CHEMICAL ENGINEERING TRANSACTIONS
VOL. 62, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Fei Song, Haibo Wang, Fang He

ISBN 978-88-95608- 60-0; **ISSN** 2283-9216
DOI: 10.3303/CET1762070

Shale Gas Reservoir Forming Conditions and Target Zone Optimization in Yongshun Block of Northwest Hunan

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In this paper, the reservoir forming conditions of shale gas in the Lower Silurian Longmaxi Formation in Yongshun Block of Northwest Hunan was studied based on the field outcrops, drilling and core data, and the analysis of the results of experimental tests conducted using microsection, scanning electron microscope, x-ray diffractions, magnetic resonance imaging, isothermal adsorption, etc. and taking the stratum, petrology, geochemistry and shale gas-bearing of the black shale as the priorities. And then, the target zone optimization was carried out. The researches show that in the Longmaxi Formation, the sedimentary environment of deep-water retention basin controls the development of organic-rich shale. The sedimentary thickness is within the range of 22.26~28.63m. The TOC content in the sample is mostly over 1.5%. The kerogen type is mainly I-type. The organic matter is in the early period of the overmature stage. The shale reservoir is rich in cyclopentasiloxanel and brittle mineral, which are in favor of the fracture formation and latter reservoir fracturing improvement. Many types of pores and cracks developed, forming sound shale gas reservoir space. The shale reservoir adsorption capacity is good, with the saturated adsorption capacity reaching 1.24~3.10m^3/t and the average saturated adsorption capacity amounting to 2.11m^3/t. It has a linearly positive correlation with the TOC content. The parameter well signifies a relatively high gas content in the shale. The burial depth is appropriate and the effective exploration area reaches 540 km^2. Taking into comprehensive consideration the reservoir forming conditions, the core area of Longjiazhai syncline and Qing'anping syncline are selected as the shale gas exploration target area.

1. Introduction

Hunan is an energy deficient province known for its lack of coal, gas and oil. In recent years, a number of shale gas information wells have been completed in Northwest Hunan which well display the natural gas reserves (Qin et al., 2015; Zhou et al., 2014). Based on the results of early exploration, this paper conducts a systematic study on the forming conditions of shale gas in the Lower Silurian Longmaxi Formation in Yongshun Block of Northwest Hunan and the target zone optimization is carried out.

2. Geological Background

The tectonic location of the study area is in the fold belt of middle Yangtze Platform which belongs to Yangtze Paraplatform (South-east Edge) and Jiangnan Uplift (North-west Margin). The two is divided by the Baojing-Cili fault belts (Figure 1). The fracture movement in Northwest is relatively weak, and the structure is simpler; the Southeast features fold thrust structure. The structure in the block is relatively simple. Under the action of the Yanshanian tectonic movement, wide spaced synclinoriums were developed. From west to east, the synclinoriums consist of the Matizhai syncline, Yanjing anticline, Longjiazhai syncline, Shaba anticline, Qing'anping syncline, Hehu-Yaowan anticline, etc. trending in near-NS direction or north east-east direction. The syncline is open and no faults were developed; the anticline is closed, and relatively large-scale thrust faults or strike-slip faults were developed in the core area which is often severely denuded (Figure 1). In

Please cite this article as: Zhen Zhang, Wen Pang, Shifeng Tian, Hui Wang, Tongda Wang, 2017, Shale gas reservoir forming conditions and target zone optimization in yongshun block of northwest hunan, Chemical Engineering Transactions, 62, 415-420 DOI:10.3303/CET1762070

addition to the Carboniferous strata, the strata ranging from Sinian system to Triassic system also developed and exposed, and the Quaternary system is only distributed around Longjiazhai.

