

# Petrological characteristics and shale gas accumulation model of Wufeng-Longmaxi Formation in western Chongqing area

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## Abstract

In order to analyze the petrology characteristics and shale gas accumulation model of Wufeng-Longmaxi Formation in the western Chongqing area, a series of analyses were carried out for the typical well A1 in this area, and the petrology characteristics of the Wufeng-Longmaxi Formation in the western Chongqing area were reported and the shale gas accumulation model was analyzed. The conclusions are as follows: (1) The shale mineral components of Wufeng Formation and Longmaxi Formation in the western Chongqing area are mainly quartz and clay minerals. Reservoir space types include primary pores, secondary pores and a few micro-fractures. (2) The top and floor of the main shale gas layer of Wufeng Formation and Longmaxi Formation are compact rock strata with low porosity and low permeability, and the top and floor tight rock strata have large thickness and stable distribution, and their stress is slightly greater than that of shale gas reservoir, which has good capping and blocking performance for shale gas reservoir. (3) Shale gas Wells deployed in "broad and gentle syncline" have better production. This type of gas reservoir is influenced by multiple factors such as structure, tectonic stress, fault and overburden, and can be defined as "residual synclinal and fault slope type" shale gas accumulation model.

## Keywords

Sichuan basin, Wufeng-Longmaxi Formation, West Chongqing area, Shale gas accumulation.

## 1. Introduction

A continuous deposition of organic-rich dark shale occurred during the Late Ordovician and Early Silurian periods in the Sichuan Basin. The lower part of this formation, known as Wufeng-Longmaxi Formation, has emerged as China's most successful system for shale gas exploration and development. Currently, the cumulative proven geological reserves of shale gas in Changning-Weiyuan, Fuling, and Zhaotong national shale gas demonstration zones exceed  $17,000 \times 10^8 \text{ m}^3$ , with a cumulative gas production exceeding  $300 \times 10^8 \text{ m}^3$ . Large-scale beneficial development of shale gas has been achieved in the Upper Ordovician Wufeng Formation and Lower Silurian Longmaxi Formation, while exploration and development of deep shale gas have also commenced in recent years[1-3]. The shales within the Wufeng Formation and Longmaxi Formation in the Sichuan Basin have generally undergone complex tectonic movements. Influenced by deep burial and intense uplift, most areas exhibit a burial depth greater than 3,500 m for organic-rich marine shales; moreover, the extent of deep shale areas can reach up to  $12.8 \times 10^4 \text{ km}^2$ —twice that of middle-shallow shales[4]. Therefore, focusing on the deep shales within the Wufeng-Longmaxi Formation in western Chongqing as our research subject matter allows us to establish an accumulation model for these deep dark shales—a valuable

contribution towards enhancing our understanding and methodologies related to enriching deep shale gas resources—and provides support for future exploration and development endeavors targeting China's vast reservoirs.

