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RESEARCH PAPER

Geological difference and its significance of marine shale gases in South China

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Abstract: Organic-rich marine shales are developed in both the Cambrian Qiongzhusi Formation and the Ordovician Wufeng Formation–Silurian Longmaxi Formation in South China, but are different in the drilling results of shale gas exploration. Comparing the differences in shale gas formation conditions between Qiongzhusi and Wufeng-Longmaxi has practical and theoretical significance. This study reveals: (1) in the Sichuan Basin, the Wufeng-Longmaxi Formation has slightly higher TOC than the Qiongzhusi Formation, whereas Qiongzhusi Formation has some local high TOC areas outside of the Sichuan Basin; (2) the Qiongzhusi Formation has much higher thermal evolution degree than the Wufeng-Longmaxi Formation; (3) with undeveloped organic pores, the Qiongzhusi Formation has a 1/3 to 1/2 porosity of the Wufeng-Longmaxi Formation; (4) Qiongzhusi shale has a lower gas content, only 1/2 of that in Wufeng- Longmaxi shale; (5) the Qiongzhusi Formation is mainly composed of siliceous shale and the silica is hot water origin, whereas the Wufeng-Longmaxi Formation consists mainly of calcareous siliceous shale and the silica is biogenic origin; (6) the Wufeng-Longmaxi Formation has overpressure, while the Qiongzhusi Formation is normal in pressure. The reasons for the differences are: (1) different sedimentary environments affect TOC and shale thickness; (2) the Qiongzhusi Formation is over-mature, which caused depletion of hydrocarbon generation, organic carbonization, porosity reduction, and gas content drop; (3) the bad roof and floor conditions of the Qiongzhusi Formation are not good for shale gas preservation; (4) Wufeng-Longmaxi Formation is located in the slope and syncline accompanied with overpressure, and is in favor of preservation and high production of shale gas; (5) the uranium content in the Qiongzhusi Formation is twice that of the Wufeng-Longmaxi Formation, which is the main reason of its higher thermal evolution degree. It is concluded that shale gas enrichment in the marine shale in South China requires favorable geological conditions: organic-rich intervals, moderate thermal evolution, rich organic pores, high gas content, good roof and floor preservation conditions, and moderate burial depth. The Wufeng-Longmaxi Formation has better shale gas enrichment conditions and higher resource potential, whereas the Qiongzhusi Formation has poorer shale gas accumulation conditions and limited favorable areas.

Key words: South China; shale gas; Cambrian Qiongzhusi Formation; Ordovician Wufeng Formation; Silurian Longmaxi Formation; shale gas enrichment; geological condition

Introduction

In South China, which covers 15 provinces/municipalities to the south of Qinling-Dabie Mountains, the Paleozoic marine organic-rich shales are widely developed. The Upper Ordovician Wufeng Formation-Lower Silurian Longmaxi Formation and the Lower Cambrian Qiongzhusi Formation are the most perspective shale plays. They have been included as key objects in basic geological study on marine shale and exploration practice[1–8]. Up to the end of 2015, four Wufeng Formation-Longmaxi Formation shale gas enrichment areas had been discovered in the Sichuan Basin, namely, Fuling, Changning-Weiyuan, Zhaotong, and Fushun-Yongchuan, with proven shale gas reserves of 5 441.29×10^8 m^3 (3 805.98×10^8 m^3 in Fuling, and 1 635.31×10^8 m^3 in Changning-Weiyuan). These areas has been successfully put into industrial development, and contributed a production of approximately 45×10^8 m^3 in 2015. In contrast, the Qiongzhusi Formation has demonstrated poor results in drilling and exploration, with gas show only locally, although it also contains organic-rich shale. As excellent resource rocks, the Qiongzhusi Formation and the Wufeng Formation-Longmaxi Formation are main gas contributors in Anyue gas field and Carboniferous-Permian gas field discovered in the Sichuan Basin, respectively[9–10]. Both of them have good hydrocarbon generation capability, but differ greatly in results of shale gas exploration. According to outcrops, core observation and test data, this paper

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describes the geological characteristics of Wufeng Formation-Longmaxi Formation and Qiongzhusi Formation shale gases in the Sichuan Basin and its periphery, and discusses their differences and relevant causes. In this way, the main controlling factors for marine shale gas enrichment are identified to guide the shale gas exploration potential evaluation and favorable area optimization. This is important in understanding China's shale gas exploration and utilization situations and prospects.

1. Comparison of shale gas accumulation conditions

Till the end of 2015, in South China, there were more than 450 shale gas wells drilled in the Wufeng Formation-Longmaxi Formation, with industrial gas flows in 230 wells, and over 40 wells drilled in the Qiongzhusi Formation (Fig. 1), with industrial gas flows in only four wells in the Weiyuan-Qianwei area in the Sichuan Basin which produced at low yield and only minor gas obtained in other areas (Table 1). Clearly, these two sets of formations are greatly different in shale gas exploration results.

