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ORIGINAL ARTICLE

Distribution and controlling factors of the oolitic shoal deposits in the sequence stratigraphic framework: a case study of the Lower Triassic Feixianguan Formation, eastern Sichuan Basin, China

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Abstract
As one of the main reservoirs types in the Sichuan Basin, the granular shoal reservoirs of the Feixianguan Formation have great potential for oil and gas exploration. Therefore, it is very important to study the sedimentary evolution characteristics and the distribution of shoal deposits of the Feixianguan Formation. In this paper, the sequence stratigraphy, sedimentary characteristics and distribution characteristics of the granular shoal deposits of the southwestern section of the Kaijiang–Liangping Trough in the Sichuan Basin were investigated, through core observations, thin section analysis, and field profiles measurement and sampling, combined with well-logging data and interpretations of two and three-dimensional seismic data of the local area. According to the identification marks, three sequence boundaries (SB1, SB2, and SB3) and two third-order sequences (SQ1 and SQ2) were identified, and a transgressive systems tract (TST) and highstand systems tract (HST) were distinguished in each third-order sequence. The analysis of the Feixianguan Formation sedimentary facies indicated that this formation developed in a carbonate platform setting. In the depositional period of SQ1, the study area inherited the sedimentary pattern of the Changxing Formation and developed carbonate platform depositions. During the SQ1-HST stage, the platform margin shoals and the intra-platform shoals in the study area were relatively well developed. During the SQ2-TST period, oolitic shoals were developed in the region, but their thicknesses were smaller than those of SQ1-HST. In addition, the distribution pattern of sedimentary facies was similar to that of SQ1-HST. The platform marginal zone was relatively narrow at that time, whereas the open platform was more widely distributed, and the distribution areas of platform margin shoals and intra-platform oolitic shoals were relatively limited. During the depositional period of SQ2-TST, the sea level dropped to the lowest level of the studied interval, and limited and evaporation platform facies developed in the study area. Based on previous studies, the influence of different factors on the deposition of the shoals in the Feixianguan Formation were evaluated. The results showed that under the influence of sea level, basement faults, and hydrodynamic conditions, the platform margin area in the study area was more favorable to the development of granular shoals, and the growth model of the granular shoals was "accretion before migration".

Keywords Sichuan Basin · Sequence stratigraphy · Sedimentary facies · Feixianguan Formation · Distribution of carbonate shoal · Controlling factors of oolitic shoal deposits

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Introduction

In recent decades, Chinese scholars have systematically studied the ancient carbonate reservoirs in three basins in Western China (Zhu et al. 2007; Shen et al. 2015). To date, carbonate reservoirs of reef-shoal, karst, and dolomitization types have been found in the carbonate strata of the Ordos Basin, Sichuan Basin, and Tarim Basin in Western China (Zhao et al. 2012; Shen et al. 2015, 2019), and these reservoirs have shown good oil and gas display from deep and ultra-deep carbonate strata (Sun et al. 2013; Jia et al. 2018;

Yu et al. 2018a). Therefore, shoal reservoirs, as one of the main types of carbonate reservoirs, have been widely investigated by researchers in China and other parts of the world (Makhloufi et al. 2013; Zhao et al. 2014; Hollis et al. 2017; Yu et al. 2018b; Ding et al. 2019).

In the past two decades, Chinese oil and gas geologists have made a series of discoveries in the study of carbonate strata in the Sichuan Basin (Liu et al. 2017a, b, c; Ma et al. 2019; Wei et al. 2020). In recent years, researchers have focused on the exploration of the Lower Cambrian Longwangmiao Formation and the Sinian Dengying Formation (Gu et al. 2015; Zhou et al. 2016; Luo et al. 2017; Yang et al. 2017), the Upper Permian Changxing Formation and the Lower Triassic Feixianguan Formation (Liu et al. 2013; Liu et al. 2016a, b, c; Ma et al. 2016; Liu and Xie 2018; Zhou et al. 2019), the Middle Permian Qixia and Maokou Formations (Hu et al. 2012; Yang et al. 2015; Xiao et al. 2016).

Among these, the Lower Triassic Feixianguan Formation in the Sichuan Basin, as one of the main gas-producing formations, developed a carbonate oolitic shoal facies reservoir. Furthermore, many scholars have studied the sedimentary characteristics of the Feixianguan Formation, and have proposed that the Feixianguan Formation in the Sichuan Basin inherited the sedimentary pattern of the underlying Changxing Formation and developed carbonate platform deposition (Hu et al. 2019; Wu 2019). In addition, these researchers have considered that the Feixianguan Formation and the Changxing Formation have a "filling and leveling" relationship. Other scholars have studied the reservoir characteristics and main controlling factors of the Feixianguan Formation (Liu et al. 2017a, b, c). These scholars have suggested that sedimentary microfacies, sea-level fluctuations, and diagenesis played important roles in the development of oolitic shoal reservoirs in the Feixianguan Formation (Ma et al. 2016; Jiang et al. 2018; Li et al. 2018; Liu and Xie 2018).

However, because of the strong heterogeneity of the shoal reservoirs (Qiao et al. 2016), it is difficult to accurately predict the positions of oolitic shoal bodies. In addition, studies on the paleogeographic patterns and reef-shoal sedimentary characteristics of the Changxing to Feixianguan depositional period in the southwestern Kaijiang–Liangping Trough are relatively scarce. Therefore, the understanding of the sedimentary characteristics and distribution patterns of shoal bodies in the Feixianguan Formation is lacking.

This paper is aimed, based on comprehensive analysis of logging data, cores, thin sections, and field profiles, to establish the sequence stratigraphic framework of the Feixianguan Formation in the study area, and to investigate the sedimentary characteristics of this formation, intending to clarify the sedimentary evolution of the Feixianguan Formation in the southwestern part of the Kaijiang–Liangping Trough, as well as the distribution of granular shoals and the main controlling factors within the sequence framework. This work will provide a good reference for gas exploration and development of the Feixianguan Formation in the southwestern Kaijiang–Liangping Trough in the eastern Sichuan Basin.

Geological setting

Tectonic setting

The Sichuan Basin, covers an approximative area of 19×10^4 km^2, and is a diamond-shaped basin in the southwestern part of China (Jiang et al. 2015; Shi et al. 2018) (Fig. 1a). It is the second largest structural unit in the northwest part of the upper Yangtze craton. It is located in Sichuan Province and the surrounding areas of Chongqing. According to the characteristics of the present tectonic setting in the basin, the Sichuan Basin is divided into six secondary tectonic zones (Fig. 1b).

The basement of the Sichuan Basin is pre-Sinian metamorphic rock. From the beginning of its deposition, the Sichuan Basin has been filled with marine carbonate rocks from the Sinian to the Middle Triassic, followed by continental strata form the Upper Triassic to Neogene (Zhou et al. 2019). According to previous studies, the Sichuan Basin has been attributed to a stage of cratonic evolution originating from the late Sinian to the Middle Triassic. Since the deposition of the Dengying Formation in the Sinian, two tectonic movements have taken place in the Sichuan Basin: the Xingkai Rifting Movement (Pt3–Є1) and the Emei Rifting Movement (D2–T1) (Luo 1983; Luo et al. 2001). As a result, the cratonic sedimentation period of the Sichuan Basin experienced two complete tectonic cycles of weak tension to weak extrusion (Liu et al. 2016b).

Stratigraphy in the study area

The study area is located in the southwestern part of the Kaijiang–Liangping Trough in Liangping County and its surrounding area (Fig. 1c, d), with an approximative area of 2000 km^2.

A series of NW tensional basement faults developed in the Sichuan Basin under the influence of the Emei Rifting Movement (Luo 1983). Because of differential subsidence, the Upper Permian Changxing Formation and the Lower Triassic Feixianguan Formation of the Sichuan Basin were deposited on shallow carbonate platform and deep-water trough environments (Cheng et al. 2010; Liu et al. 2016a) (Fig. 1c). It has been confirmed by previous studies that the strata of the Feixianguan Formation are well developed, and a carbonate platform sedimentary model has been proposed

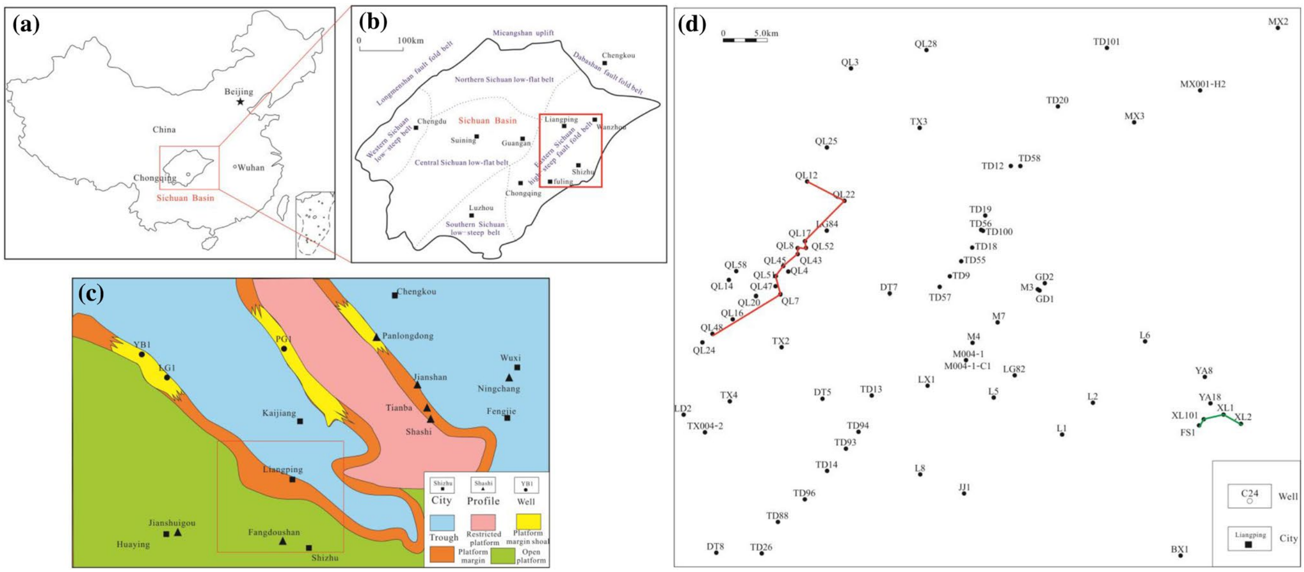

Fig. 1 **a** The geographical position of Sichuan Basin in China; **b** secondary structural area of Sichuan Basin; **c** paleogeographic map of the Feixianguan Formation in Eastern Sichuan Basin (modified from); **d** well sites in the study arae

(Ehrenberg et al. 2008). The study area is located on the transition area from platform to trough sedimentary units.