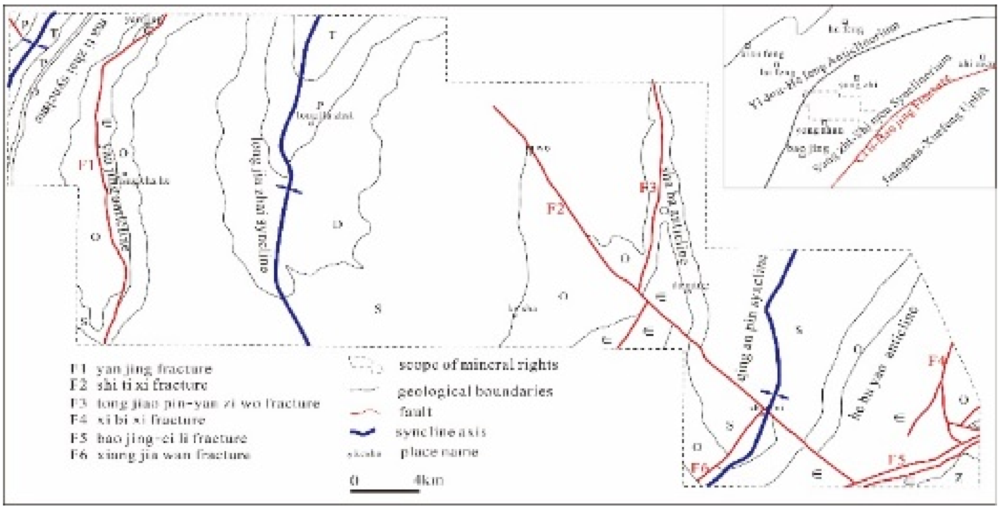

Figure 1: Structure outline map of block area

3. Shale Gas Reservoir Forming Conditions

The reservoir forming of shale gas is mainly controlled by many factors such as the shale lithology and thickness, organic geochemical index, reservoir porosity and permeability, brittle mineral content, air permeability, burial depth and preservation conditions (Lan et al., 2016; Nie et al., 2012)

3.1 Lithology and thickness

At the initial stage of early Silurian Longmaxi Formation, Northwest Hunan retained the relatively closed environment of deep water retention basin of Upper Ordovician and formed a set of deposits dominated by black shale. Brittle black siliceous rocks and siliceous shale are locally visible, and graptolite fossils are rich as well. After the metaphase of Longmaxi Formation, the input of lots of terrigenous materials made the water become shallow and the silty and chiltern increase. The color of the deposits turned grey and sage green, and no longer had hydrocarbon generation potential (Zhu et al., 2010)

Figure 2: Core and microscopic photos of Longmaxi Formation

(a) graptolite fossils in the grey and deep grey shale; (b) there is a heavy presence of graptolite fossils in the dark-gray to black shale section, which are densely distributed in a bamboo leaf shape; (c) horizontal beddings were developed in the black shale and silty shale and slight wave beddings are occasionally seen; (d) plane-polarized light; containing silt shale; (e) plane-polarized light; cloud and mud containing siltstone; (f) plane-polarized light; carbon and silt containing shale

The measured thickness of the field section of Longmaxi Formation was within the range of 22.26m~ 28.63m, with a tendency of gradual thickening from east to west. Yongye No.2 Well consists of ash black shale, black shale and silty shale. Horizontal bedding was developed and slightly wave-shape bedding is occasionally seen in the shales. The demethicone content is high. The shale is relatively pure, with sliding surface and sound brittleness. The fracture surface produced graptolite fossils (Figure 2 (a), 2 (b) and 2 (c)). Combining the outcrop, core, and experimental analysis, Longmaxi Formation can be further divided into three parts (Table 1)

Table 1: Lithologic Characteristic of Longmaxi Formation

Lithology	Color	TOC/%	Thickness/m	Pyrite	Demethicone	Carbon	Graptolite
Batt	ash black	<1.0	8~15	general	low	low	general
Silty Shale	black	1.0~2.0	10	fairly rich	low	low	fairly rich
Siliceous Shale	black	2.0~4.0	5~15	rich	high	high	rich

The lower part mainly consists of black silty shale. After identification under the microscope, it is found that the particle size is small and the shale content is high. There is a small amount of quartziferous silt particles and microfractures and a large amount of graptolite and pyrite (Figure 2 (d)); the middle part mainly consists of dark grey cloud siltstone and the content is about 66%-80%. According to the identification under the microscope, the size of the main particle reaches the silt level (Figure 2(e)). The component is mainly quartz. There is a small amount of feldspar; the argillaceous components account for about 10% and pyrite and graptolite are rich. The upper part mainly consists of dark grey mudstone. The particle size is found small after identification under the microscope and shale content is high. There is a small amount of quartzose silt granules and graptolite and pyrite (Figure 2 (f)).

