Hindawi
Geofluids
Volume 2022, Article ID 5942370, 21 pages
https://doi.org/10.1155/2022/5942370

Research Article

Diagenesis and Its Impact on the Reservoir Quality of Continental Shales: A Case Study of the Lower Jurassic Da'anzhai Member of the Ziliujing Formation in the Sichuan Basin, China

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Received 14 July 2021; Accepted 24 January 2022; Published 22 February 2022

Academic Editor: Mehdi Ostadhassan

The Jurassic continental shale oil (gas) is a favorable unconventional resource in the Sichuan Basin of China. In this paper, analysis methods such as core and outcrops observation, thin section identification, scanning electron microscopy (SEM), and X-ray diffraction (XRD) are used to describe the characteristics of lacustrine fine-grained rock reservoir in Da'anzhai Member of the Ziliujing Formation in Sichuan Basin, and it discussed the influence and control of lacustrine fine-grained rock diagenesis on the quality of the reservoir, in order to determine the shale reservoir control factors. The results show that there are three types of rocks in the Da'anzhai Member, which are mudstone, siltstone, and limestone, and the rock combination of shell shale intercalated with shell limestone is developed in the Da 2 submember. Fine-grained sedimentary rocks in this section have undergone compaction, cementation, dissolution, metasomatism, transformation of clay minerals, and hydrocarbon generation of organic matter, which are currently in the middle diagenetic stage A or B substage. Compaction and cementation are the main factors that control the physical use of shale and limestone, and strong cementation is the main reason for the tightness of limestone reservoirs in the Da'anzhai Member in the northern and eastern parts of Sichuan Basin. The difference between dissolution and cementation is the main control factor for the formation of limestone or argillaceous limestone reservoirs in the same section in central Sichuan Basin. The organic-rich shale and shell shale of the Yuanba and Fuling area are the most favorable reservoirs of the Ziliujing Formation in this region. The shell limestone that experienced favorable dissolution in the Da'anzhai Member in the central of the Sichuan Basin has become a limestone reservoir. Discussing the impact of continental fine-grained rock diagenesis on the reservoir can better explore and develop similar intervals, enrich unconventional shale oil and gas accumulation and storage theories, and provide basic theoretical support for finding favorable unconventional shale oil and gas reservoirs.

1. Introduction

At present, unconventional tight oil and shale oil and gas are becoming the new growth spots of oil and gas exploration [1]. Continental shale oil and gas are the most promising types of source rock in China [2]. Generally, unconventional oil and gas reservoirs are mainly fine-grained sedimentary rock reservoirs. Limited by ultra-micro experimental conditions, the deposition and diagenesis of fine-grained materials are relatively weak areas in the field of oil and gas geology [3, 4]. The Jurassic lacustrine fine-grained sedimentary rocks in the Sichuan Basin have shown large oil and gas exploration potential [5–11], so the research on the rocks is of great significance.

Jurassic strata are large-scale coal-bearing strata in central and western China; however, it is a large lacustrine sediment of shallow inland lake-semi-deep lake facies in the Sichuan Basin [2, 12–14]. In the Early-Middle Jurassic, several sets of black organic-rich shale in the Ziliujing Formation are widely distributed in the central, northern, and eastern Sichuan areas (Figure 1). The exploration of this continental fine-grained rock sequence has mainly focused on tight reservoir such as Da'anzhai Member and Shaximiao Formation in the past [15–17], and 541 industrial oil and gas

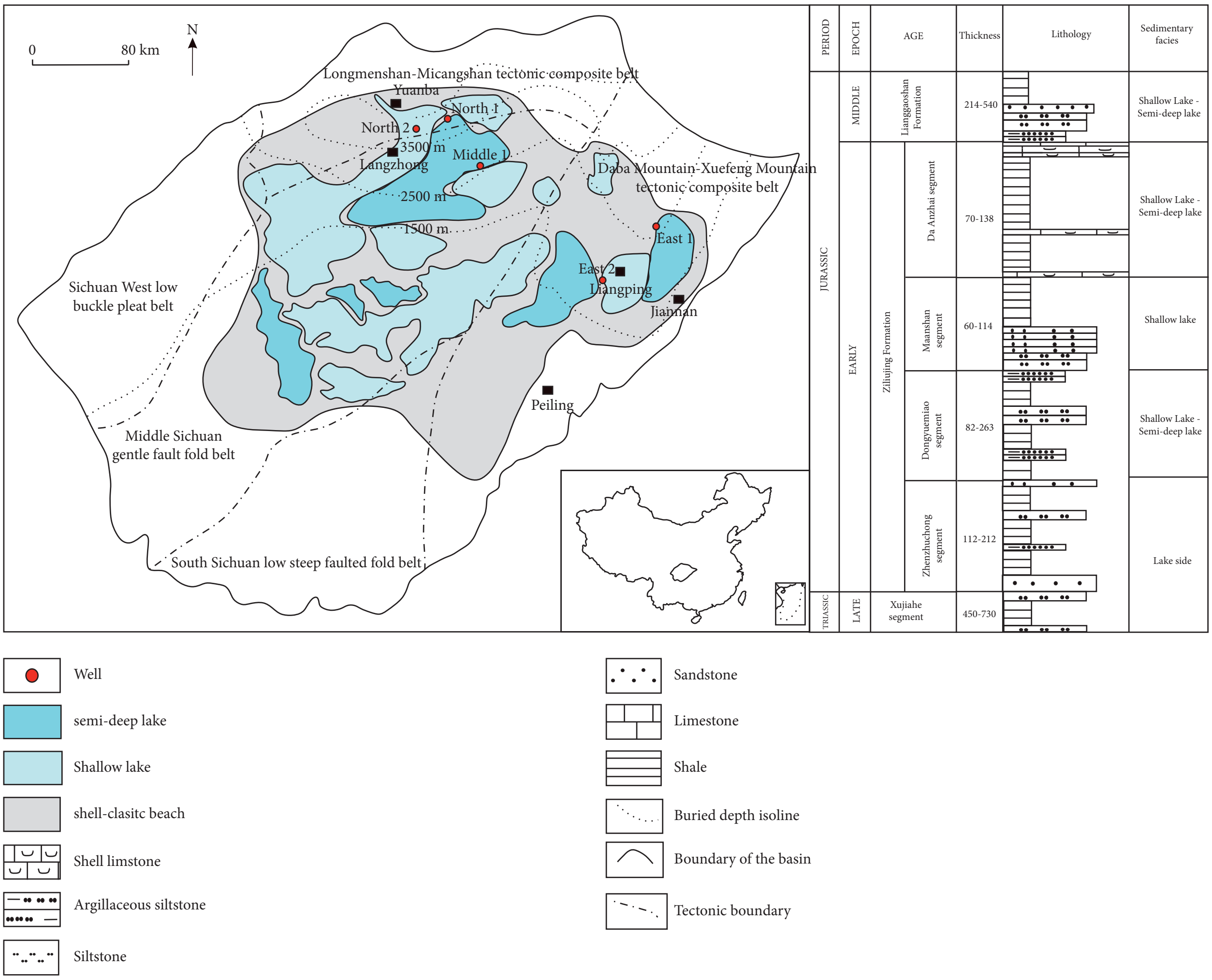


Figure 1: The division of tectonic units in the Sichuan Basin and the shale deposition and distribution characteristics of the Da'anzhai Member of Ziliujing Formation in Jurassic.

wells have been obtained in the shell limestone of the Da'anzhai Member in central Sichuan Basin [8]. But the shell limestone reservoir is tight, and the exploration is poor. The recent research found that the shale in the Da'anzhai Member has a wide area, large thickness, good physical properties, and common oil and gas displays with great potential to exploration; high-yield shale gas was discovered in the Da 2 submember of Da'anzhai Member [2, 10, 18, 19]. In the Da'anzhai Member of North Sichuan area (Yuanba area), 5 wells have been drilled, and medium-high-yield industrial gas flow was found [20], confirming that the lacustrine fine-grained sedimentary rocks have the potential for production of unconventional oil and gas [2, 15, 17, 21]. It has gone through the process of recognizing that this series of calcareous limestone and limestone is reservoirs, and shale is source rock, to limestone is not reservoir and shale is source reservoir. In recent years, a series of research has been conducted on the lithology, geochemical characteristics, physical properties, oil and gas properties, and exploration potential of this terrestrial sequence [5–11, 15–24]. Compared with marine shale, lacustrine fine-grained sedimentary rock is more affected by the sediment environment, with faster phase transitions, more complex lithology and diagenesis, stronger heterogeneity, and lower organic matter content and maturity [20, 21, 24]. The current exploration results of the Da'anzhai Member of the Jurassic show that the central Sichuan area mainly produces continental shale oil, while the eastern and northern areas mainly produce continental shale gas. Why do siltstone and limestone appear in the local deep layers of the Jurassic in the northern and eastern parts of the Sichuan Basin and do not accumulate oil and gas; instead, fine-grained sedimentary rocks such as relatively tight shale and mixed rocks become high-yield oil and gas producing layers, while limestone in the middle section found rich oil and gas in the rock again? Why is shell shale a favorable reservoir? Therefore, it is essential to investigate the control factors of fine-grained sedimentary rocks for reservoir quality. This article aims to clarify the diagenesis characteristics, evolution, and control of diagenesis on the reservoir of the continental fine-grained sedimentary rock reservoir in the central, northern, and eastern regions of the Sichuan Basin, especially the Da'anzhai Member in the Yuanba (the northern Sichuan Basin) and Fuling (the northern Sichuan Basin) area, in order to explore the store mechanism of fine-grained sedimentary rock reservoirs and the basis of heterogeneity, to provide theoretical support for finding favorable continental tight oil and gas reservoirs in the Da'anzhai Member in other areas.

2. Regional Geological Setting

The Sichuan basin has experienced multiple stages of evolution of the early Paleozoic craton depression, the late Paleozoic craton rift, and the Mesozoic and Cenozoic foreland depression [25]. The Late Permian-Late Triassic Indosinian tectonic movement led to the withdrawal of the basin's seawater and the overall uplift, and the gradual transformation from marine sediment to continental sediment. The sediment period of the Da'anzhai Member of the Ziliujing Formation was the period with the weakest extension and the most stable orogenic activity. The depression rate of the whole basin was much greater than the accumulation rate of terrigenous clastics, which led to the formation of the largest lake basin in the early Jurassic [26]. From bottom to top, the Jurassic in the Sichuan Basin is the Lower Jurassic Ziliujing Formation, Middle Jurassic Qianfoya Formation (Liangshan Formation) and Shaximiao Formation, Upper Jurassic Suining Formation, and Penglaizhen Formation, of which Ziliujing Formation is further divided into four lithological Members: Zhenzhuchong Member, Dongyuemiao Member, Ma'anshan Member, and Da'anzhai Member (Figure 1). Controlled by the tectonic subsidence and lacustrine transgression of different grades of basins, three sets of shallow lake-semi-deep lake facies organic-rich mud shales are developed in the Dongyuemiao Member, Da'anzhai Member, and Qianfoya Formation (Liangshan Formation) [13, 27]. All of these layers have well fracturing tests to obtain shale oil and shale gas, showing great prospects for shale gas exploration and development. The Da'anzhai Member is the heyday of the lake basin, which has experienced a complete sedimentary cycle including expansion-peak-contraction, forming a sequence of black shale development with the greatest potential for terrestrial hydrocarbon generation in the Da'anzhai Member [15, 28, 29]. At this time, the basement of the lake basin is asymmetrical, the south slope is gentle, and the north is steep. The Da'anzhai Member is divided into the Da 1 submember, Da 2 submember, and Da 3 submember from top to bottom. Lacustrine transgression began in the Da 3 period (early) and reached the largest lacustrine transgression in the Early Jurassic [13]; it is a shallow carbonate lake shell-clastic beach and beach-interacting mud sediment. The rocks are mainly dark gray-brown gray shell, crystalline limestone, siltstone, mudstone, and shale; by the Da 2 period (middle period), the lake has reached the widest lake flooding period and is lakeside storm beach and mud from intermediate depth lake sediment microfacies, and lithologies are thick layer of dark gray-grey brown mud shale intercalated with thin layer of she. Sometimes, the shale and limestone are interbedded or striped, and mud-in-lime and mud-in-silt are common; in Da 1 period (late period), the basin began to lake regression and was mainly carbonate shallow lake shell beach sediment. The lithology was composed of thick-layered dark-gray, gray-black clastic limestone intercalated with thin mudstone.

