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RESEARCH PAPER

Formation and distribution of the high quality reservoirs in a deep saline lacustrine basin: A case study from the upper part of the 4th member of Paleogene Shahejie Formation in Bonan sag, Jiyang depression, Bohai Bay Basin, East China

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Abstract: The upper part of the 4th member of Paleogene Shahejie Formation in Bonan sag, Bohai Bay Basin, East China was taken as the study object. Conventional core analysis, casting and conventional thin section inspection, scanning electron microscope observation, particle size analysis and fluid inclusion analysis were carried out on cores, and the data from these analyses and tests was used to find out the evolution of diagenetic environment of the saline lacustrine basin and the main factors controlling the deep formation of high quality reservoirs. The diagenetic environment of the saline lacustrine basin experienced alkali and acid alternation. In the early alkali diagenetic environment, large amounts of carbonate cement filled the primary pores, making the reservoir porosity reduce sharply from 37.3% to 18.77%, meanwhile, keeping the primary pores from compaction, and retaining the dissolution space. In the middle-late stage of acid diagenetic environment, early carbonate cement was dissolved, resulting in rise of reservoir porosity by 10.59%, and thus the formation of the deep high quality reservoirs. The distribution of high quality deep reservoirs is controlled by the development of gypsum salt rock, source rock, fracture system and sedimentary body distribution jointly. Deeply buried high quality reservoirs in the upper part of the 4th member of the Shahejie Formation in Bonan sag are nearshore subaqueous fan-end sandstone and some fan-medium fine conglomerate buried at 3 400–4 400 m in the north steep slope.

Key words: Bohai Bay Basin; Bonan sag; 4th member of Paleogene Shahejie Formation; saline lacustrine basin; high quality reservoir; formation mechanism

Introduction

The previous studies on high quality deep reservoirs focus on fracture zones created under tectonic actions[1] and solution pores and vugs in carbonate[2]. It has been widely accepted that deep clastic formations are densified[3–4] with no effective reservoirs. The traditional understanding of lack of high quality clastic rock reservoirs in deep formation has been guiding the oil and gas exploration in the Bonan sag. The Bonan sag is a secondary structural unit of Jiyang depression in the Bohai Bay Basin, where 62% of its proven reserves are in the zone with secondary pores at the depth of 2 000–3 200 m in the 3rd member of the Paleogene Shahejie Formation in the middle and shallow layers (shortened as Es_3). However, as the target of oil and gas exploration shifts to the deep saline lacustrine basin represented by the upper part of the 4th member of Shahejie Formation (shortened as the upper Es_4), it is found that upper Es4 does not follow the laws of rich secondary solution pores at 2 000–3 200 m depth in the Es_3, on the contrary, some zones of ultra-low porosity caused by cementation of calcite are found at 2 800–3 200 m depth. As the organic acid generated during the thermal evolution of source rock could dissolve the calcite cement, zones with secondary pores may exist in the deep reservoirs[5-7]. Therefore, in this paper, taking the Paleogene upper Es_4 in the Bonan sag as an example, based on the data obtained from sedimentary, reservoir and geochemical tests and analysis of drilling cores, along the main line of diagenetic environment evolution analysis of the

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saline lacustrine basin, the forming mechanism and distribution laws of high quality reservoirs in the deep lacustrine basin have been examined to provide guidance on the oil and gas exploration in the deep formations of the saline lacustrine basin.

1. Overview of the study area

The Bonan sag is a half-graben sag with fault in the north and stratigraphic overlap in the south located in the northeast of Jiyang depression in the Bohai Bay Basin, East China, where north-east fault, northeast-east fault and a series of nearly east-west faults have been developed due to the effects of multi-stage tectonic movements. The sag is filled with Kongdian Formation, Shahejie Formation and Dongying Formation of the Paleogene System, Guantao Formation and Minghuazhen Formation of the Neogene System, and Pingyuan Formation of the Quarternary System. During the deposition period of the upper Es4, the salinity of water in the lacustrine basin was relatively high [8], lowstand systems tract, transgressive systems tract and highstand systems tract were developed from the bottom to the top, forming a set of complete three-order sequence, and the sediment types include nearshore subaqueous fan, fan delta, sandstone beach bar, carbonate beach bar, and saline lake, etc. (Fig. 1). In middle-shallow reservoirs in the upper Es_4, primary pores filled with calcite cement are common (Fig. 2a-2b) and clay mineral cements formed under the alkaline diagenetic environment, such as chlorite and filiform or flaky illite, also exist (Fig. 2f). The calcite cement filling the pore space prevented the primary pores from being compressed (Fig. 2b, 2c, 2e), thus preserving the dissolvable space and laying a solid foundation for the development of high quality reservoirs in the deep saline lacustrine basin.

