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Research article

Preservation conditions for marine shale gas at the southeastern margin of the Sichuan Basin and their controlling factors

Hu Dongfeng*, Zhang Hanrong, Ni Kai, Yu Guangchun

Sinopec Exploration Southern Company, Chengdu, Sichuan 610041, China

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Abstract

Complex tectonic movements and high thermal maturity of marine shale dominate South China, where preservation conditions are critical for shale gas enrichment and productivity. Based on the exploration practices of the Silurian shale gas at the southeastern margin of the Sichuan Basin in recent years, conventional gas and shale gas were compared in terms of their preservation conditions. The results revealed that superior roof and floor conditions are indispensable to shale gas preservation. Moreover, the self-sealing ability and the huge gap of up to 2–8 times between vertical and lateral permeability of shale gas reservoirs determine the lateral diffusion as the basic pattern of shale gas migration. The unconformity at the bottom of Lower Cambrian leads to worse preservation conditions in the system, and cutting by faults may accelerate the diffusion of shale gas. Major controlling factors for shale gas preservation and their criteria of discrimination were also investigated. It is suggested that: (1) the strength of tectonic modification is the major factor controlling shale gas preservation. Broad and gentle structures with continuous seals and an anticlinal setting are more favorable for the enrichment of shale gas, and a closed evolutionary environment with late uplifting is more favorable for the preservation of shale gas; (2) shale gas can be preserved well in downdip areas without faults or effectively closed or shielded by faults and areas far away from outcrops or zones with stratigraphic hiatus; (3) pressure coefficient is a comprehensive indicator for discriminating preservation conditions. In the study area, the pressure coefficient is in positive correlation with shale gas production and the high or super-high pressure of reservoir is a signal of good preservation condition for shale gas; and (4) in the areas within the southeastern Sichuan Basin, other than those close to erosion zones or hiatus, the Wufeng Fm. of Upper Ordovician and the Longmaxi Fm. of Lower Silurian present high pressure coefficient (up to 2.25) generally, demonstrating good preservation conditions for shale gas, while the pressure coefficient reduces progressively toward or outside the margin of the basin, corresponding to downgrading preservation conditions.

Keywords: Sichuan Basin; Southeastern margin; Ordovician; Silurian; Marine shale gas; Conventional gas; Difference; Roof and floor conditions; Preservation conditions; Structural style; Pressure coefficient

1. Introduction

Compared with shale gas in the U.S., marine shale gas in South China has its unique characteristics. It has experienced complex tectonic movements like Caledonian, Hercynian, Indosinian and Himalayan, and the Lower Paleozoic marine shale series of strata was highly evolved. The exploration practices of Lower Paleozoic marine shale gas in the Sichuan Basin and its periphery show that marine mud shale has a favorable material basis, and has demonstrated universal gas show in drilling but obtained diverse results in gas production testing. More and more attention has been paid to the preservation conditions, which are generally believed as a key factor for the enrichment and high yield of shale gas.

Based on the exploration of Silurian shale gas at the southeastern margin of the Sichuan Basin, this paper discusses the main controlling factors for preservation conditions of shale gas, and presents the difference of preservation conditions between shale gas and conventional gas.

* Corresponding author.
E-mail address: hudf.ktnf@sinopec.com (D. Hu).
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2. Difference of preservation conditions between shale gas and conventional gas

Preservation conditions are also important in the conventional hydrocarbon exploration in South China. Numerous scholars have conducted thorough study [1−10], especially on the destruction of reservoirs in the following 6 aspects [1]: faulting-fragmentation, denudation, meteorological water infiltration, deeply buried thermal metamorphism, caprock effectiveness and natural gas leakage, and magmatic intrusion thermal metamorphism. Main parameters [2] for evaluating preservation conditions include caprock, tectonic movement, gasfield (reservoir) formation time, magmation, source-reservoir-caprock assemblage in time and space, source rock quality and reservoir pressure.

The preservation conditions of shale gas are somewhat similar to those of conventional hydrocarbons, but due to the characteristics of shale gas itself, the study on its preservation conditions is somewhat different from that on the conventional hydrocarbons.

