Formation Environment and Development Models for the Lower Cambrian Source Rocks of the Southern North China Plate, China

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ABSTRACT: In this article, the lower Cambrian marine shale of the southern part of the Ordos basin is taken as an example to investigate the formation environment and development models of source rocks with high organic abundance in the ancient strata of the southern North China plate. The lower Cambrian shale source rocks had a thickness of 10−80 m, with high total organic carbon contents (an average of 2.68% and maximum of 9.39%) and favorable organic matter types—mainly sapropelinite macerals—and yet low S1, S2, and hydrogen index, which indicate that the source rocks have relatively high thermal maturity. Therefore, it is demonstrated that marine shale of the lower Cambrian proves to be excellent gas source rocks at the southern part of the Ordos basin and are presently distributed mainly in the south part of the North China plate. During the early Cambrian period, paleoproductivity was relatively high, as indicated by the rich C27 sterane contents, high sterane/hopane ratios, and high tricyclic terpane/hopane ratios in biomarkers and high P and Ba values in trace elements. The tectonic setting promoted the formation of highly abundant source rocks with favorable preservation conditions, as suggested by the relatively high V/Cr ratios and low Zr/Rb and Pr/Ph ratios. Thus, the paleoproductivity and preservation conditions were the main factors controlling the occurrence of highly abundant source rocks. The formation of highly abundant source rocks was under the joint effects of the tectonic setting and the undercompensation environments of the passive continental marginal slope of the Paleo-Qinling Ocean and deepwater bays. The paleo-geomorphologic troughs and/or fault depressions (because of tectonic movement) and deepwater bay environments together influenced the development scale of highly abundant source rocks, whereas the deepwater shelf environment of the continental marginal slope ensured the high quality of the source rocks.

1. INTRODUCTION

Ancient strata in China, from the Proterozoic to the Paleozoic,1 have a wide distribution of about 300 × 104 km,2 mainly in the Yangtze craton in the south, the Tarim basin in the west, and the North China craton in the middle of China.2 Along with the rich achievements increasingly emerging from the hydrocarbon exploration in ancient strata around the world,3−5 major breakthroughs have also been seen in the oil and gas exploration of ancient Ediacaran (Sinian) and Cambrian strata of China.5 For example, natural gas with a high production up to about a million cubic meters was discovered in the old petroleum system of the Gaoshiti−Moxi tectonic belt, which lies in the Leshan−Longnvsi paleouplift of the Sichuan basin in the Yangtze plate. A region of oil and gas accumulation was found in the Yingshan formation of the middle northern slope and the Halahatang district in the northern Tarim basin.

These oil and gas exploration efforts in ancient strata have demonstrated that premium highly abundant marine source rocks are developed in ancient strata, such as in the Moxi district of the Yangtze plate, with thick laminated premium source rocks in the lower Cambrian Qiongzhusi and Maidiping formations.6 In the Tarim basin, highly abundant source rocks have also been found in the lower Cambrian Yuertusi formation.7 The high-quality marine shale with a thickness of 10−40 m in the lower Cambrian Madian formation of the Huainan region has been discovered, in the southeastern part of the North China plate.8 The total organic carbon (TOC) in this shale amounted to 11.2%; vitrinite reflectance ($R_o$) ranged from 2 to 3.5%; and the organic matter was classified as type I.
In fact, the whole southern part of the North China plate, including the Ordos basin, the Yangtze plate (Sichuan basin), and the Tarim plate (Tarim basin), is analogous in terms of paleogeography and the paleosedimentary environment and possessed similar favorable sedimentation and accumulation conditions. Thus, one naturally begins to wonder whether highly abundant source rocks are also developed in the lower Cambrian of the Ordos basin, as in the Sichuan and Tarim basins, also located in the Eurasian plate. Field outcrops in the southern North China plate revealed a series of highly abundant lower Cambrian marine shales and bitumen, which indicated that hydrocarbon generation, migration, and accumulation once occurred in the lower Cambrian source rocks.

