Origin and Distribution of Grain Dolostone Reservoirs in the Cambrian Longwangmiao Formation, Sichuan Basin, China

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Abstract: Dolostones in the Cambrian Longwangmiao Formation have become one of the most significant gas exploration domains in China. Over a trillion cubic meters of gas reservoirs have been discovered in the Gaoshiti-Moxi area; however, the origins and distribution of the dolostone reservoirs are not well understood. This work discussed the geology and geochemistry of the dolostone reservoirs in the Longwangmiao Formation to determine their origin and distribution. Two understandings are acquired: firstly, a carbonate ramp provided excellent conditions for grain beach deposition, while the presence of a hypersaline lake was favorable for the contemporaneous dolomitization of grain beach deposits. Petrographic and geochemical evidence further confirm that the Longwangmiao dolostone was formed during the contemporaneous stage. Secondly, the reservoir characteristics indicate that the grain beach sediments provide material basis for the development of the Longwangmiao dolostone reservoirs. Reservoir dissolution simulation experiments show that the porosity of the reservoirs was formed by dissolution during contemporaneous and burial stages. The dissolution pores formed during the contemporaneous stage were controlled by sequence interfaces. The large scale dissolution vugs formed during the burial stage subsequently spread along the pre-existing porosity and fracture zones. This study therefore identified that the development of grain dolostone reservoirs in a shallow water ramp under arid climatic conditions generally met the following conditions: (1) reefal beach deposits lay a foundation for reservoir development; (2) superficial conditions are an important determining factor for reservoir porosity; and (3) burial conditions provide environment for porosity preservation and modification.

Key words: Sichuan Basin, Longwangmiao Formation, grain dolostone, meteoric dissolution, buried dissolution, origin of reservoir, distribution of reservoir

1 Introduction

Although the Cambrian strata show a significant potential in the Sichuan Basin, gas exploration in the past 50 years has been focused on the Sinian Dengying Formation with the Cambrian in a subordinate position. In 1996, the drilling of the Middle-Upper Cambrian Xixiangchi Formation in Weiyuan structure (<2500m) obtained gas yield of 2.28×10^4 m^3/d through drill-stem tests. After more than 40 years of exploration in Cambrian, 14 fractured reservoir systems were discovered in 2004–2006, with total gas yield of 35.2×10^4 m^3/d. Since very few wells specifically targeted at this interval, the Cambrian sequence has not been fully explored. In 2005, the porous dolostone gas reservoir was discovered in the Lower Cambrian Longwangmiao Formation for the first time in the Well Weihan 1. This well, targeting specifically at the Cambrian, obtained gas yield of 11×10^4 m^3/d, which opened the prelude of Cambrian Longwangmiao Formation exploration. Since then, the Longwangmiao exploration has been focused on the deep section (below 4500m), and over trillion cubic meters of gas reservoirs have been discovered in the Gaoshiti-Moxi area east of Weiyuan structure in 2011–2013 (Pang Xiongqi et al., 2015) (Fig. 1).

With the deepening of exploration, the origins and distribution of dolostone reservoirs have not been fully understood in the Longwangmiao Formation dolostone exploration. Because of the strong heterogeneities of the dolostone reservoir, it is difficult to predict the reservoir distribution based on limited well data. It is also difficult to extrapolate the data from the existing discoveries to adjacent area.
The origins and distribution of dolostone reservoirs in the Longwangmiao Formation are not fully understood. The strong heterogeneities of the dolostone reservoir and limited well data have caused difficulties in the prediction of the reservoir distribution. Difficulties have also arisen in the extrapolation of data from the existing discoveries in the adjacent areas. However, many studies have evaluated the dolostone reservoirs in Longwangmiao Formation in the Sichuan Basin (Dai Zongyang et al., 2007, Li Ling et al., 2008, Yang Yu et al., 2013). Dai Zongyang et al. (2007) formed conclusions based on the research in Leshan-Longnvshi area that the dolostone reservoir in the Longwangmiao Formation was a fracture-cavity type. Li Ling et al. (2008) considered the Longwangmiao dolostone reservoirs in the Weiyuan area were controlled by a beach facies deposit, and the contemporaneous dissolution related to eustatic sea level change. Yang Yu et al. (2013) proposed the reservoirs in the Gaoshiti-Moxi area were controlled by a beach facies deposit, and the supergene karst related with Tongwan movement. However, the above studies did not clarify the origin and distribution of the Longwangmiao dolostone reservoirs or the main controlling factors in the distribution of the reservoirs. In this study, the Longwangmiao dolostone reservoirs were characterized through a field geological survey, rock and thin section identification, reservoir geochemistry and reservoir simulation experiments. This information was utilized to infer the origin of the reservoirs and form conclusions regarding the factors controlling the reservoir distribution. This study therefore provides information to assist with the exploration of the Longwangmiao Formation.

