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Geological Characteristics and Challenges of Marine Shale Gas in the Southern Sichuan Basin

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Abstract: After more than 10 years of exploration, development, research, and practical efforts, China has opened up new perspectives for the commercial exploitation of marine shale gas. While high shale gas production is a main driver for energy security and economic development in China, there have been few attempts to systemically scientific analysis the challenges, prospect, development strategies, and goals for shale gas. Here, we present a detailed comparison of the differences in shale gas between the Sichuan Basin and North America from multiple dimensions, explain how and to what extent recent advances have been made, discuss the current challenges, and provide strategies to deal with these challenges. We demonstrate that a total of 13 graptolite zones developed in the Wufeng–Longmaxi Formations, achieved by representative cores from 32 coring wells and 7 outcrop profiles, can establish the chronostratigraphic framework in the Sichuan Basin, which leads to the potential impact of high-quality reservoir distribution and shale gas production. Shale gas is still faced with the challenges of complex underground and surface conditions, low single-well EUR, and immature deep development engineering technology. To circumvent these issues, here, we propose several strategies, including sweet-spot optimization, low-cost drilling techniques, and efficient fracturing technologies. Our results strengthen the importance of adopting fundamental theoretical research and practical and feasible development goals to realize more commercial discoveries of shale gas of diverse types and higher growth of shale gas reserves and production.

Keywords: southern Sichuan Basin; Wufeng–Longmaxi Formation; shale gas; graptolite

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1. Global Shale Gas Exploration and Development

1.1. Shale Gas Exploration and Development in USA

With the large-scale development of unconventional oil and gas, the oil and gas industry in the USA has ushered in a “second spring” [1]. The “first spring” of oil and gas development in the USA occurred in the 1980s [1]. Due to the large-scale development of conventional oil and gas reservoirs during this stage, the annual gas production in the USA continued to increase from the 1960s, reaching its peak of 587.7 $\times$ 10^9 m^3 in 1971 [2]. In 1973, the import volume of oil and gas reached 0.313 $\times$ 10^9 t, with a foreign oil dependence of 23%. After 1971, as the challenge in discovering large new conventional gas reservoirs increased and the scale of natural gas reserves showed insufficient momentum, the annual gas production in USA continued to decrease [3]. In 2005, the annual gas production was only 489.4 $\times$ 10^9 m^3, reaching a historic low; the import volume of oil and gas was 0.726 $\times$ 10^9 t, with a high foreign oil dependence of 49% [4]. Afterwards, the exploration and development efforts for unconventional oil and gas in USA unprecedentedly increased, and its annual gas production experienced another peak [4]. As of 2020, its unconventional oil and gas production accounted for 72% of the total production in the USA, ushering in a “second spring” for the oil and gas industry in the USA.

Currently, the growth of shale gas production in the USA has become a major domain for global natural gas reserves and production increase. In the year 2018, the United States recorded a total gas production of 835.9 × 10^9 m^3, of which 607.2 × 10^9 m^3 was shale gas, accounting for 73% [3,4]. In 2019, the total gas production in the USA was 920.9 × 109 m3, of which 714 × 10^9 m^3 was shale gas, accounting for 78%. In 2020, the United States achieved a total gas production of 1150 × 10^9 m^3, of which 733 × 10^9 m^3 was shale gas, accounting for 64%. In 2021, the United States achieved a substantial gas production volume of 1179.8 × 10^9 m^3, of which 757.2 × 10^9 m^3 was shale gas, accounting for 64% [2].

According to reports from BP and the US Energy Information Agency (EIA), global gas production was 3857.5 × 10^9 m^3 in 2018, 3989.3 × 10^9 m^3 in 2019, 3861.5 × 10^9 m^3 in 2020, and 4036.9 × 10^9 m^3 in 2021 [4]. It can be seen that from 2019 to 2021, the global gas production gradually increased by 131.8 × 10^9 m^3 each year compared with the previous year (including 106.8 × 10^9 m^3 of shale gas production), −127.8 × 10^9 m^3 (including shale gas production of 19 × 10^9 m^3), 175.4 × 10^9 m^3 (including 14% of the global natural gas growth in shale gas production) [2,3].

1.2. Exploration and Development of Shale Gas Resources in the Southern Region of China

(1) China has complete types, multiple strata, and abundant resources of shale gas.

According to the evaluation results of the former Ministry of Land and Resources of China, China's shale gas geological resources are 121.9 × 10^{12} m^3, and the technically recoverable resources are 21.8 × 10^{12} m^3 [5]. However, according to the evaluation results of PetroChina Research Institute of Petroleum Exploration and Development, China has 80.5 × 10^{12} m^3 of geological resources and 12.85 × 10^{12} m^3 of technically recoverable resources of shale gas [6]. China's shale gas can be divided into three types: marine facies, transitional facies, and continental facies, developed in major petroliferous basins [6]. At present, the efforts made in China to explore and develop shale gas resources mainly focus on the marine shale of the Wufeng–Longmaxi Formations deposited at the turn of the Late Ordovician and Early Silurian in the southern Sichuan Basin [7].

(2) China's journey of shale gas exploration and development has progressed through four distinct stages, ultimately leading to its rapid advancement.

China initiated its shale gas resource assessment in 2006. Through more than ten years of continuous exploration, it has gone through four stages: evaluation for selecting regions, pilot testing, the construction of demonstration regions, and industrial exploitation, realizing "resource ascertainment, productivity evaluation, technology breakthrough, and beneficial development" [8]. The period from 2006 to 2009 was the stage of evaluation for selecting regions, which defined the status of marine shale in the Wufeng–Longmaxi Formations, selected favorable regions, and laid a foundation for the forthcoming shale gas commercial development in China [6]. The period from 2010 to 2013 was the pilot test stage, which broke through the three gateways of single-well gas production and technical and commercial development, thus filling the gap in domestic shale gas development and further strengthening the confidence in shale gas development. The period from 2014 to 2016 was the construction stage of the demonstration regions, which improved the core technologies utilized in the process of shale core sampling, further implemented the resource potential, and initially completed the system construction, thus laying the foundation for accelerating development. The period since 2017 has been the stage of industrial exploitation. Through the work of this stage, the annual production of shale gas in China reached 22.8 × 10^9 m^3 by 2021. China's shale gas has grown from nothing. Its shale gas production has exceeded 10 × 10^9 m^3 in six years, and then achieved a second historical leap of 10 × 10^9 m^3 in the following two years [8].

Shale formations have gained increasing attention in recent years due to their potential as a source of hydrocarbons, but their complex and heterogeneous nature poses significant challenges for exploration and production. To fully understand the behavior of shale formations, it is essential to investigate their chemical and flow properties, as these can have a significant impact on the efficiency and sustainability of hydrocarbon development [7]. Chemical-based studies of shales have focused on characterizing their mineralogy, organic matter content, and pore structure, as well as identifying potential adsorption sites for hydrocarbons and other fluids [8]. Flow-based studies of shales, on the other hand, aim to elucidate the mechanisms governing fluid transport and storage within the rock matrix, as well as the interactions between different phases (e.g., water, oil, gas) [7,8]. Recent advances in analytical techniques, such as high-resolution imaging and spectroscopy, have enabled researchers to probe the chemical and flow properties of shales at increasingly fine scales, providing new insights into their behavior and potential for hydrocarbon recovery. Despite these advances, many questions remain regarding the complex interplay between chemical and flow processes in shales, and further research is needed to optimize development techniques and improve our understanding of these critical resources.

The permeability of shale formations is known to be strongly influenced by the presence of micro- and nanopores, which can significantly affect fluid transport and storage within the rock matrix [9]. Micro- and nanopores in shales are typically characterized by their small size and complex geometry, which can make it difficult to accurately model and predict their impact on permeability [10]. Despite these challenges, recent studies have demonstrated that micro- and nanopores can have a significant effect on shale permeability, with some estimates suggesting that they may account for up to 90% of the total porosity [9,10]. The interaction between micro/nanopores and other structural and chemical features of shales, such as clay minerals and organic matter, can also play an important role in determining their impact on permeability [9,10]. Understanding the behavior of micro- and nanopores in shales is therefore essential for accurately predicting and optimizing hydrocarbon recovery. Advances in imaging and analytical techniques, such as scanning electron microscopy and synchrotron-based X-ray tomography, have enabled researchers to probe the structure and behavior of micro- and nanopores in shales at increasingly fine scales, providing new insights into their impact on permeability and fluid flow [9,10].