For a long time, some scholars have focused on evaluating the source rocks of the ancient petroleum system, especially the lower limit, on the organic matter abundance of ancient marine source rocks. Unconventional oil and gas exploration all over the world has demonstrated that hydrocarbon accumulation is controlled by mature source rocks with high hydrocarbon abundance. Generally, in the source rocks of ancient strata that experienced a high degree of thermal evolution, free hydrocarbons ($S_1$) and pyrolysis hydrocarbons ($S_2$) are difficult to measure, and highly abundant source rocks can only be characterized based on the TOC. TOC depends on the environment in which the source rocks developed, with factors such as organic matter productivity, conditions of preservation, and deposition rate.

Figure 1. Maps showing the paleotectonics (modified from Feng et al., 2004; Chen et al., 2008) (a) and residual stratigraphic thickness and sampling locations (modified from Lin et al., 2012) (b) in the lower Cambrian of the North China plate.
discusses the formation environment and development models of the marine source rocks with high organic matter abundance in the ancient strata of the southern North China plate, based on the analysis of the tectonic background, organic geochemical characteristics, paleoproductivity, and preservation conditions.

2. GEOLOGICAL SETTING

The Ordos basin is part of the North China plate and is located at the northern margin of the eastern Qinling–Dabie Mountain tectonic belt, which crosses the whole North China plate and its southern marginal tectonic belt. The southern margin of the Ordos basin in the Cambrian was a passive continental margin, whereas the northern and southwestern margins were active continental margins in the early Paleozoic. At the southern border of the basin, the Luanchuan–Gushi–Hefei fault zone is in close proximity to the northern Qinling fold belt, and it is in the east of the lower Yangtze region (Yangtze plate) with the Tanlu fault zone at the border (Figure 1a); a notable difference between the Ordos basin and the Bohai bay basin is that the former is characterized by a NE–NNE structure.

The entire early Paleozoic is considered to be a time when all the paleo-Tarim plate, paleo-North China plate, and paleo-Yangtze plate existed, among which ocean basins were distributed. The North China plate, where the Ordos basin is located, was separated by the paleo-Asian Ocean from the Siberia plate group, whereas its south blocks such as the Qaidam and Yangtze plates were divided by the northern Qilian Ocean and the Qinling Ocean. In all of these plates or microplates, stable deposits of early Paleozoic age are found, dominated by carbonate deposits, such as the sedimentary association dominated by carbonate rocks, with minor clastic rocks in the North China plate. At the margins of these plates, various forms of continental marginal sedimentation have been observed, as well as a sedimentary association of the continental shelf slope—deep sea clastic rocks interbedded with carbonate rocks.

The Cambrian is well developed at the southern margin of the basin, namely the Dongpo, Xinji, Zhushadong, Mantou, Maozhuang, Xuzhuang, Zhangxia, and Sanshanzhu formations from bottom to top, and two sets of source rocks are found in the Proterozoic Cuizhuang formation and the lower Cambrian, respectively, with multiple Cambrian reservoirs (Figure 2). The lower Cambrian source rocks at the southern margin of the basin have a thickness of 10–80 m and are mainly composed of mudstones and shales. Because of the relatively high degree of thermal maturity in the source rocks, portions of the mudstones and shales have evolved into metamorphic slate and phyllite. Moreover, because of the closure and orogenic uplift of the Qinling Ocean, the North China plate rose considerably, and thus most of the region has undergone denudation. Only in the southern part of the North China plate do the lower Cambrian strata remain, with a thickness of 0–200 m (Figure 1b). The lower Cambrian marine shale source rocks in the southern North China plate formed in an environment classified as the continental marginal slope, with the overlying thick Xinji formation sandstones, Mantou formation sandstones, Zhangxia...
hydrocarbons (S2) were low in quantity, ranging from 0.01 to 0.06 mg/g; the measured quantity of pyrolysis hydrocarbons (S2) in particular had a maximum of only 0.05 mg/g. The hydrogen index (HI) of 0–60 mg/g was also low. $T_{\text{max}}$ of the source rocks had the highest value of 544 °C, and a portion of the samples had $T_{\text{max}}$ over 450 °C (Table 1). In addition, bitumens, which are formed by residual oil cracking, have been seen in the outcrops and through the microscope.39,40 The features mentioned above clearly suggest that the lower Cambrian marine shale source rocks at the southern margin of the Ordos basin generally had high TOC values, with a broad range from 0.12 to 9.39% (average: 2.68%). Samples containing TOC over 1% accounted for 61% of the total, which indicates that the source rocks are rich.38

