Lithofacies paleogeography and favorable gas exploration zones of Qixia and Maokou Fms in the Sichuan Basin

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Abstract

In the Sichuan Basin, the Middle Permian marine carbonate rocks are important natural gas pay zones with immense exploration potential, but the facies belts and distribution situations of layered dolomite reservoirs are not clear, which hinders the progress in natural gas exploration. In view of the sedimentary background of the Sichuan Basin, field outcrop section, drilling data and seismic data were comprehensively analyzed with the favorable reservoir intervals in the framework of sequence stratigraphy as the key research units. Research results about its lithofacies paleogeography were obtained as follows. First, a gentle slope SW high and NE low was presented during the sedimentation of the Qixia Fm in the Middle Permian. In the Maokou Fm of the Middle Permian, however, a series of the NE-W trending intra-platform rifts were developed in this setting, and eventually a paleogeographic pattern of NE-dipping alternative uplift and depression was evolved. Second, in the Qixia Fm, the transgressive tract was in an open platform environment and the highstand system tract evolved into a rimmed platform. And the platform margin beach in the area of Jiange-Ya'an is the favorable reservoir facies belt. And third, in the Maokou Fm, the transgressive tract was in the carbonate shelf environment and the highstand system tract evolved into a rimmed platform. And the platform margin reef flat in the area of Jiange—Ya’an and the syncline margin beach in the area of Yanting—Guang’an are favorable reservoir facies belts. It is concluded that the two grain beach facies belts in the areas of Jiange—Ya’an and Yanting—Guang’an were the favorable zones for the large-scale development of Middle Permian layered dolomite reservoirs and they are the main target of subsequent natural gas exploration.

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The Qixia and Maokou Fms in the Middle Permian are major natural gas pay zones in the Sichuan Basin. Since 1955 when exploration breakthroughs were made in Well Zi 2 and Well Long 10, a total of 325 gas reservoirs have been discovered, with proven natural gas reserves of \(850 \times 10^8\) m\(^3\), cumulative gas output of \(535.3 \times 10^8\) m\(^3\), and the maximum annual gas output up to \(30.75 \times 10^8\) m\(^3\), laying a good foundation for the establishment of natural gas base in southwest China. In recent years, high-yield gas flow was successively obtained in the layered dolomite reservoirs of Qixia Fm and Maokou Fm in such wells as Nanchong 1.
more, it was clarified that the Jiange analysis of outcrops and drilling and seismic data. Further-
prepared the paleogeographic maps of favorable reservoir in-
achievements and the lithofacies of known wells, the authors
achievements in these aspects [1–6]. Based on their
achievements and the lithofacies of known wells, the authors
prepared the paleogeographic maps of favorable reservoir in-
tervals in the Qixia and Maokou Fm after a comprehensive
analysis of outcrops and drilling and seismic data. Further-
more, it was clarified that the Jiange–Ya’an platform margin
grain beach and the Yanting–Guang’an syncline grain
beach were favorable facies belts for natural gas accumulation,
designating the direction for the future exploration of natural
gas in this basin.

1. Paleogeographic setting

1.1. Sequence stratigraphic characteristics

Generally, the Middle Permian Qixia Fm and Maokou Fm
in the Sichuan Basin constitute a set of marine sedimentary
strata of carbonate intercalated with shale and siliceous rock.
Upwardly, the Qixia Fm is divided into the first member and
the second member (P1q1 and P1q2, respectively). The P1q1 is
subdivided into b and a submembers (P1q1b and P1q1a, respectively). The Maokou Fm is divided into the first, second,
third and fourth members (P1m1, P1m2, P1m3 and P1m4,
respectively). The P1m1 is subdivided into c, b and a sub-
members (P1m1c, P1m1b and P1m1a, respectively), and the
P1m2 is also subdivided into c, b and a submembers (P1m2c,
P1m2b and P1m2a, respectively). Previously, the Middle
Permian stratigraphic sequence was usually divided into 3 to 6
third-order sequences [7–9]. Based on the seismic response
characteristics and the logging data, the authors divide it into
three sequences, i.e. SQ1 (P1q), SQ2 (P1m1–P1m3), and SQ3
(P1m4) (Fig. 1). Affected by the Dongwu movement, the
Maokou Fm suffered denudation, with SQ3 partially preserved
and local denudation to SQ2.

1.2. Paleogeographic framework

The Qixia and Maokou Fms were deposited after uplifting,
denudation and deplanation during the Caledonian and early
Hercynian movements, showing a paleogeographic setting of
being high in the southwest and low in the north. In order to
objectively reflect the paleogeographic morphology, it is
restored with the impression method. Specifically, based on
the maximum flooding surface of the Qixia Fm, the contour
map for transgression system tracts (TSTs) is prepared, on
which the thick areas indicate a low paleogeographic
morphology, and the thin areas indicate a high paleoge-
ographic morphology (Fig. 2-a). As can be seen from Fig. 2-a,
the high paleogeographic area is in agreement with the
Leshan–Longnüsi paleo-uplift in the Caledonian, while the
low paleogeographic area is in agreement with the distribution
of Carboniferous. It suggests the obvious inheritance to the
pre-Permian paleogeographic framework. The Qixia Fm TSTs
overlap from the northeastern Sichuan Basin to the south-
western Sichuan Basin, which further reveals the paleo-
geomorphology of being high in the southwest and low in the
northeast.

