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ORIGINAL ARTICLE

General depositional features of the carbonate platform gas reservoir of the Lower Triassic Jialingjiang Formation in the Sichuan Basin of southwest China: Moxi gas field of the central basin

Xiucheng Tan · Ling Li · Hong Liu · Bing Luo · Yan Zhou · Jiajie Wu · Xiong Ding

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Abstract The Lower Triassic Jialingjiang Formation gas reservoir in Sichuan Basin of southwest China is a representative carbonate platform reservoir. However, it has not been well studied due to relatively less production in comparison with the reservoir in the well-known underlying Upper Permian Changxing and Lower Triassic Feixianguan formations. Thus, to provide supplement to the hot study of carbonate platform reservoirs in the Sichuan Basin, the authors describe the general depositional features of the carbonate platform gas reservoir of the Jialingjiang Formation based on a case study of the representative second member of the formation (termed as Jia 2) in the Moxi gas field of the central basin. The features mainly include depositional setting, lithology, depositional structure, depositional sequence and reservoir space. These results lead to a conclusion that the Jialingjiang Formation reservoir (the second member in particular) is not of a tidal flat deposition in an intertidal (to supratidal) environment as previously suggested but of restricted and evaporative carbonate platform deposition in a subtidal environment. The tidal flat-like (i.e., platform flat) facies occur only in the Jia 2^2-B layer. Moreover, the restricted–evaporative carbonate platform facies can be further divided into 5 subfacies and 23 microfacies, of which the facies of grain shoal and dolomitic flat are relatively favorable for the development of reservoirs. Their depositional model, distribution and evolution were further tentatively suggested. The facies are subject to paleotomography and sea level variations. These results also have general implications for the carbonate platform reservoirs elsewhere.

Keywords Carbonate platform · Carbonate rock · Depositional facies · Tidal flat · Grain shoal · Lower Triassic Jialingjiang Formation · Moxi gas field · Sichuan Basin

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

X. Tan (✉) · L. Li · H. Liu · B. Luo · Y. Zhou · J. Wu · X. Ding
School of Resource and Environment, Southwest Petroleum University, Chengdu 610500, Sichuan, China
e-mail: tanxiucheng70@163.com

Introduction

The Sichuan Basin in southwest China is petroliferous and predominant in gas bearing at present (Yang et al. 2010), with the production and cumulative proven gas reserve being about 1.8×10^{10} and 2.0×10^{12} m^3, respectively, by 2009 (Ma et al. 2010). Of the reservoirs, the Permian and Triassic lead in producing (ca. 37% of the entire production), which mainly include the Upper Permian Changxing, Lower Triassic Feixianguan and Jialingjiang formations from base to top (Zhu et al. 2006; Ma et al. 2010). Comparatively, the Changxing and Feixianguan reservoirs have been studied widely, e.g., the famous Puguang gas field of the northeastern Sichuan Basin (Ma et al. 2008); in contrast, the Jialingjiang Formation reservoir has not been well investigated due to less hydrocarbon production. Thus, a study of reservoir geology on the Jialingjiang Formation can provide supplement to the present hot studies of the Permian–Triassic gas reservoir geology in China.

For the Jialingjiang Formation gas reservoir, the Moxi gas field of the central basin is the most representative one

(Xu et al. 2006). Gas accumulates mainly in the second member of the formation (termed as Jia 2) (Xu et al. 2006). Thus, the research on the Jia 2 reservoir of the Moxi gas field has important and wide implications. Some works have been carried out and focused on reservoir depositional features. In some of the works, the reservoir is believed to be of an evaporative carbonate platform deposition when considering depositional evolution of the entire Sichuan Basin (Wang 1985; Wang et al. 1989). However, microfacies of the carbonate platform has not been well constrained in the works. This was somewhat improved by Zou et al. (1990), who proposed a tidal flat deposition. According to the work, the reservoir was deposited mainly in the intertidal (to supratidal) zone, and thus has a stable occurrence. However, complex gas and water relations have been revealed by more and more exploration and research results, suggesting that the reservoir does not distribute stably (e.g., Zhao et al. 2005a, b; Xu et al. 2006; Zhou et al. 2007). Therefore, the tidal flat may not be the facies type.

General depositional features of the Jia 2 reservoir in the Moxi gas field are reported in more detail than before, based on which the depositional model and evolution were addressed.

Geological setting

The Moxi gas field is located in the central low-flat belt of the Sichuan Basin, trending roughly in northeast to southwest (Fig. 1a) (Xu et al. 2006; Dai et al. 2008). It has succeeded in gas exploration and exploitation since the first well drilling of Moshen 1 in 1977 (Fig. 1b). The gas production and proven reserve is about 4.0×10^8 m^3 per year and 3.3×10^{10} m^3, respectively (Zhao et al. 2005).