(3) Oil companies of China have built a shale gas demonstration zone in South Sichuan, forming a super large gas region of 10×10^{12} m^3.

China's marine shale gas production and reserves have ushered in a rapid growth stage. In 2013, the national shale gas production was only 0.2×10^9 m^3; in 2014, it was only 1.2×10^9 m^3; in 2018, it exceeded 10×10^9 m^3 (10.8×10^9 m^3); in 2019, it reached 15.4×10^9 m^3; in 2020, it reached $\times 10^9$ m^3; and in 2021, it reached 22.8×10^9 m^3 (Figure 1), with an average growth rate of 28% in the past four years, accounting for 27% of the total production of unconventional natural gas [9]. By 2021, China had produced 92.084×10^9 m^3 of shale gas and submitted 2742.205×10^9 m^3 of proved geological reserves of shale gas. Since 2015, PetroChina has submitted 1696.546×10^9 m^3 of proven geological reserves of shale gas through four rounds of declaration, accounting for 62% of the confirmed geological reserves for shale gas in China [10].

PetroChina and Sinopec have discovered two large-scale reserve regions in the Changning–Weiyuan gas shale play and the Fuling gas shale play. Hereinto, the area of South Sichuan is about 43,000 km^2, with a favorable workable area of 20,000 km^2 at a burial depth less than 4500 m, and a reserve scale of about 10×10^{12} m^3; the area of East Sichuan is about 18,000 km^2, with a favorable workable area of 6000 km^2 at a burial depth less than 4500 m, and a reserve scale of about 3×10^{12} m^3.

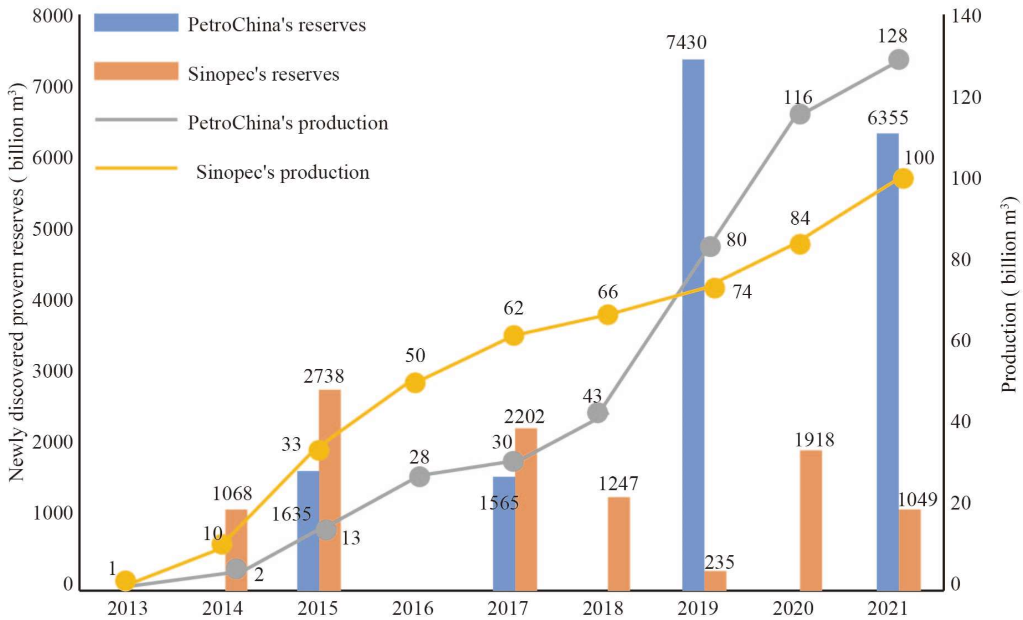

Figure 1. Cumulative histogram of China's shale gas production in recent years.

The proven reserves and production of PetroChina have surpassed Sinopec for three consecutive years, occupying a leading position in the industry (Figure 1). PetroChina has produced 44.131 $\times$ 10^9 m^3 of shale gas, accounting for 48% of the total, and has submitted 1696.546 $\times$ 10^9 m^3 of proven reserves, accounting for 62% of the total [11]. It has spudded in 1519 development wells, completed 1318 wells, and produced 1150 wells, with total gas production of 44.131 $\times$ 10^9 m^3. In 2021, it submitted 635.50 $\times$ 10^9 m^3 of proven reserves and produced 12.799 $\times$ 10^9 m^3 of gas. Sinopec has produced 47.953 $\times$ 10^9 m^3 of shale gas, accounting for 52% of the total, and has submitted 1045.655 $\times$ 10^9 m^3 of proven reserves, accounting for 38% of the total. In 2021, it submitted 104. 883 $\times$ 10^9 m^3 of proven reserves and produced 10 $\times$ 10^9 m^3 of gas [12].

1.3. Shale Gas in New Domains

In recent years, larger discoveries and industrial gas flows of shale gas have been obtained in the Cambrian Qiongzhusi Formation, Permian Wujiaping Formation, Permian Longtan Formation, and Jurassic Ziliujing Formation in the Sichuan Basin, and in the Ordovician Wulalike Formation and Permian Shanxi Formation in the Ordos Basin (Table 1). They include marine, transitional, and continental shale types. They are important future replacement domains after the marine shale of Wufeng–Longmaxi Formations [12].

The Qiongzhusi Formation shale in the Sichuan Basin has made new exploration breakthroughs in the Weiyuan anticline, Leshan–Longnüsi paleo-uplift, and other areas (Figure 2), with the highest tested production rate of 258.6 $\times$ 10^3 m^3/day in Well Jinshi-103HF [13]. The highest tested production rate in the Northeastern Sichuan–Western Hubei region is 320.6 $\times$ 10^3 m^3/day in Well Daye-1. The Lianggaoshan Formation achieved high production, with a daily gas production rate of 114.5 $\times$ 10^3 m^3 and a daily oil production rate of 112.8 m^3. A total of 33 wells in the Carboniferous–Permian transitional facies at the eastern margin of the Ordos Basin obtained industrial gas flows from shale intervals, with a maximum test production rate of 80 $\times$ 10^3 m^3/day. The Middle Ordovician marine Wulalike Formation shale at the western margin of the Ordos Basin obtained 264.8 $\times$ 10^3 m^3/day in the gas test of the horizontal well Zhongping-1, which is the first high-yield well in the northern marine shale gas exploration, opening a new situation for resource evaluation in the western part of the basin [14].

Table 1. Evaluation of shale gas resources in new regions and new layers.

Basin	Shale Type	Formation	Shale Thickness/m	ORGANIC TYPE	Ro /%	Reservoir Thickness /m	TOC /%	Porosity /%	Gas Content /m^3/t	Brittle Mineral Content /%	Area of Favorable Regions /10^4 km^2	Resources of Favorable Regions /10^4 km^2	Major Well	Tested Production /10^4 m^3/d	Strategic Ranking
Sichuan	Marine	Cambrian Qiongzhusi Fm.	100–700	I	3.2–3.6	17–150	1.7–4.8	2.0–5.7	1.6–4.3	61–82	1.1	3.7	Jinshi-103HF	25.86	Large-scale breakthrough
		Permian Wujiaping Fm.	30–50	II	2.9–3.4	5–40	0.2–8.7	2.2–9.9	0.1–10	40–89	0.9	3.5	Daye-1 Hongye-2HF	32.06 15.2	Strategic preparation
	Transitional	Permian Longtan Fm.	40–120	II_1 + II_2 + III	1.0–3.1	20–80	0.5–15	1.1–9.0	0.6–8.8	23–60	1.6	4.4	Dongyeshen-1HF	31.2	Strategic preparation
	Continental	Jurassic Ziliujing Fm.	40–80	II_1 + II_2	0.8–1.4	20–40	1.2–2.0	4–8	0.9–3.8	54–77	0.65	2	Pingan-1	11.45	Strategic preparation
Ordos	Marine	Ordovician Wulalike Fm.	50–100	I + II_1	0.7–2.0	45	0.7–1.7	3–7	1–3	75	0.9	1	Zhongping-1	26.48	Large-scale breakthrough
	Transitional	Permian Shanxi Fm.	15–56	II_2–III	2.0–2.7	32	0.1–26	0.5–4.7	2.2–6.8	65–70	0.6	1	Daji-51 (Jiping-1H)	7.97	Strategic preparation

