Sedimentary Evolution Characteristics of Fine-Grained Lithofacies under the High-Resolution Isochronous Shelf System: Insights from the Wufeng-Longmaxi Shales in the Sichuan Basin

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The deposition and evolution of fine-grained sediments is a hot topic in fine-grained sedimentary rock studies and is important for accurately evaluating shale gas sweet spots. In this paper, the fine-grained deposition and evolution characteristics of the Wufeng-Longmaxi shales, major targets for Chinese shale gas exploration, were studied by using core observations, thin section analyses, scanning electron microscopy, geochemical analysis, and fossil identification. This work accurately identified six typical lithofacies; among them, the organic matter-rich siliceous shale facies (OMRSSF), the high-organic matter siliceous argillaceous shale facies (HOMSASF), and the medium-high organic matter low calcareous siliceous shale facies (M-HOMLCSASF) are favorable facies for shale gas exploration. The high-resolution isochronous unit in the shelf fine-grained sedimentary system was established, and the differential evolution of lithofacies in the system tract was discussed. The lithofacies deposition and differentiation in the transgressive system tract were controlled by the transgressive scale and tectonics under increasingly shallow water conditions. The lithofacies deposition and differentiation in the regressive system tract were controlled by tectonics and the preexisting lithofacies. The lithofacies in the regressive system tract had more frequent facies transitions and greater differentiation than those in the transgressive system tract, and they exhibited significant spatiotemporal inheritance. Sequential differential sedimentary sequences and symmetric differential sedimentary sequences were distinguished in the continental shelf sedimentary system. The lithofacies depocenters and subsidence centers were consistent in the transgressive system tract, while the tectonically active paleocontinent was important in the regression system tract. This study is of great significance for further high-resolution exploration of marine shale and improvement of the theory of shelf fine-grained sedimentary systems.

1. Introduction

With the successful exploitation of gas in shale units in North America, such as the Barnet, Marcellus, and Woodford shales, and in China, including the Wufeng-Longmaxi shales [1–3], marine shale has attracted the attention of international sedimentologists. However, marine shale is a type of fine-grained sediment with small-scale cyclic characteristics.
and strong heterogeneity, and accurately understanding and predicting the lateral and vertical sedimentary characteristics of organic-rich marine shale changes have become key scientific issues [4–8].

An increasing number of reports indicate that the establishment of a sequence stratigraphic framework and the evolution of sedimentary facies are valuable tools for the evaluation of these successions [9–11]. Sequence stratigraphic concepts are valuable tools for establishing the high-resolution temporal framework of strata, but accurately identifying sequence boundaries is a difficult topic, especially in fine-grained sediments [12]. Continental-shelf facies shale is a key lithofacies connecting the land and the ocean and also the position of condensed sections from in sequence stratigraphy theory. Due to the lack of a systematic classification basis in fine-grained sediments, the identification of sequence boundaries is still controversial [9, 13–15].

The sedimentary theory that the environment is caused and the facies is the result reveals that sedimentary facies deposition and basin filling result from the comprehensive control of factors, such as the basin structure, sediment supply, climate change, and global/regional relative sea-level change [16–19]. Scholars in traditional sedimentary geology often start with tectonic evolution, analyze the deposition in the basin, and provide guidance for oil and gas reservoir exploration with the facies control theory [20]. However, for fine-grained shale, it is difficult to accurately clarify the difference in sedimentary quality in larger-scale sedimentary facies, consequently, smaller-scale lithofacies are the key factors affecting the resource sweet spots in shale. From the early single-factor control concept to the current multifactor coordinated control concept in lithofacies development model of shale, fine-grained sedimentary evolution has attracted wide attention from scholars [21–24]. Although scholars have published some reports, the sedimentary evolution of these in fine-grained sedimentary systems is still a weak area of research. For example, the establishment of a high-resolution isochronous framework, the change in fine-grained sedimentary facies in the region, and the influence of structures on the fine-grained sedimentary system are still controversial [24–30].

Therefore, this paper takes the shale of the Wufeng-Longmaxi Formation as a case study and applies the fine-grained facies division method to organic and inorganic mineral components and the comprehensive sequence identification method, to analyze the temporal and spatial evolution characteristics of the fine-grained sediments and explore the evolution of differences in sedimentary quality in marine shale. This study not only has certain theoretical significance in terms of revealing the differences in the deposition of fine-grained sedimentary rocks on the continental shelf but also provides a unique opportunity to predict the location of sweet spots in shale reservoirs in the exploration for shale gas.

2. Geological Setting

The Sichuan Basin is a superimposed and gas-rich basin that covers an area of approximately 26 × 10^4 km^2. During the Late Ordovician to early Silurian period, the Sichuan Basin of the South China Plate was located near the paleoequator ([31, 32], Figure 1(a)). The Sichuan Basin was the northwestern portion of the Yangtze platform, which was covered by the Tethyan Sea in this period ([32, 33], Figure 1(b)). After the mid-Katian age, the Sichuan Basin became a restricted basin dominated by underwater highland and paleoulfs, which was influenced by gradual intensification of the Guangxian Orogeny [34, 35]. During the Late Ordovician Period, the uplifts in the Jiangnan-Xuefeng region, central Sichuan, and central Guizhou collectively appeared above sea level, transforming the study area from a broad sea during the Early-Middle Ordovician period into a semienclosed area with shallow water surrounded by uplifts during the Early-Middle Ordovician period [36], and a series of black shales was deposited, forming the upper part of the Wufeng Formation (Figure 1(c)). With the arrival of the Hirnantian glacial period [37], a large number of organisms became extinct, and only the cold-water Hirnantian fauna survived. Therefore, a large number of Hirnantian fauna fossils were deposited in this argillaceous calcareous shale at the top of the Wufeng Formation, forming the Guanyinqiao Beds. By the early Silurian, glacial melting released enough water to cover the Yangtze platform with seawater again [38], tectonic movement was more intense than before, and a set of graptolitic black shales was deposited, forming the Longmaxi Formation [25, 39, 40].

The position of the key well is shown in Figure 1(b). The Longmaxi Formation consists of the first member (S1l1), the second member (S1l2), and the third member (S1l3). The Wufeng Formation and S1l1 of the Longmaxi Formation are collectively known as Wufeng-Longmaxi shales (Figure 1(c)). The Fuling gas field is China’s most successful shale gas field, and the main producing formations are the Wufeng Formation and S1l1 of the Longmaxi Formation (Figure 1(c)). The study area in this paper covers the Sichuan Basin and its surrounding areas. Our goal is to clarify the evolution characteristics of marine fine-grained sediments and to construct a sedimentary model of continental shelf shale.

