The Lower Silurian Longmaxi Formation in the southern Sichuan Basin is composed of a series of dark carbonaceous shales deposited in a hydrostatic shelf reduction environment. In this study, the ratio of uranium to thorium (U/Th), the total organic carbon (TOC), and the biological silicon content (Si Bio) were selected as the characteristic parameters to precisely analyze the sedimentary environment and its impact on reservoir quality. The results show that the Weiyuan area in the Early Silurian Longmaxi period experienced two transgression-regression cycles, forming two third-class sequences, SSQ1 and SSQ2, which can be divided into six sedimentary microfacies: organic-rich siliceous argillaceous shelf, organic-rich silicon-containing argillaceous shelf, organic-rich silty argillaceous shelf, deep-water silty argillaceous shelf, shallow-water silty argillaceous shelf, and shallow-water argillaceous silty shelf microfacies. The organic-rich siliceous argillaceous shelf and organic-rich silicon-containing argillaceous shelf developed in the deepest transgressive system tract (TST1), with high U/Th, high TOC, and high Si Bio, which are identified as the main control facies for reservoir development. These two microfacies are located in the middle of the study area, while a transition occurs in the east affected by the Neijiang Uplift. According to the classification criteria proposed in this article, the favourable shale gas reservoirs in Weiyuan area are characterized with high U/Th (>1.25), high TOC (>3%), and high Si Bio (>15%). This paper proposed an evaluation method for shale sedimentary facies based on elemental and electrical logging characteristics, avoiding the limitations of core samples, which makes the quantitative division of shale sediments and the efficient recognition of high-quality reservoirs available. It is of great significance for delineating the potential production areas in the study area and beneficial for the scaled development of shale gas reservoirs.

1. Introduction

Shale gas refers to the accumulation of free or absorbed natural gas in reservoir rocks dominated by organic-rich mudstone and shale [1–3]. The organic-rich shale is mainly developed in a low-energy reduction sedimentary environment with abundant sources of organic matter, fast deposition rate, and relatively deep and stable water bodies [4–6]. Previously, different reports confirmed the presence of diverse hydrodynamic conditions under altered sedimentary environments [7]. Shale gas reservoirs that grow in different sedimentary microenvironments have inimitable total organic carbon (TOC) characteristics, gas contents, porosities, sedimentary structural characteristics, reservoir thicknesses, and mineral compositions [8, 9]. Variances in physical characteristics can enhance the quality of shale gas reservoirs and evolve the control effect of sedimentary microfacies on the changes and distributions of reservoir properties [8, 10–13]. In recent years, research on shale sedimentary facies has been directly used to determine favourable zones and well drilling locations [14–16]. The basis of previous research on shale sedimentary facies is mostly
thick section analysis, TOC measurements, and helium observations, whole-rock mineral X-ray di...sedimentary facies and studied the characteristics of lithofacies at different scales and their significance for SHA...exploration. Radwa et al. [19] analyzed the sedimentary facies of the upper Bahariya sandstone reservoir in the East Bahariya area of the Northwest Desert of Egypt based on the analysis of core photos, microresistivity imaging logging, mud logging, and conventional wireline logging data. Sun et al. [20] reconstructed the sedimentary evolution and analyzed the variation in sedimentary characteristics by means of visual categorization and analyzing grain size frequency distribution of sediments from boleholes for Quaternary in northern Jianghan Basin. By analyzing the characteristics of lithofacies, trace-element ratios, and size of pyrite framboids, Han et al. [21] found that the dominant factors controlling organic matter enrichment in the Ordovician-Silurian Wufeng-Longmaxi Formation in the southeastern part of the Upper Yangtze region were regional tectonic activity. Wu et al. [22] described the associations of organic matter and mineral (OMMA) and demonstrated the impact of OMMA on the quality of shale gas reservoirs for shales in Wufeng and Longmaxi Fm. in Sichuan Basin. Chen et al. [23] compared the upper Permian Longtan Formation in the Qingle area of western Guizhou based on rock type, mudstone colour, biological distribution, etc., based on the analysis of sedimentary facies from typical wells and typical sections. They analyzed the sedimentary environment of the organic-rich shale. Quaid et al. [24] characterized four different lithofacies in the Roseneath and Murteree shales in Cooper Basin, Australia, through a combination of wireline logging analysis, thin section petrology, X-ray diffraction, and pyrolysis analysis and established a deposition model for the Roseneath and Murteree shales. Mohammed et al. [25] discussed the geochemical and petrological characteristics of shale samples from two wells in the Late Jurassic Arwa member in the Al-Jawf Basin, Yemen; analyzed the abundance of organic matter, kerogen type, thermal maturity, and biogenicity; and evaluated the organic matter source and environmental conditions during shale deposition using biomarkers and stable isotope analysis results. Although these analytical methods are accurate and useful, they are limited by the number of core samples and core sampling costs. It is impossible to efficiently characterize the distribution of sedimentary facies based on microscopic reservoir research.