The Feixianguan Formation overlies conformably the Changxing Formation and underlies conformably the Jialingjiang formation. The thickness of the Feixianguan Formation is about 400–600 m. In this study, the Feixianguan Formation in eastern Sichuan has been examined by dividing it into four lithologic sections; from the bottom to the top, they are Fei 1, Fei 2, Fei 3 and Fei 4 (Fig. 2). The lithology of the first member of the Feixianguan Formation (Fei 1) is mainly micritic limestone with argillaceous limestone at the top, and calcareous mudstone and shale 2–10 m in thickness are common at the bottom. The gamma curve is generally large. The lithology of the second member of Feixianguan Formation (Fei 2) mainly composed of micrite limestone, and oolitic grainstone and intraclastic grainstone are present in some wells. The lithology of the third member of Feixianguan Formation (Fei 3) mainly composed of micrite limestone, oolitic grainstone, and intraclastic grainstone. The top and bottom of the third member of Feixianguan Formation are mostly micritic limestone. The lithology of the fourth member of the Feixianguan Formation (Fei 4) is mainly composed of mudstone, with 1- to 3-m-thick gypsum and dolomite in the middle.

The member Fei 1, which is mainly characterized by micritic limestone, with rare oolitic grainstone was deposited on sedimentary environments such as open platform, platform margin, slope front, and trough. The member Fei 2 deposited on a platform following the slope and trough deposition. The oolitic shoal mainly started to develop at the later stage of member Fei 2 deposition and continued through the deposition stage of member Fei 3. The lithology of the sediment deposited on these shallower shoal is characterized by oolitic grainstone, oolitic dolomite, and a small amount of bioclastic grainstone. The Member Fei 4 which is represented by purple mudstone, argillaceous dolomite, gypsum, and gypsum dolomite were deposited in the restricted platform and evaporative platform environments.

Methodology

The data used in this study included well-logging data from 26 wells, core data from seven wells, and more than 800 thin sections from five wells and four field profiles. The carbon and oxygen isotope data of the adjacent area were also used.

Sequence stratigraphy and sedimentary facies analysis

In this study, the detailed core data and well-logging data of seven wells in the unexposed area were used, also in the exposed area, sedimentary facies analysis was carried out based on the strata and sedimentary structures of four profiles. Moreover, at the Sedimentary Basin Experimental Center of Yangtze University, polarizing microscopy was used to observe more than 800 thin sections from five wells and four profiles, for detailed sedimentological and petrological research. All thin sections were stained with Alizarin red S to distinguish dolomite from calcite.

The sequence stratigraphic framework of the study area was established by identifying the sequence boundaries of

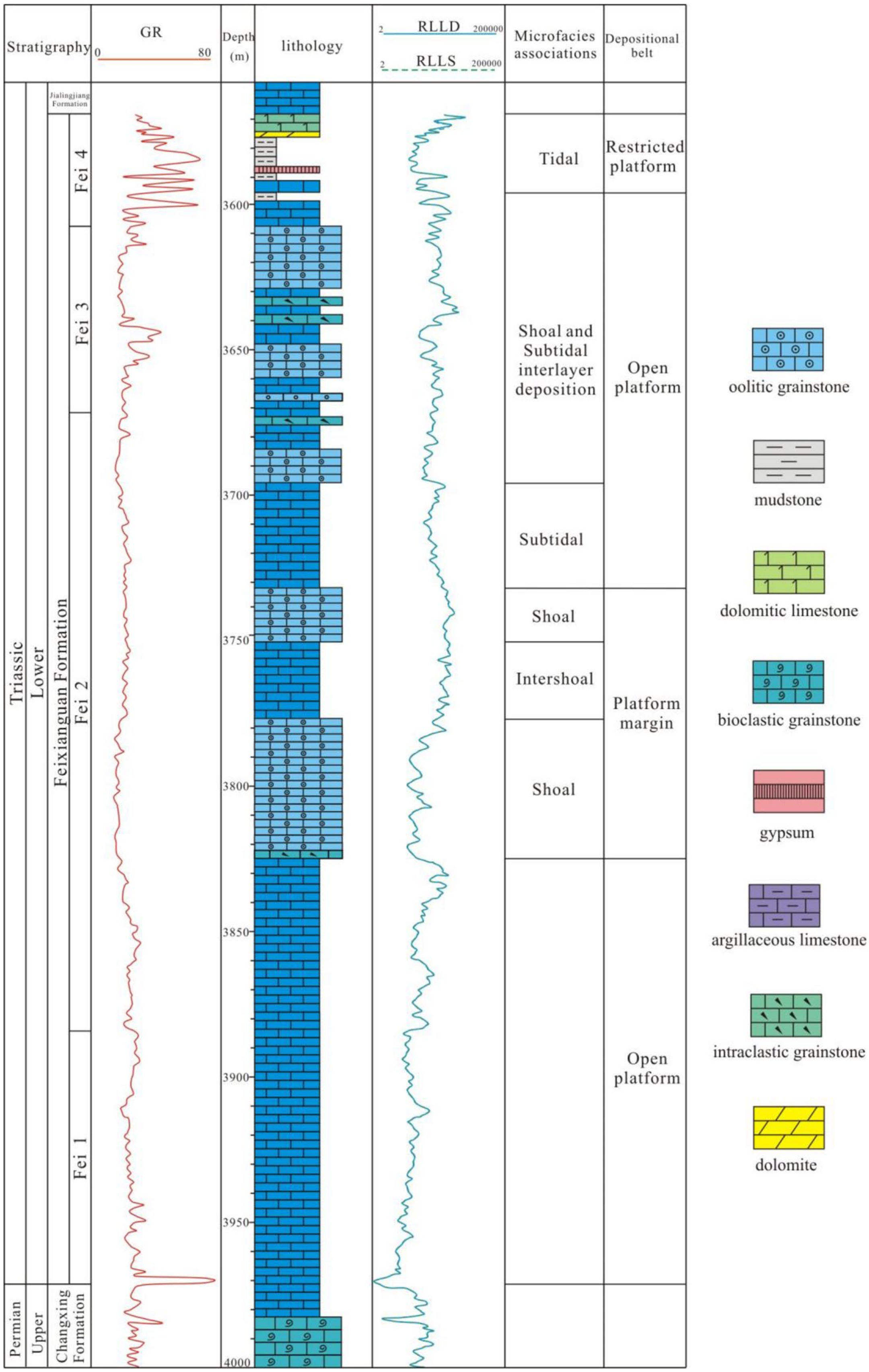

Fig. 2 Sequence and sedimentary characteristics of the Feixianguan Formation in the eastern Sichuan Basin

field profiles and well-logging data. In addition, carbon isotope data were used to constrain the division of sequences and systems tracts in the sequence stratigraphic framework. Thus, the lithofacies, paleogeographic characteristics and shoal distribution were evaluated in the third-order sequence stratigraphic framework.

Carbon and oxygen isotope analysis

The carbon and oxygen isotopic data used in this study were from the Feixianguan Formation of the Shashi Profile, Yunyang County. In the process of sampling, care was taken to collect fresh samples and avoid structural faults, calcite veins, and karst caves. These methods were mainly adopted to ensure the validity of the samples.

In this study, the whole-rock carbon and oxygen isotopes were tested and analyzed at the Lake and Basin Sedimentation Laboratory of Yangtze University. DELTA V Advantage gas isotope ratio mass spectrometer was used by applying the phosphoric acid method for experimental analysis. The test standard was IAEA-CO-8, and the accuracy of $\delta^{13}C$ and $\delta^{18}O$ analyses and tests was 0.2‰. Before the samples were processed, they were ground to more than 200 mesh size in an agate mortar to ensure the full contact of sample powders with phosphoric acid. Moreover, a value of $\delta^{18}O > -10‰$ verified the corrosion of the samples. It was confirmed that the samples were not significantly altered by diagenesis.

Results

Facies

Based on observation and analysis of the cores, thin sections, well-logging data, and field profile data, the lithofacies of the Feixianguan Formation in the southwestern part of the Kaijiang–Liangping Trough were identified as outlined in Table 1 (Dunham 1962).