3. Data and Methods

With the commercial development of Wufeng-Longmaxi shales gas sources, many shale wells have been drilled in the Sichuan Basin and its surroundings by SINOPEC; among them, 41 wells with complete data were selected for this study (Figure 1(b)). These wells provide conventional log data, spectral gamma-ray logging data, and lithologic data. In this study, paleontological identification data (137 samples) from the Jy1 well and DyA well were tested by the Key Laboratory of Resource Stratigraphy and Paleogeography at the Chinese Academy of Sciences. The basic data includes 1221-meter core observation and description and measurement of 16 outcrop sections (the locations are shown in Figure 1(b)). A total of 174 thin sections samples from Jy1, JyB, JyC, WyA, and WyB were observed in the Experimental Research Center of Wuxi Research Institute of the Petroleum Geology of SINOPEC. The whole-rock X-ray diffraction analysis was performed on Panalytical X’Pert Pro X-ray diffractometer numbered 8649, total organic carbon (TOC) data test by
LECO CS-200C030 Sartorius 2004P T009S instrument, and the tests of 722 samples from wells Jy1, WyA, YyA, RyA, NyA, DyB, PyA, LyA, and WyB were all tested at the Experimental Research Center of Wuxi Research Institute of the Petroleum Geology of SINOPEC. Scanning electric microscope (SEM) observations of 135 samples from Jy1 and JyB
were also tested at the Experimental Research Center of Wuxi Research Institute of the Petroleum Geology of SINOPEC. Trace element analysis was performed on the NexION300D plasma mass spectrometer numbered 10742 in Analysis and Testing Research Center, Beijing Institute of Geology, Nuclear Industry.

To understand the characteristics of local sedimentary deposition and the spatiotemporal evolution of the shale system, this study took Wufeng-Longmaxi shales as an example to accurately identify and divide the lithofacies in the shale. Based on the core outcrops, slices, and scanning electron microscope data, macro- and microscale facies characterization was performed. Reservoir-related parameters were also determined. The integrated sequence division method based on chemical parameters, lithology, logging data, and fossil data was used to establish an isochronous stratigraphic framework, and the basin-filling and evolution characteristics of the shale in this isochronous system were systematically described.

4. Results and Discussion

4.1. Fine-Scale Identification of Marine Shale Facies

4.1.1. Quantitative Identification of Marine Shale Lithofacies. Lithofacies analysis is the most important method for the fine-scale study of continuously deposited continental-facies shale. Lithofacies are often identified by factors such as color, mineral composition, sedimentary structure, and organic matter (OM) content [17, 19, 23, 24]. This paper uses the method of mineral composition and OM to identify lithofacies [41, 42]. The shale in the study area is mainly composed of quartz, clay minerals, and carbonate minerals. A three-terminal graphical analysis was performed, and the mineral components in the study area were clustered on the quartz-clay line. The contents of quartz and clay minerals varied from 15 to 80%, while the overall carbonate content was low and mainly concentrated at 0 to 30% (Figure 2). Therefore, according to the definition of lithofacies, considering mineral composition characteristics, shale evaluation, and environment, we selected quartz minerals, clay minerals, carbonate minerals, and OM as lithologic identification factors for qualitative analysis. Quantitative lithofacies identification was carried out with 50% and 25% as the classification limits, increasing the carbonate minerals content by 10%, and with TOC contents of 4%, 3%, 2%, and 1%. Based on the XRD (X-ray powder diffraction) analysis in the study area, the data points are projected onto a mineral ternary diagram, and combined with TOC data, key lithofacies are identified. To eliminate sample errors and abnormal data points generated by special minerals, only the dominant lithofacies need to be considered. A large amount of statistical data can be used to accurately characterize the geological patterns. A total of 6 typical lithofacies were identified in the study area (Figure 2): OM-rich siliceous shale facies (OMRSSF), high-OM siliceous argillaceous shale facies (HOMSASF), medium-high-OM low calcareous siliceous shale facies (M-HOMLCSASF), low-medium-OM argillaceous shale facies (L-MOMASF), low-OM silty clay shale facies (LOMCSASF), and low-OM shelly facies (LOMSF).

4.1.2. The Key Features of Typical Lithofacies. The OMRSSF showed off-white and gray-yellow weathering in the outcrop profile, and the fresh surfaces were gray-black and black (Figures 3(a) and 3(j)). It is mainly developed in the shale section with high gamma ray (GR) values at the bottom of the Wufeng and Longmaxi Formations. The lamination is well developed, and the laminae are relatively straight, indicating a quiet and stable sedimentary water body. The laminae show an even distribution of sand particles and a large number of radiolarian fossils (Figure 4(a)), with siliceous shell walls. Parts of the shell walls are replaced by pyrite, and dolomite with a semimorphic shape is observed. Siliceous materials often have cryptocrystalline, amorphous structures, including a spheroidal structure, and their origins are mostly biological (Figure 4(h)). Pyrite and OM are related and the microscopic form of the pyrite framboidal. OM has relatively well-developed pores and a good pore structure (Figure 4(h)). The TOC is greater than 4%, the siliceous content is greater than 50%, and the OM content is directly proportional to the siliceous content. The clay mineral content is less than 50%, and the carbonate content is generally no more than 25% (Figure 2).

The HOMSASF shows a gray-white to light-gray weathering color in the outcrop profile and gray-black on the fresh surface and in core (Figures 3(b) and 3(k)). The thickness of the single layer of this lithofacies on the outcrop is approximately 3–5 m, and the boundaries between layers are clear, straight, and continuous (Figure 3(k)). Pyrite is well developed, with visible clumps and lens shapes (Figure 3(b)). The siliceous content is 40–50%, the clay mineral content is also 40–50%, and the carbonate content is low, not exceeding 10% (Figure 2). The OM content is relatively high, generally greater than 3% and less than 4%. The quartz silt distribution in the lamina is relatively uniform, with a maximum silt particle diameter of 0.06 mm. Micritic calcite is uniformly distributed; the particles have star-like shapes. There are spots of fine-grained pyrite locally (Figure 4(b)). The pore structure is dominated by bedding fractures and organic pores, while siliceous pores are dominated by autogenous quartz and biological quartz (Figure 4(i)). Most of the authigenic minerals have amorphous structures that are more angular than those in organic-rich shale (Figure 4(i)). The fossils observed are mainly the WF and LM1 and LM1–3 graptolite zones (Figure 5).

