Advances on Depositional Mechanism of the First Member of Lungmachi Formation and Advice for Future Studies

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Abstract. The marine shale of Wufeng-Lungmachi Formation (WLF) in Middle and Upper Yangtze area is the reservoir for the biggest shale gas field outside North America. Clearly explaining the formation and distribution law of this set of high-quality shales is particularly essential. This article summarizes the advances on diverse lithofacies types, elemental geochemical analyses of paleo-productivity, redox conditions, and influence of special event-volcanic eruptions (represented by K-Bentonite). Moreover, this article also points out that, current “Formation (Member)” scale of studies cannot clearly explain the formation and distribution law of the high-quality shale required by commercial development and proposes that it is particularly urgent to carry out theoretical and practical studies on the main controlling factors of vertical heterogeneity of black shales, especially the first member of Lungmachi Fm.

1. Introduction
The research on the main controlling factors and enrichment mechanism of shale gas in China is still in the exploratory stage, and the selection of the zones and targets of shale gas accumulation is the key point to realize commercial development. The marine shale in Middle and Upper Yangtze area contains the greatest shale gas resources potential in China [1], and commercial development currently concentrates in the Wufeng-Lungmachi Formation (WLF). The black organic graptolite shale in the lower part of the WLF is the most favourable target for shale gas development, especially the first member of Lungmachi Formation (LF1) deposited in late Hirnantian to Rhuddanian Stage, which is the most favourable for commercial horizontal shale gas wells. During these two stages, the black shales developed across all the ancient latitudes and bathymetric depths, marking an important global Oceanic Anoxic Event (OAE) [2]. This set of black shales is widely distributed in the northern continental shelf of Gondwana (Fig. 1), and is called “hot shale” in the oil and gas fields in North Africa and the Middle East, with TOC up to 17% [3]. The main control on high shale gas yield has similarity in Sichuan basin and the other areas in the world, that is, the yield of shale gas wells is positively related to the high quality reservoir drilled rate by horizontal wells in the similar engineering process conditions. The development practice (Fig. 2) found that although all the targets of horizontal wells are within LF1, and the vertical distance of different targets of the same platform was only a few meters, there may be daily yield difference of tens of thousands of cubic meters. Therefore, it is particularly important to clearly explain the formation and distribution law of this set of high-quality shales. However, the depositional mechanism of early Silurian organic-rich shale in Yangtze area has not been thoroughly studied [4]. There are relatively few studies on its sedimentary
process and changes in sedimentary environment. This paper mainly summarizes current research on the development mechanism of the early Silurian black shale in the upper Yangtze region, and proposes the problems to be solved in the future.

2. Geological backgrounds
In most parts of Middle and Upper Yangtze area, LF1 overlies Kuanyinqiao Bed (KB), a set of shell marl only about 30cm thick [6]. The thickness of LF1 is generally no more than 40m, and there are three depositional centres in Southern Sichuan, Western Hubei-Eastern Chongqing and Southeastern Sichuan (Fig. 2). It is widely accepted that LF1 in the Middle and Upper Yangtze area is a set of stable deposits developed on deep water shelf surrounded by Chuanzhong Uplift, Qianzhong Uplift and Xuefeng Uplift with an opening in the north (Fig. 2).

Figure 1. Global and South China Plate paleogeographic reconstruction during Early Silurian (modified from [5]).
Figure 2. Tectonic-depositional environment in the early Lungmachi stage on the Upper and Central Yangtze (modified from [5]).

For a complete graptolitic biozone succession, the first graptolite zone (LM1) of LF is the last graptolite belt of the Hirnantian Stage, corresponding to the Gamma high and organic rich black shale at the bottom of LM (Fig. 3). The overlying LM2 is the first graptolite belt of the Rhuddanian Stage, Silurian Period. The graptolite zones’ progressive distribution pattern from LM1 to LM5 demonstrates the process of deepening seawater and expanding distribution of black shale [6] (Fig. 3). The investigation of the regional graptolite zone displays that both the top and bottom of LF have obvious diachronous characteristics [6] (Fig. 3).