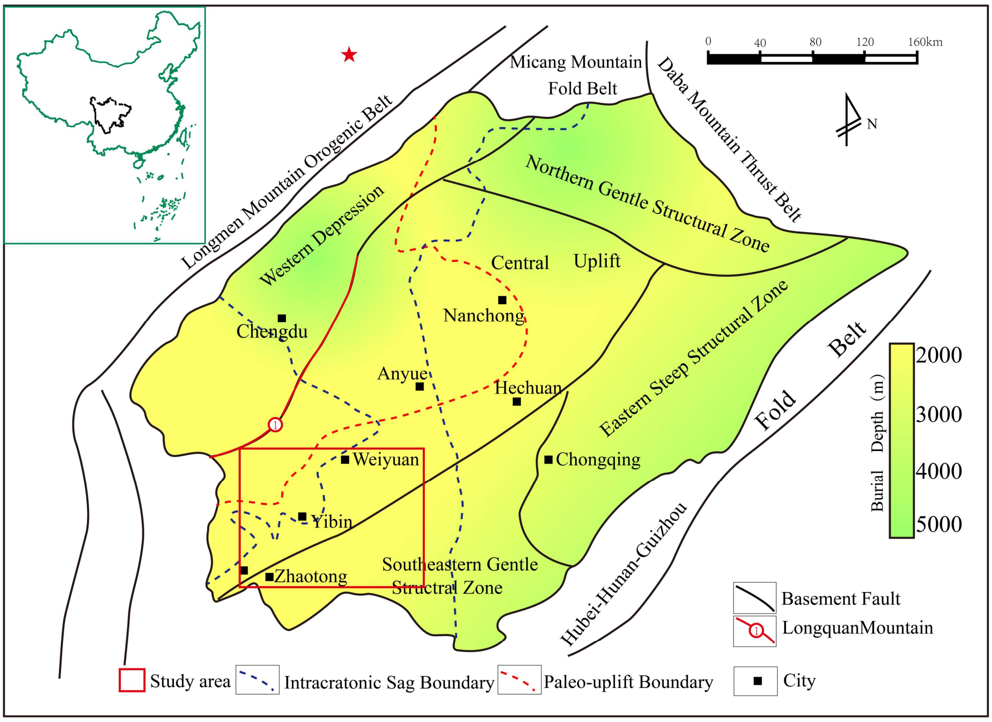

Figure 2. Geological settings of shale gas play in Sichuan basin revised by reference [15]. Reprint with permission from Ref. [15]. 2021, Guangzhao Zhou.

It is predicted that during the 15th to 16th Five-Year Plans, the resource potential assessment of new shale gas layers can take two steps: strategic large-scale breakthrough in the marine Qiongzhusi Formation in the Sichuan Basin and the marine Wulalike Formation in the Ordos Basin; strategic preparation for the Longtan Formation/Wujiaping Formation and the Ziliujing Formation in the Sichuan Basin, and the Shanxi Formation in the Ordos Basin [16].

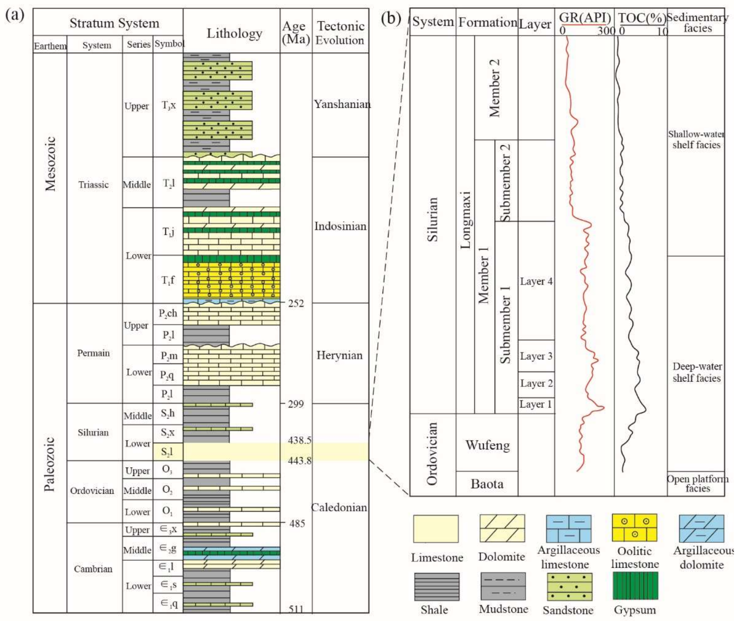

Figure 3. Chronostratigraphic division of the Wufeng–Longmaxi black shales in South China revised by reference [17]. (**a**). Strata of Paleozoic and Mesozoic; (**b**). Strata of Wufeng-Longmaxi Formation. Reprint with permission from Ref. [17]. 2017, Caineng Zou.

2. Geological Characteristics of Marine Shale Gas in South China

Previous exploration and development practices have confirmed that the enrichment of marine shale gas in South China, like conventional gas, also has "sweet spots", and the identification and evaluation of high-quality shale sections is the key to the assessment of shale gas resource. Shale gas reservoirs are characterized by fine grain size, strong reservoir heterogeneity, complex and diverse formation environment, etc. [18]. The reservoir evaluation of shale gas is hindered by the difficulties in identifying sweet spots in shale, unclear distribution rules of sweet spots, and other problems.

2.1. A Fine Division Framework for the Chronostratigraphic Units of Wufeng–Longmaxi Formations Is Established

Specific layers regulate the spatial distribution of superior shale sections, and the chronostratigraphic division and correlation is the essential factor. However, due to the fine grain size and black marine shales in South China, chronostratigraphic division and correlation are difficult. Paleontologists found that graptolites evolved very quickly, especially during the Ordovician and Silurian periods. Many new species of graptolites were formed every few hundred thousand years, and new evolution occurred at the fastest interval of 0.1 Ma. Therefore, graptolites can be used as a gold caliper to determine the age of strata [19].

In order to systematically identify graptolites in the marine shales of the Wufeng–Longmaxi Formations in South China, a chronostratigraphic framework of the region is established (Figure 3). Previous researchers conducted systematic identification of graptolites and delineation of graptolite zones on representative cores from 32 coring wells and 7 outcrop profiles in South China, achieving fruitful results [20]. The research results indicate that there are a total of 13 graptolite zones developed in the Wufeng–Longmaxi Formations in South China (Figure 4) [21]. Hereinto, the Ordovician Katian Wufeng Formation develops graptolite zones of Dicellograptus complanatus (WF1), Dicellograptus complexus (WF2), and Paraorthograptus pacificus (WF3), in which WF3 can be further divided into the Lower Subzone, the Tangyagraptus typicus Subzone, and the Diceratograptus mirus Subzone. The Hirnantian Wufeng Formation develops a graptolite zone of Persculptograptus extraordinarius (WF4), and the Hirnantian Longmaxi Formation develops a graptolite zone of Normalograptus persculptus (LM1) [22]. LM1 contacts with the Guanyinqiao Formation with relative conformity. The Rhuddanian stage within the Longmaxi Formation is characterized by the presence of graptolite zones of Akidograptus ascensus (LM2), Parakidograptus acuminatus (LM3), Cystograptus vesiculosus (LM4), and Coronograptus cyphus (LM5). The Aeronian develops graptolite zones of Demirastrites triangulates (LM6), Lituigraptus convolutes (LM7), and Stimulograptus sedgwickii (LM8). The Telychian develops a graptolite zone of Spirograptus guerichi (LM9) [23].

