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The influences of sea-level changes on the quality of bank reservoirs of the Lower Cambrian Longwangmiao Formation, in the Gaoshiti-Moxi area, Sichuan Province, China

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A B S T R A C T

Reservoir properties of banks of the Longwangmiao Formation show strong lateral and vertical variations in the Gaoshiti-Moxi area, central Sichuan. In this study, we utilized outcrop, core data, thin sections, wireline logs, and seismic data to investigate the influences of sea-level changes on the development of banks and penecontemporaneous dissolution which controlled the formation of high-quality bank reservoirs. Our results revealed that the Longwangmiao Formation corresponds to a third-order sea-level change cycle, which consisted of a rapid sea-level rise and a slower sea-level fall; we further identify four fourth-order sea-level cycles. Bank reservoirs are dominated by grain dolostone, silt to fine sand-sized crystalline dolostone, and mottled silt to fine sand-sized crystalline dolostone. The main reservoir spaces were pores and vugs, with an average porosity of 4.81% and average permeability of 4.75×10^{-3} μm^2. Bank deposition and dissolution during the third-order sea-level fall developed better than during the rising period, and the late fall stage was better than the early fall stage. Under the influence of fourth-order sea-level changes within the third-order sea-level change, the development of banks shows strong variations between different areas, which are evidenced by the fact that banks in the Moxi block were better developed than those in the Gaoshiti block. Bank dissolution in the Moxi block developed during the early and the late stage within the third-order sea-level fall, whereas the Gaoshiti block was developed only during the late stage. Therefore, we have concluded that sea-level changes played a significant role in controlling the quality of bank reservoirs in the Gaoshiti-Moxi area.

1. Introduction

Oil and gas exploration of central Sichuan paleo-uplift began in the 1960s. After more than 40 years, the Sinian Gasfield in Weiyuan Structure had been the only discovery in this area. Since 2006, the research and risk exploration of CNPC had been implemented on the Gaoshiti-Moxi area, east of the central Sichuan paleo-uplift. Since 2011, the Southwest Oil and Gas Field Company has deployed two exploration wells, Gs1 and Mx8, which have acquired more than 35.3 mmcf of natural gas. Since then, exploration of the Lower Cambrian has been strengthened, resulting in the discovery of the oldest and largest marine carbonate gas reservoir in the Longwangmiao Formation (Du et al., 2014; Zou et al., 2014).

Reservoir properties of the Longwangmiao Formation in Sichuan Province were influenced by sedimentation and karstification (Li et al., 2014). Previous studies showed that sea-level changes not only controlled the development of banks (Zhao et al., 2014a,b; X.Z. Wang et al., 2002; Shen et al., 1999; Gao et al., 2006; Wan and Sun, 2009; Bao et al., 2007), but also influenced the development of primary pores (Esrafili-Dizaji and Rahimpour-Bonab, 2009; Ding et al., 2012). This study aimed to analyze the relationship between high-quality reservoirs and past sea-level changes in the Gaoshiti-Moxi area.

Abbreviations: CNPC, China National Petroleum Corporation; Gs, Gaoshiti; Mx, Moxi; Myr: million year, EW; east west, mmcf: million cubic feet; GR, natural gamma ray; RT, true formation resistivity; RXO, flushed zone formation resistivity.

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2. Geological background

2.1. Paleogeography

The Sichuan and Chongqing Provinces in southwestern China, have an eastward gentle-slope appearance, which consisted of two uplifts (central Sichuan uplift, eastern Chongqing uplift) and two depressions (eastern Sichuan depression, western Hunan depression) underwater, during the Longwangmiao period (Fig. 1) (Wang et al., 2002; Xu et al., 2002; Song, 1996, Huang et al., 2009; Luo et al., 1998; Qiang et al., 1993). Previous studies suggested that the sedimentary environment was dominated by a restricted platform during the Longwangmiao period (Feng et al., 2001, 2002; Zhang et al., 2010; Li et al., 2012; Yang et al., 2012), whereas recent studies indicated that it was a carbonate slope steepening at the far end, which was deposited following a stage of sustained subsidence (Yao et al., 2013; Du et al., 2014; Zhao et al., 2014a,b; Zou et al., 2014; Zhou et al., 2014). From west to southeast, and northeast, the inner slope was distributed with various dolostones in bank, inter-bank and evaporative lagoon-evaporative tidal flat facies; the middle slope had various storm limestones, and grain limestone, leopard skin-like dolomitic grain limestone, crypt algal laminite dolostone of aggradation origin on ancient upland deposited, and outer slope-basin facies consisting of thin plate, nodular muddy mud-sized crystalline limestone, and limy mudstone (Fig. 1b) (Zou et al., 2014).

The Gaoshiti-Moxi area, in the eastern Sichuan Province, near the city of Suining and Anyue, is located in the central Sichuan uplift (Fig. 1b) (Xiao et al., 2014; Xu et al., 2014; Zhou et al., 2014). Banks and inter-banks dominated the study area, and the underwater uplift controlled the development of banks. Moxi and Gaoshiti blocks are two highlands in the study area, deposited grain dolostone, silt to fine sand-sized crystalline dolostone, which record a high-energy environment in the inner slope (Du et al., 2014, Zou et al., 2014). The setting was favourable for the development of multi-cyclic, horizontally migrating and vertically superimposed banks, and banks distributed in a northeastern stripe on the two highlands. Muddy dolostone and mud-sized crystalline dolostone, were deposited in the dip between the two highlands, which is indicative of water that was limited, when an inter-bank sea developed (Fig. 1c).

