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Research Article

Characteristics of the Changxing Fm biohermal gas reservoir in the Yuanba Gasfield, Sichuan Basin and development countermeasures☆

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Abstract

Located in the Sichuan Basin, the Yuanba Gasfield is the deepest high-sulfur carbonate gas field among those discovered in the world. Its biohermal gas reservoir of the Upper Permian Changxing Fm is characterized by ultra depth, multi-stage small and scattered reef, thin reservoir, poor physical properties, strong heterogeneity, complex fluid distribution, and low production of vertical wells. The development of the biohermal gas reservoir is subject to many difficulties. For example, it is necessary to deepen the studies on time−space distribution laws of reef dolomite reservoirs; it is difficult to characterize small reefs precisely and predict thin reservoirs quantitatively; the deployment and optimization design of horizontal wells are influenced by multiple factors; and the difficulty for horizontal wells with long horizontal sections to run through high-quality thin reservoirs is high. In order to develop the Yuanba Gasfield efficiently, therefore, it is necessary to carry out a series of technical researches on the distribution laws and development models of biohermal reservoirs, precise characterization of small reefs, quantitative prediction of thin reservoirs, optimization design of horizontal wells in banded small reef gas reservoirs, and real-time trajectory optimization and adjustment of horizontal wells in ultra-deep thin reservoirs. These research results provide a powerful support for the development and construction of the Yuanba Gasfield. Based on these technologies, China's first ultra-deep high-sulfur large biohermal gas field was built with a mixed gas annual production capacity of 40×10^8 m^3. The successful commissioning of the Yuanba Gasfield lays a basis for the leading position of China in the field of high-sulfur gas field development. In addition, it is of great significance to the long-term stable gas supply in 70 cities of six provinces and two municipalities along the "Sichuan-to-East China Gas Transmission Pipeline", as well as to the industrial structure adjustment in central−western China and the economic development along the Yangtze River.

Keywords: Sichuan Basin; Yuanba Gasfield; Late permian; Biohermal gas reservoir; Reservoir; Development model; Reef characterization; Horizontal well design; Trajectory optimization

The Yuanba Gasfield is the deepest carbonate gas field with high sulfur content ever discovered around the world. Gas accumulations in the Upper Permian Changxing Fm mainly occur in marginal platform dolomite of organic reef and bank facies. More and more gas reservoirs with high sulfur content have been discovered in China and abroad [1−3]. The development of such reservoirs is among the major national energy strategies for promoting gas industry and technical research in China. But commercial production is challenging and there are no successful cases for Ref. [4]. In this paper, reservoir distribution, quantitative prediction of small reefs and thin reservoirs, horizontal well design for belt-like small biohermal gas reservoirs, and real-time adjustment of horizontal wellbore track through ultra-deep thin reservoirs are discussed, followed by the analyses of possible strategies on high-efficiency gas reservoir development.

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1. Gas reservoir geological features

The Changxing Fm biohermal gas reservoir in the Yuanba Gasfield features large burial depth, small size, scattered distribution, small thickness, poor petrophysical properties, strong heterogeneity, complex fluid distribution, and low vertical-well production.

1.1. Ultra-deep reservoirs

Tectonically, the Yuanba Gasfield lies at the joint of the northern Sichuan depression and central Sichuan gentle structural belt in the Sichuan Basin. The Changxing Fm presents a NE-inclined monoclinal structure. Its average burial depth exceeds 6600 m (the top and bottom of the Changxing Fm were drilled at 6239−7244 m). Among deep reservoirs in China for exploration and development in recent years [5−10], the Changxing Fm gas reservoir in the Yuanba field is the deepest one for commercial production. The Changxing Fm gas reservoir is 700−1500 m deeper than the Longgang gas field, 800−1500 m deeper than the Puguang field, 2600 m deeper than the Wubaiti field, and 3200−3700 m deeper than the Tieshan field.