The Da'anzhai Member is widely distributed in central, northern, and eastern Sichuan Basin (Figure 1). This section of the central Sichuan Basin is relatively buried shallow, and shell-beached limestone is the main oil and gas producing layer. It generally has poor reservoir physical properties and low resource abundance, the single-well production is low, the recovery rate is low, and the local production is high. The limestone interbed is medium-thin carbon-lean limestone or lime-bearing mudstone and shale. It is tight, and there are no reports of shale and mudstone oil and gas layers. The Da 2 submember of the Da'anzhai Member in the northern and eastern Sichuan Basin is the 'sweet spot' of Jurassic shale oil and gas, shown as large sediment thickness, wide distribution area, moderate burial depth, moderately high TOC content, better organic matter type, moderate thermal evolution, and high content of brittle minerals. The thickness of shale is generally 20~80 m, black organic-rich shale is mainly distributed in the central and northern part of the basin, the thickness is 20~50 m, and the area is about $2 \times 10^4\,km^2$. The sediment thickness of the Da'anzhai Member in the YuanBa area is 70~138 m, generally about 90 m. The center of the lake basin is basically located in the Yilong area. From the center to the periphery, it is distributed in intermediate depth lake area, Lake Slope area, shallow lake area, lakeside area, and river area. The sediment subfacies of the Da'anzhai Member include lakeshores, shallow lakes, and intermediate depth lakes, gradually transitioning from the center of the lake basin to shallow lakes and lakeshores [29].

3. Methods and Experimental Data

In this paper, 106 samples of lacustrine fine-grained rock from the Da'anzhai Member of the Jurassic Ziliujing Formation in the northern area, eastern area, and central area in Sichuan Basin were collected, including 45 core samples from three wells in the northern area, 34 core samples from three wells in the eastern area, and 27 samples of central Sichuan Basin. Reservoir geology and geochemistry experiments were carried out in the Sedimentary Reservoir Laboratory, Petroleum Geology Laboratory, and State Key Laboratory of Petroleum Resource and Prospecting in China University of Petroleum (Beijing), including thin section examination, X-ray diffraction analysis (XRD), scanning electron microscopy (SEM), X-ray energy dispersive spectrometer (EDS), and pulse decay permeability experiment analysis that were carried out. Based on GB/T 29172–2012 and GB/T 34533–2017, the experiment achieved high-precision characterization of the permeability of shale samples. Test and experimental analysis in Da'anzhai Member were completed, such as mineral composition and structure, relative content analysis of whole-rock elements and clay minerals, organic carbon content, organic matter types and maturity, porosity and permeability, micro-pore size, and distribution.

Various methods were used to determine the composition of the lithological minerals (Table 1). Some samples have high porosity and low permeability, because these samples have some isolated macropores, and the porosity is high. At the same time, the connectivity is poor, so the permeability is not high. The composition is different in different regions. The Da'anzhai Member of the basin is dominated by shale and limestone, and the limestone is dominated by interbeds. The cumulative thickness is 15 m~28 m, which accounts for the proportion 24%~31%, only in Jiannan area dominated by sandstone interbeds. The Liangping outcrops reveal a complete stratum from the upper part of Da 1 submember to the top of the Da 3 submember, showing different combinations of shale and limestone (Figure 2). Rocks from multiple wells also show the development of different lithology and lithology combinations, fractures, and special bedding fractures in the Da'anzhai Member (Figure 3). XRD analysis shows the mineral composition of different wells (Figure 4).

The helium method was used to measure porosity and permeability (Table 2, Figure 5). The porosity of the fine-grained sedimentary rock of the Da'anzhai Member in the northern area ranges from 1.11% to 8.42%, with an average porosity of 5.14%, and most of data are above 2%; the permeability ranges from 0.0032~50.3038 mD, with an average permeability of 2.2736 mD. The porosity of the fine-grained sedimentary rock in eastern area is between 0.36% and 7.98%, the average porosity is 1.23%, the permeability ranges from 0.05 to 2.6132 mD, and the average permeability is 0.7941 mD. The minimum porosity of the fine-grained sedimentary rock in the central Sichuan Basin is only 0.19%, the maximum is 5.94%, and the average value is only 1.16%. Among them, the most distributed porosity is 0.5~1%, and the porosity above 80% is 0.5~1.5%, and the average permeability is only 0.0203 mD, the most distributed in 0.001~0.1 mD, of which 80% is less than 0.1 mD, belongs to the ultralow porosity and ultralow permeability reservoir, and is a typical unconventional tight limestone oil reservoir.

4. Results

4.1. Rock Components, Rock Types, and Combinations

4.1.1. Rock Components. The clay mineral content of the Jurassic Ziliujing Formation in the Sichuan Basin ranges from 19.5% to 70.6%, with an average of 48.6%; the quartz + feldspar content ranges from 14.2% to 79.4%, with an average of 38.2%; the content of carbonate mineral ranges from 0 to 48.8%, and the average is 11.5% [18, 24]. In the Da'anzhai Member, the clay mineral content ranges from 21.5% to 68.3%, with an average of 48.3%; the quartz + feldspar content ranges from 17.1% to 60.3%, with an average value of 35.7%; the carbonate mineral content ranges from 0 to 48.8%, and the average is 12.6%. The two mineral combinations (quartz + feldspar and carbonate minerals) are important brittle minerals in shale, and their high content is conducive to reservoir fracturing and inducing new fractures [30].

In the northern Sichuan Basin, the quartz content of the Da 2 submember ranges from 15.30% to 66.20%, with an average of 36.85%, and feldspars are very few. The total amount of clay minerals is 10~83%, with an average of 37.95%, mostly less than 50%. Carbonate minerals are mainly calcite; the content of calcite ranges from 0% to 90%, with an average content of 20.87%. It has a high content in limestone and is produced as a biological shell. The fine-grained sedimentary rocks in this section mainly consist of ordered illite-smectite clays, illite, and chlorite. The relative content of different clay minerals is 15~56% in illite-smectite clays, with an average of 36.90%, and illite is between 16 and 35%. The average is 21.87%, kaolinite is 9~23%, the average is 15.93%, chlorite is between 15 and 31%, and the average is 22.60%, and the smectite content in the Illite-Smectite Clays is 12~30%, mostly less than 15%, which is an orderly mixed layer.

Shale minerals in the Ziliujing Formation of the Lower Jurassic in the eastern Sichuan Basin are composed of quartz and feldspar, clay minerals, carbonate minerals (mainly calcite), and a small amount of pyrite, siderite, and gypsum. Clay minerals are mainly illite and illite-smectite clays [18]. The quartz content in the Da'anzhai member of the eastern area is between 25.9% and 49.2%, with an average content of 31.06%. The feldspar is mainly plagioclase, and the content is less than 5%. The content of clay minerals is 40~67.1% with an average of 53.42%. The content of carbonate minerals is between 1.6 and 18.2%, mainly calcite, with an average of 11.47%. The lithology is black, dark-gray mudstone and shale. The quartz content of the second submember of the Da'anzhai Member in eastern area is between 21.5 and 40.3%, with an average content of 30.15%. The feldspar is dominated by plagioclase, and the content is less than 5%. The content of clay minerals is 42.5~68.3%, with an average of 54.64%. The content of carbonate minerals is between 0 and 30.6%, mainly calcite, with an average of 11.95%. The lithology includes gray or gray-black shale, gray-black shell shale, and gray-black lime shale.

The thickness of the black shale in the second submember of the Da'anzhai Member is 20~80 m, the average TOC is greater than 2%, the kerogen is of type II1 to II2, with a Ro of 1.1%~1.4%, located in the light oil-condensate oil and gas window, the porosity of shale is 2%~6%, with shale fractures, and the content of brittle minerals such as siliceous and limestone is generally above 50%. The underground pressure coefficient of shale in the Da 2 submember of the Da'anzhai member in the Sichuan Basin is 1.2~1.8, and the amount of hydrocarbons retained is 89~207 mg/g·TOC, the oil is lighter, with shallow buried depth, and it has geological engineering conditions similar to those of North American shale oil and gas [2].

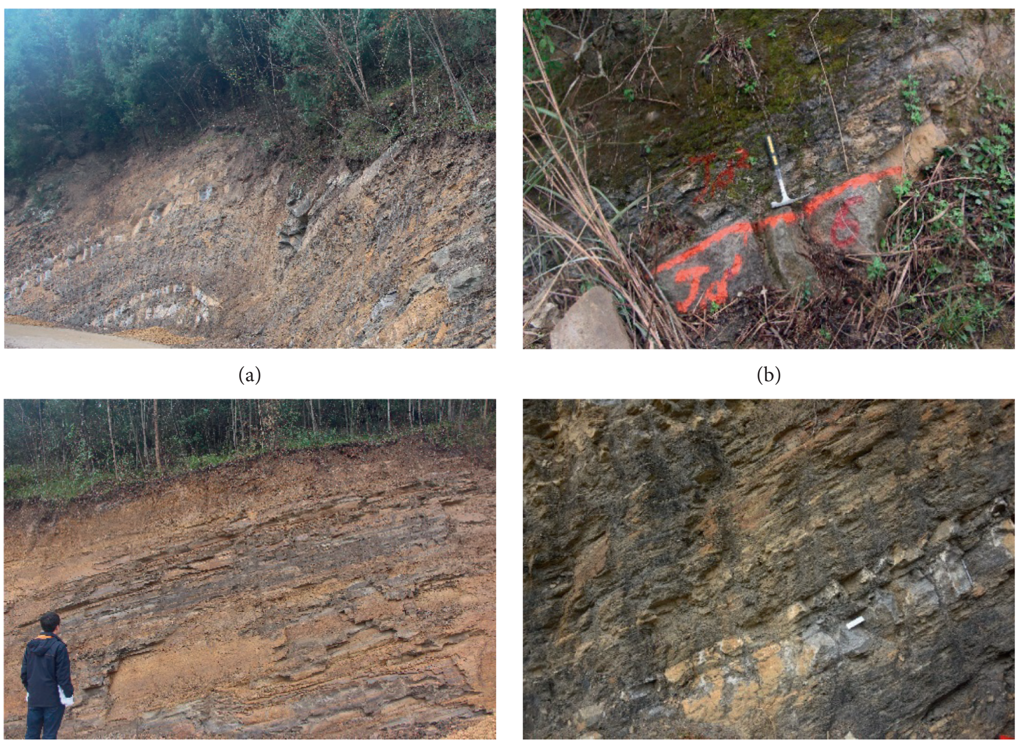
4.1.2. Rock Types and Combinations. Fine-grained sedimentary rock is a rock composed of fine-grained sediments with a particle size of less than 62 μm, also called mudstone. The mineral components are clay minerals, felsic minerals, carbonate minerals, and organic matter [24, 31], which are used as the basis for classification. According to the TOC

Table 1: The XRD analysis of mineral components and corresponding porosity-permeability data tables of fine-grained rocks in the Da'anzhai Member in different areas of the Sichuan Basin.

