Difference analysis of shale gas-bearing property --A case study of the shale within Lower Cambrian Niutitang Formation on the margin of palaeouplift

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Study on geological conditions, main controlling factors of gas bearing and enrichment regularity of Cambrian shale gas in southern China

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The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

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Yufang Wang: Writing – review & editing. Ting Wang: Writing – review & editing. Haohan Li: Writing – review & editing. Hongbo Liang: Writing – review & editing. Shujing Bao: Writing – review & editing. Mingna Ge: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

Keywords

Gas-bearing, Periphery of palaeouplift, shale gas, Niutitang Formation, Lower Cambrian

Abstract

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As a kind of high-quality clean energy and national strategic mineral resources, shale gas has developed rapidly in recent years and has become an important field for increasing oil and gas storage and production in China. However, it is mainly concentrated in the Marine Wufeng-Longmaxi shale Formation in Sichuan Basin. On the basis of the study of reservoir control model of early paleouplift, the characteristics of sedimentary facies, structural preservation, shale distribution, organic geochemistry, mineral association, reservoir physical property and gas-bearing are studied by taking the typical wells of Hannan palaeouplift, Shennongjia palaeouplift, Huangling palaeouplift and Xuefengshan palaeouplift in the periphery of Sichuan Basin. The organic matter type of the 7 wells in the study area is mainly type I, the average organic carbon content is 1.5% -3.56%, the average Ro is 2.37% -3.9%, the brittle minerals are mainly quartz, the content of quartz is 28% -53%, and the average porosity is 0.51% -3.34%. The pores contain organic pores, inorganic pores and micro-fractures, and the fractures are mostly -2 -filled with calcite. Gas content 0.13m³ /t -4.19m³ /t. Through comparative analysis of main controlling factors affecting gas content of shale, the causes of gas diversity of Niutitang Formation shale on the periphery of palaeouplift are identified. The results show that: (1) The differences in preservation conditions caused by structural strength, fracture development degree and the coupling relationship with tectonic fractures are the key factors restricting the gas content of shale; (2) The difference of thermal evolution degree caused by early deep burial time, long deep burial time and fast deep burial is the key factor restricting the gas content of shale; (3) The difference of hydrocarbon generation potential caused by sedimentary subfacies in the same facies zone is an important factor restricting the gas-bearing capacity of shale; (4) There are good geological conditions for the generation of shale gas in the periphery of palaeouplift, and the areas with good preservation conditions such as the lower Plate of thrust nappe, the degree of thermal evolution is less than 3.0%, and the deepwater facies of trough are favorable directions for further exploration.

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Difference analysis of shale gas-bearing property ——A case study of the shale within Lower Cambrian Niutitang Formation on the margin of palaeouplift

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Abstract: As a kind of high-quality clean energy and national strategic mineral resources, shale gas has developed rapidly in recent years and has become an important field for increasing oil and gas storage and production in China. However, it is mainly concentrated in the Marine Wufeng-Longmaxi shale Formation in Sichuan Basin. On the basis of the study of reservoir control model of early paleouplift, the characteristics of sedimentary facies, structural preservation, shale distribution, organic geochemistry, mineral association, reservoir physical property and gas-bearing are studied by taking the typical wells of Hannan palaeouplift, Shennongjia palaeouplift, Huangling palaeouplift and Xuefengshan palaeouplift in the periphery of Sichuan Basin. The organic matter type of the 7 wells in the study area is mainly type I, the average organic carbon content is 1.5% - 3.56%, the average Ro is 2.37% - 3.9%, the brittle minerals are mainly quartz, the content of quartz is 28% - 53%, and the average porosity is 0.51% - 3.34%. The pores contain organic pores, inorganic pores and micro-fractures, and the fractures are mostly

filled with calcite. Gas content 0.13m³/t - 4.19m³/t. Through comparative analysis of main controlling factors affecting gas content of shale, the causes of gas diversity of Niutitang Formation shale on the periphery of palaeouplift are identified. The results show that: (1) The differences in preservation conditions caused by structural strength, fracture development degree and the coupling relationship with tectonic fractures are the key factors restricting the gas content of shale; (2) The difference of thermal evolution degree caused by early deep burial time, long deep burial time and fast deep burial is the key factor restricting the gas content of shale; (3) The difference of hydrocarbon generation potential caused by sedimentary subfacies in the same facies zone is an important factor restricting the gas-bearing capacity of shale; (4) There are good geological conditions for the generation of shale gas in the periphery of palaeouplift, and the areas with good preservation conditions such as the lower Plate of thrust nappe, the degree of thermal evolution is less than 3.0%, and the deepwater facies of trough are favorable directions for further exploration.