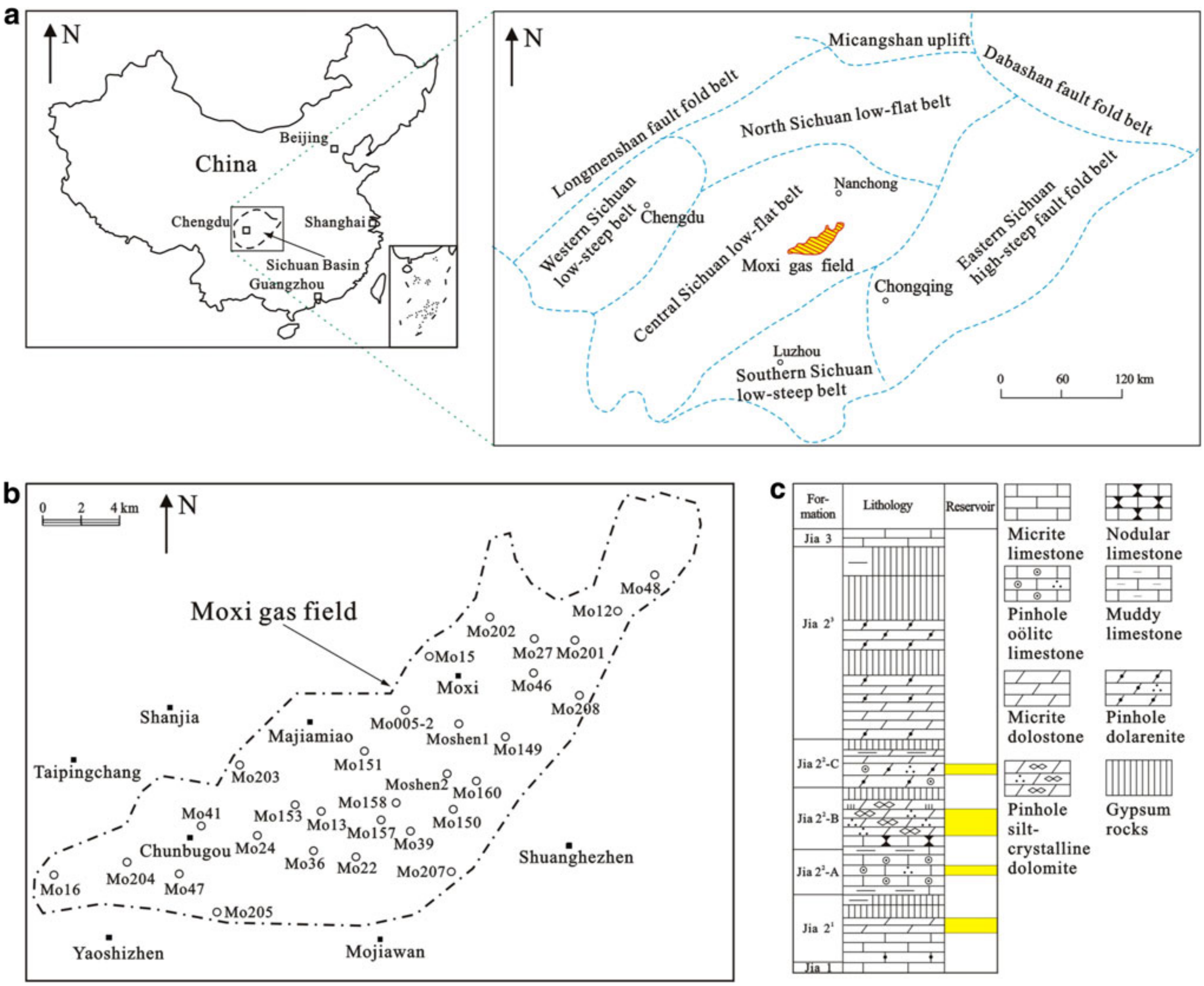

Fig. 1 **a** Tectonic units in the Sichuan Basin and the location of the Moxi gas field. **b** Some representative wells in the Moxi gas field. **c** Generalized stratigraphy of the Moxi gas field

During Early Triassic Jialingjiang time interval, the Moxi area was located in the central part of the Upper Yangtze Craton marine basin, i.e., the marine central Sichuan subbasin (Wang 1985). There are five members in the Jialingjiang Formation, termed as Jia 1 to Jia 5 from the base to top (Xu et al. 2006). The earliest Jia 1 time interval witnessed a general marine transgression, thus with a predominant deposition of marine carbonates. Subsequently, the Jia 2 stage is characterized by a general marine regression and frequent sea level fluctuations. Hence, the formation is composed mainly of marine carbonates and evaporites, with some terrestrial clastic rocks (e.g. mudstone) (Figs. 1c, 2) (Xu et al. 2006). The formation is subdivided into three members, termed as Jia 2^1, Jia 2^2 and Jia 2^3 from the base to top. Gas accumulates mainly in the Jia 2^2 reservoir, with <10% contribution from the Jia 2^1 reservoir (Fig. 1c). The Jia 2^2 reservoir can be further subdivided into three layers based on lithological difference, i.e., A, B and C layers from the base to top (Fig. 1c).

There are mainly four types of rocks deposited in general, including limestones, dolostones, gypsum rocks and mudstones/shales. The limestones cover four types, e.g., muddy limestone, micrite limestone, sparry calcarenite and sparry oölitic limestone. They are all predominantly grey to dark grey in color and occur principally in the lower part of the Jia 2^1 member, middle and upper part of the Jia 2^2-A layer and the lower part of the Jia 2^2-B and -C layers. Of

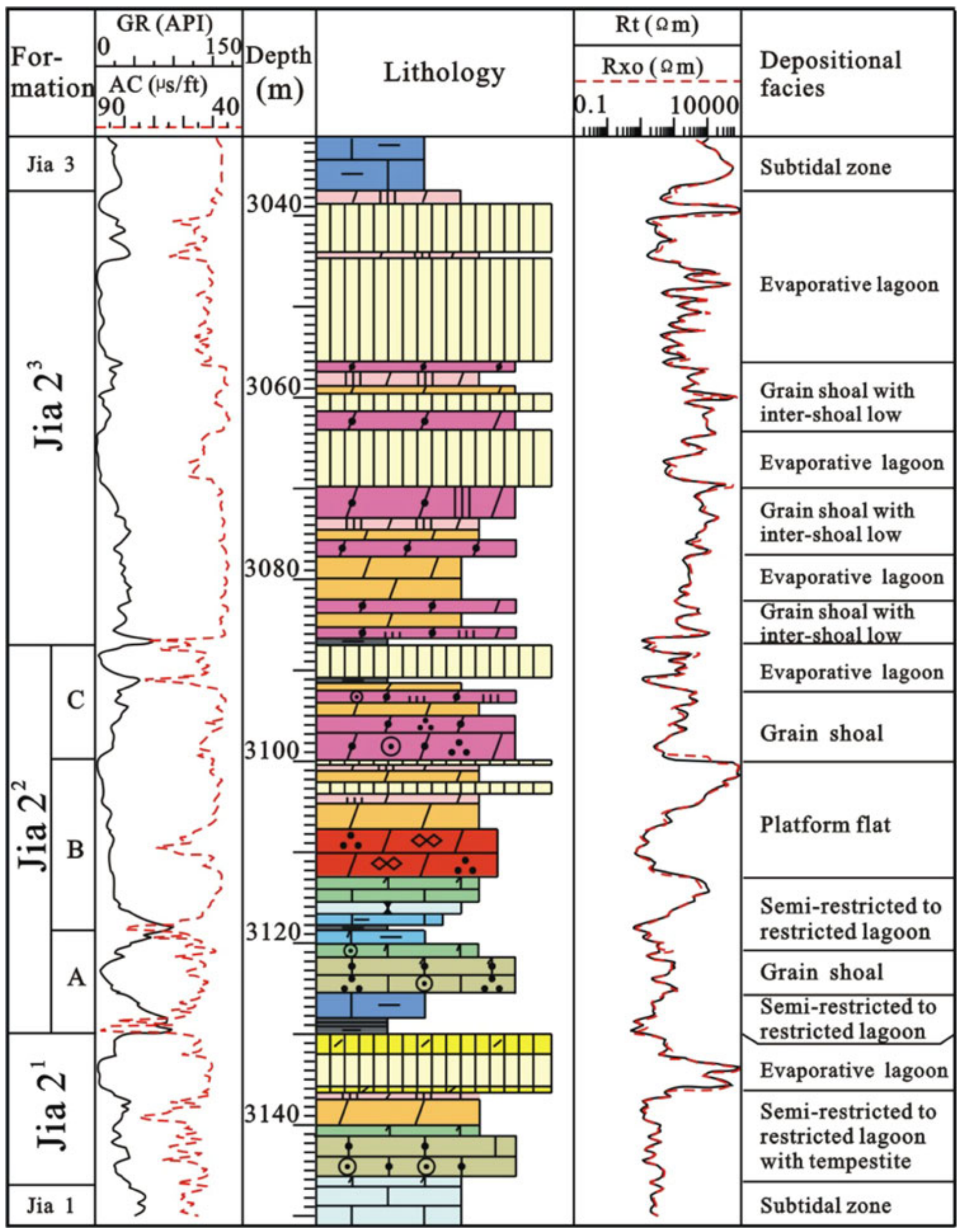

Fig. 2 Generalized features of lithology, logging and depositional facies of well Mo 13. The well is a representative exploration well in the Moxi gas field. See Fig. 1b for the location of the well. See Fig. 1c for the lithological legend

the four main types of the limestones, the muddy and micrite limestones were deposited during the time interval of submarine transgressions, during which the water had good exchange and normal salinity. In contrast, the sparry calcarenite and oölitic limestone were deposited in an environment with relatively high energy, and thus are potential good reservoir rocks (Qiang 1998; cf. Ehrenberg 2006; Wannier 2009; Paola et al. 2010).

The dolostones are generally micrite to silt-crystalline dolostones with dark grey to khaki in color, and occur mostly in the middle part of the Jia 2^1 member, Jia 2^2-A and Jia 2^2-B layers, and middle to lower part of the Jia 2^2-C layer. Individual thickness of the dolostone layers ranges from tens of centimeters to several meters, indicating varying depositional conditions. Solution pores and vugs with partially filled gypsum and pinholes can be observed in some cases, providing relatively good conditions for reservoir formation.

