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Main factors controlling the formation of basement hydrocarbon reservoirs in the Qaidam Basin, western China

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A B S T R A C T

Basement hydrocarbon reservoirs are widely distributed worldwide. In recent years, a major breakthrough has been made in basement-rock hydrocarbon exploration in the Qaidam Basin, and basement-rock reservoirs have become important exploration targets in the basin. Basement hydrocarbon reservoirs are a special type of oil and gas reservoirs. This type of reservoir requires not only the same formation conditions as conventional hydrocarbon reservoirs but also some unique reservoir conditions. In this study, several geochemical, geophysical, and geological methods are used to assess the hydrocarbon accumulation conditions and mechanisms of the basement-rock reservoirs found in the Qaidam Basin, and the main factors controlling the reservoirs are proposed. Major hydrocarbon-generation depressions controlled the overall basement-rock reservoir distribution, paleo-uplifts (or paleo-salients) and paleo-slopes controlled the hydrocarbon migration directions, faults and unconformities controlled hydrocarbon-migration channel systems, and weathered-crust reservoirs of basement rocks controlled hydrocarbon enrichment. In addition, a suitable cap rock is an important requirement for preservation. Suggestions for future explorations have been put forward in this study, which will be of significance for guiding petroleum exploration in the area. Promising future exploration areas include the western part of the Kunbei fault-terrace zone in the front of the Kunlun Mountains, the paleo-uplift in the western part of the Altun Mountains front, and the Pingtai and the Mahai–Dahonggou paleo-uplift in the front of the Qilian Mountains.

1. Introduction

There is still no universal definition of basement hydrocarbon reservoir. As one example, the definition of basement rock in the “Dictionary of Geology” of the American Geological Institute is (1) igneous and metamorphic complex rocks that lie unconformably beneath sedimentary rocks and (2) the crust that is under sedimentary rocks, the lower limit of which is the Moho discontinuity. Most of the basement rocks are Precambrian, some are Paleozoic and Mesozoic, and some are Cenozoic (Bates and Jackson, 1987). Many definitions of basement hydrocarbon reservoirs have been proposed in China, falling into two types: one viewpoint states that basement rock is a crystalline basement and hydrocarbon reservoirs that formed in the igneous and metamorphic rocks of the crystalline basement are basement hydrocarbon reservoirs (Chen and Li, 1987; Gan, 1987), whereas the other viewpoint regards the basin development period as the standard and hydrocarbon reservoirs that formed in the sedimentary rocks before the formation of the basin or the crystalline basement are basement hydrocarbon reservoirs (Tong and Xu, 1987; Tian et al., 1987; Ma, 2011). Considering the geological background of the Qaidam Basin, the first viewpoint is adopted in this study.

Basement hydrocarbon reservoirs are widely distributed worldwide (Wu et al., 2014; Chen and Zhou, 2012; Sircar, 2004; Landes et al., 1960; Harris et al., 2002). Basement-rock reservoirs have been discovered in more than 30 basins globally, such as in paleo-platforms (e.g., North and South America), young platforms (e.g., western Siberia and western Europe), Mesozoic strata (e.g., the Vietnamese continental shelf), and young orogenic folds with intermontane depressions (e.g., Argentina and Venezuela). Basement hydrocarbon reservoirs are important petroleum exploration fields in China (Fan and Xie, 1985). In early 1957, industrial oil flow was obtained from the Carboniferous metamorphic basement in Keramay, which is located in the north western Dzungaria basin; in 1959, the Yaerxia Silurian metamorphic rock reservoir, a famous high-yielding field, was found in the western

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Jiuxi basin; during the 1960s and 1970s, as part of oil and gas explorations, a group of basement hydrocarbon reservoirs (Huanghua, Jiyang, Jizhong, Liaohe, and Bohai sea area) were successively discovered in the Bohai Bay Basin of eastern China. There are 61 known hydrocarbon reservoirs in the Bohai Bay Basin, and the area still has good exploration and development potential.