Well	Depth (m)	Lithology	Brittle mineral content (%)				Total clay (%)	Clay mineral content (%)				Interlayer ratio (%)	Porosity (%)	Permeability ($10^{-3}\,\mu m^2$)
			Quartz	Feldspar	Calcite	Dolomite		I/S	It	Kao	C			
East-1	2599.25	Dark gray mudstone	26.9	3.7	0.9	1.4	63.4	69	13	6	12	25	1.12	1.46
	2600.53	Dark gray mudstone	31.2	3.2	1.6	—	64.0	57	21	8	14	25	1.25	0.38
	2607.90	Dark gray mudstone	25.9	2.5	16.8	1.4	53.4	45	26	10	19	25	0.85	0.33
	2610.10	Dark gray mudstone	33.1	2.8	13.2	2.3	48.6	50	19	10	21	25	0.65	0.20
	2611.14	Dark gray mudstone	32.1	2.5	9.4	1.8	54.2	51	15	11	23	25	1.00	0.06
	2612.80	Dark gray mudstone	49.2	3.1	5.2	2.5	40.0	53	16	13	18	25	0.38	0.05
	2614.22	Dark gray mudstone	36	3.4	12.0	—	48.6	54	14	10	22	30	1.03	0.16
	2615.26	Gray mudstone	36.3	—	6.6	2.2	54.9	56	13	11	20	30	0.72	0.15
	2616.87	Gray mudstone	34.2	2.0	7.9	1.6	54.3	63	9	10	18	30	0.43	0.08
	2619.73	Dark gray mudstone	29.8	2.9	12.2	—	55.1	57	10	13	20	30	1.13	0.28
	2623.79	Dark gray mudstone	29.5	2.1	15.4	1.6	51.4	61	11	11	17	30	0.36	0.14
East-2	2146.42	Gray mudstone	39.4	5.2	1.8	—	53.6	60	31	6	3	6	0.96	1.21
	2146.81	Gray mudstone	33.5	3.7	5.4	—	57.4	57	33	7	3	6	1.00	1.54
	2147.25	Dark gray mudstone	24.3	3.5	0.9	—	71.3	41	22	13	24	25	0.69	1.35
	2147.89	Dark gray mudstone	31.7	3.7	—	—	62.5	43	21	14	22	25	3.83	0.11
	2154.34	Dark gray shale	27.5	3.9	16.4	—	52.2	55	37	8	—	5	2.93	1.55
	2154.57	Dark gray shale	22.5	4.0	23.7	—	49.8	65	29	6	—	5	2.61	1.69
	2155.35	Dark gray shale	25.4	5.6	11.5	—	57.5	66	26	8	—	5	1.18	0.42
North-1	3746.68	Dark gray shell mudstone	32.6	3.0	23.2	—	41.2	44	22	17	17	6	4.85	4.93
	3748.05	Dark gray silty mudstone	35.6	3.4	6.5	—	54.5	41	22	14	23	5	6.91	0.20
	3748.88	Gray shell shale	40	3.4	25.2	—	31.4	44	16	16	24	5	4.97	1.89
	3750.60	Silty mudstone	46.9	7.0	3.0	—	43.1	41	21	16	22	5	5.12	0.02
	3752.36	Dark gray mudstone	39.9	3.7	0.7	—	55.7	41	22	15	22	5	5.78	0.22
	3754.13	Dark gray mudstone	32.1	1.8	6.5	—	59.6	56	20	9	15	8	5.41	0.21
	3755.32	Gray-black shell limestone	20.2	-	59.4	—	20.4	50	22	10	18	7	2.81	0.01
	3757.01	Gray-black shell limestone	15.3	4.0	52.9	—	27.8	33	23	15	29	4	3.05	0.01
	3757.52	Gray-black mudstone	35.5	4.4	7.1	—	53.0	15	35	21	29	4	5.99	2.81

Table 1: Continued.

Well	Depth (m)	Lithology	Brittle mineral content (%)				Total clay (%)	Clay mineral content (%)				Interlayer ratio (%)	Porosity (%)	Permeability ($10^{-3}\,\mu m^2$)
			Quartz	Feldspar	Calcite	Dolomite		I/S	It	Kao	C			
Middle-1	2228.31	Gray mudstone	26.4	5.9	12.2	4.9	50.6	49	30	10	11	5	3.07	1.65
	2237.80	Gray-black shell mudstone	25.3	6.6	18.1	3.2	46.8	39	25	23	18	5	2.41	1.22
	2255.32	Gray-black shell mudstone	25.9	3.3	18.6	2.9	49.3	36	31	18	10	6	1.07	0.64
	2263.17	Gray-black mudstone	25.3	2.1	8.8	-	62.4	33	32	17	8	8	1.74	2.12



(a) (b) (c) (d)

Figure 2: Fine-grained rock lithology and lithological combination of the Da'anzhai Member, Liangping outcrops, Sichuan Basin. (a) Assemblage of limestone at the top of the Da 1 submember and shale at the lower part of the Da 2 submember. (b) At the interface between Da 1 and Da 2 submember, shale and limestone are in contact. (c) Thick-layered shell shale of the Da 2 submember. (d) Assemblage of shell shale and shell limestone, Da 2 submember.

content classification that reflects the difference in the degree of organic matter enrichment [8, 18], the classification is based on the content of clay minerals, felsic minerals at the silt level and carbonate minerals as three terminal elements [3, 4, 18, 24, 32]. The fine-grained sedimentary rocks of the Da'anzhai Member in the area are divided into four categories: mudstone, siltstone, limestone, and mixed rock (Figure 6). According to the mineral content of the Da'anzhai Member, mudstones can be subdivided into mudstone, silty mudstone, and lime mudstone; siltstones are divided into siltstone, lime siltstone, and argillaceous siltstone; limestones can be subdivided into limestone, silty limestone, and argillaceous limestone; mixed rocks are divided into argillaceous fine-grained mixed rock, lime fine-grained mixed rock, and silty fine-grained mixed rock. 0.5%~1.0%, 1.0%~2.0%, >2.0% is the TOC classification limit, which is defined as carbon-bearing, carbonaceous, and carbon-rich, as the classification prefix of fine-grained sedimentary rocks. Combine inorganic (mineral component content) and organic (TOC) to establish a fine-grained sedimentary rock classification scheme.

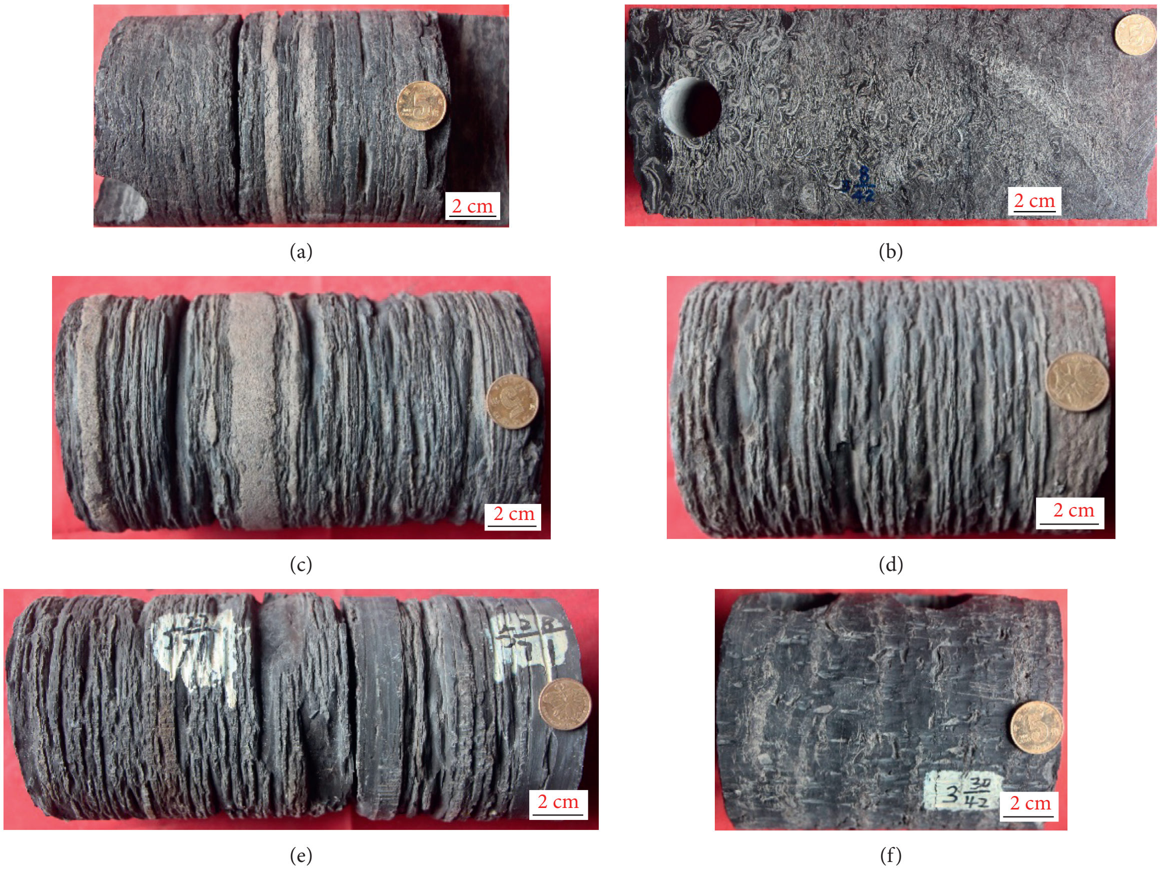


Figure 3: The lithology and laminar fracture of the fine-grained rock core of the Da'anzhai Member in the Sichuan Basin. (a) Shell limestone, shale intercalated with shale, lamina fractures developed, l North-1 Well, 3755.3 m. (b) Argillaceous shell limestone, shells arranged along the lamina, East-2 Well, 2152.5 m. (c) Intercalated limestone of gray-black shale, East-1 Well, 2618.23 m. (d) Black shale, laminar, and laminar fractures, East-1 Well, 2620.45 m. (e) Black shale, laminar and laminar fractures, East-1 Well, 2623.12 m. (f) Lime mudstone, East-2 Well, 2156.34 m.

In the core and field profile, the limestone of this section is mainly shown by shells. The mudstone is darker in color, with millimeter-level or micron-level horizontal textures. Therefore, the mudstone is characterized by the development of shale (Figures 2, 3). This section mainly develops shell limestone (Figures 7(a)), argillaceous shell limestone, shale, shell shale (Figures 7(b) and 7(c) and 7(d)), silty shale (Figures 7(e) and 7(f)), mud/argillaceous siltstone, argillaceous fine-grained mixed rock, and shelled fine-grained mixed rock. There are a variety of shale, limestone, siltstone, and mixed rock of unequal thickness interbedded and assemblage [18, 24], interbedded shell shale and shell limestone, thick shell limestone interbedded with thin shell shale and thin mixed rock, thick shale interbedded with thin shell limestone, mudstone and silty mudstone interbedded.

In the eastern Liangping section, there are mainly gray thick-to-middle-layered shell limestones in Da 1 and Da 3 submembers, characterized by limestone intercalated with shell shale, and the sequence of the transitional section of the Da 2 submember is thin shell limestone interbedded with shell shale. The thick gray-black shell shale in the Da 2 submember is most characterized by the combination of medium-thin layered shale and medium-thin layered limestone as characteristic rocks (Figures 2, 3). Rock in northern area also has the characteristics of this rock type combination. In the central Sichuan Basin, the rock of Da 1 and Da 3 submember is mainly gray thick-layered shell limestone and micrite limestone, and argillaceous interbeds are rare. The rock in Da 2 submember is mainly interbedded limestone and mudstone; in mudstone, the lime matter and the shell are mostly mixed in a dispersed state.