The gypsum rocks include blocky and lamellar anhydrock, ptygmatic and nodular gypsolytes, and gypsum breccia. They are all generally dark grey in color. Individual thickness of the rocks is similar to that of the dolostone layers, i.e., ranging from tens of centimeters to several meters. Thus, varying depositional conditions may also be indicated.

The mudstones/shales are mainly dark grey, grey dark and grey green in color, with flaggy muddy limestones occurring as interbeds. Very thin sheets of gypsum rocks are present in some cases, implying a possibly slim evaporative depositional environment. In addition, horizontal and intercalated bedding can be commonly observed, indicating a relatively low-energy depositional condition.

In summary, as shown in Fig. 1c, there are mainly four gas-producing reservoirs, of which the Jia 2^1 member and Jia 2^2-B layer consist mainly of silt-crystalline dolostone, while the Jia 2^2-A and -C layers are dominated by grain rocks (e.g., oölitic limestone and dolostone, calcarenite, and dolarenite) (Zhou et al. 2007, 2009).

General depositional features

The depositional facies of the Jialingjiang Formation in the Moxi gas field has disputes on carbonate platform or tidal flat deposition so far (e.g., Zou et al. 1990). For the perspective of the carbonate platform deposition, it has only been proposed based on the depositional setting of the Upper Yangtze marine Basin during Triassic and thus has not been well investigated. For the perspective of the tidal flat facies, it has been suggested that the depositional environment is mainly intertidal (-supratidal). Evidence supports the carbonate platform deposition and can be summarized into five zones as listed below. The deposition is further suggested to occur in a subtidal environment and the tidal flat-like facies is only developed in the Jia2^2-B layer.

Depositional setting

During Early Triassic Jialingjiang time interval, the Moxi area was located in the evaporative marine basin of the Upper Yangtze Region (Wang 1985), with a distance of ca. 200 km to the western paleocontinent (Tian 1989). Thus,

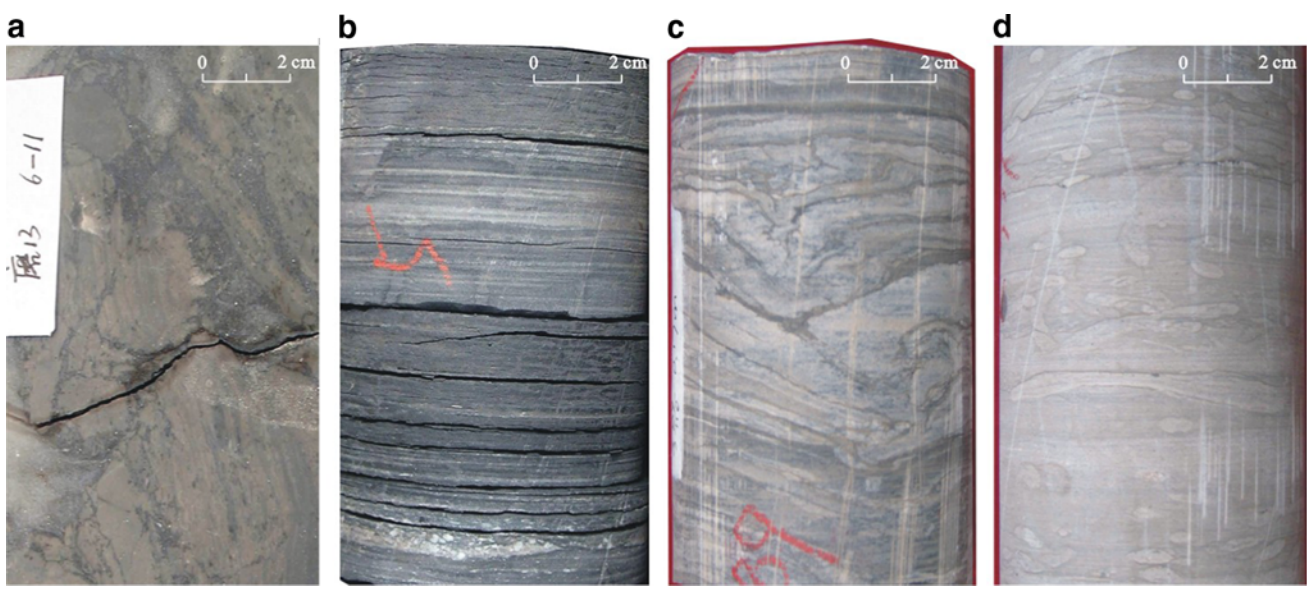

Fig. 3 Representative depositional structures in the Jia 2 member. **a** Gypsum breccia, well Mo 13, 3,102.1 m, Jia 2^2-B layer. **b** *Dark grey* micrite limestone, lamellar scolite, well Mo 149, 3,171.5 m, Jia 2^1 member. **c** *Dark* and *blue grey* limy mudstone, rhythmic bedding, well Mo 149, 3,145.8 m, Jia 2^2-A layer. **d** Laminar gypsolyte, rhythmic bedding, well Mo 45, 318.0 m, Jia 2^2-C layer. See Fig. 1b for the location of the wells