2.1. Roof and floor conditions and shale gas preservation

Roof and floor conditions are the most different preservation conditions between shale gas and conventional gas. Roof and floor refer to the overlying and underlying strata directly contacting the gas shale interval. They play an important role in the storage of shale gas, and also affect the performance of shale fracturing. The roof and floor can be any rock like mudstone, shale, tight sandstone and carbonate, and their quality depends on physical properties and closeness. Such quality is critical to the preservation of shale gas − good roof and floor can form fluid compartment [11] together with the gas shale interval, effectively slackening the outward migration of shale gas and thus allowing the shale gas to be effectively preserved; whereas poor roof and floor has poor closeness to the fluid, in which case the petroleum is apt to be dissipated outward and thus the shale gas reservoirs are destroyed.

Two shale gas series of strata (Silurian and Cambrian) were explored at the southeastern margin of the Sichuan Basin, but success has been obtained only in Silurian. We believe that the difference in preservation conditions resulted from diverse roof and floor properties is one of the key factors influencing the shale gas exploration effect. According to the Silurian exploration, the roof of Upper Ordovician Wufeng Fm. − Lower Silurian Longmaxi Fm. Member I shale gas reservoir is a large set of gray − dark gray argillite intercalated by thin silty mudstone and siltstone developed in Longmaxi Fm. Member II and strata above it, with a thickness of about 170 m, and the floor is the gray knotty rock limestone, marlstone and limestone successively deposited in Upper Ordovician Jiancaogou Fm. and Middle Ordovician Baota Fm., with a total thickness ranging 30−40 m. The roof and floor of Wufeng Fm. − Longmaxi Fm. shale gas reservoir, regardless of mudstone, siltstone or limestone, are very tight and have a good sealing ability. For instance, the siltstone developed in the Longmaxi Fm. Member II in Well JY2 has an average porosity of 2.4%, average permeability of 0.001 6 mD, and formation breakthrough pressure of 69.8−71.2 MPa at 80 °C; whereas the rocks like gray knotty rock limestone successively deposited in Jiancaogou Fm. and Baota Fm. have an average porosity of 1.58%, average permeability of 0.001 7 mD, and formation breakthrough pressure of 64.5−70.4 MPa at 80 °C, which reflects that the roof and floor provide good seal for the Wufeng Fm. − Longmaxi Fm. Member I shale gas reservoir. As for Lower Cambrian shale gas interval, the roof is the upper Niutitang Fm. tight mudstone that has a good sealing ability, but the floor is the Sinian Dengying Fm. paleo-weathering crust. Tongwan movement resulted in the development of Dengying Fm. palaeokarsts and fractures in geologic history. Lower Cambrian shale gas ceaselessly migrated out through the Dengying Fm. unconformity oil and gas migration "speedway", and resulted in the destruction of shale gas reservoirs. For instance, Lower Cambrian high-quality mud shale is developed in Well TX1, but the floor is the Sinian Dengying Fm. paleo-weathering crust, and the post-frac effect is unsatisfactory.

2.2. Self-sealing ability of shale gas

Mud shale is a kind of tight pulveryte that often acts as the caprock of conventional hydrocarbons. Owing to the special occurrence mechanism of shale gas and the low porosity and low permeability of mud shale, shale gas accumulation doesn't require the same harsh preservation conditions as conventional oil and gas reservoirs. Mud shale has a sealing ability itself, and can act as the caprock of shale gas reservoirs. Especially for thicker mud shale, when the thickness exceeds the maximum range of hydrocarbon discharge at both top and bottom in the hydrocarbon generation peak stage of mud shale, gas will be effectively sealed in the mud shale itself.

Therefore, if mud shale has certain thickness itself, it can self-seal to trap some shale gases (which, however, do not always have industrial values). For instance, the Silurian is buried below 500 m in Well JY1, which achieved good oil and gas shows in drilling. Preservation conditions are seldom considered when shale gas plays are evaluated in North America, since the gas shale structure is stable and the shale gas can be trapped due to the shale's self-sealing ability.

Two mud shale samples were used to simulate and measure the permeability of Wufeng Fm. − Longmaxi Fm. mud shale in Well JY2 under confining pressure. As the buried depth increases, the pressure rises, and the permeability of the samples drops from 2.675 4 mD and 0.707 8 mD to 0.071 3 mD and 0.004 1 mD respectively (Fig. 1), by two orders of magnitude, indicating a sharp reducing process of permeability of mud shale during sedimentation. Under deep-buried circumstances, according to microanalysis data, Lower Paleozoic marine mudstone has very low permeability and thus has self-sealing ability.

The breakthrough pressure of Longmaxi Fm. Member I gray black mudstone in Well JY4 is measured as 41.6 MPa,