The M-HOMLCSASF is grayish black and gray in the core and is mostly developed near the carbonate platforms of the Chuanzhuang paleo-oolite and Qianzhong paleo-oolite. The laminae are relatively straight, with a thickness of approximately 1 mm, and the boundaries between layers are clear and continuous (Figures 3(c) and 3(d)). The contents of siliceous and clay minerals are all from 25 to 50%, and the carbonate content increases to 10–25%. The OM content is relatively high, generally greater than 2% but less than 4%. Under the microscope, the mineral particles are oriented, and horizontal bedding is well developed. The OM is dispersed in the mineral matrix in an amorphous form, with a small
amount of rubble debris, which is distributed in bands. The self-shaped dolomite particles show obvious dissolution. There is cementitious gypsum in the micropores, and residual linear pores are developed between clay minerals (Figures 4(c) and 4(j)). Pyrite is relatively abundant and it macroscopically developed in a stratified layer (Figure 3(d)), and microscopic morphology is framboidal (Figure 4(j)).

The L-MOMASF is gray in the outcrop profile and core (Figures 3(e) and 3(l)). Pyrite is relatively abundant, with clump-like and lens-like morphologies and a framoidal micromorphology (Figures 3(e) and 4(k)). The clay mineral content is between 50% and 70%, the siliceous content is between 30% and 50%, and the carbonate content is low, not exceeding 10%, indicating that the brittleness is low and that this unit does not easily fracture. The OM content is medium-low, usually 1~3%. The lamellas show a silt content of 9% and an uneven distribution. There is a small amount of fine-grained powdery pyrite locally, and wavy nonparallel laminas are observed. The thickness of the laminas is 0.01 to 0.13 mm. The fibrous clay minerals are directionally distributed, and a small number of inorganic pores are seen locally. OM pores are poorly developed, the overall rock is dense, and pores are rare (Figures 4(d) and 4(k)). The siliceous material is mainly terrigenous detrital silica, and a small amount of autogenous quartz and biological quartz are present (Figure 4(k)).

The LOMSCSF is mainly gray, and the lamina is observed. The thickness of the laminas is less than or equal to approximate 1 mm (Figures 3(f) and 3(g)). Some laminas are approximately 50 μm thick, and the layers are straight. The light-colored laminas are dominated by light-colored minerals, such as terrestrial quartz and feldspar. Quartz is present in a floating state, with poor classification, medium roundness, and a subangular-subrounded shape. The dark
laminas are dominated by clay minerals and contains a certain amount of OM. The clay minerals are mostly scaly or amorphous. A small amount of mica is seen, forming a rhythmic layer between light and dark laminas (Figure 4(e)). The clay mineral and siliceous content ranges from 40 to 50%, while the carbonate content generally does not exceed 10%. Rock pores are not well developed, and OM is dispersed in the micropores among the minerals. The clay minerals have a small number of micropores and that are partially filled with OM. The silt particles are mainly feldspar and quartz (Figure 4(l)). The main difference between this lithofacies and the high-OM siliceous clay shale is that the OM content is lower and the proportion of biogenic proportion is lower. This lithofacies is mainly terrestrial silt, and the sediment size relatively coarse. The OM content is 1%-2%.

The LOMSF is mainly gray and dark gray on the outcrop profile, and the core is gray-black (Figures 3(h) and 3(m)). The shell fossils range in size from 1 * 1.3 cm to 0.2 * 0.5 cm, and the abundance ranges from 10 to 80%. Some shell fossils are relatively well-preserved. The broken shells are arranged in parallel layers, most of which are concave, and a few are oriented vertically (Figures 3(h) and 3(m)). The carbonate and clay mineral contents are high, while the quartz and feldspar contents are low. The OM content is also low, with sporadic high-value points, and the regional differences vary from 1 to 2%. This type of petrographic fossils is extremely commonly developed and is mainly shell fossils, including brachiopods, pelecypods, and echinoderms (Figures 4(f) and 4(g)). This lithofacies can be divided into argillaceous limestone and carbonate mudstone.

Therefore, OMRSSF, HOMSASF, and M-HOMLCSASF have more abundant organic matter than other lithofacies, which means better source rock properties. The pore structure of this type of reservoir is relatively good, and the bedding fractures and organic pores are well developed, resulting in a good shale gas storage space. In addition, the content of brittle minerals is higher than 50%, which is more prone to fracturing. Therefore, these three types of facies are favorable sweet spots for shale gas exploration. L-MOMASF, LOMSCSF, and LOMSF have less organic matter content, only a small amount of micropores in clay minerals are developed, and organic matter pores are poorly developed, so they are not a favorable sweet spot for shale gas exploration.

4.2. Sequence Stratigraphic Analysis

4.2.1. High-Resolution Sequence Stratigraphic Interface Identification of Marine Shale. Researchers often use well logging curves, lithology combinations, and lithologic in drilling cores, and geochemical parameters to identify sequence stratigraphic interfaces in shales [1, 13, 15, 43]. This study is based on the establishment of a comprehensive classification
method for marine shale. After analyzing the lithology, logging data, fossils, and geochemical data of the key drilling and field sections in the study area, four sequence boundaries (SB1, SB2, SB3, and SB4) were identified. Additionally, three maximum flooding surface interfaces, MFS0, MSF1, and MSF2, were identified (Figure 5).

