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Original research paper

Facies and porosity origin of reservoirs: Case studies from the Cambrian Longwangmiao Formation of Sichuan Basin, China, and their implicationson reservoir prediction

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Abstract

The dolostone of the Cambrian Longwangmiao Formation has been a significant gas exploration area in Sichuan Basin. In Gaoshiti-Moxi regions, a giant gas pool with thousands of billion cubic meters' reserve has been discovered. However, the origin of the reservoir and the distribution patterns are still disputed, eventually constraining the dolostone exploration of the Longwangmiao Formation. This paper focuses on the characteristics, origin, and distribution patterns of the dolostone reservoir in the Longwangmiao Formation based on: the outcrop geological survey, cores, thin-sections observation, reservoir geochemical characteristics study, and reservoir simulation experiments. As a result, two realizations were acquired: (1) The Cambrian Longwangmiao Formation could be divided into an upper and lower part in the Sichuan Basin. Based on the two parts of the Longwangmiao Formation, two lithofacies paleogeographic maps were generated. In addition, the carbonate slope sedimentary models were established. The grainstone shoals are mainly distributed in the shallow slope of the upper part in the Longwangmiao Formation. (2) The grainstone shoals are the developing basis of the dolostone reservoir in the Longwangmiao Formation. Moreover, the contemporaneous dissolution was a critical factor of grainstone shoal reservoir development in the Longwangmiao Formation. Controlled by the exposure surface, the dissolution vugs are not only extensively distributed, but also successively developed along the contemporaneous pore zones. Hence, the distribution patterns could be predicted. The geological understandings of the origin of dolostone reservoir in the Longwangmiao Formation show that the reservoir distributed in the areas of karstification in the Gaoshiti-Moxi regions, as well as the widespread grainstone shoals in the whole basin, are the potential exploration targets.

Keywords: Sichuan Basin; Longwangmiao Formation; Carbonate slope; Dolograinstone shoal reservoir; Genesis and distribution of reservoir

1. Introduction

The Cambrian is an essential domain for gas exploration in the Sichuan Basin. However, in the past 50 years, the Cambrian has become the secondary target when exploring the primary Sinian Dengying Formation gas reservoirs. Following the conclusion that the Caledonian paleo-uplift favored oil and gas accumulation [1], oil and gas exploration in the Weiyuan structure (<2500 m) has experienced more than four decades of exploration since obtaining 2.28 × 10^4 m^3/d in the open hole test to the Middle-Upper Cambrian Xixiangchi Group in Well Wei 12 in 1966. In 2004−2006, 14 gas-bearing fracture systems were discovered in wells, such as Wei 42 and Wei 26. The aforementioned wells have a total obtaining productivity of 35.2 × 10^4 m^3/d and 1.73 × 10^8 m^3, respectively.

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Furthermore, the estimated dynamic natural gas reserves are 14.79×10^8 m^3. A few drilled wells exclusive to the Cambrian led to poor exploration. In 2005, Well Weihan-1 specific to the Cambrian was drilled in the Weiyuan Structure. The drilling led to the discovery of pore dolomite gas reservoir, from which the tested natural gas productivity is 11×10^4 m^3. The finding started the prelude to the exploration of the Longwangmiao Formation and actively exploring deeper layers (>4 500 m). From 2011 to 2013, a large gas field at a scale of 10^{12} m^3 was discovered in the Gaoshiti-Moxi area in the eastern Weiyuan Structure [2−4] (Fig. 1).

By the deepening of exploration, ambiguous understanding of the genesis and distribution of this pore dolomite gas reservoir has become the bottleneck restraining the exploration of the Longwangmiao Formation and shown in the following two aspects. The first aspect is that there is less understanding to the sedimentary facies of the Longwangmiao Formation, especially the development scale and distribution law of granular shoal, limited the prediction of the reservoir distribution, so the evaluation of the favorable facies belt should be focused on. As for the second aspect, the unclear controlling factors on the strong reservoir heterogeneity, for example, resulted in a significant difference in the reserves abundance and production in the Gaoshiti-Moxi area, and unclear genesis and prediction of high-quality reservoirs directly affected the exploration process, so controlling factors on the development of high-quality reservoirs should be focused on.