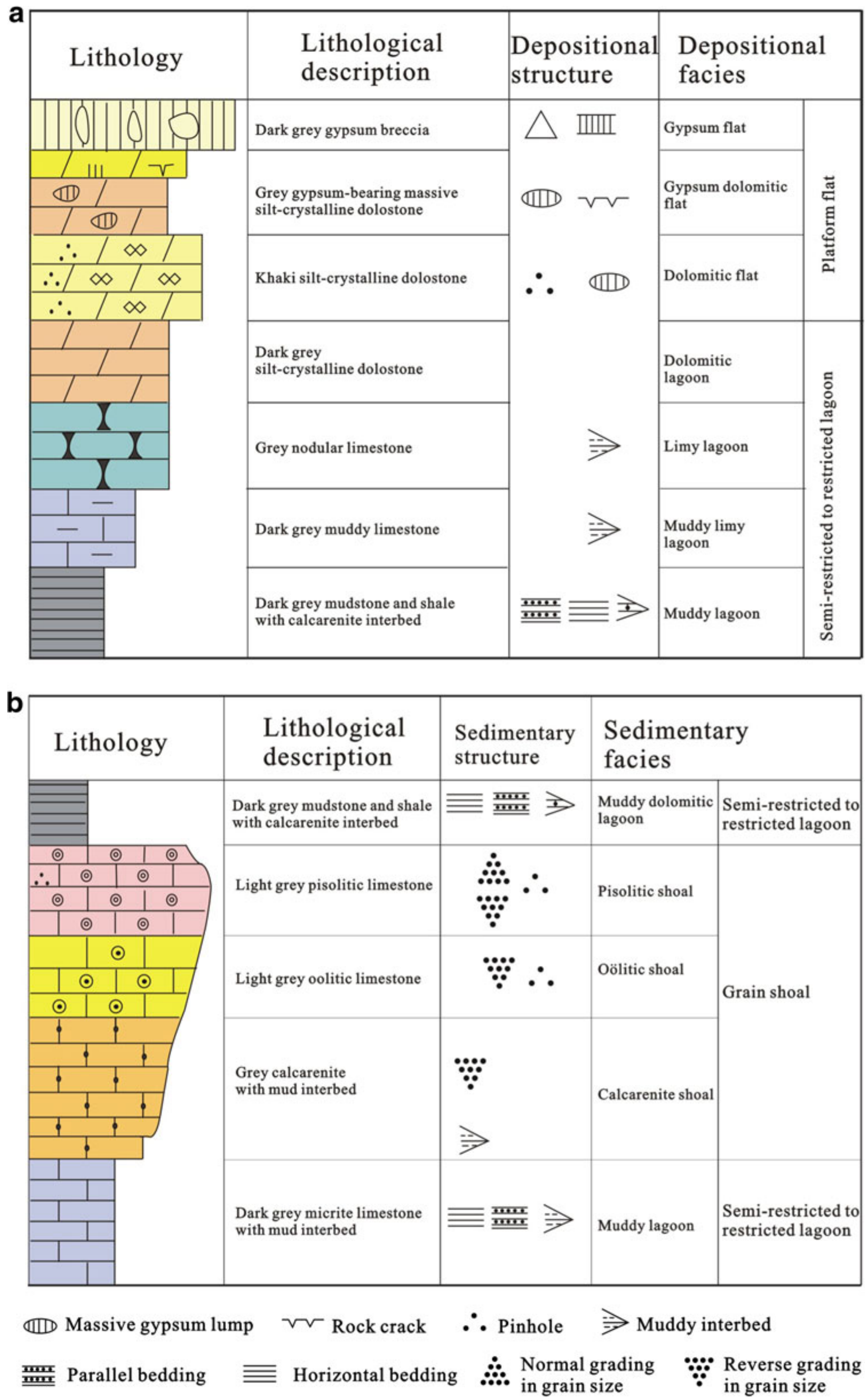

Fig. 4 Representative depositional sequences in the Jia 2 member. **a** Well Mo 14, 3,146.9–3,162.3 m, Jia 2^2-B layer, shallowing-upward deposition. **b** Well Mo 14, 3,165.0–3,167.7 m, Jia 2^2-A layer, shallowing-upward deposition, reverse grading in grain size. See Fig. 1b for the location of the wells

the setting is not favorable for the development of the tidal flat deposition, which often occurs in the coastal area (Ma et al. 2008). Thus the setting is favorable for the carbonate platform deposition (Wang 1985; Wang et al. 1989).

Lithology

During the Jia 2 time interval, the seawater was several meters in depth and the tomography further had morphological rises

Table 1 Generalized depositional faices of the second member of the Lower Triassic Jialingjiang Formation (Jia 2 member), Moxi gas field

Facies	Subfacies	Microfacies
Restricted to evaporative platform	Grain shoal	Oölitic shoal, calcarenite shoal
	Platform flat	Dolomitic flat, gypsum flat, dolomitic gypsum flat, gypsum dolomitic flat, intra-flat depression
	Inter-shoal low	Dolomitic inter-shoal low, gypsum inter-shoal low, limy inter-shoal low
	Semi-restricted to restricted lagoon	Limy lagoon, dolomitic lagoon, muddy lagoon, dolomitic-limy lagoon, limy dolomitic lagoon, gypsum dolomitic lagoon, tempestite deposition
	Evaporative lagoon	Gypsum lagoon, dolomitic gypsum lagoon, muddy gypsum lagoon, tempestite deposition

and falls (Tan et al. 2008). As a consequence, different types of rocks distributed irregularly. This is a typical feature of carbonate platform deposition, differing from the feature of the tidal flat deposition, in which the rocks commonly have a zoned occurrence (e.g., Guo et al. 1994).

In particular, the mudstones and gypsum rocks are commonly grey green and dark grey in color (e.g., Hou et al. 2004; Xu et al. 2006). This indicates that the rocks were in general deposited under a subtidal environment, different from the tidal flat deposition, in which the climate is commonly hot and dry and thus the mudstones and gypsum rocks are often purple in color (Qiang 1998).

With respect to the gypsum rocks, more and more exploration results reveal that the rocks occur widely and stably (e.g., Xu et al. 2006), implying a deposition in the late stage of a seawater salinization cycle (Qiang 1998). This is a typical feature of the subtidal carbonate platform deposition, and is different from the restricted pond deposition of the tidal flat facies. In the tidal flat deposition, the intertidal to supratidal environment is not only influenced by the tidal fluctuation but also by wind storm and meteoric incursion, and thus the gypsum rocks commonly have an unstable and limited distribution (Qiang 1998; e.g., Zou et al. 1990).

Therefore, based on the above discussion, it can be indicated that the tidal flat deposition was not well developed in general. In addition, the tidal flat-like deposition may develop only during the Jia 2^2-B time interval. This is typically evidenced by rock features. For example, pytgmatic and thin-bedded gypsum rocks, and gypsum breccia were only observed in the Jia 2^2-B layer (Fig. 3a); these are typical indication of the tidal flat deposition (Qiang 1998).

Depositional structure

Large quantities of depositional structures indicating low-energy environment were observed in general, e.g., lamellar scolite, lamellar bedding, interbedded bedding and rhythmic bedding (Fig. 3b–d). This indicates that the carbonates were generally deposited in a subtidal environment, which is inconsistent with the intertidal to supratidal environment of the tidal flat facies (Qiang 1998). Thus, the depositional facies belongs to carbonate platform.

In addition, some exposed depositional records were observed only in the Jia 2^2-B layer, including gypsum breccia (Fig. 3a), rock cracks and meteoric leaching and dissolution (Tian 1989; Hou et al. 2004). This indicates that the facies whose environment is similar to that of the tidal flat may occur only in the Jia 2^2-B layer, in agreement with the lithological indications discussed on the above.

Depositional sequence

The depositioanl sequence is generally characterized by a shallowing-upward deposition, as limestones, dolostones and gypsum rocks distributed from the base to top in succession (Fig. 4a). In addition, dark grey mudstones and shales were present at the base of the limestones (Fig. 4a), most likely formed in the submarine transgression period and subtidal environment. This is inconsistent with the tidal flat deposition, whose environment is principally intertidal to supratidal.

In particular, for the grain rocks, it is characterized by reverse grain size in ascending order (Fig. 4b). This implies that the depositional facies is not tidal flat, which commonly has features such as base scouring and normal grain grading bedding (e.g., Zou et al. 1990; Qiang 1998).

Reservoir space

The water was several meters in depth during the Jia 2 time interval (Tan et al. 2008). Therefore, the carbonates can be easily exposed if the deposition is the tidal flat as the environment is intertidal to supratidal and cyclic marine regression took place commonly. In turn, the carbonates are easily in contact with meteoric incursion, and may be dissolved. Thus, the reservoir space should be composed mainly of solution pores (e.g., Yu et al. 2007). However, this feature is only observed in the Jia 2^2-B layer, which represents the maximum of marine regression. In addition, with respect to the developing area, it is only in the structural highs, i.e., the area from wells Mo 13-Mo 151, to Mo 208, to Mo 24-Mo 206-Mo 207, and to Mo 48 (Fig. 1b)

(Tan et al. 2008; Zhou et al. 2009). Hence, the Moxi area was generally not exposed above the mean sea level, except for during the Jia 2^2-B time interval.

Depositional features of representative and key reservoir intervals

Based on the above discussion, it can be indicated that the depositional facies of the Jia 2 reservoir is not the tidal flat predominantly, which occurred limitedly only during the Jia 2^2-B time interval. Moreover, the carbonate platform is most likely an epeiric platform under subtidal environment, considering that the Sichuan Basin belongs to a carbonate platform deposition during Early Triassic (Wang 1985; Wang et al. 1989; Yuan et al. 1998; Cao et al. 2004) together with a wide occurrence and rhythmic deposition of gypsum rocks (cf. Wang et al. 2005). The paleoclimate is semi-arid to arid and hot as evidenced by the wide occurrence of the gypsum rocks indicative of a dominant evaporation effect. Thus, the platform is a type of restricted to evaporative marine carbonate platform and the platform facies can be further divided into 5 subfacies and 23 microfacies (Table 1).

