Research Article

Study of Diagenesis and Pore Evolution of Triassic Jialingjiang Formation in Southern Puguang Gasfield

Qi Chen,^{1,2} Quan-wen Liu,² and Shenjian Wang²

¹State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu, Sichuan 610500, China

²Guangdong University of Petrochemical Technology, Guangdong, Maoming 525000, China

Correspondence should be addressed to Quan-wen Liu; lqw005533@163.com

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The second member of Jialingjiang formation is considered to be an important gas reservoir with good exploration prospects in the southern Puguang gasfield. The diagenesis types are analyzed and different diagenetic stages are divided by analyzing carbon and oxygen isotopes as well as observing the slices. The widespread forms of diagenesis in the research area principally include compaction, cementation, pressure solution, dolomitization, recrystallization, dissolution, and tectonic disruption, among which cementation, dissolution, dolomitization, and recrystallization contribute greatly to the development of porosity in the reservoir. The reservoir has experienced four diagenetic stages: syndiagenetic stage, early stage of diagenesis, diagenetic stage, and late diagenetic stage. Most of the primary pores were destroyed in the diagenetic evolution stages of reservoir; the present porosity mainly belongs to the secondary pores.

1. Introduction

Puguang gasfield is located in the northeast of Sichuan basin and considered the largest gasfield in the marine carbonate environment in China. Permian Changxing and Triassic Feixianguan formations are the main dolomite reservoir forming layers [1, 2] with characteristics of large thickness and good physical properties.

With the development of exploration and research, geologists have gradually realized that the lower Triassic Jialingjiang formation has developed a good dolomite reservoir and could also be considered as a key exploration target. Jia-2 members are formed in the shallow sea with thicknesses of 168 m to 215 m (Figure 1). Their lithology, which consists of argillaceous limestone, dolomite, and gypsum rocks, is dominated by algal dolomite and doloarenite. As for a typical low porosity and low permeability reservoir, there is strong heterogeneity, rock porosity is between 1.96% and 4.2%, and permeability is generally less than 10 mD. Diagenesis has great influence on the pore evolution and transformation of the reservoir, especially dolomitization, compaction, pressure solution, and cementation [3–5].

2. Types of Diagenesis

Carbonate diagenesis includes the processes that occur between the deposit formation and initial metamorphism under high temperature and pressure, including the ones such as cementation, dolomitization, and dissolution. It also includes some microscopic processes such as the development of micropores, trace element migration, and stable isotope variation.

While cementation, compaction, and pressure solution have a negative influence on reservoir porosity and recrystallization and metasomatism have little effect on the physical properties of the reservoir, dolomitization, dissolution, and tectonic rupture are the main processes that improve the reservoir properties and also the major influencing factors on the carbonate reservoir pore spaces of Jia-2 member in southern Puguang gasfield.

2.1. Cementation. Cementation comprises processes leading to the precipitation of minerals in primary or secondary pores and requires the supersaturation of pore fluids with respect to the mineral. It is a very significant factor in diagenesis and

FIGURE 1: The Jia-2 formation of the top surface structure of the study area.

FIGURE 2: Silty dolarenite, S2, 2355.04~2355.65 m, T_1j^2 .

is a form of destructive diagenesis, with the early diagenetic cementation leading to reduced primary porosity.

Based on the calcite cement structure from the core slice, the cementation of Jia-2 member is divided into three stages.

The primary pores and the early dissolution pores were all filled during early cementation and the cement is mainly of fibrous or foliaceous types (Figure 2). A comparison of

the morphological characteristics of calcite cementation of carbonate rocks in different diagenetic environments showed this kind of cement to be the main diagenetic feature in the syngensis-marine environment.

In the fine-grained calcite cement, generally produced from the fillings in the interstices among carbonate grains, the calcite surface is comparatively clean and calcite crystals gradually become thicker from the grains to the center of the interstices (Figure 3). This type of cementation is closely related to the presence of atmospheric water; it is assumed that the cement might be produced due to the cementation of the atmospheric water before burial and compaction processes.

The late cementation and filling mainly show the filling of the early corrosion holes and tectonic fissures in dolomite grains and the cementation of some intercrystalline dissolution pores. Therefore, it is possible to conclude that the cement is a diagenetic product.

2.2. Compaction and Pressure Solution. The compaction of carbonate rocks in Jia-2 member of the southern Puguang gasfield is different; while some areas are strong, others

FIGURE 3: Gypseous dolarenite, S1, 3575.24~3575.56 m, T_{1j}^2 . FIGURE 5: Dolarenite, S2, 3655.65~3655.84 m, T_{1j}^2 . FIGURE 4: Dolarenite, S1, 3585.04~3585.16 m, T_{1j}^2 . FIGURE 6: Dolomicrite: bird's-eyes were filled with calcite or gypsum, S1, 3571.8~3572.1 m, T_{1j}^2 .

are feeble, which might be related to the difference in the sedimentary fabric of the carbonate rocks. In the strongly compacted areas, the carbonate particles are generally similar to lenticular and augen (Figures 4 and 5).

