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Research Article

Effect of pore structure on the seepage characteristics of tight sandstone reservoirs: A case study of Upper Jurassic Penglaizhen Fm reservoirs in the western Sichuan Basin

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Abstract

Tight sandstone reservoirs are characterized by complex pore structures and strong heterogeneity, and their seepage characteristics are much different from those of conventional sandstone reservoirs. In this paper, the tight sandstone reservoirs of Upper Jurassic Penglaizhen Fm in western Sichuan Basin were analyzed in terms of their pore structures by using the data about physical property, mercury injection and nuclear magnetic resonance (NMR) tests. Then, the seepage characteristics and the gas–water two-phase migration mechanisms and distribution of tight sandstone reservoirs with different types of pore structures in the process of hydrocarbon accumulation and development were simulated by combining the relative permeability experiment with the visual microscopic displacement model. It is shown that crotch-like viscous fingering occurs in the process of gas front advancing in reservoirs with different pore structures. The better the pore structure is, the lower the irreducible water saturation is; the higher the gas-phase relative permeability of irreducible water is, the more easily the gas reservoir can be developed. At the late stage of development, the residual gas is sealed in reservoirs in the forms of bypass, cutoff and dead end. In various reservoirs, the interference between gas and water is stronger, so gas and water tends to be produced simultaneously. The sealed gas may reduce the production rate of gas wells significantly, and the existence of water phase may reduce the gas permeability greatly; consequently, the water-bearing low-permeability tight sandstone gas reservoirs reveal serious water production, highly-difficult development and low-recovery percentage at the late stage, which have adverse impacts on the effective production and development of gas wells.

Keywords: Sichuan Basin; Late Jurassic; Penglaizhen Fm; Tight sandstone; Pore structure; Relative permeability experiment; Visual microscopic model; Gas–water two-phase; Seepage characteristics

Plenty of exploration and development practices and research results show that the complex seepage characteristics of tight sandstone gas reservoirs are the main factors influencing productivity and development of gas wells and the microscopic pore structures of reservoir rocks are the key factors influencing hydrocarbon accumulation and seepage capacity. In recent years, many scholars have been focusing on the pore structures of tight sandstone reservoirs and the seepage characteristics of gas and water. Gao Wanglai et al. [1–5] proposed that the seepage characteristics of fluids in tight sandstone reservoirs were controlled by many factors, such as physical property, pore structure and water saturation. When reservoir seepage mechanisms are analyzed, the impacts of pore structures and fluids should be considered. To some extent, these researches analyzed the effects of pore structures on seepage characteristics, but they could not describe authentically and visually the specific migration mechanisms of gas–water two-phase fluids in complex pore structures and