2 Geological Setting

The Cambrian sequence in the Sichuan Basin is well developed and lies as a disconformity in contact with the Sinian Dengying Formation. The Upper Cambrian and Lower Ordovician units were formed during continuous deposition. The Cambrian system is subdivided into the Lower Cambrian Qiaongzhushi, Canglangpu and Longwangmiao Formations and the Middle-Upper Cambrian Gaotai and Xixiangchi Formations. The Qiongzhushi Formation is 91–400 m thick and is considered to be the main source rock. The stratigraphy (from lower to upper units) includes black carbonaceous shale, shale, sandy shale, siltstone, and sandstone. The Canglangpu Formation is a clastic sedimentary unit with a total thickness of 50–200m, consisted of a lower mauve shale unit and an upper carbonate unit which is interbedded with shale. The Longwangmiao Formation is composed mainly of dolostones, containing limestone in the base, evaporate in the middle and some clastics in the top, with a total thickness of 39.5–797m. The Gaotai Formation is mainly dolostone, with a total thickness of 50–100 m. The formation is characterized by mauve and varicolored sandstone, and mudstone which contains a dolostone composition. The Xixiangchi Formation is mainly dolostone, with a total thickness of 100–500 m.
Liu Baojun et al. (1994) suggested that the carbonate ramp developed during the Early Cambrian as the Longwangmiao Formation was being deposited. Three local depressions formed in the upper Yangtze shallow water ramp, located west of Leshan area and south of Chongqing. These local depressions formed three shallow water evaporitic basins, with a combined area of $3 \times 10^4 \text{ km}^2$–$5 \times 10^4 \text{ km}^2$. Drilling of the Lin 7 well identified gypsum in the Longwangmiao Formation, with a total thickness of 690.5 m. This confirmed the existence of a gypsum basin in the southern Sichuan Basin. Along the gypsum basin margins, oolitic, arenstritic and bioclastic bank bodies were formed as high energy deposits near the paleographic highs. As a result of sea level eustacy and wave disturbance, the bank bodies migrated laterally, leading to widespread occurrence of beaches in carbonate ramp during the deposition of the Longwangmiao Formation. The presence of a gypsum basin provided a favorable setting for the contemporaneous dolomitization of grain beach.

Wang Zhecheng (2013) concluded the tectonic evolution of Sichuan Basin can be divided into seven stages: (1) rifting basin stage in Nanhua period; (2) Weiyuan-Longnvshi paleo-uplift forming as a result of the Chengjiang movement; (3) uplift and erosion associated with the Tongwan movement, which controlled the development of karst reservoirs of Member II and Member IV in the Dengying Formation; (4) extensional movement associated with the Xingkai movement, which controlled the deposition of materials during the Early Cambrian period; (5) Leshan-longnvshi paleo-uplift forming during the Late Silurian as a result of the Caledonian movement. The Longwangmiao strata was exposed and eroded in the southern Sichuan Basin. Along the gypsum basin margins, oolitic, arenstritic and bioclastic bank bodies were formed as high energy deposits near the paleographic highs. As a result of sea level eustacy and wave disturbance, the bank bodies migrated laterally, leading to widespread occurrence of beaches in carbonate ramp during the deposition of the Longwangmiao Formation. The presence of a gypsum basin provided a favorable setting for the contemporaneous dolomitization of grain beach.

3 Methodology

Samples used in this study were sourced from Weiyuan-Gaoshiti-Moxi area in the Lower Cambrian Longwangmiao Formation, located in the Sichuan basin, China (Fig. 1). Samples were collected for petrographical and geochemical analyses, and for use in reservoirs simulation experiments.

Ten samples were cut into large thin sections and stained with Alizarin red S and potassium ferricyanide (Dickson, 1965). The thin sections were examined using an optical and cathodoluminiscence (CL) microscope. CL microscopy was performed on a CL8200MK5 cold cathode apparatus attached to a Leica 4500 microscope, operating at 10–15 kV voltage and 400–500mA beam current.

Carbon, oxygen and strontium isotope measurements were undertaken on the different fabric components of six samples, using a micro-drill to generate powders for analysis. For stable carbon and oxygen isotope analysis, approximately 10 mg of powdered was reacted with 100% phosphoric acid for 4 hours at 90°C. The resultant CO2 was measured for oxygen and carbon isotopic ratios on a DELTA V Advantage mass spectrometer. The $\delta^{13}$C and $\delta^{18}$O were reported relative to the Vienna PeeDee Belemnite (VPDB) standard, with an accuracy of ±0.1‰ and ±0.2‰, respectively. For strontium isotope analysis, powder samples of 100–150mg were dissolved using a mixture of anhydrous 1ml HNO3 and 1ml HF in a crucible at 190°C for 48 hours. Strontium was extracted using conventional exchange procedures (Baadsgard, 1987). The $^{87}$Sr/$^{86}$Sr ratios were measured on a Triton Plus thermal ionization mass spectrometer, with analytical precision of 5ppm.

