemistry. In this study, a continuous transect from the shallow shelf to the deep shelf in western Chongqing was selected, and it is aimed to reveal the controlling factors of high-quality shale in spatial and temporal views, by using the geochemical proxies including paleoproductivity, paleoredox, and ocean upwelling.

2. GEOLOGICAL BACKGROUND

During the late Ordovician, the Yangtze Plate converged with the Cathaysia Block, forming numerous paleo-uplifts at the plate boundary and changing the appearance of the Yangtze Sea in the Early Paleozoic.[18] The Sichuan Basin belongs to the Upper Yangtze Plateau Craton Basin, which is bounded by the Guizhou Oldland in the south, the Central Sichuan Paleouplift in the west, the Yichang Paleouplift in the east, and the Yangtze Sea in the north (Figure 1a). The outer shelf was located in the northeastern and southwestern parts of the Sichuan Basin, and western Chongqing was located in the shallow water regions in the central part of the Sichuan Basin between the two deepwater basins.[19] The stratigraphy of the upper Wufeng to lower Longmaxi Formations was established by Chen et al., via the application of both graptolite and logging (Table 1).

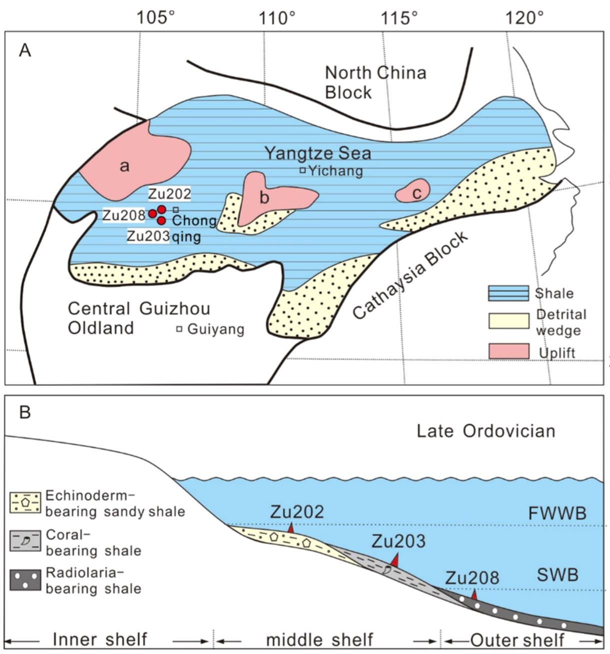

Figure 1. (a) Paleogeography of the Sichuan Basin during the Late Ordovician (modified from Wang et al.). (b) Depositional transects along Zu202, Zu203, and Zu208 in the Chongqing area (Chen et al.). FWWB: fair weather wave base and SWB: storm wave base.

The Wufeng and Longmaxi Formation shale in the western Chongqing region is rich in drilling, coring, and logging data and is one of the most studied regions in the Sichuan Basin. Based on these data, the upper Wufeng Formation and the lower Longmaxi Formation sedimentary paleogeography was reconstructed by Chen et al.[20] Microfacies analysis showed that in the late period of the Wufeng Formation, a significant regression occurred in the western Chongqing area, resulting in the exposure of shallow waters in the northwest and southeast of the study area and fine sandy shales containing benthic bioclasts widely developed in the middle and deep water regions. In the early period of the Longmaxi Formation, a rapid transgression occurred and a set of homogeneous siliceous shales were widely deposited in the study area. The microfacies analysis provided a continuous, high-resolution section transect of the studied wells: well Zu202 was deposited in the inner shelf; well Zu203 was located in the middle shelf; and well Zu208 was deposited in the outer shelf regions (Figure 1b). This continuous transect can provide a high-resolution spatial and temporal framework for tracing the shale formation process and mechanism.

3. RESEARCH METHODS

The shale samples of the Wufeng Formation and Longmaxi Formation in the study area were sampled with high resolution, and a total of 258 samples were tested for major elements, trace elements, and total organic carbon (TOC) contents. All of the tests were performed in the State Key Laboratory of Biogeology and Environmental Geology, China University of Geosciences (Wuhan). The main elements were analyzed by the X-ray melting method and determined by an XRF-1800 wavelength scanning X-ray fluorescence spectrometer. Based on the repeated tests of two national standard samples (GSR-5 and GSR-6), the error of the main elements was better than ±10%. Trace element analysis uses an Agilent 7500 inductively coupled plasma mass spectrometry (ICP-MS) instrument to complete the analysis and test after acid dissolution of the sample. The total organic carbon (TOC) was tested with a Leco 244 carbon analyzer. According to the repeated tests of the international standard sample AR4007, the error of TOC was better than ±0.2%.

