Research article

Sequence and sedimentary features of the Changxing Fm organic reefs and their control on reservoir development in the Yuanba Gas Field, Sichuan Basin

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Abstract

In the Yuanba area, Sichuan Basin, the gas reservoirs in the Upper Permian Changxing Fm are now at the development stage. With the smooth progress of development, it is urgent to characterize the reservoir architectures accurately and summarize the controlling factors for reservoir development. In this paper, research was mainly performed on the Changxing Fm organic reefs in terms of their sequence stratigraphy, sedimentary facies, and reservoir characteristics and architectures based on core observation and thin section analysis, combined with physical property data and logging curves analysis results. It is shown that the Changing Fm can be divided into two third-order sequences and six fourth-order sequences, their electric logs are characterized by abrupt change above and below the high-frequency sequence boundary and are consistent with the sedimentary cycles controlled by high-frequency sequences. Besides, the Changxing Fm organic reefs mainly represents zonal distribution outside SQ2 platform margin, and they are vertically composed of two obvious two reef sedimentary cycles and laterally developed in asymmetric patterns (early in the east and late in the west). Finally, in general, organic reef (bank.) reservoirs are mainly composed of low-porosity and moderate-low-permeability dissolved dolomite reservoirs, and they are mostly distributed at reef caps in the upper-middle parts of the two fourth-order sequences, with the characteristics of multiple beds, thin single beds, different types of reservoirs with different thickness interbedded with each other, strong heterogeneity and double-layer reservoir architectures. It is concluded that the distribution of organic reef microfacies in this area is controlled by high-frequency sequence, which is the key controlling factor for reservoir development and spatial distribution.

The gas reservoir in the Permian Changxing Fm in NE Sichuan Basin, with proven gas reserves of several hundred billion cubic meters, is one of the largest gas reservoirs discovered by Sinopec in recent years. Currently, it is at progressive productivity construction stage, and shows a good potential for development [1–8]. Previous scholars have performed specific and in-depth study on the deposition and reservoirs of the gas reservoir [9–23]. For example, Guo Tonglou [13] proposed that the distribution of reservoirs was significantly controlled by third-order sequence system tracts. Long Shengxiang et al. analyzed the conductive system and formation stage from the perspective of hydrocarbon accumulation and proposed diffusion reservoir-formation mechanism [1] or analyzed the controlling factor for reservoir development from the perspective of diagenesis [19,21,22,24]. The results mentioned above have provided important guidance for the exploration and evaluation of the Yuanba Gas...
Field. However, the Changxing Fm gas reservoirs in the Yuanba Gas Field are now at development phase. Particularly, the organic reef flat reservoir of Member 2 of Changxing Fm is the major target for the productivity construction of the Sinopec Southwest Branch Company. With the smooth development of gas reservoirs and the increasing need of fine reservoir description, particularly, due to the relatively limited coring data, in-depth study should be conducted on how to identify the high frequency sequence boundary of the entire well section using well logs [25]. Based on seismic data and geological and well logging data, high frequency sequence and sedimentary microfacies as well as their relation with reservoir spatial distribution should be analyzed. Moreover, reservoir structures should be finely described and the controlling factors for reservoir development should be summarized in order to construct an accurate reservoir geological model and provide a basis for fine reservoir seismic prediction. Using drilling cores, thin section observation and physical property data, combined with logging and seismic methods, the relations between carbonate reservoirs and sequences, deposition and reef reservoirs of the Changxing Fm in the Yuanba area were studied. The control of sequence and deposition on reservoir development and distribution was clarified and the reservoir architecture model was summarized, in order to provide a basis for further fine description and effective development of organic reef gas reservoirs of Changxing Fm in the Yuanba area.