The occurrence of pressure solution is a very common phenomenon in carbonate rocks, and it always develops in the rocks with significantly different sedimentary structures. The dissolution products formed by pressure solution provide a source for cementation and filling in other locations. Stylolite is a direct evidence of pressure solution. The process of pressure solution in Jia-2 member of the southern Puguang gasfield is quite developed, which is mainly embodied in the form of developed stylolite. While the microfabric on the two sides of stylolite is clearly different, it exhibits uniformity on the same side.

2.3. Dolomitization. Dolomitization in Jia-2 member is the most significant type of diagenesis. A characteristic analysis of dolomite grains and geological conditions shows that penecontemporaneous dolomite may also have different development patterns [6–8].

Most of the dolomite muds, in which parallel laminae, bird's-eyes, and mud plates are developed, rarely contain fossils (Figures 6 and 7). Based on the low degree of order and enrichment of the carbon and oxygen heavier isotopes, two kinds of genetic models of dolomite were put forward

FIGURE 7: Gypseous dolomicrite: bird's-eyes were filled with gypsum, S1, 3586.79~3586.95 m, T_{1j}^2 .

for the study area, that is, capillary concentration model and evaporative pumping model (Figure 8).

Many geological data records have shown that the Jialingjiang formation developed gypsum-salt layers with different thicknesses, which means that the formation continued to develop intermittently under high salinity and evaporative environments. The high Mg/Ca ratio and Mg^{2+} -rich hypersaline fluids permeated into the underlying carbonate sediments, and the impact of seepage reflux also promoted the formation of carbonate sediments (Figure 9). The dissolution

TABLE 1: Carbon and oxygen isotopic sampling data for carbonate rocks.

Order	Sample description	Well	Layers	Depth (m)	$\delta^{13}\text{C}$ PDB (‰)	$\delta^{18}\text{O}$ PDB (‰)
1	Dolomicrite	S1	T_{ij}^2	3568.89–3568.93	1.62	−3.66
2	Calcareous dolarenite	S1	T_{ij}^2	3571.51–3571.56	0.84	−3.92
3	Gypseous dolomicrite	S1	T_{ij}^2	3571.8–3572.1	−0.58	−3.71
4	Argillaceous gypsodolomite	S1	T_{ij}^2	3576.9–3577	4.77	−3.12
5	Globular dolomite	S1	T_{ij}^2	3580.7–3580.26	4.54	−2.62
6	Gypsodolomite	S1	T_{ij}^2	3583.1–3583.21	4.88	−3.02
7	Gypseous dolarenite	S1	T_{ij}^2	3585.04–3585.16	4.88	−3.37
8	Dolarenite	S1	T_{ij}^2	3586.58–3586.76	5.12	−4.33
9	Gypseous dolomicrite	S1	T_{ij}^2	3586.79–3586.95	4.34	−4.35
10	Fine silty dolomite	S2	T_{ij}^2	3648.94–3649.23	1.47	−5.78
11	Fine silty dolomite	S2	T_{ij}^2	3651.19–3651.43	1.55	−2.62
12	Fine silty gypsodolomite	S2	T_{ij}^2	3654.96–3655.12	4.93	−2.79
13	Gypsodolomite	S2	T_{ij}^2	3666.35–3666.44	6.2	−4.43
14	Fine silty dolomite	S3	T_{ij}^2	2364.6–2364.66	3.67	−5.22
15	Fine silty dolarenite	S3	T_{ij}^2	2366.53–2366.65	−0.81	−3.43
16	Calcite dolomite	S3	T_{ij}^2	2374.15–2374.23	1.57	−3.88
17	Calcite dolomite	S3	T_{ij}^2	2378.64–2378.75	0.28	−5.15
18	Microspar dolarenite	S3	T_{ij}^2	2378.75–2379.1	−3.18	−5.35
19	Gypsodolomite	S4	T_{ij}^2	3827.79–3827.89	3.15	−2.61
20	Sparry gypsodolomite	S4	T_{ij}^2	3828.22–3828.35	4.12	−2.88
21	Granular gypsodolomite	S4	T_{ij}^2	3828.85–3828.96	4.25	−2.78
22	Fine silty gypsodolomite	S4	T_{ij}^2	3830.45–3830.58	4.68	−5.32
23	Laminated fine silty dolomite	S4	T_{ij}^2	3831.6–3831.72	5.22	−3.56
24	Fine silty dolomite	S4	T_{ij}^2	3832.52–3832.64	5.32	−3.87

FIGURE 8: The mechanism of evaporation pump.