The current study institutes and demonstrates a classification standard for the sedimentary microfacies of the Longmaxi shale based on elemental and electrical characteristics by innovatively introducing geochemical elemental changes and electrical characteristics into the sedimentary microfacies division, which can be used in the quantitative evaluation of shale sedimentary microfacies without core data. As shale gas and oil are both generated and stored in shale, sedimentary facies control the development of shale reservoirs. The efficient division of sedimentary facies can quickly locate high-quality shale reservoirs and is of countless importance for selecting shale gas areas and well-drilling locations.

In this study, a comprehensive division of sedimentary microfacies is carried out based on elemental characteristics, electrical properties, and core analysis and laboratory data from 12 shale evaluation wells in the Lower Silurian Longmaxi Formation in the Weiuyuan area of the southern Sichuan Basin, China. In-depth analysis of the relationship between microfacies and locations of high-yield wells is directed, the classification standard of the sedimentary microfacies in the Weiuyuan area is recognized, the main control facies and belts for high shale gas production are elucidated, and the empathetic of the distribution rules of high-quality reservoirs is excavated, providing a theoretical basis for the selection of favourable shale gas zones and well-drilling locations in this area.

2. Geological Setting

2.1. Sedimentary and Stratum Characteristics. During the deposition of the Wufeng Fm., the region west of Longmen Mountain, located to the west of the Sichuan Basin, was rifted during the continuous subduction of the Paleo-Tethys Ocean. With the northward subduction of the South Qinling Ocean to the north of the Sichuan Basin, the Yangtze Block approached the North China Block, while the Cathaysian Block to the east of the Sichuan Basin was further strapped to the northwest. Consequently, the Qinzhong Uplift was exposed to the water surface, resulting in further narrowing of the Upper Yangtze Craton Basin. By the time of deposition of the Longmaxi Fm., the Qinzhuang Uplift further expanded and connected with the Kangdian Ancient Land in the western Sichuan Basin. To the east of the Sichuan Basin, the Xuefeng Underwater Uplift started to form. The initial development of the Xuefeng Underwater Uplift to the east of the basin and the further uplift in the Chuanzhong area made the sedimentary environment of the Sichuan Basin and its surrounding areas a comparatively quiet shelf environment surrounded by a paleoulplift belt with a semiclosed water body. The Early Silurian sedimentary evolution in the Weiuyuan area has shown that during the Rhuddanian Stage, from 440 Ma to 438 Ma, the sedimentary basin in the Weiyuan area was high on both sides and low in the middle due to the compression of the Qinzhou Uplift and Chuanzhong ancient uplift [26]. The Longmaxi Formation deposited a set of deep-water organic-rich siliceous shales in a deep-water anoxic outer shelf sedimentary environment. After entering the Aeronian Stage, the Weiyuan area was still in a deep-water marine environment. The deposition rate of the organic-rich shale was low, and comparatively thin black shales were deposited. During the late Longmaxi Terechian stage, tectonic compression was more intense, and the strata continued to be uplifted; consequently, shallow-water inland shelf subfacies were successively deposited in the Weiuyuan area [27].

The target layer of the current project is the Longmaxi Fm., a set of stable dark marine shales that can be divided into the Longmaxi-1 Member and Longmaxi-2 Member by
logging characteristics. The natural gamma curve presents a sharp upward peak at the Wufeng Fm. and Longmaxi Fm. boundary, showing a maximum at the bottom of the Longmaxi Fm. According to the halfway point between the rising gamma and declining density logs, the Longmaxi Fm. can be divided into the Longmaxi-1 Member and the Longmaxi-2 Member from bottom to top (Figure 1(a)). The Longmaxi-1 Member features a set of black carbonaceous shales deposited after rapid sea level rise during the Early Silurian. This member is rich in paleontological fossils such as graptolite, with silty bands at its top. The Longmaxi-2 Member is composed of grey and grey-green shale, with many silty bands and a few graptolites [28, 29].