1. Geological overview

The Yuanba Gas Field, located in the front of Longmen Mountain northern segment, is in a low-lying structural area affected by the orogenic belt of Longmen, Micang and Daba Mountains [26]. However, the overall structure is slightly affected by tectonic movement. The Yuanba area represents a large low-lying negative structure as a whole. Its northwest part is the southwestward pitching end of Jiulong Mountain anticline, which is the highest structure in the gas reservoir; its southern part is a gentle slope of Central Sichuan Uplift, which inclines into the gas reservoir northward; and its northeast part is the western end of depression (or large complex syncline), which is the lowest structure in the gas reservoir (Fig. 1). All the low-lying structures in the region (or local structural high) are of NW-trending, except for the pitching end of Jiulong Mountain anticline in the northwest part, which is of NE-trending. Regionally, the stratigraphic occurrence is gentle with simple structures and undeveloped faults [1].

The Upper Permian strata in NW Sichuan Basin were deposited in extensional background, when Middle Permian erosion surface transgression occurred. Differential subsidence resulted in differential depositional environments, forming a depositional pattern of “alternate platform and shelf”, which controlled the development of the organic reef and bank of Changxing Fm [2,9,10,27,28]. The area of Guangyuan—Wangcang—Liangping—Kaijiang is in a continental shelf depositional environment, but its west and east sides are in a platform depositional environment, thus, the sedimentary facies represents continental shelf—slope—platform margin—carbonate platform from continental shelf to platform successively [9–12].

2. Sequence features and sedimentary microfacies

2.1. Sequence boundary identification and sequence division

The Changxing Fm is generally 40–360 m thick, but its reef bank sediments are mostly 130–210 m thick or 360 m thick locally. Using detailed logging cuttings and core observation results, the well logs were calibrated, and combined with the lithological response features of well logs, the sequence boundaries were identified. The Changxing Fm is divided into two third-order sequences, i.e. SQ1 and SQ2, with the sequence boundaries of SB0, SB1 and SB2. SB0 boundary is a typical lithological and lithofacies transitional surface; below it, about 5 m thick carbonaceous shale is developed, representing high GR, high AC and low RD, which is an important stratigraphic correlation marker bed of the study area. Its well logging features are significantly different from that of the (bioclastic) limestone at the base of Changxing Fm.
above SB0 boundary (Fig. 2). In platform margin, SB2 boundary represents an exposed unconformity surface; above it, the dolomite of Changxing Fm with prominent mold pores is developed, which is the exposure marker of the top and bottom structure during syngenetic period; below it, a set of about 3 m thick argillaceous limestone is developed at the bottom of Member 1 of Feixianguan Fm, representing high GR, low RD and smooth DEN curve (Fig. 2). In intra-platform, SB2 boundary is a lithological and lithofacies transitional surface. Similar to SB2 boundary, SB1 boundary is also an exposed unconformity surface, but smaller in scale; below it, the dolomite of Member 1 of Changxing Fm is developed, with low density and high acoustic wave; above it, tight micrite is developed, with high density, low acoustic wave. Resistivity curve represents abrupt change below and above the boundary (Fig. 2). In intra-platform, SB1 boundary is also a lithological and lithofacies transitional surface and it is characterized by the abrupt increase in GR value above the boundary. The system tract boundary within sequence is mainly lithological and lithofacies transitional surface. Since the study area is located in platform margin and intra-platform, LST is not developed, but TST and HST are extensive. Thus, the marlstone of the maximum marine flooding surface with high GR value is the marker bed for system tract boundary (Fig. 2).