Table 1 Main types of lithofacies of the Feixianguan Formation in the study area

Lithofacies codes	Lithofacies	Description	Depositional environments
Lf1	Oolitic grainstone	The content of oolites is more than 50%, and the oolites mostly present a spherical shape. The diameter of the oolites is about 0.2–1.0 mm, and some of the oolites have undergone dolomitization to varying degrees	Moderate-to-high energy depositional environment
Lf2	Bioclastic grainstone	The main bioclastic components are gastropods, which may contain a small amount of oolite and intraclast	Moderate-to-high energy depositional environment
Lf3	Intraclastic grainstone	The shape of the intraclast is irregular, the particle size is variable, a small amount of them are well sorted and well rounded	High-energy depositional environment
Lf4	Dolomitized intraclastic grainstone	The grains are mainly oolitic and endoclastic, and dolomite crystals are euhedral and subhedral	High-energy depositional environment
Lf5	Oolitic wackestone	The content of ooids is relatively low (10–30%), and the main component is argillaceous calcite	Moderate-to-low energy depositional environment
Lf6	Intraclastic wackestone	The content of the intraclast is lower than intraclastic grainstone	Moderate-to-low energy depositional environment
Lf7	Micritic limestone	It is composed of argillaceous calcite with very little (< 10%) or no granular component	Low-energy depositional environment
Lf8	Silty dolomite	It is mainly composed of powdery dolomite, and dolomite crystals are mostly euhedral and subhedral	Low-energy environment, like restricted tidal flat and restricted lagoon
Lf9	Gypseous silty dolomite	It is mainly composed of powdery dolomite, dolomite crystals are mostly euhedral–subhedral, and gypsum is in patch distribution	Evaporate environment, like restricted tidal flat
Lf10	Gypsum	Layered gypsum is mainly developed in the fourth member of Feixianguan formation	Evaporate environment of restricted lagoon
Lf11	Mudstone	Dark gray, gray black dark mudstone	Low-energy environment of basin or trough

According to the combination patterns of the lithofacies, five types of facies associations, FA1–5, were identified as described below.

Platform margin facies association (FA1): this facies association comprises well-sorted oolitic grainstone (LF1; Fig. 3a–c), intraclastic grainstone (LF3; Fig. 3d), and bioclastic grainstone (LF2) facies. Light-gray thick-bedded oolitic grainstone facies is the dominant lithofacies. The, oncoid grainstone facies (Fig. 3d), as well as dolomitized intragranular grainstone (Lf4) are present in minor amount at the top. This facies association, which is mainly present in the second and third members of the Feixianguan Formation (Fei 2 and Fei 3), represents deposition on a beach at a platform margin. This lithofacies association is generally considered to be a product of a platform margin grainy beach or open platform grainy beach with high-energy sedimentary environment.

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Open platform facies association (FA2): this facies association comprises light-gray thin-layered oolitic wackestone (Lf5), intraclastic wackestone (Lf6), and thick-layered micritic limestone (Lf7) interlayers, as shown in Table 1. It is developed in the first to third members of the Feixianguan Formation (Fei 1–3). Sedimentary structures such as cross-bedding can be observed (Fig. 4b). This lithofacies assemblage typically represents the product of the sedimentary environment between grainy beaches on the edge of the middle- to low-energy platform or the subtidal environment of the open platform.

Restricted platform facies association (FA3): this facies association is mainly composed of gray-to-dark gray thick-layered micritic limestone (Fig. 4c) (Lf7) and silty dolomite (Lf8), and is mainly found in the second and third members of the Feixianguan Formation (Fei 2 and Fei 3). Small amounts of dry cracks, shallow-water sedimentary structures and exposed sedimentary signs can be seen, which represent environments with low hydrodynamic energy.

Evaporation platform facies association(FA4): this facies association is composed of purple-red and light-gray micritic limestone (Lf7), off-white layered gypsum(Fig. 4d) (Lf10), and gypseous silty dolomite (Lf9), typically with a small amount of silty dolomite (Lf8). These sedimentary deposits reflect a relatively dry and evaporative sedimentary environment, and are mainly distributed in the fourth member of the Feixianguan Formation (Fei 4).

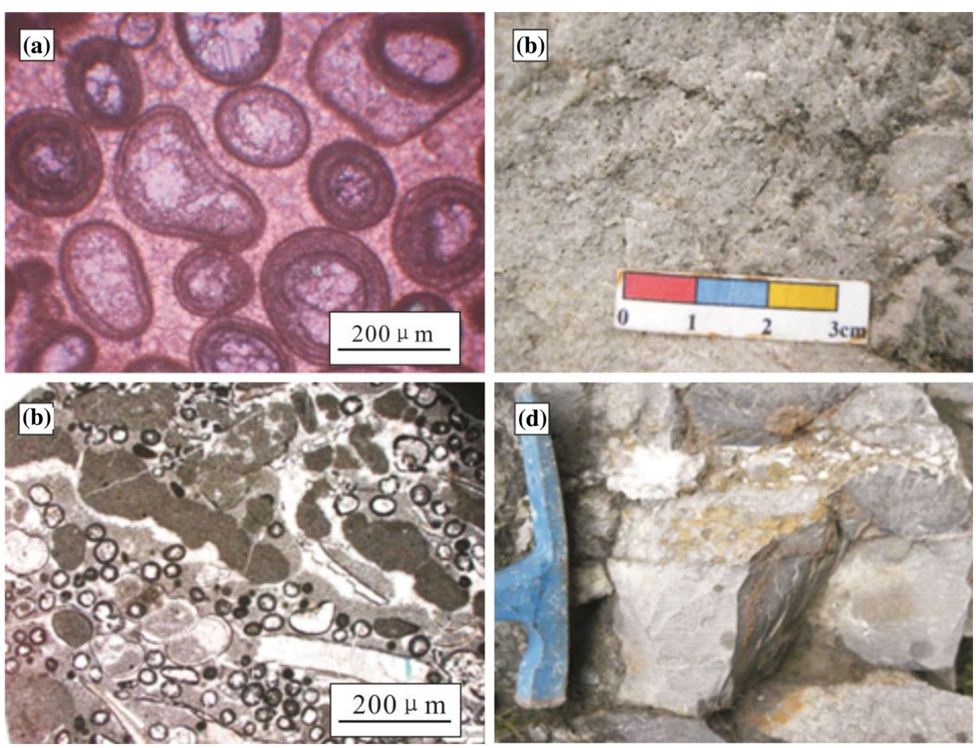

Fig. 3 Typical sedimentary characteristics of the Feixianguan Formation. **a** Oolitic limestone. QL45, Fei 3, 3752.19–3752.27 m, (-). **b** Light-gray and brown-gray oolitic limestone, Feixianguan Formation, Ningchang Profile. **c** Oolitic grainstone, Jianshan Profile, Fei 3, (-). **d** Light-gray intraclastic grainstone, Ningchang Profile

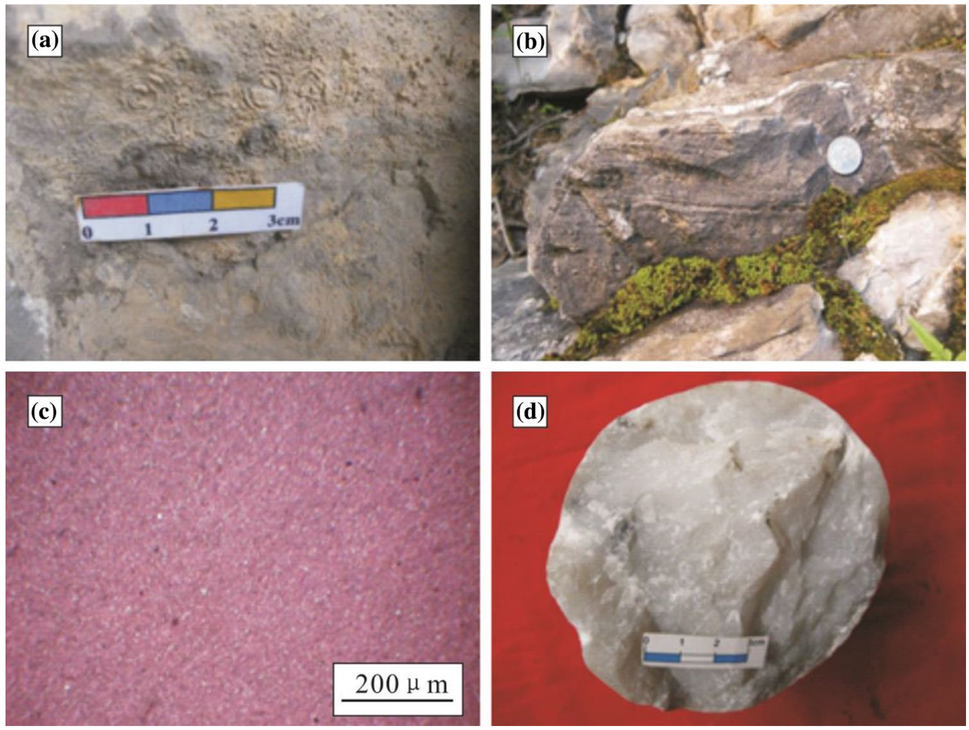

Fig. 4 Typical sedimentary characteristics of the Feixianguan Formation. **a** Brown-gray oncolitic limestone, Shashi Profile. **b** Hummocky cross-stratification, Qishuigou Profile. **c** Micrite limestone. QL45.3754.93–3755.05 m, (-). **d** Gypsum, TD9, No. 2–136

Basin (or Trough) facies association (FA5): this facies association comprises dark micritic limestone, mudstone, and shale (Lf11); it typically represents the product of a low-energy basin or trough sedimentary environment.

Sequence framework

Establishment of the sequence stratigraphic framework plays a vital role in the study of sedimentary facies and paleogeographic reconstruction in a basin (Gawthorpe et al. 1994; Zecchin et al. 2006). Many methods have been used to divide the sequences of the Feixianguan Formation in the Sichuan Basin, and different sequence division schemes have been established (Li et al. 2007; Zhou et al. 2008; Dai et al. 2009; Zheng et al. 2009). This paper mainly uses seismic, core, and isotope data to guide sequence division based on the theory of sequence stratigraphy and carbon isotope stratigraphy. Furthermore, the sequence division scheme and systems tract identification are determined.