Fluid inclusion analysis was conducted on double polished thick (~100μm) sections. Fluid inclusion petrography was carried out using a Zeiss microscope equipped with transmitted and UV light. Microthermometry was undertaken with a Linkam THMSG 600 cooling-heating stage, and calibration was performed using synthetic fluid inclusions at −56.6°C (CO2), 0.0°C (H2O) (Tran Mydung et al., 2016). A LABRAM HR800 Raman spectroscope was adopted to analyze the components of gases in the inclusions using a 375 nm Ar ion laser.

Trace element and rare earth element analyses were conducted on double polished thick (~120μm) sections by Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS), following the experiment procedures of Fan Chenzi et al. (2013). Crystal structure parameters were measured on XPert MPD X-RAY diffraction (XRD).

Reservoir cores with different lithology, porosity and permeability were chosen to perform dissolution simulation experiments using the Dissolution Kinetics Physical Simulation Unit of HTHP. The experiments were undertaken to simulate water-rock reaction under different condition and investigate the pore evolution processes of the reservoirs. The simulation experiment could be carried out at temperatures ranging between 25 and 400°C; pressures ranging between normal and 100 Mpa; and a fluid flow velocity of between 0.1 and 10 ml/min.

4 Results

4.1 Petrographic characteristics
Observations of rock cores and thin sections from the ten wells in the Weiyuan-Gaoshiti-Moxi-Longnvshi area confirmed that the Longwangmiao dolostones were comprised mainly of dolarenite and dolomicrite, with rare oolitic dolostones.

The dolarenite was likely derived from the bioclastic arenstritic limestones, as the remaining bioclastic arenstritic texture was composed mainly of silty, finely crystalline dolomite, with minor idiomorph dolomite cements and saddle dolomite (Figs. 2a–d). The oolitic dolomite was likely derived from the oolitic limestones, as indicated by the intact texture. The composition of the oolite was primarily silty, micritic crystalline dolomite with minor idiomorph dolomite cements (Fig. 2e). The dolomicrite displays characteristic lamination, indicating an origin from micrite limestones with no visible dolomite cements (Fig. 2f).

4.2 Carbon, oxygen and strontium isotope

Carbon, oxygen and strontium isotope measurements were conducted on different fabric components including host rock, idiomorph dolomite cement, and saddle dolomite. The analytical data is listed in Table 1.

The isotopic characteristics of the carbon, oxygen and strontium data were divided into three groups (Fig. 3). The host rocks (including dolomicrite, oolitic dolostone, and silty, finely crystalline dolostone) had oxygen isotope values of between $-6.50‰$ and $-7.95‰$, and carbon isotope values of between $-0.79‰$ and $-1.6837‰$. The idiomorph dolomite cements had oxygen isotope values of...
between $-8.14\%$ and $-9.08\%$, and carbon isotope values between $-1.16\%$ and $-2.10\%$. The saddle dolomite had an oxygen isotope value of between $-10.48\%$ and $-11.52\%$, and carbon isotope of between $-2.21\%$ and $-4.08\%$. The strontium isotopic values of the host rocks, idiomorph dolomite cements and saddle dolomite were similar, with values between 0.709248 and 0.710474.

4.3 Cathodoluminescence and trace element

As shown in Fig. 4, based on the cathodoluminescence characteristics and Fe and Mn contents analysis of the Longwangmiao samples, the results could be divided into four distinct zones: (1) I zone of bright luminescence, where Mn>100 ppm and Mn/Fe >1, for saddle dolomite and partial idiomorph dolomite cements; (2) II zone of non-luminescence, where Fe >4000 ppm and Mn/Fe <1, particularly for dolomicrite and oolitic dolostones; (3) III zone of non-luminescence, where Mn<100 ppm, particularly for silty crystalline dolostones and dolomicrite; (4) IV zone of both bright and dark luminescence, where Fe <4000 ppm and Mn/Fe <1, particularly for silty, finely crystalline dolostones and dolomite cements.

4.4 Rare-earth element

The characteristics of the rare earth elements are outlined in Fig. 5. The results identified a negative Ce and negative Eu anomaly in the host rock and a positive Eu anomaly in the cement.

4.5 Fluid inclusion

The fluid inclusion homogenization temperature and components were measured on the saddle dolomite from WH101-4 well in the Longwangmiao Formation. The
microphoto, homogenization temperature and component characteristics of the fluid inclusion in the saddle dolomite are shown in Fig. 6. These results identified a high inclusion homogenization temperature of between 200–220°C and high N₂ concentrations.