The standard criteria for shale reservoir classification were employed from the scheme of the CNPC Chuanqing Drilling Engineering Company Limited International Ltd. (Table 2). Based on the standard criteria for each parameter, class I scored 1, class II scored 0.7, and class III scored 0.4. Then, a comprehensive evaluation of shale was performed by using a weighted approach, and the weighting coefficients for each

Table 1. Stratigraphy of the Wufeng Formation and Longmaxi Formation Based on the Graptolite and Logging (after Chen et al.)

formation	member	submember	bed	graptolite zone	stage	series
Longmaxi	Long 1 (L-1)	Long 1_2 (L-1_2)		LM6–8	Rhuddanian	Lower Silurian
		Long 1_1 (L-1_1)	Long 1_1^4 (L-1_1^4)	LM5		
			Long 1_1^3 (L-1_1^3)	LM4		
			Long 1_1^2 (L-1_1^2)	LM2–3		
			Long 1_1^1 (L-1_1^1)	LM1	Hirnantian	Upper Ordovician
Wufeng	Guanyinqiao			WF4		
	graptolite shale			WF2–3	Katian	

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Table 2. Criteria for Shale Classification, Employed from the Enterprise Standard of CNPC Chuanqing Drilling Engineering Company Limited

evaluation parameters	units	individual classifications and scores		
		I	II	III
TOC	%	>3	2−3	<2
porosity	%	>5	3−5	<3
		>4	3−4	<3
free and adsorbed gas volume	m^3/t	>3	2−3	<2
brittleness index	%	>55	35−55	<35

parameter are 0.2, 0.3, 0.3, and 0.2 for porosity, TOC, gas contents, and brittleness index, respectively. The formula for the shale comprehensive evaluation is shale index = 0.2 × porosity classification score + 0.3 × TOC classification score + 0.3 × gas content classification score + 0.2 × brittleness index classification score. A shale index ≥0.85 is a denoted as class I reservoir, with >0.6 as a class II reservoir and <0.6 as a class III reservoir.

4. RESULTS AND DISCUSSION

4.1. Microfacies Analysis and Paleoceanographic Interpretation. Nine microfacies were identified in this study based on their petrographic features and fossils (Table 3) and data sourced from Chen et al.[20] The results of microfacies analysis enable a high-resolution reconstruction of eustatic sea level changes, a crucial factor governing the enrichment of organic matter. These nine microfacies can be grouped into sedimentary environments corresponding to the inner shelf, middle shelf, and outer shelf. Calcareous shale, fine sandy shale, and bioclastic limestone are interpreted to be deposited in the inner shelf regions; silty shale, sponge-bearing siliceous shale, and coral-bearing siliceous shale correspond to the middle shelf; and radiolaria-bearing siliceous shale, siliceous shale, and tuffaceous shale are interpreted to be deposited in the outer shelf. On the basis of microfacies analysis, high-resolution eustatic sea level curves have been established, and it shows that a rapid regression occurred between the transition of Wufeng and Longmaxi Formations, which is immediately followed by a rapid transgression at Bed $Long1_1^1$.

4.2. Distribution of High-Quality Shale in the Inner Shelf Region and the Main Controlling Factors. The depositional environment of the upper Wufeng Formation at Well Zu202 was interpreted as an inner shelf, which mainly comprised siliceous shale interbedded with thin-bedded silty sandy shale and fine sandy shale; three sets of thin-bedded class I reservoirs were developed, which correspond to organic-rich siliceous shale in the middle Wufeng Formation and fine sandy shale in the uppermost Wufeng Formation. The class I reservoir developed in the middle Wufeng Formation was related to the high productivity and intermittent anoxia, reflecting a volatile depositional environment in shallow water regions (Figure 2). Furthermore, the ocean upwelling indicators (Co*Mn) showed that the intervals of the class I reservoir correspond to intense ocean upwellings, a pattern that falls between the present-day Cariaco and Namibian oceans[21] (Figure 3).

During the early period of the Longmaxi Formation, a rapid transgression occurred and resulted in the widespread deposition of thick-bedded siliceous shale and silty shale. A set of class I reservoirs developed in the Bed $Long1_1^1$, which mainly consists of siltstone shale, were deposited in the context of low-productivity and anoxic conditions.

The anoxic conditions were intermittent, reflecting unstable environments in the shallow water regions. Furthermore, the ocean upwelling indicator (Co*Mn) showed that ocean upwellings in the Bed $Long1_1^1$ were intense but without a significant increase in productivity (Figure 2). Upward, two sets of thin-bedded class I reservoirs developed in the Bed $Long1_1^3$, which mainly consists of siliceous shale that was characterized by oxidization and low productivity, which was different from the class I reservoir environment that developed in the Wufeng Formation and the Bed $Long1_1^1$, suggesting that the development of high-quality shale in Bed $Long1_1^3$ is less influenced by the primary sedimentary conditions.