The Longmaxi-1 Member is divided into the underlying Longmaxi-11 Submember and the overlying Longmaxi-12 Submember by lithological characteristics. The Longmaxi-12 Submember is dark grey shale at its bottom, while the underlying Longmaxi-11 Submember is grey-black shale at its top. The natural gamma curve in the Longmaxi-11 Submember is generally higher than that in the Longmaxi-12

Figure 1: Electrical stratification characteristics of the Longmaxi Fm. in the Weiyuan area.
Submember, and the increasing trend is enhanced at the bottom of the Longmaxi-1_2 Submember. After entering the Longmaxi-1 Submember, a decrease in acoustic timer difference occurs and institutes a box-shaped curve. In contrast to the acoustic time difference, the waveform density first increases in the form of a funnel and decreases in a box shape after entering the Longmaxi-1_2 Submember (Figure 1(b)).

In the Longmaxi-1_1 Submember, four microlayers, namely, Microlayer ①, Microlayer ②, Microlayer ③, and Microlayer ④, are divided according to their electrical characteristics (Figure 1(c)). Microlayer ① has higher gamma than the bottom of its overlying Longmaxi-1_2 Submember. Compared with the underlying Microlayer ①, Microlayer ① has a box-shaped low natural gamma curve, lower acoustic time difference, and higher density. Microlayer ① has a high gyro-shaped natural gamma curve, showing a high acoustic time difference and low density. Microlayer ② has a low flat box-shaped natural gamma curve, similar to the natural gamma curve of Microlayer ①. The maximum natural gamma value in the Longmaxi Fm. is observed at the bottom of Microlayer ①, and the boundary of Microlayer ① is at the halfway point of the decreasing natural gamma curve.

2.2. Tectonic Characteristics. The study area is located in the southeastern slope belt of the Weiyuan Anticline (Figure 2). The Lower Silurian Longmaxi Fm. has been gnarled totally in the northwestern Weiyuan area and amplifying gradually to the southeast. The strata dip gently, and the burial depth increases gradually from northwest to southeast. The faults in the study area are normally less developed, and only a few northeast-southwest faults are present in the southeast region.

3. Samples and Data Sources

The data employed in this study come from 12 assessment wells in the study area, which are distributed in different structural positions throughout the Weiyuan block. In Well 8, 21 core samples were collected from the bottom of the Longmaxi Fm. and analyzed by a Rock-Eval 6 pyrolysis instrument to obtain the TOC content, rock pyrolysis, and
Figure 3: Continued.
thermal maturity. Ten core samples were selected for thin section fluorescence analysis, 10 core samples were selected for Ar-ion milling scanning electron microscopy analysis (AIM-SEM), and 23 core samples were selected for X-ray diffraction analysis. Eighteen core samples from Well 12, 30 core samples from Well 20, 23 core samples from Well 8, and 38 core samples from Well 23 were tested by a Rock-Eval 6 pyrolysis instrument to obtain the TOC.
contents and examined by an Axios-MAX X-ray fluorescence spectrometer to obtain the U and Th contents. A total of 142 cutting samples in the target layer were collected from Well 7. Element contents, including Si, Al, Ti, V and Cr, were analyzed by a CIT-3000SY X-ray fluorescence spectrometer. In addition, 40 core samples of the Lower Silurian Longmaxi Fm. were taken from Well 3, Well 2, Well 14, Well 10, Well 1, Well 11, Well 4, Well 7, and Well 8 to test the TOC contents by a CS230 carbon-sulfur analyzer, and the quartz content was evaluated by X-ray diffraction analysis. Logging data, including GR, AC, CNL, DEN, TOC, U, and Th curves, provided by China Petroleum Logging Co., Ltd. Southwest Branch were collected from 10 wells, together with the testing production data of 13 horizontal wells in the study area.

4. Sedimentary Facies Characteristics

Previous studies on the sedimentary facies of the Lower Silurian Longmaxi Fm. in the Sichuan Basin have shown that this formation consists of shallow sea shelf facies deposited in an inner shelf environment corresponding to the upper Longmaxi Fm. and an outer shelf depositional environment corresponding to the lower Longmaxi Fm [30–33]. The outer shelf is below the storm wave base with a water depth of 40 m~200 m, which represents a quiet, oxygen-poor, and deep-water-reducing marine environment. The lithology is mainly black, grey-black carbonaceous argillaceous shale, grey-black shale, and silt-containing shale. The inner shelf is in a relatively shallow-water area between the normal wave base and storm wave base with a water depth of 20 m~40 m and is a standing water low-energy environment that is merely affected by severe storm waves. The sediments are mainly dark terrigenous argillaceous siltstone and silty mudstone. The main research goal in this study is targeting the bottom of the Longmaxi Fm., which belongs to the outer shelf sedimentary facies.