Accordingly, the reef bank of the Changxing Fm in the platform margin of the Yuanba area is divided into two complete third-order sequences (SQ1 and SQ2), and then, the Changxing Fm is divided into Chang 1 Member and Chang 2 Member (Fig. 2). SQ1 is composed of bioclastic limestone, dolomitic bioclastic limestone and calcite dolomite. Its resistivity curve represents high value as a whole, but low value in reservoir interval (Fig. 2); however, it should exclude the impact of shale content on resistivity (such as the non-reservoir section with high GR value). A completed third-order sequence is composed of open platform or platform margin shoal sediments. For SQ2, dark gray marlstone and gray limestone are developed at its base, constituting the TST of third-order sequence in relative low-energy environment; bioclastic limestone, reef limestone and dolomitic limestone

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**Fig. 2.** Individual well sedimentary facies and reservoir evaluation map of the Changxing Fm (Well Yuanba 2). (Note: 1 in = 25.4 mm, 1 ft = 0.3048 m).
are developed in its middle, light gray dolomite, dissolved dolomite and bioclastic dolomite are developed at its top and organic reef and flat are developed in platform margin (Fig. 2), constituting the HST of third-order sequence. SQ2 is constituted by TST and HST. Some wells represent high GR value and high resistivity value, but low resistivity value in reservoir interval. Each third-order sequence of the Changxing Fm is divided into three fourth-order sequences, with lithology shifting from micrite into bioclastic limestone and from bioclastic limestone to dolomite, and resistivity curve changing from high to low values. Thereby, multiple sedimentary assemblages shallowing upward are constituted. For example, platform margin bioclastic bank, interflat and two phases of organic reef sediments are developed in the three fourth-order sequences of Member 2 of Changxing Fm (Fig. 2).

Well-seismic calibration results show that the third-order sequence boundary has prominent response in seismic profile. SB0 boundary corresponds to the zero phase of moderate—strong wave crest and wave trough, which is relatively clear and can be easily tracked in the entire region (Fig. 3). SB2 boundary corresponds to a wave trough reflection in seismic profile; however, it represents strong wave trough reflection with good continuity in platform margin, but moderate—weak wave trough reflection with good—poor continuity in intra-platform. SB1 boundary represents moderate—weak reflection with poor continuity and low frequency, which is difficult to be tracked in the entire region. The fourth-order sequence boundary occurred in the organic reef facies belt in the platform margin, with lithology transiting from limestone with high impedance into the dissolved dolomite with low impedance. In seismic profile, it represents the reflection features of wave trough. Therefore, based on the division of drilling sequence, constrained by the sequence boundary interpreted by seismic data, an inter-well (high frequency) sequence stratigraphic framework was established.

2.2. Description of sedimentary facies

In (high frequency) sequence stratigraphic framework, based on the analysis of lithofacies and well logging facies [29], the division of individual well facies and well-tie facies were completed. For individual well facies, taking Well Yuanba 2 as example, the Chang 1 Member composed of marl, micrite and bioclastic limestone mainly represents open platform facies, including inter-flat, bioclastic bank and sand cutting flat subfacies. The lithofacies assemblage corresponded well to the fourth-order sequence from bottom to top, which means that low-energy sediments, including marl and micrite, are developed in the lower part of fourth-order sequence and high-energy sediments, including bioclastic limestone or dolomite are developed in the upper part of fourth-order sequence (Fig. 2). Chang 2 Member composed of micrite, bioclastic limestone, reef limestone, bioclastic dolomite and microcrystalline dolomite mainly represents the organic reef bank facies of platform margin, including inter-flat, bioclastic bank, organic reef, and back reef bank subfacies. The lithofacies assemblage corresponded well to the fourth-order sequence from bottom to top, which means that micrite and bioclastic limestone are developed in the lower part of fourth-order sequence, reef limestone is developed in the middle part of fourth-order sequence and bioclastic limestone, bioclastic dolomite and microcrystalline dolomite are developed in the upper part of the fourth-order sequence. In addition, the structure of organic reef is well reflected, with reef base (bioclastic bank), reef core (organic reef) and reef cap (bioclastic bank or tidal flat) developed from bottom to top [20] (Fig. 2), at least including two large reef cycles composed of reef base—reef core—reef cap and reef core—reef cap. At the late development stage of organic reef, the sediments of bioclastic bank and tidal flat are intensively dolomitized.