During the deposition of the Maokou Fm, affected by the
tectonic tension in the early stage of Dongwu movement [10],
the basement faults striking NW and NE were resurrected,
leading to the development of a series of intra-platform rifts
striking NW and SE. According to the paleogeographic setting
of strata thickness restoration in the late stage of Maokou Fm
HST (Fig. 2-b), the rifts are obvious along the Wancang–Liangping–Fengjie zone, and they became deep intra-
platform depression in the late stage of Maokou Fm deposi-
tion. During the deposition of Changxing Fm in the Late
Permian, the intra-platform depression further rifted and
evolved into the “Kaijiang–Liangping trough” [11]. The intra-
platform rift divides the Sichuan Basin into alternative uplifts
and depressions, contributing significantly to the distribution
of sedimentary facies belts.

On the basis of paleogeographic setting study and with the
favorable reservoir intervals as units, plenty of data (e.g. well
logging facies, seismic facies, and cutting/core logging) were
used to prepare the paleogeographic maps for the late stages of
the Qixia Fm HST (P1q2) and of the Maokou Fm HST
(P1m2–P1m1). The features and distribution are discussed below.

2. Paleogeographic features of lithofacies

2.1. Qixia Fm

The TST in the Qixia Fm contains open platform facies—
shallow water open platform facies in the southwest, and
deeper water open platform facies in the east and north of the
Sichuan Basin.

After the compensation and leveling in TST, Qixia Fm,
evolved into rimmed platform facies in the late stage of HST,
with three facies belts (i.e. platform margin, open platform and
deep platform depression) (Fig. 3). The platform margin facies
distributes along the Jiange–Ya’an zone, with a thickness of
40–60 m and the existence of grain beach. It is composed of
3–4 grain beach cycles revealed by field outcrops and drilling
results, with a single cycle thickness of 5–10 m. The GR
curve presents as a large box-shaped motif with low values
(Fig. 4-a). The lithologies mainly comprise of gray-light gray
grainstone, residual granular dolomite and macular dolomitic
limestone or lime dolomite. The dolomite has a cumulative
thickness of 20–45 m, being the favorable zone for the
development of large-scale reservoirs. The open platform
facies distributes expansively in central Sichuan and
eastern Chongqing, with a strata thickness of 15–30 m,
generally 20 m. Drilling results reveal the presence of intra-platform grain beach facies and inter-beach sea subfacies. The intra-platform grain beach mainly comprises of bioclastic limestone intercalated with thin-layered residual grain dolomite, and the GR curve presents as a small box-shaped motif with low values (Fig. 4-b). It contains 2–3 cycles, with a single cycle thickness of 3–5 m. On the top of the beach cycle, there is thin-layered dolomite with a cumulative thickness of 3–8 m, suggesting a secondary favorable zone for the development of large-scale reservoirs. The inter-beach sea mainly comprises of bioclastic micrite limestone and bioclastic limestone, showing medium to low GR value and serrated structure intersected with small box-like responses (Fig. 4-c). The deep platform depression facies mainly distributes in the north of Chongqing, with a thickness of 10–15 m. It contains dark gray bioclastic micrite limestone and ox-eye shaped limestone, with a large amount of muddy and siliceous materials, showing a medium GR value and a serrated shape.

2.2. Maokou Fm

The transgression system tract (TST) in the Maokou Fm was the product in the maximum transgression in the Middle Permian. Due to the rapid rise in sea level, the platform was submerged in the Qixia Fm period, and the whole Sichuan Basin evolved into the carbonate shelf in deeper water. The shallow shelf in the southwest is comprised of gray to dark gray micrite limestone and ox-eye shaped limestone. The deep shelves in the north and east of the Sichuan Basin were deposited with a set of dark gray to black ox-eye shaped limestone, containing a large amount of muddy and siliceous materials.

In the HST, an intra-platform rift was developed as a result of the extension of basement fault striking NW, and it was overlapped by the alternative uplifts and depressions under the background of being high in the southwest and low in the northwest. This paleogeographic setting controlled the facies
distribution in HST. As shown in Fig. 5, in late HST, three facies belts were developed, i.e. platform margin, open platform, and deep platform depression. The platform margin facies distributes along the Jiange—Ya’an zone with a stratigraphic thickness of 40—60 m, comprising of a series of echelon beaches striking NW and presenting discontinuous reflection with weak amplitude and strata thickness enlargement (Fig. 6-a). It contains 2—3 grain beach cycles revealed by field outcrop and drilling data. For each cycle, the GR curve presents low values and large box-shaped motif (Fig. 7-a), and the lithology is gray—light gray bioclastic limestone, arenaceous limestone and dolomite. The platform depression margin beach facies distributes along the Yanting—Guang'an zone, with a stratigraphic thickness of 40—50 m, and it is composed of multiple grain beaches in contiguous superimposition, presenting intermittent weak amplitude and messy reflection features in seismic profile (Fig. 6-b). The GR curve shows two box-shaped motifs with low values (Fig. 7-b). The lithologies revealed by drilling contain bioclastic limestone intercalated with grain dolomite, with a thickness of 15—30 m.