FIGURE 9: The mechanism of seepage reflux.

of dolomite grains and dolomitization in the high porosity layers of the grain bank are related to the mixed action of water, which can explain the development of the mixed dolomitization [9].

Oxygen and carbon isotope analyses were carried out on the dolomite with different fabrics in Jia-2 member. According to the basic principles of carbon and oxygen isotopes and the corresponding data (Table 1), the factors that controlled the sedimentary and diagenetic environment of dolomite sediments were analyzed.

(a) *General Characteristics.* Usually, the original $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (‰) values of seawater are relatively large with abundant

heavy oxygen and heavy carbon isotope contents, while the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of evaporate rocks (dolomite, gypsum) are even larger. The fluid system affected by fresh water and $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values of its minerals is relatively low and the values vary in a large range.

Based on the drilling data from south Puguang gasfield, the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (‰) isotopes have abundant heavy oxygen and heavy carbon content and show the average values of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ as -3.82‰ and 2.96‰ , respectively. The values of oxygen and carbon isotopes are moderately concentrated. Oxygen isotopic values vary from -5.78‰ to -2.61‰ , and carbon isotopic values range from -3.18‰ to -5.32‰ (Figure 10).

TABLE 2: Relationship between carbon and oxygen isotopic and sedimentary environment.

	Grain dolomite	Dolomicrite	Gypsodolomite	Calcite dolomite	Gypsum limestone
$\delta^{13}\text{C}$ (PDB, ‰)	1.02	1.91	2.25	1.59	2.58
$\delta^{18}\text{O}$ (PDB, ‰)	-3.92	-4.2	-3.6	-4.67	-4.62
Depositional environment	Intertidal flat	Tidal flat	Tidal flat	Tidal flat	Tidal flat
Dolomitization	Mixed water	Seepage reflux	Evaporating pumping

FIGURE 10: The distribution of oxygen and carbon isotope.

FIGURE 12: Relationship between carbon isotope and porosity.

FIGURE 11: Relationship between carbon isotope and porosity.

(b) *Characteristics of Carbon Isotope.* Carbonate rocks store organic and inorganic carbon dioxide. The lack or enrichment of carbon isotopes is caused by oxidizing or fermentation reactions or by deep-seated reducing heat fluid action; therefore, the $\delta^{13}\text{C}$ value in carbonate minerals can indicate the carbon source [10].

Carbonate and organic carbon are the main carbon pool of sedimentary rocks and their average $\delta^{13}\text{C}$ value varies from 1‰ to -23‰, respectively. With regard to the isotopic composition characteristics, the carbon can have completely different origins. According to the above data, the proportion of organic carbon in the Jia-2 member of dolomite is low; that is, organic carbon is not included in the formation of carbonate deposits and diagenesis. The carbon isotope content of Jia-2 member shows that the layers with high porosity have low values of carbon isotopes [11]. This value is lower than that of normal seawater and higher than that of fresh water, which is influenced by the atmospheric water and may be the result of the mixed water [12]. The layers with low porosity have a high value of carbon isotopes, likely due to the seepage reflux and evaporative pumping (Figure 11).

Based on the basic lithological data, that is, grain dolomite $\rightarrow$ calcite dolomite $\rightarrow$ dolomicrite $\rightarrow$ gypsodolomite, the average value of $\delta^{13}\text{C}$ has increased gradually, which reflects that the main body of rocks is controlled by evaporation and high salinity water (Table 2). The carbon isotope of the porous layer as well as the beach sediments is relatively light, which has a good correlation with the sedimentary environment.

(c) *Characteristics of Oxygen Isotope.* General characteristic shows that $\delta^{18}\text{O}$ in dolomite is between -5.78 and -2.61‰ and the average is -3.82‰, so the dispersion is not great, confirming the presence of a comparatively uniform sedimentary diagenetic environment [13]. Similar to the carbon isotope, the oxygen isotope in the high-pore layer is comparatively light but heavier than the atmospheric water, which indicates the influence of mixing water (Figure 12).

Thus, it can be said that mixing water dolomitization is very important in the formation of reservoirs; however, since it is influenced by the sedimentary environment in Jia-2 member, steady facies cannot always be observed. Therefore, not many regions and tectonics are completely dolomitized by mixing water. Only when the sedimentary environment is in the facies stage and can be dolomitized with mixing water can an effective reservoir come into being.

2.4. *Dissolution.* Dissolution is a very important constructive diagenesis for Jia-2 member, and it plays a very central role in the formation of the effective reservoir. Through the observation and analysis over large amounts of slices, it was found that the major dissolution in the third stage of the carbonate development, respectively, corresponds to the syngenetic diagenetic stage, the middle diagenetic stage, and the late diagenetic stage [14].