## 2. Geological setting

The West Chongqing area is located in the southeast of Sichuan Basin, spanning Sichuan Province, Chongqing and Guizhou Province. The strata in the area are well developed. The shallow metamorphic rocks of the former Sinian Banxi Group are the sedimentary basement [5]. The Sinian-Middle Triassic in this area is a Marine sedimentary stage dominated by carbonate rocks with many sets of mud, shale and a small amount of sandstone and siltstone. The upper part of Silurian system is heavily denuded and unconformable with the bottom of Permian system. The top of the Middle Permian Maokou Formation is denuded, and there is unconformity contact with the Upper Permian Wujiaping Formation. The Middle Triassic Leikoupo Formation suffered denudation and was in unconformable contact with the Upper Triassic. The Late Triassic to Quaternary is a continental sedimentary stage dominated by sandstone and mudstone. The Jurassic is in unconformity contact with the Upper Triassic Xujiahe Formation, and the Cretaceous is in unconformity contact with the lower Jurassic. In addition, unconformity surface is occasionally developed within each layer. The fold deformation in this area is intense and complex tectonic movement has occurred in multiple periods [6-7]. The secondary tectonic belt in the region is a "narrow and steep anticline, wide and gentle syncline" interlocking fold assemblage pattern, and 4 groups of NE-SW long axis anticline belts and 4 groups of NE-SW broad syncline belts are developed. They are Banqiao syncline, Laisu-Yunjin syncline, Linjiang syncline, Guangpu-Huguosi syncline, Xishan-Xindianzi anticline, Dongshan-Huangguashan - Qianziba anticline, Xiwenquan - Huaguoshan - Liuhechang anticline, Wennan - Linfengchang - Tanghe anticline. The Luzhou Palaeouplift is a compressed-superposition palaeouplift developed in the craton. Its formation and evolution history almost run through the whole Triassic period, and it has obvious stage characteristics. The formation is closely related to the orogeny of South China Plate in the IndoChinese Period, and is mainly due to the remote transfer effect from the squeezing stress of Xuefeng orogenic belt in Jiangnan to the northwest direction. As a result, the main body of Luzhou palaeohigh struck northeast and expanded to northwest and southeast. The late Luzhou Palaeohigh was subjected to extensive superposition transformation, and the strata on the west flank of the palaeohigh were well preserved, characterized by a NW trending monoclinical structure. The strata on the eastern flank of the palaeouplift were subjected to late multi-lateral tectonic extrusion, and fault-related folds were mainly developed. The uplift core area was involved in the tectonic deformation belt in southeast Sichuan, and the original form of the ancient uplift was destroyed. The west Chongqing area is mainly located in the southwest of Luzhou palaeouplift.

## 3. Petrological characteristics

The mineral components of the shale of Wufeng-Longmaxi Formation in western Chongqing area are mainly quartz and clay minerals. The quartz content ranges from 23.3 to 72.5%, with an average of 47.4%. The content of clay minerals ranged from 13.1 to 44.9%, with an average of 27.8%. The average carbonate mineral is 15.2%, and the content of plagioclase is mainly distributed between 1.6% and 10.8%, with an average of 5.4%. The average content of potassium feldspar is only 0.8%, which is because most of the potassium feldspar is transformed into illite clay minerals in the diagenetic process. The quartz mineral content tends to increase with the increase of burial depth, while the clay mineral content tends to decrease with the increase of burial depth. Among the clay minerals, the content of illite is the highest, ranging from 47% to 92%, with an average of 66.85%. Chlorite content ranges from 0 to 21%,

with an average of 13.23%. The content of the mixed layer is close to that of chlorite, ranging from 4% to 37%, with an average of 19.9%.

The reservoir space types of shale reservoirs in Wufeng-Longmaxi Formation in western Chongqing area include primary pores, secondary pores and a few micro-fractures. The primary pores mainly include intergranular pores and intragranular pores. The secondary pores are mainly intergranular pores, intragranular pores and organic pores. Based on the core fracture observation of typical Jingwufeng Formation and Longmaxi Formation in western Chongqing area, it is concluded that high Angle fractures and vertical fractures are rare, while horizontal fractures are relatively developed. Only the small high-angle and vertical joints were seen locally, and the whole was not developed. The horizontal bedding fractures in the whole well section are developed in each small layer, with less calcite and quartz filling.

