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Research article

Sedimentary features and exploration targets of Middle Permian reservoirs in the SW Sichuan Basin

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Abstract

The exploration direction and targets for the large-scale Middle Permian gas reservoirs in the Sichuan Basin are hot spots and challenges in current exploration researches. The exploration successes of large gas field of Cambrian Longwangmiao Formation in Gaoshiti-Moxi region, Central Sichuan Basin, indicated that prospective sedimentary facies belt was the basis for the formation of large gas fields. In this paper, based on seismic data, outcrop data and drilling data, the tectonic framework and sedimentary features of the Middle Permian in the SW Sichuan Basin were comprehensively studied. The following conclusions were reached from the perspective of sedimentary facies control: (1) during the Middle Permian, this region was in shallow water gentle slope belts with high energy, where thick reef flat facies were deposited; (2) the basement was uplifted during Middle Permian, resulting in the unconformity weathering crust at the top of Maokou Formation due to erosion; the SW Sichuan Basin was located in the karst slope belt, where epigenic karstification was intense; and (3) reef flat deposits superimposed by karst weathering crust was favorable for the formation of large-scale reef flat karst reservoirs. Based on the combination of the resources conditions and hydrocarbon accumulation conditions in this region, it was pointed out that the Middle Permian has great potential of large-scale reef flat karst gas reservoir due to its advantageous geological conditions; the Middle Permian traps with good hydrocarbon accumulation conditions were developed in the Longmen Mountain front closed structural belt in the SW Sichuan Basin and Western Sichuan Basin depression slope belt, which are favorable targets for large-scale reef flat karst reservoirs.

Keywords: Sichuan Basin; Southwest; Middle Permian; High energy shallow water gentle slope; Reef flat facies; Unconformity karst weathering crust; Karst slope belt; Karst reservoir; Exploration target

After over six decades of exploration, several medium and large natural gas fields (e.g. Puguang, Longgang, and Yuanba) have been discovered and built in the Upper Permian Changxing Formation in the Sichuan Basin. High-productivity natural gas flows have also been tapped in Middle Permian. For example, in the Northeastern Sichuan Basin, Well Long 4 obtained 20.97×10^4 m^3/d gas in the Maokou Formation, and Well Yuanba 3 obtained 160×10^4 m^3/d gas in the Maokou Formation; in the Southern Sichuan Basin, Well Tai 4 obtained 202×10^4 m^3/d gas in the Maokou Formation, and Well Wei 3 obtained 8.94×10^4 m^3/d gas in the Maokou Formation. Recently, Well Shuangtan 1 drilled by CNPC in Shuangyushi closed structure in the NW Sichuan Basin, tapped 100×10^4 m^3/d gas in the Qixia Formation and Maokou Formation, indicating huge natural gas potential in Permian. However, no large-scale gas field has been discovered in the Middle Permian yet, and the large-scale gas pools discovered so far are all carbonate solution fissure and cave reservoirs related to fractures. Controlled by fracture karst system, these reservoirs are poor in continuity, complex in gas and water distribution, and limited in scale.

The exploration experience obtained from the discovery of large-scale gas fields in the Permian Changxing Formation in Puguang, Longgang and Yuanba in the NE Sichuan

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Basin, and in the Cambrian Longwangmiao Formation in Gaoshiti-Moxi region in the Central Sichuan Basin shows that: favorable sedimentary facies belt is the basis for forming large gas fields. Puguang, Longgang and Yuanba large gas fields are all distributed in large-scale reef flat belt facies in the platform margin in the Changxing period in the Kaijiang-Liangping area, and Gaoshiti-Moxi large gas fields are all located in large-scale flat facies inside the platform in the Longwangmiao period; the formation of reservoir beds in large-scale gas fields are mainly controlled by reef flat deposition, dolomitization and denudation [1–7]. Inspired by successful experiences and cognitions, some researchers studied the origin of Middle Permian reservoir beds from the viewpoints of "sedimentary facies control" and "diagenetic facies control". The viewpoint of sedimentary facies control held that in the background of Middle Permian large gentle slope during Hercynian, large-scale reef flats are the base for forming high-quality reservoir beds, and coupling of dolomitization and dissolution in reef flat facies is the condition for forming high-quality reservoir beds [8,9]. The viewpoint of diagenetic facies control maintained that Emei taphrogeny during Hercynian led to mantle magma invasion along the basement tensional faults, and thus the hydrothermal sedimentary environment (hot sub-basin) during the deposition of Middle Permian or hydrothermal diagenetic environment during the Middle Permian diagenetic process is the major controlling factor for forming large-scale dolomite reservoirs [10–12]. The studies of the above two viewpoints tried to explore the major controlling factors for forming large-scale dolomite reservoirs in Middle Permian, and to guide exploration in the Middle Permian. Mainly based on the study on the deposition features of Permian in the SW Sichuan Basin, we advanced some findings on exploration targets from the viewpoint of sedimentary facies control in this paper.

