Study on Geological Characteristics of Typical Shale Gas Reservoirs in China

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Abstract. Shale gas is a kind of natural gas produced from a very low porosity and permeability, dark organic rich shale system. Compared with American shale, Chinese shale has a large amount of brittle minerals, with a brittleness coefficient of 46.15%, North America 38.27%, and China shale ratio as a whole Shale brittleness is better in America. This paper carefully analyzes the geological characteristics of typical shale gas reservoirs in China, analyzes the sedimentary environment and the distribution of organic shale, judges the characteristics of high-quality shale in the "dessert section", and evaluates the organic pores as the important reservoir space and preservation conditions for shale gas enrichment. Compared with the geological conditions of shale gas reservoirs in North America, the burial depth of China’s marine shale is 1500-5000m, and the best recoverable area of China’s marine shale is located at the structural edge with developed fractures.

Keywords: Shale Gas; Geological Characteristics; Gas Reservoir; Structure; Pore.

1. Shale Gas Development Status
Shale gas has become a new trend of energy economic development in various countries due to its wide distribution, clean, large reserves and environmental protection. Since the US began drilling shale gas wells in 1821, it has mainly experienced four stages: the first stage (1821-1978), the stage of occasional discovery of shale gas; the second stage (1978-2003), the stage of understanding shale gas accumulation mechanism, innovation and technological breakthrough; the third stage (2003-2006), the technical development from vertical wells to horizontal wells, and the promotion and application of hydraulic fracturing technology Stage 4 (from 2007 to now), shale gas globalization stage. See Figure 1.
2. Domestic Development Status

Since 1960s, natural gas has been found in mud shale of LongMaXi formation in Sichuan, Ordos and other basins in China. In 1966, 2.46×10^4 m^3 daily industrial gas flow was measured in the shale formation of the lower Cambrian in Sichuan Basin. Subsequently, in the shale formation of LongMaXi formation of Lower Silurian of Upper Ordovician, 3500 m^3 natural gas was obtained after acidizing. Chinese scholars began to pay attention to shale gas as a strategic energy source after 1980. Since 2000, based on the investigation of shale gas theory, drilling and fracturing technology in foreign countries, various petroleum units in China have carried out shale gas reserves and resource development potential evaluation in China from the review of old data and geological outcrop survey. In 2009, the Ministry of land and Resources launched the project of "shale gas resource potential and favorable area optimization in key areas of China", and drilled the first shale gas resource survey well in the practical sense in PengShui County, Chongqing. In 2011, the Chinese Academy of engineering carried out the research on "China's unconventional natural gas development and utilization strategy", and considered that China's recoverable shale gas resources were 10.50×10^{12} m^3, and proposed the development stage and regional map of China's shale gas. In 2012, the Ministry of land and Resources announced publicly that China's total shale gas resources are 134.42×10^{12} m^3, of which the recoverable resources are 25.08×10^{12} m^3. In terms of shale gas drilling, China's oil companies started shale gas exploration and investigation in 2009. In 2010, PetroChina drilled vertical well W201 in WeiYuan area, South Sichuan, and fractured shale gas in LongMaXi formation of Lower Silurian. In 2012, N201-H1 well was drilled in ChangNing area, and the daily production of shale gas was 15×10^4 m^3 from WuFeng Formation to LongMaXi formation, which was the first breakthrough in shale gas exploration and industrial development in China. In November of the same year, Sinopec drilled JY1HF well in JiaoShiBa area, FuLing, Southeast Sichuan Province, and tested the strata from WuFeng Formation to LongMaXi formation to obtain 20.3×10^4 m^3 / D shale gas. By the end of 2017, FuLing shale gas field has proved the geological resource reserves of shale gas of 6000×10^8 m^3, and has built up a shale gas field with a total production capacity of 100×10^8 m^3. At present, the annual production of shale gas can reach 60.4×10^8 m^3.

Subsequently, Sinopec has successively obtained shale gas industrial gas flow from WuFeng Formation to LongMaXi formation and QiongZhuSi formation in WeiYuan RongXian, RongChang YongChuan, DingShan and other areas of Sichuan Basin. New exploration and discovery of continental shale gas are obtained in ZiLiuJing formation and XuJiaHe Formation in FuLing, YuanBa, JianNan and other areas of Sichuan Basin. PetroChina has formed mature shale gas development bases in WeiYuan, ChangNing and other areas to the south of Sichuan Province, with proven shale gas geological resource reserves of more than 3000×10^8 m^3.

The geological survey of shale gas was carried out by China Geological Survey Bureau in the unconventional oil and gas exploration areas in Central China, such as Hunan and Hubei, and new atmospheric shale gas discoveries were made in the lower Cambrian and Silurian strata of YiChang. By the end of 2016, China's shale gas exploration and development has completed 24760km 2D earthquake, 4013km^2 3D earthquake and 1161 wells. Four shale gas development bases, FuLing, WeiYuan,
ChangNing and ZhaoTong, have been formed in Sichuan Basin. By the end of 2017, China's total proved geological shale gas reserves exceed $1 \times 10^{12} \text{m}^3$.