4.2. Diagenetic Minerals

4.2.1. Quartz. Part of the fine-grained sedimentary rock diagenetic quartz mineral is transformed into clay minerals (Figures 7(c) and 7(d), 8(a)), and the other part is the original components of the shell (Figures 8(b) and 8(c) and 8(g)), which is replaced by silica matter, forming a kind of quartz crystal with a relatively intact degree of self-shape. The distribution of diagenetic quartz is controlled by diagenetic conditions and environment. Quartz precipitated from clay mineral transformation during diagenesis is micrometer-sized particles embedded in the clay matrix with a size between 1 and 3 μm. The crystals are in the form of short chains, clusters of small crystals, patches, or small crystals. Quartz crystallites appearing in metasomatism often exist in

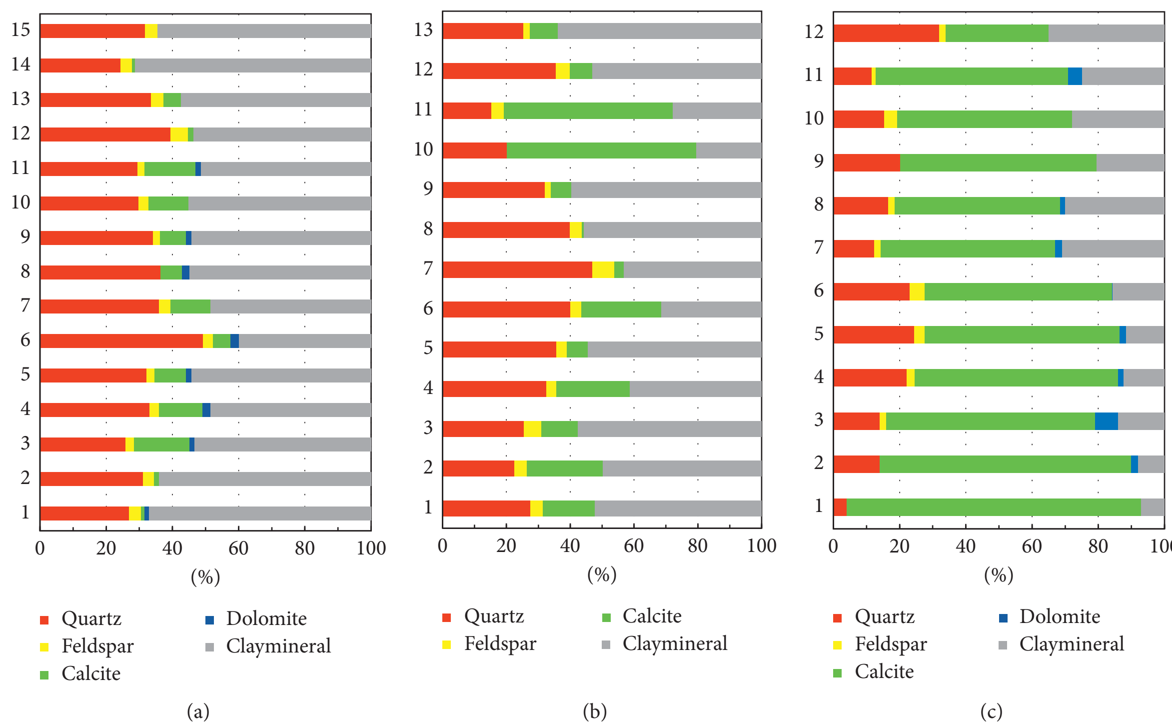


Figure 4: XRD analysis of the distribution of different mineral compositions of fine-grained rocks in the Da'anzhai Member in the Sichuan Basin. (a) Characteristics of the mineral composition in the northern Sichuan Basin, 15 samples. (b) Characteristics of the mineral composition in the eastern Sichuan Basin, 13 samples. (c) Characteristics of the mineral composition in central Sichuan Basin, 12 samples.

contact with the particles of the biological medium and grow from the edges to the inside of the shell to form a tooth-like structure (Figures 7(c) and 7(d)). The diagenetic quartz with a good degree of self-shape is different from the breccia, rhombohedral, irregular, laminar, or grains with weak orientation sedimentary quartz mineral, and the distribution is extremely irregular (Figure 8(f)).

4.2.2. Clay Mineral. The diagenetic clay minerals in the fine-grained sedimentary rocks are mainly illite and chlorite. The Illite-Smectite Clays are an orderly mixed layer, and the relative content of montmorillonite is 12~30%, mostly less than 15%. Clay minerals in diagenesis are mostly recrystallization of illite and montmorillonite and other minerals transformed into illite and chlorite (Figures 8(b) and 8(h)). Autogenous kaolinite (Figure 8(d)), chlorite, and illite are formed in the micropores. Clay minerals and carbonic minerals and silica substances are interchangeable (Figure 8(d)).

4.2.3. Carbonate Mineral. Diagenetic carbonate minerals are mainly calcite (Figures 7(c) and 7(c), 8(e), and 8(i)), and a little dolomite. The source is mainly lime-mud and shells deposited in the original basin. The conversion and recrystallization of carbonate minerals occurred during the diagenesis of lime-mud and biological shells, the earlier aragonite mostly transformed into low-magnesium calcite (Figures 7(c) and 8(i)) and dolomite crystals with different forms. Diagenetic calcite recrystallization and sparry cementation are common in the limestone layer of the Da'anzhai Member. Sparry calcite can be found as dissolution and refilling phenomenon for several periods. The shale and siliceous shale both with argillaceous and siliceous as the main components found that clay minerals and siliceous are replaced by Calcite and are distributed in sporadic and poecilitic crystals. A small amount of deposited lime-mud recrystallizes locally enriched and shown to be lamellar or microlamellar.

4.2.4. Pyrite: Strawberry-Like Pyrite Is a Product of the Syngenetic and Early Diagenetic Stages. It is densely packed and mostly forms strawberry-like spherical aggregates with a particle size ranging from a few microns to tens of microns. Strawberry-like pyrite in this section is generally more than 10 μm (Figure 3(f)); the larger diameter reflects that it may be formed in the oxygen-containing terrestrial deep lake-semi-deep lake environment in the syngenetic period. According to the particle size of the pyrite, it is shown that the pyrite of the Da'anzhai Member is mainly formed in oxygen-containing water, and the oxygen-containing interface is above the sediment/water interface. Strawberry-like pyrite can also be formed before burial; it is closely related to the expansion of the lake basin area and the deepening of sedimentary water bodies in the Da'anzhai Member.

4.2.5. Types of Diagenesis. The fine-grained sediments of the Da'anzhai Member have undergone compaction, cementation, recrystallization, metasomatism, dissolution,

Table 2: Data table for porosity-permeability of Da'anzhai Menber, Sichuan Basin.

Area	Lithology	Helium porosity (%)	Permeability ($10^{-3}\,\mu m^2$)
North	Gray-black carbonaceous mudstone	6.25	2.77
	Gray-black carbonaceous shale	5.69	0.39
	Dark gray silty mudstone	1.11	0.0032
	Dark gray silty mudstone	2.21	0.0044
	Gray-black carbonaceous shale	5.65	0.53
	Gray-black carbonaceous shale	6.44	0.63
	Gray-black carbonaceous shale	5.58	0.9
	Gray-black carbonaceous shale	6.91	0.2
	Gray-black carbonaceous shell mudstone	4.85	4.93
	Gray-blacks hell shale	4.97	1.89
	Gray-black carbonaceous shale	4.55	0.02
	Gray shell limestone	1.69	0.008
	Gray-black carbonaceous shale	3.58	0.009
	Gray-black carbonaceous shale	5.12	0.02
	Gray-black carbonaceous shale	4.51	0.04
	Gray-black carbonaceous mudstone	5.57	7.07
	Gray-black carbonaceous shale	6.59	0.18
	Gray-black carbonaceous shale	5.03	0.16
	Gray-black carbonaceous shale	5.07	14.51
	Gray-black carbonaceous shale	6.13	0.0808
	Gray-black carbonaceous shale	5.79	0.5985
	Gray-black carbonaceous shale	6.28	0.4829
	Gray-black carbonaceous shale	5.61	0.185
	Gray-black carbonaceous shale	6.16	0.1144
	Gray-black carbonaceous shale	6.21	0.0297
	Gray-black carbonaceous shale	7.47	0.3176
	Gray-black carbonaceous shale	4.98	0.0107
	Gray-black carbonaceous shale	8.42	50.3038
	Gray-black hell shale	6.51	6.8034
	Gray-black hell shale	3.61	0.0159
	Gray-black hell shale	7.97	0.2009
	Gray-black carbonaceous shale	3.65	0.0169
	Gray-black hell shale	3.72	0.0325
	Gray-black carbonaceous shell shale	8.33	1.4172
	Gray-black hell shale	7.37	1.2813
	Gray-black carbonaceous shell shale	3.57	0.0148
	Gray-black hell shale	2.6	0.0064
	Brown-grey mud-bearing shell limestone	3.05	0.0071
	Brown-grey mud-bearing shell limestone	2.81	0.0054
	Brown-grey mud-bearing shell limestone	3.85	0.1173
	Gray-black hell shale	4.11	0.0517
	Gray-black carbonaceous shell shale	5.89	1.023
	Gray-black hell shale	5.31	2.435
	Brown-gray lime mudstone	5.78	0.2207

Table 2: Continued.

Area	Lithology	Helium porosity (%)	Permeability ($10^{-3}\ \mu m^2$)
East	Gray-black hell mudstone	1.02	4.46
	Gray-black hell mudstone	1.21	1.68
	Gray-black shale	1.15	0.4
	Gray-black shale	1.29	0.55
	Gray-black shale	1.83	0.76
	Gray-black hell mudstone	2.07	1.25
	Gray-black shale	1.34	0.71
	Dark gray mudstone	1.12	1.46
	Dark gray mudstone	1.25	0.38
	Dark gray mudstone	0.65	0.2
	Dark gray mudstone	1	0.06
	Dark gray mudstone	0.38	0.05
	Dark gray mudstone	1.03	0.16
	Gray mudstone	0.72	0.15
	Gray mudstone	0.43	0.08
	Dark gray mudstone	1.13	0.28
	Dark gray mudstone	0.36	0.14
	Dark gray mudstone	0.36	0.07
	Dark gray mudstone	0.88	0.08
	Dark gray mudstone	0.65	0.1
	Dark gray mudstone	0.45	0.52
	Gray-black shell mudstone	0.77	1.17
	Gray-black shell mudstone	1.07	0.52
	Gray-black shale	1.09	0.39
	Gray-black shale	1.23	1.78
	Gray-black shell mudstone	1.11	0.32
	Gray-black shale	1.38	1.41
	Gray shell Mudstone	7.98	2.61
	Gray-black shale	0.59	1.39
	Gray-black shale	1.51	0.77
	Gray-black shell mudstone	1.22	0.72
Middle	Dark gray argillaceous shell limestone	0.52	0.0041
	Gray argillaceous limestone	0.62	0.0062
	Gray shell limestone	0.79	0.0147
	Gray limestone	0.63	0.0066
	Gray shell limestone	0.19	0.0024
	Gray shell limestone	0.82	0.0102
	Gray shell limestone	0.94	0.0302
	Gray limestone	5.94	0.0964
	Gray limestone	0.65	0.0046
	Dark gray argillaceous limestone	0.73	0.0095
	Gray shell limestone	1.22	0.0145
	Gray limestone	0.81	0.0094
	Gray shell limestone	1.24	0.0061
	Gray shell limestone	1.35	0.0191
	Gray limestone	0.57	0.074
	Gray limestone	1.47	0.0092
	Gray limestone	1.76	0.1229
	Gray shell limestone	1.52	0.0089
	Gray shell limestone	0.24	0.0019
	Gray shell limestone	0.77	0.0083
	Gray shell limestone	0.36	0.0071
	Gray shell limestone	0.96	0.0094
	Gray shell limestone	2.14	0.0269
	Gray argillaceous limestone	1.78	0.0166
	Gray argillaceous shell limestone	0.85	0.0099
	Gray shell limestone	1.41	0.0064
	Gray limestone	1.04	0.0093

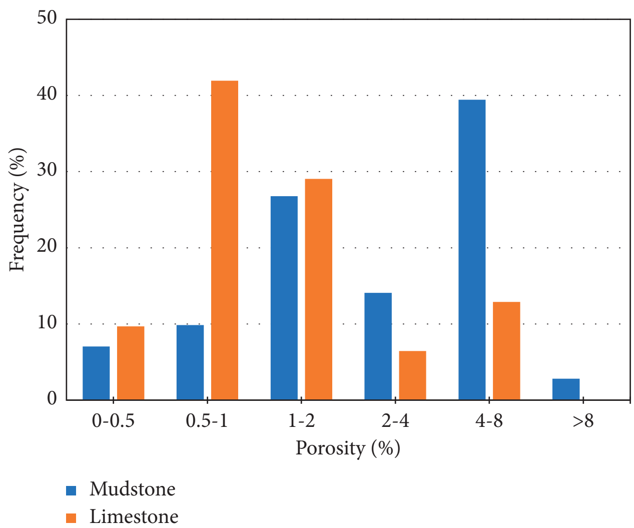


Figure 5: Porosity frequency histogram of two lithological structures in Da'anzhai Member of the Sichuan Basin.