2. Main factors controlling the diagenetic environment of saline lacustrine basin

The carbonate cements in tightly cemented zone of the upper Es_4 of Bonan sag are related to the alkaline fluid produced by gypsum rock deposited at the early stage, but whether or not the carbonate cements can be dissolved to create secondary pores is related to the activity of acidic fluid at the middle and late stages. The active time and concentration of alkaline and acidic fluids jointly determine the forming time and scale of the high quality deep reservoirs.

2.1. Gypsum rock evolution controlling alkaline fluid

There are two sources of alkaline fluid: (1) The alkaline layers and alkaline brine existing in the saline lacustrine basin maintain the contemporaneous and penecontemporaneous alkaline diagenetic environments[9–10], and the alkaline fluids generated during the conversion of deposited gypsum to anhydrite maintain the alkaline environment at the early and middle diagenetic stages[9,11]. As the environment of saline lacustrine basins can be divided into “deep water” to “shallow water” environment, there are different opinions on the source of salts in lacustrine basins[12], and a series of different theories are derived therefrom, for example, salts are sourced from the saline hydrothermal fluids upwelling from the deep strata under the action of fault activities[13]; alkaline brine is produced by the remaining salts from transgression[12], super-thick alkaline layers are formed under arid environment over a long period of time[9]. (2) The highly mature organic matter generates condensate oil and wet gas, which damage

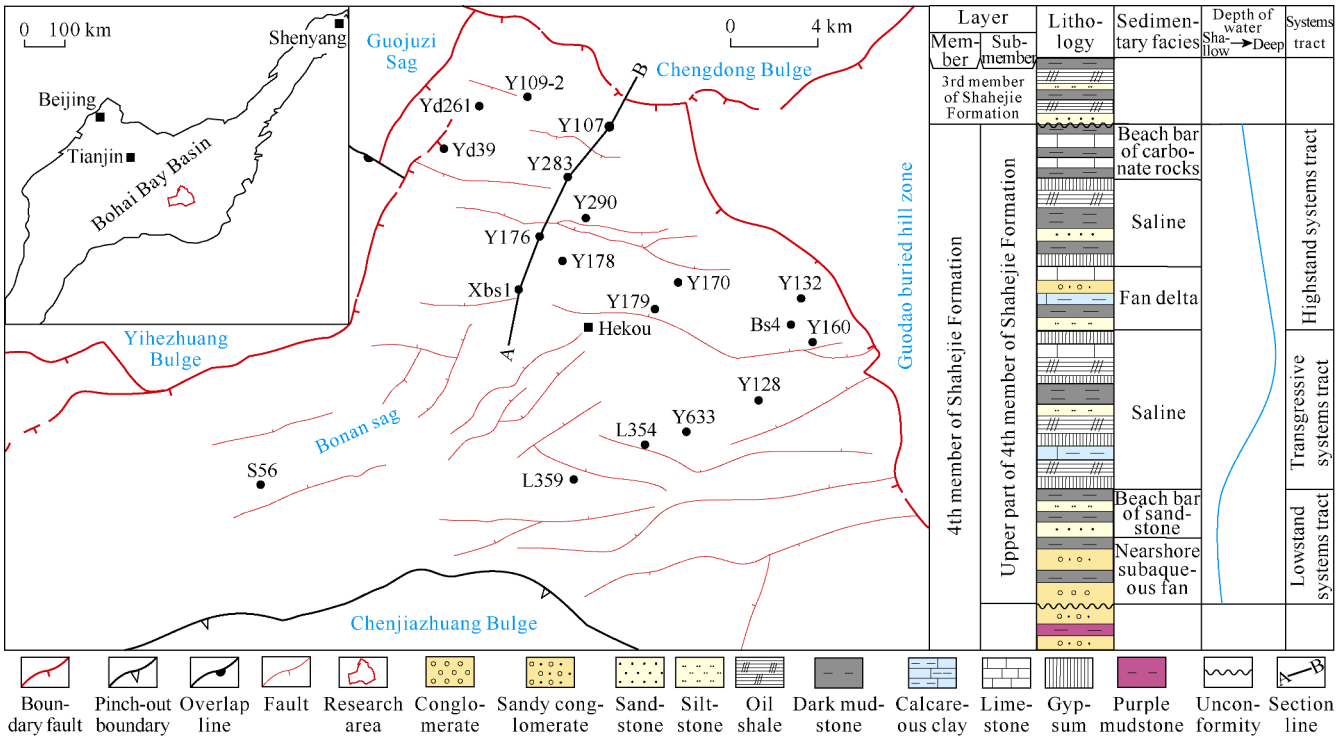

Fig. 1. Location of Bonan sag and composite stratigraphic columns of upper Es_4.