SB1 is a lithological interface between nodular limestone and the OMRSSF shale, and it represents a lithological change between groups. Previous studies have also shown that this is an unconformity interface [25, 26, 29, 42]. The development of the WF2 graptolite zone indicates that the stratum belongs to the Wufeng Formation. There is an obvious abrupt change in the GR and KTh curves, a threshold value appears, and the GR curve increases rapidly. The LLD and LLS curves also show abrupt changes. The Th/U ratio and clay mineral content begins to decrease, while quartz content gradually increases. According to the cyclic characteristics of TOC [44], below the sequence interface, the OM content gradually decreases from bottom to top, but above the interface, it gradually increases from bottom to top. The changes in the OM content and in the Th/U and Th curve characteristics indicate that SQ1-TST developed over two transgressive stages. Previous studies of fossils from the Late Ordovician to the early Silurian period on the Yangtze platform showed that in the lower part of the *Tangyagruptus typicus* subzone, that is, the WF3 stage, there is evidence of a large relative sea-level rise [38]. The maximum flooding surface, MFS0, is the boundary between the Wufeng Formation shale and the Guanyinqiao muddy limestone. It has a high TOC value and a low Th/U value. Previous studies of the Hirnantian glaciation at the end of the Ordovician period also revealed the occurrence of glacial retreat events [45–47]. The appearance of Hirnantian fauna represents the beginning of the highstand system tract (HST), and extremely low LLD and LLS curve values and low illite/clay values represent the characteristics of glacial development (Figure 5).

SB2 is the lithofacies transition surface between the two studied formations. The black OMRSSF shale at the bottom (a) Jy1, 2385.43 m, HOMSASF, pyrite spots, uniformly distributed; (b) Jy1, 2332.63 m, L-MOMASF, wavy nonparallel lamina is developed; (e) Jy1, 2375.44 m, LOMSCSF, the light-colored lamina is dominated by terrestrial quartz and feldspar, and the dark lamina is dominated by clay minerals and organic matter; (f) Jy1, 2371.4 m, LOMSF; (g) WyB, 3765.53 m, LOMSF; (h) Jy1, 2411.05 m, OMRSSF, organic matter, organic pores, and biological quartz are well developed; (i) Jy1, 2382.42 m, HOMSASF, the pore structure is dominated by bedding fractures and organic pores, while the siliceous component is dominated by autogenous quartz and biological quartz; (j) WyA, 3584.6 m, M-HOMLCSASF, self-shaped dolomite, linear pores, and frambooidal pyrite; (k) Jy1, 2335.3 m, L-MOMASF, the rock is densely developed with poor pores; (l) JyB, 2519.8 m, LOMSCSF, the silt particles are mainly feldspar and quartz).
of the Longmaxi Formation is in unconformable contact with the LOMSF of the Guanyinqiao Beds in the lower Wufeng Formation. SB2 developed in the period of the LM1 graptolite zone, and the morphology of the LM1 fossil is very different from that of the Hirnantian fauna of WF4 [34]. Above the interface, the GR, LLD, and LLS curves increase rapidly, the Th/U value is extremely low, and the U, Th, and K contents increase sharply. Below the interface, the low levels of the elements K and Th represent a very low glacial deposition rate, terrestrial supply, and little volcanic eruption activity [48].

Two cycles of TOC, Th, and (S1+S2)/TOC developed. The value of Th/U is less than 1. Thus, there were two facies of transgression, producing two quasisequences. The end of the second cycle of TOC, when TOC = 4, is marked by MSF1 of SQ2. Above the interface, the Th/U value is greater than 1, and (S1+S2)/TOC starts to approach 0. Striae and nodular pyrite are present around the interface, indicating a deep-water reducing environment.

SB3 is the boundary between the L-MOMASF shale and the LOMSCSF shale. The GR curve exhibits a sharply increasing trend, indicating another transgressive process. The Th/U values have higher values, while the LLD and LLS values change from high values to low values. The two cycles of Th, U, K, and Th/U development also indicate another transgression. The high TOC, high Th content, and low U content are characteristics of the sequence boundary SB3. There is also a subflooding surface (SFS) below SB3, which distinguishes EHST (early highstand system tracts) and LHST (late highstand system tracts). The LLD and LLS curves show similarities between the two facies, while the characteristics of Th/U and TOC show heterogeneity between the two facies. The EHST is characterized by Th/U values of 1-2, and TOC values of 2-4%, and the LHST is characterized by Th/U value of 2-4, and a stable TOC values of 2%. The diversity of LM5 begins to increase [40], and the number of branches begins to increase, indicating that the water body was shallower, which further distinguishes the EHST and the LHST of the HST.

SB4 is the boundary between members S1l2 and S1l1 and is the lithological interface between the sections. At the boundary, S1l1 comprises L-MOMASF shale, and S1l2 comprises argillaceous siltstone. The LM9 graptolite zone is observed at SB4, and it has a low GR value of 78.5 API and an extremely high resistivity of 267.8 Ω. The high K, Th, and Th/U values represent the end of the cycle, and the developmental characteristics of TOC support this conclusion. MSF2 corresponds to the maximum TOC value, which is 3.26%. The two small cycles in the Th/U curve and the abnormal enrichment of the U element indicate an anoxic environment. The decrease in the Th content indicates a low
deposition rate. Under MSF 2, the average TOC is 2.2%, and the Th/U ratio is 1.9%; above the interface, the average TOC is 1.2%, and the Th/U value is 2.8% (Figure 5).

### 4.2.2. Characteristics of Sequence Development

According to the characteristics of interface identification, Wufeng-Longmaxi shales are divided into three third-order sequences and seven system tracts (Figure 5 and Table 1). The Wufeng Formation features the a third-order sequence SQ1, which includes SQ 1-TST and SQ 1-HST. S 1l1 of the Longmaxi Formation is divided into two third-order sequences of SQ 2 and SQ 3; SQ 2 includes SQ2-TST, SQ2-EHST, and SQ 2-LHST, while SQ 3 includes SQ 3-TST and SQ 3-HST. The Th/U and TOC data reflect the redox conditions. A Th/U value of less than 2 indicates an anoxic environment, and a high content of OM indicates a higher degree of reduction in the water during deposition [49–52]. The development of framboidal pyrite also indicates a strongly reducing sedimentary environment. The crosscontrolled sequence framework based on Jy1 is established (Figures 6 and 7).

Profi le "X" shows the deposition process between paleouplifts. The uplift of the Jiangnan-Xuefeng paleouplift had a great impact on shale deposition, while the Chuanzhong paleouplift had a greater influence on the deposition of carbonate minerals in the shale (Figure 6). Profile "Y" shows the deposition pattern between the paleouplift and the paleoocean. The thickness of the sediment gradually increases from the land to the ocean, and LOMSCSF was deposited in the middle (Figure 7).