3.2 Organic Geochemical Characteristics

The results (Figure 3 (a)) of the identification test of the kerogen maceral of five core samples from Longmaxi Formation in Yongye No. 2 Well show that the maceral is mainly composed of sapropel formation with a content of 89%~92%. Under the microscope, the amorphous body of sapropel is dominant, with cloud-shape or batt-shape appearance. Its profile curve is irregular since its center is thick and the edge is thin. Its color is mainly grey brown and black brown. It is transparent with no fluorescence. The vitrinite takes up 3%~9%. The histological features are vitrinite-like macerals with even texture, straight edges. They are fragmented and brown. There is no fluorescent light. The inertinite accounts for 1%~3% and the histological features are finely dispersed granules, which are dark and non-transparent under the transmission light. The size of the granules is different and there is no fluorescent. There is no exinite (resinite and non-resinite). The kerogen type index (TI) is within the range of 80.75~85.75 and the average is 82.65 (Figure 3(b)). The kerogen type is all I-type (The TI of I-type kerogen is larger than 80).

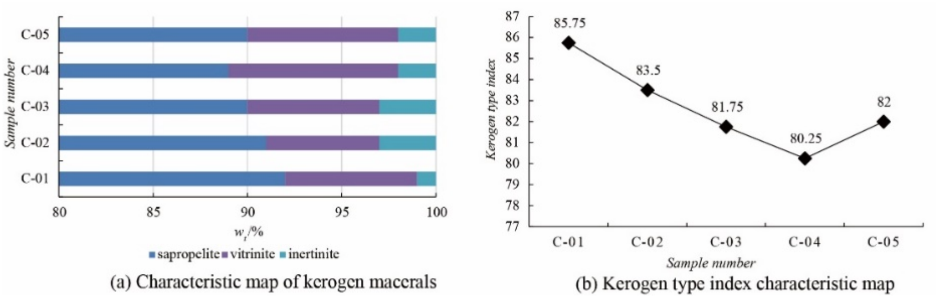

Figure 3: Discrimination of organic matter types of Longmaxi Formation in Yongshun block

Rich organic matter is the foundation of shale gas enrichment. For the southern marine source rocks, the degree of evolution is high, and the value of "S1 + S2" obtained using rock pyrolysis method is generally lower than 0.1mg/g, so there is no significance to evaluate the source rock. TOC is used here to evaluate the rich organic matter in source rocks. The test results of 33 samples of Longmaxi formation collected in the field showed that the TOC content is 1.16% ~ 4.31%, and the average is 2.06%. The TOC content of 33% samples was more than 2.0%. The TOC content in west Longshen No.2 Well is up to 5.96%, while the TOC content in east Yongye No.2 well is only around 2%. The TOC longitudinal change feature of the core of Longmaxi Formation in Yongye No.2 Well is obvious. And the TOC of siliceous shale, silty shale and batt gradually decreases to 0.5% from above 2.0%. And the pyrite and graptolite content also changes regularly accordingly.
Internationally, it is generally accepted that the best parameter for studying the thermal evolution of kerogen is the vitrinite reflectance (Ro). However, the marine strata in the lower palaeozoic group in southern China feature old stratigraphic age, high degree of thermal evolution, and shortage of vitrinite in organic matter (Xue et al., 2015). Currently, the asphalt (or vitrain) reflectivity Rb is generally adopted to figure out the vitrinite reflectance Ro to evaluate the maturity. The vitrinite reflectance test results of the 28 field samples were within the range of 1.87%~3.15%. And the vitrinite reflectance Ro of nearly 90% samples is 2.0%~3.0%, 3% lower

than 2.0% and 7% higher than 3.0%. It can be seen that the organic matter of black shale in Longmaxi Formation is basically in the early stage of postmature, the organic matter transformation rate is high, and the black shale has already generated a lot of gas.