4.6 Crystal structure characteristics

The primary crystal structure parameters of interest for the dolostones included the degree of order, unit cell parameter, lattice defect, planar fringe and interplanar spacing (Scholle et al., 2003). These parameters were closely related to the crystal growth velocity (Donald et al., 1987), and provided useful information for the research of dolostone origins. The crystal structure analysis of the dolomicrite, oolitic dolostone, silty, finely crystalline dolostone, idiomorph dolomite cements and saddle dolomite from the Longwangmiao Formation are listed in Table 2.

5 Discussions

5.1 The origin of dolostone

The origin of dolostones has undergone extensive research, with a focus on the development of dolomitization models. Eight dolomitization models have been identified as follows: (1) seawater-seepage/reflux dolomitization (Adams et al., 1961; He Xunyun et al., 2014); (2) capillary concentration dolomitization (Bush, 1973); (3) evaporative pumping dolomitization (McKenzie et al., 1980); (4) mixed water dolomitization (Badiozamani, 1973); (5) adjustment-compaction dolomitization (Hardie, 1987; Montanez, 1994); (6) burial-
compaction dolomitization (Mattes et al., 1980); (7) seawater thermal convection dolomitization (Vahrenkamp et al., 1994); and (8) tectonic hydrothermal dolomitization (Graham et al., 2006). It should be noted that regardless of the model, dolomitization always occurs in two stages: the contemporaneous stage and the burial stage.

In general, the contemporaneous replacement of dolomite is related to the evaporitic environment and is characterized by the preservation of the original crystalline texture. In contrast, burial dolostones display an enhanced crystalline texture (Zhao Wenzhi et al., 2012, 2014a; Zheng Jianfeng et al., 2013). Based on the petrographic analysis (Fig. 2), the dolarenite, oolitic dolostone and dolomicrite originated from metasomatism in the contemporaneous stage, as evidenced for by the retained original crystalline texture. The remaining arenitic and oolitic textures were composed of silty, finely crystalline dolostones and silty, micritic crystalline dolostones, respectively, suggesting the dolostones could have formed during the contemporaneous stage and not undergone recrystallization during the burial stage. The idiomorph dolomite cements and saddle dolomite likely formed during the burial stage, filling in the dissolution pores and fractures. The development of hypersaline lakes in the Longwangmiao period provided the paleoclimate and paleogeographic environment for the contemporaneous replacement dolostones. Therefore seawater-seepage/reflux dolomitization (Adams et al., 1961) and evaporative pumping dolomitization models (McKenzie et al., 1980) could explain the origin of the Longwangmiao dolostones.

The carbon and oxygen isotopes became lighter, suggesting a deeper burial depth and higher temperature of the diagenetic environment (Arthur et al., 1983; Hoefs, 1987; Bai Xiaoliang et al., 2016). From the carbon, oxygen and strontium isotopic characteristics outlined in Fig. 3, it was inferred that the replacement dolomite with highest carbon and oxygen isotope were formed at relatively low temperatures in the near surface environment. In contrast, the dolomite cements had relatively lower carbon and oxygen isotope signatures, and could therefore have originated in the shallow-middle burial diagenetic environment with relatively higher temperatures. The saddle dolomite had the lowest carbon and oxygen isotope values, and could therefore be related to hydrothermal fluid with highest diagenetic temperature. The replacement dolomite had a relatively high strontium isotope value compared with the coeval seawater’s strontium isotope (Dension, 1998; Veizer et al., 1999), which could be correlated with the evaporitic environment.

The degree of luminescence in the cathodoluminescence analysis was controlled by the concentration of Fe and Mn in the mineral (Machel, 1985; Budd et al., 2000). It is generally accepted that the dark light of the cathodoluminescence of a mineral without reductive Fe and Mn, is related to an oxidizing environment. In contrast, the bright light of a mineral with high Mn/Fe values is related to a reducing environment under burial conditions. The last stage of cementation is normally non-luminescent. According to the analysis of the relationship between Fe and Mn concentrations and cathodoluminescence in the Longwangmiao dolostones (Fig. 4), it was concluded that replacement dolostones with the Mn/Fe <1 value were formed in an oxidizing environment in the contemporaneous stage. This was likely related to evaporitic seawater. The silty, finely crystalline dolostones with bright luminescence could have formed through burial reconstruction. Idiomorph dolomite cements and saddle dolomite characterized by high Mn/Fe values and bright luminescence were likely formed in reducing environments during burial, while partial cements with non-luminescence located in the IV area could represent the final cementation in the late burial stage.