**SQ 2** corresponds to the Wufeng Formation and includes the transgressive system tract (TST) in the lower part of the Wufeng Formation and the HST in the upper part. Black siliceous shales were deposited in the TST, with TOC values greater than 4% and an average value of 4.6% (Figure 5). The quartz content is high, with an average value of 58% (Figure 5). The Th/U ratio is less than 2, and the sedimentary environment was a weakening oxidizing-reducing environment (Table 1). The average TOC is 3.99%, and the average thickness is 4.55 m (Table 1). The OMRSSF and HOMSASF were well developed (Figures 6 and 7). The shelly facie of the Guanyinqiao Beds is mainly developed in a shallow-water continental facies sedimentary environment in the HST area, which is a shallow water continental facies sedimentary environment. Due to the sudden expansion of the Antarctic ice sheet, the global relative sea level fell by 50 to 100 m [36], resulting in a global biological extinction event and the average thickness is 0.35 m (Table 1). The OMRSSF and HOMSASF were well developed (Figures 6 and 7). The shelly facie of the Guanyinqiao Beds is mainly developed in a shallow-water continental facies sedimentary environment in the HST area, which is a shallow water continental facies sedimentary environment. Due to the sudden expansion of the Antarctic ice sheet, the global relative sea level fell by 50 to 100 m [36], resulting in a global biological extinction event and the average thickness is 0.35 m (Table 1). The OMRSSF and HOMSASF were well developed (Figures 6 and 7). The shelly facie of the Guanyinqiao Beds is mainly developed in a shallow-water continental facies sedimentary environment in the HST area, which is a shallow water continental facies sedimentary environment. Due to the sudden expansion of the Antarctic ice sheet, the global relative sea level fell by 50 to 100 m [36], resulting in a global biological extinction event and the average thickness is 0.35 m (Table 1). The OMRSSF and HOMSASF were well developed (Figures 6 and 7).

**SQ 3** represents a period of rapid transgression to slow regression in the Longmaxi Formation and includes the

### Table 1: The average value of Th/U, TOC, and thickness of the system tract of the key wells.

|          | Jy1 | PyA | NyA | DyB | YyA | WyB | RyA | Mean |
|----------|-----|-----|-----|-----|-----|-----|-----|------|
| Th/U     |     |     |     |     |     |     |     |      |
| SQ 1-TST | 0.98| 1.2 | 1.0 | 1.9 | 1.7 | 2.1 | 1.1 | 1.43 |
| SQ 1-HST | /   | /   | /   | /   | /   | /   | /   | /    |
| SQ 2-TST | 0.81| 0.6 | 0.79| 1.49| 0.55| 0.48| 0.9 | 0.80 |
| SQ 2-EHST| 1.6 | 1.0 | 1.3 | 2.5 | 2.1 | 1.7 | 1.43| 1.66 |
| SQ 2-LHST| 2.35| 2.5 | 2.4 | 3.8 | 2.5 | 2.2 | 1.59| 2.48 |
| SQ 3-TST | 2.1 | 2.4 | 2.2 | 3.1 | 1.8 | 2   | 1.8 | 2.2  |
| SQ 3-HST | 2.8 | 4.2 | 2.5 | 4.1 | 2.6 | 3   | 3.2 | 3.2  |
| TOC (%)  |     |     |     |     |     |     |     |      |
| SQ 1-TST | 4.6 | 3.2 | 4.4 | 4.3 | 2.8 | 3.4 | 5.2 | 3.99 |
| SQ 1-HST | /   | /   | /   | /   | /   | /   | /   | /    |
| SQ 2-TST | 4.1 | 3.6 | 4.1 | 4.2 | 4.1 | 4.8 | 4   | 4.13 |
| SQ 2-EHST| 3   | 2.75| 2.5 | 3.6 | 2.85| 2.9 | 3.6 | 3.03 |
| SQ 2-LHST| 1.6 | 1.1 | 1.5 | 3.4 | 2.3 | 2.7 | 2.8 | 2.2  |
| SQ 3-TST | 2.2 | 3.2 | 2.5 | 3.1 | 2.5 | 2.7 | 2.3 | 2.64 |
| SQ 3-HST | 1.2 | 1.6 | 1.3 | 2.8 | 1.8 | 1.6 | 1.7 | 1.71 |
| Thickness (m) |     |     |     |     |     |     |     |      |
| SQ 1-TST | 4.46| 4.3 | 4.572| 2.912| 7.894| 3.2 | 4.5 | 4.55 |
| SQ 1-HST | 0.6 | 0.3 | 0.15 | 0.6 | 0.22 | 0.2 | 0.4 | 0.35 |
| SQ 2-TST | 12.41| 8.66| 7.8 | 11.66| 6.5 | 5.855| 3.196| 8 |
| SQ 2-EHST| 22.925| 11.74| 16.141| 16.18| 7.6 | 14.523| 6.002| 13.59 |
| SQ 2-LHST| 24.218| 40.25| 26.855| 13.92| 27.4 | 9.702| 12 | 22.05 |
| SQ 3-TST | 11.102| 14.75| 9.348| 8 | 6.125| 6 | 2.8 | 8.30 |
| SQ 3-HST | 15.628| 22.5 | 17.784| 12.9 | 16.159| 20.54| 3 | 15.50 |

Lithosphere
TST, EHST, and LHST. The OMRSSF was well developed in TST (Figures 6 and 7). The content of quartz is high, with an average of 48%, and the content of clay is low, with an average of 28% (Figure 5). The GR curve is a finger-box destructive type, which represents a process of rapid and continuous transgression (Figure 5). The overall Th/U value is less than 1, indicating a strong reducing sedimentary environment, which was beneficial to the enrichment of OM and pyrite (Figure 5 and Table 1). There are two quasisequences, reflecting the two stages of the SQ1-TST (Figure 5). The average TOC is 4.13% and the average thickness is 8.01 m (Table 1). In SQ2-EHST, the clay content gradually increases, with an average value of 39%, and the quartz content gradually decreases, with an average value of 40% (Figure 5). The average TOC is 3.03%, the average Th/U ratio is 1.66, and the average thickness is 13.59 m (Table 1). All those indicate the sedimentary environment was a strong reducing-reducing environment and with higher sedimentary rate than TST. The HOMSASF were well developed (Figures 6 and 7). In the SQ2-LHST, the average TOC value is 2.2%, and the average Th/U value ratio is 2.48 indicating sedimentary environment was weak oxidizing-weak reducing environment. The average thickness is 22.05 m and thicker than EHST (Table 1). Shallow water lithofacies such as L-MOMASF and HOMLCSASF were more developed in LHST than EHST (Figures 6 and 7). The box-type pattern in the GR curve represents a process of continuous marine regression (Figure 5). The overall trend is that the water body become shallower, resulting in shallow-water deposition.