3.3 Reservoir Feature

The porosity, permeability, pore type and mineral composition of shale are important indicators to evaluate the characteristics of shale reservoir, which directly determine the size and seepage capacity of the reservoir space in the shale and also affect the shale gas development effect.

Li et al., (2007) and Ross et al., (2008) believe that only the brittle shale with low Poisson ratio, high elastic modulus and abundant organic matter are the main targets of shale gas exploration.

It can be observed from the field outcrops that the siliceous shale is hard and brittle, with joints developed. After X-ray diffraction whole rock analysis was carried out to 51 field samples, it is found that the shale mainly consists of quartz surface and clay mineral. The quartzite content is 32.56% ~ 69.38%, and the average content is 49.26%. The clay mineral content is 14.27%~56.34%, and the average content is 29.8%. In addition, there are also plagioclase, potassium feldspar, calcite, dolomite, pyrite and other minerals (Figure 6). The content of brittle mineral in the black shale of Longmaxi Formation is 41.13%~84.95% and the average content is 66.76%, which indicates that the brittleness of the shale in Longmaxi Formation is high, which is favorable to the late fracturing transformation of the reservoir.

The shale porosity is low, which is generally 2% to 15%; the penetration rate is very low, and is within the range of Yana Darcy to Microdarcy. According to the United States gas shale statistics, the shale core porosity is from 4.0% to 6.5%, with an average of 5.2%; the penetration rate is generally 0.001~2.0mD and the average is 0.0409mD. This paper mainly analyzes the bound water saturation, gas saturation at the initial state of the shale, oil porosity and gas saturation parameters in the NMR test of the shale of Longmaxi Formation in Yongye No. 2 Well. The oil porosity of the samples of Longmaxi Formation was 0, and the gas saturation was 84.38%~93.85%, with an average of 90.86%. The water saturation at the initial state of the shale was within the range of 6.15%~15.62% and the average is 9.14%. The bound water saturation is within the range of 88.85%~98.5% and the average is 92.41%. The test results show that the shale porosity is within the range of 4.03%~6.03%. The pulse permeability is (0.000296~0.000791) $\times 10^{-3} \mu m^2$, with an average of $0.000492 \times 10^{-3} \mu m^2$. The reservoir is of low porosity and low permeability type.

It was found through the argon ion polishing and scanning electron microscope that the pores developed in the shale reservoirs in Longmaxi Formation include organic matter pores, mineral dissolution holes, pyrite intergranular pores and microcracks. The size of the micropores is between tens to hundreds of nanometers, and the microcracks are tens of nanometers in width and about a few microns in length.

The isothermal adsorption curves obtained through isothermal adsorption experiment not only reflect the methane adsorption capacity of shale gas under different pressures, but also reflect the maximum capacity of shale reservoir (ROSS et al., 2008; ROSS et al., 2009; ROSS et al., 2007). The experiment (Table 2) was conducted to test the isothermal adsorption capacity of eight field samples from Longmaxi Formation. The saturation adsorption capacity was within the range of 1.24~3.10m^3/t, and the mean value was 2.11m^3/t. The Langmuir's Volume of five samples from Yongye No.2 Well is 1.27~5.95 m^3/t, and the mean value was 3.62m^3/t; the Langmuir pressure is 1.4~3.97 MPa and the mean value is 2.75Mpa. All these data show that the black shale has sound methane adsorption capacity. After the linear simulation of the saturated adsorption capacity and TOC content of field samples, it is found that R^2 is as high as 0.765, suggesting that there is a highly positive linear relationship between the two, i.e. the higher TOC is, the stronger the saturated adsorption capacity will be.