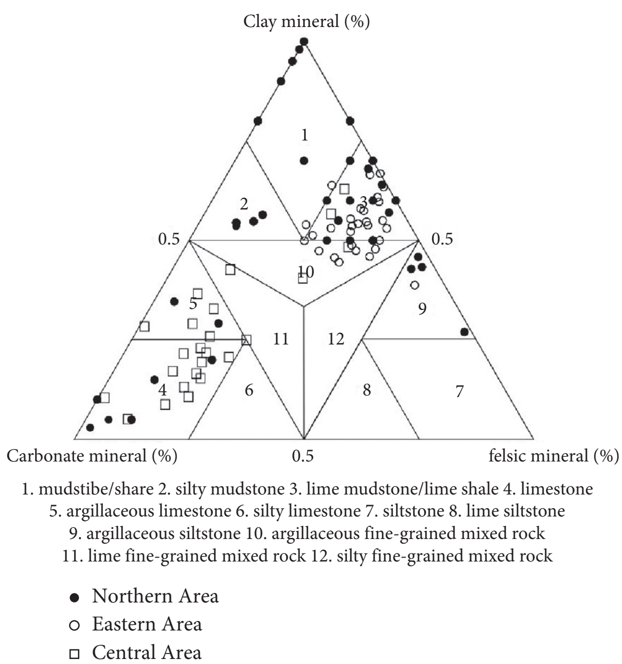


Figure 6: Fine-grained sedimentary rock classification schemes of Da'anzhai member of Jurassic in Sichuan Basin.

transformation of clay minerals, and organic matter evolution and other diagenesis. They are transformed into fine-grained sedimentary rocks, forming an ultralow porosity-low permeability tight reservoir at present.

4.2.6. Compaction. Under the action of stress, the original moisture of the fine-grained sediment is discharged, the pores are significantly reduced, and the fine-grained sediment is consolidated. Compaction exists in different diagenesis stages of mudstone, limestone, and siltstone and has a huge impact on mudstone and shale reservoirs. In the early stage of diagenesis, the sediments were loose, and there were many primary pores; as compaction continued to occur and the strength gradually increased; the muddy state gradually changed from a loose state to a consolidated state. Compaction is the most obvious effect of shale change.

Under the influence of compaction, the biological fragments in the fine-grained sedimentary rocks of the Da'anzhai Member in the northern area are arranged in a directional arrangement. It can be found that the shell layers in the shell limestone and shell shale are stacked in sequence (Figures 7(a) and 7(b) and 7(d)), and the contact relationship between the quartz particles in the siltstone (Figure 8(f)) and between the calcite particles in the limestone is concave-convex contact.

4.2.7. Cementation. Cementation of fine-grained sedimentary rocks in the Da'anzhai Member is divided into three categories: calcareous cementation, siliceous cementation, and iron cementation.

The siliceous cementation is mainly manifested as the spontaneous enlargement of quartz and the spontaneous quartz crystals (mainly crystal cluster). The phenomenon of authigenic growth of quartz occurs only in the intercalation of argillaceous siltstone and fine sandstone in the Da'anzhai Member; clusters of authigenic quartz crystals are common in mud shale and shell mud shale and are mostly found diagenetic transformation in clay minerals or siliceous substitution of other components (Figures 8(b) and 8(e)).

Calcareous cementation is mainly composed of intergranular and intercrystalline diagenetic authigenic calcite. The Sichuan Basin was a freshwater carbonate lacustrine environment during the deposition of the Da'anzhai Member. Sparry calcite cements were commonly developed in the shell limestone and shell shale of the Da'anzhai Member. It is a granular and poecilitic crystal with a partially metasomatic shell (Figures 7(c) and 7(d)).

Iron cements are mostly distributed in authigenic pyrite aggregates in shale and limestone and between siltstone grains. Pyrite cement can be seen in organic-rich shale and shell mud shale in the Da'anzhai Member of this area, and it is a strawberry-like monomer or aggregate (Figure 8(c)).

4.2.8. Metasomatism. Calcite in the bioclastic that was replaced by quartz is common in the shell shale and shell limestone of the Da'anzhai Member (Figures 7(c) and 3(d), 8(a) and 8(c)). Quartz and clay minerals can also be found to be replaced by calcite (Figure 8(e)). The quartz crystallite from quartz replaced bioclastic (Figures 7(c) and 7(d), 8(a)) shows that it often exists at the contact of the bioclastic particles, growing from the edge to the inside of the shell to form a tooth-like structure, and sometimes calcite and quartz are mixed and alternate. Quartz appears to be produced in rhombohedral crystals of calcite, and calcite is also distributed in shale in a granular form. Quartz precipitated from the clay mineral transformation during diagenesis is micrometer-sized particles embedded in the clay matrix, and its size is between 1 and 3 μm. The crystals are in the form of short chains or clusters of small crystals, or in the form of patches and small crystals among the different components;

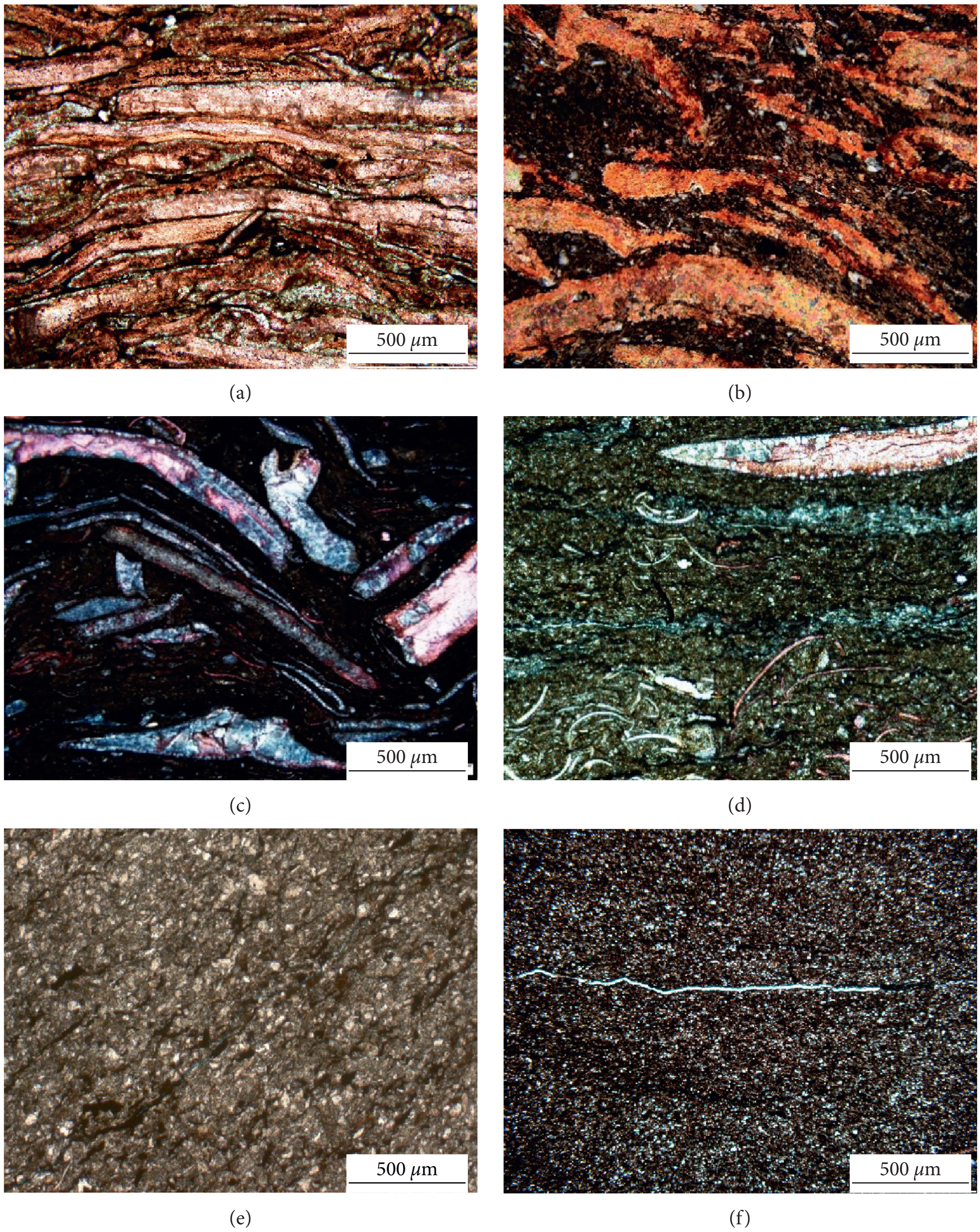


Figure 7: Microscopic lithology characteristics of fine-grained rocks in the Da'anzhai Member in the northern Sichuan Basin. (a) Shell limestone, North-1 Well, 3755.5 m (−). (b) Shell shale, North-1 Well, 3759.6 m (−). (c) Shell shale, shell silicification, North-1 Well, 3746.7 m (+). (d) Laminar shell shale, North-1 Well, 3789.1 m (−). (e) Weak laminar silt-bearing shale, North-2 Well, 3990 m (−). (f) Shale or mudstone and cracks, North-1 Well, 3750.7 m (−).

it appears that quartz replaces clay minerals. Siltstone contains quartz and calcite replacing preformed clastic components and diagenetic minerals.

4.2.9. Recrystallization. In the Da'anzhai Member, the internal components of the biological shell particles in the shell shale and shell limestone changed during the diagenesis, and the recrystallization phenomenon was obvious. The original composition inside the particles was aragonite, and the low-magnesium calcite was finally changed through recrystallization. Currently, almost all shell particles in the research area are calcite minerals (Figures 7(a) and 7(b), 8(i)), and lime mud has also transformed sparrow calcite. At the same time, the illite in the clay minerals in shale has also changed from small, dispersed crystallites to larger flaky mineral crystals.