Of the facies types listed in Table 1, grain shoal and dolomitic flat are potential good gas reservoir facies as they have relatively high porosity (>5%), according to the data reported by Zhou et al. (2007, 2009). In contrast, the other facies are characterized by rocks deposited in relatively low-energy environments, and thus have low physical properties (<5% porosity) (Zhou et al. 2007, 2009). Depositional features of the two representative and key reservoir intervals include the grain shoal facies mostly developed in Jia 2^2-A and -C layers and dolomitic flat facies mostly developed in Jia 2^2-B layer.

Grain shoal

During the Jia 2 time interval, the Moxi area was generally a restricted to evaporative epeiric platform (Wang 1985; Wang et al. 1989), thus having relatively low hydrodynamic conditions (Liu 1989; Qiang 1998). As a consequence, grain shoals occur locally when and where wave and storm had impacts (Wang et al. 2005; cf. Zhao et al. 2005a, b; Ma et al. 2007, 2008). With respect to the developing time, it is during the submarine transgression and early marine regression, when the depositional interface was located near the mean sea level. With respect to the developing locations, it is in the structural highs.

In the grain shoal deposition, rock types mainly include sparry oölitic and bioclastic limestone, and dolarenite in light grey color, and sparry dolarenite and oölitic dolostone in dark grey to khaki color (Figs. 2, 4b). In depositional sequence, it is characterized by a shallowing-upward and coarsening upward deposition (Fig. 4b). The grains are mainly oölitic and calcarenite grains, with the presence of some rudite, bioclastic and pisolite grains. Thus, the grain shoal facies can be divided mainly into two types of subfacies. The first is the oölitic facies, which is developed typically in the Jia 2^2-A layer. It comprises sparry oölitic limestones and dolostones, with preservation of residual inter-granular pores being reservoir space (Fig. 5a). In addition, contemporaneously to penecontemporaneously diagenetic solution pores are present due to exposure under meteoric environments (Fig. 5a). They provide good conditions for the development of reservoir porosity. In contrast, the other microfacies types (i.e., calcarenite and dolarenite shoal) were developed mainly in the Jia 2^2-C layer, with residual inter-granular and solution-enlarged pores being reservoir space (Fig. 5b).

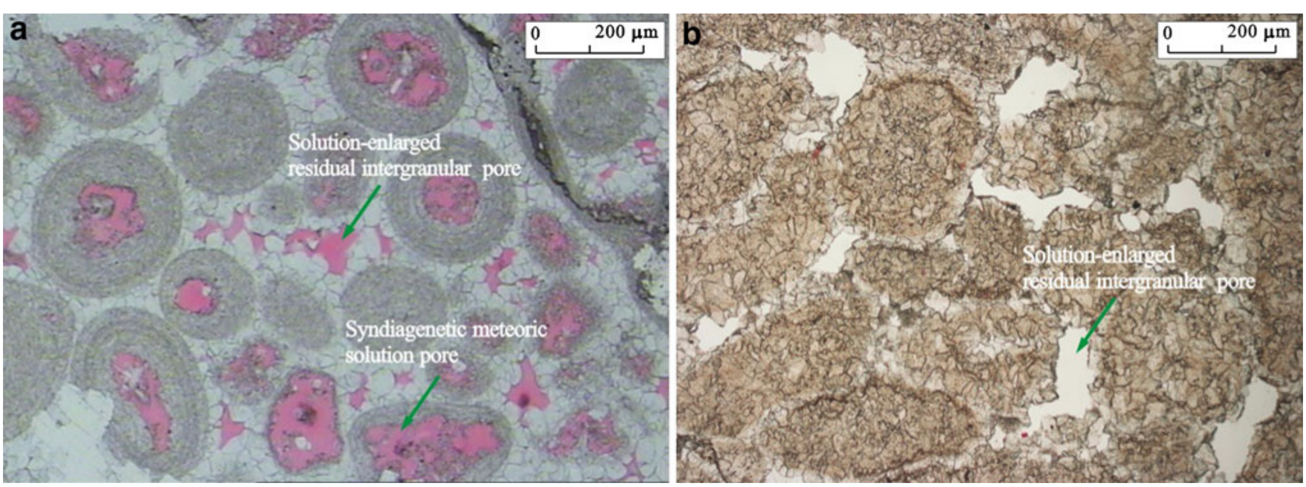

Fig. 5 Rock and pore types of grain shoal facies. **a** Sparry oölitic limestone, well Mo 13, 3122.1 m, Jia 2^2-A layer, red casting thin section, plane-polarized light. **b** Sparry dolarenite, well Mo 149, 3113.2 m, Jia 2^2-C layer, rock thin section, plane-polarized light. See Fig. 1b for the location of the wells

Platform flat

As discussed above, the tidal flat-like deposition may be developed mainly and only in the Jia 2^2-B layer. In addition, the Jia 2^1 member has also been reported (e.g., Tan et al. 2008). Rock types include dark grey micrite limestone, micrite to silt-crystalline dolostone, khaki silt-crystalline dolostone, gypsum dolostone, and anhydrock. It is characterized by a shallowing-upward deposition, with little development of grain rocks (Fig. 4a). The strata can be correlated extensively (Tan et al. 2008), implying that the time interval was subject to a continuous marine regression. The depositional interface of the underwater structural highs was near the mean sea level during the regression, as the structural highs—far away from the continent (ca. several hundred meters; Tian 1989)—had a relatively flat tomography and the water was very shallow of several meters. As a consequence, the area was mainly under an intertidal to supratidal environment, being exposed to meteoric incursion cyclically or for a long time, and with relatively weak influence of tidal and wave. These features indicate a tidal flat-like deposition to certain degrees.

However, it is not the typical and standard tidal flat facies. The typical tidal flat in definition is located in the coastal zone with influence of tidal flow. In contrast, here the so-called tidal flat during the Jia 2 time interval in the Moxi area is located inside the shallow water platform, mainly with influence of cyclic variation of mean sea level (Qiang 1998). This facies is termed as platform flat.