The stable distribution of GB is an effective means for selection of high-quality shale gas reservoir and core areas, and this easy-to-recognize marker layers include two graptolite belts, Normalograptus extraordinarius and N. persculptus. It was deposited during the Hirnantian great glaciation, which was the peak of the early Paleozoic glaciation [7]. During glaciation, tropical sea surface temperature sharply dropped 5-8 °C [7] in a short time (< 0.5 Ma) [8], and sea levels also dropped dramatically. Outcrops and well data, such as Well Wei 201, show widespread shallow water oxic environment with local deep-water environment in Sichuan basin, consistent with international sedimentary characteristics of the same period [2].
3. Advances on depositional mechanism of black shales and the first member of Lungmachi Formation (LF1)

3.1. Advances on the depositional mechanism of black shales

Black shales are most often described as argillaceous, argillaceous-pelitic, argillaceous-siliceous and argillaceous-carbonate sediments with higher amounts of more or less transformed organic matter responsible for their black or dark grey colour [10], shales that serve as high quality shale gas reservoir are characteristic of high TOC, high porosity, high gas content and high siliceous content [1].

There have long been two major contrasting opinions on the formation mechanism of black shale: one is the water stagnation/hypoxia preservation condition opinion, in which water body is highly stratified to prevent vertical mixing and oxygen supply to underlying water [11]; Another is the view of high primitive marine surface biological productivity, high productive surface water causes high organic flux [12]. Studies also show that the terrestrial debris flux also affects the burial of organic matter. Therefore, the formation of black organic rich shales is the comprehensive result of multiple
factors, such as the primary productivity of the ocean surface water, water redox conditions and the terrestrial debris flux [13].

The period during Ordovician-Silurian transition is characterized by dramatic climate and sea level changes [14]. Except for the great changes in fauna communities such as graptolite and Hernantian fauna [15], the biomarkers of black shale hopane/sterane ratio in the Baltic depression during the same period showed the changes of marine microbial communities through Katian, Rhuddanian and Hirnantian stages [14]. Organisms forming organic shales vary through different historical periods, and the organic matter producers in the pre-Jurassic are still not completely clear [13]. It is generally believed that the active ocean circulation leads to mixing of pelagic elements and strong upwelling, which promotes the productivity of phytoplankton [16]. The rapid global transgression after the Hernantian ice age, and the near-simultaneous OAE under the control of strong irregular landforms, resulted in the development of huge amount of black shale in the northern Gondwana shelf [17]. Many studies concentrate in the aspects of their oil, gas and minerals of economic value, but only recently there have been few pure geochemical studies, such as biomarkers, carbon isotopes and element composition, to explore their nature and significance [13]. Although very important, the mechanism of the accumulation of early Silurian organic shales in the Yangtze region has not been deeply studied [4].

Elemental geochemistry and petrology studies are effective means to analyze the ancient productivity, redox environments and terrestrial influence of the formation of organic rich black shales.

3.1.1. Studies on lithofacies of black shales

The variable geochemical composition, lithologic and complex sedimentary structures of the world-class source rock of the lower Carboniferous Barnett shale is a clear example of the heterogeneity of the black shale lithofacies, which proves that the black shale is a reflection of the complexity and numerous processes [18]. 10 types of lithofacies were determined through detailed core observation and thin section identification [19]. Each class of lithofacies represents relatively homogenous shale reservoirs. Systematic lithologic investigation, including mineral composition, organic carbon content, gas content, lithology-air content relevance, promotes the development of shale gas [20]. A lot of lithofacies studies have been carried out on Barnett shale and the Marcellus shale. However, black shale lithofacies studies mainly concentrate on lacustrine shales in China, studies on marine shale are just beginning and exploring the lithological classification of calcareous shale, siliceous shale, silty shale and so on [21]. Lazar et al. gave the shale lithofacies identification and classification system through outcrop, core and thin section [22].

3.1.2. Elemental geochemical analyses of paleo-productivity, redox conditions for black shales

Elemental geochemical analyses mainly utilize the enrichment or loss of elements to reconstruct paleo-marine environments. There are four major sources of elements in sedimentary rocks: terrestrial detritus input, biogenesis, authigenic mineral and enrichment during early diagenesis. The last three sources are closely related to the sedimentary environment of ancient oceans and are important indicators for the reconstruction of paleo-marine environment. The sources and their contribution of elements in shales should be evaluated first to eliminate the influence of non-autogenetic portion. Usually, Al(Ti, Th), background elements representing terrestrial input, are used for standardization (X element standardized value =X element value/Al element value) [23], or using XEF (XEF= X element standardized value/X late-Archean Australian shale value). By using the multi-element indexes, we can obtain a reliable conclusion about ancient environmental redox status, avoiding the distortion of a single indicator.