Keywords: Gas- bearing; Periphery of palaeouplift; Shale gas; Niutitang Formation; Lower Cambrian

1. Introduction

The shale gas revolution in the United States has made the United States the largest natural gas producer in the world (HAMMES et al., 2012). Commercial production of major shale gas reservoirs from Barnett to Marcellus (Abouelresh et al., 2012; 3. Bruner et al., 2015), successfully reversed the situation of US natural gas

imports to exports, while changing the world's energy market land-scape. China's shale gas has experienced nearly 20 years of exploration and has entered the substantial commercial development stage. In 2013, China's shale gas production was only 200 million cubic meters, and with the progress of exploration and development theory and technology, Shale gas production has achieved rapid growth. In 2018, the production exceeded 10 billion cubic meters, and in 2020, it exceeded 20 billion cubic meters, with a 15% - 40% increase in production, and its growth gas source was mainly concentrated in the Wufeng-Longmaxi Formation, Sichuan Basin (He et al., 2016). The cumulative proved geological reserves have exceeded 2 trillion square meters, and the cumulative shale gas production has exceeded 70 billion square meters. However, China's shale gas production in 2022 is 24 billion cubic meters, up 4.3% year-on-year, slowing down compared with previous years. China's external dependence on natural gas is still at a high level of 40%. In the background of energy security and carbon peak and carbon neutrality, it is urgent to increase the exploration and development of shale gas in new areas, new layers, new types and new fields (He et al., 2021). Previous studies have shown that the periphery of palaeouplift has low thermal evolution and relatively stable structural characteristics, which is an important target area for the investigation of Cambrian shale gas in southern China, and important discoveries have been made in many areas of the periphery of Palaeouplift. The Well EYY1HF in Huangling Uplift, western Hubei Province has a daily gas output of 78,300 m^3 and an open flow rate of 28.84×10^4 m^3 (Bao et al., 2018), the daily gas of Well Eyiye 1 was 6.02×10^4 m^3 with an open flow rate of 12.38×10^4 m^3

(Li et al., 2019; Zhang et al., 2020), Well SNY1 in Hannan Uplift has a stable production flow of 21×10^4 m^3 / day, all of which obtain high production shale gas, achieving a major breakthrough in low-pressure shale gas reservoir. However, Well GDD1, HY1 and HD 1 in Xuefeng Uplift, Well EHD1 in Shenlongjia Palaeouplift and Well SNY1 in Hannan Palaeouplift only found oil and gas ~~display~~ but no ~~shale~~ industrial gas flow (Xie et al., 2014), demonstrating the gas diversity of Niutitang formation on the periphery of Sichuan Basin Outer palaeouplift. Taking four typical wells around the palaeouplift as analysis objects, based on the analysis of shale gas geological conditions, the research focuses on analyzing and discussing the influencing factors and main controlling factors that affect the gas content of shale ~~gas~~ on the periphery of the ancient uplift, in order to find favorable areas for Niutitang shale gas exploration in the outer Sichuan Basin and serve a new round of oil and gas prospecting breakthrough.

2. Geological setting and sampling sections

The Cambrian shales in south China generally have a high degree of thermal ~~evolution,~~ and the study area is located in the eastern and northern margins of Sichuan Basin, from north to south are respectively Hannan ~~Palaeouplift,~~ Shenlongjia ~~Palaeouplift,~~ Huangling ~~Palaeouplift~~ and Xuefengshan Palaeouplift. The paleouplift experienced tectonic uplift in the Paleozoic, and its rigid basement structure was stable, which was conducive to shale gas preservation. For the southern Cambrian ~~ancient~~ formations, the paleouplift has early uplifting time and short deep burial time, and the thermal ~~evolution~~ of the Cambrian shale is lower than that of other regions.

Seven wells on the periphery of four ancient uplifts were selected as the research objects, including Well 1 and Well 2 on the southern margin of Hannan Ancient Uplift, Well 3 on the western margin of Shenlongjia Ancient Uplift, Well 4 on the southwest margin of Huangling Ancient Uplift and Well 5 on the southeast margin of Huangling Ancient Uplift, Well 6 and Well 7 on the southwest margin of Xuefengshan Ancient Uplift (Fig.1).

