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Tight oil accumulation of the redeposited carbonates in the continental rift basin: A case study from Member 3 of Shahejie Formation in Shulu sag of Jizhong depression, North China

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ABSTRACT

Tight oil in the redeposited carbonates was mainly distributed in the Lower Submember of Member 3 of Shahejie Formation in Shulu sag of Jizhong depression, North China. Through high-resolution 3D seismic data, well logging data and drilling data, the Lower Submember of Member 3 of Shahejie Formation was divided into 5 third-order sequences and 15 parasequence sets. The redeposited marl and rudstone were major reserving horizons of tight oil, and ten reserving space types were developed and could be classified into two main categories, i.e., pores and fractures. Two types of tight oil reservoirs were established, i.e., the marl hydrocarbon reservoir of the source-reservoir integration and the rudstone hydrocarbon reservoirs of the source-reservoir paragenesis. The assemblage relationship among the high-quality source rocks, system tracts with the source-reservoir configuration was the major control factor for tight oil accumulation in the redeposited carbonates. The lacustrine transgressive system tracts and highstand systems tracts in SQ1 to SQ5 were the favorable horizons for development of the marl hydrocarbon reservoir, the lowstand system tracts in SQ1 to SQ3 were the favorable horizons for development of the rudstone hydrocarbon reservoir.

1. Introduction

Tight oil was a new hotspot in global unconventional hydrocarbon exploration and development after exploration of shale gas (Pollastro et al., 2008; Sun et al., 2011). It had been commercially developed in the United States, Canada and other countries (Lin et al., 2011), and became another strategic breakthrough since the discovery of shale gas (Gaswirth et al., 2013). But in China, tight oil and gas exploration and development is still in the beginning and exploring stage (Guan et al., 1995; Zou et al., 2010). Carbonate rock was an important reservoir type, where the oil and gas production accounts for more than a half of the global total production (Lv and Jin, 2000). Previous researchers thought that the lacustrine carbonates had short sedimentary period with instable distribution, therefore, researches on carbonate reservoir mainly focused on the marine carbonate for a long time (Hong et al., 2012; Yang et al., 2013), especially reef and shoal carbonates (Peng, 2011). In general, the lacustrine carbonate rock, especially the fine-grain carbonate, had not been well-studied. The lacustrine carbonate rocks were developed in the Eocene Lower Submember of Member 3 of Shahejie Formation in Shulu sag of Jizhong depression, North China, which had been studied by many researchers. For example, Jiang et al. (2007) divided carbonates in the Lower Submember of Member 3 of Shahejie Formation into nine kinds of lithofacies, and identified five types of sedimentary facies; meanwhile, in combination with sequence analysis, the tectonics, climate and provenance were regarded as the major control factors of carbonate deposit. Zhao et al. (2014a) studied the organic geochemical and reservoir characteristics of marl in detail, and through analysis of the marl-rudstone tight oil and gas accumulation characteristics, this kind of reservoir was quite rich in oil and gas resources with great exploration potential (Zhao et al., 2014b). Carbonate fragments of ancient carbonates eroded by late mechanical weathering were transported and redeposited in the basin, and this kind of the carbonates were called the redeposited carbonate which accounted for more than 80% of total rocks. In Shulu sag, the redeposited carbonate mainly was the marl and rudstone.

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With the constant increasing degree of hydrocarbon exploration, the exploration potential of slope zones and normal structure zones in the mature exploration areas decreased. As the recent theory of “oil accumulation in troughs within the continental fault depression” was proposed (Zhao et al., 2011), troughs in the hydrocarbon-rich depressions had gradually become an important field of hydrocarbon exploration nowadays. Related studies showed that the Lower Submember of Member 3 of Shahejie Formation in Shulu sag was the deep lacustrine to the semi-deep lacustrine deposits which dominated by the dark mudstone, marl and rudstone, and hydrocarbon indications and commercial hydrocarbon flows in rudstone and marl had been discovered in eight wells including Well J98, Well J116, Well JG11 and Well ST 1H (Qiu et al., 2006a; Su et al., 2008). The marl-rudstone intervals had become an important exploration target bed. The Lower Submember of Member 3 of Shahejie Formation varied greatly in formation thickness with a range between 300 m and 1600 m from the western slope to the eastern trough of the Shulu sag. Constrained by restricted borehole distribution, poor seismic data quality and other conditions, the Lower Submember of Member 3 was divided into one third-order sequence and three system tracts (Kuang et al., 2007; Jin et al., 2008). By now, it was difficult for this subdivision scheme to meet the need of accurate recognition of sedimentary facies types and the marl-rudstone reservoir bodies, as well as deep study of such hydrocarbon reservoir types and control factors.