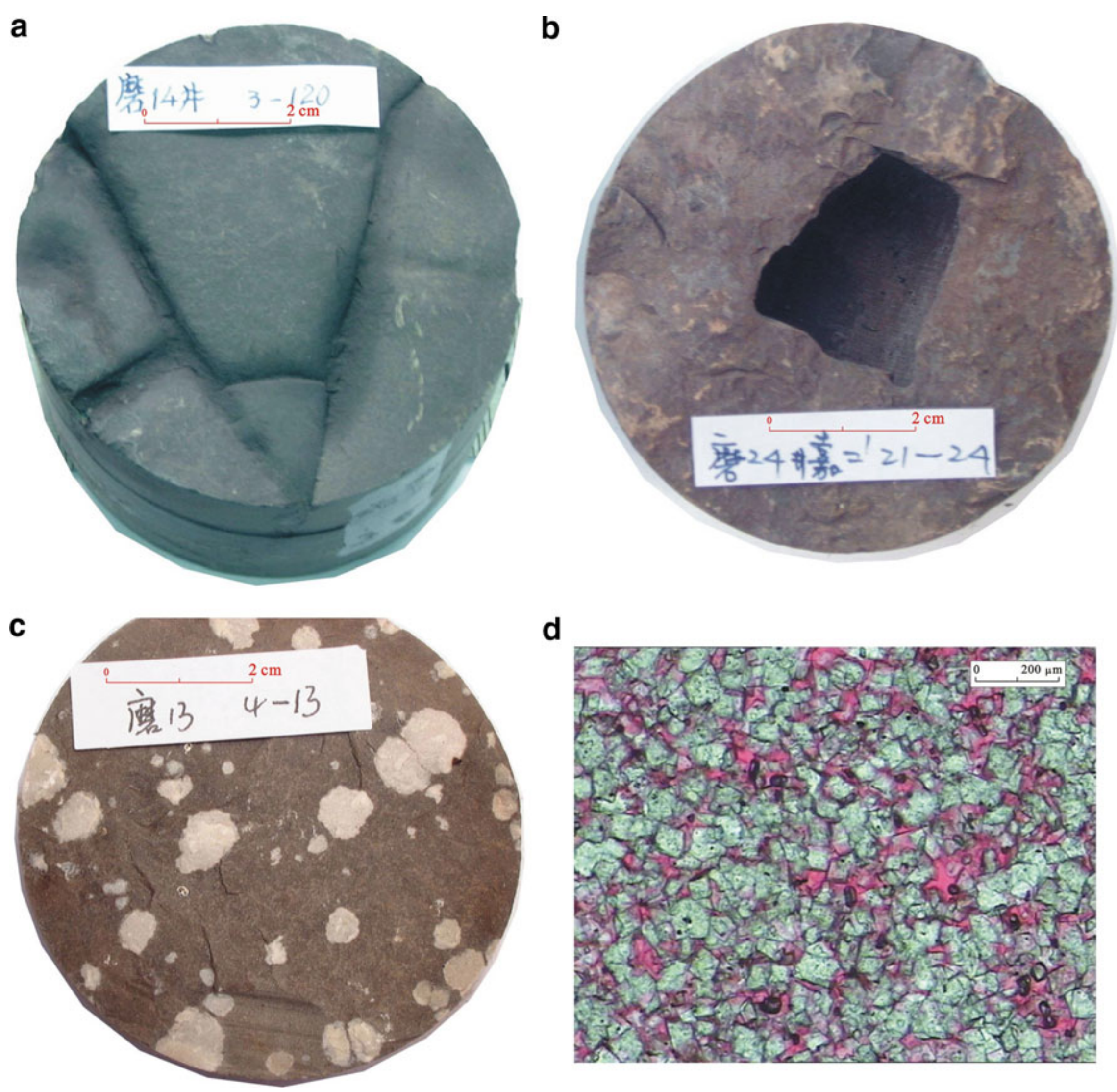

Fig. 6 Rock and pore types of platform flat facies. **a** Muddy dolostone, rock cracks, well Mo 14, 3,157.7 m, Jia 2^2-B layer, core observation. **b** *Dark purple* mudstone, well Mo 24, 3,106.2 m, Jia 2^2-B layer, core observation. **c** *Khaki* silt-crystalline dolostone with pinhole development, bearing blocky gypsum lumps, well Mo 13, 3,115.0 m, Jia 2^2-B layer, core observation. **d** *Grey* silt-crystalline dolostone, well Mo 24, 3,105.7 m, Jia 2^2-B layer, red casting thin section, plane-polarized light. See Fig. 1b for the location of the wells

The Jia 2^2-B layer of well Mo 14 is representative (Fig. 4a). Its depositional features can be generalized into six folds: (1) exposed depositional textures (e.g., rock cracks; Fig. 6a); (2) gypsum breccia with origin of exposed solution in contemporaneous diagenesis (Fig. 3a); (3) purple red to dark purple mudstones suggestive of an oxic environment (Fig. 6b); (4) khaki micrite and silt-crystalline dolostones with solution pores of meteoric leaching origin (Fig. 6c, d); (5) shallowing-upward depositional sequence (Fig. 4a); and (6) grain rocks lacking depositional structures of tidal origin (Figs. 2, 3, 4) (cf. Wang et al. 2005).

In addition, the platform flat facies can be subdivided into microfacies including dolomitic, gypsum dolomitic, gypsum and muddy flat, based on different rock types. Of the flat facies, the dolomitic flat is potential good reservoir facies with >5% porosity. (Zhou et al. 2009), whose rock types mainly comprise silt-crystalline dolostones with grey to dark grey and khaki in color. Solution pores and vugs with filled gypsum were observed in some cases (Fig. 6c, d).

The platform flat is located in the intertidal to supratidal environments. As a result, a strong evaporation leads to penecontemporaneously diagenetic dolomitization, and primary limy sediments are transformed to micrite to silt-crystalline dolostones. The lower part of the platform flat is relatively pure dolostones in general, which is favorable for diagenesis (e.g., syndiagenetic meteoric leaching, re-crystallization and burial dissolution) to form silt-crystalline dolostones with the development of inter-crystalline primary and solution pores (Fig. 6d). This is the special feature of the Jia 2^2-B layer reservoir, which distributed stably in the entire Moxi area (Tan et al. 2008; Zhou et al. 2009). In contrast, the upper part of the platform flat commonly has relatively high amount of muddy components, and thus is not favorable for later diagenesis. This, in turn, is not favorable for the development of reservoirs.

Depositional model and evolution of representative and key reservoir intervals

Jia 2^2-A layer (grain shoal)

During the Jia 2^2-A time interval, the Moxi area was characterized by a deposition of grain shoal and semi-restricted lagoon. Microfacies include shoal core, shoal core to margin, shoal margin to inter-shoal low, and mud-limy lagoon (Fig. 7a). The early stage of this interval was dominated by a limestone deposition due to rapid marine transgression (Fig. 2). Subsequently, only the depositional interface of the underwater structural highs was near the mean low tidal level (cf. Huang and Zeng 1995). Thus, the water was in general shallow and commonly exposed to meteoric leaching, further leading to the development of solution reservoir pores (Fig. 5a). To the late stage of the Jia 2^2-A interval, a rapid marine transgression results in the entire area locating below the mean low tidal level. Consequently, limy lagoon facies occurred widely (Fig. 2).

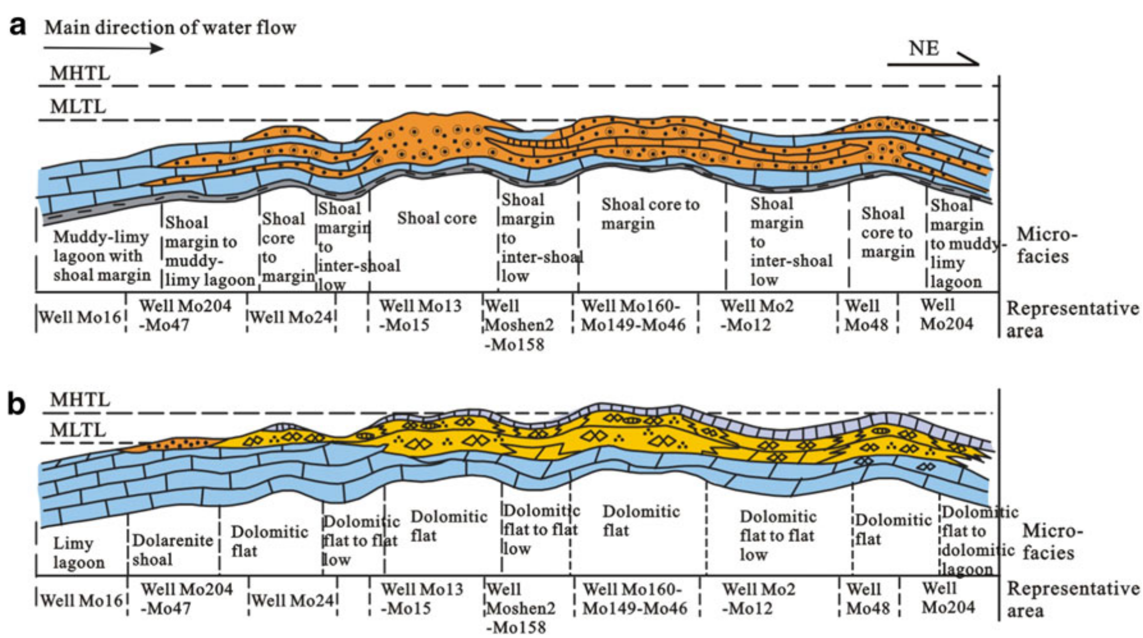

Fig. 7 Sketch depositional model of representative and key reservoir intervals. **a** Jia 2^2-A layer with grain shoal development. **b** Jia 2^2-B layer with platform flat development. See Fig. 1b for the location of the wells, and Fig. 1c for the lithological legend. MHTL and MLTL refer to mean high and low tidal level, respectively

