Deep-water depositional mechanisms and significance for unconventional hydrocarbon exploration: A case study from the lower Silurian Longmaxi shale in the southeastern Sichuan Basin

Chao Liang, Zaixing Jiang, Yingchang Cao, Minghao Wu, Ling Guo, and Chunming Zhang

ABSTRACT

The purpose of this work was to study the depositional mechanisms and significance of the Longmaxi shale in the Sichuan Basin in southern China. Seven lithofacies were identified based on the detailed observation of outcrops and cores using petrographic and scanning electron microscope examination of thin sections and other data analyses: (1) laminated calcareous mudstone, (2) laminated carbonaceous mudstone, (3) laminated silty mudstone, (4) laminated claystone, (5) laminated siliceous shale, (6) siltstone, and (7) massive mudstone. The laminated mudstone and laminated claystone originated from suspension deposition, and siliceous shale is associated with ocean upwelling, whereas massive mudstone and siltstone were primarily deposited by turbidity currents. The depositional mechanisms have a great effect on the source rock and reservoir properties. Suspension deposition near oceanic upwelling zones can provide favorable conditions for the production and preservation of organic matter and are thus conducive to the formation of high-quality source rocks (total organic carbon content up to 5.4%). The reservoir storage spaces are primarily interlaminated fractures and organic pores with good physical reservoir properties (high porosity, permeability, and brittle mineral content). Turbidity currents may carry a large
A quantity of oxygen to the seafloor, resulting in the oxidation of organic matter, which is unfavorable for its preservation. The lithofacies formed by turbidity currents have relatively low total organic carbon contents (average: <1%). Structural fractures and intergranular pores are the primary storage spaces that are present in the reservoir. In summary, organic-rich shale and siliceous shale that was deposited from suspension near upwelling zones are key exploration targets for shale oil and gas. The widely distributed, multilayer, tight sandstone is important in the exploration for tight oil. A better understanding of the deposition mechanism and its effect on oil reservoirs may assist in identification of favorable areas for exploration.

INTRODUCTION

Unconventional oil and gas hydrocarbon resources are emerging because global energy demand is growing, and the existing resources of conventional oil and gas are becoming scarcer; this phenomenon makes the discovery and use of unconventional oil and gas resources an important field of exploration globally (Scott and Glasspool, 2005; Zhang, 2010). Several notable unconventional hydrocarbon resources in China are shale oil, shale gas, and tight oil (Jia et al., 2012). It is worth noting that these reservoir layers are mainly deposited in deep-water environments. Deep-water deposition has been the focus of much attention, and research has mainly focused on the flow patterns and flow manner. Research has also focused on the establishment of models, including the turbidity current and Bouma sequence models (Bouma, 1962; Shanmugam, 1997; Posamentier and Walker, 2006), turbidite mudstone (Potter et al., 2005; Ochoa et al., 2013), sandy debris flow (Shanmugam, 2006; Xian et al., 2013), mass transport deposition (Weimer and Slatt, 2007; Moscardelli and Wood, 2008), and related topics. The depositional mechanisms that occur in the bathyal and deep-sea regions include mass flow, bottom currents driven by gravity, contour currents, deep-water traction currents, and suspension deposition and corresponding sedimentary facies (Loucks and Ruppel, 2007; Abouelresh and Slatt, 2012; Shanmugam, 2012).

In recent years, shale oil, shale gas, and tight oil have been the main exploration targets and have succeeded conventional hydrocarbon resources (Zhang et al., 2007; Zou et al., 2010a; Huang et al., 2012; Jia et al., 2012). Many studies have been done on the source rocks (Li et al., 2008; Liang et al., 2009; Zou et al., 2010a) and reservoir properties (Loucks et al., 2009; Jiang et al., 2010; Guo et al., 2011a; Slatt and O’Brien, 2011) of shale reservoirs. These properties are closely related to the depositional mechanisms (Aplin and Macquaker, 2011). The Sichuan Basin is an important shale gas strategy experimental site, and the lower
Silurian Longmaxi Formation shale (generally called Longmaxi shale) is the main target material (Guo et al., 2011b; Huang, 2011; Liang et al., 2012). Previous studies have shown that the Longmaxi shale was deposited in deep-water environments (Su et al., 2007; Pu et al., 2010). However, the deposition mechanism and its implications for the source rocks and shale reservoirs are less well explored. This paper focuses on the lower Silurian Longmaxi shale, particularly on the characteristics of its lithology and the depositional mechanisms, to reveal their influence on the source rock and reservoir properties.

The objective of this paper is to (1) characterize the lithofacies of the Longmaxi shale; (2) analyze the depositional process of the lithofacies and depositional model; and (3) discuss the reservoirs, the relationship between the deposition mechanisms and characteristics of the source rocks, and the exploration of shale oil and gas and tight oil in the study area and, perhaps, other areas.