Sequence boundaries identification

Sequence boundaries correspond to different levels of sequences. Guided by Vail's theory of sequence stratigraphy, this study identified sequence boundaries based on electrical and lithological data of cores, lithological data of field profiles, seismic profile data, and carbon isotope data.

1. Lithological and electrical analysis

In this study, electrical markers were used to identify sequence boundaries according to changes in natural gamma-logging curves. Lithological markers were used to analyze the characteristics of sequence boundaries based on lithologic identification through observation of cores, field profiles, and thin sections.

For example, the selective dissolution of atmospheric freshwater often represents short-term exposure, which is a typical feature of locally exposed unconformity boundaries. According to Vail's theory of sequence stratigraphy, the Feixianguan Formation in the study area was divided into two third-order sequences (SQ1 and SQ2), corresponding to three sequence boundaries (SB1, SB2, and SB3) (Fig. 5).

2. Carbon isotope analysis

In this study, the effectiveness of the carbon istotopes used was tested. This verification confirmed that the samples selected in this study were almost unaffected by later diagenetic alteration. Thus, the carbon isotopes retained the original sedimentary characteristic information. Previous studies have suggested that the numerical changes of carbon and oxygen isotopes are positively correlated with changes in sea-level rise and fall (Kaufman and Knoll 1995; Yang et al. 2014). Positive deviation in the $\delta^{13}C$ values indicates the sea-level rise, whereas the opposite trend reflects the sea-level fall. Some researchers have interpreted this phenomenon as a result of the combination of paleoclimate, biological productivity, and carbon burial (Li et al. 2019).

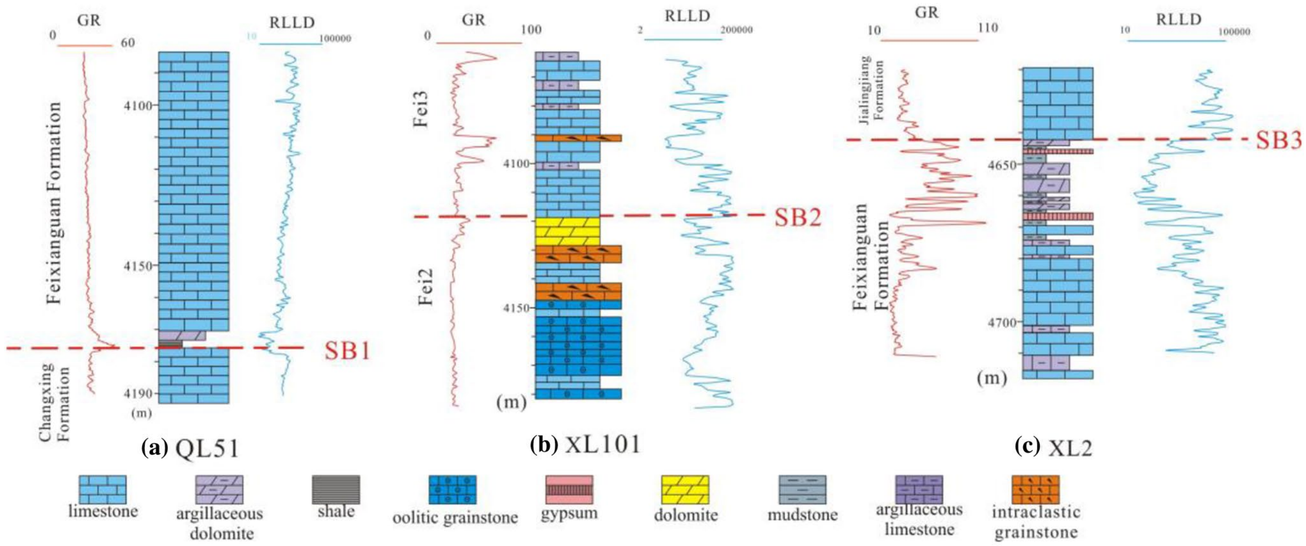

Fig. 5 Electrical markers of sequence boundaries of the Feixianguan Formation in eastern Sichuan Basin, China

In this study, samples of the Feixianguan Formation from the Shashi Profile were analyzed for carbon and oxygen isotopes (Fig. 6, Table 2). The thickness of the Feixianguan Formation in this section is about 442 m. A total of 42 samples were collected (Table 2). The average sampling interval is about 10.8 m.

Characteristics of third-order sequence boundaries

SB1 is the boundary between the Changxing Formation and Feixianguan Formation (Fig. 5a), through observation, the lithology at this boundary has changed significantly. The natural gamma-ray and resistivity curves show abrupt responses at this boundary (Fig. 5a). In the seismic section, the interface is located in the transition zone of a peak to a trough (Fig. 8).

SB2 is the interface between Fei 2 and Fei 3 (Fig. 5b). The interface is locally exposed as an unconformity interface, which is an erosional interface formed by the relative fall of sea level. Beneath this interface, the dolomite at the top of Fei 2 is in contact with the argillaceous limestone and micritic limestone at the bottom of Fei 3. In the seismic section, there is regional stability characterized by continuous strong reflection (Fig. 8).

The SB3 interface is the boundary between the Feixianguan Formation and Jialingjiang Formation (Fig. 5c). It is a lithological/lithofacies transition boundary formed by regional sea-level changes, with no obvious signs of subaerial exposure and erosion. Beneath this interface, there is a set of purple-red mudstone, gypsum, and salt rock deposits of the restricted and evaporative platform of Fei 4, and above the interface, there is a thin layer of light-gray micritic limestone of the open platform of the first member of the Jialingjiang Formation. The interface shows continuous strong reflections in the seismic profile and is easy to identify in the study area (Fig. 8). In the logging curves, it is characterized by low natural gamma values and high resistivity beneath the interface, with the opposite being true above the interface (Fig. 5c, Fig. 7).

Sequence stratigraphic framework

According to the characteristics of the second-order sedimentary cycle, the Feixianguan Formation shows an upward transition to a shallow sedimentary sequence. Starting from the relatively deep-water depositional environment of dark shale and micritic limestone in the early stage of the Feixianguan Formation, the area experienced the deposition of grainstone (mainly oolitic limestone, followed by intraclastic grainstone and bioclastic grainstone), and ultimately evolved into a micritic dolomite and evaporite tidal flat environment. According to the characteristics of the third-order cycles, the Feixianguan Formation can be divided into two third-order sequences (Fig. 8). Transgressive systems tracts (TST) and highstand systems tracts (HST) developed in each third-order sequence.

The first sequence (SQ1) roughly corresponds to the first to second members (Fei 1–2) of the Feixianguan Formation. The bottom of Fei 1 starts with argillaceous micritic limestone and dark gray mudstone, which comprise the TST. During the HST period, large amounts of oolitic dolomite developed at the platform margin, forming an important reservoir section of the Feixianguan Formation. In the trough (or basin) area, argillaceous limestone or calcareous mudstone mainly developed; at the top of the HST, gypsum and gypseous dolomite developed on the platform, and

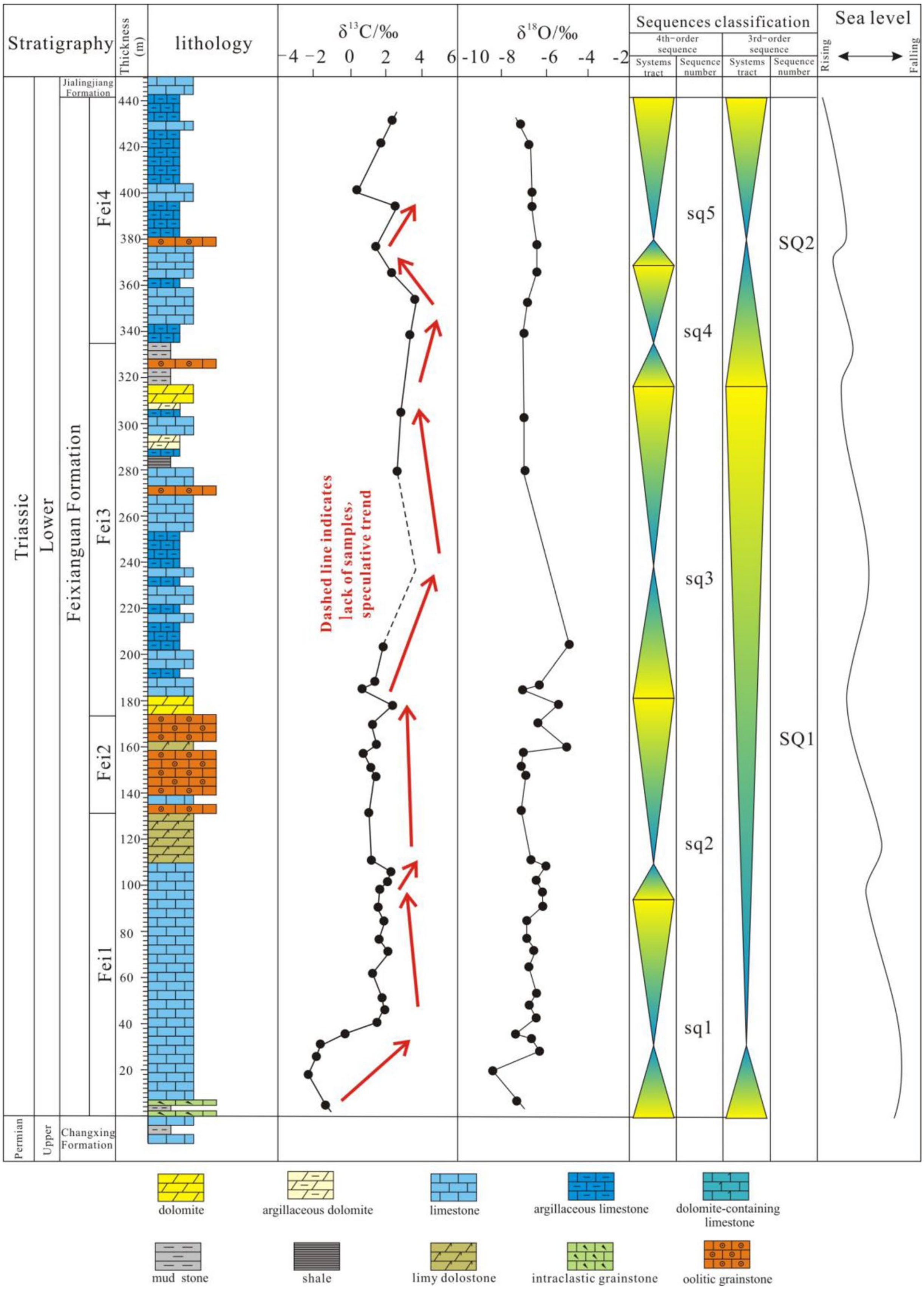

Fig. 6 Sequence stratigraphic division and carbon isotope analysis of Shashi Profile in Yunyang County