The negative Ce and Eu anomaly was considered to be a result of the Ce$^{3+}$ in the contemporaneous stage oxidizing into insoluble Ce$^{4+}$, while Eu$^{3+}$ reduced into soluble Eu$^{2+}$. The positive Ce and Eu anomaly resulted from Ce$^{3+}$ reducing into insoluble Ce$^{2+}$ in the burial stage, while Eu$^{3+}$ oxidized into insoluble Eu$^{2+}$ (Olivarez et al., 1991; Cai et al., 2008; Hu Zhonggui et al., 2009; Wei Jia et al., 2014). Accordingly, the replacement dolomite which contained a negative Ce and Eu anomaly (Fig. 5) likely formed in an oxidizing environment during the contemporaneous stage. The cement which contained a positive Eu anomaly (Fig. 5) likely formed in a reducing environment under burial conditions. The fluid inclusion analysis (Fig. 6) indicated that the saddle dolomite with high homogenization temperatures and high N$_2$ content were formed in a hydrothermal environment.
According to the crystal structure analysis in Table 2, the replacement dolomite and saddle dolomite in the Longwangmiao Formation were characterized by a low degree of order because they formed rapidly. In contrast, the dolomite cements had a high degree of order due to slow growth. The replacement dolomite had a low crystal growth velocity along the C crystallographic axis, and therefore had the lowest unit cell parameter. In contrast, the cement had a higher unit cell parameter, while the saddle dolomite had the highest unit cell parameter due to the high growth velocity along the C axis. The high growth velocity of the saddle dolomite could lead to defects in the crystal lattice and crystal plane bend. In contrast, the crystal plane of the idiomorph dolomite cement was more regular than the saddle dolomite. The crystal structure of the dolomite therefore proved that the dolarenite, oolitic dolostone and dolomicrite originated through metasomatism in the contemporaneous stage, and the idiomorph dolomite cements and saddle dolomite were formed in the burial stage.

Based on the results of the petrographic and geochemical analyses, we concluded that the dolomitization of the Longwangmiao Formation occurred in the contemporaneous stage, and a proportion of the dolomite cements were formed in the burial stage.

5.2 The characteristics and origin of the dolostone reservoirs

The petrographic and geochemical analyses undertaken in this study were utilized to clarify the origin of the Longwangmiao dolostones. However, the influence of the dolomitization on porosity remains uncertain (Fairbridge, 1957; Lucia, 1999; Moore, 2001; Erdogan et al., 2002; Zhao Wenzhi et al., 2014a, 2014b). This study used the characteristics of the reservoirs, including reservoir heterogeneity and effective distribution, together with the reservoir simulation experiments, to determine the influence of dissolution as opposed to dolomitization in the development of the Longwangmiao dolostone reservoirs.

5.2.1 Grain beach sediments provided material basis for the development of the Longwangmiao dolostone reservoirs.

The composition of the Longwangmiao dolostones was primarily dolarenite and dolomicrite, with rare oolitic dolostone. The main body of the reservoirs was comprised of dolarenite, and could be derived from the bioclastic arenstritic limestones. The remaining bioclastic arenstritic texture was composed of silty, finely crystalline dolomite with abundant intercrystalline pores, intercrystalline dissolution pores, dissolution pores and fractures which were partially filled with bitumen, idiomorph dolomite cements and saddle dolomite (Figs. 2a–d). The oolitic dolomite was likely derived from the oolitic limestones which had an intact texture, and the oolite is now made of silty, micritic crystalline dolostones, with intergranular pores filled with a few dolomite cements (Fig. 2e). Dolomicrite displayed characteristic lamination with few dissolution pores along the fractures, indicating an origin from micritic limestones (Fig. 2f).

The effective drilling catching rate and the thickness of the dolostone reservoirs in the Longwangmiao Formation in the Moxi structure were higher than in the Gaoshiti structure. This was a result of the development of the grain beach sediment in the Moxi structure being greater than in the Gaoshiti structure. The thickness of the Longwangmiao Formation in the Gaoshiti-Moxi area was between 100–120 m. The average thickness of the grain beach sediment in the Longwangmiao Formation, including the Moxi 8 (80 m), Moxi 9 (58 m), Moxi 11 (92 m), Moxi 12 (68 m), Moxi 13 (90 m), Moxi 17 (60 m), and Moxi 21 (64m) wells was 72.14 m. The thickness of the grain beach sediment in the Gaoshi 1, Gaoshi 2, Gaoshi 3 and Gaoshi 6 wells in the Gaoshiti structure were 47 m, 27 m, 36 m and 47 m, respectively, with average thickness of 39.25 m.