GEOLOGICAL SETTING

The study area is located in the southeastern Sichuan Basin (Figure 1A), which is one of the most important petroliferous basins in southern China. The administrative regions include the southeastern area of the city of Chongqing, the southwestern area of Hubei province, and the northwestern area of Hunan province (Figure 1B). The formation and evolution of the Sichuan Basin can be subdivided into four major stages (Mao et al., 2006): (1) the Early–Middle Proterozoic (Pt2–Pt3) basin base formative stage, (2) the Sinian–Middle Triassic (Z1–T2) passive continental margin stage, (3) the Late Triassic (T3) basin–mountain conversion and foreland basin formation stage, and (4) the Jurassic–Quaternary (J–Q) foreland basin tectonic stage (Shen et al., 2007). Because of the tectonic compression in the Late Triassic, folds and faults are well developed in the study area. The folds present as duplex anticlines, duplex synclines, and box-shaped anticlines and synclines. The faults in the study area mainly include thrust faults, reverse faults, and normal faults. The normal faults mainly developed along the anticline axis, and the reverse faults mainly developed along the wings of the anticlines with a steep dip (up to 80°). These fractures, which were affected by tectonic activity in different periods, are complex and show interrelated cutting, which can be observed in the well cores. These fractures can be good pathways for shale gas migration from the source to the reservoir.

The study area experienced the tectonic evolution of the Sichuan Basin (Hao et al., 2008; Liang et al., 2012). The thick Longmaxi shale was deposited in a passive continental margin environment during the early Silurian, which corresponds to a major global transgression (Su et al., 2007). The Longmaxi shale is underlain by thick, shallow Ordovician marine limestone and capped by mid-Silurian Luoreping light gray to yellow siltstone (Figure 1C).

The anoxic environment caused by the transgression is favorable to the preservation of thick black shale deposits. The Longmaxi shale is widely distributed in the Sichuan Basin, although strata are missing in the middle, covering an area of approximately 12.82 × 10⁴ km² (4.95 × 10⁴ mi²) (Pu et al., 2010). The black shale’s interval thickness ranges from 50 to 300 m (164–984 ft), which gradually increases to the southeast and northeast. The total organic carbon (TOC) content has the same trend. The calcium content increases to the south, and silt increases to the west (Liu et al., 2013). The Longmaxi shale in the study area has considerable thickness and is rich in organic matter, which makes it an important source rock for shale gas exploration in the study area. Several well-described outcrops and well Yuye-1 allow us to examine the detailed lithological features and deposition mechanism of this thick black shale. The Longmaxi shale is mainly black mudstone in the middle and lower intervals, and graptolite fossils are common, whereas silty mudstone, turbidite siltstone, and gravity slumps occur in the top of the interval.

METHODOLOGY

This study uses a comprehensive approach that integrates principles of sedimentology, mineralogy, petrology, sequence stratigraphy, and reservoir geology. The basic data include 324 m (1063 ft) of core from well Yuye-1, 870 m (2854 ft) of outcrop sections from 10 profiles (locations shown in Figure 1B), a total of 337 thin sections, x-ray
diffraction data, geochemical elements data, and source rock data (vitrinite reflectance [$R_o$], TOC, and maceral compositions) from well Yuye-1 and outcrops, with samples collected at 2.5-m (8.2-ft) intervals from well Yuye-1 and at 1.25-m (4.1-ft) intervals in the long outcrop profiles, such as Hongyanxi Outcrop and Lujiao Outcrop; scanning electron microscope (SEM) observations were conducted from 35 samples. The gamma values of cores and outcrops were collected at 25-cm (9.84-in.) intervals and constructed by the portable $\gamma$ spectrometer (Science Applications International Corporation GR-135). The whole-rock and clay mineral x-ray diffraction tests were carried out at the Research Institute of Petroleum Exploration and Development, China National Petroleum Corporation. Source rock analysis ($R_o$, TOC, and maceral composition) was conducted at the Guangzhou Institute of Geochemistry, Chinese Academy of Science. The element analyses were carried out at the Research Institute of Petroleum Exploration and Development, China National

Figure 1. (A) Sketched structural map of the Sichuan Basin, south China. (B) Map showing the study area, outcrops, and well site. (C) Stratigraphic column and study interval (modified from Guo et al., 2011a).
Petroleum Corporation. Because of the high degree of thermal evolution and the type I, type II kerogen, the vitrinite reflectance values were calculated using the empirical formula $R_o = 0.618BR_o + 0.4$ (Zhang and Zhu, 2006); $BR_o$ here indicates the bitumen reflectance. The factors in this formula (0.618 and 0.4) were ultimately gained on the basis of a large number of calibration verifications (the $R_o$ and the $BR_o$ values), and their values have been used for calibration verification in the Longmaxi shale, Sichuan Basin (Han et al., 2013; Huang et al., 2013; Zhang et al., 2015). The SEM observations and reservoir property analyses were conducted by the Langfang Branch of the Research Institute of Petroleum Exploration and Development, China National Petroleum Corporation. The lithology and mineralogy of the target layers in the study area were based on detailed observation of cores and outcrops, SEM observation, and whole-rock and clay mineral x-ray diffraction analysis. Source rock characteristics were described in terms of organic maceral composition, TOC tests, and backscatter SEM analysis. Reservoir pores were mainly identified by using SEM and field emission SEM. The depositional model was established by integrating the cores, outcrops, and analytical data.