Table 2 $\delta^{13}C$ and $\delta^{18}O$ isotope analyzed results of the Feixianguan Formation in the study area

No.	Sample no.	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)	No.	Sample no.	$\delta^{13}C$ (‰)	$\delta^{18}O$ (‰)
1	ST-2-1	− 1.473	− 7.329	23	ST-14-3	0.915	− 7.172
2	ST-3-1	− 2.465	− 8.440	24	ST-14-4	0.904	− 7.088
3	ST-4-1	− 2.042	− 6.319	25	ST-15-1	1.520	− 5.121
4	ST-5-1	− 1.726	− 6.713	26	ST-16-1	1.395	− 6.300
5	ST-5-2	− 0.318	− 7.324	27	ST-17-1	2.262	− 5.424
6	ST-5-3	1.394	− 6.636	28	ST-18-1	0.582	− 6.901
7	ST-5-4	1.685	− 6.768	29	ST-19-1	1.237	− 6.398
8	ST-5-5	1.585	− 6.525	30	ST-19-2	1.806	− 4.903
9	ST-6-1	1.176	− 6.722	31	ST-21-1	2.667	− 6.922
10	ST-7-1	1.677	− 6.490	32	ST-24-1	2.724	− 7.074
11	ST-7-2	1.499	− 6.828	33	ST-27-1	3.387	− 7.040
12	ST-7-3	1.682	− 6.956	34	ST-28-1	3.572	− 6.800
14	ST-7-4	1.530	− 6.071	35	ST-28-2	2.194	− 6.462
15	ST-9-1	1.544	− 6.293	36	ST-29-1	1.239	− 6.442
16	ST-9-2	1.603	− 6.450	37	ST-31-1	2.473	− 6.738
17	ST-9-3	1.842	− 6.199	38	ST-31-2	0.299	− 6.727
18	ST-9-4	2.098	− 6.038	39	ST-32-1	− 0.409	− 6.895
19	ST-10-1	1.095	− 6.643	40	ST-32-2	− 0.409	− 6.895
20	ST-12-1	0.967	− 7.113	41	ST-32-3	2.713	− 7.226
21	ST-14-1	0.398	− 7.271	42	ST-32-4	− 3.532	− 8.321
22	ST-14-2	1.262	− 7.099				

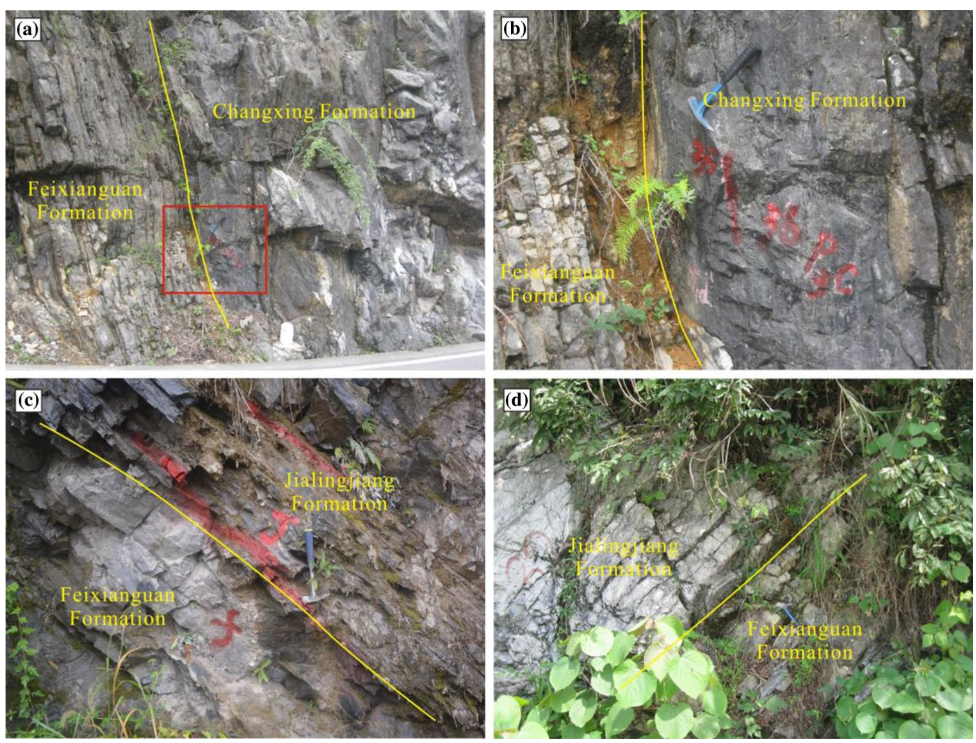

Fig. 7 Typical characteristics of the sequence boundaries of the Feixianguan Formation in the eastern Sichuan Basin. **a** Lithological and lithofacies transition boundary between the Changxing Formation (right) and Feixianguan Formation (left), Jianshan Profile. **b** Partial enlargement of the red box in **a**. **c** Lithological and lithofacies transition boundary of the Feixianguan Formation (left) and Jialingjiang formation (right), Fangdoushan Profile. **d** Lithological and lithofacies transition boundary of the Jialingjiang Formation (left) and Feixianguan Formation (right), Jianshuigou Profile

argillaceous limestone developed in the trough (or basin) area.

The second sequence (SQ2) roughly corresponds to the third to fourth members (Fei 3–4) of the Feixianguan Formation. The TST corresponds to Fei 3. With the slow rise of sea level, this period was dominated by open platform sedimentation, and oolitic shoals were scattered on

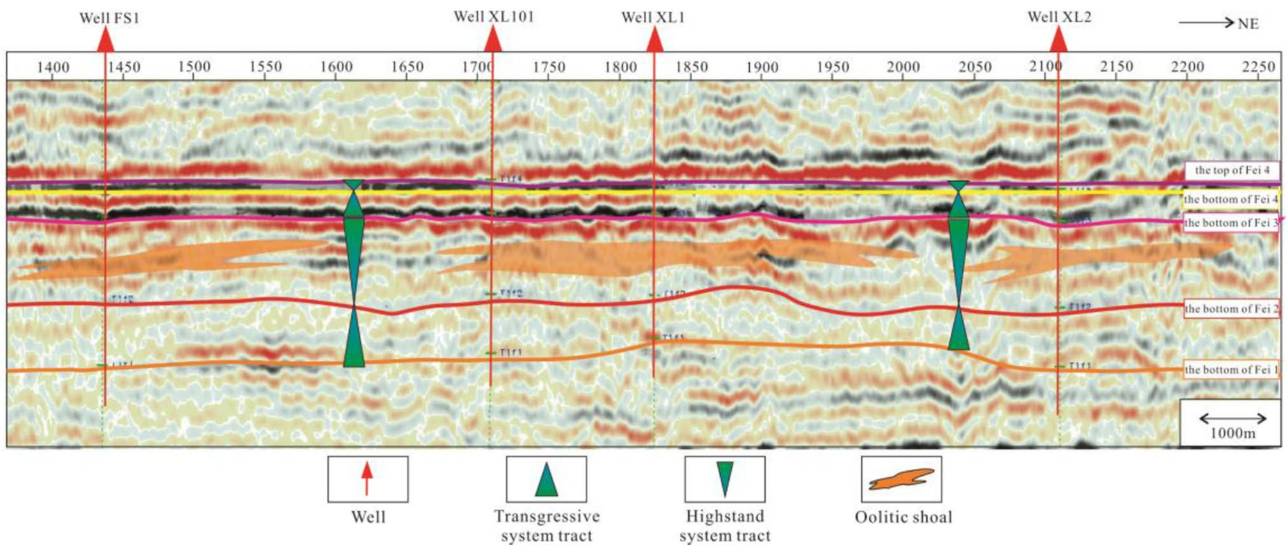

Fig. 8 Seismic profile showing the sequence stratigraphic framework of the Feixianguan Formation in the study area

the open platform. Fei 4 corresponds to the HST, where tidal and lagoon microfacies were widely developed.

Discussion

Distribution characteristics of oolitic shoals in the sequence stratigraphic framework

The sequence stratigraphic framework was established according to the characteristics of the field profiles, sequence boundaries, and drilling data. This framework has the following characteristics: (1) the Feixianguan Formation in the study area is well preserved without sedimentary interruption; (2) the oolitic shoals mainly developed in the HST of SQ1 and the TST of SQ2; (3) during the deposition of the HST of SQ2, a set of purple-red mudstone and argillaceous dolomite deposits with gypsum developed stably across the entire area and can be compared throughout the area; these deposits also form a good regional caprock (Fig. 9).