Based on high-resolution 3D seismic data and drilling data, through single-well sequence analysis in the slope area and seismic sequence analysis in the trough area, the Lower Submember of Member 3 of Shahejie Formation was subdivided into five third-order sequences and 15 parasequence sets, thereby a high-resolution isochronous sequence stratigraphic framework was established, laying a foundation for understanding hydrocarbon-generating potential, studying sedimentary system, clarifying control factors of tight reservoir, and predicting tight oil distribution.

2. Geological setting

The Shulu sag was located in the south of Jizhong depression, Bohai Bay Basin, that was a Paleogene listric sag developed on Paleozoic basement. It was characterized by faulting in the eastern part and overlapping in the western part, and spanned to Xinhe fault on the east, Ningjin high on the west, Shenxian sag on the north and Xiaoliucun low high on the south, with an exploration area of about 700 km^2 (Fig. 1). The tectonic unit consisted of two highs, three troughs and western slope. Vertically, it was composed of Neogene Minghuazhen Formation and Guantao Formation, Paleogene Dongying Formation and Member 1, Member 2 and Member 3 of Shahejie Formation (Kuang et al., 2007). During the early depositional period of Member 3 of Shahejie Formation, activity of Xinhe fault was strong, the sedimentary strata was overlapped gradually towards the western slope, and the subsidence center was located on the downthrown side of Xinhe fault (Fig. 2). The sag was controlled by Jingqiu and Taijiazhuang paleostructures on the south and north respectively, and the lacustrine basin was divided into the south, central and north parts where water was incompletely connected, resulting in formation of three troughs. The water from the northern part in the sag became salty gradually toward the south, circulation of water environment in the central and south parts were poor, and sedimentary sequences of sandstone, mudstone-marl and rudstone-gypsum salt rock were deposited from the north trough to the south trough in the sag (Su et al., 2008). Marl and rudstone reservoirs in the Lower Submember of Member 3 of Shahejie Formation were mainly distributed in the central trough with an area of about 200 km^2, and the strata thickness in the depositional center was up to 1600 m, which dominated by deep lacustrine to semi-deep lacustrine deposits with multiple vertical progradation and retrogradation cycles. Since 2012, targeting to marl and rudsone reservoirs in the Lower Submember of Member 3 of Shahejie Formation, three exploratory wells, i.e., Well ST1H, Well ST2X and Well ST3 were drilled successively, and the commercial hydrocarbon flows were achieved, indicating a good exploration prospect.

3. Sequence stratigraphy

3.1. Sequence subdivision

A majority of previous drilling wells were located in the slope of Shulu Shulu with depth less than 3800 m and incomplete strata. The seismic data was characterized by low resolution and poor quality, 3D seismic survey only was restricted in the slope and the normal structure zone, leading to rough sequence subdivision resolution.

In 2012, high-density all-around 3D seismic acquisition was deployed by Huabei Oilfield Company in tight oil exploration of the central trough with folds of 256 and bin size of 20 m × 20 m, and the area of the merged 3D seismic data was covered over 700 km^2. Thereby, in order to make a preliminary exploration of tight oil in the central trough, three deep wells, i.e., Well ST1H, Well ST2X and Well ST3, were drilled successively with drilling depth in range of 4003 m and 4387 m which drilled through the Lower Submember of Member 3 of Shahejie Formation.

Based on the above 3D high-resolution seismic data in the trough, through well logging, mud logging and testing data, over 20 key exploratory wells were utilized to calibrate precisely synthesized records, analyze single-well and connecting-well sedimentary associations and sedimentary cycles, and recognize drilling sequence boundaries. Results showed that the Lower Submember of Member 3 of Shahejie Formation was divided into one second-order sequence, and further divided into five third-order sequences, named SQ1, SQ2, SQ3, SQ4 and SQ5 in ascending order; then, six sequence boundaries were recognized correspondingly, i.e., SB0, SB1, SB2, SB3, SB4 and SB5 in ascending order, and each third-order sequence was further divided into three system tracts, i.e., lowstand system tract (LST), lacustrine transgressive system tract (TST), and highstand system tract (HST); it also was subdivided into 15 parasequence sets (C1-C15); thereby a high-resolution sequence stratigraphic framework for the Lower Submember of Member 3 of Shahejie Formation was established (Figs. 3 and 4).

3.2. Sequence boundary characteristics

Accurate recognition of sequence boundaries was not only a key to scientific sequence stratigraphic subdivision, but also a basis for study of sequence stratigraphic sedimentary system (Chen et al., 2001). Third-order sequences reflected variations of subsidence rate and deposition rate, which were closely related with change of sedimentary environment. In a continental basin, most third-order sequence boundaries were conversion surfaces of sedimentary facies (Jiang et al., 2009). Therefore, a sequence boundary was mainly recognized and subdivided using variations and some special responses between overlying and underlying lithology, sedimentary facies assemblage, seismic reflection termination relationship, electrical logging curves, organic geochemical parameters etc.

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