The open platform facies mainly distributes widely in the central Sichuan Basin—eastern Chongqing. It can be divided into two subfacies, i.e. intra-platform grain beach and inter-platform sea. The former mainly distributes in the
Anyue—Qijiang and Leshan—Xingwen zones, roughly striking NW and with a thickness of 30—45 m. It is mainly composed of bioclastic limestone intercalated with thin-layered dolomite, and the GR curve shows medium-sized box-shaped motif with low values, including 2 to 3 cycles. The latter is mainly comprised of bioclastic micrite limestone and bioclastic limestone, with a thickness of 20—30 m, and the GR curve shows medium low values and a serrated motif intercalated with small box-shaped response. The deep intra-platform depression facies mainly distributes in the Wang-cang—Liangping—Fengjie zone, with a stratigraphic thickness of 10—15 m. The lithologies revealed by filed outcrop and drilling data include dark gray bioclastic micritic limestone containing muddy and siliceous thin-layered siliceous limestone. The GR curve shows median values and a serrated motif (Fig. 7-c), with continuous high-amplitude seismic reflection features in seismic profile.

3. Favorable exploration zones

It is revealed by drilling data that the thin-layered dolomitic reservoirs in the Qixia and Maokou Fms are mainly developed in grain beach facies. Therefore, scale-distributed dolomite reservoirs will be discovered after scale-developed grain beach facies are identified. The study of sedimentary facies mainly distributes in the Wancang—Liangping—Fengjie zone, with a stratigraphic thickness of 10—15 m. The lithologies revealed by filed outcrop and drilling data include dark gray bioclastic micritic limestone containing muddy and siliceous thin-layered siliceous limestone. The GR curve shows median values and a serrated motif (Fig. 7-c), with continuous high-amplitude seismic reflection features in seismic profile.

3.1. Jiange—Ya’an zone

It is the most favorable zone for the exploration of the Qixia and Maokou Fms. The reasons are as follows: First, this zone reflects a favorable superimposition of the platform margin beach in late HST of the Qixia Fm and the platform margin (reef) beach in late HST of the Maokou Fm. Second, field outcrop and drilling data indicate that this zone contains two sets of layered dolomite reservoirs (P1q2 and P1m3) and the potential karst reservoir of the Maokou Fm. Drilling of Wells Hanshen 1 and Kuang 2 suggests that the P1q2 dolomite reservoir has a thickness of 30—70 m, an average porosity of 4.8%, and a predicted distribution area of 25000 km². Third, a high-yield gas flow was obtained in the Qixia and Maokou Fms of Wells Dashen 1 and Shuangtan 1, indicating excellent accumulation conditions of this zone.

3.2. Yanting—Guang’an zone

This zone is the most favorable exploration zone of the Maokou Fm for the following reasons. First, this zone is located in the platform depression margin facies belt in late HST of the Maokou Fm, with contiguous distribution of beaches, covering an area of 15000 km². Second, drilling results suggest the presence of P1m2—P1m3 layered dolomite reservoirs, which are mainly composed of grain dolomite and moderate—fine crystalline dolomite, with the reservoir space dominated by small dissolved pores and cavities, the reservoir thickness of 15—35 m, and an average porosity of 3.84%. Third, high-yield gas flow was obtained in the Makou Fm of Wells Nanchong 1, Gaungtan 1 and Moxi 39, indicating that it is the favorable zone for natural gas accumulation.
Fig. 5. Paleogeographic map of lithofacies at the late stage of the Maokou Fm HST in the Sichuan Basin.

Fig. 6. Seismic response profile.
4. Conclusions

1) The Qixia and Maokou Fms were deposited in the paleogeographic background of being high in the southwest and low in the northeast. Affected by the extension of basement fault trending NW, a series of intra-platform rift striking NW were superimposed. Specifically, the Wangcang–Liangping–Fengjie intra-platform rift evolved into intra-platform deep depression, which demonstrated an obvious control on the lithofacies of the Maokou Fm.

2) The TST in the Qixia Fm was an open platform environment, being shallow in the west and deep in the east. The HST evolved into a rimmed platform. The platform margin beach facies distributes along the Jiange–Ya’an zone, presenting a favorable reservoir facies belt in the Qixia Fm.

3) The TST in the Maokou Fm was a carbonate continental shelf environment and the HST was a rimmed platform. It contains platform margin (reef) beach. Besides, platform deep depression margin beach facies distributes along the Yanting–Guang’an zone, forming a unique “double grain beaches reservoir facies belt”.

4) The Jiange–Ya’an and Yanting–Guang’an zones are potential favorable exploration zones, following the southern part of the Sichuan Basin. The former is superimposed with the platform margin facies in the Qixia and Maokou Fms and contains two sets of layered dolomite reservoir related to beach facies. The latter is the platform depression margin facies in the Maokou Fm, with continuous distribution of grain beaches and scale-developed layered dolomite reservoirs.

References