As shown in Fig. 8a, the shoal core and core to margin microfacies were present widely, and the facies of inter-shoal low was developed due to tomographic rises and falls. The shoal core is characterized by a deposition of oölitic limestones, with big cumulative thickness of grain rocks and big thickness of individual shoal body (commonly >3 m). In addition, rocks with the development of pinholes were present. These are favorable for the development of reservoirs, commonly with >7% porosities (Zhou et al. 2009). Besides the shoal core, the shoal core to margin facies also has good reservoir property with porosity generally >5% (Zhou et al. 2009), worse than that of the shoal core. A lagoon deposition with limited amounts of grain rocks and little occurrence of pinholes in rocks are developed in the outer area, and the facies commonly had <5% porosity and thus cannot form good reservoir in general.

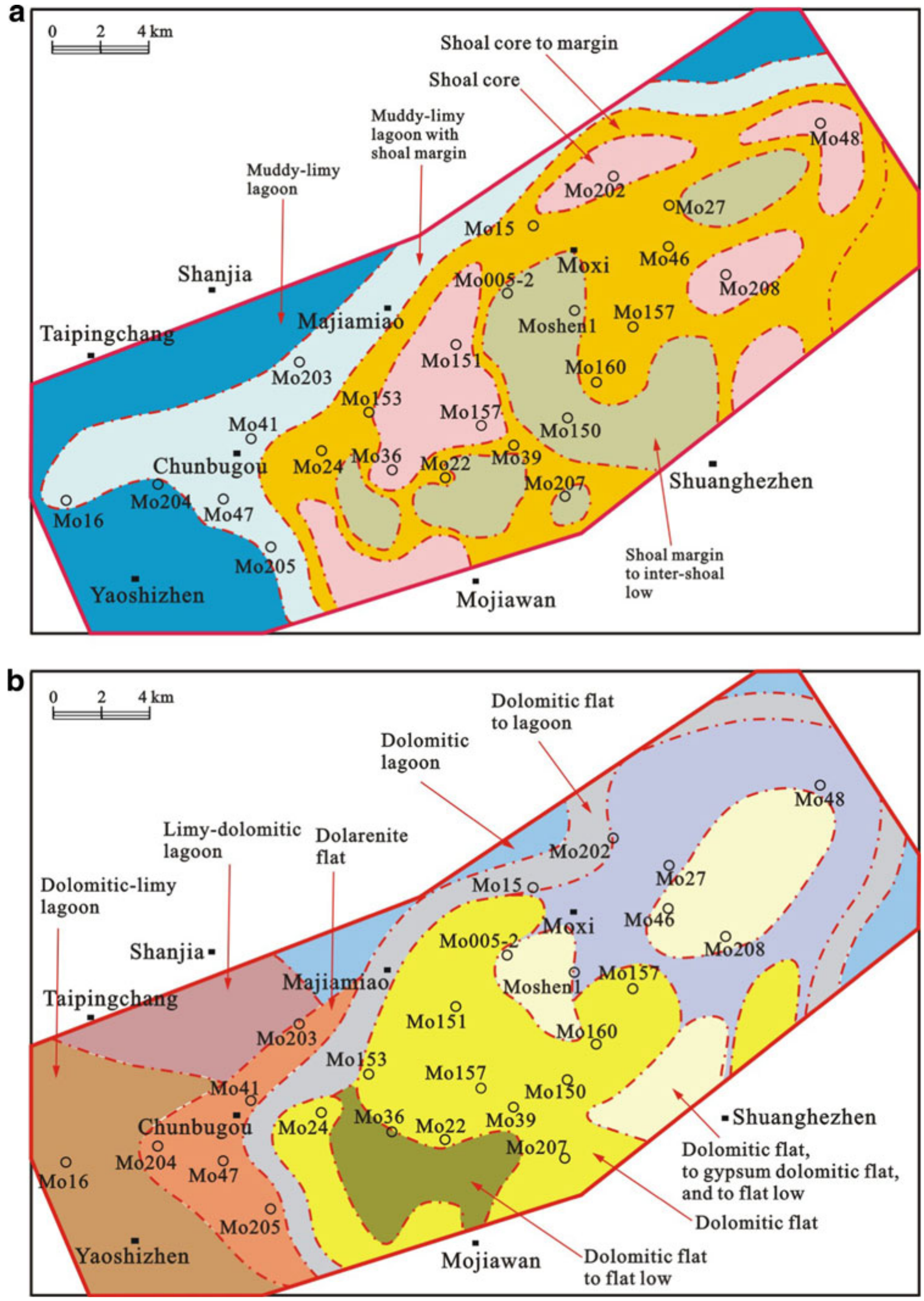

Fig. 8 Sketch depositional facies distribution of representative and key reservoir intervals. **a** Jia 2^2-A layer with grain shoal development. **b** Jia 2^2-B layer with platform flat development. See Fig. 1b for the location of the wells

Jia 2^2-B layer (platform flat)

During the Jia 2^2-B time interval, the evaporation effect increased due to marine regression. The dolomotization is one of the results of this event. The depositional interface of the underwater structural highs was above the mean low tidal level and some even above the mean high tidal level due to the regression (Fig. 7b). As a consequence, meteoric leaching leads to the development of solution pores and good reservoirs (Fig. 6d).

The depositional framework inherited from that of the Jia 2^2-A time interval in general, and the depositional environment was more evaporative and the depositional energy was lower. As a result, the depositional facies mainly include platform flat and semi-restricted to restricted lagoon. Microfacies comprise dolomitic flat, gypsum dolomitic flat, flat low, dolarenite shoal, dolomitic-limy lagoon and dolomitic lagoon (Fig. 7b). Of these facies, the dolomitic flat can form good reservoir mainly due to meteoric leaching (Fig. 6d), as discussed previously. This type of microfacies distributed in the central part of the area (Fig. 8b). In contrast, the eastern area from well Mo 27 to Mo 48 is characterized by a deposition of dolomitic flat, gypsum dolomitic flat and flat low (Fig. 8b). The gypsum cementation was developed greatly due to high water salinity. Thus, this area is not favorable for the development of reservoirs as the dolomitic-flat area. A deposition of flat low is dominated between these two facies and was seldom exposed during the syndiagenetic stage. Hence, it likely cannot form good reservoir space. As to the lagoon microfacies, it is also not favorable for the the development of reservoirs due to little presence of primary and secondary pores and vugs. In addition, there is a deposition of dolarenite, whose depositional interface was near the mean low tidal level (Figs. 7b, 8b). This is favorable for the development of reservoirs with a nearly 5% porosity (Zhou et al. 2009), being not so good as the dolomitic flat because the depositional energy is lower (Fig. 7b) (Qiang 1998).