3. Samples and analytical methods

3.1. Samples

In this study, data were collected from 7 wells in the paleouplift, including 35 samples from Well 1, 25 samples from Well 2, 18 samples from Well 3, 120 samples from Well 4, 50 samples from Well 5, 49 samples from Well 6, and 12 samples from Well 7. Detail information of studied wells are listed in Table 1.

3.2 Experimental methods

In this study, seven wells from four palaeouplifts were selected to carry out organic geochemical experiments, such as TOC, Asphalt reflectance, organic matter types, etc. Reservoir physical properties, such as rock and mineral composition, porosity, permeability, pore type, fracture development, etc. Gas content testing experiments, such as field Desorption gas content measurement, gas component analysis, isothermal adsorption, etc. In addition, the well logging data, hydrocarbon generation history and structural evolution history in the study area were studied.

The experiments of organic geochemistry and reservoir physical properties were determined by the Geochemical Laboratory of Yangtze University. Since the sample

comes from the old formation of Niutitang Formation, the sample does not contain vitrinite, which cannot be measured by conventional vitrinite reflectance. The bitumen reflectance was measured and converted to Ro. The gas content and gas composition were determined by YSQ-Ⅳ analytical analyzer, which was independently developed. During the determination process, continuous drainage gas collection method was applied to collect gas samples and analyze gas composition. The desorption gas and residual gas were directly measured by this method, and the total gas content was finally calculated by combining with the simulation of lost gas.

4. Results

4.1. Organic geochemical characteristics

The research area consists of seven wells that are deposited in the continental shelf to slope facies. The dominant organic matter type is Type I, with high organic carbon content. These wells are located on the periphery of an ancient uplift. According to the theory" Reservoir control at the margin of paleo-uplift "(Zhai et al., 2017), Compared with southeast Chongqing area and West Hunan and Hubei area, the degree of thermal evolution in the study area is relatively low, which is the main consideration for drilling.

The kerogen type of Well 1 is type I, and the organic carbon content is 0.52% - 3.02%, with an average of 1.5%. TOC of the lower and middle parts with good gas con-tent can reach more than 2.0%. The maturity of organic matter is high, and the results of Ro range from 2.48% to 4.36%, with an average of 3.0%, which is in the stage of over-mature evolution. TOC content of 31 core samples from Well 2 ranges

from 0.88% to 8.61%, with an average value of 3.37%. The shale with TOC>2% has a thickness of 78m, and the ~~maturity~~ of 34 samples ranges from 2.04% to 3.14%, with an average value of 2.66%, and is in the over-mature cracking gas stage. The main types of organic matter are type I and type Ⅱ$_1$ (Xu et al., 2019).

The TOC of Well 3 Niutitang Formation is between 0.49% - 4.14%, with an average of 1.96%, and the vitrinite reflectance Ro is between 3.02% and 3.25%, which has entered the mature evolution stage, and the maceral of kerogen is dominated by sapropelic amorphous type. TOC of the Niutitang Formation of Well 4 ranges from 0.04%-3.88% with an average of 2.01%, and the lower part of the second segment of Niutitang Formation with a better gas content ranges from 0.68%-3.88% with an average of 2.44%. The vitrinite reflectance Ro is between 2.0% and 2.77%, which entered the mature to overmature stage. The TOC of the gas-bearing shale of Well 5 Niutitang Formation ranges from 0.43% - 10.45% with an average of 2.62%, and the TOC of the shale of 1832 m - 1872 m ranges from 1.23% - 10.45% with an average of 3.45%. The maceral of kerogen is mainly sapropelic amorphous type, organic matter type I, Ro ranges from 2.06% - 2.66% with an average of 2.29%, which is in the stage of over-mature evolution.

The abundance of organic matter in Niutitang Formation in the South Guizhou Depression is generally high (Teng et al., 2008). The TOC of Niutitang Formation in Well 6 ranges from 0.60% to 8.89%, with an average of 3.55%. Ro ranges from 1.43% to 2.81%, with an average of 2.37%, which belongs to the early stage of maturation and overmaturity. The main kerogen was type I, and a small amount was

type Ⅱ1. In addition, 30 stable carbon isotope experiments of kerogen show that δ13C‰ ranges from -29.2‰ to -34.7‰, indicating that it is type I kerogen. The TOC of Niutitang Formation in Well 7 is 0.25% - 8.72%, with an average of 3.56%. Ro has the characteristics of upper and lower height, the distribution range is 3.26% - 4.4%, the average is 3.9%, and it is in the late over-mature - metamorphic stage, especially after the bottom 997 m, Ro is greater than 4%, and it is in the metamorphic stage. The organic matter type is mainly type Ⅰ (Table 2).

