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Study on the Formation Mechanism of Shale Roof, Floor Sealing, and Shale Self-Sealing: A Case of Member I of the Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation in the Yangtze Region

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Similar to North America, China has abundant shale resources. Significant progress has been made in the exploration and exploitation of shale gas in China since 2009. As the geological theory of unconventional oil and gas was proposed, scientists have started researching conditions for shale gas preservation. The shale roof and floor sealing and the shale self-sealing are the critical objects of such research, which, however, are still in the initial stage. This article studies the formation mechanism of shale roof and floor sealing and shale self-sealing by taking marine shales from Member I of the upper Ordovician Wufeng Formation–lower Longmaxi Formation in the upper Yangtze region as the research object. Analyses were performed on the TOC content, mineral composition, and porosity, as well as the FIB-SEM, FIB-HIM, and gas permeability experiments on the core samples collected from the marine shales mentioned above. The conclusions are as follows: for the sealings of shale roof and floor, the regional cap rocks, roof, and floor provide sealing for shales due to physical property differences. For the self-sealing of shales, the second and third sub-members of Member I of the Wufeng Formation–Longmaxi Formation mainly develop clay mineral pores which are dominated by macropores with poor connectivity, while the first sub-member of Member I of the Wufeng Formation–Longmaxi Formation mainly develops organic-matter pores, which are dominated by micropores and mesopores with good connectivity. Owing to the connectivity difference, the second and third sub-members provide sealing for the first sub-member, while the methane adsorption effect of shales can inhibit large-scale shale gas migration as it decreases the gas permeability; thus, the organic-rich shales from the first sub-member of Member I of the Wufeng Formation–Longmaxi Formation provides sealing for itself.

Keywords: marine shale, roof and floor sealing, self-sealing, organic-matter pores, adsorption capacity

INTRODUCTION

As the economy in China has been developing fast in recent years, the demand for natural gas has increased vastly nationwide, while the domestic output of such a resource is far from sufficient for the demand. Therefore, all the major oil companies successively established four natural import channels, respectively, from the northeast, northwest, and southwest as well as by sea transportation. However, the gradually increasing import of and dependence on natural gas from abroad in recent years pose a mighty challenge against China's energy security (Curtis, 2002; Guo, 2016; Zou et al., 2017). Fortunately, China, similar to North America, has tremendous shale gas resources and has made significant progress in the exploration and exploitation of shale gas since 2009 (Guo, 2021).

As the geological theory of unconventional oil and gas was proposed, scientists have started researching on conditions for shale gas preservation (Guo et al., 2017). In the geological theory of conventional oil and gas, pelite is one of the most common cap rocks in the oil and gas field, and oil geologists have studied the sealing provided by pelite cap rocks for underlying reservoirs (Guo et al., 2020). Shales can be converted into source rocks when they satisfy certain conditions. When their thickness is bigger than the maximum distance between the hydrocarbon expulsion from the top and the bottom at the peak time of hydrocarbon generation of the shales, gas will be effectively sealed in them. Nevertheless, the geological theory of conventional oil and gas does not consider shales as reservoirs, and the research on vertical sealing from the perspective of pore characteristics is limited. The largest difference between shale gas and conventional gas in preservation conditions lies in the roof and floor conditions, as the roof and floor may feature the lithology of mudstone, shale, tight sandstone, or carbonatite, and its quality depends on the physical properties of the rock (Zou et al., 2015; Guo et al., 2016; Zou et al., 2016). The lithology of the roof and floor is critical to the preservation conditions of shale gas because the roof and floor with quality lithology in combination with a gas-preserving shale bed can form a fluid compartment, which effectively slows the outward migration of shale gas and thus makes it well preserved (Zou et al., 2017; He et al., 2019; Zou et al., 2020). On the contrary, the roof and floor with poor lithology provide weak sealing for fluids, easily dissipating oil or gas outward and thereby wasting shale gas reservoirs. In North America, the overlying and underlying strata of the Barnett shale reservoirs are both tight limestones, while the overlying strata of the Marcellus and the Haynesville shale reservoirs are shales and their underlying strata are tight limestone, all forming good-quality sealing strata which provide good preservation conditions and gas-bearing properties for shales (Zou et al., 2019).

A series of studies have been conducted on the shale roof and floor sealing and the shale self-sealing. Wei et al. (2017) concluded that the shale gas layer of the Wufeng–Longmaxi Formation is a typical "top-covered and bottom-clogged" type, which is favorable for shale gas preservation. It has sealing capacity for the following reasons: its floor strata are composed of nodular and regular limestone of the Linxiang and Baota Formations with dense lithology. Besides, the matrix porosity and permeability are generally less than 2% and $0.1 \times 10^{-3} \mu m^2$, respectively. No fractures and sedimentary discontinuity exist. The marine mud shale of the Wufeng–Longmaxi Formation has a large specific surface area during the formation process of large amounts of shale gas, with copious hydrocarbon-friendly organic pores being formed. The shale gas is first adsorbed on the surface of these pores before it is stored in the pores or fractures of large diameters in a free state. Wei et al. (2017) and Cui et al. (2020) concluded that the top and bottom strata of the upper Ordovician Wufeng–lower Silurian Longmaxi shale gas formation are dense and exhibit low pore, low permeability characteristics. They also observed that the replacement and breakthrough pressures vary in different regions. For the top strata sample, both pressures were negatively correlated with the permeability: the lower the porosity degree and permeability, the stronger the replacement and breakthrough pressures. The gas-bearing capacity has a significant positive correlation with the microcosmic sealing capacity of the roof strata and a slight positive correlation with that of the floor strata, which means that the variances in the sealing capacity of the roof strata have more significant impact than those in the sealing capacity of the floor strata on the enrichment degree of shale gas (Cui et al., 2020).