Based on the data investigation of drilling shale gas wells, Chinese scholars successively put forward the "binary enrichment" law of marine shale gas in complex structural areas, "structural dessert" and "continuous dessert area" shale gas enrichment mode. With the gradual maturity of exploration and development technology, exploration and evaluation technologies such as dessert evaluation and target optimization in marine shale gas area are also gradually mature, and shale gas technologies such as geological description of shale gas reservoir, shale gas productivity evaluation and development optimization are preliminarily formed; safe, efficient and fast drilling of horizontal wells, cluster perforation of pumping bridge plug, staged fracturing, synchronous fracturing and zipper fracturing. With the development of technology and technology, the company has the technical ability to develop shale gas with a scale of 3500m in shallow sea; the mountain well factory operation mode has been formed, which greatly improves the construction efficiency. Compared with single platform and single well drilling, the drilling and well construction period has been shortened year on year More than 30%; supporting the formation of waste residue, waste liquid and waste gas recycling, harmless treatment of cleaner production technology system. In the research and development of key fracturing equipment, domestic units have developed and localized 3000 fracturing trucks with independent intellectual property rights, formed a technical series of integration of research and development, test and manufacturing of domestic high-power fracturing units, independently developed domestic fracturing tools such as open hole packer and bridge plug, and realized commercial production.

3. Geological characteristics of shale in China

Shale gas exploration and development belongs to unconventional natural gas. It needs to drill horizontal wells and carry out staged fracturing to artificially transform shale reservoirs, so as to obtain the maximum natural gas flow. Shale gas reservoir is characterized by continuity, self generation and self storage. The geological evaluation system of shale quality includes two aspects: (1) evaluation of shale gas bearing parameters, including TOC, porosity, organic matter type, gas content, maturity, etc; (2) as shale gas production is closely related to fracturing, fracturing evaluation has become another very important evaluation content in shale gas geological research. The understanding of shale gas by Chinese geologists has experienced a continuous development process. In the early stage, learn from North American experience and focus on shale quality evaluation. Through the summary of exploration practice,

3.1. Sedimentary environment and process control the distribution of organic rich shale

Global shale gas exploration and development practice shows that in order to obtain high production of marine shale gas, it is necessary to have a certain continuous thickness of organic rich shale (TOC value greater than 2%). At the beginning of the study, Chinese scholars focused on the study of source rocks, and made a lot of researches on the origin, distribution and development of source rocks. Until 2009, Chinese researchers identified seven favorable sedimentary facies developed by four sets of marine source rocks, i.e. lower Cambrian, Upper Ordovician Lower Silurian, lower Permian, and Upper Permian. They summarized these seven favorable sedimentary facies into three models, and comprehensively analyzed the temporal and spatial distribution of TOC, $R_0$ and other important parameters of source rocks.

3.2. Characteristics of high quality shale in "dessert section"

Compared with other small layers, No. ①-③ of WuFeng LongMaXi shale gas "sweet spot section" has the following characteristics:

(1) High organic carbon content

In LongMaXi formation, the average content of organic carbon is more than 3%. According to the statistics of organic matter composition of ①—③sublayer in JiaoShiBa, YongChuan, WeiYuan and other areas, the organic matter of shale is mainly composed of non animal detritus organic matter such
as phytoplankton, suspected source, bacteria and solid asphalt, accounting for 70% - 80% of the total micro component; animal detritus accounts for 20% - 30%, in which graptolite accounts for more than 90% of the animal detritus, and the rest are chitinacea, etc. The average TOC is less than 2% in the shale, and the organic macerals are mainly animal clastic (graptolite, chitinacea, etc.), accounting for 47% - 76% of the total macerals, while the non animal clastic organic matter accounts for 24% - 53%.

(2) High siliceous content

The average siliceous content of ①—③ sublayer is about 60%. There are a large number of siliceous radiolaria and siliceous sponge spicules distributed in the shale, and the highest content of Radiolaria is 30%. The content of Radiolaria is up to 30%. The content of biogenic quartz accounts for 67% - 90% of the siliceous content. The average siliceous content of other small shale layers is 42% - 53%, and the siliceous is mainly composed of clastic quartz.

(3) High porosity

The pore type of ①—③ shale is mainly organic matter, accounting for more than 50%. The average porosity is more than 5%, and the average pore diameter of matrix is more than 7nm. CT scan of black siliceous shale with TOC value of 5.89% in small layer (see Fig. 2-a), the reservoir space is mainly organic pores, mainly medium-sized Nanopores with 30 nm, with good connectivity between pores, with porosity of 5.06%.