Longitudinal development characteristics of oolitic shoals

A large number of previous studies have shown that the change of sea level in a fast transgression and slow regression is conducive to the development of granular carbonate shoals (Li et al. 2008). Through observations of a large number of cores and field profiles of the Feixianguan Formation in the study area, it was found that frequent sea-level rise and fall activities are beneficial to oolitic shoal deposition caused by the influences of the tide, storms, waves, and multiple other factors. As shown in Fig. 10, intershoal sea to platform margin oolitic shoals and subtidal to intra-platform oolitic shoals formed in the Feixianguan Formation, which are two types of upward-shallowing sedimentary sequences.

Rapid transgression leads to the rise of sea level and increase in accommodation. At this time, a local geomorphic high position occurred on the platform margin because of the high-energy environment near the wave base, which was conducive to the construction of oolitic beaches. In addition, local geomorphic high points at the edge of the platform caused by the high-energy environment near the wave base surface were conducive to the construction of oolitic shoals.

With the deepening of the transgressive water, oolitic shoals continued to accumulate, and the thicknesses of the shoal bodies increased. Because of frequent sea-level changes, the shoal bodies underwent vertical accretion and superposition; the cumulative thickness of the shoal cores in the study area can reach more than 150 m. When the sea level was at the highest point, the tops of the oolitic shoals can be exposed and stop growing, and can even undergo lateral migration; if the exposure time is short, the original sedimentary pattern would not be changed, but the oolitic shoal bodies would continue to develop at the inherited high geomorphic points.

During the HST of SQ1, the platform margin facies was affected by waves and/or storms, where the water energy was high. In this facies, the thickness of the platform margin shoal deposits is relatively large, and with the frequent rise and fall of sea level, the shoal deposits often underwent vertical aggradation and superposition (Fig. 13b). In the late period of the HST, the shoals often underwent lateral migration (Fig. 13c, d). Compared with the platform margin, the interplatform area was mainly affected by the tide, the water energy was lower than that of the platform margin area, and the oolitic shoal deposits were relatively thin.

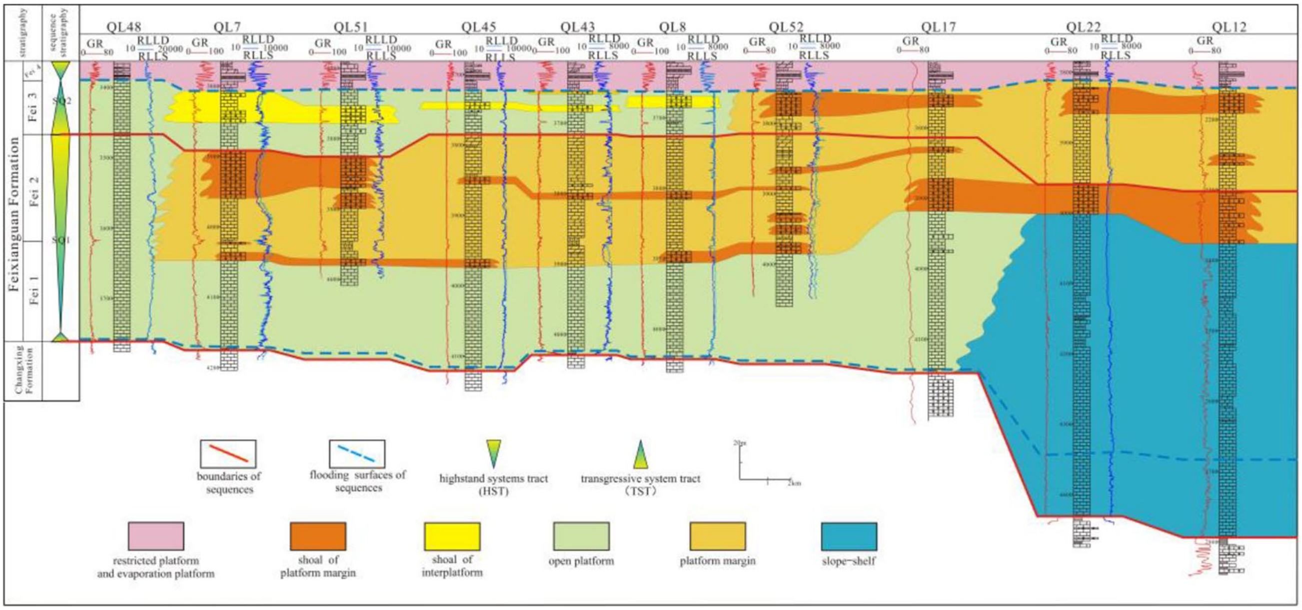

Fig. 9 The characteristics of sedimentary facies association in the sequence stratigraphic framework (the location is shown in the red line in Fig. 1d)

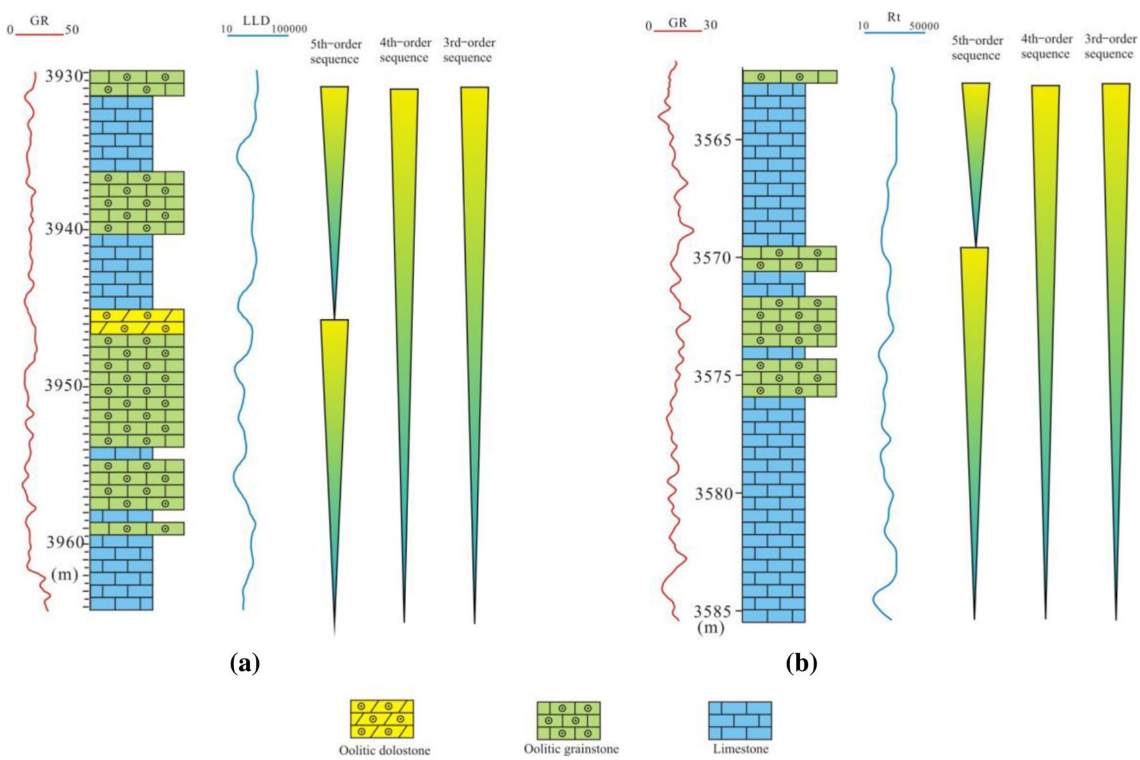

Fig. 10 Typical sedimentary sequences of cores of the Feixianguan Formation in the study area. **a** Is from QL52. **b** Is from QL58

Based on previous studies, upward-shallowing sedimentary sequences are considered to be beneficial to the deposition of oolitic beaches. However, during deposition of the third member of the Feixianguan Formation (Fei 3), because of the sedimentary filling effect of the first and second members of the Feixianguan Formation (Fei 1 and Fei 2) on the succession of the Changxing Formation, the platform area expanded to the trough. During the depositional period of the third member of the Feixianguan Formation (Fei 3), the platform margin facies in the study area migrated northward, and the water on the platform was shallow.

In the early TST of SQ2, sea level rose to a height favorable for the deposition of oolitic shoal, and a thin layer of the interplatform oolitic shoal microfacies was deposited at the paleogeomorphological high points (Fig. 13e). Then, with further sea-level rise, the depositional process of the oolitic beaches ended.

Transverse distribution characteristics of oolitic shoals

During the HST of SQ1, with the rapid rise and slow fall of sea level in the early stage, the platform margin facies existed in a high-energy environment, which was conducive to the deposition of oolitic shoals on the platform margin, and the platform margin shoals underwent aggradation. With the further fall in the sea level, accommodation was reduced, which was not conducive to the continued aggradation of the oolitic shoals, and the platform margin facies expanded to the trough facies area along with the platform facies. At the same time, the large part of the original slope reached the wave base surface, and there was enough space for the growth of the shoals, which resulted in lateral growth of the shoals with the migration of the platform edge. This resulted in the trend of continuous growth of the shoal bodies in the horizontal direction (Fig. 9).

Distribution of oolitic shoal facies in sequence stratigraphic framework

Based on comparative analysis of the sequence stratigraphy and petrology, combined with the regional sedimentary background, distribution maps of sedimentary facies under the third-order sequence stratigraphic framework of the Feixianguan Formation were drawn to explore the distribution patterns of oolitic shoal facies in the sequence stratigraphic framework.