## 4. Shale gas accumulation characteristics

### 4.1. Reservoir forming

Wufeng Formation-Longmaxi Formation is a self-generated gas reservoir, in which Wufeng Formation-Longyi 1 sub-member is the main production layer, and its core sample average TOC is 3.5%, which belongs to the high-quality source rock segment. Meanwhile, Wufeng Formation-Longyi 1 sub-member is also a high-quality shale gas reservoir segment. According to the test results of core samples, the reservoir space types of the Wufeng-Longmaxi Formation include primary pores, secondary pores and a few micro-fractures, with pore sizes ranging from 0.4 nm to 170 nm. The organic pores are dominated by micropores (< 2 nm) and mesoporous pores (2-50 nm), while the inorganic pores are dominated by macropores (> 50 nm). The average porosity is 5.9%. The average permeability of the matrix is  $0.41 \times 10^{-3}$  mD, and the overall physical property of the reservoir is good, which is conducive to oil and gas accumulation. In addition, there are good gas measurements in the main production interval, the highest gas measurement value is 5.28%, and the gas components are mainly methane, and the highest methane content can reach 98%. According to the classification and evaluation standards of shale gas reservoirs, the typical well A1 in this area accounts for 25.11% of first-class reservoirs and 43.94% of second-class reservoirs. Therefore, Wufeng-Longmaxi Formation can not only be regarded as a superior source rock segment, but also a good reservoir segment.

Thick gray, dark gray mudstone and gray mudstone developed from Longer Formation to Shiniulan Formation in western Chongqing, with a thickness of more than 500 m, which has good capping ability and can be used as a high-quality regional capping layer of shale gas reservoir in Wufeng Formation and Longyi member. This set of strata can also be called the indirect roof of Wufeng Formation and Longyi 1 sub-member, the main production layer of shale gas. The thick tight shale of Longyi-2 submember is directly overlaid by Longyi-1 submember. This set of strata can be called the direct roof of the main production layer, and its rock porosity is 1.2% ~ 2.4%. The underlying layer (floor) of the shale gas reservoir is continuously deposited in the Ordovician Baota Formation, with a deposition thickness of about 40m. Its lithology is continuously deposited gray nodular marl with hard and brittle texture, which is in an integrated contact relationship with the shale gas reservoir. The porosity of the floor rock is about 0.11% ~ 1.5%. The roof and floor of the main shale gas layer of Wufeng Formation and Longyi 1 sub-member are compact rock with low porosity and low permeability, and the dense rock thickness and stable distribution of the roof and floor are slightly greater than the shale gas reservoir, which has good sealing and partition performance of the shale gas reservoir. Good sealing layer conditions form the roof and floor of the shale gas reservoir of Wufeng Formation and Longyi member. In the process of shale gas reservoir formation and multi-stage structural transformation, good roof and floor conditions have a good sealing and

preservation effect on shale gas reservoirs[8], effective plugging of shale gas reservoirs is conducive to the rich accumulation and occurrence of shale gas.

#### 4.2. hydrocarbon accumulation mode

During the sedimentary period of the Wufeng-Longmaxi Formation, the Sichuan Basin was in a tectonic setting surrounded by uplift on three sides, and the whole basin had poor connectivity with the offshore sea, forming a shallow shelf sedimentary environment of relatively deep water, dominated by muddy sediments and rarely bioturbated. Sedimentation includes undercurrent deposition, storm deposition, biological deposition and suspension deposition.

Two major transgressions occurred during the Wufeng-Longmaxi Formation. The first occurred in the early sedimentary stage of the Wufeng Formation[9]. Due to the influence of transgression, the sedimentary environment changed from oxidation to anoxic/oxygen-poor conditions, and a set of silicic shale developed under the joint action of biological deposition and suspended deposition. Due to the anoxic environment and the low sedimentation rate caused by the poor flow of water occlusion[10], organic matter is preserved and has a high TOC content. In the middle and late sedimentary period of Wufeng Formation, the Hernandtian glaciation began, the global temperature dropped sharply, and the rapid growth of glaciers in Gondwana continent of Antarctica led to a significant decrease in global sea level, and a relatively semi-closed and retained sedimentary system was formed in the study area. At this stage, due to the shrinkage of the water body, the concentration of nutrients increases sharply, the primary productivity increases greatly, and the whole water body has become an oxygen-poor saturated retention water body. The decrease of sea level led to the increase of terrigenous debris supply, but in the middle stage, the shale deposition rate was slow, the temperature decreased, and a large number of organisms were extinct and buried, forming a set of organic and calcareous siliceous shales. Since the ice age of Gondwana ancient land began in the deposition period of Guanyinqiao Member at the top of Wufeng Formation, the sea level fell and the water became shallower, and the allochthonic organisms were transported by storms on the sedimentary background of the shelf, thus forming the calcareous mudstone deposits containing shells. The Gondwana ice sheet melted in the early stage of the Longmaxi Formation, and the sea level soared rapidly due to the second transgression movement[11]. The deep-water shelf facies developed, which was an anoxic/oxygen-poor sedimentary environment, and a set of organic-rich siliceous shales were formed under the combined action of biological and suspended sediments.