SQ3 corresponds to a secondary transgressive-regressive development period. In the TST area, there are interbedded layers of gray clay shale and silty sand. The GR curve represents a tooth-shaped regressive-progressive interactive type, showing the transition from rapid transgression to slow transgression (Figure 5). The MOMASF was well developed in TST (Figures 6 and 7) and with an average thickness of 8.30 m (Table 1). The average TOC is 2.64%, and the average thickness is 8.30 m (Table 1), indicating weakly oxidizing environment. A few LM6 graptolite zones and all LM 7 graptolite zones are observed (Figure 5). Most of the LM 8 and a few LM 9 graptolite zones are observed in SQ 3-HST, and the shallow-water fossil species and forms gradually increase. The values of Th/U are all much greater than 2, indicating oxygen-enrich oxidizing environments in shallow water (Table 1). The LOMASF was well developed in HST (Figures 6 and 7), and the sedimentation rate rapidly accelerated, which the terrigenous debris delivered to the system also increased.

4.3. Sedimentary Filling of Lithofacies Controlled by the High-Resolution Sequence. The system tract characteristics of the isochronous units show that the area of the TST is controlled by the transgression magnitude and paleouplifts.
are also different facies features in the continental-facies shale. The transition from a deep-water environment to a semideep-water environment to a shallow-water environment presents the characteristics of sequential differentiation. If the sedimentary depocenter is consistent with the lithofacies, the degree of facies differentiation is small. The sedimentary depocenter varies more diversified across multiple lithofacies. The area of the regressive system tract is controlled by tectonic processes and the previously deposited lithofacies. In areas with glacial coverage, the extent of ice cover needs to be considered. Facies transitions in the regressive system tract are frequent, and the sediments are more differentiated than those in other system tracts. The three sedimentary depocenters are obvious, and they are vertically and horizontally inherited. In SQ2-LHST, the Jiangnan-Xuefeng uplift had the effect of controlling the lithofacies in the southeastern part of the Sichuan Basin.

4.3.1. Facies Differentiation of the Marine Shale Transgressive System Tract. The relative sea level associated with system tracts in the tertiary was greatly affected by regional tectonics. Three large-scale transgressions were identified based on the degree of tectonic movement and the magnitude of the transgression (Figures 8(a)–8(c)). There are characteristics resulted in a high degree of facies differentiation. From SQ1-TST to SQ2-TST, the facies change is small, while from SQ2-TST to SQ3-TST, the facies change is large. The TST was dominated by a deep- to semideep-water shelf. OMRSSF, HOMSASF, and MOMASF were the main developmental facies.

During the period of the SQ1-TST, the northeastern-southeastern areas of the Sichuan Basin formed siliceous deep-water shelf sediments, and the OMRSSF was well developed (Figure 8(a)). There were two depocenters. The depocenter in eastern Sichuan was consistent with the lithofacies distribution, indicating that the sediment source was marine material. The depocenter in western Sichuan developed multiple lithofacies, indicating that the differentiation of lithofacies was the result of the combined action of paleoland and paleoocean.

During the period of the SQ2-TST, the sedimentary pattern changed. After the global ice age, a rapid transgression once again occurred in the Sichuan Basin, which was located on the passive continental margin of the northern margin of the Yangtze platform. It presented a pattern of confined narrow sags in the Chuanzhong paleouplift, Qianzhong paleouplift, and Jiangnan-Xuefeng paleouplift (Figure 8(b)).
OMRSSF was deposited on the siliceous deep-water shelf in the study area. Due to the tectonic compression of the Huaxia block, siltstone facies began to appear near the Jiangnan-Xuefeng Mountain uplift [19, 31, 53]. The entire continental shelf system was a semideep-water to deep-water sedimentary system.

**Figure 8:** Distribution characteristics of lithofacies in the transgressive system tract and the glacial regression period. (a) SQ1-TST, (b) SQ2-TST, (c) SQ3-TST and (d) SQ1-HST.
Due to early sedimentary filling, the third transgression exacerbated the differentiation of lithofacies, and tectonic compression had a significant effect on the sediments deposited during the secondary transgressions (Figure 8(c)). The deposits in the study area evolved into argillaceous semideep-water shelf sediments of the MOMASF. Consistent with the position of the depocenters of SQ$_2$-TST, there were also two depocenters. The depocenter in western Sichuan formed the MOMASF, and the sediment was semideep-water sediment. The depocenter in eastern Sichuan straddles shallow- and semideep-water areas, reflecting the impact of the Jiangnan-Xuefeng uplift on the transgression. The sharp contrast between the two depocenters in eastern and western Sichuan shows that the difference in paleogeographic structure was the main factor controlling the differentiation and deposition of different lithofacies. The differences in sedimentary facies indicate the direction of transgression. Compared with that of SQ$_1$-TST and SQ$_2$-TST, the consistency of the SQ$_3$-TST in the western Sichuan depocenter and the associated lithofacies indirectly indicate the occurrence of this transgression.

4.3.2. Facies Differentiation of the Marine Shale Regressive System Tract. The tectonic activity and deposited lithofacies deposition in the TST controlled the deposition process in the HST. As the previously deposited lithofacies leveled the depocenter of the paleogeomorphology and considering the equilibrium settlement process, the new lithofacies deposition occurred in the depocenter. Large relative sea level changes also increase the degree of lithofacies differentiation. The lithofacies deposited in the marine shale regressive system tract fully shows the particularity of the sedimentation process. The first type is the regressive system tract caused by the formation of the glacial period. The first type is the regressive system tract caused by the development of a glacial period. This type of system tract cannot be explained by the differentiation of conventional sedimentary facies. For such units, such as the SQ$_2$-HST, it is necessary to consider the extent of the ice sheet and sedimentary erosion intensity (Figure 8(d)). The lithofacies in this type of regressive system tract are less differentiated than those in other system tracts. The second type of deposits, such as the regressive system tracts of SQ$_2$ and SQ$_3$, is the regressive system tract affected by the pattern of regression and microtopography (Figure 7). Lithofacies and sedimentary differences occur in this type of regressive system tract. The facies controlling effect of the Jiangnan-Xuefeng uplift on the southeastern Sichuan region was greatest during deposition of SQ$_2$-HST, and this unit has a vertical spatiotemporal inheritance. The facies transitions of the sediments in the regressive system tract are relatively frequent, with great differentiation, and depocenters are observed.