4.2.10. Dissolution. The dissolution of carbonate shells and interstitials in the Da'anzhai Member is developed, and there are early and late dissolutions. The early dissolution strength

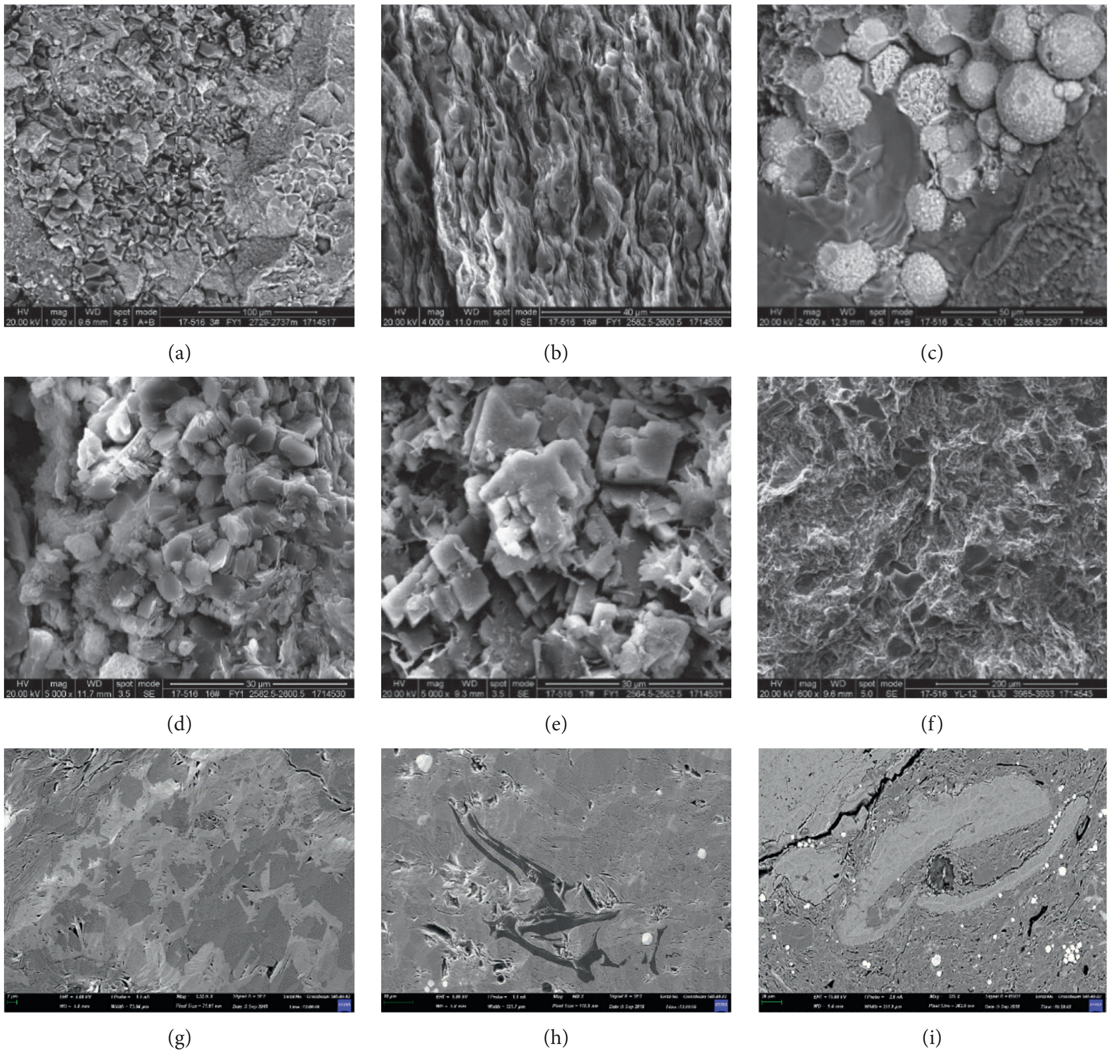


FIGURE 8: The microscopic characteristics of fine-grained sedimentary rocks in the Da'anzhai Member of the Jurassic in the Sichuan Basin. (a) Silicification of the shell in shale, East-1 Well, 2735.2 m. (b) Shale, illite arranged in shale orientation and micro-pore, East-1 Well, 2592.6 m. (c) Authigenic siliceous and authigenic pyrite aggregates, East-1 Well, 2697 m. (d) Kaolinite microcrystals in shale pores, East-1 Well, 2592.6 m. (e) Calcite crystals and dissolution, illite and calcite alternate, East-1 Well, 2582.3 m. (f) Shale mechanically deposited quartz particles, strong compaction, North-2 Well, 3992.2 m. (g) Transformation of autogenic quartz crystals and clay minerals and inorganic micropores, North-1 Well, 3935.9 m. (h) Mixed layer clay-illite and organic matter, North-1 Well, 3864.9 m. (i) Shell, organic matter and clay and inorganic micropores, North-1 Well, 3938.07 m. All photos are SEM photo, the last three are samples prepared by argon ion polishing.

is strong and most. The dissolution of fine-grained sedimentary rocks in this section is different in different blocks. The late dissolution of limestone in the north and east is not obvious, the filling is more intense, and the dissolution of bioclastics and early cements in the basin is uneven. The dissolution of shell limestone is obvious in the middle and shallow shells, and there are also dissolution phenomena in the deep shell limestone and shell shale, and multistage dissolution and filling (cementation) phenomena.

4.2.11. Transformation of Clay Mineral. When the buried depth of mudstone and shale increases, the formation temperature rises to 70°C~100°C, and the pressure increases to a certain value, the clay minerals will precipitate interlayer water and cations, and the transformation of clay minerals will occur, showing that the montmorillonite or illite-Smectite Clays mixed layer in the mud shale transforms into illite or illite-Smectite Clays mixed layer minerals (Figures 8(b) and 8(g) and 8(h)), and the illite-Smectite Clays mixed layer ratio (montmorillonite content) in deep shell shale is less than 10%.

4.2.12. Diagenetic Evolution of Organic Matter. The total organic carbon content (TOC) of the dark mud shale of the Da'anzhai Member is 0.54%~2.32%, with an average of 1.30%; the oil production potential $(S1 + S2)$ is 0.38~13.33 mg/g, with an average of 4.46 mg/g; the hydrocarbon production index (PI) is 0.22~0.51, with an average of 0.32; hydrogen index (HI) is 49.91~360.34 mg/g, with an average of 201.09 mg/g; productive carbon (PC) is 0.03%~0.77%, with an average of 0.37%; hydrocarbon index (HCI) is 20.33~214.22 mg/g, with an average of 97.73 mg/g. It shows that the dark mud shale of the Da'anzhai Member has a relatively high content of organic matter, and it is a set of medium-high source rocks. The type of source rock kerogen is mainly sapropel, and the reflectance of vitrinite organic matter (Ro) is 0.78%~1.76%, with an average of 1.16%; the Ro of the northern area is between 1.44% and 1.83%, with an average of 1.67%. In the mature and high mature stage, the Ro of the eastern area is between 1.% and 1.5% (Table 3), with an average of 1.27%, in the mature stage; the Ro of the central Sichuan Basin region is between 0.9% and 1.4% (Table 3), with an average of 1.14%, which is also in the mature stage (Table 3). In the Da'anzhai Member, regarding the interaction between fluid and rock, the transformation of organic matter from immature to mature, organic matter undergoes complex changes, and different hydrocarbon generation evolution (irreversible evolution of gaseous-liquid hydrocarbons), and organic matter discharge from carbon-rich shale (hydrocarbon expulsion and acid expulsion, etc.) to generate hydrocarbon and reservoir, showing different diagenetic environments and diagenetic processes.

5. Discussion

5.1. Division of the Diagenetic Stages. The fine-grained rock that is most in the shale of the Da 2 submember is multiple normal clastic rock (siltstone) and carbonate rock (limestone) interbeds in lithological combination. This combination of coarse and fine lithology has the same temperature and pressure field, which is similar to the evolution process of the diagenetic fluid and the diagenetic environment. Therefore, the diagenesis stage can be divided according to fresh water-brackish water in "Diagenetic Stages of Clastic Rocks" (SY/T5477-2003); according to the ratio of mixed layers of Illite-Smectite Clays, organic matter vitrinite reflectance Ro, the highest pyrolysis peak temperature (T_{max}), the combination type of clay minerals, and the pore development status (Table 4), the reservoir of the Da'anzhai Member of the Ziliujing Formation in basin has experienced early and middle diagenetic stages and is now in the A and B substages of the middle diagenetic stage (Figure 9).

The higher Ro value of organic vitrinite reflectance in the Da'anzhai Member of the northern and eastern area reflects that it is in the high-maturity stage of condensate oil-moisture. The Tmax value and the ordered mixed layer ratio reflect that it is in the high-maturity stage, corresponding to the B substage of the middle diagenesis. There are few primary pores in this section, developing recrystallization, authigenic intercrystalline pores (complex linear micropores), micro cracks, and dissolution pores of clay minerals; the Illite-Smectite Clays have experienced disorder to order, the appearance and transformation of kaolinite, the appearance of inorganic acid and organic acid successively, the pores from primary to secondary, and the sediments from loose to consolidated and then dense. The Illite-Smectite Clays experienced the transformation of syngenetic, early diagenetic and mid-diagenetic. The Ro value of limestone and limestone mudstone in the Da'anzhai Member in the central Sichuan Basin is low, mostly less than 1.2%, and is in the mature stage. The mixed layer ratio (montmorillonite) of the Illite-Smectite Clays is about 35%, which comprehensively shows that it is in the middle diagenetic substage A, the dissolution pores and dissolution-expanded fractures are both developed in this type of shell limestone, and the porosity can reach 5~10%.

The Da'anzhai Member in the northern area has evolved from the syngenetic period, the early diagenetic period, to the middle diagenetic period and undergoes compaction in the early diagenetic stage A, and its porosity is greatly reduced. Compared with the compaction of sandstone, limestone, and shale, it is stronger and is the most important diagenesis. The original pores of mudstone range from almost 70% to 10~15%, and the shale fractures dominated by the shale lamella fractures are strongly compressed and dense. In the early diagenetic stage B, compaction is still the main factor in reducing pores in shale, reducing pores by about 5%, and fine-grained rocks begin to appear secondary dissolution pores. Currently, the total porosity of shale is about 5~10%. In the mid-diagenesis stage A, a large number of organic acids are generated, and a large number of organic pores and dissolution pores are developed. The lamellation fractures are slightly widened due to dissolution, and the overall porosity remains unchanged; in areas where organic matter is not developed, compaction still exists, the shale porosity decreases slowly, and the porosity decreases by 2~3%; in the middle diagenetic stage B, various diageneses in the shale are still unevenly developed, the brittleness of the rock is enhanced, the rock is brittle, and the shale is easy to crack and form microcracks. The shale porosity keeps stable, and the total porosity is about 5%. After the above diagenesis stages, secondary pores and fractures such as intercrystalline pores, dissolution pores, organic pores, lamellation fractures, and microfractures have been formed. The primary pores in siltstone and shell limestone are almost not developed (Figure 10). The fine-grained rock in this study period experienced a series of diageneses, mainly composed of clay mineral intercrystalline pores and organic evolution pores, and few developed dissolved pores. Due to the strong cementation and filling of the limestone shell, the pores and cracks expanded by dissolution in the late stage are mostly filled and healed, and their physical properties are generally worse than those of shale (Figure 11).

5.2. The Impact of Diagenesis on the Reservoir. The fine-grained rock of the Da'anzhai Member has undergone compaction, cementation, dissolution, recrystallization, metasomatism, clay mineral transformation, authigenic mineral formation, and organic matter evolution and finally formed an ultra-low porosity-low permeability tight reservoir. Statistics show that the physical properties of different lithologies in the Da'anzhai Member of the northern area and the eastern area are different (Tables 2, 3). The physical properties of mudstone and shell shale are generally better, while siltstone and limestone are relatively dense. The closed

Table 3: Ro statistical table of Da'anzhai Member of Jurassic shale in Sichuan Basin.

Area	Layer	Sample (A)	Minimum (%)	Max (%)	Average (%)
Northern	Da'anzhai member	10	1.44	1.83	1.67
Eastern		26	1.1	1.5	1.27
Central		16	0.9	1.4	1.14

Table 4: Division basis of diagenetic stage of Da'anzhai member in Sichuan Basin.