Based on the outcrops, core observation and test data, the Wufeng Formation-Longmaxi Formation and the Qiongzhusi Formation are investigated for their geological characteristics of shale gas. They are variable vertically. In order to effectively reflect their geological characteristics of shale gas, this paper mainly deals with the organic-rich shale intervals on the basis of representative wells and field data. According to the comparison, these two sets of shale formations are greatly different in organic matter abundance, thermal evolution degree (R_o), porosity, gas content and pressure coefficient (Table 2).

1.1. Organic matter abundance

As shown in Table 2, the TOC value of Wufeng Formation-Longmaxi Formation is slightly higher that of Qiongzhusi Formation, and the latter is abnormally high locally. (1) Inside the Sichuan Basin, the maxiumum TOC vlaue of Wufeng Formation-Longmaxi Formation ranges from 5.1% to 6.8% with an average of 3.6%, while the maximum TOC value of Qiongzhusi Formation varies between 3.6% and 5.9% with an average of 2.9%. (2) In the periphery of Sichuan Basin, the TOC values of Wufeng Formation-Longmaxi Formation are lower than those inside the basin. The TOC value of Well Pengye1 ranges from 2.6% to 4.2% with an average of 3.2%. (3) In the Sichuan Basin and its periphery, the TOC values of Qiongzhusi Formation are similar and abnormally high locally. In southeastern Chongqing, northern Yunnan-Guizhou, western Guizhou and other regions, the maximum TOC values are 2.7%–8.0% with an average of 2.9%, similar to those inside the Sichuan Basin. In northwestern Hunan, the TOC values are abnormally high locally. Organic-rich shale in Well Changye 1 is 130 m thick and has the TOC value varying from 2.1% to 17.6% with an average of 9.8%, which might be related to hot water environment and local concentration of radioactive materials.

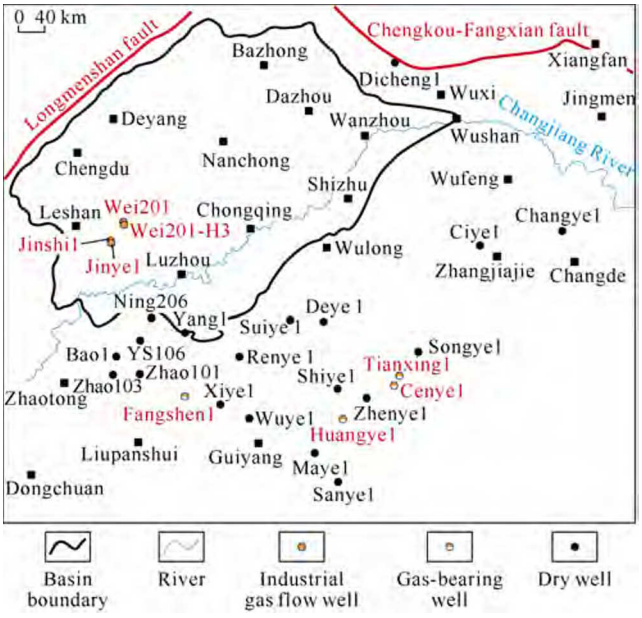

Fig. 1. Shale gas well distribution of Cambrian Qiongzhusi Formation in South China.

Table 1. Test production data for shale gas in Qiongzhusi Formation in South China

Area	Well	Initial test production/ ($m^3 \cdot d^{-1}$)
Inside the basin (Weiyuan-Qianwei)	Wei201	1.08×10^4
	Wei201-H3	2.83×10^4
	Jinshi1	2.50×10^4
	Jinye1	8.60×10^4
Outside the basin	Tianxing1	2 000
	Huangye1	420
	Fangshen1	20
	Cenye1	Minor gases

1.2. Thermal evolution degree of organic matter

The R_o values for source rocks with high evolution degree are measured by the laser Raman spectrum method. The thermal evolution degree of organic matter in natural solids can be obtained indirectly by the information of D and G peaks appeared in Raman scattering of such organic matter[11]. The peak separation and height ratios of G and D peaks tend to increase with R_o. The relevant matching formula has been proposed[11]. The Raman spectroscopy measurement for organic macerals indicates that the thermal evolution degree of Qiongzhusi Formation is obviously higher than that of Wufeng Formation-Longmaxi Formation (Fig. 2). The R_o value of the former ranges between 2.9% and 4.5%, generally 3.0% and 4.2%, in over-mature stage, and that of the latter varies from 1.9% to 3.55%, commonly 2.0% to 3.0%, in high-over mature stage. At similar burial depth, the R_o value of Qiongzhusi Formation is 0.7%–2.0% higher than that of Wufeng Formation-Longmaxi Formation (Table 3).