4.2. Reservoir property

The brittle mineral content of core samples from Well 1 Niutitang Formation ranges from 52.7% to 74.1%, mainly quartz. The main clay minerals are chlorite, kaolin-ite, illite and montmorillonite. The measured porosity ranges from 0.02% to 5.17%, with an average value of 2.01% by Overburden pore permeability test. The porosity measured by mercury injection experiment was 1.7% - 2.78%, with an average value of 2.15%. The permeability ranges from 0.00053 mD to 0.0041 mD, with an average value of 0.0008 mD, which belongs to the low porosity ultra-low permeability reservoir. The pores can be divided into three categories: mineral matrix pores, organic matter pores and micro-fractures, among which micro- fractures are mainly marginal cracks be-tween organic matter and inorganic minerals, with a slit width of 0.5μm - 8.6μm (Wang, 2014). The brittle mineral content of Niutitang Formation in Well 2 ranges from 40.6% to 64.8%, with an average of 53.6%, among which quartz content is the highest, ranging from 47% to 25.6%, with an average content of 37.16%. The pore types are mainly mineral dissolution pores,

intercrystalline pores of pyrite are occasionally found, and organic pores are few. Microfractures are abundant, and the seam width is 0.5μm -8.6μm (Wang et al., 2014).

The brittle mineral content of Niutitang Formation in Well 3 is the highest 74%, and the average is 50%. The porosity is 1.45%-8.04%, with an average of 3.33%, and the permeability is 0.0005 mD -0.004 mD, with an average of 0.0015 mD. The pore types include intergranular pores, intra-granular pores, organic pores, solution pores, mold holes and micro-fractures. The fractures are mainly high Angle fractures with large dip Angle and low density. Some fractures have crossover phenomenon and are mostly filled with calcite.

There are differences in mineral composition among different formations in Well 4 Niutitang Formation. The lower part of the second segment of Niutitang Formation, which has the best gas content and the highest organic matter abundance. It is dominated by quartz with an average content of 37%, followed by carbonate rock, clay (illite and chlorite), the average content of 19%, the pyrite content is relatively high, up to 3% on average. Other segment are dominated by calcite. The porosity ranges from 2.01% to 3.61%, with an average value of 2.88%. Permeability ranges from 0.00031 mD to 0.00078 mD with an average of 0.00054mD. The pores are rich in organic matter, followed by the solution pores and micro-fractures, which is a low porosity and ultra-low permeability reservoir. A total of 34 (half) filling cracks and 66 open cracks were picked up from the electrical imaging data. The dip Angle of the opening seam is between 20.3 and 89.7, and the inclination is mainly south. The

fracture trajectory is clear, indicating that the fracture has good connectivity and ductility (Liu et al., 2019) (Fig. 2).

The brittle mineral content of Well 5 is high, ranging from 45% to 75%, shale gas- bearing interval from 1788 m to 1872 m, in which the content of carbonate and clay minerals is higher in the shale from 1788 m to 1832 m, and the content of quartz minerals is lower. The mineral content in the smaller depth section changes greatly, and the material composition is ~~obviously~~ heterogeneous. The content of quartz and clay minerals is high and the content of carbonate minerals is low in the shale of 1 832 m -1 872 m, and the mineral content changes relatively little in the shale of small depth, and the rock mineral composition is relatively stable. The reservoir space is divided into three types: inorganic pore, organic pore and microfracture. Microfractures are mainly layered fractures inside clay minerals, which have good extensibility and connectivity, and can optimize the transformation of pore system (Li et al., 2003).

The brittle mineral content of Well 6 is high, ranging from 37% to 68%, with an average of 51%. The quartz content is 28%-53%, with an average of 37.8%. The average porosity and permeability of Niutitang Formation are 0.51% and 0.001mD respectively. The microcosmic reservoir space is dominated by matrix pores, followed by organic pores. Pyrite is common and a few residual pores can be seen. The fractures are mainly manifested as tensile cracks and slip cracks. Affected by the detachment structure, it is mainly filled with calcite veins. The above two groups of fractures have the characteristics of multi-phase, staggered with each other, and local

grid shape.