(a) Elemental geochemical analyses of paleo-productivity

High marine primary productivity generates high organic matter flux, and high organic matter flux causes trace metal elements to form local sulfate reduction microenvironment due to the decomposition of organic matter, or the buried quantity of trace metal elements due to complexation with organic matter will increase. Therefore, trace metal elements, including Ba, Mo, Fe, Si, Cu, Ni, Cd and Zn, and the relationships between C, N and P isotopes, and organic carbon flux in water can be
used to reconstruct the surface biological productivity of water. Reconstruction of the ancient productivity is often based on fluctuations rather than absolute elemental content values; the most reliable method is to establish time-depth model to evaluate elemental content fluctuation. Each indicator can be affected by other factors and thus will have uncertainty [24], and the reconstruction of ancient primary productivity requires a reliable and operable comprehensive evaluation of multiple indicators.

Organic carbon content is the most direct indicator of ancient productivity, but it’s susceptible to diagenesis, oxidation-reduction reaction, biological effects, and terrestrial detrital dilution. The elemental geochemistry index is less affected by the thermal evolution of organic matter and has unique advantages in the study of high-over-mature marine source rocks [25].

C, N and P isotopes are susceptible to recirculation, late period diagenesis, therefore they are not very reliable signs of ancient productivity. The estimated productivity by Ba may be relatively lower due to reduction of Ba content caused by partial dissolution in the hypoxic environment [26].

Identification of siliceous biological residues of high abundance under the microscope and cathodoluminescence are used to reveal the biogenic quartz of in shales. Siliceous plankton is the main provider of primary marine productivity, and its content is closely related to the biological flourishing degree in surface water, that is, it represents the ancient marine productivity at the time of deposition [27].

(b) Elemental geochemical analyses of paleo-redox condition

The redox conditions of ocean bottom water can be divided into four types, including oxic, suboxic, anoxic and euinxic: the oxygen concentration of oxic bottom water is greater than 2ml/L, the oxygen concentration of suboxic bottom water is 0.2~2 ml/L, the oxygen concentration of anoxic bottom water is 0~0.2ml/L without free H2S, and the oxygen concentration of euinxic bottom water is 0 ml/L and contains free H2S [28]. Under the oxic condition, elements, such as U, Mo and V, show high price (U6+, Mo6+, V5+) and are prone to migrate, and under the reduction condition low price status (U4+, Mo4+, V3+) and prone to precipitate. In the euinxic environment, the thiophilic elements, such as Fe, Cu, Zn and Cd, are prone to form sulfide precipitation. The oxidation-reduction sensitive trace elements can be used to reconstruct the redox state of the ancient ocean. The U, V and Mo indexes are less affected by the thermal evolution of organic matter and have unique advantages in the study of high-over-mature marine source rocks [25]. The ratio of redox sensitive trace elements, U/Th, V/Sr, V/Cr, Ni/Co and V/(V+Ni), are useful indicators to determine the redox conditions of black shales [29].

The ratio of V/(V+Ni) is an effective indicator for redox conditions: the ratio<0.46 indicates the oxic environment, 0.46~0.57 indicates the suboxic environment, 0.57~0.83 indicates the anoxic environment, and 0.83~1.00 indicates the euinxic environment [30]. V/Cr<2 represents the oxic environment, while V/Cr >2 represents the anoxic environment [31]. δU=U/[(U+Th/3)/2], δU>1implies the anoxic environment, <1implies the normal oxic environment. Ce/La<5 indicates the oxic environment, 1.5~1.8 indicates the suboxic environment, >1.8 indicates the anoxic environment [32].

The burial of Mo isotope is related to dissolved H2S concentration. As a global paleo-redox indicator, Mo isotope is the most sensitive to ocean vulcanization, and it is a good indicator to distinguish the anoxia reduction from the euinxic environment [33]. Mo/TOC in the sediment can roughly reflect Mo concentration in the sedimentary water, and it can clearly reflect the local restricted extent of the basin. The enrichment coefficient ratio of Mo and U (MoEF /UEF) reflects the differences of Mo and U enrichment degree, useful for distinguishing the restriction of sedimentary environment and identifying the renewal rate of water body. Studies on multiple sedimentary basins both in modern and ancient times have proved Mo highly reliable [34, 35].