Previous studies on the shale roof and floor sealing and shale self-sealing are not in-depth enough to study their formation mechanisms. By contrast, this article carried out research in this regard by taking JiaoYe1 well of the Jiaoshiba block located in the southeast of the Sichuan Basins in the upper Yangtze region in southern China as the study object. The Longmaxi Formation contains three members along the vertical direction, namely, Members I, II, and III from the bottom to the top. Based on the characteristics including rock colors, lithology, the combination of them both, and the combination of well logs, Member I of the Longmaxi Formation can be further divided into three sub-members, which are Sub-members I, II, and III from the bottom to the top, of which Sub-member I of Member I of the Wufeng Formation–Longmaxi Formation is currently the primary target strata of shale gas production in Sichuan Basins (Guo et al., 2016; Guo et al., 2017; Zhang et al., 2018a; Zhang et al., 2019a; Guo et al., 2020; Nie et al., 2020) (**Figures 1–3**). This article analyzed the mechanism of shale roof and floor sealing formation from the perspective of porosity, breakthrough pressure, and permeability, and marine shale self-sealing formation from the

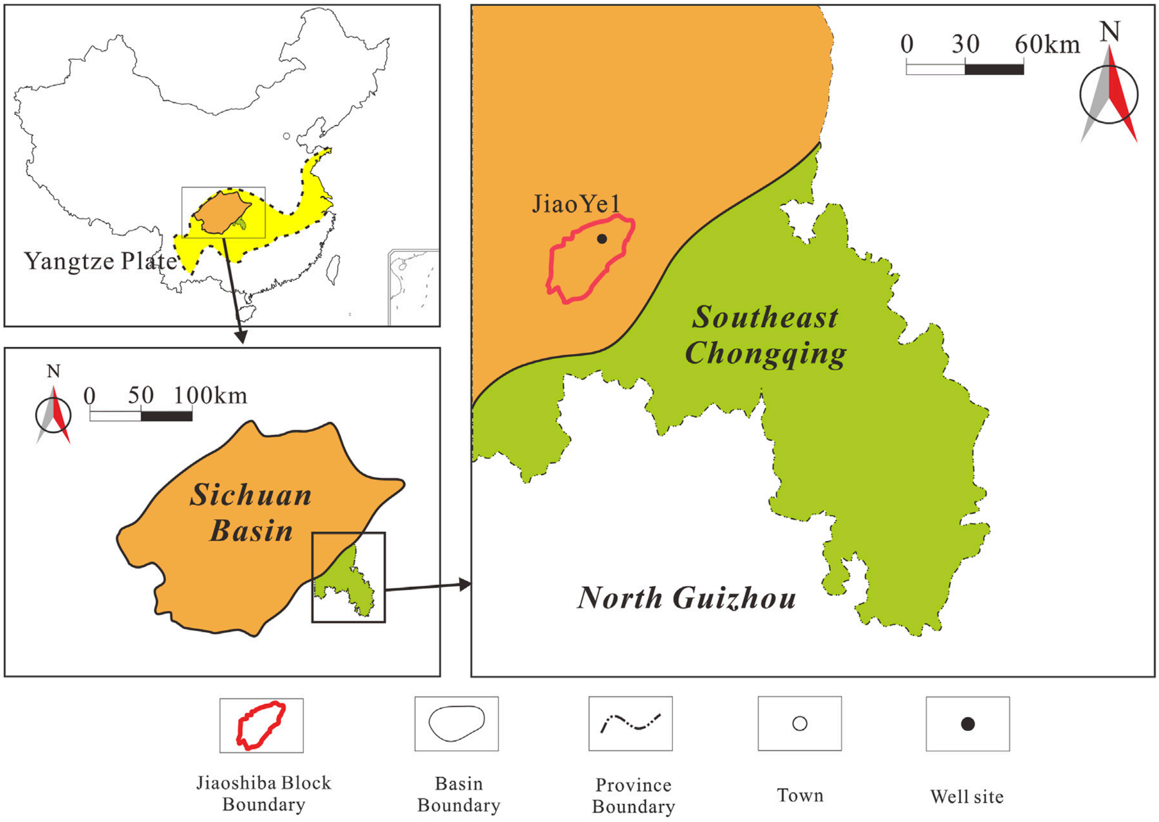

FIGURE 1 | Locations of the Jiaoshiba Block in the southeast of the Sichuan Basins in southern China and JiaoYe1 well. Modified from references (Zhang et al., 2018a; Zhang et al., 2019a; Nie et al., 2020).

perspective of porosity compositions, porosity structures, and adsorption effect.