During the depositional period of SQ1-TST, the Feixianguan Formation inherited the sedimentary pattern of the platform and trough area that existed in the depositional period of the Upper Permian Changxing Formation. In this period, because of the deposition mode of filling and leveling, the thickness of strata in the southwest–northeast direction increased, and the variation of this thickness was large (about 2–100 m). At this time, the distribution of sedimentary facies was relatively simple. Based on the sedimentary background of the Changxing Formation, The Changxing Formation was deposited on the platform at the southwestern part of the study area, whereas it is deposited on the slope and trough (basin) at the northwestern part of the study area. The boundaries of the facies were mainly between Well QL17 and QL22, TD 4 and TD 57, and M4 to M7 (Fig. 11a).

In the depositional period of SQ1-HST, the strata thickness was the largest; this interval was also the main stage of the Feixianguan Formation "filling up" the ancient landforms that formed in the depositional period of the Changxing Formation. The thickness of the strata formed in this period is generally within 300–600 m, thin in the south and thick in the north. With the continuous decline of sea level and the enhancement of hydrodynamic force, a large number of oolitic shoals were deposited in the area, mainly concentrated around QL7 to QL 52, TX 2, TD 5, LX 1, and L2 to FS1. In this period, the direction of the sedimentary units was similar to the stratigraphic distribution. Compared with the depositional period of SQ1-TST, the boundaries of the units were generally shifted northward, reflecting the decline of relative sea level and migration toward the basin. From south to north, the study area successively underwent deposition of open platform, platform margin, slope, and trough. The platform margin facies generally developed platform margin oolitic shoals in QL7 to QL17, QL22, DT 7, TD 4 to TD 102, and L1 to XL 1, with a large thickness. The local high points on the open platform developed interplatform oolitic shoal facies (Fig. 11b).

In the depositional period of SQ2-TST, the distribution range of the thickness of strata was generally from 60 to 140 m, and the sedimentary characteristics inherited the earlier trends, with thinner deposition in the south and thicker deposition in the north. Oolitic shoals of certain scales developed in the region, but their overall thickness was smaller than that of SQ1-HST. Although small-scale transgression occurred in this period, the relative sea level fell in the second-order cycle. Therefore, the boundaries of the facies moved farther toward the basin. The distribution pattern of the sedimentary facies was similar to that of SQ1-HST, but the platform margin facies was relatively narrow, whereas the open platform was relatively widely distributed, and the distribution area of the oolitic shoals on the platform margin and platform was relatively limited (Fig. 11c).

During the depositional period of SQ2-HST, under the early sedimentation, regional filling up and leveling were completed, forming a peneplain landform, and the sea level dropped to the lowest level of the studied interval. In addition, the thickness of strata in this stage was stable and thin, generally from 20 to 40 m. At this time, restricted platform and evaporation platform developed in the study area (Fig. 11d).

Controlling factors of distribution of oolitic shoals

The formation of carbonate rocks, especially reefs and oolitic shoals, requires a high-energy conditions, and their development and distribution are restricted by a variety

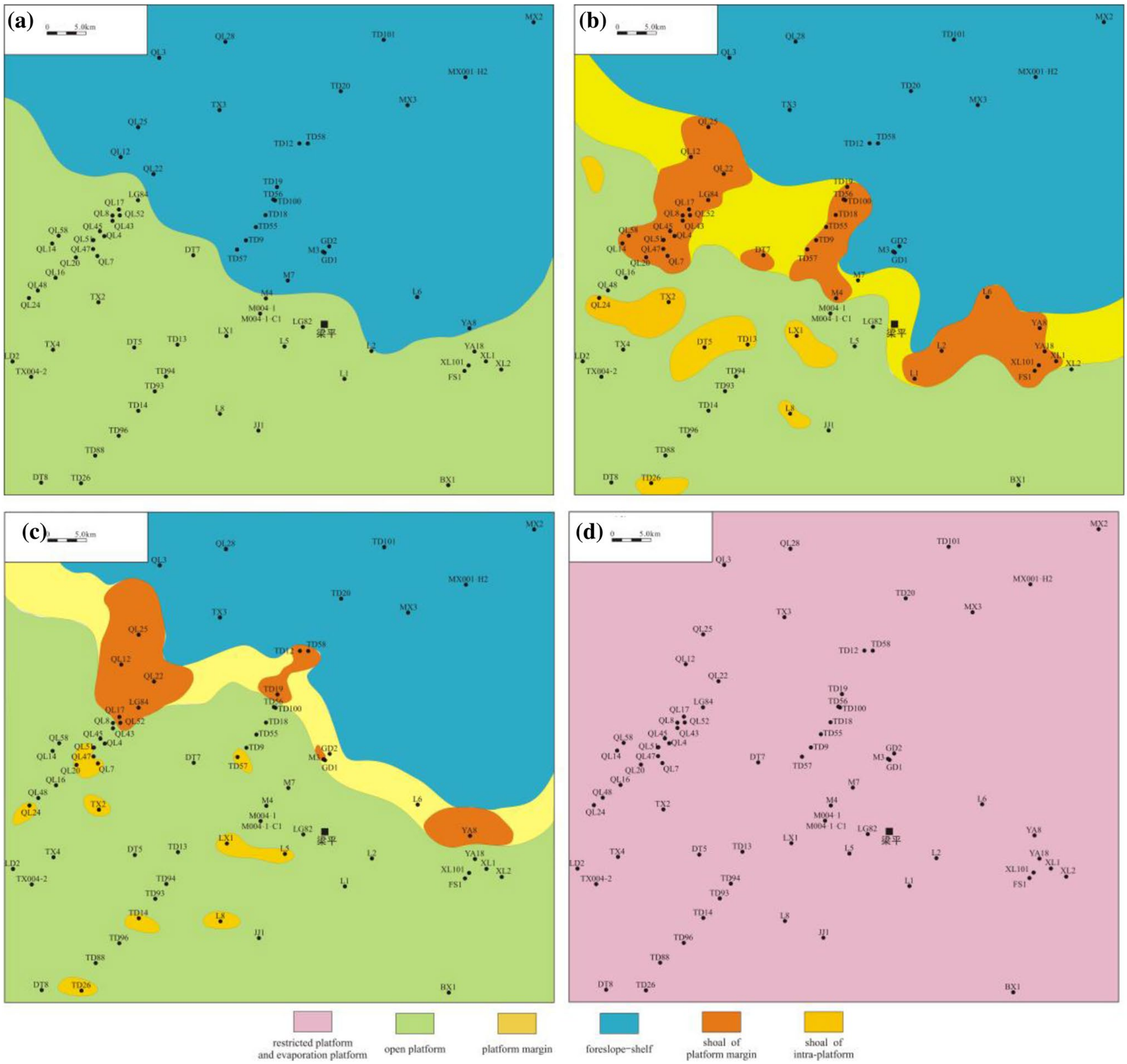

Fig. 11 Distribution of sedimentary units and facies association in sequence stratigraphic framework of the Feixianguan Formation. **a** SQ1-TST; **b** SQ1-HST; **c** SQ2-TST; and **d** SQ2-HST

of depositional conditions (Gao et al. 2015; Wang et al. 2018). It has been shown that paleogeomorphology, water environment, and paleoclimatic conditions play important roles in the deposition and distribution of carbonate oolitic shoals. Based on a comprehensive analysis of field profiles, cores, and drilling data, combined with previous research results, it was determined that the development and distribution of oolitic shoals in the Feixianguan Formation in the study area were controlled by sea level change, basement fault activity, and the paleoclimate.

Sea level change

Previous studies have shown that the growth and development of oolitic shoals require a relatively high-energy sedimentary environment (Zhang et al. 2020). The rise and fall of sea level control the underwater energy. Some researchers have argued that there is enough accommodation for oolitic shoals to form during periods of sea-level rise, and that oscillatory sea-level rise and fall in particular are conducive to the development of oolitic shoals (Li et al. 2008; Bergman et al. 2010).

The Feixianguan Formation in the study area underwent multiple intervals of sea-level rise and fall, which were favorable to the development of oolitic shoals. The thickness of shoal deposits is relatively high, mainly ranging between 50 and 90 m, with a maximum thickness of up to 140–150 m (Fig. 12). Vertically, it usually forms a facies association that becomes shallower upward.

Basement structure and micropaleogeomorphic high points

Influenced by the Emei Rifting Movement, during the late Permian and early Triassic, the Sichuan Basin was affected by the tensional and torsional activities of the basement faults, and differential settlement occurred. In the Sichuan Basin, the Chengkou–Exi Trough, Kaijiang–Liangping Trough, and Pengxi–Wusheng Platform Depression are found, which are nearly parallel in a northwest direction, resulting in the paleogeographic pattern of "three uplifts and three depressions" (Wang et al. 2017).

Here, we take the Kaijiang–Liangping Trough, which has been studied by many researchers, as an example. In the early stage of deposition of the Changxing Formation and Feixianguan Formation, the trough was in a typical fault depression development stage, in which a set of low-energy and deep-water sediments were deposited. Along the platform margin on both sides of the trough, the reefs deposition of the Changxing Formation platform margin and the shoals deposition of the Feixianguan Formation platform margin developed.

The middle and late period of deposition of the Feixianguan Formation was the development stage of the depression. The interior of the open platform was also affected by the base faults, forming a micropaleogeomorphic high point, and oolitic shoals were deposited on the platform. In the late period of deposition in the Feixianguan Formation, with the continued decline of sea level, the evaporation platform and restricted platform facies developed in the study area.