Based on the statistics of the physical properties of the 496 samples from the Moxi 8, Moxi 9, Moxi 11, Moxi 12, Moxi 13, Moxi 17 and Gaoshi 6 wells (Fig. 7), it was found that the samples with porosity below 2% and permeability below 0.01 mD accounted for 46.57%, and were mainly comprised of dolomicrite. The samples with a porosity of between 2% and 6%, and a permeability of between 0.01 mD and 1 mD accounted for 45.37%. The samples with a porosity of more than 6% and permeability above 1 mD accounted for 8.06%, and were primarily composed of dolarenite. The dolomicrite was classified as a non-reservoir type with no obvious pores, while the dolarenite was classified as an effective reservoir characterized by a strong heterogeneity and a varying range of porosity and permeability. The largest and smallest porosity values in the dolarenite were 11.28% and 0.32%, while the largest and smallest permeability values were 108.10 mD and 0.0001 mD. There was no good correlation between the porosity and permeability, indicating the reservoirs belonged to a fractured-vuggy type.

5.2.2 Fabric-selective dissolution pores were formed through contemporaneous sealevel-controlled subaerial exposure and meteoric leaching

Although the grain dolostones were the main reservoirs in the Longwangmiao Formation, not all grain dolostones were effective reservoirs according to the results of rock
cores, thin sections and logging of wells Moxi 8, Moxi 9, Moxi 11, Moxi 12, Moxi 13, Moxi 17, Gaoshi 1, Gaoshi 2, Gaoshi 3, Gaoshi 6, Anping 1 and Baolong 1. Porous grain dolostones, tight grain beach dolostones and tight dolomicrite were vertically stacked to form repeated cycles.

Synthesis column maps of lithologies, lithofacies, and reservoir distribution of the Longwangmiao Formation of the Moxi 21 well (Fig. 8), identified that the Longwangmiao Formation consisted of dolomicrite, tight silty dolarenite, tight finely crystalline dolarenite and porous finely crystalline dolarenite. The total thickness was 120 m and the dolarenite thickness was 70 m. Three main cycles were identified as shoaling upward, composed of dolomicrite in the bottom of the cycle, tight silty dolarenite in the middle, and porous finely crystalline dolarenite in the top. The effective reservoirs were distributed in the three cycles’ top, with thickness of 2 m, 6 m, and 5 m, respectively, accounting for 18.60% of the total dolarenite.

Based on logging data and lithological identification, it was confirmed that the Longwangmiao Formation in the
Gaoshiti-Moxi area consisted of one to three cycles shoaling upward (Table 3). The effective reservoirs in the top of the cycle correlated with sea level controlled subaerial exposure and meteoric leaching.

A simulation experiment was undertaken to further verify that meteoric erosion after dolomitization in the contemporaneous stage played an important role in the formation of porosity. Samples with similar porosities and permeabilities were selected for the dissolution simulation experiment to study the influence of mineral components on dissolution. Samples included the clastizoicmicrite, micrite limestone, muddy limestone, and silty, finely crystalline dolostones. The experimental conditions included the use of a 2 ml/L acetic acid solution, an open flow system with a flow rate of 3 ml/min, surface dissolution and a 30 minute reaction time for each P-T point (with a total of 13 points).

It was observed that the dissolution rate of limestone was higher than dolostones at low temperature; however, this difference diminished with increasing temperature (Fig. 9). Three major conclusions were reached following the experiment: (1) contemporaneous meteoric leaching postdated dolomitization; (2) non-dolomitized components and gypsums were easily leached away in meteoric erosion to form fabric selective porosity, whereas dolomitized components remained unchanged. Some fabric selective dissolution was also observed in the contemporaneous stage.

### Table 3 Statistical list of cycles, beach and reservoir thickness of the Longwangmiao Formation in Gaoshiti-Moxi area

<table>
<thead>
<tr>
<th>Well</th>
<th>items</th>
<th>The first cycle</th>
<th>The second cycle</th>
<th>The third cycle</th>
<th>Notes</th>
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<tbody>
<tr>
<td>Moxi 8</td>
<td>Cycle thickness</td>
<td>4645–4735m</td>
<td>/</td>
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<tr>
<td></td>
<td>Beach thickness</td>
<td>80m</td>
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<td></td>
<td>Reservoir thickness</td>
<td>60m</td>
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<tr>
<td></td>
<td>Cycle thickness</td>
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<td>4620–4582m</td>
<td>4582–4550m</td>
<td></td>
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<td>Moxi 9</td>
<td>Beach thickness</td>
<td>8m</td>
<td>32m</td>
<td>18m</td>
<td>3 cycles shoaling upward</td>
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<tr>
<td></td>
<td>Reservoir thickness</td>
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<td>25m</td>
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<td>Cycle thickness</td>
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<td>4722–4689m</td>
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<td>50m</td>
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<td>Reservoir thickness</td>
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<td>22m</td>
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<td>2m</td>
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Fig. 9. Dissolution simulation experiment to study the influence of mineral components on dissolution degree (samples used came from the Longwangmiao Formation in Moxi 12 well and Moxi 13 well).
pores which were formed through the dissolution of non-dolomitized limy components, could be found in the samples from the Moxi 12 well at a depth of 4644.50 m, and the Moxi 17 well at a depth of 4663.97 m in Figs. 2d–e; and (3) burial dissolution created porosity in both limestones and dolostones.