Area	Division standard				Diagenetic stage
	Ro	T_{max}	Clay mineral	Pore type	
Northern	1.44~1.83%/ 1.67% (10)	371~501°C/ 468°C (25)	Illite-smectite clay + illite + chlorite + kaolinite (35)	Intercrystalline pores, dissolution pores, organic pores, and microcracks (50)	Mid-diagenetic stage B substage
Eastern	1.1~1.5%/ 1.27% (17)	354~487°C/ 458°C (22)	Illite-smectite clay + illite + chlorite + kaolinite (40)	Dissolution pores, organic pores, intergranular pores, microcracks (48)	Mid-diagenetic stage B substage
Central	0.9~1.4%/ 1.14% (6)	440~450°C/ 448°C (12)	Illite-smectite Clays + illite + chlorite + kaolinite (13)	Organic pores, intercrystalline pores, intergranular pores of clay minerals, intragranular pores, microcracks (20)	Mid-diagenetic stage A substage

Tag: Minimum ~ Max/Average (sample number).

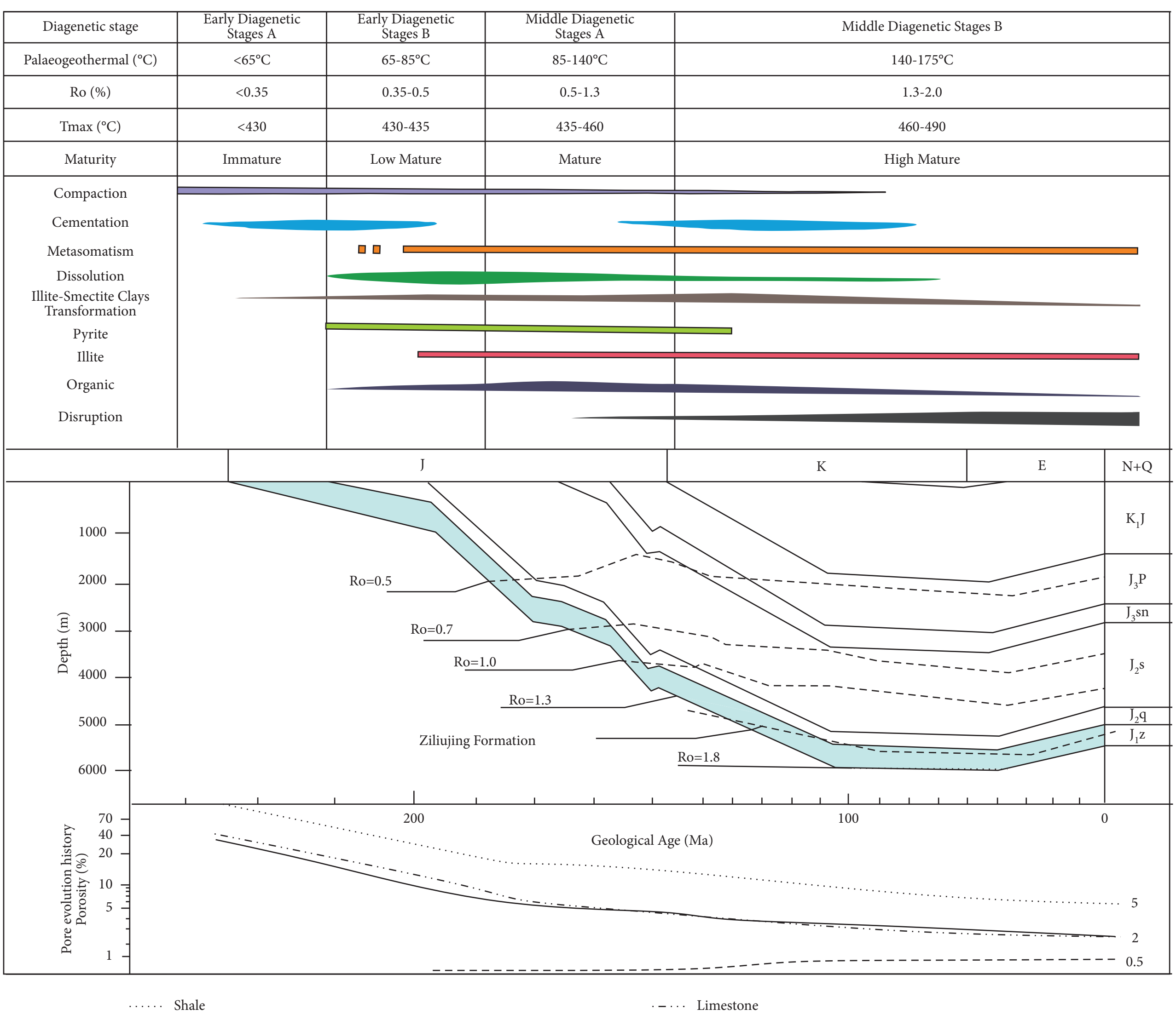


Figure 9: Diagenetic evolution sequence of Da'anzhai Member of Jurassic Ziliujing Formation in Sichuan Basin.

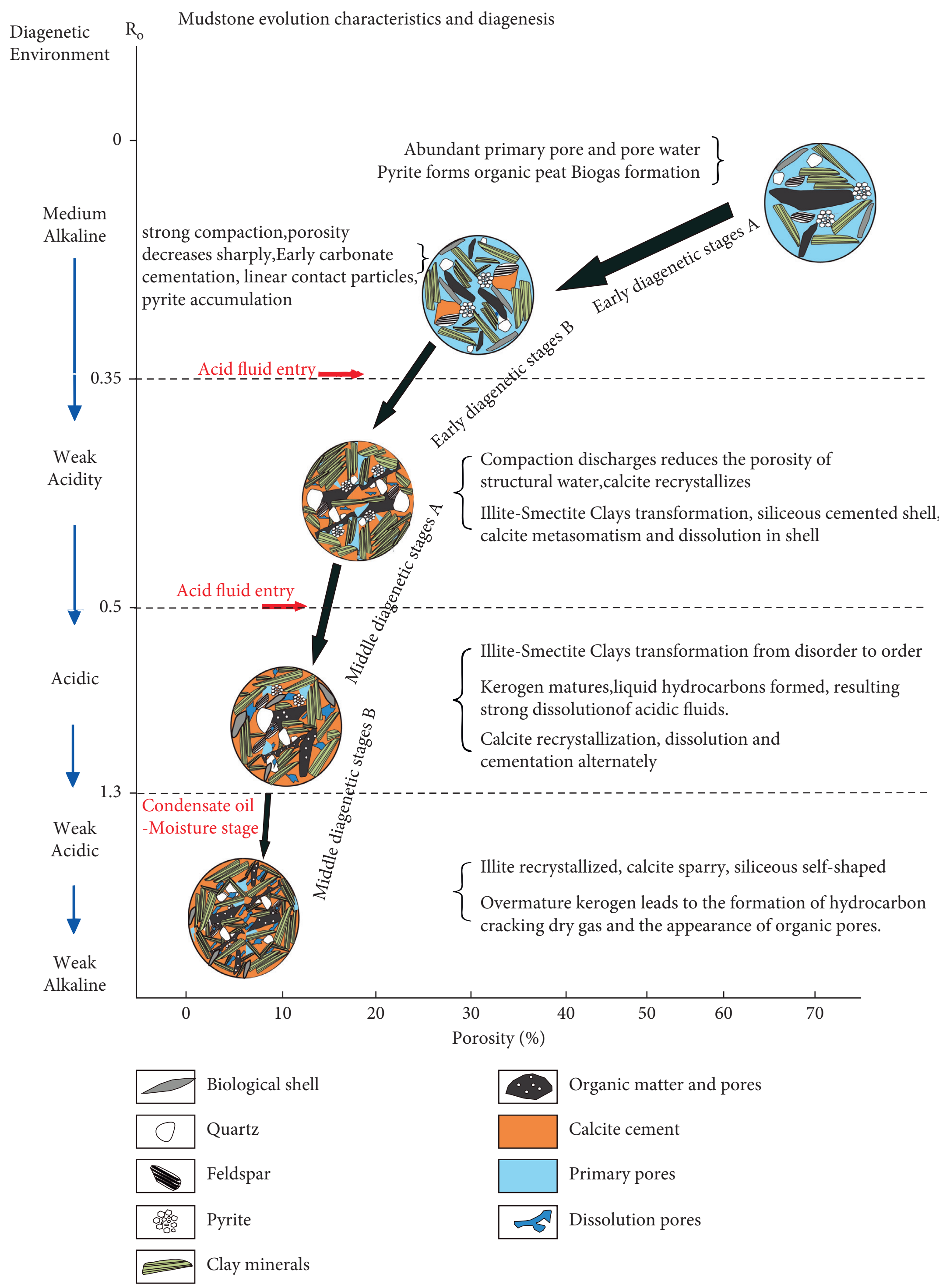


FIGURE 10: Diagenesis and pore evolution model of shale in Da'anzhai Member in northern area.

coring gas test experiment of the Da 2 submember in the northern area shows that shale and shell limestone are interbedded, and thick shell limestone is intercalated with thin shell shale in two lithology combinations. It is shale and shell shale that is outgassing, not limestone and shell limestone (Figure 12). The gas output of the 5~10 m shell shale layer is better than the thin shell shale layer; the combination of thick shell limestone and thin shell shale has little gas output or no gas [24]. Different regions and different types of tight rocks have different types of diagenesis and transformation effects. Relatively speaking, limestones are mainly subjected to cementation reformation, siltstones are mainly subjected to compaction reformation, and mudstone or shale compaction reformation is strong.

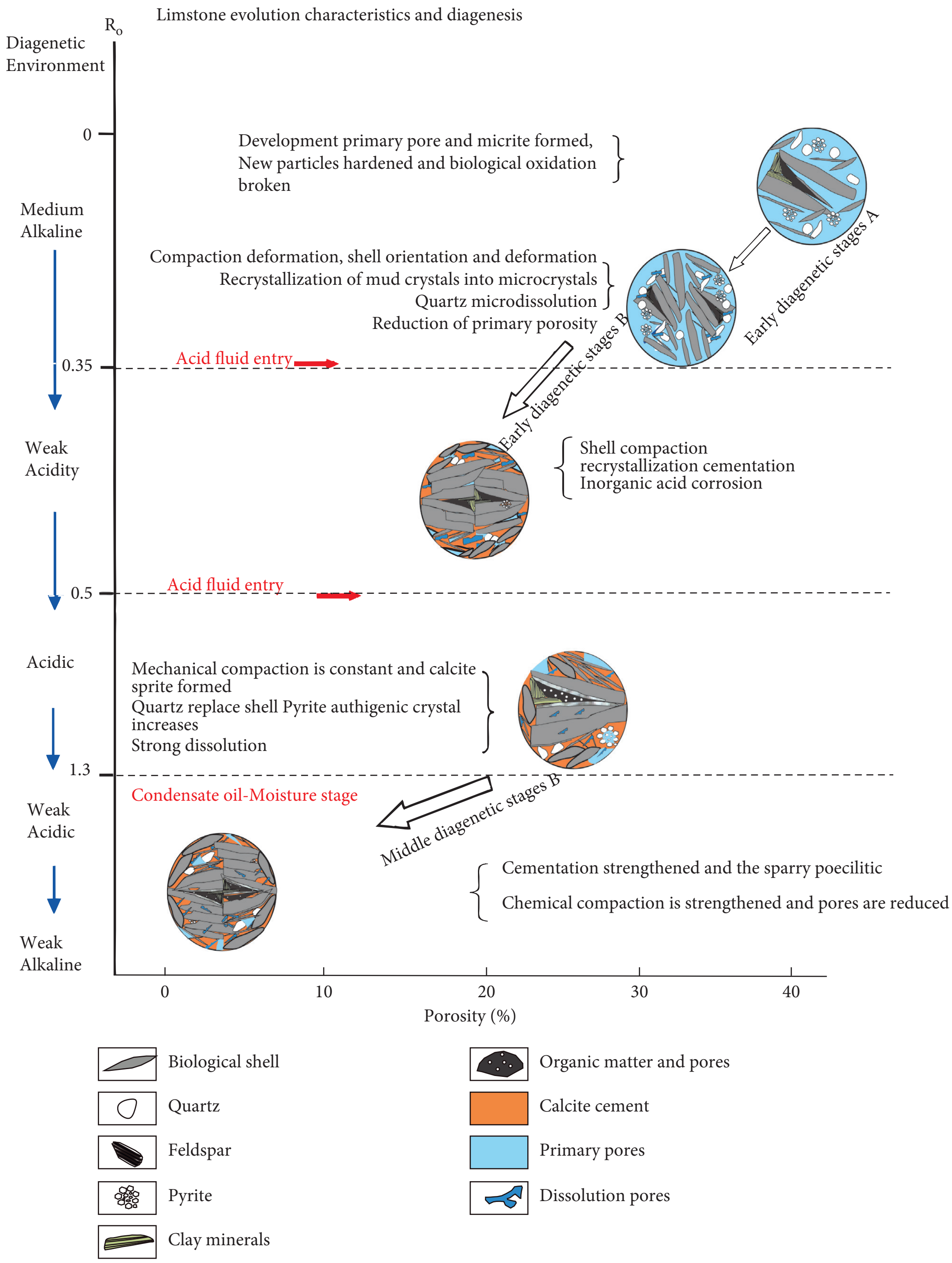


Figure 11: Diagenesis and pore evolution model of limestone in Da'anzhai Member in northern area.