**MINERALOGY AND LITHOFACIES**

**Mineralogy**

The Longmaxi shale is dominated by quartz and clay minerals (Figure 2A), with subordinate plagioclase, potassium feldspar, calcite, dolomite, and pyrite (Table 1). The quartz content is 28%–81% (average: 43.2%) and mainly occurs as silt grains from terrestrial transportation, indicating a relatively strong terrestrial sediment supply. Amorphous silica can also be found in the shale and is mainly composed of the skeletons of organisms, such as diatoms, radiolarians, and sponges (Figure 3A, B). The clay mineral content ranges from 12% to 65% (average: 39.6%). The clay minerals are mainly illite, illite–smectite mixed layer minerals, and chlorite (Figure 2B). The relative content of illite is 39%–61%, whereas the illite–smectite mixed layer content is 19%–53%, and the chlorite content is 4%–32%. Feldspar accounts for 3%–20% (average: 11.9%). Calcite and pyrite are rare, and pyrite mainly occurs as framoidal pyrite (Figure 3C, D).

**Lithofacies**

The Longmaxi shale lithofacies were defined from one cored well (well Yuye-1) and several

![Figure 2](image-url)  
**Figure 2.** Ternary plot of the (A) whole-rock mineral composition and (B) clay mineral composition of the Longmaxi shale in the study area.
outcrop sections (see Figure 1B for the locations). In this study, we recognized seven lithofacies based on the mineralogy, fabric, biota, and texture.

**Laminated Calcareous Mudstone**
This lithofacies is only found in the upper Longmaxi shale interval with high calcite content. The calcite content in the calcareous shale ranges from 20% to 50%, with limy fracture surfaces visible in a handful of specimens (Figure 4A). In laminated calcareous mudstone (LCM), the bright laminae are dominantly composed of microcrystalline calcite or high-calcium clay, whereas dark laminae are mainly clay minerals rich in organic matter (Figure 5A).

**Laminated Carbonaceous Mudstone**
This lithofacies mainly occurs in the lower Longmaxi shale interval. Laminated carbonaceous mudstone (LCM-2) is black in color and stains one’s hands (Figure 4B). This lithofacies is mainly composed of clay minerals, quartz, mica, feldspar, pyrite, and calcite. Microscopic observation shows that quartz grains float among the clay minerals, ranging in size from 20 to 60 μm. Grains are poorly sorted and mostly subangular to subrounded (Figure 5B). The carbonaceous mudstone contains a large diversity of carbonized organic matter, and the organic carbon content ranges from 3% to 10% (Table 1).

**Laminated Silty Mudstone**
The laminated silty mudstone (LSM) lithofacies mainly developed in the middle and the upper...
Longmaxi shale. The bright laminae are mainly silt, and the dark laminae are mainly clay minerals (Figure 4C). Microscopic observation shows that the debris particles account for 20%–40% and are mainly poorly sorted quartz grains with medium roundness floating among clay minerals. The clay minerals are mainly scaly or amorphous, and a small amount of feldspar and mica can also be found. The black materials are mainly clay minerals rich in organic matter, which is mixed with the clay minerals and is difficult to distinguish (Figure 5C).

Laminated Claystone
The laminated claystone (LC) lithofacies is characterized by its black or dark gray color with limited hardness and its occurrence in horizontal bedding (Figure 4D). It mainly consists of clay minerals, with clay content greater than 50%. Minor amounts of clay- and silt-sized quartz and feldspar grains are floating in the clay minerals (Figure 5D).

Laminated Siliceous Shale
The laminated siliceous shale (LSS) lithofacies predominates within the lower Longmaxi shale. In handheld specimens, the siliceous shale is black or gray–black and very hard, and graptolite is abundant (Figure 4E, F). The laminae in the siliceous shale is up to 1 cm (0.39 in.) thick. The x-ray diffraction shows that the silica content in the siliceous shale is greater than 65%. The thin sections show that the silica is mostly authigenic and cryptocrystalline in texture and is abundant in silica-rich organisms (such as radiolaria and sponges) and organic matter (Figure 5E, F), which distinguishes it from the LSM.

Siltstone
This lithofacies mainly developed in the upper Longmaxi shale. Beds of siltstone (S) are commonly found in black shale and can extend for a long distance with a single layer thickness ranging from 0.05 to 2 m (0.16–6.56 ft; Figure 6A–C). Flute casts can be

Figure 3. (A, B) Siliceous organisms and (C, D) framboidal pyrite. The framboidal size is mainly less than 5 μm.
Figure 4. Macrocharacteristics of lithology deposited by suspension deposition and upwelling. (A) Laminated calcareous shale, well Yuye-1, 177.75 m (583.2 ft). (B) Laminated carbonaceous shale, well Yuye-1, 267.7 m (878.3 ft). (C) Laminated silty shale, Lujiao outcrop. (D) Laminated claystone, well Yuye-1, 306.32 m (1005 ft). (E) Laminated siliceous shale, Lujiao outcrop. (F) Laminated mudstone with abundant graptolites, Hongyanxi outcrop.
found in the outcrops (Figure 6D). In addition, liquefaction and slump structures are commonly found (Figure 7A–C). The laminae are greatly contorted and sometimes upright. Some silt blocks were formed by slumping, and slightly deformed bedding developed over the silt blocks. We can also observe graded bedding in which the grain size changes from silt to mud (Figure 7C). Rippled bedding and truncated structures (Figure 7D) also developed. Microscopy shows that the debris particles in the siltstone account for 75%–90% and are mainly composed of moderately rounded, poorly sorted quartz grains that in places exhibit corrosion along their edges (Figure 7F). Feldspar is present with a polysynthetic twin and partial