By integrating calibration results of lithostratigraphy, sea level change, and graptolite layers, a chronostratigraphic framework in the Sichuan basin is established (Figure 4). The research results indicate that the Wufeng Formation can be divided into Wu-1 and Wu-2 members, and the Longmaxi Formation can be divided into Long-1 and Long-2 members [5]. The Long-1 member is subdivided into Long-$_1^1$ and Long-$_1^2$ submembers, in which Long-$_1^1$ can be further subdivided into four layers (Long-1_1^1–4) [6]. The Wufeng–Longmaxi Formations develop three cycles of eustacy. Cycle I corresponds to the Wufeng Formation, with the highest sea level developed at the top of the Wu-1 member. Cycle II corresponds to the Long-1 member, with the highest sea level developed at the top of Long-1_1^3. Cycle III corresponds to the Long-2 member [5,6]. There is a good correspondence between graptolite zoning and lithostratigraphic zoning. The graptolite zone WF1-4 corresponds to the Wufeng Formation. The graptolite zone strata of LM1-5 correspond to the Long-1_1 submember. The graptolite zone stratum of LM1 corresponds to the Long-1_1^1, while LM2-3 corresponds to the Long-1_1^2. The graptolite zone strata of LM4 correspond to the Long-1_1^3, and LM5 corresponds to the Long-1_1^4. The graptolite zone of LM6-8 corresponds to the Long 1_2, and the graptolite zone strata of LM9 correspond to the Long-2 member [5,6].

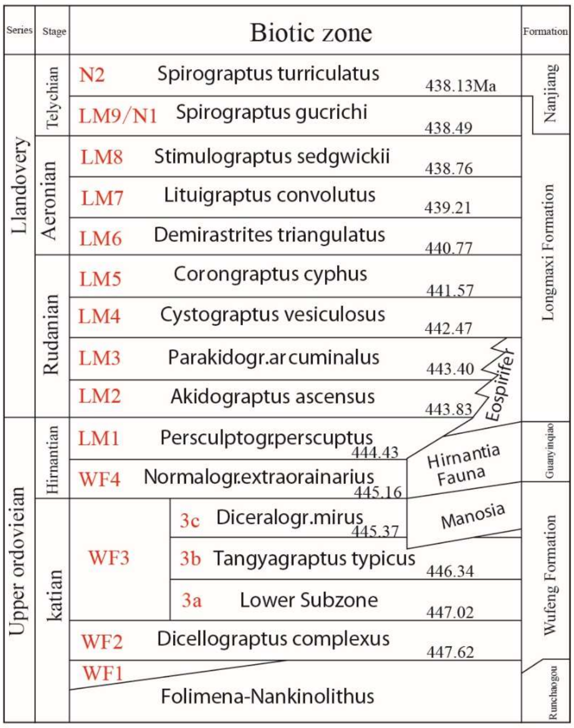

Figure 4. Graptolite zones of the Wufeng–Longmaxi black shales in South China [12,13]. Reprint with permission from Refs. [12,13]. 2017, Xu Chen, 2020, Hongyan Wang.

2.2. The Wufeng–Longmaxi Shales Have Obvious Heterogeneity in Sedimentary Reservoir Characteristics

The quality of the shale reservoir becomes gradually worse; TOC content, quartz content, and gas content are gradually reduced; clay minerals are gradually increased; grain size becomes gradually coarser; mud laminas are gradually reduced; and silt laminas are gradually increased from the bottom to the top of the Longmaxi Formation (Figure 5).

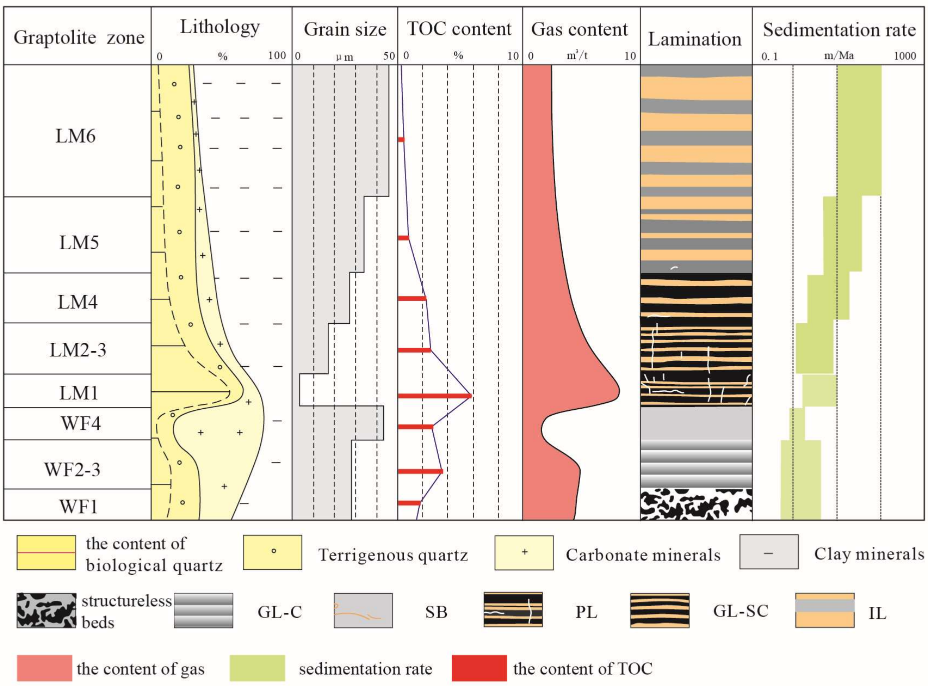

Figure 5. The parameters of shale gas in Longmaxi Formation. Reprint with permission from Ref. [14]. 2022, Zhensheng Shi.

There are two types of "sweet spot" sedimentary models vertically in the shale reservoirs of southern Sichuan Basin: rapid transgression type and slow regression type, corresponding to two high-quality shale sections, respectively, with larger differences in shale reservoir quality between the two types of "sweet spot" (Table 2). At present, the main producing layer is Long-1_1^1, which is continuously distributed in a large area, and is thin (0–3 m). It is a fast transgressive organic-rich shale, but the current productivity construction region is not completely distributed in the deep-water depression area with the largest thickness [5,6]. It is recommended to select the best among the main layer (Long-1_1^1) and prioritize the deep-water depression areas of larger thickness for development. During the later stage, it is worth further expanding to deep-water depression areas such as western Changning and the eastern part of western Chongqing [5,6].

Table 2. Comparison of shale gas reservoir characteristic parameters of two types of sweet spots.

Type of Sweet Spot	Rapid Transgressive	Slow Regressive
Layer	Long-1_1^1	Long-$1_1^{2–4}$
Thickness	0–3 m	7–26 m
TOC	3–12%	2.81–4.67%
Brittle mineral content	65–85%	55.3–68.4%
Porosity	6–11%	5.0–7.8%
Adsorbed gas content	2.3–3.5 m^3/t	1.5–2.2 m^3/t
Gas content	6.8–11.3 m^3/t	5.0–9.0 m^3/t
Typical region	Extensive distribution	Fushun-Yibin, near Well Lu-203, near Well Taihe-1

The Long-$1_1^{2–4}$ shales above the major interval become worse as a whole, but still have large exploration potential in the "sweet spots" in local deep-water depressions. For Long-$1_1^{2–4}$, which were regarded as poor target layers previously, the organic-rich shale in deep-water depressions has a thickness of 7–26 m, which has not yet been paid enough attention and is the second "sweet spot" section [5,6], in which three "sweet spot" zones in deep-water depressions have been predicted, with an additional "sweet spot" area of approximately 4000 km^2 and a resource of 2×10^{12} m^3. "Sweet spots" in deep-water depressions may also be developed in local areas in Long-1_2. Therefore, it is recommended to search for new "sweet spots" in deep-water depressions in the layers (Long-$1_1^{2–4}$, Long-1_2) above Long-1_1^1.

2.3. The Distribution of Wufeng–Longmaxi Shales Is Controlled by Paleo-Uplifts, and the Quality of Shale Reservoirs in Deep-Water Depressions Is the Best

(1) The distribution of shales is controlled by paleo-uplifts, and shales are distributed between paleo-uplifts.