5.2.3 Burial dissolution played a significant role in reservoir formation in the Longwangmiao Formation.

Experimental results concluded that primary pores and fabric selective pores were related to meteoric leaching in the Longwangmiao dolostone reservoirs. However, observations of rock cores and thin sections identified that non-fabric selective pores were also important, accounting for above 50% of the total porosities in the Longwangmiao reservoirs. The non-fabric selective pores were mainly developed in the grain dolostones where dolomite was dissolved (Figs. 10a–b), and a few were found in dolomicrite along fractures (Figs. 10c–d). These non-fabric selective pores were the products of burial dissolution and developed along the pre-existing porosity zones and fracture zones with inheritance. This was proved through the reservoir dissolution simulation experiment as shown in Figs. 10e–f.

Previous studies determined that burial dissolution processes formed dissolution pores under the condition of organic acid, thermochemical sulfate reduction (TSR) and hydrothermal fluid in burial environment (Moore, 2001; Bildstein et al., 2001; Cross et al., 2004; Graham et al., 2006; Jin Zhijun et al., 2006; Zhu Guangyou et al., 2006, 2012; Liu Chunyan et al., 2008; Cai Chunfang et al., 2012, 2014; Liu Shugen et al., 2014). In order to quantitatively study the contribution of burial dissolution to the physical properties of the reservoirs, quantitative dissolution simulation experiments were performed on samples with varying porosities and permeabilities, including the oolitic dolostone, silty-finely crystalline dolostone, and dolarenite. The experiment included the use of a 2 ml/L acetic acid solution, open-flow system with a flow rate of 1 ml/min, internal dissolution and a 30 minute reaction time for each P-T point (with a total of 11 points). The results of this experiment are shown in Fig. 11. The results indicated the following: (1) samples with different pore structures required different times to reach equilibrium; (2) the ion concentration of Ca$^{2+}$ + Mg$^{2+}$ in solution increased with increasing temperature and pressure before chemical equilibrium, while the ion concentration of Ca$^{2+}$ + Mg$^{2+}$ in solution decreased slightly with increasing temperature and pressure after chemical equilibrium. The solubilities of different samples were uniform at 160°C and 50 Mpa; (3) After the dissolution simulation experiment had concluded and between temperature and pressure, the porosity and permeability of the reservoirs increased significantly.

Fig. 10. Burial dissolution vugs in the Longwangmiao dolomites.

(a), Dolarenite, with abundant dissolution pores and bitumen (Moxi 12 well, 4942.52 m, core); (b), Dolarenite, without psammitic texture, with abundant dissolution pores and bitumen (Moxi 13 well, 4615.35 m, cast section, plane polarized light); (c), Dolomicrite, tight, dissolution pores developed along the fractures (Moxi 12 well, 4620.76 m, cast section, plane polarized light); (d), Dolomicrite, tight, dissolution pores developed along the fractures (Moxi 13 well, 4614.75 m, thin section, fluorescence); (e), Dolarenite, with intercrystal pores, intercrystal dissolution pores, and fractures (Moxi 13 well, porosity: 9.85%, permeability: 2.17 mD, before dissolution simulation experiment); (f), Same view field with E, expanded dissolution pores developed along the pre-existing porosity zones and fracture zones after dissolution simulation experiment, porosity: 21.35%, permeability: 6.18 mD.
pressure conditions of 160°C and 50 MPa, and 190°C and 60 MPa, the permeabilities of the samples increased by 4.75–7.48 mD, and the porosities increased by 2%–3% (Table 4). As a result of these conditions, the pore structure improved (Table 4). The results of the experiment indicated that burial dissolution throughout geological time could form large scale reservoirs.

The distribution rule of burial dissolution pores is key to predicting large scale reservoir formation. Two samples, limearenite (with a porosity of 4.44% and a permeability of 3.6 mD), and dolarenite (with a porosity of 19.76% and a permeability of 1.71 mD), were selected for additional simulation experiments to study the effect of the physical properties of reservoirs on the degree of dissolution. The experiment used a 1 ml/L acetic acid solution, an open-flow system with a flow rate of 1 ml/min, internal dissolution and a 30 minute reaction time for each P-T point (with a total of 11 points). The experiment is outlined in Fig. 12. The results indicated that the dolarenite sample which originally had a high porosity was more soluble than the limearenite under high temperature and pressure conditions. Therefore, it was inferred that in a burial environment, the dissolution rates of carbonates were influenced most strongly by pre-existing porosity and permeability conditions rather than by mineralogy alone. This finding was consistent with the fact that burial dissolution vugs are generally developed along the pre-porosity zones and fracture zones with inheritance.