Based on the analysis of individual well facies, the seismic profile was calibrated in detail. In seismic profile, the organic reef in platform margin represents obvious hummocky shape of “bottom flattened and top convex”, with reflection features of blank or disorder in its interior and discontinuity and onlap in its two flanks; inter-reef platform represents short axis and moderate—strong amplitude at its base and blank or weak reflection at its top; the sediments in slopes represent features of low frequency, monaxial strong amplitude and good continuity (Fig. 3). Based on the detailed calibration between individual well facies and seismic profile, combined with the sedimentary facies reflected by typical seismic facies, the sedimentary facies in well-tie cross section was identified. It can be seen that Chang 2 Member in the Yuanba area is composed of two distinct organic reef cycles, among which, the organic reef cycle at early phase becomes larger from west to east, but the organic reef cycle at late phase becomes smaller from west to east. Most organic reefs are isolated with each other.

Before deposition in this region, the Changxing Fm was in a stable platform depositional environment. During deposition, the strata were well-preserved and no intense tectonic movement took place. Since the sediments of carbonate rock reef and bank have typical paleogeomorphological features, the development and distribution of the reef bank depositional system of the study area can be comprehensively analyzed through restoring paleogeomorphological features. Paleo-geomorphological map and analysis of individual well facies
reveal (Fig. 4a) that organic reef deposits have typical positive paleogeomorphological unit and the organic reef in each reef zone is not connected with each other. Moreover, the distribution features of organic reef reflected by seismic facies is similar to that reflected by paleogeomorphology (Fig. 4b). In addition, the variegated zone in periphery is the development area of organic reef, and the light purple area the development area of patch bank within platform (Fig. 4b). Therefore, based on individual well facies and well-tie facies, constrained by the sedimentary facies reflected by paleogeomorphology, seismic facies and other seismic attributes, the planar sedimentary facies map of Chang 2 Member was drawn (Fig. 5).

Based on the analysis above, the well-tie profile of Changxing Fm in the Yuanba area indicates that during the depositional period of Chang 1 Member, the southwest part was in open platform, and the northeast part (to the east and north of Well Yuanba 101) was in slope and continental shelf. However, the overall terrain was relatively gentle and the water body was deep. Thin bioclastic and psammitic bank were developed within open platform. With the intense differentiation of sedimentary terrain, the southwest part gradually evolved into platform margin, when the thick sediments of bank were pervasive (Fig. 6). During the depositional period of Chang 2 Member, the differentiation of sedimentary terrain further intensified, when organic reef began to form along the continental margin of Kaijiang–Liangping. The Changxing Fm organic reefs in the Yuanba Gas Field were mainly distributed in the outside platform margin, representing zonal distribution and each reef belt was not completely connected (Figs. 5 and 6). Therefore, the platform margin of Yuanba area gradually evolved into a rimmed platform from a gentle slope platform at early stage (the depositional period of Chang 1 Member), showing the depositional features of early bank and late reef, front reef and back bank [13]. It indicates that, in gentle platform margin, bioclastic shoal sediments were developed at early stage (the depositional period of Chang 1 Member) and organic reef bank sediments were developed at late stage (the depositional period of Chang 2 Member), but in the interior platform at the back of the organic reef in platform margin, sediments of shoal facies were developed.

3. Basic features of organic reef (bank) reservoirs

Sedimentary features study reveals that organic reef deposits are mainly distributed in Chang 2 Member, which are a favorable interval for reservoir development. Therefore, the organic reef (bank) reservoirs of Chang 2 Member are the study focus. It should be noted that the organic reef (bank) reservoirs herein refer to organic reef and its associated bioclastic bank or the carbonate reservoirs composed of intraclastic grainstones, namely all the reservoirs in a completed organic reef structure, including the reservoirs in organic reef core (organic reef) and organic reef cap (bioclastic bank or tidal flat).