In recent years, basement-rock reservoirs have also been discovered in the Hailar basin (Ren et al., 2007), the Erlian basin (Jian et al., 2009), and the Qaidam Basin (Li et al., 2011; Chen et al., 2012a; Cao et al., 2013a, 2013b). More than 100 wells have reached the basement rock in the Qaidam Basin, mainly in the Yuejin No. II area on the hanging wall of the Alar fault, the Kunbei fault-terrace zone and Dongchaishan in the western depression; the Yuqia depression, and the Mabei, Nanbaxian, Dongping, and Niudong areas in the northern fault-block belt (Fig. 2). In these regions, commercial hydrocarbon flows have been obtained or good signs of oil and gas have been detected in the weathered crust of the basement rock in many wells.

From 2007 to 2010, during drilling in the Kunbei fault-terrace zone, an exploration breakthrough was made in the Q6, Q12, and Q16 well areas. High-yield oil and gas flows were obtained from the basement rock and industrial oil flows were also obtained from three appraisal wells in the Q4 well area. In 2011, the well Dp1 was drilled in the front of the Altun Mountains with a completion depth of 3227 m. A section of 3159.0–3182.0 m was tested by fracturing and high-yield industrial gas was obtained, with daily production of 1.12×10^5 m^3 through a 6-mm-diameter nozzle. This was the prelude to natural gas exploration in the Dongping area of the Qaidam Basin. Subsequent drilling confirmed that the gas reservoir is a blocky basement-rock reservoir that has a unified gas and water interface and a high gas column. The reservoir is the largest continental basement-rock gas reservoir in China (Ma et al., 2015). Hence, basement-rock reservoirs have become important exploration fields in the Qaidam Basin. In this study, an analysis of the mechanisms of hydrocarbon accumulation in the basement-rock reservoirs in the Qaidam Basin and the main factors controlling the reservoirs are proposed. On the basis of the results, future exploration directions are proposed, which will be useful for future oil and gas exploration in the area.

2. Geological setting

The Qaidam Basin with a total area of 121,000 km^2 is the largest intermontane basin of the northeastern Tibetan Plateau and contains Mesozoic and Cenozoic sequences of lacustrine sediments (Ke et al., 2013). The basin has an elevation mainly of 2500–3000 m above sea level, in contrast to the surrounding mountains, which rise to elevations of 4000–5000 m. The basin, which is an irregular rhombic basin, is constrained by four mountain ranges: the Qilian Mountains to the northeast，the Kunlun Mountains to the south, the Altun Mountains to the northwest, and the Elashan Mountains to the east. Tectonically, the basin is structurally bounded by three large fault systems (Fig. 1a): the South Qilian thrust belt to the northeast (Yin et al., 2002, 2008), the East Kunlun thrust belt to the south (Clark et a1., 2010; Chen et al., 2012b), and the left-lateral strike-slip Altun fault to the northwest (Yin et al., 2002). The 3D-structural pattern displays high-angle conjugate reverse faults, which can be interpreted as pop-ups or an impingement structure affecting both the crystalline basement and the Mesozoic–Cenozoic cover.

On the basis of the basement, stratigraphic distribution, style of structural deformation, details of basin evolution, and distribution of petroleum systems, in terms of structure, the basin can be divided into three tectonic units: the northern fault-block belt, the western depression, and the eastern depression (Fig. 1b).