Thin-bedded class I reservoir at well Zu202 is distributed in the middle of the Wufeng Formation and the middle of the Longmaxi Formation, and the thick-bedded class I reservoir developed at the top of the Wufeng Formation and the bottom of the Longmaxi Formation. From microfacies analysis, it can be seen that the depositional environment dominated by siliceous shale and silty sandy shale is favorable for the formation of a class I reservoir (Figure 4). Well Zu202 is located in the inner shelf area. The well-established eustatic sea level curve at Zu202 shows that intervals of class I reservoir were formed during high sea levels, suggesting that variations in sea levels exerted a significant influence on the enrichment of organic matter, a kinetic mechanism that has been well investigated by Cai et al.[22]

4.3. Distribution of High-Quality Shale in the Middle Shelf Region and the Main Controlling Factors. The depositional environment of the late period of the Wufeng

Table 3. Microfacies Description and Corresponding Depositional Environments in the Study Area (After Chen et al.[20])

microfacies	description	depositional environment
MF1: radiolaria-bearing siliceous shale	dark-gray laminated siliceous shale rich in radiolaria and organic matter	outer shelf
MF2: siliceous shale	dark gray laminated shale with abundant silt-sized quartz	
MF3: tuffaceous shale	dark gray shale containing banded or lenticular pale yellow volcanic tuff	
MF4: silty shale	shale containing occasional layers of silt-sized quartz, showing lenticular or flaser bedding	middle shelf
MF5: sponge-bearing siliceous shale	dark gray shale with fragmented siliceous sponges and occasional sponge spicules	
MF6: coral-bearing siliceous shale	relatively well-reserved corals floated in the dark gray shale	
MF7: calcareous shale	gray shale with abundant bioclasts including echinoderms	inner shelf
MF8: fine sandy shale	dark gray shale containing abundant medium- to well-sorted fine-grained quartz, with occasional fragments of echinoderms and brachiopods	
MF9: bioclastic limestone	limestone containing abundant bioclasts including benthic trilobites, ostracods, and brachiopods	

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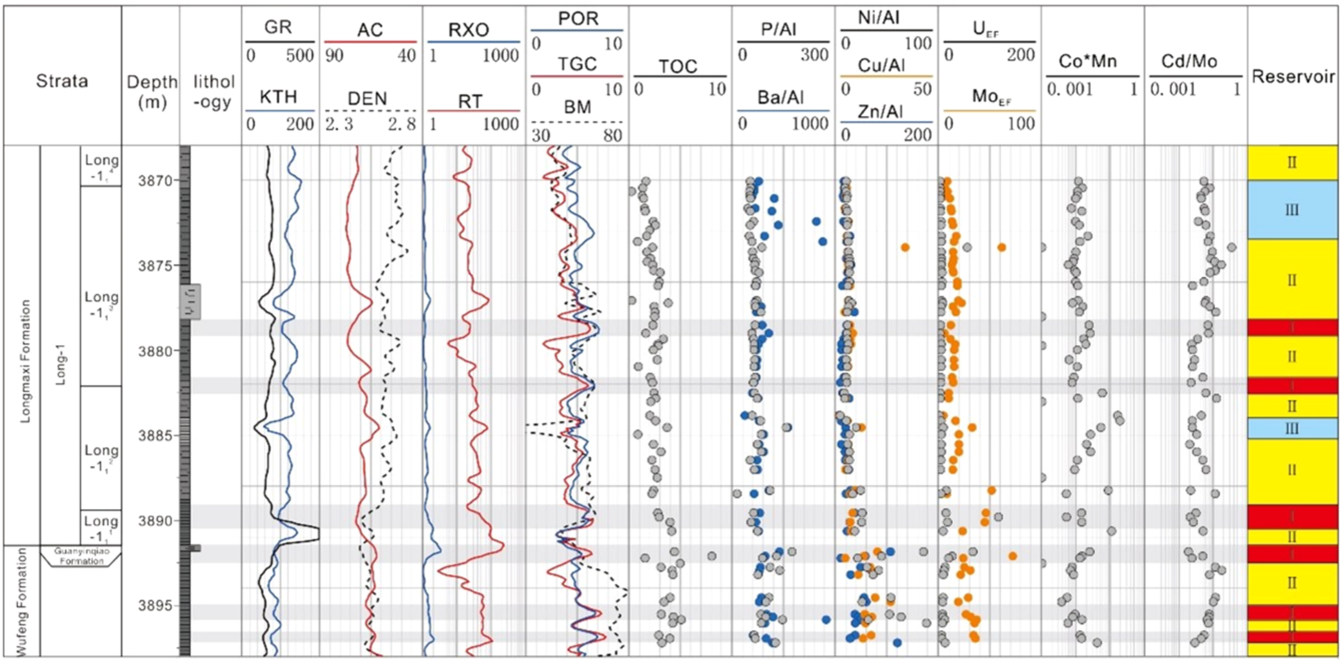

Figure 2. Composite figures showing paleoproductivity, paleoredox conditions, ocean upwelling, and high-quality shale distributions at well Zu202.