During the sedimentary period of Ludan Stage, the overall tectonic pattern did not change much from the late sedimentary period of Wufeng Formation. Due to the warming of the climate, the glacier melts rapidly, the sea level rises greatly, and the famous global transgression event occurs. The sea level in the study area has risen rapidly and is in good contact with the outside pan-ocean. The upwelling of ocean currents has brought a large amount of nutrients, and organisms such as planktic algae and graptolites have flourished and reached an unprecedented high primary productivity. Due to the early and long-term closed and stranded environment, water body stratification with the outside pan-ocean water body occurs, and dissolved oxygen is consumed by a large number of biological death and oxidation decomposition, resulting in the anaerobic stage of the water body at this stage, and free H<sub>2</sub>S may still exist in some areas. From the late Rudanian stage to the early Ellonian stage, the overall lithofacies paleogeographic pattern hardly changed, but the sea level decreased significantly, the sea area became more closed, in a strongly closed state, the sedimentation rate increased significantly, and the clay minerals increased significantly, indicating that the terrigenous clastic material increased, the primary productivity of the ocean decreased, and black shale was deposited, mainly clayey siliceous shale and calc-siliceous shale. In the late Longmaxi Formation, i.e., the Ellonian sedimentary period, the sea level gradually dropped, and

the anoxic environment was destroyed due to the influence of underflow deposition. Siltaceous shale was included in the clayey shale segment, the deposition rate was relatively fast, and the sedimentary environment changed from anoxic/oxygen-poor to oxygen-rich, which made it difficult for organic matter to be preserved[12].

The structure of well A1 is located in the low steep fold belt in southern Sichuan, and the structural belt presents the characteristics of NE-SW distribution, "anticline narrow and steep, syncline wide and slow", and is arranged in rows and belts, with the characteristics of divergence from northeast to southwest. Well A1 is located in the "broad and gentle syncline". Affected by the compressive tectonic stress, the formation of Wufeng-Longmaxi Formation in Well A1 will form faults. Due to the direction of the tectonic stress, most of the faults formed are nappe reverse faults, which have good sealing property and also cause the formation to repeat. On one side of the fault, shale gas is affected by buoyancy and diffusion, and migrates to the high part of the structure, and is blocked by the reverse fault laterally, and the shale gas stays in the fault footwall. On the other side, shale gas escapes laterally along the syncline. Under the influence of the early Yanshan Movement and the late Yanshan movement and the early Himalayan movement, the footwall of the reverse fault developed a multi-stage complex micro-fracture network with relatively good physical properties, which is conducive to the reservoir reconstruction by fracturing. Because the gas reservoir of Wufeng-Longmaxi Formation in Well A1 is located in the syncline area, the gas source in the low part is limited, and the gas reservoir is smaller in scale than that in the high part. The Wufeng-Longmaxi formation gas reservoir in Well A1 is affected by multiple factors such as structure, tectonic stress, fault and overburden. According to the characteristics of well A1, the reservoir formation model of the shale gas reservoir in the Wufeng-Longmaxi Formation can be classified as "residual syncline-fault slope type".