Thus, the formation of basement faults not only affected the formation and extinction of the trough, but also controlled the paleogeographic pattern of lithofacies and the distribution of oolitic shoals in the depositional period of the Feixianguan Formation. That is, the platform margin on both sides of the trough formed by the basement faults and the micropaleogeomorphic high points on the platform were conducive to the development of oolitic shoals (Wei et al. 2019).

Hydrodynamic conditions

Generally, the formation of carbonate rocks requires a relatively warm, clear, and shallow water environment, whereas oolitic shoals require a hydrodynamically strong and energy-efficient sedimentary environment. A number of studies have shown that ancient monsoons also had impacts on the deposition of carbonate reefs and oolitic shoals (Mehrabi et al.

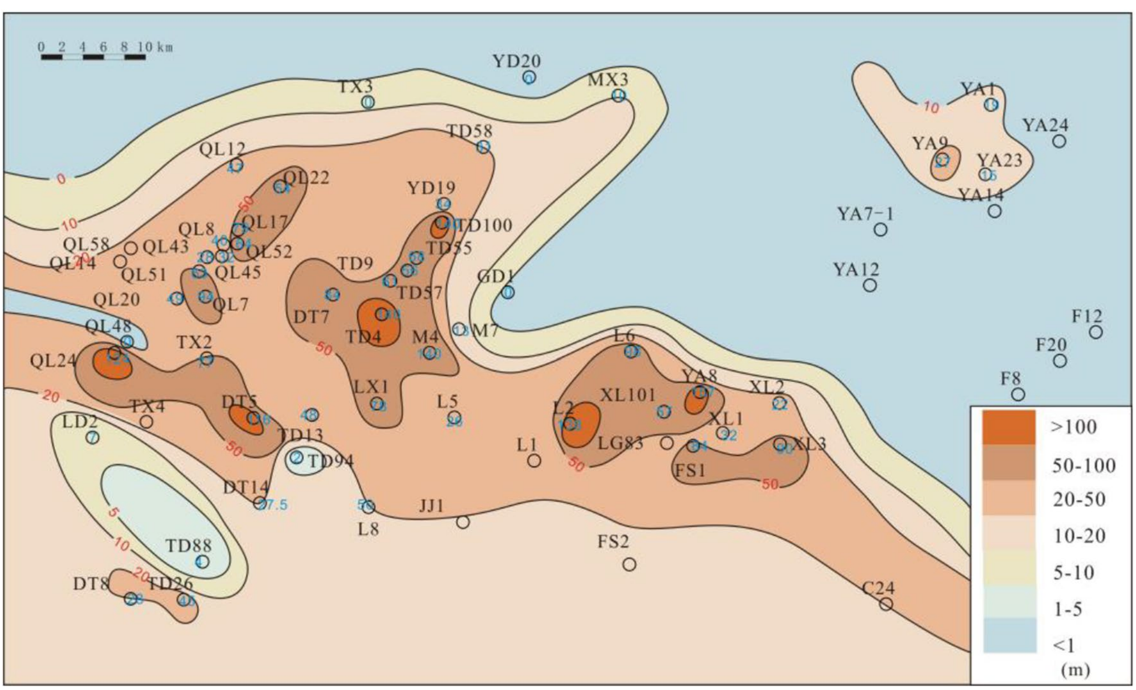

Fig. 12 Thickness of oolitic shoals in the Feixianguan Formation

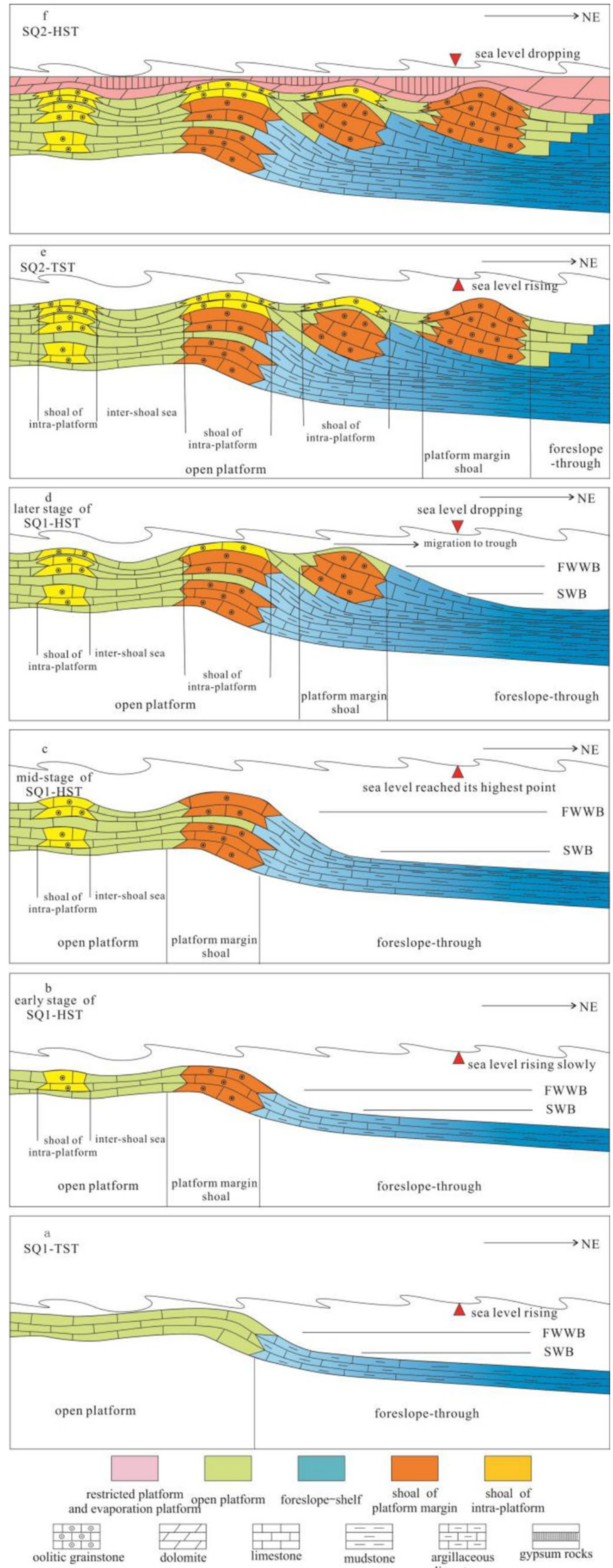

Fig. 13 Development model of oolitic shoals in the Feixianguan Formation. **a** SQ1-TST. **b**–**d** SQ1-HST. **e** SQ2-TST. **f** SQ2-HST

2015; Dravis and Wanless 2017). In this study, it was found in the field profiles that characteristics of storm deposits such as hummocky cross-bedding developed in the depositional period of the Feixianguan Formation (Fig. 4b). It was thus confirmed that the occurrence of storms stirring the water in the sedimentary period was more conducive to the increase of water energy and the deposition of oolitic shoals.

In summary, under the comprehensive influences of sea level, basement faults, and hydrodynamic conditions, the platform margin and the micropaleogeomorphic high points on the platform in the study area were conducive to the development of oolitic shoals, and the development mode of oolitic shoals presented the growth mode of "aggradation before migration" (Fig. 13). These findings will have certain guiding significance for the paleogeographic reconstruction of the Feixianguan Formation in the study area.

Conclusion

Based on the observation of cores and thin sections of the Feixianguan Formation in the eastern Sichuan Basin and the observation and description of field profiles, combined with the analysis of drilling, carbon isotope, and logging data, the sequence stratigraphy, sedimentary characteristics, and distribution patterns of oolitic shoals of the Feixianguan Formation were investigated. The following conclusions were obtained:

(1) According to data from cores, thin sections, well-logging, and field profiles, combined with previous research results, a carbonate platform sedimentary system developed in the depositional period of the Feixianguan Formation in the study area, and 5 types of sedimentary facies association were identified in this area: platform margin, open platform, restricted platform, evaporation platform, slope, and trough (or basin). These can be further divided into 11 microfacies.

(2) According to the characteristics of the sequence boundaries of the Feixianguan Formation, combined with the previous research and analysis, three sequence boundaries were identified in the Feixianguan Formation in the eastern Sichuan Basin. There are two types of boundaries: lithological and lithofacies transition boundaries and locally exposed unconformity boundaries. In addition, the analysis of carbon isotope data also showed the corresponding sea-level change characteristics. Furthermore, the Feixianguan Formation was divided into two third-order sequences (SQ1 and SQ2). TSTs and HSTs developed in the third-order sequences.

(3) Based on the analysis of the sequence stratigraphy and sedimentary facies in the study area, the distribution patterns of oolitic shoals in the sequence stratigraphic framework were studied. In the depositional period of SQ1, the study area inherited the sedimentary pattern of the Changxing Formation and developed carbonate platform sedimentation. Oolitic shoals were relatively well developed in the platform margin and platform facies in the depositional period of SQ1-HST, and the boundaries of facies were generally shifted northward. In the depositional period of SQ2-TST, oolitic shoals developed in the area, but their thicknesses were thinner than those formed in the SQ1-HST period. The distribution pattern of sedimentary facies was similar to that of SQ1-HST, but the platform margin was relatively narrow, whereas the open platform was relatively wide, and the distribution area of oolitic shoals on the platform margin and platform was relatively limited. During the depositional period of SQ2-HST, a peneplain landform formed in the region, associated with the lowest sea level of the studied interval. Restricted platform and evaporation platform facies were developed.

(4) Based on previous studies and the sedimentary characteristics of the Feixianguan Formation, the influences of different factors on the deposition of the oolitic shoals were evaluated. The results show that, under the comprehensive influence of sea level, basement faults, and hydrodynamic conditions, the platform margin facies in the study area was favorable for the development of oolitic shoals, and the development of the oolitic shoal microfacies presented the growth mode of "accretion before migration."

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