Based on the geological survey on outcrop, core and thin section observation, reservoir geochemistry analysis and simulation experiments, combined with drilling and seismic data, this paper studies the sedimentary facies and reservoir genesis of the Longwangmiao Formation in the Sichuan Basin and proposes two points: (1) the Cambrian Longwangmiao Formation can be divided into upper and lower members, and based on which two lithofacies paleogeographic maps were plotted, and the sedimentary models of the gentle carbonate slope were established, where the grainstone shoal is mainly distributed in the upper member. (2) The grainstone shoal is fundamental to the development of the dolomite reservoir; penecontemporaneous dissolution is key to the pore development of the grainstone shoal reservoir, and controlled by the exposed surface, dissolved vugs were developed in a large scale in the burial period and succeeded the pore zone developed in the penecontemporaneous period. These understandings are of great significance to the prediction of favorable reservoirs in the Longwangmiao Formation in the Sichuan Basin.

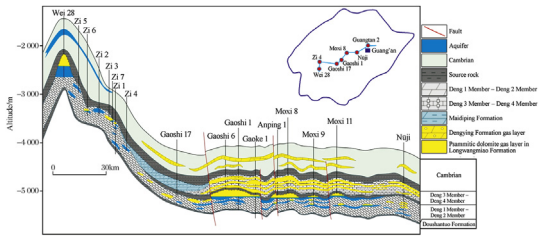

Fig. 1. Gas reservoir profile of the Sinian-Cambrian in the Weiyuan-Longnüsi area of the Sichuan Basin.

2. Regional geological background

The Cambrian of the Sichuan Basin are well developed [5,6], and the Cambrian bottom unconformably contacts the Sinian Dengying Formation, and the Cambrian top is continuous to the Lower Ordovician. From bottom to top, the Cambrian is divided into the Lower Cambrian Qiongzhusi Formation, the Canglangpu Formation, and the Longwangmiao Formation, and the Middle-Upper Cambrian Gaotai Formation and the Xixiangchi Group. The Qiongzhusi Formation bottom is composed of black carbonaceous shale and mudstone, and upward arenaceous shale, siltstone, and sandstone with local intercalation of carbonate rocks. This Formation contains major Cambrian source rocks with a thickness of 91−400 m. The Canglangpu Formation, 50−200 m thick, is deposits of clastic rock, where the bottom is intercalated with aubergine shale (lower red layer), and the top is intercalated with shale. The Longwangmiao Formation is dominated by a large section of dolomites, 39.5−797 m thick, with increasing limestone in the lower part, frequent gypsum intercalations in the middle and minor sandstone and mudstone intercalations in the upper part. The Gaotai Formation is dominated by clastic rocks, mainly aubergine mottled sandstone (upper red layer), mudstone intercalated with dolomite, with a thickness of 50−100 m. The Xixiangchi Group contains a large section of dolomite, with a thickness of 100−500 m.

Liu et al. [7] pointed out that in the study on the lithofacies paleogeography of the Longwangmiao Formation period in the Early Cambrian, typical gentle carbonate slopes were developed in the Longwangmiao Period, and in the upper shallow Yangtze slope, three local sags were developed in the west of Leshan and the south of Chongqing, cover an area of $(3−5) \times 10^4$ km^2, and formed three shallow evaporation salt basins. The Longwangmiao Formation in Well Lin 7 is a gypsum-salt rock with a thickness of 690.50 m. To the northwest, the thickness of the gypsum salt rock declines in a semi-annular zone and becomes 0 in Longnvsi, Gaoshiti, Anpingdian in central Sichuan Basin, and in Ziliujing, Laolongba, and Weiyuan in southwest Sichuan Basin. The varying trend is evident, confirming the existence of the Linfengchang salt basin in southern Sichuan Basin and demonstrating the distribution pattern of the northwestern margin of the gypsum salt basin. The geomorphic highs in the margin of the gypsum salt basin contain oolitic, psammitic, and bioclastic shoal bodies due to stronger water body energy. Moreover, affected by eustasy and wave, the shoal body shows a lateral migration, which resulted in the wide distribution of the carbonate slope in the Longwangmiao Formation period. The existence of the gypsum salt basin provides the geological background for dolomitization of granulite in the contemporaneous stage.

Wang et al. [8] pointed out that the tectonic evolution of the Sichuan Basin experienced seven stages: (1) The evolution of the rift basin in Nanhua Period; (2) The formation of the Weiyuan-Longnvsi paleo-uplift in the Chengjiang Movement

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