Yang Yu (2013) proposed that the reservoirs in the Gaoshiti-Moxi area were controlled by supergene karst as a result of the presence of a large scale karst development zone, and the occurrence of mud breccia in the Longwangmiao Formation in the Moxi 17 well. The occurrence of the mud breccia was thought to be the fillings of the karst cave. It is the view of the authors of this study that although karstification contributed to the formation of pores in the grain dolostones in the Longwangmiao Formation, they were not the dominant factor. The reasons are twofold. Firstly, matrix pores were the main reservoir space type in the Longwangmiao reservoirs. Furthermore, no large scale karst cave was observed, and the breccia could have been associated with fault breccia rather than cave fillings. Secondly, the results in Fig. 9 identified that the dissolution rate of the dolostones was significantly slower than that of the limestones at low temperatures. Consequently, the large scale dissolution could not occur in the Longwangmiao dolostones in the supergene environment. According to the above studies, it is therefore concluded that the grain beach sediments provided a material basis for the

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**Table 4 Porosity and pore throat varying after the quantitative dissolution simulation experiment**

<table>
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<th>Type</th>
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<th>After experiment</th>
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<td>5.67e+10</td>
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<td>Connected volume(μm³)</td>
<td>1.84e+10, accounting for 35.60%</td>
<td>4.05e+07, accounting for 71.40%</td>
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<tr>
<td>Pore</td>
<td>Volume(μm³)</td>
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<td>4.32e+10</td>
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<td>Radius (μm)</td>
<td>Avg: 36.17; Min: 3.107; Max: 211.5</td>
<td>Avg: 36.12; Min: 3.324; Max: 961.8</td>
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<tr>
<td>Amount</td>
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<td>Throat</td>
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<td>Radius (μm)</td>
<td>Ave:18.67; Min: 2.77; Max: 152.7</td>
<td>Avg: 26.02; Min: 3.061; Max: 746.9</td>
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</table>
formation of the reservoirs, and the meteoric water corrosion was related to a sea level controlled subaerial exposure. Burial dissolution was the key factor for the development of the Longwangmiao dolostone reservoirs.

6 Conclusions

The study of the origin of the dolostone reservoirs in the Cambrian Longwangmiao Formation in the Sichuan Basin, reveals that grain dolostone reservoirs was formed in a shallow water ramp under arid climatic conditions. The conceptual models developed in this study can be used in similar geological settings elsewhere.

(1) Reefal beach deposits lay a foundation for the reservoir development. Carbonate ramps provide excellent conditions for grain beach deposition, while the presence of hypersaline lakes creates favorable conditions for the contemporaneous dolomitization of grain beach deposits. Porous reservoirs occurred in the grain dolostone sequence; however, not all grain dolostones formed a good quality reservoir. As shown in Fig. 8, dolostones in the Longwangmiao Formation in the Moxi 21 well occurred vertically in three cycles. These included the high porosity grain beach dolomites in the upper cycle (mainly dolarenite), grain beach tight dolostone in the middle cycle and inter-beach tight dolomicrite in the lower cycle. Cross sections linking the boreholes (Fig. 13) indicate that the reservoirs were spatially highly heterogeneous, whereas the porous components were influenced by the grain beach facies and sequence boundaries (i.e., the exposure surface).

(2) Superficial conditions are an important determining factor for reservoir porosity. There are three potential ways for porosity to develop in the superficial environment: (i) preservation of the original porosity; (ii) fabric selective dissolution of unstable minerals, such as aragonite and high magnesian calcite in the early superficial environment; and (iii) vug formation through non-fabric selective dissolution of carbonate in the late superficial environment. The intergranular pores in the grain-dolostone reservoirs in the Longwangmiao Formation were derived primarily from the first and second scenarios, whereas the non-fabric selective dissolution pores in the Gaoshiti-Moxi area were most likely a result of the third scenario, and occurred during the uplift and erosion of the Tongwan Movement.

(3) Burial conditions set the environment for porosity preservation and modification. Secondary porosities such as dissolution vugs were likely formed through organic acid dissolution, thermochemical sulfate reduction and hot fluid interactions in the burial environment. Quantitative
simulation experiments of dolomite dissolution using samples from the Longwangmiao Formation indicated that dissolution vugs occurred at a large scale, particularly along the pre-porosity zones and fracture zones, where the inherited distribution was predictable.

Acknowledgements

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developed by Hao Qingqing

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