The spatial distribution of black shales regulates the geographic distribution of high-quality shale reservoirs. Through the analysis of more than 120 appraisal wells in the study area, 32 outcrop profile exploration, and 3D seismic interpretation of 800 km^2, the planar distribution of black shale of the Wufeng-Longmaxi Formation is determined. During the sedimentation period of the Longmaxi Formation, two major paleo-uplifts were developed in the Sichuan Basin and its surrounding regions [24]. Among them, the southeastern part was the Dianzhong–Xuefeng paleo-uplift, and the northwestern part was the Central Sichuan paleo-uplift (Figure 6). During that time, two significant sedimentary regions emerged: the southwest and northeast sedimentary areas. Overall, the distribution of the southwestern sedimentary area is relatively limited, while the distribution of the northeastern sedimentary area is relatively open, with large stratigraphic thickness. Within these two major sedimentary regions, the thickness of the strata gradually increases then decreases from southeast to northwest. The Wufeng Formation has a smaller thickness, while the Longmaxi Formation exhibits a greater thickness. Additionally, there are differences in the location of the sedimentary centers [16].

The shale of the Longmaxi Formation has a thickness ranging from 100 to 500 m and is characterized by the presence of two major sedimentary centers (Figure 6). The first depocenter was located in the Lu-202–Jiangjin area, with shale thickness of 400–500 m [18]. The second depocenter can be divided into two secondary centers. The first secondary center was located in Fuling region, with shale thickness greater than 500 m. Another secondary center was located in Zhongxian–Lichuan region, with a shale thickness of over 500 m. Compared to the Wufeng Formation, the sedimentary center of the Longmaxi Formation has clearly shifted from south to north [20].

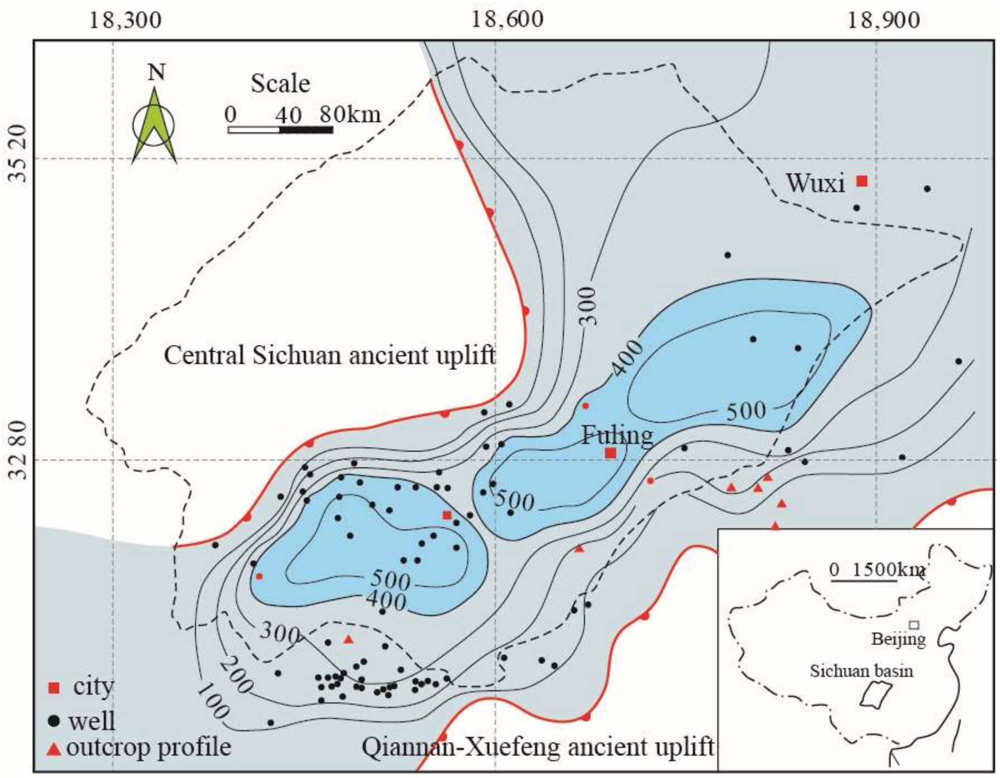

Figure 6. Black shale thickness map of the Longmaxi Formation in South China. Reprint with permission from Ref. [19]. 2021, Zhensheng Shi.

(2) The planar quality of shale reservoirs is controlled by sedimentary microfacies, and the microfacies in deep-water depressions is the best.

Black shale is widely developed in the deep-water shelf subfacies, with the largest thickness, TOC, and quartz content in the shale of the deep-water depression microfacies. Systematic analysis confirms the sedimentary facies pattern of black shale in the Wufeng–Longmaxi Formations in South China. During the sedimentation of the Wufeng–Longmaxi Formations, the Cathaysia Block and Yangtze Block collided with each other [24]. During the Early Silurian, the compression in the southeast direction increased, and the Sichuan Basin and its surrounding regions continued to rise. The Central Sichuan paleo-uplift gradually expanded, and the sea area shrank and the seawater became shallower, intensifying the differentiation of sedimentation. The black shale of the Wufeng–Longmaxi Formations was a coastal-shelf sedimentary facies model (Figure 7). From shallow water to deep water, coastal facies, shallow-water shelf facies, semideep-water shelf facies, and deep-water shelf facies were successively developed. The sediment is mainly sandy and has a relatively low mud content. The shallow-water shelf facies is located between the normal wave base and the storm wave base, with a water depth of 20–60 m. The sediment is mainly composed of silty mudstone and clayey mudstone, with interbedding sandy and muddy beddings. The semideep-water shelf facies is located between the storm wave base and the oxidation–reduction interface, with a water depth of 60–120 m, developing dolomitic shale and thin interbedded horizontal beddings of sandstone and mudstone interlayers. The deep-water shelf facies is located below the oxidation–reduction interface, with siliceous shale. Its sedimentary structure is mainly composed of horizontal beddings of graded sandstone and mudstone interlayers, as well as banded silty horizontal beddings [25]. Different lithofacies of black shale exhibit significant variations in TOC. Among them, deep-water shelf shale has the highest TOC, while coastal and shallow-water shelf shale has relatively lower TOC [26].