Table 1. Experimental Data of TOC Determination and Rock Pyrolysis of the Lower Cambrian Shale Source Rocks from the Southern Margin of the Ordos Basin

| sample no. | TOC (%) | $S_1$ (mg HC/g rock) | $S_2$ (mg HC/g rock) | $T_{\text{max}}$ (°C) | HI (mg HC/g TOC) |
|------------|---------|----------------------|----------------------|----------------------|------------------|
| H001       | 0.37    | 0.01                 | 0.01                 | 419                  | 2.72             |
| H002       | 0.12    | 0.01                 | 0.01                 | 382                  | 8.14             |
| H003       | 0.98    | 0.00                 | 0.01                 | 544                  | 1.03             |
| H004       | 0.26    | 0.01                 | 0.01                 | 423                  | 3.83             |
| H005       | 1.29    | 0.00                 | 0.02                 | 459                  | 1.55             |
| H006       | 1.39    | 0.00                 | 0.01                 | 483                  | 0.72             |
| H007       | 1.34    | 0.00                 | 0.01                 | 464                  | 0.75             |
| H008       | 1.44    | 0.01                 | 0.02                 | 460                  | 1.39             |
| H009       | 1.59    | 0.01                 | 0.02                 | 429                  | 1.26             |
| H010       | 0.98    | 0.00                 | 0.01                 | 470                  | 1.02             |
| H011       | 6.64    | 0.00                 | 0.02                 | 489                  | 0.30             |
| H012       | 9.19    | 0.01                 | 0.01                 | 445                  | 0.11             |
| H013       | 2.12    | 0.01                 | 0.01                 | 372                  | 0.47             |
| H014       | 4.99    | 0.00                 | 0.01                 | 354                  | 0.20             |
| H015       | 3.54    | 0.01                 | 0.02                 | 430                  | 0.56             |
| H016       | 6.13    | 0.01                 | 0.01                 | 385                  | 0.16             |
| S017       | 0.13    | 0.01                 | 0.01                 | 390                  | 7.98             |
| S018       | 2.34    | 0.01                 | 0.01                 | 365                  | 0.43             |
| S019       | 0.14    | 0.00                 | 0.00                 | 503                  | 7.29             |
| S020       | 0.14    | 0.00                 | 0.01                 | 480                  | 7.37             |
| S021       | 0.12    | 0.00                 | 0.00                 | 442                  | 8.18             |
| S022       | 0.25    | 0.00                 | 0.00                 | 500                  | 4.00             |
| S023       | 1.52    | 0.01                 | 0.01                 | 481                  | 0.66             |
| S024       | 2.47    | 0.01                 | 0.01                 | 485                  | 0.40             |
| S025       | 4.08    | 0.01                 | 0.02                 | 484                  | 0.49             |
| S026       | 2.02    | 0.01                 | 0.02                 | 430                  | 0.99             |
| S027       | 0.69    | 0.01                 | 0.01                 | 411                  | 1.44             |
| S028       | 7.67    | 0.01                 | 0.01                 | 419                  | 0.13             |
| S029       | 9.39    | 0.02                 | 0.02                 | 415                  | 0.21             |
| S030       | 0.72    | 0.02                 | 0.01                 | 367                  | 1.40             |
| S031       | 1.57    | 0.01                 | 0.01                 | 361                  | 0.64             |

formation oolitic dolomites, and Sanshanzi formation dolomites acting as the major reservoirs. These reservoirs and lower Cambrian source rocks together facilitate excellent source—reservoir configurations.

3. RESULTS AND DISCUSSION

3.1. Organic Geochemical Features of the Lower Cambrian Source Rocks. The lower Cambrian marine shale source rocks at the southern margin of the Ordos basin generally had high TOC values, with a broad range from 0.12 to 9.39% (average: 2.68%). Samples containing TOC over 1% accounted for 61% of the total, which indicates that the source rocks are excellent.38 However, the free hydrocarbons ($S_1$) and pyrolysis hydrocarbons ($S_2$) were low in quantity, ranging from 0.01 to 0.06 mg/g; the measured quantity of pyrolysis hydrocarbons ($S_2$) in particular had a maximum of only 0.05 mg/g. The hydrogen index (HI) of 0–60 mg/g was also low. $T_{\text{max}}$ of the source rocks had the highest value of 544 °C, and a portion of the samples had $T_{\text{max}}$ over 450 °C (Table 1). In addition, bitumens, which are formed by residual oil cracking, have been seen in the outcrops and through the microscope.39,40 The features mentioned above clearly suggest that the lower Cambrian source rocks have undergone a relatively high degree of thermal evolution.