1.2. Multi-phase small scattered reefs

As per well drilling and seismic data, the Yuanba Gasfield was on the marginal gentle-slope platform on the west side of the Kaijiang−Liangping shelf during the Changxing Fm deposition [11−13]. The degree of slope was 8°−10° [14−17]. In such an environment with relatively weak hydrodynamic conditions, organic reefs grew slowly in the form of vertical accretion and lateral migration. As a result, many late reefs are superimposed upon early reefs and scatter laterally in a wide area; a single reef is small in size. Flood [18]made a study of bioherm limestone deposited in the Heron Island in 1993. They found that reef-bank deposits on the marginal gentle-slope platform nowadays have similar features, i.e. small single reef size, multi-phase stacking of reefs in vertical direction, and scattered distribution in lateral direction. As per the studies made by Ma et al. [16], Wang et al. [17], Guo [19], and Zhao et al. [20]. On the temporal−spatial configuration of the Changxing Fm marginal platform reef-bank system, multi-phase organic reefs exist in the Yuanba Gasfield and migrate laterally in different directions.

1.3. Strong heterogeneity

1.3.1. Poor reservoir properties

Analysis of 465 core samples acquired from 16 wells shows that the porosity of the Changxing Fm reef-facies reservoirs in the Yuanba Gasfield ranges from 0.53% to 23.59%, with an average of 4.87%. Samples with a porosity above 2% average at 5.76%. About 47% of the total samples have a porosity of 2−5%. About 21% of the total samples have a porosity below 2% and between 5% and 10%. The permeability ranges from 0.0007 to 1720.7190 mD, with a geometric average of 0.5111 mD. Most samples have a permeability between 0.002 and 0.250 mD and above 1 mD (Fig. 1). The wide span of permeability indicates strong heterogeneity. As per log interpretation of 23 wells, the porosity of Changxing Fm reef-facies reservoirs ranges from 2.0% to 14.2% (Fig. 2), with an average of 4.8%. The permeability ranges from 0.01 to 13483.89 mD, with a geometric average of 0.99 mD. In general, the Changxing Fm reservoir is of low porosity and medium to low permeability.

1.3.2. Small reservoir thickness.

In the Yuanba Gasfield, the average thickness of reef-facies reservoirs in 23 wells is 58.8 m. Grade I gas layers are 0−15.8 m thick with an average of 2.66 m and account for 4.72% of the total reservoir thickness. Grade II gas layers are 0−56.3 m thick with an average of 18.5 m and account for 32.85% of the total reservoir thickness. Grade III gas layers are 2.1−67.3 m thick with an average of 25.8 m and account for 45.83% of the total reservoir thickness. Gas-bearing layers are 0−20.8 m thick with an average of 2.21% and account for 3.92% of the total reservoir thickness. Gas−water layers are 0−34.65 m thick with an average of 2.72 m and account for 4.82% of the total reservoir thickness. Water layers with low gas saturation are 0−59.6 m with an average of 4.05 m and account for 7.19% of the total reservoir thickness. Water layers are 0−8.45 m thick with an average of 0.37 m and account for 0.65% of the total reservoir thickness (Fig. 3).

1.3.3. Strong heterogeneity

As per reservoir correlation, the Changxing Fm reservoir of reef and bank facies exhibits strong heterogeneity both in vertical and lateral directions. Generally speaking, different types of reservoirs have different thickness and may not be connected laterally; reservoir thickness also changes greatly in lateral direction (Fig. 4).

1.4. Complex gas−water distribution

As per log interpretation and testing results, it is inferred that the Changxing Fm gas reservoir in the Yuanba Gasfield exists in a separate reef and has relatively isolated gas−water system. There are no regional water bodies which occur as edge water or bottom water. Studies show that gas−water distribution in reservoirs of reef facies in No. 2, No. 3 and No. 4 reef fairways is obviously dominated by present structures. Generally, the wells drilled at the structural lows produced water, especially in YB273, YB28 and YB103H wells. But in No. 1 reef fairway, there is no remarkable relationship between gas−water production and structural location. Wells YB9, YB107 and YB10-1H all produced water with different volumes (Fig. 5).

1.5. Low vertical-well productivity

As per the testing results of 15 wells, vertical wells drilled in the Yuanba Gasfield have low productivity of Changxing Fm biohermal gas. Openflow capacity was tested to range at (7−318) × 10^4 m^3/d and the average was 149 × 10^4 m^3/d.