The content of quartz minerals in Niutitang Formation of Well 7 is 35.1% - 51.8%, with an average of 43.5%. The brittle mineral is high, which is conducive to the later fracturing. The upper part of Niutitang Formation has an average porosity of 2%, which corresponds to high gas content. The reservoir space is dominated by inorganic mineral matrix pores, with micro-fractures and undeveloped organic pores. Micropores are connected with microfractures, forming a complex network of pores and fractures with good connectivity (Diaz et al., 2013). More high-angle fractures are often filled with quartz, calcite, pyrite and other minerals, and the filling degree is relatively high.

4.3. Gas-bearing

The highest total hydrocarbon in Well 1 Niuitang Formation 2201.00m-2271.00m and 2353.00m-2387.00m is 4.28%. The Desorption gas content is 0.2 m^3/t -4.5m^3 /t, in which the gas content is greater than 2 m^3/t between 2150 m and 2380m. The total gas content of Well 2 is 0.77 m^3/t -3.39m^3/t, showing high gas content. The gas content increases gradually with the depth.

The overall gas content of Well 3 is low, and the maximum gas content is 0.13m^3/t in the 1156.62m - 1852.76m. At the top of Niutitang Formation 1454 m - 1591m, a gas anomaly occurred, with a maximum total hydrocarbon value of 3.65%.

The Desorption gas content of Well 4 is 0.13m^3 / t- 2.16m^3 /t, and the total gas content is 0.26m^3 / t- 4.48m^3 /t, among which 2980 m - 3055m has a higher gas content with an average of 2.3m^3/t. The core bubbles violently ~~in water immersion test~~, and the gas ~~ignition~~ is flammable. The test shows that the daily gas production is 7.83×10^4 m^3 /d, and the open flow rate is 28.84×$10^4$$m^3$ / d. The gas content of Well 5 is 0.58 m^3 /t -

5.48m^3 /t. Among them, the gas content of the well depth of 1837 m - 1872m is greater than 2 m^3/t, and the average is 2.78 m^3/t; the gas content of the well depth of 1854 m - 1872m is greater than 3 m^3/t, and the average is as high as 3.8 m^3/t. The daily gas production is 6.02×$10^4$$m^3$/d and the open flow is 12.38×$10^4$$m^3$/d.

The Desorption gas content in Well 6 ranges from 0.09 m^3/t to 1.11m^3/t, with an average value of 0.42 m^3/t. The total gas content of upper well samples is relatively high. The gas content of Niutitang Formation in Well 7 ranges from 0.06 m^3/t - 1.97m^3/t with an average of 0.32m^3/t. There are two high gas content segments in the middle and upper part. The first segment is 957 m - 975m with calcareous carbonaceous shale and the maximum gas content is 1.1m^3/t. Second, in the 1005m - 1013m segment, gas penetration occurred at the wellhead during drilling, and the maximum gas content was 1.97m^3/t. The gas logging showed a high gas anomaly with a maximum value of 7.92% (Fig. 3).

5. Discussion

Previous studies on the geological conditions of shale gas formation on the periphery of palaeouplift put forward a new shale gas enrichment model in the slope belt of palaeouplift margin, which is "favorable facies zone is the foundation, organic matter content is the guarantee, basement uplift and evolution is the key", and guided the breakthrough of shale gas exploration. However, the Niutitang shale, which is also located in the periphery of the ancient uplift in the outer Sichuan Basin, still has great differences in ~~gas- bearing properties~~. By analyzing the relationship between degree of thermal evolution, structural preservation condition, sedimentary subfacies, reservoir physical property and gas- bearing, the main controlling factors of gas- bearing in shale surrounding different palaeouplift are studied.