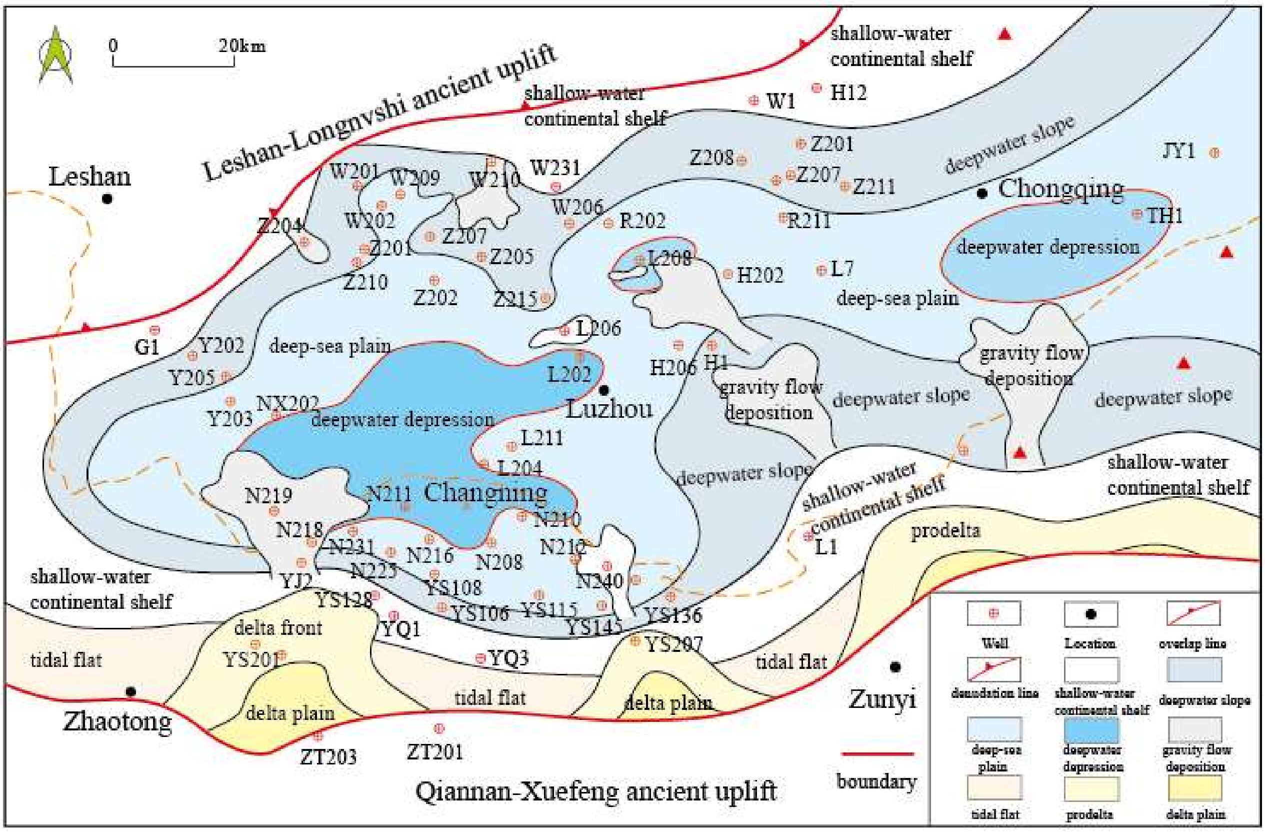

Figure 7. Sedimentary facies model of the Wufeng–Longmaxi Formation in Sichuan Basin]. Reprint with permission from Ref. [22]. 2023, Hongyan Wang.

3. Challenges

The gas shale play of the Wufeng–Longmaxi Formation has several unique characteristics compared to shale gas in other countries and regions [27].

(1) The surface conditions in the southern Sichuan region are complex, and change rapidly and horizontally. The surface conditions in the southern Sichuan shale gas area are complex and can be observed in three main aspects: ① The exposed rock types are diverse and change rapidly horizontally. The Cambrian, Ordovician, Silurian, Permian, and Triassic formations are all exposed, with predominant rock types including sandstone, shale, and carbonate rocks. Sandstone and carbonate rocks constitute a significant proportion, with an 80% exposure ratio in the Ning 209 three-dimensional area in the Changning region. ② The surface terrain is characterized by complex mountainous topography, with significant elevation differences and rapid horizontal changes. In the Ning 209 three-dimensional area in the Changning region, the maximum elevation difference reaches 1600 m. ③ The deep shale gas production areas are industrially developed and densely populated, with numerous factories and towns.

(2) The underground structures undergo intense deformation, and the geostress is complex [28]. The deep shale gas area has experienced multiple tectonic movements, including the Caledonian, Hercynian, Indosinian, Yanshanian, and Himalayan periods. These have resulted in intense deformation of underground structures, and complex conditions such as variable geostress directions and high construction pressures. The study area exhibits various geological formations and fault systems in different directions, with well-developed minor structures and microfractures.

(3) The optimal target formation thickness is small. In the North American region, high-quality shale formations have a relatively large thickness. However, in the southern Sichuan region, the optimal target reservoir thickness is relatively small. In areas such as Weiyuan and Changning, it can be as thin as 0–5 m, while in the Luzhou area, it is slightly thicker, but still only around ten meters.

3.1. Complex Surface and Underground Conditions

Currently, the Arkoma Basin, Fort Worth Basin, Louisiana Salt Basin, Appalachian Basin, and other areas are where shale gas is mostly found in the United States [29], which are mainly cratonic basins or foreland basins. The stable tectonic background not only forms flat surface topographic conditions, but also creates relatively simple underground structural features, which greatly reduces the difficulty and cost of shale gas in the USA.

As for the exploration and development of shale gas in China, the exploration and development regions are mainly in the Sichuan Basin and its surrounding regions. The main blocks include Weiyuan, Zigong, Luzhou, Changning, Zhaotong, West Chongqing, Jiaoshiba, Dingshan, and other regions. Due to the impact of multiple tectonic movements such as Indosinian movement, Yanshan movement, and so on, these regions are mostly mountainous, with complex terrain conditions. Such conditions not only cause high predrilling costs for shale gas exploration and difficulty in well site selection and well location approval, but also cause complex underground geological conditions and other problems, thus causing great difficulties in drilling [30].

To date, the shale gas of the Wufeng–Longmaxi Formation is at depths of 3500 m and below. The deep shale formations have undergone multiple tectonic evolutions, making it extremely challenging to predict and verify fractures. Secondly, deep shale formations exhibit significant heterogeneity, with very low geophysical resolution. This makes it difficult to apply the evaluation and prediction methods used for shallow sweet spots. Thirdly, deep seismic signals are weak, leading to low accuracy in interwell predictions and difficulties in identifying high-potential targets. Fourthly, there is a lack of systematic experimental research on the adsorption and free gas occurrence mechanisms. Hence, the scientific understanding of the impact of thermal effects on the occurrence of shale gas is still limited.

The present challenges can be addressed through the implementation of the following proposed strategies: enhancing geological evaluation theory and technology [16], and scientifically revealing the pore system characteristics of shale gas in deep layers. Research on the diagenetic mineral genesis mechanism, variations and controlling factors of adsorbed and free gas proportions in water-bearing shales, and other related aspects are still lacking. Key breakthroughs can be made in the identification of diagenetic mineral element migration, reconstruction of diagenetic pore evolution processes, and understanding the differential development mechanisms, as well as the distribution and quantitative characterization of adsorbed and free gas in water-bearing shales.

For the innovative development of precise prediction technology for sweet spots in shale gas of deep layers [18], recommendations include performing three-dimensional numerical simulations to study structural deformation and conducting comprehensive evaluations of crucial factors in deep shale formations. Additionally, it is essential to establish high-precision characterization methods for identifying geological engineering sweet spots in deep shale formations. Critical advancements should prioritize the development of technologies for identifying and predicting structural fractures within complex deformation zones, utilizing big data deep learning techniques for predicting geological engineering sweet spots.

3.2. Low Single-Well EUR and Recovery Ratio

Since the first shale gas horizontal well, Wei-201-H1, was drilled in 2011, significant advancements have been made in shale gas exploration and development technology by PetroChina, and the number of fracturing stages, single-well EUR, etc. [31], have greatly improved (Table 3). For example, in 2014, PetroChina drilled one well in marine shale, with a fracturing stage length of 1450 m, and 17 fracturing stages. The test production was 66,200 m^3/d, with a daily production of 32,700 m^3 in the first year and a single-well EUR of 0.47 × 10^8 m^3. But by 2021, the number of drilled marine shale wells of PetroChina had reached 213, with a fracturing stage length of 1588 m, a fracturing stage number of 19.82, a test production of 170,500 m^3/d, a daily production of 62,000 m^3 in the first year, and a single-well EUR of 0.81 × 10^8 m^3.

Table 3. Production performance indexes of PetroChina's shale gas-producing wells in Wufeng–Longmaxi Formations in South China.

Production Index	First Year of Production								Mean
	2014	2015	2016	2017	2018	2019	2020	2021	
Well number	1	83	62	61	130	209	309	213	133
Length of fracturing stage (m)	1450	1365	1433	1470	1513	1534	1543	1588	1487
Number of fracturing stages	17	18	20	22.2	25.5	25.3	22.76	19.82	21
Test production (10^4 m^3/d)	6.62	17	21.9	20.15	23.24	23.77	21.96	17.05	19
Production rate (10^4 m^3/d)	3.27	8.2	8.97	6.92	7.99	8.62	7.74	6.2	7.2
EUR (10^8 m^3)	0.47	0.89	0.97	0.89	0.93	0.94	0.82	0.81	0.84

However, the shale gas of Longmaxi Formation in South China still has problems such as low single-well EUR and recovery ratio, and there is still possibility for the optimization of well pattern and well spacing [32]. Taking the Louisiana Salt Basin in North America as an example, the average single-well EUR can reach 2.5 × 10^8 m^3, and the recovery ratio is higher than 50%. In terms of well pattern and well spacing, the well spacing of the Barnett shale in North America is 150–200 m, that of the Hayneville shale is about 150 m, and that of the Marcellus shale is 100–200 m. However, the planned well spacing for the marine shales in South China is 400–500 m, and there is still some interference for a well spacing of 300 m. The optimal economic well spacing needs to be determined.