GEOLOGICAL SETTINGS

Sedimentary and Stratum Characteristics

Previous studies have shown that (Mei et al., 2012; Wang et al., 2015; Mou et al., 2016; Zhang et al., 2019b; Wu et al., 2019; Zhang et al., 2020a; Ma et al., 2020) the upper Yangtze region turned into a cratonic basin after the Cathaysia plate extrusion during late Ordovician–early Silurian. The sedimentary strata of late Ordovician in the upper Yangtze region are named as the Wufeng formation, while the sedimentary strata of Early Silurian in the same region are named as the Longmaxi formation, which can be divided into Member I, II, and III from the bottom to top. The target stratum for the study in this article is Member I of the Wufeng–Longmaxi Formation. The shale in such a member features bipartite lithology: Sub-member I of Member I of the Wufeng Formation–Longmaxi Formation is dominated by black siliceous organic-rich shale, while Sub-members II and III of Member I of the Longmaxi Formation is a combination of dark gray and silty shales, and siltstone.

Tectonic Characteristics

As evident from previous studies (Li et al., 1995; Li et al., 2002; Wang and Li, 2003; Zhang et al., 2017; Hu et al., 2018; Yang et al., 2019), the primitive continental crust in southern China was separated into two ancient plates in the early Mesoproterozoic period, of which one is the Yangtze plate and the other the Cathaysia plate. The two plates were stretching during the early Cambrian when large-scale transgressions occurred, leaving behind the sedimentation of a set of organic-rich shales that almost totally cover the plates. Afterward, the water body decreased; fine and silty shales gradually became coarse clasolites like siltstone and sandstone. When the Cathaysia late extruded the Yangtze plate in the Ordovician period, the water body further decreased, and the sedimentary system was changed from clasolites to carbonanites. The large-scale transgressions that happened in the late Ordovician–early Silurian changed it back to the sedimentary system of clasolites and left behind the sedimentation of a set of organic-rich shales in the deep-water shelter surrounded by the ancient continent. The Cathaysia plate started subduction toward the Yangtze plate and collided with it during the Cambrian–Silurian period. Then, the two plates merged with each other as the complete South China plate at the end of the Silurian period.

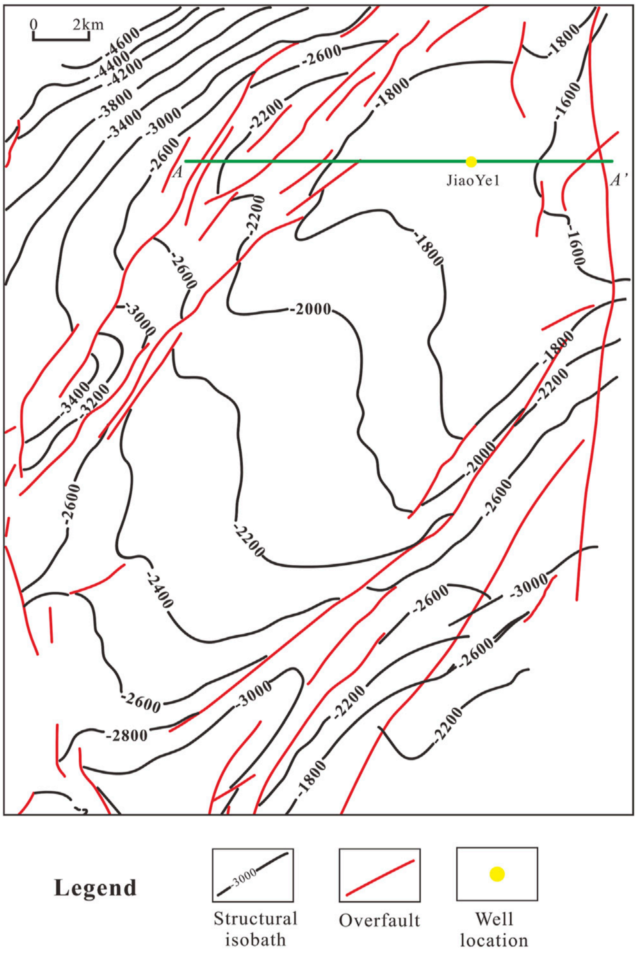

FIGURE 2 | Bottom structure map of Wufeng Formation in Jiaoshiba Block. Modified from references (Nie et al., 2020).

SAMPLES, EXPERIMENTS, AND DATA SOURCES

Member I of the Wufeng–Longmaxi Formation from the JiaoYe1 well was evenly sampled every 2 m, and 42 pieces of cores were collected in total. The porosity was tested with a Poro PDP-200 porosity tester, the TOC content was tested with an OG-2000V carbon and sulfur analyzer, and the analysis of X- and clay minerals was conducted with a YST-I mineral analyzer. The data reported by Guo et al. (2016) were referred to for part of the test data (Guo et al., 2016). The data reported by Guo et al. (2017) and Jin et al. (2018) were referred to for the porosity test data of the gypsum rock from Members II and III of the Longmaxi Formation in the shale roof, and the Lower Triassic Jialingjiang Formation in the regional cap rocks as well as the Linxiang and Baota Formations in the shale floor (Guo et al., 2017; Jin et al., 2018). Part of the samples with different TOC contents was used for FIB-SEM (focused ion beam–scanning electron microscopy) experiments with a Helios NanoLab 660 apparatus and FIB-HIM (focused ion beam–helium ion microscopy) experiments with a Zeiss Orion NanoFab apparatus. Samples were collected from the stratum parallel to the 2,396 m organic-rich shales of the Longmaxi Formation Member I in Jiaoye No. well with a size of 2.5 cm (diameter) × 5 cm (length) each. They were used to measure core permeability with N_2, CH_4, and CO_2, under the pressure of 5 MPa.