Previous studies have provided detailed evidence from the lower Cambrian source rocks in the Hefei basin of the northeastern North China plate, which indicated that a set of high-quality source rocks developed in this region. This finding is consistent with our understanding of the highly abundant lower Cambrian shale source rocks recently discovered at the southern margin of the Ordos basin. Based on the previous studies and our latest outcrop investigations, it is believed that lower Cambrian source rocks mainly developed in the southern North China plate and comprise a set of excellent gas source rocks, with high TOC values, favorable organic matter types, and yet high thermal maturity.

3.2. Formation Environment of the Highly Abundant Marine Shale Source rocks. 3.2.1. Tectonic Setting. In the Cambrian period, the northern and southern parts of the North China plate became passive continental margins because of the expansion of the ocean basin, whereas the interior of the North China plate was tectonically stable with transgression at the margins, and evolved into a cratonic basin dominated by a wide coastal tidal flat—shallow sea platform. The southern passive margin developed mainly between the current Xian—Nanyang—Hefei fault zone and the Shandang suture zone, west of the Helan aulacogen.34 In the Cambrian period, the whole North China region, including the Ordos basin, underwent great uplift and depression with alternating distribution. At the southern margin of the Ordos basin, a NE-trending bay named the Fuping—Luochuan bay developed (Figure 1).
The source rock features, sedimentary structural environment, and lithological association characteristics of the surrounding lower Cambrian source rocks are compared in the southern North China plate, and the premium lower Cambrian source rocks discovered in the Yangtze and Tarim plates revealed extreme similarities. The comparison of the formation environment in the lower Cambrian source rocks from the three regions, combined with the analysis and observation of the typical outcrop sections, paleostructure restorations, and stratigraphic correlations, indicates that the lower Cambrian marine source rocks at the southern margin of the Ordos basin were also controlled by the Fuping−Luochuan bay. That is to say, the source rocks formed in the bay are generally thicker (Figure 1b).

The early Cambrian paleotectonic setting of the southern North China plate has vital, decisive effects on the formation and preservation of the source rocks that developed in the lower Cambrian period. Under the control of the formation environment of the slope at the platform margin of the Paleo-Qinling Ocean and the paleotrough and/or the paleofault depressions, the lower Cambrian source rocks of the Ordos basin developed mainly in the southern part of the North China plate and currently remain in the paleogeomorphic trough and the NE-trending bay (Figure 1a).

3.2.2. Paleoproductivity. Paleoproductivity directly affects the distribution of highly abundant source rocks. Biogeochemistry indicates that certain elements, such as P, Ba, and Cu, can be used as paleoproductivity indicators to characterize the strength of paleoproductivity. The element P exists in organisms in the form of $PO_4^{3-}$, and once this phosphate runs out, there is no available source for supplementation. Thus, the P content can represent primary productivity. Figure 3a illustrates that the TOC values of the source rocks grow as the P content increases. The P contents of the lower Cambrian source rocks in the southern Ordos basin ranged from 106.2 ppm to 14,251.78 ppm, with an average of 1617.92 ppm. Meanwhile, the maximum TOC value (9.39%) corresponded to a high P content of up to 9668.25 ppm. The Ba content, as a paleoproductivity indicator, can, to some extent, reflect the degree of bloom of various lower algae. After the elimination of the effects of terrigenous Ba, the Ba content of the lower Cambrian source rocks found in the southern Ordos basin ranged from 106.2 ppm to 14,251.78 ppm, with an average of 1617.92 ppm. Meanwhile, the maximum TOC value (9.39%) corresponded to a high P content of up to 9668.25 ppm. The Ba content, as a paleoproductivity indicator, can, to some extent, reflect the degree of bloom of various lower algae.

Figure 3. TOC vs P (a) and Ba (b) in the lower Cambrian marine shale source rocks of the southern margin of the Ordos basin.