Conclusions

1. The Jia 2 member of the Moxi gas field was generally not of a tidal flat deposition in an intertidal (to supratidal) environment, but of restricted and evaporative carbonate platform deposition in a subtidal environment. The tidal flat-like (i.e., platform flat) facies occurred only in the Jia 2^2-B layer.
2. The restricted–evaporative carbonate platform facies can be further divided into 5 subfacies and 23 microfacies, of which the grain shoal and dolomitic flat facies are relatively favorable for the development of reservoirs. Their depositional model, distribution and evolution were tentatively established.
3. The Moxi gas field in this study is the most representative one of the Jialingjiang Formation gas reservoir of carbonate platform so far in the Sichuan Basin. Thus, the above results offer supplement to the present hot studies of reservoir deposition on the Permian–Triassic gas reservoir of the basin. It can be predicted that more and more Jialingjiang reservoirs can be discovered and need further researches for improving the understanding on the reservoir. In addition, the results also have general implications for the carbonate platform reservoirs elsewhere.

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References

Cao J, Tan XC, Chen JS (2004) Sedimentary facies and their evolution characteristics in Jialingjiang Formation of Jianwei Area, Southwest Sichuan Basin. Geol J China Univ 10:429–439 (in Chinese with English abstract)

Dai JX, Zou CN, Qin SF, Tao SZ, Ding WW, Liu QY, Hu AP (2008) Geology of giant gas fields in China. Mar Petrol Geol 25:320–324

Ehrenberg SN (2006) Porosity destruction in carbonate platforms. J Petrol Geol 29:41–52

Guo ZW, Deng KL, Han YH (1994) Formation and development of Sichuan Basin. Geological Publishing House, Beijing, pp 1–39 (in Chinese)

Hou FH, Jiang YQ, Fang SX (2004) Petroleum geological conditions of the Triassic Jialingjiang Leikoupo and Xiangxi formations central to southern Sichuan Basin. Technical report. Central Branch of PetroChina Southwest Oil and Gas Field Company, Chengdu, pp 1–103 (in Chinese)

Huang JX, Zeng W (1995) The development and distribution of the Triassic bank-microfacies in the 2-section of Jialingjiang Group and its gas-poal control nature in the eastern part of Sichuan Basin. Acta Sedimentologica Sinaca 13(Supplement):109–117 (in Chinese)

Liu DC (1989) The relationship between sedimentary facies of Lower Triassic Jialingjiang Formation and hydrocarbon accumulation, northeast Sichuan province and adjacent area. Oil and Gas Geology of Marine Deposit Region 3:35–42 (in Chinese with English abstract)

Ma YS, Guo XS, Guo TL, Huang R, Cai XY, Li GX (2007) The Puguang gas field: new giant discovery in the mature Sichuan Basin, southwest China. AAPG Bulletin 91:627–643

Ma YS, Zhang SC, Guo TL, Zhu GY, Cai XY, Li MW (2008) Petroleum geology of the Puguang sour gas field in the Sichuan Basin, SW China. Mar Petrol Geol 25:357–370

Ma YS, Cai XY, Zhao PR, Luo Y, Zhang XF (2010) Distribution and further exploration of the large-medium sized gas fields in Sichuan Basin. Acta Petrolei Sinica 31:347–354 (in Chinese with English abstract)

Paola R, Andrea O, Ornella B, Michele C, William GZ (2010) Depositional setting and diagenetic processes and their impact on the reservoir quality in the late Visean-Bashkirian Kashagan carbonate platform (Pre-Caspian Basin, Kazakhstan). AAPG Bulletin 94:1313–1348

Qiang ZT (1998) Carbonate rock reservoir geology in China. Petroleum University Press, Beijing, pp 1–363 (in Chinese)

Tan XC, Luo B, Li L, Luo YH, Yang JL, Yao YB, Li JL, Zou J, He XQ (2008) Fine subdivision and correlation of multi-cycle carbonate platform successions: a case study of the second member of the Jialingjiang Formation in the Moxi structure, central Sichuan Province. J Stratigraphy 32:207–212 (in Chinese with English abstract)

Tian DX (1989) Sedimentary characteristic in the second member of Jialingjiang Formation of Lower Triassic in the center of Sichuan Basin. Oil and Gas Geol Mar Depos Reg 3:50–55 (in Chinese with English abstract)

Wang HZ (1985) Paleogeography of China. China Map Press, Beijing, p 39 (in Chinese)

Wang BJ, Bao C, Xiao MD (1989) Petroleum geology of China: Sichuan oil and gas region. Petroleum Industry Press, Beijing, pp 1–78 (in Chinese)

Wang YG, Zhang J, Liu XG, Xu DZ, Shi XR, Song SJ, Wen YC (2005) Sedimentary facies of evaporative carbonate platform of the Feixianguan Formation of Lower Triassicin northeastern Sichuan Basin. J Palaeogeogr 7:357–371 (in Chinese with English abstract)

Wannier M (2009) Carbonate platforms in wedge-top basins: An example from the Gunung Mulu National Park, Northern Sarawak (Malaysia). Mar Petrol Geol 26:177–207

Xu CC, Li JL, Yao YB, Yang JL, Gong CM (2006) Cases of discovery and exploration of marine fields in China (Part 8): Triassic T_3j_2 reservoir of Moxi gas field in Sichuan Basin. Mar Orig Petrol Geol 11:54–61 (in Chinese with English abstract)

Yang RJ, Liu SG, Wu XC (2010) Distribution and formation mechanism of lime mudstone in Upper Triassic in northwestern Sichuan, China. Carbonates Evaporites 25:275–281

Yu BS, Fan TL, Huang WH, Liu ZB, Gao ZQ (2007) Predictive model for karst reservoirs in sequence stratigraphic framework. Acta Petrol Sinica 28:41–45 (in Chinese with English abstract)

Yuan ZH, Feng ZZ, Wu SH (1998) Study on lithofacies paleogeography of Jialingjiang Formation of Lower Triassic in the Middle Yangtze region. Acta Sedimentologica Sinaca 33:180–186 (in Chinese with English abstract)

Zhao YH, Zhang XL, Luo YH (2005) Gas reserve of the second member of the Jialingjiang Formaiton, Moxi gas field. Technical report. Central Branch of PetroChina Southwest Oil and Gas Field Company, pp 1–109 (in Chinese)

Zhao WZ, Luo P, Chen GS, Cao H, Zhang BM (2005b) Origin and reservoir rock characteristics of dolostones in the early Triassic Feixianguan Formation, NE Sichuan Basin, China: significance for future gas exploration. J Petrol Geol 28:83–100

Zhou Y, Tan XC, Liu H, Luo YH, Zhang XL (2007) Oölitic limestone reservoir characteristics and its genetic mechanism of Jia 2 member in Moxi Gas Field. J Southwest Petrol Univ 29:30–33 (in Chinese with English abstract)

Zhou Y, Tan XC, Liu H, Yang JL, Yao YB, Li JL, Zhong H, Lin JP (2009) Evaluation of porous carbonate reservoir of Jia 2 member in Moxi Structure of Sichuan Basin. Acta Petrol Sinica 30:372–378 (in Chinese with English abstract)

Zhu GY, Zhang SC, Liang YB, Ma YS, Dai JX, Li J, Zhou GY (2006) The characteristics of natural gas in Sichuan basin and its sources. Earth Sci Frontiers 13:234–248 (in Chinese with English abstract)

Zou SC, Xia XY, Zeng CX (1990) Comprehensive resource evaluation and exploration strategy shaping of the Lower Triassic, central to southern Sichuan Basin. Technical report. Central Branch of PetroChina Southwest Oil and Gas Field Company, pp 1–63 (in Chinese)