RESULTS AND DISCUSSION

Sealing of Shale Roof and Floor

As shown in **Figure 4**, JiaoYe1 well is a typical shale gas well in the Jiaoshiba Block of the eastern Sichuan region. The lithology of Member I of the Wufeng–Longmaxi Formation (referred to as Wu-Long Formation Member I hereinafter) is mainly a sedimentary shale under the deep-water shelter, that is, pure shales. The shale roof belongs to Member II of the Longmaxi Formation (referred to as Long Member II hereinafter) and Member III of the Longmaxi Formation (referred to as Long Member III hereinafter). The lithology of Long Member II is gray-dark gray siltstone, while that of Long Member III is gray-dark gray mudstone. The regional cap rocks are the gypsum rocks of the Lower Triassic Jialingjiang Formation, which is universally developed in the Sichuan Basins. The shale floor is the dark gray mud-

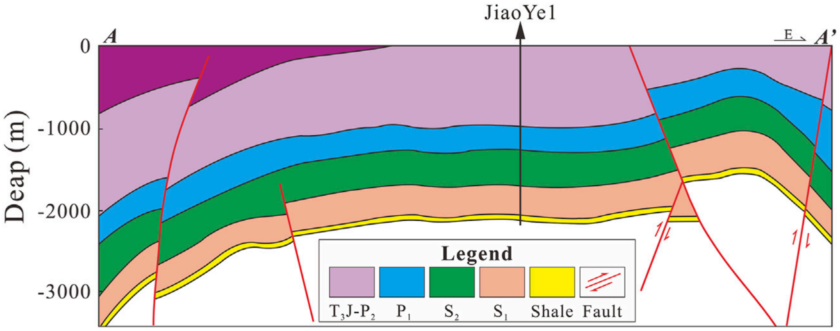

FIGURE 3 | Pass the JiaoYe1 well strata section in the Jiaoshiba block. Modified from references (Nie et al., 2020).

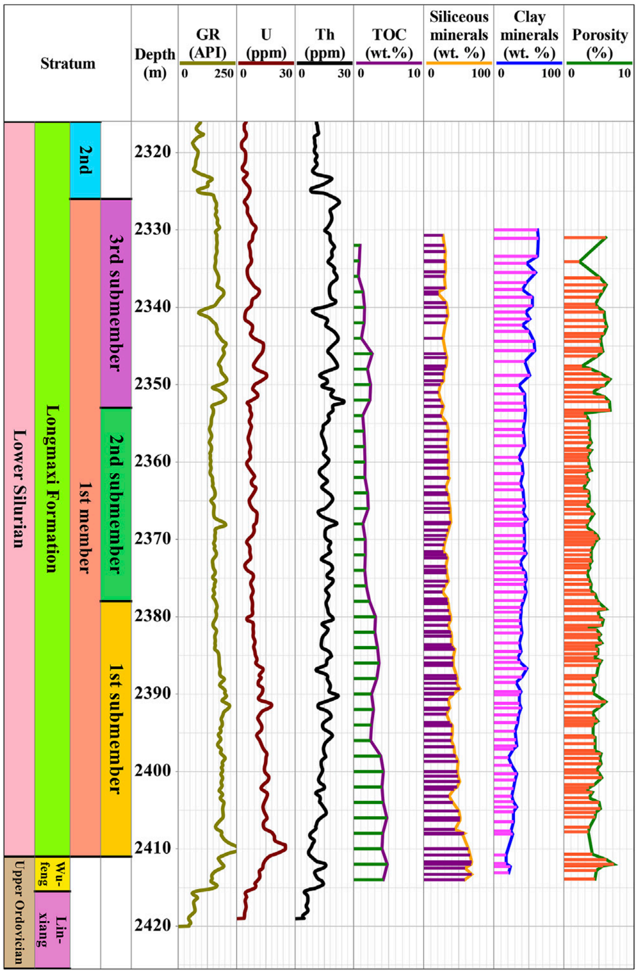

FIGURE 4 | Divisions of sub-members of JiaoYe1 well Longmaxi Formation Member I and analysis results of their mineral composition, TOC content, and porosity (refer to **Figure 1** for the well location).

bearing nodular limestone of the upper Ordovician Linxiang Formation and the gray limestone of the Middle Ordovician Baota Formation (Wang et al., 2019; Wu et al., 2019; He et al., 2020).