4.1. Markers of Sedimentary Facies. Markers of sedimentary facies form the basis of facies analysis and palaeogeographical studies [34, 35]. The current project has been inclusively focused on the development of classification and sedimentary microfacies characteristics based on previous studies and sedimentary facies markers such as sedimentary structures, paleontological markers, sequence characteristics,
geochemical elements, and logging facies characteristics in the Longmaxi Fm. in the study area.

4.1.1. Sedimentary Structures. Sedimentary structures are moulded under physical, chemical, and biological impacts during or after sediment deposition, showing heterogeneous sediment compositions, structures, and colours [36]. Principal observations from Well 8 showed that multiple bedding structures are urbanised in the Longmaxi-1 Submember, chiefly horizontal bedding, rhythmic bedding, and massive bedding, indicating weak hydrodynamic forces during deposition. Bright-dark horizontal beddings are composed of thin layers of silt and black peat. Moreover, small amounts of dolomite and needle-shaped mica are found in the silt (Figures 3(a)–3(c)).

4.1.2. Palaeobiological Markers. Palaeobiological markers are the imperative indicators for unifying marine and nonmarine facies in sedimentary environments. The environment strictly controls the distribution of biotic groups and ecological geographies [37]. There is adaptive and differentiated specific biota in different sedimentary environments [38, 39]. The core and thin section identification data of Well 8 show that the Longmaxi Fm. consists of diverse graptolite fossils. As relatively large and well-preserved fossils, monograptids and rastrites are most commonly observed in the core (Figures 3(d)–3(f)). These organisms have been recognised to live in a deep-water environment (usually below 60 m) characterized by a quiet and reducing environment. In general, graptolites were first observed in Microlayer ④. In addition, abundant siliceous skeletons of organic fossils, such as sponges, radiolarians, and spicules, can also be found (Figures 3(g)–3(i)), representing a deeper deep-water shelf sedimentary environment.

4.1.3. Characteristics of Synsedimentary Minerals. The syngentic mineral assemblage is a central indicator to assess the oxidizing or reducing conditions of a sedimentary environ-

ment [31]. Since Fe is sensitive to the Eh value of the medium, in the reducing environment of marine basins, with a decrease in the Eh value, the valence of Fe also changes accordingly, and it is more likely to form ferrous pyrite. Pyrite patches, pyrite bands, and pyrite clumps are frequently seen in the black shale of the Longmaxi Fm. in the study area, especially in the bottom strata. Additionally, the appearance of framboidal pyrite indicates that the basin was in a strongly reducing environment during the early deposition of the Longmaxi Fm. (Figures 3(j)–3(l)).

4.1.4. Geochemical Element Features. Early studies have demonstrated that various macro- and microelements are indicators of the sedimentary environment [40–44]. In the study of the shale sedimentary environment, aluminium (Al), uranium (U), and the U/Th ratio are usually used to indicate the water depth of the sedimentary environment [45]. Based on elemental mud logging data of 12 evaluation wells in the study area, U/Th and biogenic silicon $S_{Bio}$ are
selected as characteristic parameters to build the classification criteria of sedimentary microfacies in this area.

(1) U/Th. The microelements U and Th, as imperative indicators of the paleo-ocean oxidation-reduction environment, are frequently used as the criteria to judge oxidizing or reducing environments according to the ratio of U/Th [46]. In the large-scale transgression period, the sedimentary environment in the Weiyuan area was anoxic and strongly reducing, conducive to the enrichment and preservation of organic matter. Therefore, the organic-rich shale was mostly formed in an anoxic environment. Correspondingly, the content of U increased sharply, ranging from 10 ppm to 40 ppm, and the U/Th value increased to more than 2.0. In contrast, the sedimentary environment formed during regression was shallow water with relatively oxidizing solid conditions. There was a less organic matter in this environment, but siltstone, silty mudstone, and calcareous silty mudstone were easier to form, reflecting that the transitional marine environment was affected by the supply of terrestrial sediments. Correspondingly, the content of U decreased sharply, ranging from 5 ppm to 15 ppm, and the U/Th value decreased to 0.5~1.25 [47].