5.2.1. The Impact of Compaction on Reservoir. Fine-grained sediments associated with compaction are caused by the 90% reduction in the original pores of pure mudstone and shale composed of clay minerals at various stages of the consolidation diagenesis process. It is the most important diagenesis that controls whether the shale reservoir space of the Da'anzhai Member is preserved. Under pressure, the original fluid of the mud-grained sediments is discharged, the pore volume between the primary grains is greatly reduced, most of the pores in the mud disappear, and the physical properties become worse; the rock type and mineral composition of the fine-grained sedimentary rock also have changed significantly. This change is extremely obvious in the early diagenesis of mud-grained sediments, with some directional arrangement of particles; relatively the influence of felsic and carbonate minerals is less than that of

Figure 12: Schematic diagram of gray-black shale core immersion test. The gray-black shale of the Da 2 submember of Da'anzhai Member is better, and many needle-like, granular bubbles are found intermittently in the shale, North-2 Well, 3909.78~3910.08 m.

the shale component. The silty mudstone and argillaceous siltstone in this section are also clearly reformed by compaction. This is because the clastic in which quartz is most formed due to sedimentation and diagenesis is mostly distributed in the clay, and the quartz and clay are interspersed and mixed, compaction and consolidation are stronger, and later transformation is also more difficult.

Sedimentation makes siliceous or organic matter in continental shale mostly develop layered or laminar structures, and shell shale lamellation is developed. Sediment mud-sized quartz particles and other particles present micron-level weak laminar arrangement, which is beneficial to structural transformation and compaction deformation in the later period, making it easy to form microlaminates and microcracks. The strong compaction effect makes the water flow out of the mud and also causes the microaggregation of different components of the mud, the aggregation of flake minerals and the weakly oriented laminate arrangement, forming bedding fractures; during the subperiod B and later stages of middle diagenetic rocks, compaction transformed into dissolution, forming parallel gaps with a certain opening, which prepares space for the accumulation and storage of free gas and absorbed gas, and it is also an important type of fracture developed in the rock. The occurrence of bedding fractures is parallel or approximately parallel to the interface of the laminae, and the bedding fractures are also clearly developed in the thin shale interval with dense laminae, reflecting that the degree of development of bedding fractures in shale is closely related to the laminae [33–36]. The openings of bedding fractures usually vary greatly. Where the openings of bedding fractures are large, the fracture surfaces are mostly distributed in a bay-like shape, with obvious dissolution characteristics [35, 36].

In the outcrops and core, the bedding fractures in shale are usually parallel or approximately parallel to the bedding plane and are distributed intermittently, with small scale and high density of bedding fractures (Figures 2 and 3). Bedding fractures are formed primarily in the process of compaction and dissolution. They are an effective storage space and seepage channel for shale reservoirs and are significant in improving the quality of shale reservoirs. Whether the deposition and compaction to form microlaminates with different components (laminates under the microscope) are developed and whether the siliceous and limeous components are arranged in a microscopic orientation determines the quality of the reservoir.

5.2.2. The Impact of Cementation on the Reservoir. Cementation will reduce the porosity and permeability of the fine-grained sedimentary rock reservoir, which is mainly made up of fragile minerals. There are mainly calcareous and silica cements in the Da'anzhai Member in the northern and eastern area. Siliceous cementation is mainly manifested as the filling of authigenic quartz crystallites and can be found in mud shale, shell shale, and shell limestone in this section. Most of the cements are diagenetic transformation crystals of clay minerals and quartz metasomatism for Calcite shell, and autogenous quartz crystals filling the micropores are rare. Sparry calcite cements are commonly developed in the shell limestone and shell shale. Strong cementation is the main factor in the compactness of the limestone in this section of the Sichuan Basin. The moderate degree of cementation ensures that the shell shale can accumulate oil and gas in this area.

5.2.3. The Influence of Dissolution on Reservoir. The shell limestone of the Da'anzhai Member is mainly developed in the shell-shoal microfacies of shallow lake subfacies. The strong wave action results in good permeability, rich diagenetic fluids, strong dissolution of early shell limestone, formation of early secondary pores, and easy diagenetic fluid. The shell limestone appears during multiple periods of dissolution and filling, but the pores and fractures are mostly healed by the fillings in the later period, and the pores are not easy to preserve. It is difficult for the late shell limestone of the Da'anzhai Member in northern and eastern areas to form a larger permeable circulation system with adjacent shale. Diagenetic flows containing organic acids rarely seep into shell limestone, and late dissolution of shell limestone is rare. However, these diagenetic fluids can only circulate in a small area in the shell shale that is close to the acid source and developed with microlamellar layers. Compared with conventional reservoirs, fine-grained sedimentary rocks have smaller pores, lower permeability, and insignificant fluid exchange. It is a relatively small and gridded closed diagenetic system. The dissolution caused by organic acids is more common in shell shale.

The shell limestone of the Da'anzhai Member in the central Sichuan area (in the central Sichuan structure) is mainly developed in the shell beach microfacies of shallow lake subfacies, and the wave actor is strong. The shell limestone is susceptible to leaching and dissolution, forming secondary pores, cementing, and metasomatism, which is strong in the early diagenesis period, filling the early dissolved pores and intergranular pores in the shell; in the late early diagenesis and the middle diagenesis substage A, due to the formation of organic acids, the calcite minerals dissolved again, and there are more intergranular dissolved pores and grain margin fractures. The developed dissolution has greatly improved the reserve performance of limestone reservoirs in the Da'anzhai Member in the central Sichuan Basin.

5.2.4. The Influence of Metasomatism on Reservoir. In general, quartz has been found to replace calcite in the mudstone and limestone of the Da'anzhai Member (Figures 3(d) and 3(e)). The early metasomatism of the carbonate shell by quartz formed a shell case that is relatively less erodible and resistant to compaction, which is a kind of protection for the shell, and this kind of protected shell is not easy to corrode. The solubility of calcite and SiO2 changes with temperature and Ph value in the opposite way. Quartz metasomatic calcite mainly occurs under shallow burial conditions. In this section, the calcite, which replaces the quartz and clay minerals, reduces the porosity of fine-grained sedimentary rocks; the dolomite that replaces calcite increases the storage space.

5.2.5. The Impact of Clay Mineral Transformation on Reservoir. As the burial depth increases, the temperature and pressure increase correspondingly, the layered clay minerals will undergo conversion between clay minerals, and the disordered mixed layer will transform into ordered clay minerals, forming the orderly mixed layer in the Da 2 submember of the northern and eastern area, which contains less than 10% montmorillonite, and the intense transformation also formed thick flaky illite with high crystallinity and high order, accompanied by a large number of clay mineral flaky holes and contraction fracture; it discharged a large amount of interlayer water and iron-magnesium-containing materials, which are conducive to the formation of microscopic pores in fine-grained sedimentary rocks and the catalysis of hydrocarbon generation.

5.2.6. The Impact of Diagenetic Evolution of Organic Matter on the Reservoir. Different regions of fine-grained sedimentary rocks in this section have different degrees of evolution and different reservoir reforms. Organic acids formed by the evolution of organic matter in the Da'anzhai Member in central Sichuan Basin play an important role in the dissolution of shell limestone and micrite limestone; carbon-rich shale organic matter discharges acid and hydrocarbon in large quantities in the Da'anzhai Member of the northern and eastern area, and it also contributes to microfractures. The development of dissolution pores is also mainly controlled by organic acids produced during the maturation of organic matter. The favorable organic matter types and thermal maturity of fine-grained rocks in the Da'anzhai Member provide abundant nanopores and improve the quality of fine-grained sedimentary rocks reservoir physical properties.

In summary, the better physical properties of shale and shell shale reservoirs in the Da'anzhai Member in northern and eastern areas are mainly due to the fact that such rocks have microlamellar layers, highly ordered clay minerals, and higher organic matter content; moreover, the transformation of clay mineral and organic matter evolution play an important role in the porosity of the reservoir during the diagenetic evolution process, resulting in better storage performance than the limestone and argillaceous siltstone of the same interval. The shell shale produced a large amount of gas during the test, but the adjacent shell limestone has no bubbles. Appropriate dissolution and relatively little cementation in the central Sichuan area make this section of limestone a conventional reservoir. Compaction and cementation in this section are the most important diagenesis for the deterioration of the physical properties of fine-grained sedimentary rock reservoirs. Dissolution has a certain impact on the reservoir, while metasomatism and recrystallization have little effect on the physical properties of the reservoir.

6. Conclusion

(1) The fine-grained rock of the Da'anzhai Member has undergone compaction, cementation, dissolution, recrystallization, metasomatism, transformation of clay minerals, the formation of authigenic minerals, and the organic matter evolution, forming ultra-low-porosity-low-permeability shale and limestone reservoirs; compaction and cementation are the main factors that control the shale and limestone physical. Dissolution has a certain impact on the reservoir, while metasomatism and recrystallization have little impact on the reservoir.

(2) The fine-grained rock of the Da'anzhai Member in central Sichuan Basin is in substage A of mid-diagenetic rocks, and the Da'anzhai Member in northern and eastern areas is in the substage B of mid-diagenetic rocks; the difference in diagenesis leads to the Da 1 submember limestone as the conventional reservoir and the target layer in the central Sichuan area, the Da 2 submember carbon-rich shale as unconventional shale oil and gas reservoir and target layer in northern and eastern area.

(3) Strong cementation is the main reason for the tightness of the limestone reservoirs in the Da'anzhai Member of the northern and eastern areas. The difference between dissolution and late cementation is the main controlling factor for reservoir formation, which decides whether limestone or argillaceous limestone in the same section can be reservoirs in the central Sichuan Basin, and proper dissolution makes it a favorable conventional limestone reservoir.

(4) The degree of development of internal laminae and microlaminates in shale reservoirs is formed by the original deposition, compaction, and other processes of the Da'anzhai Member in the northern and eastern area, and whether the brittle minerals (quartz, calcite, etc.) are arranged in an orderly microlaminated layer has a significant impact on fine-grained sedimentary rock reservoirs; organic-rich shale and shell shale are favorable reservoir rocks in this section.

Data Availability

The data used to support the study are available within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

Thanks are due to the special project undertaken by Sinopec Petroleum Exploration and Production Research Institute leading experts such as Hu Zongquan, Liu Guangxiang, Feng Dongjun, Zhu Tong, Liu Zhongbao, and Wang Pengwei and collaborators such as Professor Jin Zhenkui, Associate Professor Zhao Jianhua. Thanks are also due to the graduate students Wang Huan, Li Xin, Xiao Jinguang, Li Zhong, Guo Qiheng, Li Shuo, Lu Pin, and other students who participated in the research work in the past five years. Special thanks are due to the students and reviewers for the hard work of the postcompilation papers.

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