As shown in **Table 1**, the Wu-Long Formation Member I shale of JiaoYe1 well and its roof and floor are successive sedimentations, with the latter featuring stable distribution, tight lithology, high thickness, high breakthrough pressure, and excellent sealing (Dong et al., 2018). The roof of the Wu-Long formation Member I shale is the gray-dark gray siltstone of Long Member II (10 ~ 35 mm thick in the Jiaoshiba region) and the gray-dark gray mudstone of Long Member III (100 ~ 140 mm thick in the Jiaoshiba region), and the average porosity, permeability, and breakthrough pressure of the two members mentioned above are respectively 2.4%, 0.0016 × $10^{-3}\mu m^2$, and 69.8 ~ 71.2 MPa (Borjigin et al., 2017; Dong et al., 2018). Meanwhile, the floor of the Wu-Long Formation Member I shale is the nodular limestone of the Lingxiang and Baota Formations (30 ~ 40 mm thick in the Jiaoshiba region with average porosity of 1.58%), featuring a permeability of 0.0017 × $10^{-3}\mu m^2$ and a breakthrough pressure of 64.5 ~ 70.4 MPa (Nie et al., 2019; Jin et al., 2020). The structural evolution simulation indicated that the gypsum rock on the top of JiaoYe1 well located at the higher part of the structure was destroyed (5 ~ 0 Ma before the present which is relatively late), while the section of the well located at the lower part of the structure still preserves the gypsum rock stratum that is 70 ~ 250 mm thick with porosity generally smaller than 2.00%, and breakthrough pressure generally over 60 MPa as well as excellent sealing performance. As the gypsum rock located in the deep part is highly plastic, its sealing performance for natural gas is further enhanced at the same time (Wu et al., 2018; Liu et al., 2019).

Based on the discussions above, the regional cap rocks (gypsum rock of the Lower Triassic Jialingjiang Formation), the roof (Long Member II gray-dark gray siltstone/dark gray lime shale and Long Member III gray-dark gray mudstone), and the floor (dark gray mud-bearing nodular limestone of the Linxiang Formation and gray limestone of the Baota Formation) provide sealing for the shale due to the difference in their physical properties.

Self-Sealing of Shales

The Difference in TOC Content, Mineral Composition, Pore Type, and Pore Structure

Table 2 shows the analyses on TOC content and mineral compositions, according to which the contents of brittle minerals and TOC decreased gradually from Sub-member I of the Wu-Long Formation Member I in the lower part (the average value is 65.9 and 3.58%, respectively) to Sub-member III of the Long Member I in the upper part (the average values are 46.8 and 1.72%, respectively). In contrast, the contents of clay minerals increased instead (from 34.1 to 53.2%). The differences in mineral compositions and TOC content between all Wu-Long Formation Member I sub-members indicated different pore types. The shale pores can be classified as organic-matter pores, brittle mineral pores, and clay mineral pores based on their existing state.

Guo et al. (2016) quantitatively specified the contribution of every type of pores to the shale porosity with the help of physical models of porosity rocks. Due to the difference in mineral compositions and TOC content of shales, every sub-member contains different pore types (**Table 2**) (Guo et al., 2016; Guo et al., 2017; Guo et al., 2020). The percentage of clay mineral pores in the total porosity gradually increased from Sub-member I of the Wu-Long Formation Member I in the lower part to Sub-member III of the Long Member I in the upper part, while that of organic-matter pores in the total porosity gradually decreased at the same time (Guo et al., 2016; Guo et al., 2017; Guo et al., 2020).

In order to analyze the porosity structure characteristics of shales in different members, this article performed observation of the organic-matter pores in Sub-member I of JiaoYe1 well Long Member I and the clay mineral pores of Sub-member III of JiaoYe1 well Long Member I by FIB-SEM experiment. Sub-

TABLE 1 | Lithology, porosity, thickness, and breakthrough pressure of JiaoYe1 well shale and its roof and floor, and regional cap rocks. Some data in the table are from references (Guo et al., 2016; Guo et al., 2017; Guo et al., 2020).

Type	Description	Stratum	Lithology	Average porosity (%)	Thickness (m)	Breakthrough pressure (MPa)
Combination	Regional cap rocks	Lower Triassic Jialingjiang Formation	Gypsum rock	< 2.00	70	> 60
	Shale roof	Member III of Lower Silurian Longmaxi Formation	Gray-dark gray mudstone	2.40	128	69.8 ~ 71.2
		Member II of Lower Silurian Longmaxi Formation	Gray-dark gray siltstone		34	
	Shale	Member I of Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation	Shale	4.77	89.5	43.87 (gas reservoir pressure)
	Shale floor	Upper Ordovician Linxiang Formation	Dark gray mud-bearing nodular limestone	1.58	> 30	64.5 ~ 70.4
		Middle Ordovician Baota Formation	Gray limestone			

TABLE 2 | Mineral composition, TOC content, and percentage of various pore types of shales from Member I of the Wufeng Formation–Longmaxi Formation. Some data in the table are from references (Guo et al., 2016; Guo et al., 2017; Guo et al., 2020).

Stratum	Brittle mineral content (%)	Clay mineral content (%)	TOC content (%)	Total porosity (%)	Percentage of every type of pore (%)		
					Brittle mineral pore	Clay mineral pore	Organic-matter pore
Sub-member III of Long Member I	37.2 ~ 63.3 /46.8	36.7 ~ 62.8 /53.2	0.6 ~ 2.93 /1.72	3.44 ~ 7.13 /5.36	3 ~ 6.6 /5	53 ~ 88 /71	8.7 ~ 41 /24
Sub-member II of Long Member I	43.7 ~ 66.6 /58.5	33.4 ~ 46.3 /41.5	1.39 ~ 2.46 /1.81	2.49 ~ 4.72 /3.72	4.9 ~ 8 /6	57 ~ 70 /64	24 ~ 37 /30
Sub-member I of Wu-Long Formation Member I	53 ~ 83.4 /65.9	16.6 ~ 47 /34.1	1.06 ~ 5.28 /3.58	2.83 ~ 5.89 /4.60	4.4 ~ 10 /6	17 ~ 77 /43	18 ~ 76 /51

member I of Long Member I was found to contain a large number of organic-matter pores with big diameters (micropores, mesopores, and macropores <200 nm), of which most are elliptical ones (A of **Figure 5**). Meanwhile, Sub-member III of Long Member I was found to contain clay mineral pores fewer than organic-matter pores in quantity, but bigger in diameter (macropores of 200 nm ~ 1 μm), and most of the pores were in irregular shapes.