The SQ$_1$-HST period of the Wufeng Formation corresponded to a glacial regression period, and the global regression led to the study area being a shallow-water shelf sedimentary environment (Figure 8(d)). The sedimentary thickness is thinner in the north and thicker in the south. The LOMSF is the main facies that developed, and the area also features shallow carbonate deposits and deeper argillaceous deposits [54]. During this period, the entire Upper Yangtze platform was located near the equator, indicating the formation of low-latitude glaciers [55]. Glacial effects caused large-scale biodiversity events worldwide [56–58]. Sheehan claimed that an extinction occurred in a time-transgressive manner, occurring earlier in shallow waters and later in deep waters [59]. According to Mitchell et al. [60], the Yangtze area at that time was a sanctuary for graptolites. These characteristics explain the origin of the graptolites in the LOMSF (Figure 4(g)). Cool-water brachiopod fossils of the Hirnantian fauna are also present in the LOMSF (Figure 4(g)), which is consistent with previous findings [61]. The LOMSF developed in an ancient confined area, which is consistent with the previous speculation that the Yangtze area was the last biologically active area under global glaciers [62]. Paleoulifts reduced the impact of glaciers on the survival of organisms to a certain extent. The clay shale lithofacies that developed along the outer periphery represents the ice cap coverage area, with a limited sediment supply and weak biological and chemical reaction activities (Figure 8(d)). The sediment thickness is thin, and it was easily eroded by later transgressions.

The sedimentary period of the SQ$_2$-EHST inherited the development model of the SQ$_1$-TST and gradual transition to the HOMASF. Semideep-water shelf sediments developed with obvious facies changes (Figure 9(a)). From the deepest water in northeastern Sichuan, the OMRSSF turned transitional to the HOMASF. The MOMASF deposition in the semideep-water environment was continuous and represented the transition zone to the shallow-water environment. The structural uplift of the Jiangnan-Xuefeng uplift expanded the extent of the silstone facies. Three depocenters appeared in northeastern Sichuan, southeastern Sichuan, and western Sichuan, with thicker sediments than those in SQ$_2$-TST. The basin maintained the paleogeographic pattern of three uplifts and one depression, even though the influence of the Jiangnan-Xuefeng uplift was small (Figure 9(a)). In the SQ$_2$-LHST depositional period, the deep-water shelf sedimentary facies disappeared from the Sichuan Basin and its periphery (Figure 9(b)). There are two bifurcations in lithofacies sedimentary differentiation, one pointing to the northeastern Sichuan and one pointing to the Jiangnan-Xuefeng uplift. The LOMASF deposition occurred in response to the compression of the Sichuan Basin by the Huaxia plate, and the extent of the silstone facies continued to expand. Considering the source factors, the depocenter in southeastern Sichuan was located in the zone impacted by the tectonic activity associated with the Jiangnan-Xuefeng uplift. During the deposition period of SQ$_3$-HST (Figure 9(c)), the whole area was a shallow-water shelf. The LOMASF developed in the depocenters of northeastern Sichuan, southeastern Sichuan, and western Sichuan, while the IOMASF (Infertile organic matter content argillaceous shelf facies) was deposited in the periphery. According to the lithofacies distribution, the influence of the Jiangnan-Xuefeng uplift on the basin has ceased.

4.4. Evolution Characteristics of Fine-Grained Sedimentary Facies. The Wufeng-Longmaxi Formations can be divided
FIGURE 9: Distribution characteristics of lithofacies in the regressive system tract. (a) SQ2-EHST, (b) SQ2-LHST and (c) SQ3-HST.
into two deposition stages: the depositional period of the Wufeng Formation and the depositional period of 5111 of the Longmaxi Formation. Unlike tidal shale facies, shelf shale facies include both deep- and shallow-water deposits [63, 64]. These deposits can be divided into two types of lithofacies sequences: one is the conventional differential sedimentary sequence between a paleocontinent and the paleoocean (Figure 10(a)) and the other is the symmetrical differential sedimentary sequence on a paleocontinent (Figure 10(b)). According to the principle of lithofacies differentiation,
sedimentary lithofacies remain the same if they have the same environment and material source. This set of shale filled from top to bottom, taking the lithofacies of the system tract as the top boundary and the system tract as the base sedimentary unit. According to the principles of sedimentology, the paleogeographic pattern of the bottom boundary was first determined, and then, the lithofacies evolution pattern was established in the process of shale settlement.

4.4.1. Evolution of Facies between Paleoland and Paleocean.
During the sedimentary period of the Wufeng Formation, a relatively gentle shelf pattern formed between the Qianzhong uplift and the passive continental margin. A rapid transgression is favorable for sediments to be deposited across a continental shelf. These sediments originated from the ocean and were derived from biological sources [19, 24, 62]. Therefore, a gentle tectonic environment similar to that of North American shale is an important factor in the development of organic-rich shale. During the transgression period, from the paleocontinent to the paleocean, the sediments in a deep-water shelf were dominated by OMRSSF. The calcareous transition zone formed only near the paleocontinental area associated with the carbonate platform. The closer the location was to the ocean, the greater the thickness of the sediment, which proves that the sediment originated from the ancient ocean. Volcanic materials from volcanic activity also provided a large amount of nutrients for the paleocean, which increased paleoproducitivity. The sedimentary environment was a weak redox environment (Figure 10(a)). During the transgression, the climate became colder, and ice sheets formed. The study area is dominated by terrestrial sediments (Figure 5(d)), with LOMSF developed and deposited on the base of the waves. The deeper water sediments belong to the off-site transportation sediments, which agrees with previous research results [54]. Due to the ice sheet cover, there is almost no sedimentation in the area near the paleocean, and the overall environment is a weakly oxidizing environment (Figure 10(a)).