## 5. Conclusion

Based on the systematic study of mineralogy of dark shale formations in Wufeng Formation and Longmaxi Formation of shale gas Wells in western Chongqing area and the analysis and discussion of shale gas accumulation characteristics, the following conclusions are drawn:

(1) The shale mineral components of Wufeng-Longmaxi Formation in western Chongqing area are dominated by quartz and clay minerals. Quartz minerals tend to increase with the increase of burial depth, and clay mineral content tends to decrease with the increase of burial depth. (2) The reservoir space types of the Wufeng-Longmaxi Formation shale reservoir in the west Chongqing area include primary pores, secondary pores and a few micro-fractures. The primary pores mainly include intergranular pores and intergranular pores. The secondary pores are mainly intergranular pores, intragranular pores and organic pores. (3) Under the influence of compressive tectonic stress, faults will be formed in the Wufeng Formation-Longmaxi formation. Due to the direction of tectonic stress, most of the faults formed are nappe reverse faults, which have good sealing property and also cause formation repetition. On one side of the fault, shale gas is affected by buoyancy and diffusion, and migrates to the high part of the structure, and is blocked by the reverse fault laterally, and the shale gas stays in the fault footwall. On the other side, shale gas escapes laterally along the syncline. The gas reservoir of Wufeng-Longmaxi Formation in the study area is affected by multiple factors such as structure, tectonic stress, fault and overburden. Therefore, the shale gas reservoir formation model of Wufeng-Longmaxi Formation can be defined as "residual syncline-fault slope type".

## References

- [1] X. H. MA. Enrichment laws and scale effective development of shale gas in the southern Sichuan basin[J]. Natural Gas Industry, 2018, 38(10):1-10.

- [2] X. H. MA. Natural gas and energy revolution: A case study of Sichuan-Chongqing gas province[J]. Natural Gas Industry, 2017, 37(1): 1-8.
- [3] X. H. MA. A golden era for natural gas development in the Sichuan basin[J]. Natural Gas Industry, 2017, 37(2):1-10.
- [4] X. S.GUO. The law of "dual enrichment" of Marine shale gas in Southern China: Knowledge on shale gas exploration practice of Longmaxi Formation in Sichuan Basin and its periphery [J]. Acta Geologica Sinica, 2014, 88(7): 1209-1218.
- [5] M. J. WANG. et al. Petroleum Geology of China (Volume 10), Sichuan Oil and Gas Area [M]. Beijing: Petroleum Industry Press, 1989.
- [6] C. N. ZOU, Q. ZHAO, H.Y. WANG, et al. The main characteristics of marine shale gas and the theory & technology of exploration and development in China[J]. Natural Gas Industry, 2022, 42(8): 1-13.
- [7] Y. Q. ZHU, X. Z. WANG, M. Y. FENG, et al. Lithofacies classification and its relationship with reservoir of the Lower Paleozoic Wufeng-Longmaxi Formation in the Eastern Sichuan Basin[J]. Lithologic Reservoirs, 2016, 28(5): 59-66.
- [8] J. WU, Z.Q. HU, J. XIE et al. Macromicroscopic occurrence mechanism of organic matter in shale of Wufeng-Longmaxi Formation, Sichuan Basin and its periphery [J]. Natural Gas Industry, 2018, 38(08): 23-32.
- [9] W. B. SU, Z. M. LI, Eddensohn F R, et al. Main controlling factors of spatiotemporal distribution of black rock series in Wufeng-Longmaxi Formation, South China and its enlightenment[J]. Earth Science-Journal of China University of Geosciences, 2007, 32(6): 819-827.
- [10] C. M. ZHANG, W. S. ZHANG, Y. H. GUO, Sedimentary environment of Longmaxi Formation in southeastern Sichuan-northern Guizhou and its influence on source rocks[J]. Earth Science Frontiers, 2012, 19(1): 136-145.
- [11] X. CHEN, J. Y. RONG, Z. Y. ZHOU, et al. The central Guizhou uplift and Yichang uplift at the Ordovician-Silurian boundary in the Upper Yangtze region[J]. Chinese Science Bulletin, 2001, 46(12): 1052-1056.
- [12] Y. K. GENG. Research on quality control factors of shale reservoir in Longmaxi Formation, Southeast Sichuan [D]. (Ph.D. China University of Petroleum (Beijing), China 2017.