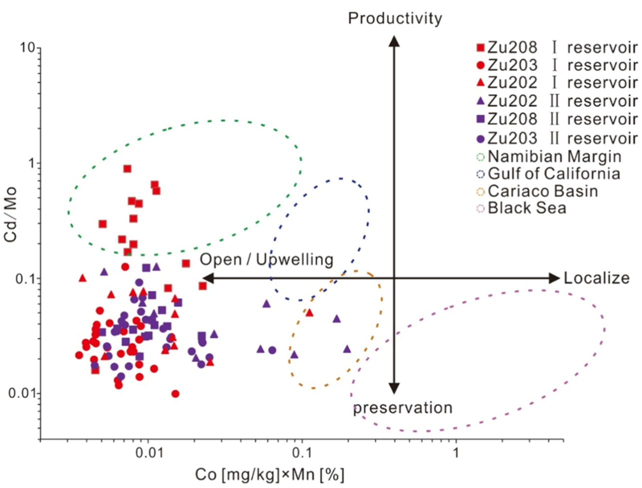

Figure 3. Cross-plots of Cd/Mo versus Co of wells Zu202, Zu203, and Zu208. Note that class I reservoirs of the uppermost Wufeng and lowermost Longmaxi Formations fall within the regime of the present-day Namibian Margin and Cariaco Basin, suggesting intense upwelling and high or intermediate productivity[21] (the regime for the present-day Namibian Margin and Cariaco Basin is after Sweere et al.)

Formation at well Zu203 was interpreted as a middle shelf, which mainly comprised thin-bedded siliceous shale and striated tuffaceous shale; a thicker set of class I reservoir was developed at the uppermost Wufeng formation, which mainly comprised siliceous shale that was characterized by higher productivity and persistent anoxia, a pattern different from that of the inner shelf region, reflecting the environmental stability of the middle shelf region (Figure 5). The ocean upwellings were intense in the late period of the Wufeng Formation, which is similar to the time-equivalent intervals at well Zu202, suggesting that wells Zu202 and Zu203 were deposited in the similar bathymetric locations that were subjected to ocean upwellings.

A thick-bedded class I reservoir developed within Bed $Long1_1^1$ at Zu203, which corresponds to a paleoceanic environment featured by low productivity and persistent anoxia, and the intensity of ocean upwelling in Bed $Long1_1^1$ was similar to that in the late period of the Wufeng Formation (Figure 5). The thicker class I reservoirs in Bed $Long1_1^3$ correspond to oxidized conditions and low productivity, indicating that the depositional conditions were not the main factors controlling the development of high-quality reservoirs in Bed $Long1_1^3$.

Based on the reconstructed paleoceanography, flat topography, within the middle shelf region, is favorable for the formation of thick-bedded class I reservoir. The thick-bedded class I reservoirs are mainly distributed at the top of the Wufeng Formation and the bottom of the Longmaxi Formation as well as at the Bed $Long1_1^3$. From the microfacies vertical sequence of well Zu202, it is known that the depositional environment dominated by siliceous shale and tuffaceous shale is favorable for the formation of a class I reservoir (Figure 6). The well-established eustatic sea level curve at Zu203 shows that intervals of the class I reservoir were formed during high sea levels. It shows that sea level change has a promoting effect on the development of class I reservoirs.

4.4. Distribution of High-Quality Shale in the Outer Shelf Region and the Main Controlling Factors. The depositional environment of the upper Wufeng Formation at well Zu208 was an outer shelf and mainly deposited thin-bedded radiolarian siliceous shale and thick-bedded silty shale, both of which developed thick-bedded class I reservoirs, with the silty shale and radiolarian siliceous shale in the upper part of the Wufeng Formation corresponding to depositional environments of high productivity and intermittent anoxia (Figure 7). Furthermore, the ocean upwelling was intense, and the current circulation pattern resembles the present-day Namibian basin, which is characterized by strong ocean upwelling and high productivity (Figure 3).