1. Deposition features of Middle Permian

1.1. Development of high-energy reef flat deposits in shallow water gentle slope

Before the deposition of the Middle Permian, the "big uplift and big depression" framework caused by the Caledonian tectonic cycle in the Sichuan Basin experienced "planation and compensation" because of large-scale whole-slab uplifting of the basin basement during early Hercynian, forming "gentle slope type" basement with the feature of "peneplane" during the deposition of the Middle Permian [13,14]. During the deposition of this "gentle slope type" basement, influenced by the uplifting of Emei mantle plume on the southwestern edge of this basin during the initial Dongwu Movement, underwater dome-like uplift was generated on the depositional basement in SW Sichuan Basin [15–18], which gradually descended to the east and northeast directions.

The palaeogeomorphic framework of the basin basement and regional sea level changes jointly controlled the distribution of sedimentary facies belts in the Middle Permian of the Sichuan Basin. The general sedimentary framework of this basin during the Middle Permian was carbonate gentle slope, but affected by underwater paleo-uplift, the southwestern region (west of Yibin–Ziyang–Mianyang) of this basin was located in shallow water gentle slope with high energy, where large-scale deposits of reef flat facies in high energy environment developed. The seismic sections in Sinopec prospect area in the Longmen Mountain front show that the Middle Permian reflection layers have apparent instable, discontinuous, chaotic and moundy phase energy reflection features of high-energy deposition environment (Figs. 1 and 2).

The Middle Permian outcrop profiles in some areas (e.g. Yongqing in Beichuan county, Tianchi and Gaoqiao in Mianzhu city, Dafeishui in Dayi county, and Shuimo in Sanjiang Village) in the Longmen Mountain front show that the lithologies in Middle Permian Qixia Formation and Maokou Formation are mainly gray calcsparite bioclastic limestone and psammitic limestone, with coral reef limestone and sponge reef limestone (Fig. 3). Wells drilled in the SW Sichuan Basin also reveals that thick bioclastic limestone and algal psammitic limestone developed in the Maokou Formation. For example, particle rocks in Well Dashen 1, Well Ziyang 1 and Well Jinshi 1 are more than 150 m thick. Some wells (e.g. Nǔji, Langzhong 1, and Guanshen 1) drilled in broad region of this basin to the east of Yibin–Ziyang–Mianyang show that the lithology of the Middle Permian is mainly dark gray micrite and microcrystalline limestone. Seismic reflection structure also shows apparent parallel, continuous and stable features, which indicates that the Middle Permian gradually transited to deposits in gentle slope, deeper water and low energy environment. Previous studies show that Mao 2 and Mao 3 are two important flat-forming periods during the deposition of the Maokou Formation [9,19,20], and the flats generated are mainly distributed in southwestern region of this basin and consist of primarily light gray massive and calcsparite cemented red alga and green alga limestone. Compared with the Qixia period, with shallower water and stronger water energy, the Maokou period had an upper zone of shallow gentle slope extending far east, and more developed organic reef flats (Figs. 4 and 5).

1.2. Located in karst slope belt, the "Maokou Formation top" has favorable conditions for forming reef flat karst reservoirs

The Dongwu Movement during Hercynian led to differential uplift of the basement of the Sichuan Basin. Differential denudation of the Middle Permian Maokou Formation top (briefly called "Mao top") gave rise to a large-scale unconformity weathering crust. In the southwestern region of this basin, the 2nd member of the Maokou Formation outcrops in some areas (Gaoqiao in Mianzhu-Yongqing in Beichuan), and the 3rd member of the Maokou Formation outcrops in most of the rest areas, with erosion thickness of 100–154 m. Research results of palaeogeomorphology indicate that the Mao top weathering crust was located in paleo-