**Figure 5.** Microcharacteristics of lithology deposited by suspension deposition and upwelling. (A) Laminated calcareous mudstone, well Yuye-1, 200.7 m (658.5 ft). (B) Laminated carbonaceous shale, well Yuye-1, 239.1 m (784.4 ft). (C) Laminated silty shale, well Yuye-1, 178.3 m (585 ft). (D) Laminated claystone, well Yuye-1, 295.3 m (968.8 ft). (E) Laminated siliceous shale, with embedded siliceous organisms, Lujiao outcrop. (F) Siliceous sponges in laminated siliceous shale, Lujiao outcrop.
clay-mineralized at the feldspar grains edge, which is marked as a red F in Figure 7F. A few clay minerals (mainly illite) and mica fragments occur as matrix among the silt-sized grains, such as quartz and feldspar grains.

Massive Mudstone
The massive mudstone (MM), which mainly overlies the siltstone, is characterized as a massive structure and is light gray in color (Figure 7E), which clearly distinguishes it from the laminated mudstone. The light gray MM is easily identified by its internal homogeneity and massive structure (Figure 7G). It mainly overlies the massive siltstone. Microscopy shows that the MM is mainly composed of clay minerals and small amounts of silt (Figure 7G). The silt grains are disorganized and do not indicate a flow direction. Geochemical analysis shows that the TOC content of the MM is very low, averaging 0.43%, which is much lower than that of the laminated mudstone.

DEPOSITIONAL PROCESS AND MODEL

Depositional Process
The laminated mudstone (LCM, LCM-2, and LSM) and LC are characterized by fine grain size, scarce large debris, and compositions rich in pyrite and organic matter. In addition, graptolite fossils are common in these lithofacies. The laminated mudstone is continuous and thick. These characteristics indicate that these layers were formed by suspension deposition in a quiet-water region with a low deposition rate. Suspension was the main depositional process of the Longmaxi shale in the study area.

Siliceous shale is rich in silica, and most of the siliceous grains are amorphous. The origin of the silica in the siliceous shale is different from that in the laminated mudstone, which received quartz material from terrestrial sources with poorly sorted and subangular to subrounded grains (Figure 5A–D). The
Figure 7. (A) Slumping deformation in siltstone with liquefaction, well Yuye-1, 81.15 m (266.2 ft). (B) Deformation with a thickness of approximately 7 cm (2.76 in.), well Yuye-1, 90.8 m (297.9 ft). (C) Deformation, well Yuye-1, 94.1 m (308.7 ft). (D) Wavy bedding, well Yuye-1, 51.16 m (167.8 ft). (E) Gray massive mudstone, well Yuye-1, 17.6 m (57.7 ft). (F) Thin section photo of well-compacted siltstone with the presence of feldspar and clay minerals, well Yuye-1, 43.6 m (143 ft). (G) Photomicrograph of massive mudstone (Figure 7E), mainly composed of clay minerals with small amounts of silt and organic matter, well Yuye-1, 17.6 m (57.7 ft). C = clay; F = feldspar; Q = quartz.
amorphous quartz (Figure 5E, F) is associated with silica-rich organisms in the study area, indicating that it might be biogenic. The numerous silica-rich organisms may be associated with upwelling (Liu et al., 2010). Commonly, the quartz content has a negative correlation with organic matter, but the quartz content in the siliceous shale has a positive correlation with the TOC content (Figure 8), which is strong evidence of a biogenic mechanism instead of a terrestrial source. A possible interpretation is that the dissolved silica in seawater and nutrients were brought to the surface, promoting the growth of surface organisms, which effectively improved the original marine productivity and formed amorphous quartz.

The siltstone is characterized by interbedding within the black shale and flute marks (Figure 6D) in the Hongyanxi outcrop section. Furthermore, the interface between the siltstone and the underlying black shale is always sharp (Figure 6A–C), and the grain size fines upward from the base to the top (Figure 6B). Wavy bedding and horizontal bedding are also found in the siltstone. The whole deposition set, from wavy and horizontal bedding siltstone at the base to MM at the top, shows the C, D, and E sections of the Bouma sequence. The MM (Bouma section E) is characterized by massive structure, disorganized and chaotic detrital grains, and low TOC content and so obviously differs from the laminated mudstone. Previous studies show that the long axes of the detrital grains are horizontally arranged from slow suspension settling (Potter et al., 2005). The massive structure and disorganized detrital grains suggest a rapid depositional process for the MM, which is different from suspension settling. Here the MM is interpreted to have been deposited by turbidity currents. Therefore, we interpret this siltstone and MM as fine-grained turbidites formed in a deep-water environment. The low TOC content of the MM can be interpreted as the result of the turbidity currents carrying a large amount of oxygen to the ocean bottom (Figure 9), which results in the oxidation of organic matter. Turbidity currents are common in the upper and middle Longmaxi shale.