Shale gas exploitation is a pressure reduction development process primarily driven by the expansion energy of high-pressure gas [20]. The key to improving recovery rate is to maximize the utilization efficiency of elastic energy throughout the entire lifecycle of reservoir development. The production is influenced by various factors, such as the drainage area of the well, the volume of fractures controlled, the capacity of matrix supply, the flow area, the pressure difference for production, the abandonment pressure, and the production system. Based on production practices and literature research both domestically and internationally, the low recovery rates are mainly attributed to following factors: (1) low horizontal and vertical effective utilization rates, with unutilized areas between wells; (2) limited fracture control volume and small flow area; (3) unclear development mechanisms and low matrix recovery efficiency.

To increase the well drainage area and reduce unutilized reserves between wells, specific optimization measures include optimizing well spacing, optimizing horizontal section length, optimizing well types, and implementing multilayered well network development, among others. To optimize fracture parameters and increase fracture control volume, the following measures can be taken: optimizing cluster spacing, and adjusting parameters such as fracturing fluid displacement, proppant strength, and proppant concentration to enhance the complexity of the fracture network and its conductivity. As production from a fractured well progresses, the initial fractures may gradually close, leading to a decline in production. To maintain or even increase production, repeated fracturing techniques can be employed for wells experiencing declining production rates. Optimizing production methods is crucial to improve matrix recovery efficiency.

Scientifically revealing the production mechanisms of hydraulic fractured horizontal wells involves conducting research on the changes in shale pore structure and CH_4 flow mechanisms during the hydraulic fracturing and postfracturing production stages. Research should be conducted on the factors that control the desorption–diffusion–seepage of CH_4 in the presence of gas–water coexistence. Additionally, it is important to study the evolution patterns of the diversion capabilities of proppant-filled fractures and self-supporting fractures across the entire field.

To accelerate the establishment of an integrated approach for shale gas development optimization, incorporating "geology-engineering-development-economy", it is necessary to establish a comprehensive flow–multiphase flow model that considers various scales for horizontal wells. Additionally, a dynamic numerical simulator should be developed to couple the matrix, fracture, and tubing, enabling accurate simulation of postfracturing production. It is recommended to integrate numerical simulations with field trials to optimize parameters related to well networks, fractures, and exploitation methods. These optimizations may involve the combined development of shallow shale horizontal wells–vertical wells, the single-layer planar development of deep shale horizontal wells, and multilayer three-dimensional development of deep shale horizontal wells. One should consider geological, engineering, environmental, and economic cost constraints, with the goal of optimizing economic indicators, and conduct well network parameter optimization, fracture layout optimization, and production system optimization. Based on this, it is crucial to further enhance the optimization of engineering parameters, including drilling, hydraulic fracturing, and production.

3.3. Immature Engineering Technologies for Deep Shale Gas Development

At present, the engineering technologies for developing shale gas in deep marine shale in South China are not mature, and there are still four major problems, as follows [33]. (1) The drilling speed is lower: The drilling cycle of single wells in the Sichuan Basin is more than 110 days. The average drilling cycle of the Haynesville gas shale play is 35 days, while the drilling cycle in the southern Sichuan Basin is about 78.2–180 days; thus, the drilling efficiency is considerably lower compared to North America. (2) There is a larger difference in the lengths of the horizontal segments compared to North America. The lengths of the horizontal segments of the Haynesville gas field are generally around 2500 m, while in the deep layers of South Sichuan, they are only about 1500 m; thus, the difference is large. (3) The drilling ratio of high-quality reservoirs is low. Specifically, the threshold of drilling ratio of Class I reservoirs in South Sichuan is more than 90%; the drilling ratio of Shell's old wells is 58%. The drilling success rate of newly producing wells has significantly improved but remains unstable, leaving ample room for optimization. (4) The current equipment and tools fail to meet the requirements adequately. Deep shale reservoirs, due to high geotemperature and pressure that exceed the temperature resistance limits of rotary steering, MWD, and screw tools, result in frequent complex downhole accidents and severely limited drilling efficiency.

To mitigate and manage the losses of oil-based drilling fluids in horizontal wells, it is crucial to implement effective measures [34]. Additionally, effective techniques must be developed to eliminate incidents of stuck pipe and buried tool accidents. Drilling fluid losses, especially with high-density oil-based fluids, are a common challenge encountered in horizontal wells. One of the main obstacles faced is the limited availability of suitable leak-plugging materials that can effectively address this issue. The methods for effective leak plugging are also limited. Furthermore, issues such as wellbore collapse, formation cuttings, and poor wellbore cleaning lead to high torque and drag in the drilling of long horizontal sections, sometimes resulting in accidents involving stuck pipes and buried tools. Techniques to reduce or eliminate casing damage in horizontal sections are needed. The number of damaged casing strings in horizontal fracturing wells is extremely high, typically ranging from one to three deformation points per well. Problems such as drilling blockages and sticking occurrences during drilling operations significantly impact the effectiveness of hydraulic fracturing.

The existing theoretical framework is unable to meet the needs of hydraulic fracturing engineering practice. Fracture generation and proppant transport during hydraulic fracturing, as well as fluid flowback and gas production after fracturing, involve complex physical and chemical processes. Behind these processes lie numerous unresolved scientific questions, which often lead to phenomena that cannot be adequately explained by existing theories in engineering practice.

The existing process models are unable to meet the requirements for deep shale reservoir stimulation. The current hydraulic fracturing methods primarily focus on enhancing the net pressure within the fractures to attain larger stimulated volumes, often employing high-volume treatments and temporary shut-in practices. However, compared to shallow shale reservoirs, deep shale formations typically have higher closure pressures and larger horizontal stress differentials. Following the existing process models would require even larger treatment volumes and more precise shut-in pressures, imposing stringent demands on construction equipment. The current supporting processes are inadequate to meet the cost reduction and efficiency enhancement needs of deep shale.

The challenges identified above suggest the need for the implementation of targeted strategies in specific areas. Accordingly, the following strategies are proposed to address these challenges:

(1) Development of safe and intelligent fast well construction technologies. Efforts should be made to research and develop innovative technologies to facilitate drilling through extended horizontal sections in a single operation. Specifically, there is a need for environmentally friendly anticollapse drilling fluids, ultralightweight drill tools with enhanced friction-reducing capabilities, efficient techniques for wellbore cleaning, and intelligent logging technologies. These technologies aim to further improve mechanical drilling speed, minimize drilling accidents, and reduce the drilling cycle duration in challenging environments characterized by high drilling pressure, rotational speed, pump pressure, displacement, and torque. Emphasis should be placed on the development of theories and technologies pertaining to wellbore integrity management throughout the complete lifecycle of deep shale horizontal wells [35]. Efforts should be directed towards improving the wellbore integrity in deep shale long horizontal sections, minimizing or eliminating casing damage within the horizontal segment, and ensuring adequate wellbore protection during extensive and prolonged reservoir stimulation, such as repeated fracturing, as well as postfracturing production operations.

(2) The commitment is to innovate existing theories on fracturing, proppant transportation, and fluid flow in horizontal wells. This research aims to establish a scientific foundation for optimizing techniques such as seam placement methods, selection of fracturing fluids, proppant sizes, and pumping procedures. Building on this foundation, we conduct research on supercritical carbon dioxide (SC-CO_2) fracturing technology for shale gas. We have overcome the limitations of SC-CO_2 in reducing friction and increasing viscosity, and have developed ultralow-density and low-cost proppants that are compatible with SC-CO_2. By utilizing the dual physical and chemical effects of carbon dioxide, we can improve gas adsorption while achieving effective fracturing. Additionally, we have explored techniques such as oxidation-induced fracturing and liquid nitrogen fracturing in deep shale formations, and established a multiscale flow pathway from nanopores in shale to propped fractures. Furthermore, we propose harnessing fracking construction data to develop theories and methodolo-

gies for reverse inference of fracture parameters. This approach will enhance fracture monitoring and evaluation techniques, resulting in cost reductions associated with monitoring activities. In terms of revitalizing mature wells, we suggest enhancing research on repeated fracturing well selection, layer selection, and seam creation in shale gas horizontal wells to enhance productivity and recovery in mature wells.