3.1.3.Influence of special event: K-Bentonite representing volcanic eruptions

K-Bentonite is a K-rich clay rock produced by volcanic eruptions through hydrolysis, sedimentary diagenesis and alteration [36]. It is generally a grayish white thin layer of centimeter-level thickness,
and serves as extremely rare high-precision, isochronous event marker. Its porphyritic black Mica [37], Zircon, Amphibole and melt inclusion are good carriers for the absolute age dating by U-Pb, K-Ar and Ar-Ar. All-rock geochemistry and Th/U ratio are the indicators to distinguish K-bentonites formed in different periods [38]. European and north American Ordovician porphyry are the most intensively studied, e.g., the all-rock geochemical characteristics studies have achieved good results through the North America-Europe intercontinental correlation [38], while domestic studies focus on the Meso-Neoproterozoic stratigraphic dating in North China.

Multilayer of K-Bentonites developed in the LF outcrops in Yangtze area. Currently, the dating work is mainly carried out near the boundary of Ordovician and Silurian in Yichang Hubei, Taoyuan Hunan, Tongzi Guizhou and other places. It is also found that the Huanghuachang and Wangjiawan Yichang profiles can be correlated with the Tongzi Guizhou profile, which are nearly 500Km apart [39]. In recent years, shale drilling in the basin has also found the development of multi-layered porphyry [1], which further proves the large-scale regional volcanic eruption and the occurrence of Guangxi Movement [40]. Currently, only the statistical analysis of gas content in shale and the number of K-Bentonites layers in the WLF has been carried out, and it is found that LF1 with the highest gas content corresponds to medium number of K-Bentonites layers. Volcanic ash promotes ancient productivity and organic matter preservation, while too frequent eruptions are unfavourable. The geochemical analysis of the K-Bentonite itself, the geochemical component of the adjacent shale strata and the paleo-redox component is not carried out for LF1. Therefore accurate assess of the impact of the single layer of porphyry event is yet to be carried out.

3.2. Comprehensive studies on the first member of Lungmachi Formation (LF1)
Currently, elemental geochemistry studies in the WLF have obtained a wide consensus: Zhou L. et al. applied Mo element (combined with the analysis of main and trace elements) to reconstruct the redox conditions before and after the Hernantian Ice Age in Wangjiawan, Hubei, and displayed evolving process of reduction (WF) - oxidation (KB) - reduction (lower part of LF) [41]; Yan D. et al. utilized the ratio of P, Ba elements and S/C, Th/U, Ni/Co, V/Cr, and V/(V+Ni) in Yichang profile to reveal the overall reduction and high productivity conditions during sedimentation of LF [4]; The Th/U, V/Cr and Ni/Co ratios of Well Wei 201 were used by Li Y. et al. to prove that the restriction degree of the ocean basin of WF was stronger than that in the lower part of LF, belonging to a strong restriction environment[42]; Zhang L. et al. reconstructed the Hernantian paleogeography and identified three sedimentary centres; According to the analysis of TOC and V, Ni, Mo, U and Cu of LM in Well Jioaye1, Ma Y. et al. proposed that organic matter enrichment is controlled by high productivity and reduced water bodies, and they also speculated that algae bloom associated with radiolaria is the main cause [43]; Zhao J. et al. divided 7 types of black shale lithofacies in the WLF and revealed the destruction of bottom-up anoxic environment by combining the main and trace elements analyses[27]; Nie H. et al. studied the response of sedimentary environment of WLF in Sichuan Basin to Guangxi Movements[44]; Zhang Q. et al. used V/(V+Ni), V/Cr and Ce/La from Well Qianjiang 1 in southeast Chongqing to prove that the WLF was an anoxic environment in general. The bottom of LF was the most reductive, while it became less reductive both toward upward and downward. Biological Ba revealed the highest ancient productivity at the bottom of LF[45].

4. Conclusion
Through analyses, it is found that significant progresses have been achieved in the study of the depositional mechanism of FL1, as well as in the understanding of biostratigraphy, sequence stratigraphy, lithofacies paleogeography and distribution law of black shales. Current understanding is basically consistent on fluctuation of “reduction, oxidation and reduction” environments in the “Formation (Member)” scale of the WF through KB to LF and corresponding changes in ancient productivity. However, this scale of study cannot clearly explain the formation and distribution law of the high-quality shale required by commercial development. This article summarizes the advances on diverse lithofacies types, elemental geochemical analyses of paleo-productivity, redox conditions, and
influence of special event-K-Bentonite representing volcanic eruptions. Moreover, this article also proposes that it is particularly urgent to carry out theoretical and practical studies on the main controlling factors of vertical heterogeneity of black shales, especially the LF1.

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