3.1. Features of reservoir rocks

Core observation and thin microscopic identification results reveal that the reef facies reservoirs of Chang 2 Member are composed of dolomite and limestone. Dolomite includes (residual) bioclastic dolomite (Fig. 7a–d), (algae bond) microcrystalline dolomite (Fig. 7e and f), fine-moderate crystalline dolomite (Fig. 7g and h); limestone includes (dolomitic) grainstone (Fig. 8b), (dolomitic) reef limestone and powder-fine crystalline limestone, which are tight rocks and generally acts as minor reservoir rocks in the region.

The main reservoir space types of Chang 2 Member include: ① Intragranular dissolved pores of bioclast or sand cutting, which mainly occur in bioclastic dolomite, with pore diameter between 0.01 and 2.00 mm (Fig. 7a, c and d); part of intergranular dissolved pores may be corroded and reformed...
by epigenetic fluids; ② Intergranular dissolved pores, which commonly occur between grains (Fig. 7b—d) or cuts bioclastic or sand cutting grains, representing non-selective dissolution features; ③ Microcrystalline dolomite dissolved pores, which mainly occur in microcrystalline dolomite (algae bond), with pore diameter between 0.05 and 2.00 mm, representing isolated distribution (Fig. 7e and f); ④ Dolomite intercrystalline (dissolved) pores, which commonly occur in moderate—fine crystalline dolomite, with even size, part intercrystalline pores were enlarged after the dissolution at late stage, forming the intercrystalline dissolved pores of varying sizes (Fig. 7g and h); ⑤ Dissolved cavities, which may be formed due to the further enlargement of the dissolved pores of early stage, with diameter of less than 1.00 cm and bedding distribution (Fig. 7e); and ⑥ Fractures, although they are minor reservoir space (Fig. 8a and b), but have significantly increased the permeability of samples. In image logging, developed dissolved cavities and fractures are often seen in some well sections.

3.2. Physical features

According to the evaluation criteria of carbonate reservoirs in the Sichuan Basin, combined with previous classification evaluation criteria of carbonate reservoir in NW Sichuan Basin [30,31], detailed statistics were made on the reservoir samples of Chang 2 Member collected from drilled wells. The results reveal that the porosity ranges between 0.59% and 19.59%, with an average of 3.59%; the samples with porosity of over 2% account for 63.66% of total samples. Permeability ranges between 0.0045 and 1720.7 mD, with an average of 23.71 mD. However, the samples with permeability of less than 1 mD account for 57.5% of total samples. In general, the reservoirs of the study area are low porosity and moderate—low permeability reservoirs, with type II & III reservoirs as the dominant ones. In addition, the correlation between porosity and permeability is poor, especially for such samples with the porosity less than 5%, indicating the existence of microfractures.

4. Reservoir structure and its controlling factors

According to the “four-property relationship” (lithology, physical property, gas-bearing property and electrical property), the four-property relationship of the Changxing Fm reservoirs in key wells were studied using core scale calibration logging technology, combined with well logging, geology, mud logging, coring and gas test data. Appropriate model for porosity log interpretation was selected and the reservoirs of each well were analyzed and evaluated according to reservoir classification and evaluation criteria.

Individual well evaluation results (Fig. 2) show that reefbank reservoirs are developed in the Changxing Fm. Well Yuanba 2 drilled reef front and its reservoir quality is poorer than the wells drilled reef top, since reef reservoirs are only developed in the upper and middle part of Chang 2 Member. Well logging interpretation results reveal that the reservoirs are 25.2 m thick and are mainly of type III due to poor physical property (Fig. 2). Reservoirs of type II are 3.9 m, with an average porosity of 6.5%, while reservoirs of type III are 21.3 m, with an average porosity of 3.1%. Vertically, high-quality reservoirs (type II) are developed in the reef cap at the top of the fourth-order sequence.