Figure 4. Mass spectrometry results for the extract from the lower Cambrian shales from the southern part of the Ordos basin. Pr = pristane, $nC_{17}$ = $C_{17}$ n-alkane, Ph = Phytane, TT = tricyclic terpane, H = hopane series, S = sterane series, Ts = $C_{27}$ 18α, 22, 29, 30-trisnorhopane, Tm = $C_{27}$ 17α, 22, 29, 30-trisnorhopane, $C_{29}H = 17α(H), 21β(H)$-hopane, $γ$ = gammacerane, $C_{27} = 20R$-$aaa$-$C_{27}$ cholestane, $aaa20RC_{29} = 20R$-$aaa$-$C_{27}$ cholestane, and ZYZ and HLG = outcrop names. In addition, R is the abbreviation of regular steranes.

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input, mainly from lower algae. This inference is consistent with the conclusion of Dai et al.\cite{8} regarding the development of premium source rocks in the southern part of the North China plate. They proposed that the root cause for the high abundance of organic matter in the source rocks was blooms of lower algae in the southern North China plate during the early Cambrian period. Highly enriched lower algae were the major characteristic of the early Cambrian period and are also the material basis for the source rocks of similar quality in the basin Cambian system of different tectonic units of China.

Moreover, the characteristics of biomarkers from the saturated hydrocarbon extract of the source rocks are frequently used to reveal the type of organic matter input. For example, sterane/hopane ratios (S/H) and tricyclic terpene/hopane (TT/H) ratios are typically employed to evaluate whether the organic matter input was dominated by eukaryotes (mostly algae and higher plants) or prokaryotes (bacteria).\cite{51,52} Relatively high S/H and TT/H ratios generally indicate that the source of the organic matter was dominated by lower algae, as in the Paleozoic source rocks found in the Sichuan and Congo basins.\cite{53} The lower Cambrian shale source rocks in the southern margin of the Ordos basin have relatively high S/H and TT/H ratios of 0.50–1.36 and 0.70–1.13, respectively (Figure 4), which are similar to the biomarker characteristic of the Paleozoic Cambrian source rocks found in the Sichuan basin. The \( \text{aa} \times 20 \text{RC}_{27}/\text{aa} \times 20 \text{RC}_{29} \) ratios of the sterane biomarker are also often used to shed light on the input of organic matter. In general, the \( C_{27} \) cholestane series mainly comes from phytoplankton and algae, whereas the \( C_{29} \) cholestane series primarily originates from terrigenous higher plants.\cite{54,55} As shown in Figure 4, among the sterane biomarkers of the lower Cambrian source rocks, the \( C_{27} \) cholestane series is dominant, and the \( \text{aa} \times 20 \text{RC}_{27}/\text{aa} \times 20 \text{RC}_{29} \) ratios are from 1.11 to 1.35. Therefore, it can confidently be stated that the organic matter input of the lower Cambrian source rocks at the southern margin of the Ordos basin was mainly from lower algae, and the input from distal clastics was relatively minor.

In summary, the biomarker characteristics of saturated hydrocarbons in the lower Cambrian source rocks have similar implications to those based on the elemental analysis results. It is indicated that the organic matter of the lower Cambrian source rocks at the southern margin of the Ordos basin mainly came from lower algae, with less input from distal clastics. Thus, these source rocks have favorable types of organic matter, dominated by type I and partial type II kerogen, and high paleoproductivity.

3.2.3. Preservation Conditions for Organic Matter. The preservation of organic matter involves two aspects: the hydrodynamic conditions and redox conditions. The Zr/Rb ratio is often evaluated to determine the hydrodynamic strength; violent hydrodynamics are unfavorable for the formation of highly abundant premium source rocks. Highly abundant marine shale source rocks typically form below a wave base, where the wave agitation is relatively weak.\cite{56} Negative correlation is found between the TOC values and the Zr/Rb ratios representing hydrodynamic strength, which suggests that the highly abundant source rocks formed in a gentle hydrodynamic environment (Figure 5a). This inference is consistent with the sedimentary environment of the deepwater shelf in this region.\cite{51}