5.1. Analysis of rich gas conditions

（1）Correlation between gas content and maturity

On the basis of the study of 7 wells in this paper, 9 wells in the adjacent area are investigated and analyzed comprehensively (Fig. 4)—. Based on the relationship between Ro and gas content of 16 wells, it is found that: 1). The correlation between Ro and gas content is weak and linear, and the correlation coefficient is 0.47. 2). The value of Ro can qualitatively reflect the size of the gas content. ① As can be seen from the figure, there are 8 data with Ro higher than 3%, and the Ro value is 3.06% - 3.40%, with an average of 3.20%. The gas content is 0.13 m^3/t - 1.2m^3/t, the average is 0.75 m^3/t, and the gas content of 50% data is less than 1 m^3/t. ② There were 7 data whose Ro value was less than or equal to 3%, with a value of 2.15% - 2.95% and an average of 2.57%. The gas content is 1.38 m^3/t - 3.00m^3/t, with an average of 2.19 m^3/t, and the gas content of 71% data is greater than 2 m^3/t. The average Ro of the three wells obtained shale gas flow is 2.40%, and the gas content is 2.13 m^3/t - 3.00m^3/t, with an average of 2.67 m^3/t. Therefore, ~~the degree of~~ thermal evolution is the key factor affecting gas content. The Ro of well 6 is 2.37% and the gas content is low. The reason is that the gas content of well 6 is not only affected by Ro, but also restricted by other factors.

（2）Differential tectonic subsidence affects the degree of thermal evolution

Although the seven wells are located in the periphery of the outer palaeouplift of Sichuan Basin, the differences ~~of~~ thermal ~~evolution degree~~ and hydrocarbon generation are caused by different tectonic subsidence in different regions. Compared with Huangling Palaeouplift and Xuefeng Palaeouplift, Ro in Wells 4 and 5 is generally lower than 3.0%, while the minimum Ro in 7 wells are higher than 3.0%. The main reasons are as follows:

First, the deep burial time is late, the deep burial time is short, the thermal ~~evolution degree~~ is low, and it is in the best gas generation period, which is beneficial to

gas content. The Niutitang Formation shale of Huangling Uplift entered the oil-generating stage in the middle Silurian, entered the thermal cracking condensate oil-gas stage at the end of Permian, and remained relatively stable until the middle Triassic. At present, the shale Ro of Niutitang Formation in Well 4 and Well 5 is 2.26%-2.77%, and the latter is smaller with an average of 2.29%, which is in the best gas window range. From the end of Permian to the beginning of Triassic, it experienced rapid subsidence, and was in the deep burial period (>3500m) in the late Jurassic (before Yanshan uplift), with a deep burial time of about 85Ma (Fig.5). The hydrocarbon generation time of Niutitang Formation in Well 7 was early. The Niujutang Formation was buried rapidly after deposition, and entered the hydrocarbon generation threshold in the early Middle Cambrian (about 508 Ma), the burial depth exceeded 3500 m in the Late Cambrian, reached the late oil-generation and early gas generation stage until the early Middle Triassic (before the Indo uplift), and was in the continuous deep gas burial stage with the maximum burial depth exceeding 5700m and the hydrocarbon generation time exceeding 270Ma. Deep burial time (>3500m) exceeds 250Ma (Fig. 6). It can be seen that the southern margin of Huangling Uplift is generally shorter than that of Niutitang Formation on the western margin of Xuefeng uplift (Nie et al., 2021) and the deep burial time is later, resulting in a lower degree of thermal evolution and still in the optimal gas generation stage, which is more conducive to shale gas enrichment.

Second, hydrothermal intrusion along the fault may lead to an increase in the degree of thermal evolution. The comparison of Ro% between Well 7 Doushantuo Formation and Niutitang Formation shows that the Ro% of Doushantuo Formation is 3.32%-3.59%, but it is significantly lower than the lower part of Niutitang Formation. It is believed that the small fault drilled at the bottom of Niutitang may locally warm the

shale in Niutitang, resulting in abnormal maturity, while the Doushantuo shale is normal geothermal warming, which is lower than the maturity of the lower part of Niutitang Formation. The main reasons are as follows: ① the first member of Niutitang Formation consists of gray-black thin-layer siliceous rocks, phosphorus-bearing siliceous rocks and phosphorite nodules with thickness of 2 m -15m. This phosphorus may be related to the volcano, and there may be volcanic hydrothermal intrusion, which increases the temperature of Niutitang Formation. (2) The fault was drilled at the bottom of Niuitang Formation, which penetrated the Dengying Formation, and hydrothermal minerals such as barite, fluorite and quartz were found in the cracks. From this point of view, it is very likely that the hydrothermal migration of Dengying Formation along the fault affected the temperature of Niutitang Formation and accelerated the thermal evolution of organic matter.