The internal three-dimensional structure of the pores was further observed by FIB-HIM experiments. The FIB-HIM experiment was performed on samples at a depth close to that of the FIB-SEM sample, and it was found through observation that the organic-matter pores of Sub-member I of JiaoYe1 well Long Member I contain big pores with small ones inside them. With this type of "small pores inside big pores" characteristic, not only organic-matter reservoir space and specific surface area are enlarged but also the seepage channels are provided for shale gas, thus enhancing organic-matter connectivity (B of **Figure 5**) (Ji et al., 2014; Ji et al., 2015; Wang et al., 2016a; Wang et al., 2016b; Ji et al., 2016; Tang et al., 2017). The pores developed in the clay mineral pores of Sub-member III of Long Member I are more separated and fewer in quantity with poor reservoir capacity and connectivity (D of **Figure 5**).

It can be concluded from the previous discussion that the change in TOC content and mineral compositions between Sub-members II and III of Long Member I and Sub-member I of the Wu-Long Formation Member I caused the variation in porosity types and structures and the difference in connectivity, which causes Sub-members II and III of Long Member I to form sealing for Sub-member I of Long Member I.

Adsorption Effect

Samples with a dimension of 2.5 cm (diameter) × 5 cm (length) were collected from the organic-rich shales of JiaoYe1 well Long Member I at 2,396 mm along the parallel direction with the strata. These samples were measured for the flow velocity and gas permeability of the cores with N_2, $CH_{4,}$ and CO_2, respectively, under the pressure of 5 MPa (refer to **Table 3** and **Figure 6** for the measurement results).

The gas molecule adsorption by shales created the gas slippage effect (Klinkenberg effect) in the seepage channel (Zhang et al., 2019c; Zhang et al., 2020b; Liu et al., 2021a; Liu et al., 2021b); that is, the flow velocity of gas molecules in the channel center is higher than that close to the channel wall, and the closer gas molecules to the channel wall, the slower their flow velocity (Huang et al., 2020; Zhang et al., 2019d; Zhang et al., 2020c; Wang et al., 2020; Zuo et al., 2019; Xia et al., 2020; Gao, 2021; Yu et al., 2022). The gas adsorption capacity of shales can be ranked as $CO_2 > CH_4 > N_2$, while the rank is reversed regarding the flow velocity and permeability of those gases in shales as $CO_2 < CH_4 < N_2$ (**Figure 7**). It