The reservoirs in this region are composed of two large reef cycles at least (Fig. 6). Reservoirs of type I, II and III are mainly distributed in reef caps, only a small proportion of reservoirs of type III are distributed in reef cores. Reef reservoirs have features of “multiple number of layers, thin
individual layer and strong heterogeneity”. Dissolved dolomite reservoirs mostly occur in the bioclastic banks and back reef flats in the upper and middle part of reef caps. Reservoirs of type I and II are well-developed, and reservoirs of type III are composed of (limy) dolomite as well as bioclastic limestone and reef limestone, which are located in the lower part of reef caps and reef cores, respectively. It can be seen that high-quality reef reservoirs are mainly developed in the upper and middle part of the third-order and fourth-order sequences and the favorable sedimentary subfacies for reservoir development are the bioclastic banks of reef caps and back reef flats. In terms of reservoir scale and distribution, affected by the
deposition and diagenesis of organic reefs, reef cores are thicker than reef margins and back reefs are thicker than front reefs (Fig. 6). In addition, statistics show that the dolomite reservoirs of bioclastic bank subfacies in the lower part of reef caps have better physical property than that of back reef flat subfacies in the upper part of reef caps.

For different sedimentary microfacies, its hydrodynamic force and water mediums are different, thereby, the sedimentary fabric and original mineral composition are different, which have important influence on the diagenesis of late stage, resulting in different reservoir physical property. The petrophysical data of the cores of Chang 2 Member reveals that the organic reefs and shoal facies in the platform margin are the most favorable facies belts for reservoir development, where the reservoirs are high in porosity, but in the interior platforms, inter-reefs and slope belts, reservoirs are low in porosity and not well-developed (Fig. 9a).

The third-order and fourth-order sequences and relevant sedimentary facies (microfacies) control reservoir development macroscopically. The upper and middle part of the third-order sequence control the development of reef cores and reef caps, while the upper and middle part of the fourth-order sequence control the development of bioclastic dolomite and microcrystalline dolomite in reef caps, which are of type I and II dolomite reservoirs and have better physical property than type III limestone reservoirs in the lower part (Figs. 2, 7 and 8). Obviously, with the decrease of the accommodation space of high-frequency sequence, organic reef caps cyclically decline with sea level and are exposed above the sea level, forming exposed unconformity sequence, which provides favorable conditions for the leaching and corrosion of meteoric fresh water as well as the evaporative dolomitization and reflux seepage dolomitization caused by the concentrated sea water in back reefs [21,22,32] and controls the eodiagenesis to some extent. The statistical relation between lithology and porosity (Fig. 9b) reveals that reservoir physical property is closely related with dolomitization, further confirming the control of dolomitization on reservoir development [19,22].

5. Conclusions

1) The Changxing Fm in the Yuanba Gas Field is divided into two third-order sequences (SQ1 and SQ2) and six fourth-order sequences, and the wireline logs change abruptly below and above (high frequency) sequence boundary. The variation of wireline logs is consistent with the sedimentary cycles controlled by high frequency sequence boundary. For example, with the sedimentary cycle becoming shallower upward, deep and shallow resistivity changes from high to low. The organic reefs of Changxing Fm are mainly developed in platform margins in third-order sequence (SQ2), representing zonal distribution and being composed of two reef cycles with asymmetric development of “early in the east and late in the west”.

2) Reef (bank) reservoirs are dominated by dissolved dolomite reservoirs with low porosity and moderate—low
permeability, which mainly occur in the reef caps of the two fourth-order sequences, representing the features of “multiple layer number, thin individual layer, reservoirs of different types interbedded with each other and strong heterogeneity” and “double layer reservoir structure”. The development of high-quality reservoir is controlled by “high-frequency” sequence and its associated bioclastic grain dolomite of reef cap and tidal flat (algae bond) microcrystalline dolomite. “High-frequency” sequence controls the distribution of organic reef sedimentary microfacies, which is the key factor for reservoir development and space distribution.

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