The elemental content analysis in the target shale from four evaluation wells shows that the U/Th value of the Longmaxi-1 Submember is significantly higher than that of the upper Longmaxi Fm., and the peak value appears in Microlayer ①. There is a relatively good positive correlation between TOC content and the U/Th ratio, indicating that the anoxic sedimentary environment was more conducive to preserving organic matter (Figure 4).

(2) Biogenic Silicon Content Index. Shale reservoirs have low porosity and permeability, and industrial productivity requires large-scale sand-up fracturing [48, 49]. Siliceous minerals such as quartz, feldspar, and mica, both terrigenous and biogenic, are the main brittle minerals conducive to volume fracturing. However, Ti, V, and Cr are all derived from terrigenous debris. Therefore, the content of terrigenous SiO$_2$ in mineral components is significantly positively correlated with TiO$_2$, V$_2$O$_5$, and Cr$_2$O$_3$, while the content of biogenic SiO$_2$ is significantly negatively correlated [50]. The intersection diagram of SiO$_2$ content and TiO$_2$, V$_2$O$_5$, and Cr$_2$O$_3$ content shows that SiO$_2$ in the Longmaxi-1 Submember is mainly biogenic and negatively correlated with the TiO$_2$, V$_2$O$_5$, and Cr$_2$O$_3$ contents. SiO$_2$ in the Longmaxi-1 Submember to Longmaxi-2 Member is mainly terrigenous and positively correlated with the TiO$_2$, V$_2$O$_5$, and Cr$_2$O$_3$ contents (Figure 5).

Biogenic siliceous shale components, usually derived from biological skeletons, can amplify the fracturing by increasing rock brittleness and also direct organic matter accumulation. An intersection analysis of the silicon content and TOC in the cores of seven evaluation wells in the study area was conducted, and the silicon content showed a positive correlation with TOC (Figure 6). Microlayer ①, the most favourable development target layer, was deposited in a period of rapidly rising basin water level with considerable organic matter accumulation. Therefore, the silicon content in the lower Longmaxi Fm. is mostly biogenic silicon.

The current project has been cited the calculation method of excess silicon proposed by Holdaway and Clayton [51]. In contrast to the elemental mud logging data, the content of biogenic silicon $S_{\text{Bio}}$ in the Longmaxi-1, Submember is calculated for seven evaluation wells in the study area as the identification basis of sedimentary microfacies:

$$S_{\text{Bio}} = \frac{S_{\text{elementary}}}{(\text{Si/Al})_{bg}} \times A_{\text{elementary}}$$

where $S_{\text{Bio}}$ is the biogenic silicon content, %; $S_{\text{elementary}}$ is the silicon content from elemental mud logging, %; and (Si/Al)$_{bg}$ is the weighted average Si/Al elemental content ratio in the nonreservoir section of the Longmaxi Fm., which varies within 2.6~3.6, and the average value is 3.11.

4.1.5. Sequence Characteristics. This paper draws on the experience of Barnett shale in identifying multiple third-class sequences based on the U curve, GR, and TOC [52, 53]. Based on the curve form of the U log and the organic carbon mass fraction $w$(TOC), two complete third-class sequences were identified in the Longmaxi Fm. in the study area (Figure 7).

Third-class sequence SSQ1: the top boundary of SSQ1 lies at the bottom of the Longmaxi-1 Submember, and the bottom boundary of SSQ1 lies at the bottom of the Longmaxi-1 Submember. The thick black carbonaceous shale at the bottom of the Longmaxi-1 Submember formed in the transgressive system tract (TST), representing sea level rise. The U element curve is bell-shaped and increases promptly from bottom to top. The sediment is characterized

<table>
<thead>
<tr>
<th>Sedimentary facies</th>
<th>Subfacies</th>
<th>Microfacies</th>
<th>U/Th</th>
<th>TOC (%)</th>
<th>$S_{\text{Bio}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner shelf</td>
<td>Shallow-water argillaceous silty shelf</td>
<td>&lt;0.15</td>
<td>&lt;1.5</td>
<td>&lt;2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shallow-water silty argillaceous shelf</td>
<td>0.15~0.5</td>
<td>1.5~2.0</td>
<td>&lt;2.0</td>
<td></td>
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<tr>
<td>Shelf</td>
<td>Deep-water silty argillaceous shelf</td>
<td>0.5~1.25</td>
<td>2.0~3.0</td>
<td>10.0~15.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Organic-rich silty argillaceous shelf</td>
<td>0.5~1.25</td>
<td>3.0~5.0</td>
<td>10.0~15.0</td>
<td></td>
</tr>
<tr>
<td>Outer shelf</td>
<td>Organic-rich silicon-containing argillaceous shelf</td>
<td>1.25~2.0</td>
<td>3.0~5.0</td>
<td>15.0~20.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Organic-rich siliceous argillaceous shelf</td>
<td>&gt;2.0</td>
<td>&gt;5.0</td>
<td>&gt;20.0</td>
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Figure 8: Continued.
Figure 8: Continued.
**Figure 8:** Sedimentary environment in the Weiyuan area. (a) Sequence characteristics of Well 5 in Weiyuan area. (b) Sedimentary facies column and paleouplift. (c) Thickness distribution of favourable sedimentary microfacies.