Thin-bedded class I reservoirs that consist of silty shale were present in Bed $Long1_1^1$ at well Zu208. This thin-bedded reservoir was deposited under persistent anoxic conditions and high productivity caused by ocean upwelling, but the intensity of ocean upwelling during this period was significantly weaker than

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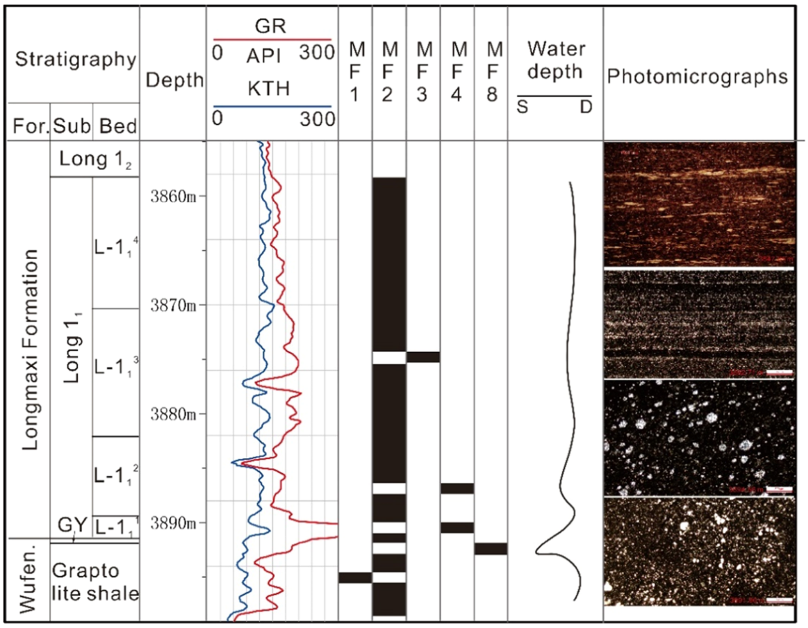

Figure 4. Vertical variation sequence of sedimentary microfacies in well Zu202 (S, shallow water; D, deep water). The data of microfacies are from Chen et al.

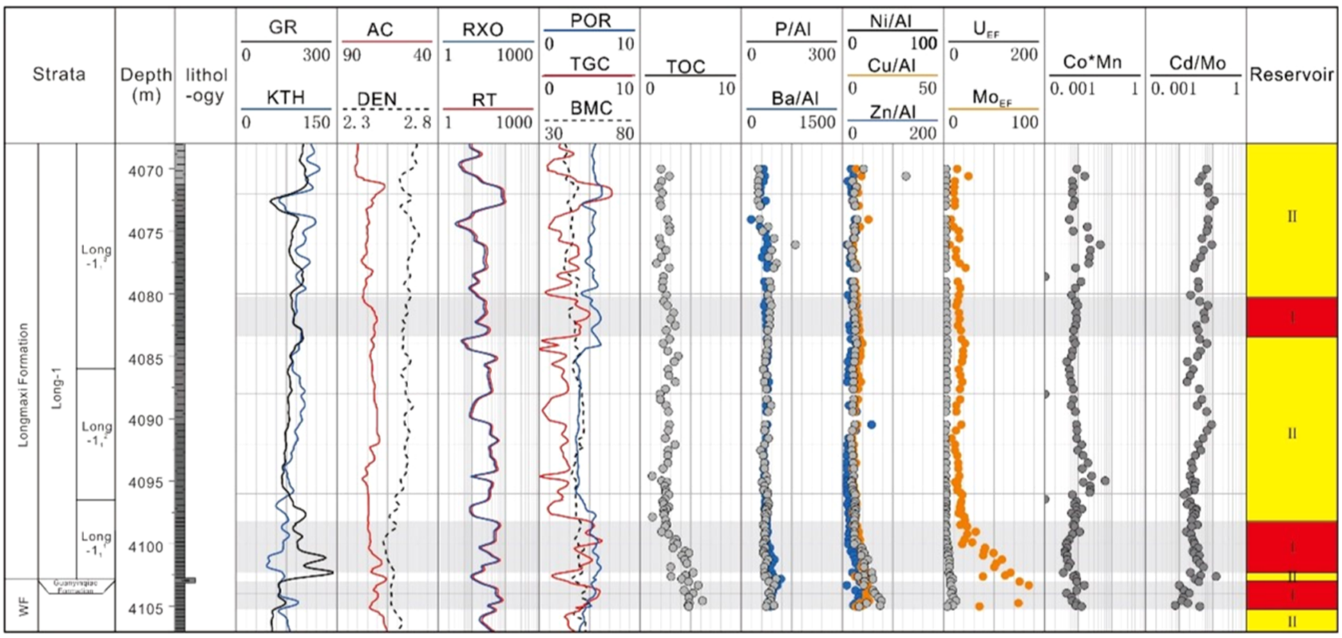

Figure 5. Composite figures showing paleoproductivity, paleoredox conditions, ocean upwelling, and high-quality shale distributions at well Zu203.

that in the late period of the Wufeng Formation (Figure 7). The Bed Long1_1^3 also developed a thin-bedded class I reservoir, which mainly comprised siliceous shale deposited under low-productivity and oxic conditions, a pattern consistent with that of Zu202 and Zu203 fully, demonstrating that the development of high-quality reservoirs in Bed Long1_1^3 in western Chongqing was less affected by the primary depositional conditions.