Redox conditions are another important aspect influencing the formation of the highly abundant source rocks. Typically, a reducing environment promotes the formation of the highly abundant source rocks, whereas in an oxidizing environment, organic matter is consumed, which adversely impacts the concentration of organic matter. In open marine environments, organic matter accumulation is typically associated with reducing environments. Organic matter mainly accumulates on the continental shelf or slope, where the oxygen content is relatively low, below 0.5 mg/L. For example, this accumulation occurs in the northeastern Pacific basin,\cite{57} the Gulf of California,\cite{58} and the Indian Ocean.\cite{59} In addition, upwelling can lead to hypoxic layers, such as in the Peru current. In this study, the redox condition of the source rocks was determined using the trace element V/Cr ratios and the pristine/phytane (Pr/Ph) ratios from biomarkers. A V/Cr ratio exceeding 4.25 indicates a reducing environment; 2–4.25 represents a hypoxic environment; and a value lower than 2 reflects an oxidizing environment.\cite{60} Figure 5b shows that the V/Cr ratios of the lower Cambrian marine shale source rocks from the southern margin of the Ordos basin were from 0.07 to 43.07, with an average of 5.75. In other words, the highly abundant marine shale source rocks mostly formed in a strongly reducing environment. The biomarker parameter Pr/Ph ratios are also often applied to evaluate the sedimentation environment during the source rock formation. Generally, the Pr/Ph ratio lower than 1.0 indicates a hypoxic environment, whereas an oxidizing environment often leads to a high Pr/Ph ratio (usually over 3.0).\cite{61} The saturated hydrocarbon biomarkers in the lower Cambrian marine shale source rocks from the southern margin of the Ordos basin showed relatively low Pr/Ph ratios, ranging from 0.31 to 0.62 (Figure 4), which also indicate that the lower Cambrian source rocks formed in a hypoxic environment.

Higher V/Cr and lower Pr/Ph ratios consistently confirmed that the lower Cambrian source rocks of the southern margin of the Ordos basin formed in a hypoxic to strongly reducing environment.

3.3. Main Controlling Factors for the Formation of Highly Abundant Marine Shale Source Rocks. Under the effects of the regional tectonic setting, where the Yangtze and North China plates rifted apart from each other during the late
Precambrian period, the southern margin of the Ordos basin was characterized mainly by deepwater sedimentation at the platform margin, and the entire margin of the North China plate was located in a deepwater shelf region. Such sedimentary environments favor the formation of source rocks with high organic matter abundance. The tectonic layout of the North China plate during the early Cambrian period had decisive effects on highly abundant source rock formation, especially the scale of the development of the source rocks. Because of the tectonization, the lower Cambrian source rocks are mainly distributed in the paleogeomorphic troughs and fault depressions of the platform marginal slope of the Paleo-Qinling Ocean, and in these paleogeomorphic troughs and fault depressions, the thickness of the source rocks increases greatly. Moreover, stratigraphic correlation, field outcrops, and geochemical data indicate that the Fuping–Luochuan deepwater bay also controlled the distribution area of the lower Cambrian source rocks. Within the bay, the source rocks formed with greater thickness and organic matter richness. It should be noted that the Fuping–Luochuan deepwater bay was located on the passive continental margin of the southern North China plate. Thus, the paleostructural setting at that time laid the foundation for the formation of the highly abundant lower Cambrian source rocks in the southern North China plate.

Figure 6 shows that the highly abundant lower Cambrian marine source rocks at the southern margin of the Ordos basin had relatively high contents of TiO$_2$ (0.04–1.61 mass %), averaging 0.60 mass %) and low SiO$_2$/Al$_2$O$_3$ ratios (1.56–11.84, with an average of 5.10). These values indicate that the sedimentation environments of the highly abundant source rocks had relatively low deposition rates, as well as lower input shares of distal clastics. The deposition rate is directly related to accommodation. The lower Cambrian source rocks at the southern margin of the Ordos basin are composed of sediments, originally from the transgressive surface, that subsequently entered the continental shelf environment after crossing the continental shelf slope belt. With the rapid expansion of accommodation for sedimentation and the relative lack of sediment supply, the lower Cambrian source rocks were mainly distributed along the paleogeomorphic troughs or fault depressions and the deepwater bay, which emphasizes the importance of the paleostructural setting in the early Cambrian period.