(a) And 1.27% TOC value of silty shale (b) CT scanning photos

Figure 2 Scanning Map of Black Siliceous Shale

3.3. Organic matter pore is an important reservoir space for shale gas enrichment

With the promotion and development of Nanotechnology, shale gas reservoir research has entered the era of Nano scale. A large number of Nano scale pores are distributed in shale organic matter, which scholars call organic matter pores. This discovery is recognized as evidence of the "source reservoir integration" characteristics of organic shale. In recent years, the shale gas exploration from WuFeng Formation to LongMaXi formation has found that the porosity and gas content of shale organic matter are important factors for single well production, and scholars regard it as one of the important parameters for judging single well high production of shale gas. Many domestic scholars have obtained the following knowledge through a large number of data statistics and research: (1) there are two types of organic matter pores: primary and secondary, and the development of secondary organic matter pores is heterogeneous; (2) the formation of organic matter pores is mainly controlled by thermal evolution, and it is found that the development degree of organic matter pores depends on the physical properties of organic matter.

3.4. One of the key factors for geological evaluation of shale gas in complex structural area is preservation condition

The pressure coefficient of shale gas reservoir is one of the important parameters for shale gas dessert evaluation. Many years of exploration and development in shale gas in China have found that shale gas with a reservoir pressure coefficient of > 1.2 has achieved high production. Whether a shale gas reservoir is well preserved can be judged by pressure coefficient, and overpressure formation indicates that the
sedimentary environment of shale gas reservoir is good. In the case of no drilling, relying on seismic and geophysical technology to predict the pressure coefficient of shale gas reservoir is still at the beginning stage, a large number of domestic and foreign scholars have found out, and have made the following common understanding: (1) shale self sealing and roof and floor conditions; (2) deep burial, uplift, fracture and fracture of structure.

3.5. Seepage characteristics of shale gas
Through the combined determination and analysis of mercury injection and liquid nitrogen adsorption on the shale samples of JY1 well, it is found that the Nano pores of shale reservoir are mainly micro Nano pores and medium Nano pores, while the large Nano pores are relatively undeveloped, and the pore diameter is mostly less than 20 nm. Shale gas exists in various forms, including free state, adsorbed state and dissolved state. The ratio of free gas and adsorbed gas is 6:4. Shale gas belongs to unconventional natural gas, which does not conform to Darcy's seepage law and the relationship between pressure and cumulative production. Its production characteristics are linear relationship between pressure and cumulative output at high pressure and nonlinear relationship at low pressure.

4. Differences at home and abroad
Shale gas in North America mainly occurs in marine shale, but in China, marine, transitional and continental shale are mainly developed. The types of marine shale organic matter in China and North America are mainly type I or type II. The age of marine shale in China is longer, buried deeper (1500-5000m), and thermal maturity is higher. The RO value is 2.0% - 3.5%. The reservoir forming conditions are more complex. After several periods of irregular structural movement, multiple natural fracture systems are generated, resulting in poor preservation conditions, more difficult exploration and development, and more risk High. The buried depth of continental shale in China is larger, but its thermal maturity is low, and the RO value is only 0.4% - 1.3%. The brittleness coefficient of shale reservoir in China is as high as 46.15%, while that in North America is only 38.27%.

Compared with American shale, Chinese shale has poor geological condition ratio, marine shale has a long history and high thermal maturity, while continental shale has a new era and low maturity, most of which are in the stage of oil generation window. China's shale gas exploration and development has roughly gone through three stages: the first stage (2003-2008), learning from foreign mature theories and technologies; the second stage (2009-2012), the stage of formulating the selection evaluation method and exploration well implementation plan; the third stage (2013-now), the stage of large-scale development. Since 2013, shale gas fields such as FuLing, WeiYuan, ChangNing and QiRong have been discovered and developed in the south of Sichuan Basin. By the end of 2018, China's total proved geological reserves of shale gas were 10455.67×10^8 m^3, including economic recoverable reserves of 1313.29×10^8 m^3 and cumulative gas production of 335.24×10^8 m^3. As the geological resource of shale gas in China is (83.3-166.0)×10^12 m^3, and the technical recoverable resource is (10.0-36.1)×10^12 m^3, China is rich in shale gas resources in general, and has become the largest shale gas producer except for the United States.

5. Conclusion
(1) The vertical depth of marine shale in China is 1500-5000m. The marine shale from the WuFeng Formation to the LongMaXi formation is older than most of the shale in foreign countries, so the shale stratum is deeply buried, and only part of the uplift area and marginal zone of the basin are shallowly buried. This increases the difficulty and risk of exploration for drilling, and puts forward higher requirements for production technology. On the other hand, the deeper the pressure is, the greater the shale gas resources are.

(2) The geological structure of marine shale in China is complex and changeable, and fault zone and fold zone are developed. Two sets of organic rich shale were deposited in the Paleozoic, and then underwent a series of structural evolution from Mesozoic to Cenozoic, which had an important impact on the preservation conditions and environment of shale gas reservoir. With the continuous evolution of
tectonic movement, the basin will be reconstructed on a large scale, and a natural fracture system will be formed at the same time.

(3) At present, the marine shale gas developed in China is mostly located in the areas with relatively shallow burial depth at the edge of the basin. These areas are mainly mountainous and hilly areas with crisscross gullies. The rugged surface environment and fragile ecological conditions bring difficulties to the well pad, pipeline construction and fracturing construction, and increase the difficulty of shale gas overall development.

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