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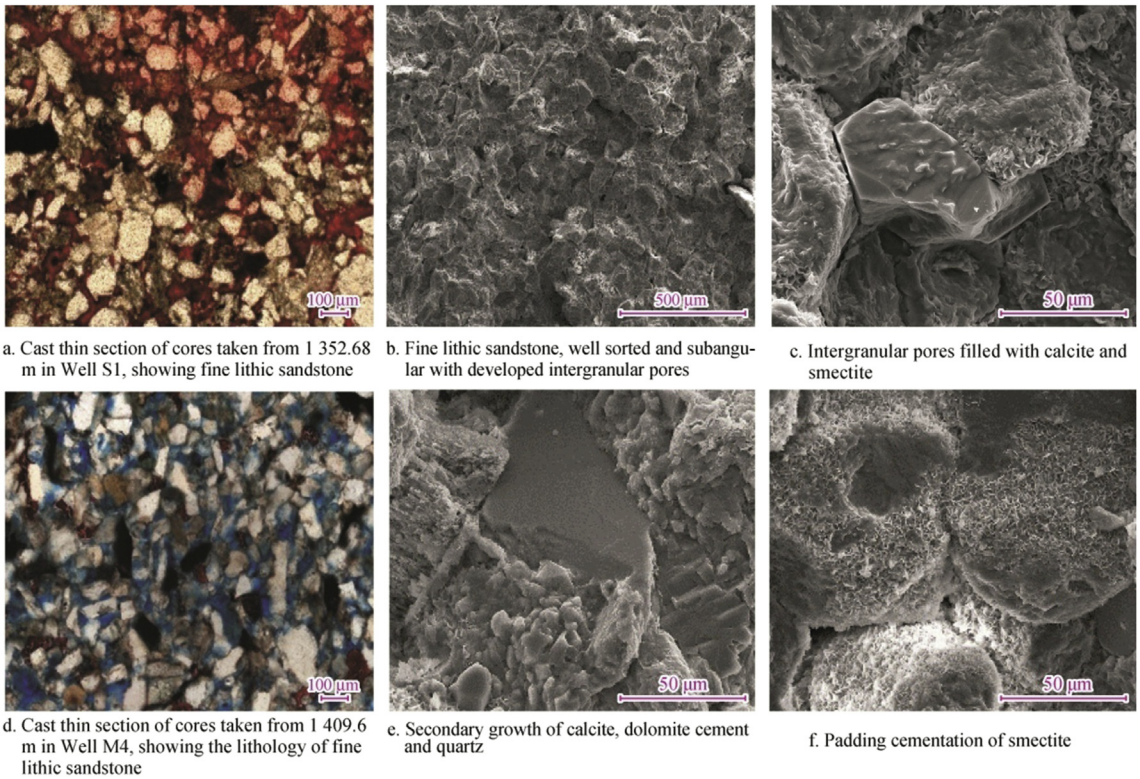
the ultimate distribution status of gas and water after their migration. Afterward, Fu Xiaoyan et al. [6–8] investigated the seepage characteristics of low-permeability oil layers by using the authentic sandstone microscopic model, which, however is poor in visualization capacity and can't describe effectively the complex two-phase seepage characteristics of low-permeability oil and gas reservoirs. Subsequently, Zhou Keming et al. [9–12] adopted the microscopic displacement model made of cast thin section to explore gas–water two-phase seepage characteristics. This model is of strong visualization capacity, so it, to some extent, is advantageous in analyzing gas–water two-phase migration and distribution characteristics. Generally, the current gas–water two-phase research based on microscopic model only describes the experimental phenomena simply, instead of analyzing the seepage characteristics based on the differences of pore structures effectively. In view of the complex characteristics of pore structures in tight sandstone, the effects of pore structures on seepage were analyzed by combining pore structure investigation and actual microscopic model, but gas–water two-phase migration mechanisms and distribution situations were still less analyzed.

In this paper, reservoir pore structures are investigated for the tight sandstone gas reservoirs of Upper Jurassic Penglaizhen Fm in Majing–Shifang block in the western Sichuan Basin. Then, relative permeability experiments and visual microscopic displacement model are combined to analyze the effects of pore structures on gas–water seepage characteristics and clarify the flowing modes and occurrence states of gas–water two-phase fluids in different types of pore structures. In this way, it is expected to provide a scientific basis for the efficient development of gas fields in this block.

1. Characteristics of tight sandstone reservoirs

1.1. Lithology and physical properties

Cast thin section and its corresponding scanning electron microscope (SEM) pictures show that the Penglaizhen Fm gas reservoirs are lithologically composed of fine–medium fine lithic sandstones (Fig. 1-a, -d) and they are sorted well with subangular roundness (Fig. 1-b). Quartz is the main mineral and its average content is 64.93%. The content of debris and feldspar are 29.39% and 6.08%, respectively. Reservoir pores are mainly primary intergranular pores and intragranular dissolved pores (Fig. 1-b), as well as intergranular residual pores filled with smectite and calcite (Fig. 1-c). Cements include calcite and a little amount of dolomite and gypsum (Fig. 1-e). Cementation is mainly in the patterns of padding cementation of smectite (Fig. 1-f) and secondary growth cementation of quartz and albite (Fig. 1-e), and secondarily filling cementation of I/S mixed layer. The porosity is 2.82–15.26%, averaging 8.66%, and the permeability is 0.001–0.919 mD, averaging 0.125 mD. According to the sandstone gas reservoir classification standard [13], the Penglaizhen Fm sandstones in the western Sichuan Basin are assigned to low-porosity and low-permeability tight sandstone gas reservoirs.



a. Cast thin section of cores taken from 1 352.68 m in Well S1, showing fine lithic sandstone

b. Fine lithic sandstone, well sorted and subangular with developed intergranular pores

c. Intergranular pores filled with calcite and smectite

d. Cast thin section of cores taken from 1 409.6 m in Well M4, showing the lithology of fine lithic sandstone

e. Secondary growth of calcite, dolomite cement and quartz

f. Padding cementation of smectite

Fig. 1. Cast thin section of tight sandstone reservoirs and its corresponding SEM pictures.

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