**Depositional Model**

Based on the detailed observation and description of a long Hongyanxi outcrop (Figure 10; see location in Figure 1B), a vertical sequence of different lithofacies and depositional mechanisms was constructed (Figure 11).

The lithofacies and deposition processes show that suspension is the main depositional process; the laminated mudstone (LCM, LCM-2, LSM, and LC) and fine grain sizes are effective evidence for suspension deposition. The massive siltstone, which has a flute-cast interlayer in the black shale, indicates that deposition occurred as a result of turbidity currents. Additionally, the presence of MM indicates
deposition by turbidity currents because it overlies the turbidite siltstone, has poor TOC content, and lacks fossils. Laminated siliceous shale abundant in silica-rich organisms and authigenic silica suggests that upwelling contributed to the formation of the lower Longmaxi shale. In addition, as evidenced by hummocky cross bedding and rippled bedding (Figure 7D), the upper Longmaxi shale was also affected by storm currents, although the influence was weak and limited (Guo et al., 2011a).

In the lower Longmaxi shale from 83 to 53 m (272–174 ft), suspension is the dominant deposition mechanism, and the lithofacies are mainly LC with parts of laminated silty shale, siliceous shale, and siliceous mudstone. The siliceous shale suggests that the lower Longmaxi shale was affected by upwelling. The lithofacies are rich in organic carbon and pyrite, with abundant graptolite fossils, laminae, and rare coarse clastics. The graptolites in the Longmaxi shale were mainly deposited in a hemipelagic environment (Guo et al., 2011b; Liu et al., 2011), which is consistent with the well-developed laminae and lack of coarse clastics. The presence of pyrite and high TOC content suggest that the water was deep enough for suspension deposition, with anoxic water at the bottom. Additionally, the high organic carbon content suggests high original ocean productivity, which may be related to the warm climate conditions confirmed by geochemical and paleontological analyses (Guo et al., 2011b; Mou et al., 2011). The deep-water environment of the lower Longmaxi shale is confirmed by the above evidence.

In the upper Longmaxi shale from 53 to 6 m (1744–20 ft), more turbidity currents and gravity slumps are found in the sedimentary record. The lithofacies have a lighter color and a lower TOC content than those in the lower Longmaxi shale. The increase in siltstone and, in particular, the appearance of tempestite strongly suggest a shallowing water depth and reception of more terrestrial materials. An upward shallowing trend can be inferred from the TOC, lithofacies, and sedimentary structures. The two intervals correspond to the transgressive systems tract and highstand systems tract of the Longmaxi shale, respectively (Guo et al., 2011b; Liang et al., 2012).

In this paper, geochemical elements are used to analyze the sedimentary environment (Figure 12). The Ba of biological origin (bio-Ba) content and TOC content are used to analyze productivity; B, Sr/Ba, and B/Ga are used as a proxy for paleosalinity; and the V/Cr and V/(V + Ni) ratios are used as a proxy for anoxic conditions. The high bio-Ba content, averaging 420.84 µg/g (measured by the method cited in Teng et al., 2006 and Liang et al., 2014), and high TOC content, averaging 2.68%, suggest that the lower Longmaxi shale has high productivity, which gradually decreases upward (Figure 12). Other studies have shown that values of V/(V + Ni) ≥ 0.54 and V/Cr > 2 indicate an anoxic environment (Hatch and Leventhal, 1992; Wang et al., 2014; Xiong et al., 2015). The V/(V + Ni) value of the Longmaxi shale ranges from 0.62 to 0.96, and the V/Cr value ranges from 2.24 to 12.35, suggesting strong anoxic conditions in the lower Longmaxi shale, gradually decreasing upward (Figure 12). The B, Sr/Ba, and B/Ga values show that the paleosalinity increases abruptly in the lower Longmaxi shale, gradually decreasing upward. In fact, the siliceous shale mainly developed in this stage. Regional upwelling can bring deep salty water to the ocean surface and increase the surface salinity (Lei et al., 2002; Xiang and Yan, 2002; Zhang et al., 2012), which is also reflected by our geochemical Sr/Ba and B/Ga ratios (Figure 12). In the middle Longmaxi shale, the water body is still anoxic,
Figure 11. Comprehensive chart of the sequence of deposition mechanisms in the Hongyanxi outcrop. Stars mark the locations of the photographs in order, and the photos not shown in this figure refer to the photos in Figures 4 and 6.; GR = gamma ray; HST = highstand systems tract; LC = laminated calcareous mudstone; LCM = laminated carbonaceous mudstone; LCM-2 = laminated carbonaceous mudstone; LSM = laminated silty mudstone; LSS = laminated siliceous shale; MM = massive mudstone; S = siltstone; Sq1 = sequence 1; TST = transgressive systems tract.
whereas the paleosalinity and productivity gradually weaken upward. The laminated mudstone deposited by suspension mainly developed in this stage. The anoxic environment, coupled with the dropping relative sea level, is destroyed in the upper Longmaxi shale, and the effect of turbidity currents increases.