The Gaodongmiao Section, in the eastern Chongqing Province, near the city of Xiushan, is located in the eastern Chongqing uplift (Fig. 1b). In the lower part of Longwangmiao, grain limestone are interbedded with muddy mud-sized crystalline limestone. In the upper part, silt-sized crystalline dolostone are interbedded with muddy dolostone, indicative of a relatively deep shallow-marine environment in the middle slope.

2.2. Stratigraphy

The Longwangmiao Formation has been studied extensively for lithology, logging and paleontology in this area (e.g., Zhai and Song, 1989, 1996; Hao, 1991; Gao et al., 2000; Liu et al., 2008; Lu, 1962, 1982; Luo et al., 1993; Ran et al., 2008; Li et al., 2012). The formation is 80–120 m thick and is composed of grain dolostone, crystalline dolostone and muddy dolostone (Fig. 2). The base of the Longwangmiao Formation is an unconformity, with underlying thin-layers of grey-green muddy siltstone, red mudstone, and sandstone of the Canglangpu Formation. The top of the Longwangmiao Formation is also an unconformity, and it is overlain by purple, brown-red muddy dolostone, and siltstone of the Gaotai Formation (Zhai, 1989, 1996, Hao, 1991; Gao et al., 2000; Liu et al., 2008; Ran et al., 2008). Fossils, such as *Redlichia murakamii-Hoffeteiia* and *Redlichia gizhouensis*, were found in the Longwangmiao Formation (Lu, 1962, 1982; Liu et al., 2008; Luo et al., 1993). The curve shape of the GR log in the Longwangmiao Formation was characterized as serrated, distinct from the Canglangpu and Gaotai Formations (Li et al., 2012; Du et al., 2014; Zhao et al., 2014a,b; Zhou et al., 2015).

3. Data and methods

The present study was based on well, outcrop and seismic data. The well data are distributed widely across the entire study area. We selected 33 wells, with 1200 m-long cores, and one outcrop for detailed analyses (Fig. 1c). Logging data, including GR and RT, RXO, was recorded for the wells, and a total of 546 representative sediment samples were selected for lithology and petrophysical properties analyses. From these samples, 120 were prepared for thin section, and the remaining 426 were prepared to test for properties. The observational thickness of the outcrop is 184.62 m, and 40 samples were selected from the outcrop and prepared for thin section for petrologic analyses. High-resolution 3-D seismic imaging covered the entire study area with a vertical resolution of target stratum of 40 m.

According to the classification for carbonates (Feng, 1981), microfacies were determined under a Leitz polarizing light microscope. Thin sections were prepared and analyzed at the CNPC Key Laboratory of Carbonate Reservoir, PetroChina Hangzhou Institute of Petroleum Geology, Hangzhou, China. Porosity values were measured according to “Boyle Laws” using helium porosimetry. First, the bulk volume of the rock (V_b) is determined by using vernier calipers and assuming that the sample is perfectly cylindrical. Second, sealed sample in a container of known volume V_1 at atmospheric pressure P_1. This container is attached by a valve to another container of known volume, V_2, injecting helium to a pressure, P_2. When the valve that connects the two volumes is opened slowly so that the system remains isothermal, the pressure in the two volume equalises to P_3. Boyle's Law states that the pressure times the volume for a system is constant. So, the value of the equilibrium pressure can be used to calculate the volume of grains (V_g) by formula $P_1 (V_1 - V_g) + P_2 V_2 = P_3 (V_1 + V_2 - V_g)$. Then, the bulk volume and grain volume can then be used to calculate the porosity of the rock (V_p) by formula $V_p = V_b - V_g$. Finally, the porosity induced by the formula V_p/V_b. Permeability measurements were performed according to the “Darcy Law”. The porosity and permeability analyses were performed at the Institute of Petroleum Exploration and Exploitation, PetroChina Southwest Oil and Gas Field Company, Chengdu, China. In addition, log data (GR and RT, RXO) from 33 wells were evaluated using Schlumberger charts. High-resolution 3-D seismic imaging has produced favourable results using new data acquisition and processing techniques. The geophysical data were obtained from CNPC Chuanqing Drilling Engineering Company Limited, Chengdu, China.

Carbonate deposition sequences are related to relative sea-level changes (Fischer, 1964; Schlager, 1981; Spencer and Demicco, 1989; Frouin et al., 2007; Sweeney et al., 2015). Most unconformities in a sedimentary sequence can be attributed to sea-level changes of long-term third-order cycles (1–10 Myr) (Read et al., 1993; Prothero and Schwab, 2004). By analyzing the sedimentary sequences, sea-level changes can be elucidated (Vail and Audemard, 1991). In this study, cores, thin sections, drilling and logging data were used to identify the boundaries of third- and fourth-order sea-level change cycles. We then drew a composite profile including the Mx203 well, Gs10 well and Gaodongmiao outcrop section. Our comprehensive analyses of the lithology associations, sedimentary structure and omission surfaces (Clari et al., 1995; Hillgärtner, 1998) were performed to interpret the sea-level change cycles. Wave marks and mud cracks indicate a shallow environment (Pittet and Strasser, 1998). A third-order sea-level