**Figure 9:** Sedimentary model of Longmaxi Fm. in the Weiyuan area.
by rich biological content, a large number of graptolite fossils, and siliceous and calcareous bioclastic. The TOC calculated is high, \( w(\text{TOC}) \geq 5\% \), representing a high-quality reservoir section with high hydrocarbon generation potential. The organic-rich mudstone and deep-water silty mudstone in the upper Longmaxi-1 Submember are formed in the highstand system tract (HST), and \( w(\text{TOC}) \) decreases to 2\%~5\%, which is a retrograding sequence that becomes shallow upward and is the secondary source rock formed during the HST.

The top boundary of SSQ2 lies at the top of the Longmaxi Fm. The bottom boundary of SSQ2 lies at the bottom of the Longmaxi-1 Submember. The TST, developed in the microfacies of the shallow-water silty argillaceous shelf in the Longmaxi-1 Submember, is a transition from regional regression to transgression, which is correlated with the rapid rise of sea level and the rapid intrusion of water bodies. The shallow-water silty argillaceous shelf face of the Longmaxi-2 Member formed in the lowstand system tract (LST), representing a receding sea level, shallow water bodies, and relatively coarse sediments. The U element curve is funnel-shaped with a gradual decrease in amplitude, and \( w(\text{TOC}) \) is low (\( \leq 2\% \)).

4.2. Classification of Microsedimentary Facies. In this paper, based on previous studies, three parameters, namely, the U/Th ratio, the biogenic silicon content (SiBio), and the organic carbon mass fraction \( w(\text{TOC}) \), are optimized, and a quantitative classification standard of sedimentary microfacies for the Longmaxi Fm. in the study area is established. Six sedimentary microfacies are identified in the target layer (Table 1). Among them, shallow-water argillaceous silty shelf and shallow-water silty argillaceous shelf microfacies are developed in the inner shelf with a U/Th ratio less than 0.5, TOC content less than 2.0\%, and biogenic silicon content index less than 2.0\%, representing an oxidizing to weakly oxidizing sedimentary environment corresponding to a lowstand-transgressive systems tract. Organic-rich siliceous argillaceous shelf, organic-rich silicon-containing argillaceous shelf, organic-rich silty argillaceous shelf, and deep-water silty argillaceous shelf microfacies are developed in the outer shelf. Their U/Th ratio is generally between 0.5 and 3.0. The TOC content is approximated between 2.0\% and 7.0\%. The biogenic silicon content index is between 2.0\% and approximately 30.0\%, which belongs to a reducing sedimentary environment corresponding to a transgressive-highstand system tract.

Figure 8(a) shows the sedimentary characteristics of the typical wells in the Weiyuan area. When the sea level rises, the basin is in a low-energy environment and develops a TST system tract. The MFS appears in the SSQ1, suggesting a standing-water reducing environment with the lowest energy. The organic-rich siliceous argillaceous shelf and organic-rich silicon-containing argillaceous shelf develop in such environment and produce more organic contents and biogenic silica that contribute to the development of shale gas reservoir. From bottom to top, the microfacies can be divided into an organic-rich siliceous argillaceous shelf, organic-rich silicon-containing argillaceous shelf, organic-rich silty argillaceous shelf, and shallow-water argillaceous shelf microfacies.