Table 2: Sample experimental results table of isotherm adsorption test

Sample No	adsorbing capacity under different pressure (m^3/t)						
	1.1MPa	3.13MPa	5.89MPa	9.57MPa	13.25MPa	16.8MPa	Saturated adsorption capacity
Ⅱ-2	0.58	1.33	1.68	2.00	2.30	2.35	2.35
Ⅳ-3	0.71	1.88	2.50	2.74	3.00	3.19	3.10
Ⅳ-5	0.45	0.89	1.16	1.21	1.29	1.38	1.34
Ⅴ-2	0.27	0.75	0.93	1.11	1.24	1.19	1.24
Ⅴ-15	0.50	0.88	1.15	1.28	1.33	1.42	1.42
Ⅶ-2	0.76	1.61	2.10	2.37	2.59	2.72	2.72
Ⅶ-5	0.86	1.88	2.33	2.60	2.79	2.89	2.86
Ⅷ-1	0.58	1.06	1.42	1.64	1.73	1.81	1.81

3.4 Gas bearing characteristic

The vertical variation of the gas bearing characteristic of Longmaxi Formation in Yongye No.2 Well is obvious. The total gas content in the lower siliceous shale is high, which is within the range of 2.0~3.5 m^3/t. The desorbed gas dominates. The gas content in the middle silty shale is general, within the range of 1.0~2.0 m^3/t, and the desorbed gas also dominates. The gas content in the upper batt is low, which is smaller than 1.0 m^3/t. The absorbed gas dominates. The content of methane in Longmaxi Formation is more than 80%, and the content of ethane is within the range of 1.03%~2.56%, with an average of 1.84%. Nitrogen content is within the range of 2.13%~13.37%, with an average value of 4.97%. In addition, there is also a small amount of carbon dioxide and a trace of propane (Tab.3). However, the total air content in the greyish-green rock of Dingban Xintan Formation is low, smaller than 0.1 m3/t. The absorbed gas dominates. The methane content is low, remaining within the range of 10% ~ 40%. The nitrogen dominates.

3.5 Buried Depth

The depth of the bottom boundary of Longmaxi Formation in the block is 0~4,000m. Longmaxi Formation suffered severe denudation in Yanjing anticline, Shaba anticline and Hehu-Yaowan anticline, thus it is of no exploration value. Qing'anping syncline and Longjiazhai syncline are relatively gentle, both with the southern part being shallow and northern part being deep. The burial depths of Qing'anping syncline and Longjiazhai syncline are 1,000~2,500m and 1,000~4,000m respectively. Matizhai syncline is relatively closed, with the southern part being deep and northern part being shallow. Its burial depth is 1,000-2,500 m. From the technical and economic point of view, the burial depth of 500~4,000m is generally taken as the longitudinal effective exploration depth. The burial depth of Longmaxi Formation base in most of the area is appropriate, and the effective exploration area reaches 540 km^2 (Figure 4).