Based on the lithofacies, sedimentary structures, organisms, and mineral composition observations, a depositional model for the Longmaxi interval is proposed. The Longmaxi interval’s deep-water slope setting is characterized by anoxic conditions at the bottom, which is consistent with the high organic carbon and pyrite content. The evidence shows that the Longmaxi mudstone was formed by a comprehensive depositional process that included suspension, upwelling, and turbidity currents (Figure 13).

**DISCUSSION**

**Implications for the Source Rock**

The accumulation and preservation of organic matter are important factors for source rocks. Profitable accumulation and preservation conditions are prerequisites for the formation of high-quality source rock; these

![Figure 12. Geochemical analysis of the Lujiao outcrop as an indicator of the sedimentary environment of the Longmaxi shale. Bio-Ba = barium of biological origin; Form. = formation; TOC = total organic carbon.](image)

![Figure 13. Depositional model for the Longmaxi shale. The depositional setting is mainly the slope–deep sea, as shown in the red box (modified from Loucks and Ruppel, 2007).](image)
are related to the primary productivity and to oxidizing–reducing conditions. The depositional environment, which is related to the primary organism productivity and oxidizing–reducing conditions, is an important factor in the accumulation and preservation of organic matter (Arthur and Sageman, 1994; Stow and Mayall, 2000). The quality and distribution of the source rock in the Longmaxi interval is thus highly influenced by the depositional process.

Suspension deposition occurs in a deep-water setting, which commonly has a reducing environment at the ocean bottom. Dead planktonic organisms that settle onto the seabed are not easily oxidized or degraded in an anoxic environment, which is beneficial for the preservation of organic matter. This finding can be confirmed by the high TOC content of mudstone deposited from suspension. Upwelling can promote the flourishing of surface organisms, greatly improving the primary productivity. Combined with favorable preservation conditions, the siliceous mudstone and siliceous shale associated with upwelling also have high TOC contents. Bottom currents such as turbidity currents can carry a large amount of oxygen to the seabed. This can convert the hypoxic water bottom into an oxygen-rich environment (Figure 9), resulting in the oxidation of organic matter. Consequently, the TOC content in the turbidite mudstone is relatively low, presenting a light color.

The occurrence and types of organic matter differ because of the various depositional processes and lithofacies. Organic matter is mainly continuously distributed in laminated mudstone, whereas it occurs discretely in MM. The organic matter in siliceous shale and laminated mudstone is primarily type I. As mentioned above, these lithofacies are deposited by suspension. Therefore, the productivity in laminated mudstone mainly originates from hemipelagic planktonic organisms, and terrestrial organic matter is lacking. In contrast, in the MM associated with turbidity currents, the content of terrestrial organic matter increases significantly, dominated by type III organic matter (Figure 14).

Implications for Reservoir Storage Spaces

The pore spaces and types are important factors for reservoir quality, especially for shale intervals. Six types of pore spaces exist in the Longmaxi shale. Two types of pores are observed in the macroscale: structural fractures and interlaminated fractures, which are observed in cores and outcrops. Four types of pores are observed in the microscale: organic pores, intercrystalline pores, intraparticle pores, and dissolution pores, which are evident from thin sections and SEM examination.

Structural Fractures

Structural fractures form as a direct result of tectonic stress. The strong tectonic activity in the study area is conducive to the development of structural fractures, which are important reservoir storage spaces in the region. The observation of cores and outcrops shows that fracture surfaces can be straight, whereas laminae are commonly faulted, and some fractures are partially or completely filled with calcite (Figure 15A–C).

Interlaminated Fractures

An interlaminated fracture is a fracture between parallel laminae with peeling lineations (Liang et al., 2012). A mechanical property of the weak interfaces in mudstone is that they are easily stripped. A large
Figure 15. Reservoir storage space pores in mudstone. (A) Complex structural fractures filled by calcite with miscellaneous angles, well Yuye-1, 271.6 m (891.1 ft). (B) Parallel structures with a dip of approximately 30° (arrows), well Yuye-1, 208.9 m (685.4 ft). (C) High-angle fractures 1–4 mm in width, filled by calcite (arrows), well Yuye-1, 275.1 m (902.6 ft). (D) Interlaminated fractures extending along the boundary of the laminae, well Yuye-1, 189.2 m (620.7 ft). (E) Interlaminated fractures filled by calcite and pyrite, well Yuye-1, 287.1 m (941.9 ft). (F) Organic matter (OM) (black area) in a backscatter image, well Yuye-1, 280 m (918.6 ft). Q = quartz. (G) Organic pores generated by hydrocarbon expulsion in siliceous mudstone, with a pore size of approximately 10–30 μm, Shiqiao outcrop. (H) Recrystallized intercrystalline pores in calcite, with a pore size of approximately 5–20 μm, Rongxi outcrop. (I) Intercrystalline pores in clay minerals, with a pore size of 50–500 nm, well Yuye-1, 255 m (836.6 ft). (J) Intercrystalline pores between flaky clay minerals, well Yuye-1, 255 m (836.6 ft). (K) Framboidal pyrite in mudstone, with possible pores existing between the pyrite crystals in the frambooids, well Yuye-1, 290 m (951.4 ft). (L) Interparticle pores between quartz grains and clay minerals, well Yuye-1, 255 m (836.6 ft). (M) Interparticle pores, Rongxi outcrop. (N) Interparticle pores along quartz grains, Lujiao outcrop.
number of interlaminated fractures exist at the junction between the bright and dark laminae in laminated mudstone. These fractures primarily developed between the laminae and extend laterally along the laminae; some are filled by calcite (Figure 15D, E).