silicon-containing argillaceous shelf microfacies are located in outer shelf waters with the lowest energy. These waters are a strongly reducing environment with weak hydrodynamic conditions and are unaffected by ocean currents and stormy currents. Such microfacies are steadily developed in the Weiyuan shale gas field. Their representative lithologies are mainly grey-black and black carbonaceous shales and locally dark block-like silty argillaceous shales. They have the typical characteristics, namely, high U/Th (U/Th ≥ 1.25), high organic carbon mass fraction (w(TOC) ≥ 3.0%), and high biogenic silicon content (SiBio ≥ 15%). The sedimentary structure is dominated by horizontal bedding and massive bedding. Nodular, banded, and spotted pyrites are relatively developed. Many frambooidal pyrites can be observed under a scanning electron microscope. The sedimentary structure is rich in graptolite fossils and a few macrobenthos fossils, mostly silicified to varying degrees. The above characteristics reflect the sedimentary environment’s weak hydrodynamic conditions, indicating deep-water depositional characteristics, that is, low energy, reducing conditions, low speed, and undercompensation, suitable for accumulating and preserving abundant organic matter and the conversion to oil and gas under suitable conditions.

4.2.2. Organic-Rich Silty Argillaceous Shelf and Deep-Water Silty Argillaceous Shelf Microfacies. Organic-rich silty argillaceous shelf microfacies are deposited in low-energy water environments. These waters belong to a weakly reducing sedimentary environment with weak hydrodynamic conditions and are unaffected by ocean currents and stormy currents. The representative lithologies are dark organic-rich silty shales with U/Th ranging from 0.5 to 1.25, w(TOC) generally ranging from 3% to 5%, and a high biogenic silicon content (SiBio ranging from 10% to 15%). The sedimentary structure is dominated by horizontal bedding and rhythmic bedding. Nodular, banded, and spotted pyrites are relatively developed. A large number of graptolite fossils are observed in the core section. A few macrobenthos fossils and a small number of biological debris, such as siliceous spicules and ostracods, indicate deep-water depositional characteristics, that is, low energy, weakly reducing conditions, low speed, and undercompensation.

4.2.3. Shallow-Water Silty Argillaceous Shelf and Shallow-Water Argillaceous Silty Shelf Microfacies. Shallow-water silty argillaceous shelf microfacies are remarkably well established in the Weiyuan shale gas field and are generally located at the bottom of the inner shelf. Its sedimentary water body is relatively shallow and has high mud content. The representative lithologies are mainly grey-green and yellow-green silty mudstones with locally thin layers of siltstones. Shallow-water argillaceous silty shelf microfacies are situated in the shallow-water oxidizing area close to the shore. Reflected by the frequent rise and fall of sea level, the colour of sedimentary products is relatively light. The representative lithologies are mainly dark grey block-like argillaceous siltstone, silty mudstone with thin layers of grey calcium-containing argillaceous siltstone and grey-white micritic limestone, and tempestite occasionally. These two types of sedimentary microfacies develop from the Longmaxi-12 Submember to the Longmaxi-2 Member. Their U/Th ratio is usually less than 0.5. They are in an oxidizing environment with a low organic matter content, where w(TOC) is generally less than 2.0%, and the biogenic silicon content is extremely low (SiBio ≤ 2.0%). Sometimes, biological disturbance structures are found. A small number of animal combinations, such as sponge spicules, trilobites, and ostracods, are found, indicating that the hydrodynamic conditions during deposition were relatively weak and the water depth was relatively shallow, showing an oxidizing environment.

Figure 8(b) presents an east-west contrast chart of the sedimentary facies of six evaluation wells in the study area. In Figure 8(b), the organic-rich siliceous argillaceous shelf microfacies and organic-rich siliceous argillaceous shelf microfacies with a high organic matter content are mainly distributed in Microlayer (1) vertically and gradually thicken from west to east in the plane. In the middle of the study area, affected by the Neijiang ancient uplift, the water body becomes shallow, and the sedimentary facies change.

Figure 8(c) shows the planar thickness distribution of the organic-rich siliceous argillaceous shelf and organic-rich silicon-containing argillaceous shelf microfacies. The thickness of the favourable microfacies varies between 0 and 7 m, and the depocentre is located in the middle of the study area near Well 5 and Well 17.