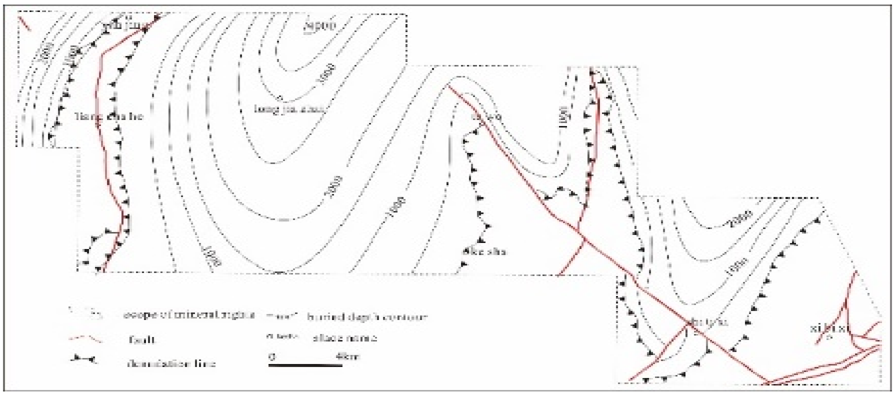

Figure 4: Buried depth map of Longmaxi Formation in block area

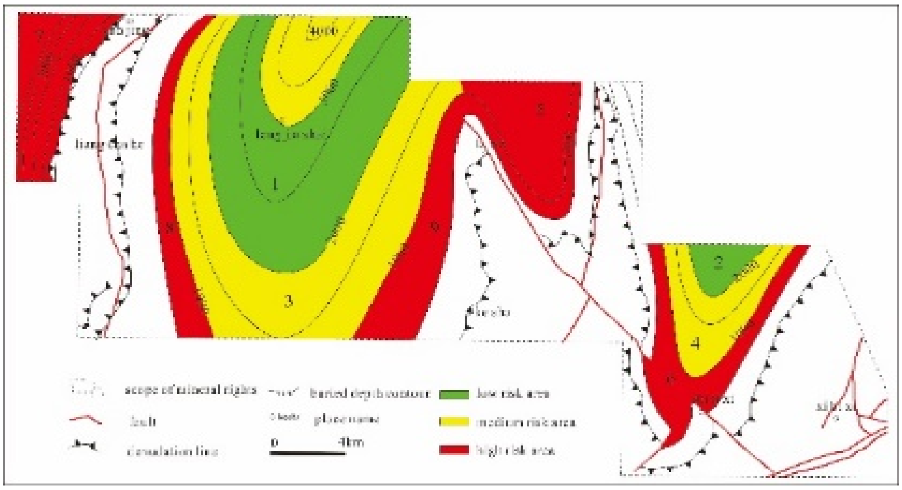

Figure 5: Evaluation of risk area and optimization of target area in Yongshun block

Combining the geological characteristics of Yongshun block, the shale thickness, organic matter abundance, organic matter thermal evolution degree, structural complexity, shale depth and other evaluation criteria are determined to estimate the risks of exploration of shale of silurian system Longmaxi Formation. And Yongshun block is divided into low risk area, middle risk area and high risk area. The comprehensive analysis shows that Longjiazhai syncline features moderate shale burial depth, gentle dip angle and large exploration area, thus it is the preferred shale gas exploration target area. Qing'anping syncline also features moderate shale burial depth, and gentle dip angle, but its exploration area is small, so that it can be taken as the secondary shale gas exploration target area. Matizhai syncline is closed, with steep dip angle and small exploration area. It is located in the northwest of the block and is not regarded as the shale gas exploration target area for the moment.

After calculation, the area of the low risk exploration area of the Silurian Longmaxi Formation is about 139k m^2 and the expected value of resource is $230×10^8$m3. The area of the medium risk exploration area is 211km^2 and the expected value of resource is $350×10^8$m3. The area of high risk exploration area is about 185k m^2, and the expected value of resource is $300×10^8$m3 (Figure 5). Thus, it can be seen that there is great potential of resource quantity in the low risk area in Yongshun block and that the resource reserves are good.

Yongye No.1 Well is located at the east wing of Longjiazhai syncline, indicating certain gas bearing feature at the burial depth of 500m. Yongye No.2 Well is located in the core part of Qing'anping, suggesting sound gas bearing capacity at the depth of 1,500m. Therefore, it is suggested to carry out shale gas exploration at the burial depth of 2,000~3,000m in the core part of Longjiazhai in the future.

4. Conclusions

The Lower Silurian Longmaxi Formation in Yongshun block is the sedimentary environment of deep-water retention basin, where the rich organic black shale is developed. The deposition thickness is around 30m. The content of organic carbon is high, and the organic matter type is I. The value of Ro is high, and it is in the early stage of ripening. All these provide sufficient material basis for shale gas accumulation.

The shale in Longmaxi Formation in Yongshun block is rich in demethicone and brittle minerals, which are in favor of the fracture formation and latter reservoir fracturing improvement. Many types of pores and cracks were developed, forming sound shale gas reservoir space. The shale reservoir adsorption capacity is good, with the saturated adsorption capacity reaching 1.24~3.10m3/t and the average saturated adsorption capacity amounting to 2.11m3/t. The saturated adsorption capacity is linearly positively correlated to TOC.

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