Organic Pores
Organic pores are well developed in the Longmaxi shale deposits, especially in those that are rich in organic matter, such as laminated mudstone and siliceous shale.

The enrichment and formation of organic pores are highly related to the maturity of the organic matter and the generation of hydrocarbons. This mainly occurs because the generation of liquids or the accumulation of gases generates bubbles (Loucks et al., 2009). Studies have shown that organic pores are important factors in the pore networks in mudstone and that they provide important reservoir storage spaces for shale gas (Loucks et al., 2009; Slatt and O’Brien, 2011). The TOC content and thermal maturity are important factors in the generation and quantity of organic pores. Pores that occur in the organic matter (Figure 15F) form honeycomb pores (Figure 15G) during the process of organic matter conversion. Organic pores are well-developed in mudstones, especially in those that are rich in organic matter, such as laminated mudstone and siliceous shale.

Intraparticle Intercrystalline Pores
Intraparticle intercrystalline pores are mainly identified in clay minerals and pyrite framboids. These pores are very common in clay minerals, with pore diameters ranging from 1 to 10 μm (Figure 15I, J). Intraparticle intercrystalline pores are in places observed in calcite (Figure 15H), where they are primarily caused by the dissolution or recrystallization of the calcite. In a deep-water environment, the pyrite content is relatively high. Previous studies have shown that intercrystalline pores in pyrite framboids are large enough for the storage of hydrocarbon molecules (Slatt and O’Brien, 2011; Loucks et al., 2012). In the study area, a large amount of pyrite framboids and intraparticle intercrystalline pores can be observed by field emission SEM, with pore diameters ranging from 20 nm to 500 μm (Figure 15K).

Interparticle Pores
Interparticle pores are mainly observed between grains of quartz, feldspar, and organic matter (Figure 15L–N). Because of variations in the mechanical properties of the grains, these pores commonly occur along the edges of grains subjected to stress. Generally, the interparticle pores do not extend far and are limited to the edges of grains. These pores help to improve the physical properties of the mudstone and are conducive to the fracturing of mudstone reservoirs.

All the pore types mentioned above are effective spaces for the storage of hydrocarbon molecules. Organic pores are probably the most important reservoir storage spaces and are important factors in the porosity networks of mudstone (Loucks et al., 2009; Zou et al., 2010b; Slatt and O’Brien, 2011). Furthermore, our studies show that the TOC content has a positive correlation with the absorbed gas and total gas content (Figure 16). The organic carbon in the Longmaxi shale interval comes from the generation of hydrocarbons in the source rock and provides organic pores. The distribution and enrichment of organic carbon is highly influenced by suspension and

Figure 16. Relationship (A) between the absorbed gas content and total organic carbon (TOC) and (B) between the pore volume and TOC.

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upwelling processes (Table 2); thus, the depositional mechanisms are key factors in predicting the potential of the source rock. Residual interparticle and intercrystalline pores are the main reservoir storage spaces in embedded siltstone, which can form a tight oil reservoir. The development of tight sandstone in deep-water regions comes from turbidity current transportation.

**Implications for Hydrocarbon Exploration**

Shale oil and gas have now become important exploration targets. In North America, the discoveries of the Bakken shale play, Eagle Ford shale play, and Haynesville shale play, among others, have proven that shale plays have huge hydrocarbon potential to secure the world’s energy future supply. A proper understanding of the depositional mechanisms and their effect on the source rock, especially on organic matter types and content, can help us find favorable exploration areas.

Generally, the laminated mudstone and siliceous shale deposited by suspension processes with upwelling are rich in organic matter; sapropelic deposits are particularly abundant in organic matter. As mentioned above, organic pores are key reservoir storage spaces; thus, organic-rich mudstone deposits could constitute high-quality reservoirs for shale gas.

These lithofacies have a well-connected porosity network, and their porosity and permeability are high. In contrast, lithofacies influenced by turbidity currents, such as MM, have low organic matter content and high clay mineral content, with little contribution of organic pores. Additionally, the lithofacies influenced by suspension and upwelling have high brittle mineral content (quartz), especially siliceous shale (up to 85%) (Table 2), which is conducive to hydraulic fracturing. The source rock, reservoir storage space, porosity, permeability, brittleness, and lithology generated by upwelling and suspension can help identify the best targets for shale oil and gas exploration, especially in siliceous shale.