4.3. Sedimentary Model. The comprehensive analysis of sedimentary physiognomies and sedimentary microfacies in the study area shows that the deposition period of the Longmaxi Fm. in this area experienced two complete three-stage sea level transgression cycles. SSQ1 starts with the Longmaxi Formation deposition, with seawater invading from the eastern Sichuan Basin. The water body increases rapidly and afterwards decreases slowly. A set of deep-water carbonaceous siliceous shales with thicknesses of approximately 50 m is deposited, which successively experiences the vertical evolution sequence of an organic-rich siliceous argillaceous shelf, organic-rich silicon-containing argillaceous shelf, organic-rich argillaceous mud shelf, and deep-water silty
argillaceous shelf microfacies. SSQ2 begins with the sedimentation of the Longmaxi-1_3 Submember and ends at the top of the Longmaxi Fm. The water depth experiences a short rise and continues to decline, and the sediments are relatively coarse-grained. The sedimentary environment transitions to shallow shelf microfacies, gradually transforming into a shallow silty argillaceous shelf and shallow argillaceous silty shelf microfacies. Affected by the Neijiang Uplift, organic-rich siliceous argillaceous shelf and organic-rich silicon-containing argillaceous shelf microfacies are not developed in the study area (Figure 9).

5. Relation between Sedimentary Facies and Shale Gas Reservoir Quality

The microfacies of the organic-rich siliceous argillaceous shelf and the organic-rich silicon-containing argillaceous shelf developed in the Longmaxi period of the Early Silurian in the study area have a U/Th ratio generally higher than 1.25 and belong to a deep-water highly reducing sedimentary environment. The sedimentary products are mainly grey-black and black carbonaceous mudstones, with thicknesses ranging from 0 m to 7.1 m, showing a trend of gradual thickening and then thinning from west to east and finally pinching out in the eastern part of the study area due to a phase change. Core tests show that the organic-rich siliceous argillaceous shelf microfacies and the organic-rich silicon-containing argillaceous shelf microfacies have a high organic carbon content (TOC > 2.0%) and a high biosilicon content (Si_bio > 15%), indicating a strong hydrocarbon generation capacity. Porosity is mostly over 3.5%, which provides storage space for hydrocarbons. The total gas content is generally more than 2.5 m³/t, which means that the microfacies have commercial exploitation value. The brittle mineral content is more than 65%, which is beneficial for volume modification (Figure 10). Considering the characteristics above, the deep-water strongly reducing marine environment suitable for organic-rich siliceous argillaceous shelf microfacies and organic-rich silicon-containing argillaceous shelf microfacies is the main controlling factor for the development of high-quality shale reservoirs.

The information gained during exploration shows that the test yield of horizontal wells in the study area is positively correlated with the drilling ratio of organic-rich silica mud shelf microfacies and organic-rich siliceous mud shelf microfacies (Figure 11). For horizontal wells with a test yield greater than \(30 \times 10^4\) m³, all fracturing sections are located in the organic-rich siliceous argillaceous shelf microfacies and organic-rich silicon-containing argillaceous microfacies.

6. Conclusions

The current study is of great significance for the readers to delineate the potential production areas and amplify the scaled development of shale gas reservoirs, by providing a more efficient and quantitative categorization method for sedimentary microfacies in shale.

The Longmaxi Fm. in the Weiyuan area comprises a set of dark carbonaceous shales formed in a hydrostatic reducing environment. Two complete third-class sequences, SSQ1 and SSQ2, composed of TST and HST can be identified in the strata. SSQ1 developed in a relatively deeper still-water environment with high TOC and high biogenic silicon content. Hot shale reservoirs are mainly formed in the TST of SSQ1.

The shale of the Longmaxi Fm. deposited in the Weiyuan area is a shelf face, which can be divided into two subfacies: the inner shelf and outer shelf. The outer shelf subfacies developed in SSQ1, while the inner shelf subfacies developed in SSQ2. According to U/Th, TOC, and Si_bio, a categorization of sedimentary microfacies is established and applied in the current project. In the outer shelf subfacies, six microfacies can be identified, including organic-rich siliceous argillaceous shelf microfacies, organic-rich silicon-containing argillaceous shelf microfacies, organic-rich silty argillaceous shelf microfacies, deep-water silty argillaceous shelf microfacies, shallow-water silty argillaceous shelf microfacies, and shallow-water argillaceous shelf microfacies.

Organic-rich siliceous argillaceous shelf microfacies and organic-rich silicon-containing argillaceous shelf microfacies are the most favourable microfacies for developing hot shale gas reservoirs. The depocentre is located in the central study area near Well 17 and Well 18. The sedimentary facies control the distribution of dark organic-rich siliceous shale, with thicknesses ranging from 0 to 7.1 m and thickening to the southeast. In the eastern part of the study area, the hot shale reservoirs are distributed in the organic-rich siliceous argillaceous shelf and organic-rich silicon-containing argillaceous shelf microfacies thin and pinch out towards the Neijiang Uplift.

Data Availability

The data are available in this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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