The first-stage dissolution mainly took place during the syngenetic stage with a close relation to the effect of the atmospheric water embodied as the bird's-eyes structures that are

FIGURE 13: Gypsous dolomicrite, S3, 2361.56~2361.72 m, T_{1j}^2 .

FIGURE 14: Silty dolomite, S2, 3648.94~3649.23 m, T_{1j}^2 .

commonly developed in fine silty dolomite. Since the development took place very early, after a long buried diagenesis process, all the dissolution pores were almost filled with gypsum and calcite. Therefore, the first-stage dissolution does not contribute much to the carbonate reservoir in Jia-2 member.

The second-stage dissolution took place during the middle diagenetic stage in a buried environment. The dissolution commonly took place along the stylolites and was closely related to the filling with organic matter (Figures 13 and 14). This kind of dissolution is quite common along the stylolites.

The third-stage dissolution is the most constructive diagenesis phase in the development of the carbonate reservoir. This dissolution phase set in comparatively late; therefore, almost all the dissolved pore space was reserved. The typical third-stage dissolution includes one of the fissures or calcite that had been filled with calcite or gypsum in early stages as well as the intracrystal pores in the coarse crystals dolomite.

2.5. Tectonic Disruption. The tectonic disruption is also a type of important constructive diagenesis for Jia-2 member, and there might be many formations of disruption and fissure. By analyzing large amounts of slices, two periods of tectonic disruption were found as indicators of significant differences in the filling due to the different time of the fissure formation. During first tectonic disruption stage, the fissures were developed with gypsum or filled with calcite. The tectonic disruption of the second stage took place comparatively

late. The unfilled fissures can often be seen in the dissolved stylolites filled with organic matter. The fissures that occurred in this stage might be related to the tectonic uplifting in the late diagenetic stage in east Sichuan, which is of comparatively high opening and no obvious filling.

3. The Formation and Evolution of the Reservoir

According to the time sequence of different types of diagenesis stages and based on the detailed analysis of different slices, combined with the study area's burial evolution, the hydrocarbon evolution, and the maturity of organic matter, the diagenetic stages can be divided into syngenetic diagenetic stage, early diagenetic stage, middle diagenetic stage, and late diagenetic stage. The corresponding diagenetic environment and diagenetic fluid are of seawater-fresh water-mixing water, shallow burial environment, middle-deep burial stages, and middle-shallow burial stage (Figure 15).

The evolution history of diagenesis reflects the evolution history of reservoir pores. During the tectonic evolution of the area and the primitive sedimentary environment macrocontrol, the pore evolution of reservoirs is decided by the diagenetic types and syngenetic combination in different reservoirs [15].

From the diagenetic stages evolution history, it can be seen that Jia-2 member experienced multistage diagenesis with complicated and diverse diagenetic types.

In the syngenetic diagenesis, the rocks have a loose structure with large quantity pore water and weak compaction. The primary pore evolution includes intraparticle pores, interparticle pores, and skeleton pores. The syngenetic dolomite evolved into small amount of intracrystal pores. In the early diagenetic stage, the compaction was strengthened so the porous water was quickly expelled and the primary pores reduced clearly. When the burial depth increased, the compaction became even stronger and the early cementation took place, so the primary pore was dramatically reduced or even disappeared. The interparticle fluid dissolved along the contact surface of grains formed afterwards and compaction dissolution fissures. Some intracrystallization pores were formed as a result of mineral transformation and recrystallization. In the middle diagenetic stage, dolomite was developed and dissolution was strengthened so large amounts of intracrystal pores and various secondary pores appeared, including interparticle pores, intraparticle pores, and intercrystal pores, which made up good reservoir space. At the latest diagenetic stage, the base of secondary pore development in early and middle diagenetic stages, the dissolution was further enlarged to form some moldic pores and superlarge pores. At the same time, the tectonic fractures developed in many stages, spread in the shape of reticula, and finally formed dolomite of high porosity.

4. Conclusion

- (1) The main diagenesis types of carbonate rocks in the research area include compaction, cementation, pressure solution, dolomitization, recrystallization,

FIGURE 15: Characteristics of diagenetic evolution.

dissolution, and tectonic disruption. Among them, cementation, dissolution, dolomitization, and recrystallization contribute greatly to the porosity development of reservoirs.

- (2) Reservoir has experienced four stages, including syngenetic stage, early stage of diagenesis, diagenetic stage, and the late diagenetic stage. Most of the primary pores in the diagenetic evolution reservoir have been destroyed, and, at present, the pores mainly belong to the category of secondary pores.

Competing Interests

The authors declare that they have no competing interests.

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