During the early stage of the TST of the S11 member of the Longmaxi Formation, due to the compression imposed by the Huaxia block, underwater uplifts formed in the DyB area and the YzA area. The uplift in the YzA area may have been the effect of the underwater uplift in western Hunan and Hubei [36]. The rapid transgression caused the entire research area to be below the base of the wave base, and the sedimentary environment was a strongly reducing environment. The volcanic activity caused by the tectonic activity was intense, which is consistent with the findings of previous studies of the development of bentonite [42]. The OMRSSF was mainly deposited during this period. The development of the three depocenters provided the basis for the distribution of the early shale in S11 of the Longmaxi Formation (Figure 10(a)). During the SQ1 to EHST period, tectonic activity resulted in further uplift, and the control of shale by paleotopography became more apparent. The MOMASF developed in the submarine uplift area, while the HOMASF developed in deeper-water areas. In the deeper areas, the sedimentary lithofacies were thicker. By the SQ2-LHST period, the depocenter had separated from the subsidence center. There were two depocenters: one was the Jy1 area where the LOMSCSF developed and the other was the TB area where the MOMASF developed. There were also two centers of subsidence: one was the passive continental margin, and the other was located in the RyA area. The sediment source of the LOMSCSF was the Jiangnan-Xuefeng uplift, which rose above the wave base, and the depositional environment was a weakly oxidizing environment. The source of the MOMASF was normal marine material, which was deposited in a weakly reducing environment between the fair-weather wave base and the storm wave base.

During the SQ2-TST period, due to earlier deposition of other lithofacies, the depocenter caused by structural uplift was gradually filled and eventually restored to the gentle structural background of the Wufeng Formation. Another transgression caused the entire area to be below the wave base, and only the area near the passive continental margin was below the storm wave base. The LM7 graptolite zone during this period had a large degree of differentiation, and volcanic activity did not occur. In the HST, the sedimentary deposition gradually transformed the shelf environment into a terrestrial environment. The depocenters were consistent with the centers of subsidence. The LOMASF was deposited in deeper waters, while the IOMASF was deposited in shallower waters.

4.4.2. Evolution of Facies between Stable Paleoland and Uplifted Paleoland.
During the period of the Wufeng Formation, the Chuanzhong uplift was a carbonate platform with an exposed surface (Figure 10(b)). It had an impact on the nearby shale sedimentary process, and the M-HOMLCSASF and LOMCASF were deposited. The Jiangnan-Xuefeng uplift had not yet emerged above the water in the study area. The study area was a half-graben basin. It was a broad shelf environment; most of which was deposited below the storm wave base. The influence of tectonic activity was small, but the volcanic activity caused by distant plate collision already had a greater impact on shale deposition during this period. The depositional environment was a weak redox environment. The OMRSSF was the main sedimentary facies. The depocenter and subsidence center were both located in the PyA area. During the SQ2-HST period, the LOMSF was deposited between the ancient continents. The ice sheet had a small effect on the lithofacies.

During the early stage of the S11 member, due to the plate collision, the Xuefeng uplift began to emerge from the water and provided a source for the development of nearby siltstones. Symmetrical basin shapes began to form. The material source of the OMRSSF shale was the sediment brought by the marine transgression from the ancient ocean. The depocenter and subsidence center were both located in the Jy1 area. During the TST and EHST periods, the depositional areas were located below the storm wave base. The presence of framboidal pyrite indicates a weakly reducing to strongly reducing environment. By the LHST, the subsidence center had transferred to the YyA area. The further uplift of the Jiangnan-Xuefeng uplift resulted in the deposition of silty material in the area of Jy, and several sets of silt-stone were
deposited near the Jiangnan-Xuefeng uplift. The depocenter was located in the PyA area, and terrigenous debris was the source of these deposits.

In the late stage of the $S_{1\text{i}}$ member, the sedimentary environment was a weakly reducing environment below the storm wave base, and the MOMASF was deposited. The Jy1 area and WYA-YYa area were the centers of subsidence. The subsidence centers and depocenters gradually migrated to the Chuanzhong uplift. The small-scale uplift controlled the deposition of the lithofacies. By the HST period, the symmetrical deposition of sediments on both sides showed that the provenance of the material was the paleoland areas. The small thickness of the deposits in the middle indicated a weak sediment source, and this area was a strongly oxidizing environment. The shelf environment between the paleoland areas gradually disappeared, and the sediment was deposited above the wave base. The basin-shaped structure was completely formed.

5. Conclusions

In this shelf fine-grained sedimentary system, a total of six typical lithofacies were identified: OMRSSF, HOMSASF, M-HOMLCSASF, LOMSCSF, and LOMSF. Macro-microscale features show that the OMRSSF, HOMSASF, and M-HOMLCSASF are favorable facies for shale gas exploration. Based on the comprehensive sequence division method on the basis of lithofacies, logging data, fossils, and geochemical data, Wufeng-Longmaxi shales were found to contain three third-order sequences and seven system tracts. This stratigraphic classification emphasizes the identified third-order sequence in the upper part of $S_{1\text{i}}$, which was influenced by tectonic activity and previous deposits. This study is not only important for the high-resolution prediction of sweet spots in unconventional exploration but also fully expands the application of classical sequence stratigraphy theory to fine-grained sediments.

The spatiotemporal sedimentary evolution in this shelf fine-grained sedimentary system shows that the lithofacies deposition and differentiation in the TST were controlled by the transgression magnitude and tectonic activity, while those in the regressive system tract were controlled by tectonic activity and the preexisting lithofacies. The lithofacies were deposited in a sequence of environments transitioning from deep to semideep to shallow water. The boundary of the depocenter was consistent with the boundary between lithofacies, and the degree of facies differentiation was small in the TST but highly differentiated in the regressive system tract. The lithofacies exhibit frequent lithofacies transitions and a significant spatiotemporal inheritance. In the $S_{02}$-LHST, the Jiangnan-Xuefeng uplift controlled the lithofacies in the southeastern Sichuan Basin, showing that local regional structures play an important role in fine-grained deposits.

Two types of sedimentary sequences have been identified for the fine-grained sediments in this shelf fine-grained sedimentary system: one was the sequence differential depositional model between paleouplifts and the paleocean, and the other was the symmetric differential sedimentary sequence between paleouplifts. These analyses show that there are also distinct facies transitions in fine-grained sediments, with depocenters and subsidence centers being transformed during the facies transition. The study of fine-grained sedimentation in sedimentology has encountered great difficulties due to fine-grained scale problems, and this study has some important implications for fine-grained sedimentary systems on shelves in other parts of the world.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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