A thick-bedded class I reservoir at well Zu208 developed during the Middle to Late Wufeng period and the Early Longmaxi, which corresponds to chalky shale. The thin-bedded class I reservoir comprising siliceous shale is distributed in the middle of the Longmaxi Formation (Figure 8). Well Zu208 is located in the outer shelf area. The well-established eustatic sea level curve at Zu208 shows that intervals of the class I reservoir were formed during high sea levels. Because well Zu208 is located in the outer continental shelf, the sedimentary environment is the most stable, and the thickness of the deposited class I reservoir is the largest.

4.5. Development Model of High-Quality Shale Reservoirs in Western Chongqing. During the Late Ordovician–Early Silurian period, remarkable biological and environmental events occurred globally, mainly including the Hirnantian glacial event,[23−25] rapid sea level rise,[26] and biological mass extinction.[27,28] The detailed biostratigraphic framework has been constructed on the Wufeng and Longmaxi Formation shales in the Sichuan Basin,[29−31] and these stratigraphic studies provide an important basis for the reconstruction of the climatic conditions, marine environment,

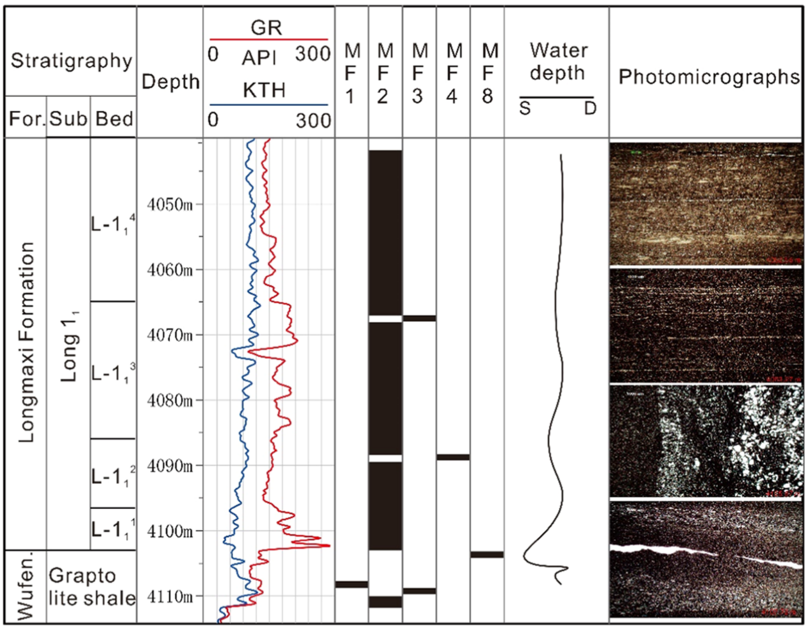

Figure 6. Vertical sequence of sedimentary microfacies and eustatic sea level changes at well Zu203. (S: shallow water, D: deep water). The data of microfacies are from Chen et al.