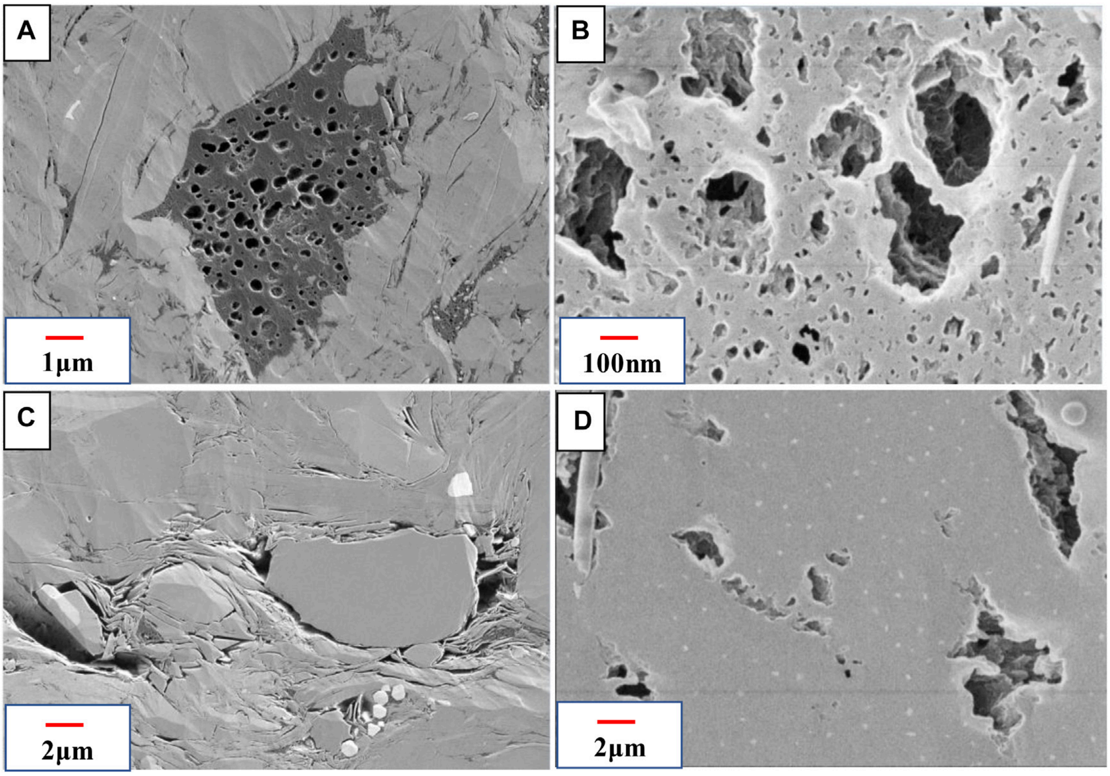

FIGURE 5 | FIB-SEM and FIB-HIM Images of Shales Respectively from Sub-members I and III of JiaoYe1 Well Wu-Long Formation. Organic-matter Pores of Sub-member I of JiaoYe1 Well Wu-Long Formation Member I, 2405 m: **(A)** FIB-SEM Image, **(B)** FIB-HIM Image. Clay Mineral Pores of Sub-member III of JiaoYe1 Well Wu-Long Formation Member I, 2342 m: **(C)** FIB-SEM Image, **(D)** FIB-HIM Image.

TABLE 3 | Flow velocity and gas permeability tests on shales with N_2, CH_4, and CO_2.

Type of gas	Pressure (MPa)	Flow velocity (ml/s)	Permeability (md)
N_2	5	1.7375	0.019256
CH_4	5	1.2285	0.012783
CO_2	5	1.0083	0.012173

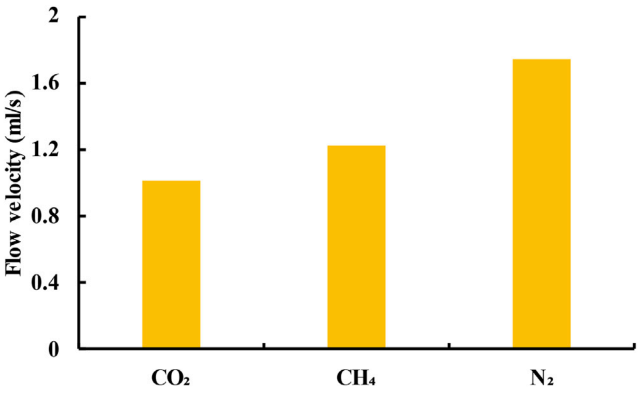

FIGURE 6 | Comparison of three different gas flow rates. The flow velocity of gases in shales is $CO_2 < CH_4 < N_2$.

indicates that the gas slippage effect is more obvious, the gas molecule flow velocity is slower, and the permeability is more decreased when the gas adsorption capacity of shales is higher (Wang et al., 2017; Zhang et al., 2018b). In organic-rich shales, the higher the quantity of adsorbed methane, the more evident the gas slippage effect; the higher the TOC content, the thicker the organic-rich shales, resulting in lower shale permeability and providing better conditions for shale gas preservation.

It can be concluded from the previous discussion that higher TOC content and adsorption capacity of shales lead to narrower effective pore throat and lower permeability, thus resulting in better self-sealing performance. Meanwhile, the self-sealing of shales can also be enhanced when the thickness of organic-rich shales is increased, and thereby, their adsorption quantity rises.

Formation Mechanism

Based on the above discussion, this article summarizes the Forming model of sealing of roof and floor and self-sealing of shale of Wufeng Formation–Longmaxi Formation as shown below (**Figure 8**). The regional cap, the roof, and floor strata of the shale (**Figures 8A,D**) have much lower porosities and higher breakthrough pressure than the shale (**Figures 8B,C**), and they are closed to the shale due to the difference

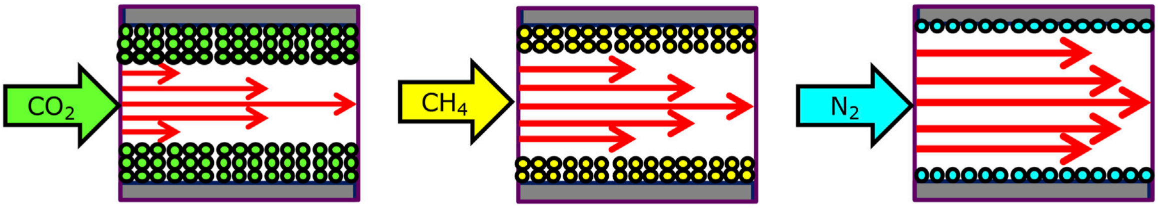

FIGURE 7 | Schematic diagram of the effect of adsorption on gas flow velocity and permeability in shale.