The siltstone and muddy siltstone embedded in mudstone should not be underestimated. Although the physical properties for a tight reservoir are poor (porosity $\phi < 10\%$, permeability $K < 0.1$ mD, and pore throat diameter $d < 1 \mu m$), tight siltstone may form tight oil reservoirs, which have been important exploration targets in the Ordos and Bohai Bay Basins (Jia et al., 2012). The oil in the Ordos Basin’s Chang-7 section (Yanchang Formation, Triassic) is generated from high-quality shale, and the reservoir is gravity flow siltstone.

The oil generated in the Chang-7 shale can migrate to the tight sandstone over a short distance, forming a typical tight oil reservoir in China. Previous studies show that the oil-bearing area of the tight reservoir in the Chang-7 section extends approximately 1200 km$^2$ (463 mi$^2$). The large volumes of oil and gas produced in the Ordos Basin are from these tight sand reservoirs.

In summary, organic-rich shale and siliceous shale deposited by suspension and upwelling are key exploration targets for shale oil and gas. The widely distributed and multilayer tight sandstones in the upper Longmaxi shale constitute good reservoirs for tight oil. Understanding depositional mechanisms

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**Table 2. Total Organic Carbon Content, Organic Matter Types, and Average Mineral Content of Different Lithofacies**

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Quartz (wt. %)</th>
<th>Clay (wt. %)</th>
<th>Feldspar (wt. %)</th>
<th>Calcite (wt. %)</th>
<th>Pyrite (wt. %)</th>
<th>TOC (wt. %)</th>
<th>OM Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCM</td>
<td>12.4</td>
<td>53.2</td>
<td>6.3</td>
<td>25.8</td>
<td>2.3</td>
<td>2.68</td>
<td>I</td>
</tr>
<tr>
<td>LCM-2</td>
<td>17.2</td>
<td>63.0</td>
<td>5.5</td>
<td>11.1</td>
<td>3.6</td>
<td>3.54</td>
<td>I</td>
</tr>
<tr>
<td>LSM</td>
<td>30.4</td>
<td>50.3</td>
<td>13.0</td>
<td>3.5</td>
<td>2.8</td>
<td>0.46</td>
<td>I, II, III</td>
</tr>
<tr>
<td>LC</td>
<td>8.2</td>
<td>83.9</td>
<td>2.6</td>
<td>0.8</td>
<td>4.5</td>
<td>3.23</td>
<td>I</td>
</tr>
<tr>
<td>LSS</td>
<td>86.2</td>
<td>6.4</td>
<td>3.5</td>
<td>0.2</td>
<td>3.7</td>
<td>3.61</td>
<td>I</td>
</tr>
<tr>
<td>S</td>
<td>73.2</td>
<td>11.9</td>
<td>13.4</td>
<td>1.3</td>
<td>0.2</td>
<td>0.24</td>
<td>III</td>
</tr>
<tr>
<td>MM</td>
<td>10.7</td>
<td>78.9</td>
<td>6.6</td>
<td>2.5</td>
<td>1.3</td>
<td>0.43</td>
<td>I, III</td>
</tr>
</tbody>
</table>

Abbreviations: LC = laminated claystone; LCM = laminated calcareous mudstone; LCM-2 = laminated carbonaceous mudstone; LSM = laminated silty mudstone; LSS = laminated siliceous shale; MM = massive mudstone; OM = organic matter; S = siltstone; TOC = total organic carbon.
and their effect on reservoirs can help us locate favorable exploration areas.

CONCLUSIONS

Seven lithofacies have been identified: (1) LCM, (2) LCM-2, (3) LSM, (4) LC, (5) LSS, (6) S, and (7) MM. The laminated mudstone (LCM, LCM-2, and LSM) and LC are characterized by laminated bedding, fine grain size, scarce large debris, and compositions rich in pyrite and organic matter. Geochemical analysis has shown that laminated mudstone and LC are formed by suspension deposition. The abundance of silica-rich organisms found in the siliceous shale has been confirmed to be associated with upwelling. Siltstone with flute-casting occurs in beds distributed in mudstone and MM, suggesting that they are deposited by turbidity currents. Suspension settling and upwelling can provide favorable conditions for the high productivity and conservation of organic matter. The associated lithofacies are rich in organic matter, with high TOC contents (up to 5.4%) and type I organic matter, and can constitute high-quality source rocks. The reservoir storage spaces in these lithofacies are mainly interlaminated fractures and organic pores, which are very important for shale oil and gas storage and migration.

In addition, the lithofacies associated with suspension and upwelling have high brittle mineral content and so are easy to fracture, which is especially true for siliceous shale. Therefore, siliceous shale can be an important interval for shale oil and gas exploration. Turbidity currents may carry a large amount of oxygen to the seafloor, resulting in the oxidation of organic matter, which is not conducive to its preservation. The mudstone formed by turbidity currents has relatively low TOC contents (<1%), and the structural fractures and intergranular pores constitute the main reservoir storage spaces. These are the principal exploration targets for tight oil.

REFERENCES CITED