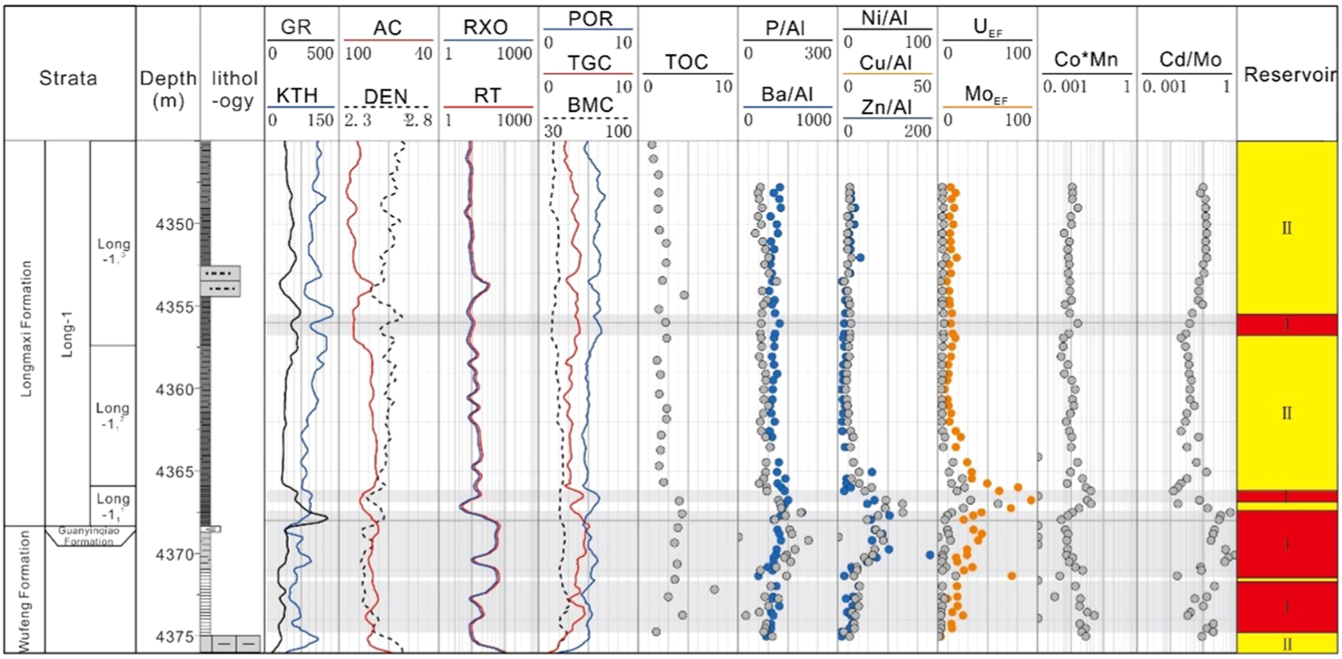

Figure 7. Composite figures showing paleoproductivity, paleoredox conditions, ocean upwelling, and high-quality shale distributions at well Zu208.

and tectonic evolution of the Wufeng and Longmaxi Formations. Previous studies indicate that the Sichuan Basin experienced substantial environmental and biological events at the uppermost Wufeng and lowermost Longmaxi Formation, a rapid regression and extreme climatic changes occurred in the Guanyinqiao Member,[32,33] and these biological and environmental events resulted in the demise of the carbonate shelf and the increased input of terrestrial-sourced detritus, both of which had a profound impact on the depositional pattern of the shales in the Sichuan Basin.

The depositional models for the high-quality shales in the Wufeng and Longmaxi Formations in western Chongqing were reconstructed based on the high-resolution paleogeography, paleoproductivity, and redox conditions (Figure 9). The main controlling factor for the formation of high-quality shale at the uppermost Wufeng formation was high productivity related to intense ocean upwellings, while different bathymetric locations had a different response to ocean upwellings. The inner shelf region was less affected by ocean upwellings and showed short-term bursts in productivity and intermittent anoxia; this short-term productivity burst resulted in the formation of a thin-bedded class I reservoir, middle shelf regions showed more persistent seawater anoxia and intermediate productivity, persistent anoxia allowed the development of an intermediate-thick class I reservoir, and outer shelf regions were strongly influenced by ocean upwellings, resulting in persistent high

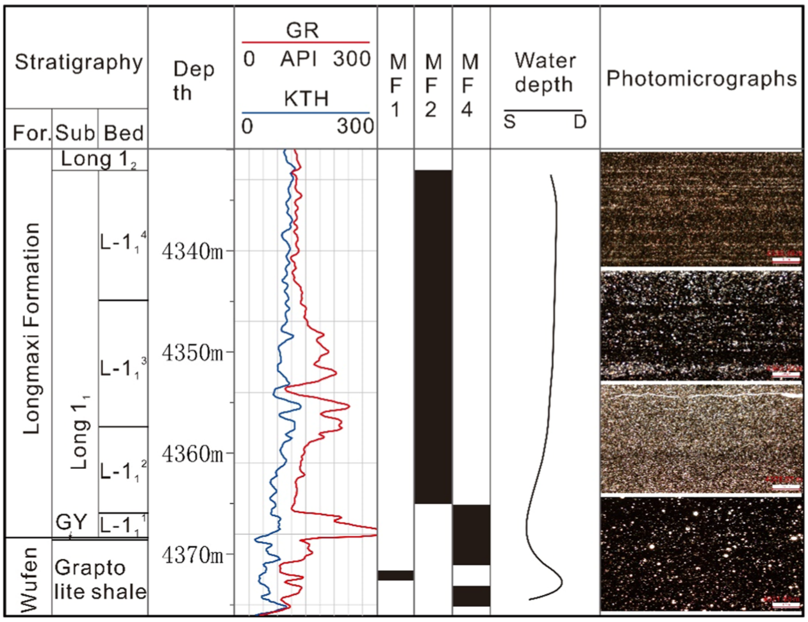

Figure 8. Vertical sequence of sedimentary microfacies and eustatic sea level changes at well Zu208 (S, shallow water; D, deep water). The data of microfacies are from Chen et al.