(3) Efficient production techniques for deep, long horizontal wells are being developed. The goal is to investigate the dynamic inflow behavior and two-phase gas–liquid flow patterns in different stages of postfracturing horizontal wells. Based on these findings, the optimization of the wellbore trajectory and structure of the horizontal section will be pursued to increase the depth of the tubing. Composite process technologies, such as platform compression gas lift, are being explored to enhance production efficiency in these wells.

(4) Environmentally friendly and safe drilling and fracturing technologies are being developed. The aim is to address the technical and economic barriers associated with the preparation of oil-based drilling cuttings for fracturing proppants and to establish novel approaches for the resource utilization of these cuttings. Research and development efforts are underway to create lightweight, modular, and intelligent drilling and fracturing equipment that is well-suited for operation in high mountain and deep valley environments. Moreover, efforts are being made to develop centralized control systems for drilling and fracturing operations. These systems will serve as essential technological support, facilitating the optimization of engineering construction processes and enabling prompt responses to emergency situations.

3.4. Shale Gas Exploration in the New Regions Has Not Yet Achieved Large-Scale Breakthrough

During various geological historical periods in China, organic-rich shales were developed, forming three types of shales: Paleozoic marine facies and transitional facies, and Mesozoic–Cenozoic continental facies [27]. The marine organic-rich shales are mainly distributed in South China and North China. The transitional organic-rich shales are mainly distributed in North China, Hexi Corridor, and Xinjiang regions. The continental organic-rich shales are mainly distributed in five major basins (Songliao, Bohai Bay, Ordos, Junggar, Tuha) [36]. The geological characteristics of China's marine organic-rich shales are very similar to those of gas-producing shales in the USA, and their gas-bearing property has been confirmed. However, the exploration of transitional and continental shale gas has only made significant discoveries at some points, and there has been no large-scale general breakthrough.

Shale gas resources are mainly in the Sichuan Basin and the Ordos Basin in China. Among them, the Jurassic shale oil and gas has problems such as unclear sidetracking test results of old wells, resource scale, "sweet spot area/section", reservoir heterogeneity, etc., which need to be deeply understood and explored. The Permian in the Ordos Basin is dominated by delta-tidal flat-bay lagoon facies. The Shanxi Formation shale is 30–85 m thick, vertically stacked with multiple layers, and has a large amount of resources. Drilling results show good prospects, but there are issues that need to be further clarified, such as enrichment characteristics, high-yield well conditions, and a low-pressure effective production method.

Currently, the shale gas research hotspot is on deep shale gas reservoirs. Previous exploration and development practices have shown that shale gas in key areas has complex geological conditions. There is an urgent need to overcome challenges in deep, low-pressure shale gas accumulation patterns, the prediction of dual sweet spots in geological engineering, and the development of low-cost, high-efficiency engineering processes. Technologies such as multilayered development and repeated fracturing need continuous research to improve the recovery rate. The geological conditions in new capacity replacement areas are complex, and there are challenges in achieving sustained production and scale development due to immature supporting technologies for efficient development and production. Conducting theoretical and technological research in different areas of shale gas is key to achieving breakthroughs in exploration and commercial development and ensuring the realization of development goals.

Based on the aforementioned challenges, we propose the following suggestions: The favorable depositional environment of the continental shelf provides the fundamental conditions for the high-quality shale. The primary reservoir space in high-quality shale is comprised of organic matter pores that are formed during diagenesis and hydrocarbon generation processes. The preservation conditions exhibit variability across different tectonic styles, leading to distinct stages of pore evolution within the shale formations. As a result, specific regions known as "enrichment zones" and "sealing zones" are formed.

There are numerous factors that influence the accumulation and preservation of shale gas in mountainous and complex structural areas. The large-scale fault is the most significant form of shale gas migration. "Slow heating and low maturity" and "tectonic uplift" are conducive to the long-term enrichment and preservation of shale gas. Regardless of the factors causing differences in gas content, they ultimately manifest in changes in pressure and pore characteristics within the shale itself. These factors should be given due attention when selecting exploration targets in mountainous and complex structural areas for shale gas.

In response to the characteristics of strong tectonic activity, low pressure coefficient, low gas content, and significant differential stress in shale gas reservoirs, research has been carried out with the analysis of prototype basins as the main approach. This includes shale oil and gas generation and expulsion simulations, paleo-pressure reconstruction, and the integration of burial history and stress analysis. The objective is to explore the mechanisms underlying the formation and accumulation of normal-pressure shale gas. A dynamic accumulation model called the "generation-expulsion-retention-accumulation" model has been established. The theory of "three-factor controlling accumulation" has been proposed. Additionally, an evaluation system for normal-pressure shale gas, with preservation conditions and stress analysis as the core, has been developed to identify optimal sweet spots and intervals. These efforts effectively guide the selection of sweet spot areas and segments.

Following the concept of "construction-transformation-artificial intervention" in shale gas exploration, the principles governing the enrichment and high productivity of normal-pressure shale gas have been systematically summarized. It has been determined that the accumulation, enrichment, and high-productivity of shale gas are controlled by three factors: depositional facies belts, preservation conditions, and stress fields. Deep-water continental shelves provide hydrocarbon sources for accumulation and control the reservoir quality of shale gas. Structural activity affects the preservation conditions and the content of shale gas, thereby controlling the degree of shale gas enrichment. Stress fields impact the complexity of natural and induced fractures, ultimately controlling individual well production and the ultimate recoverable reserves.

Vigorously carrying out low-cost engineering technology research and development is the key to achieving cost-effective development. In response to technical and cost challenges such as slow drilling speed, long cycle time, low complexity of induced fractures, and high difficulty and investment in engineering construction for shale gas, two main lines of increasing production and reducing costs have been closely focused on. Through theoretical innovation, process exploration and practice, and comprehensive supporting measures, a series of low-cost technologies have been developed, including optimized and fast drilling and completion techniques, as well as efficient fracture network transformation. These advancements have greatly reduced drilling and production costs, providing strong support for the cost-effectiveness of shale gas.

In view of the characteristics and current situation of shale gas in China, this paper proposes the following countermeasures: (1) deploying the best well pattern and well spacing at one time through large platforms; (2) implementing well pattern infilling and secondary fracturing to improve the recovery degree of shale gas resources in developed blocks; (3) strengthening preliminary evaluation on deep layers; innovating, optimizing, and solidifying the main technologies and management modes; (4) improving quality and efficiency and long-term low-cost development. These are effective ways to achieve the sustainable development of the shale gas industry.

4. Conclusions

In China, shale gas consists of 12 stratigraphic units and 43 intervals, which are developed from the Precambrian to the Paleogene. Currently, the exploration and development of shale gas primarily focus on the marine shale formations of the Wufeng–Longmaxi Formation in the southern part of the Sichuan Basin.

Based on representative cores from 32 coring wells and 7 outcrop profiles, there are a total of 13 graptolite zones developed in the Wufeng–Longmaxi Formations in the southern Sichuan basin, establishing a chronostratigraphic framework. The distribution of shale in the Wufeng–Longmaxi Formation is controlled by paleo-uplifts, with the highest-quality shale reservoirs developed in deep-water depressions. The quality of shale reservoirs on a planar scale is controlled by depositional microfacies.

Challenges of shale gas faced in the Sichuan basin include complex surface and subsurface conditions, low single-well EUR and recovery rates, immature deep-level de-velopment engineering technologies, and a lack of significant breakthroughs in the exploration of shale gas in new areas. To resolve these issues, we systematically proposed to enhance geological evaluation theory and technology and scientifically reveal the production mechanisms of hydraulic fractured horizontal wells. It is plausible that vigor-ously carrying out low-cost engineering technology research and development is the key to achieving cost-effective development.

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