The basin is filled with Mesozoic–Cenozoic sediments derived from the surrounding mountains. The sedimentary sequence is more than 16,000 m thick and lies on top of the pre-Mesozoic basement, which comprises metamorphic and igneous rocks (Fig. 1c). The Mesozoic Erathem in the basin contains Cretaceous (Quanyagou Formation) and Jurassic systems. The Jurassic System is divided from oldest to youngest into the Lower Jurassic Xiaomeigou Formation (J_1), the Middle Jurassic Dameigou Formation (J_2), and the Upper Jurassic Caishiling and Hongshuigou formations (J_3). Cenozoic deposition in the basin commenced during the Paleocene and was synchronous with the India–Asia collision. From the oldest to the youngest strata, the Cenozoic lithostratigraphic units present in the Qaidam Basin are the Lulehe (E_{1+2}), the lower member of the lower Ganchaigou (E_3^1), the upper member of the lower Ganchaigou (E_3^2), the upper Ganchaigou (N_1), the lower Youshashan (N_2^1), the upper Youshashan (N_2^2), the Shizigou (N_2^3), and the Quaternary Qigequan (Q1+2) formations. The sequence from the Lulehe Formation to the Shizigou Formation is of Tertiary age (Guo et al., 2014). The basin is an ideal place to study the tectonic uplift and the related climate and environmental change in the northeastern part of the Tibetan Plateau (Ke et al., 2013); consequently, the sedimentary record of this basin has attracted considerable attention (Zhong et al., 2004; Guo et al., 2004; Yin et al., 2008; Lu and xiong, 2009; Zhang et al., 2011; Song et al., 2013).

Source rocks are mainly black or dark gray, calcareous, and silty mudstones of Early Jurassic to Miocene age. In the northern fault-block belt, the source rocks are Lower Jurassic (J_1) and Middle Jurassic (J_2) strata; in the western depression, the main source rocks are the upper member of the lower Ganchaigou Formation (E_3^2) and upper Ganchaigou Formation (N_1; Fig. 1c).

The E_3^2 and N_1 hydrocarbon source rocks in the Zhahaquan depression in the western depression occupy an area of more than 2000 km^2 (Fig. 2). The organic carbon content is between 0.4% and 1.4%, with an average value of 0.85%. The organic matter is mainly type I and II, and the vitrinite reflectance (R_o) is between 0.5% and 1.1%, which is in the peak period of hydrocarbon generation. Thus, these rocks can provide a sufficient oil source for the Kunbei fault-terrace zone.

There were multiple depositional centers for the Lower–Middle Jurassic (J_{1+2}) sequence in the northern fault-block belt, such as the Pingdong, Kunteyi, Lenghu, Yibei, and Yuqia depressions (Fig. 2). The Yibei depression is the largest depositional center; the area of J_{1+2} strata with thickness greater than 300 m is 7500 km^2. The maximum thickness of this unit is nearly 2000 m. The burial depth of Lower Jurassic strata (J_1) in the Yibei depression is deeper (maximum depth more than 16,000 m), with a higher degree of evolution. R_o values are more than 1.3% and peak at 4.0%, which is in the dry gas stage. The second-largest depositional center is the Kunteyi depression, which has an area of 2500 km^2. The kerogen type is mainly II_2 and III, and the organic carbon content in the dark mudstone is between 2% and 2.5%. The vitrinite reflectance of the Lower Jurassic rocks (J_1) in this area is between 0.75% and 1.75%. The third-largest depositional center is the Pingdong depression, with a source rock area of 2000 km^2. In this area, the J_1 average thickness is approximately 300–600 m and the maximum thickness is more than 800 m. The kerogen is dominantly type III, the organic carbon content is between 1.5% and 3.5%, and the maturity is lower in the north and higher in the south. The highest R_o is more than 2.0%.

3. Methods and results

One geological section (Fig. 3) and four accumulation models of basement hydrocarbon reservoirs (Figs. 4–7) were constructed in the Qaidam Basin based on the interpretation of regional 2D seismic profiles in combination with geophysical, geological, and drill-hole data. Geological sections obtained from a balanced cross-section restoration provide a basis for the interpretation of the tectonic and sedimentary evolution during the Mesozoic and Cenozoic, and accumulation models of basement hydrocarbon reservoirs allow for the elucidation of the mechanism of reservoir formation.

The geochemical characteristics, origin, and source of natural gas of