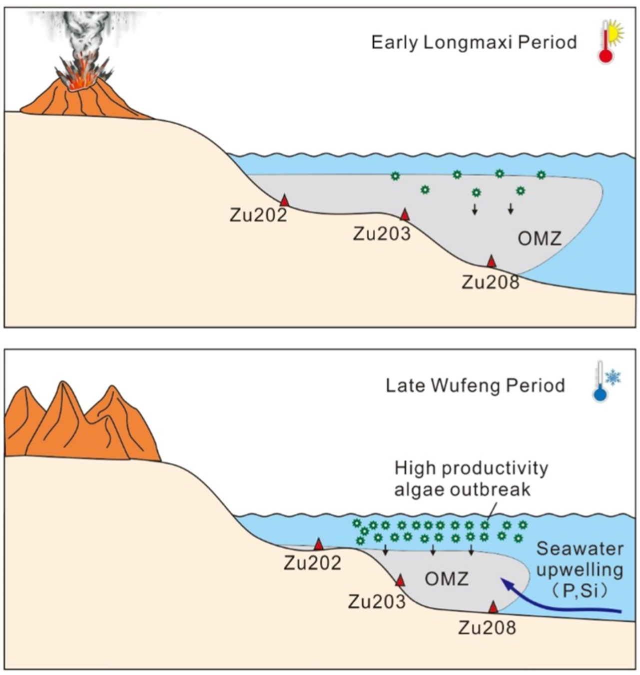

Figure 9. Depositional models of high-quality shale for the uppermost Wufeng Formation and the lowermost Longmaxi Formation in western Chongqing.

productivity accompanied by intermittent or anoxic environments, which favored thick class I reservoirs.

The depositional model for the high-quality shales during the earliest period of the Longmaxi Formation was different from that of the Wufeng Formation. The lowermost Longmaxi Formation witnessed the expansion of OMX onto shallow waters in the context of global warming, leading to widespread anoxia in the study area with low productivity probably due to weakened ocean upwelling. Moreover, the spatial heterogeneity in the high-quality shale is prominent during the earliest period of the Longmaxi Formation: the inner shelf regions were characterized by low productivity, and short-lived anoxia occurred along with thin-bedded class I reservoirs; the middle shelf regions were featured by moderate productivity and persistent anoxia and medium-thick-bedded I reservoirs; the outer shelf region corresponded to persistent anoxia, the short duration of anoxia resulting in thin-bedded class I reservoirs. This suggests that the development of high-quality shale reservoirs in the lowermost Longmaxi Formation depends mainly on anoxia rather than productivity, which is very different from that of the uppermost Wufeng Formation.

Summarizing the above two patterns, the main controlling factor for the development of the I reservoirs at the uppermost Wufeng Formation was intense ocean upwelling, while that in the lowermost Longmaxi Formation was oceanic anoxia. Furthermore, the patterns of high-quality shale enrichment and development in different paleogeographic regimes showed obvious spatial and temporal variability.

5. CONCLUSIONS

The main controlling factors in the western Chongqing area have been comprehensively constrained from temporal and spatial points of view, and the main understanding is as follows:

(1) During the late period of the Wufeng Formation, the paleoenvironment of the inner shelf region was characterized by a periodic increase in productivity, intermittent anoxia, and thin-bedded high-quality shale. The middle shelf region was characterized by persistent anoxia and moderate productivity, which resulted in the development of medium-thick-bedded high-quality shale, and the outer shelf was characterized by high productivity and persistent anoxia, which resulted in the development of thick-bedded high-quality shale. It is believed that high productivity was the main controlling factor for the development of high-quality shale in the upper part of the Wufeng Formation.

(2) During the early period of the Longmaxi Formation, the inner shelf region was characterized by low productivity and anoxia and medium-thick-bedded high-quality shale;

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the middle shelf was characterized by persistent anoxia and moderate productivity and thick-bedded high-quality reservoirs; and the outer shelf was characterized by high productivity and persistent anoxia and developed thin-bedded high-quality reservoirs. The distribution of high-quality shale is closely related to the shift of the OMZ, indicating that anoxia was the main controlling factor for the high-quality shale at the lowermost Longmaxi Formation. In addition, the development of high-quality shale in Bed $Long1_1^3$ was not affected by productivity and paleoredox conditions.

(3) The development models of high-quality shale at the uppermost Wufeng Formation and the lowermost Longmaxi Formation were established. The late period of the Wufeng Formation was characterized by strong ocean upwelling and high productivity, and productivity was the main controlling factor for the development of high-quality shale. The early period of the Longmaxi Formation was characterized by extensive seawater anoxia, and extensive anoxia was the main controlling factor in the development of high-quality shale.

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Notes

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