It should also be noted that high paleoproductivity and favorable preservation conditions are key to the formation of highly abundant source rocks. The above analysis indicates that the highly abundant lower Cambrian marine shale source rocks of the southern North China plate developed in a strongly reducing/hypoxic environment with weak hydrodynamics. A notable positive correlation was found between the lower Cambrian source rock TOC values and the V/Cr ratios characterizing the redox conditions. Most of the highly abundant source rock samples have high V/Cr ratios over 5, surpassing 30 in extreme cases (Figure 5b), which indicates that the strongly reducing/hypoxic environment was critical to the formation of the highly abundant source rocks. The continental marginal slope environment during the early Cambrian period contributed to the relatively high paleoproductivity for the formation of the highly abundant source rocks. Moreover, because of the upwelling ocean currents, organisms, especially lower algae, were rich in the deepwater continental shelf, which provided an excellent source of organic matter for the formation.
of the highly abundant source rocks. Blooms of floating lower algae consumed large quantities of oxygen in the seawater and thus created hypoxic/reducing areas on the paleogeomorphic troughs and/or fault depressions and the deepwater bay of the deepwater shelf. In addition, a series of paleogeomorphic troughs and/or fault depressions and a deepwater bay were created by tectonization, which provided the closed, strongly reducing sedimentation environment for the formation of the highly abundant source rocks.

3.4. Development Model of the Highly Abundant Marine Shale Source Rocks. In the Cambrian period, a NE-trending deepwater bay (named the Fuping–Luochuan bay) developed in the southern part of the North China plate, and toward the south, the stratigraphic thickness grew rapidly, which reflects transgression toward the direction of the continent. Nearly along the east–west direction, the lower Cambrian formation thickness was relatively high only inside the bay. The outcrops and stratigraphic correlation demonstrate that in the early Cambrian period, a set of shale source rocks was widely developed in the southern North China plate. Because of the tectonic setting, the lower Cambrian source rocks of the North China plate developed mainly in the Xi’an–Luonian–Zhumadian–Hefei region, at the southern margin of the Ordos basin.

Taking all of the above analyses into consideration, this paper concludes that the development of the highly abundant lower Cambrian source rocks in the southern North China plate was under the joint control of the tectonic setting and the undercompensation environments of the passive continental marginal slope of the paleo-Qinlin Ocean and the deepwater bay (the section position of Figure 7 is as shown in Figure 1b). The paleo-geomorphologic setting and deepwater bay together controlled the development scale of the highly abundant source rocks, which resulted in a relatively higher thickness of the source rocks in the paleogeomorphic troughs and fault depressions as well as the deepwater bay. However, the sedimentation environment of the passive continental marginal slope of the Paleo-Qinling Ocean ensured the high quality of the source rocks. Because of the sedimentation environment of the passive continental margin slope controlled by the upwelling and tectonic activity, a series of undercompensation environments in the form of paleogeomorphic troughs or fault depressions and the deepwater bay were created in the deepwater shelf region. Such environments provided the high paleo-productivity and a closed, strongly reducing sedimentation environment for the formation of the highly abundant source rocks.

Among the aforementioned analyses, the paleogeomorphic troughs or fault depressions and the deepwater bay environments of the deepwater continental shelf slope formed in the early Cambrian period are of great significance. In such environments, organic matter mainly comes from lower algae, with less from the distal clastic input. Moreover, organisms are enriched in the deepwater shelf, blooms of lower algae in particular, because of upwelling. Algal blooms consume large amounts of oxygen in the seawater and thus create hypoxic areas in the deepwater shelf regions. Also, a series of undercompensation environments, such as in the paleogeomorphic troughs or fault depressions and the deepwater bay, formed in the deepwater continental shelf slope because of tectonic activity, which favored the preservation of organic matter (weak hydrodynamics and a strongly reducing/hypoxic environment, with high paleo-productivity). To date, although the lower Cambrian strata of the southern part of the Ordos basin have not yet been encountered during drilling, many outcrop sections have revealed that the lower Cambrian rocks have highly abundant source rocks. Furthermore, bitumens are often seen in outcrops, which suggests that hydrocarbon generation, migration, and accumulation have occurred in these lower Cambrian source rocks. The accommodation space was large, and the hydrodynamics were weak in the undercompensation paleogeomorphic troughs or fault depressions and the deepwater bay. After the seawater rose above the continental marginal slope, there was adequate time for organic matter accumulation in such hypoxic environments with relatively deep water depths and a lack of distal clastic sediment supply, and the preservation conditions were excellent. Accordingly, the TOC values in the source rocks of the paleogeomorphic troughs or fault depressions and the deepwater bay became larger and larger (Figure 7). The highly abundant marine source rocks formed in such environments can still be good gas source rocks, even though they have a relatively high thermal maturity.