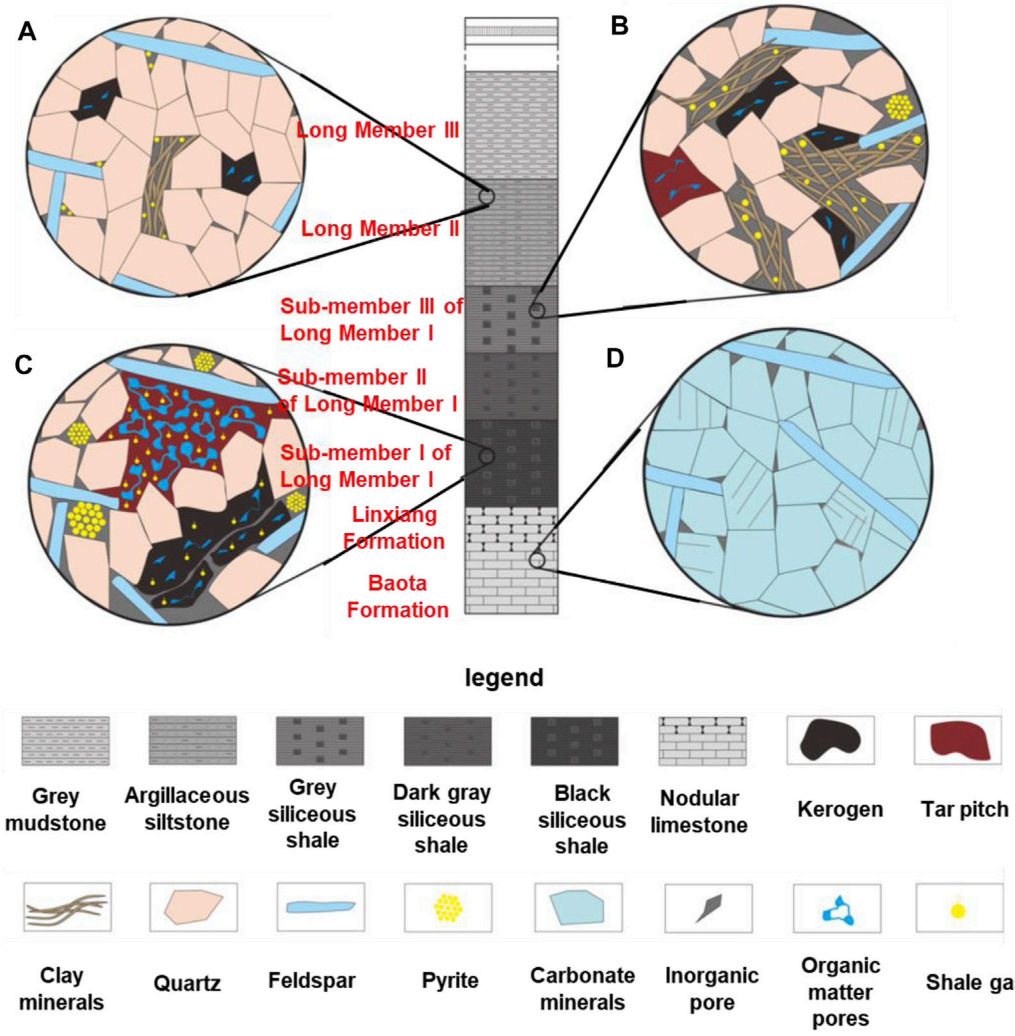

FIGURE 8 | Forming model of the sealing of roof and floor and self-sealing of shale of Wufeng–Longmaxi Formation.

in physical properties. For the shale, the second and third subsections of section I of the Longmaxi Formation mainly develop clay mineral pores, which are mainly of macropores with poor connectivity (**Figure 8B**); the first subsection of section I of the Wufeng Formation–Longmaxi Formation mainly develops organic matter pores, which are primarily micro and medium pores with good connectivity (**Figure 8C**). The connectivity difference leads to the second and third subsections forming sealing capacity to the first subsections. The adsorption of methane by the organic-rich shale in the first subsection of the Wufeng Formation–Longmaxi Formation section I (**Figure 8C**) will inhibit the large-scale transport of shale gas, thus causing the organic-rich shale to form its self-sealing capacity.

CONCLUSION

In this article, Member I of the Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation from the Yangtze region was used as the case for the study, and the marine shales from Member I of the Wufeng Formation–Longmaxi Formation of the Jiaoshiba Block in the Sichuan Basins were selected for detailed analyses. The analyses of TOC content, mineral compositions, and porosity, as well as the experiments of FIB-SEM, FIB-HIM, and gas permeability, were then conducted on the core samples from the shale gas exploration well for the study on the formation mechanism of shale roof and floor sealing and shale self-sealing, and it was concluded as follows:

1) Regarding shale roof and floor sealing: The regional cap rocks (gypsum rocks of the Lower Triassic Jialingjiang Formation), the roof (gray-dark gray siltstone/dark gray lime shales of Member II of the Longmaxi Formation, and gray-dark gray mudstone of Member III of the Longmaxi Formation), and the floor (dark gray mud-bearing nodular limestone of the Linxiang Formation and gray limestone of the Baota Formation) together had sealing effects on the shales of Member I of the Wufeng Formation–Longmaxi Formation due to the differences in physical properties.
2) For shale self-sealing: Sub-members II and III of Member I of the Longmaxi Formation are different from Sub-member I of Member I of the Wufeng–Longmaxi Formation in pore types: clay pores dominated by macropores with poor connectivity were mainly developed in Sub-members II and III, while organic-matter pores dominated by micropores and mesopores with excellent connectivity were developed in Sub-member I of Member I of the Wufeng–Longmaxi Formation. Thanks to the difference in connectivity, Sub-members II and III together formed sealing for Sub-member I.
3) The methane adsorption effect of shales decreased the permeability and inhibited the massive migration of shale gas. As a result of the adsorption effect, the organic-rich shales from Sub-member I of Member I of the Wufeng–Longmaxi Formation can seal themselves.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

PW, YL, XDY, ZC, ZL, XJY, and PL contributed to conception and design of the study. FH, LT, and YY organized the database. YZ performed the statistical analysis. ZZ wrote the first draft of the manuscript. KZ, YS, ZJ, and SJ wrote sections of the manuscript. All authors contributed to manuscript revision, and read and approved the submitted version.

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