4. CONCLUSIONS

(1) A set of highly abundant lower Cambrian marine shale source rocks occurs at the southern margin of the Ordos basin. These source rocks are mainly developed in the southern part of the North China plate and now primarily remain in the paleogeomorphic troughs and/or fault depressions and the NE-trending deepwater bay, with a thickness of 10–80 m. The TOC content is relatively high, ranging from 0.12 to 9.39%, with an average of 2.68%. Moreover, the source rocks have favorable organic matter types—mainly sapropelinite macerals—and yet have relatively high thermal maturity, which indicated that the lower Cambrian shales are considered excellent gas source rocks.

(2) For the formation of these highly abundant source rocks, the tectonic setting was fundamental, and high paleo-productivity and favorable conditions for preservation were key. The tectonic setting in the early Cambrian period determined the distribution of the lower Cambrian source rocks, mainly in the paleogeomorphic troughs or fault depressions and the NE-trending deepwater bay, which provided the high accommodation and low deposition rate for the development of the highly abundant source rocks. In addition, because of upwelling, the deepwater shelf enabled blooms of lower algae, which contributed as a source of the favorable type of organic matter and high paleo-productivity. Furthermore, the series of undercompensation environments of the paleogeomorphic troughs and/or fault depressions and the deepwater bay that formed in the deepwater shelf provided good preservation conditions for the formation of the highly abundant source rocks.

(3) The development of the highly abundant lower Cambrian source rocks in the southern part of the North China plate was under the joint control of the tectonic setting, the undercompensation environments of the passive continental marginal slope of the Paleo-Qinling Ocean, and the deepwater bay. The paleogeomorphicologic setting in the early Cambrian period and the deepwater bay environment together controlled the development of the highly abundant source rocks. In addition, the sedimentation environment of the continental marginal
slopes of the Paleo-Qinling Ocean ensured the high quality of the source rocks.

5. SAMPLING AND ANALYSIS METHODS

The mudstone and shale samples were mainly retrieved from the outcrops in Zhangwan, Shipo, Xigou, Lingbao, Guichengnan, and Chuhou in Luyuan town, Shaxi county, and in Zhoujiahe village, Zhuyang town, and Beigou village, Henan province. These sampling locations are mainly distributed on either sides of the Luo River and in Lingbao, Henan (Figure 1b). All samples collected from the outcrops were obtained in the vicinity of transportation roads (e.g., those from the Zhangwan, Guichengnan, and Shipo sections) to ensure that the samples were fresh and that the testing results would not be affected by weathering.

The TOC measurements and rock pyrolysis of 61 samples and the gas chromatography–mass spectrometry (GC–MS) testing of extracted saturated hydrocarbons from 14 source rock samples were performed at the State Key Laboratory of Petroleum Resources and Prospecting, China University of Petroleum (Beijing), with a US-made Leco CS230 Carbon Determinator (for TOC) and an OGE-II Rock Pyrolyzer (IPF Energies Nouvelles) (for rock pyrolysis). Before testing, the outcrop samples were milled into 200 mesh particles using an agate mortar and pestle, and the inorganic carbon was removed. The testing and calibration strictly followed the corresponding national standards of China (GB/T 19145-2003 and GB/T 18602-2012) and the design of the blank test. The US-made Agilent 7890-5975C GC–MS system was used for the GC–MS testing. The samples were first ground into 80 mesh particles and then extracted in a Soxlet apparatus for 24 h using methylene dichloride. The extracts were then divided into saturated hydrocarbon, aromatic hydrocarbon, nonhydrocarbon, and asphaltene as they passed through silica gel and an alumina column chromatograph.

Major and trace element analyses of the 52 samples were conducted at the China National Petroleum Corporation Key Laboratory of Reservoir Characterization, using a ZSX Primus II X-ray fluorescence spectrometer (Rigaku, Japan). The samples were first ground into particles smaller than 200 mesh, and 5 g of each sample was pressed into a tablet prior to testing. The testing and calibration were strictly in compliance with the corresponding national standards of China (GSR-5, GSR-6, and GSR-9) and the design of the blank test. The relative standard deviations of the major and trace element analysis results were lower than 1 and 2%, respectively.

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