5.2. The relationship between structural preservation and gas- bearing

（1）Major Faults characteristics

Fracture is closely related to shale gas-bearing and mainly controls the preservation conditions of shale gas. Faults can be used not only as a migration pathway of shale gas to cause gas loss and damage shale gas preservation (Gao et al., 2014), but also as a shale gas sealing formation to prevent gas loss and facilitate shale gas enrichment (Hu et al., 2014). It can even be used as a release pathway of tectonic energy to control the integrity of the formation. Therefore, by analyzing the fractures and their properties of different research objects, the influence of fractures on shale gas preservation can be comprehensively judged.

The fault structure of Qinling region in southern Shaanxi is complex, and in

addition to some regional plate edge faults and intra-plate faults, there are also buried faults (Zhang et al., 2004). Under the influence of late Indosinian and Yanshanian strong uplift, the Micangshan tectonic belt is a forward-spreading structure from north to south caused by the superposition of two thrust nappe structures in different directions. From the initial underwater uplift, it rose to land after the Indochina movement. Among them, Well 1 is mainly affected by the Yangpingguan-Yangxian fault in the near east-west direction, while Well 2 is surrounded by the Dachimba-Zhenba fault in the near east-west direction and the Sishang-Xiaoyangba fault in the north-west-southeast direction (Chen et al., 2018).

There is a regional fault-Yangriwan Fault on the western margin of Shennongjia (He et al., 2021). And Well 3 is located about 1km to the south of the fault. Several fracture zones and a buried fault were found during drilling. The core of the dark shale section has different degrees of fractures and is partially or completely filled with calcite.

There are fault structures of different periods, different scales and different directions in western Hubei, which form regular network. Some important faults constitute the division boundary of the secondary tectonic units, and have obvious control over the regional structural styles, and are also of great significance to the preservation of shale gas. Well 4 and 5 are located on the Yichang slope, with the Wuduhe fault in the southeast, which breaks into the core of the uplift and serves as the boundary of the stable region of the southern Yichang slope belt together with the Tianyangping fault (Fig.7).

The eastern part of the Qiannan Depression is bounded by the Tonren-Sandu fault and the Xuedeng Uplift (Bai et al., 2010); the southeast part is bounded by the Libo Fault and the Guizhong Depression; the southwest part is bounded by the Ziyun-Luodian-Nandan -Du 'an fault and the Luodian Fault depression; the northwest part is bounded by the Guiyang-Zhenyuan fault and the Qianzhong Uplift, and the plane is a triangle that is wide in north and narrow in south. It mainly presents three groups of fault systems with different scales in the NNE - near SN, NW, NEE - near EW direction (Peng et al., 2019).

（2）The relationship between structural preservation and gas-bearing

Well 4 and 5 are located in the bottom of thrust nappe, with relatively stable, simple structure and few faults, which is conducive to the preservation of shale gas. The Niuitang Formation of Well 1 is deformed by long-term compression, with deep gully, broken terrain and strong dynamic geological action, which is not conducive to shale gas preservation. Well 4, located about 1km south of the major fault, encountered several fracture zones and a buried fault during drilling. The core of the dark shale section has varying degrees of fractures, and is partially or completely filled with calcite. The mirror scratches can be seen in the natural section of the core of the two wells 1824.06m-1824.12m, which indicates that the tectonic movement in this area is relatively intense, which is not conducive to the preservation of shale gas.

Although Well 6 and Well 7 are located in the Qiannan Depression, Well 7 is located in the Danzhai area, which is far from the fault position, the formation of Niuitang Formation is stable, and the degree of structural deformation is relatively weak (Dan et al., 2023). However, there are three regional large faults around Well 6, and a number of secondary small faults develop near the well. Due to the relatively

staggered formation, the low-grade tension-torsion fault develops in the direction of 65° NW, making the Huangping fault zone more complicated and damaging the preservation conditions (Ge et al., 2018; 2020), resulting in slightly lower gas content in Well 6 than Well 7. In addition, there are many faults in the south Guizhou Depression with multi-stage and complex structure, and the gas components can reflect the destructive effect of faults on the gas content of shale. The nitrogen content of Well 7 is 30%, while the nitrogen content of Well 6 is 50-79%, indicating that the gas contains atmospheric components. Considering that the gas-bearing formation is connected with the atmosphere through fracture, the enrichment of shale gas is destroyed. The higher atmospheric content in Well 6 also confirms that the gas reservoir is more destructive and has relatively lower gas content.

In addition, the fracture is favorable to the gas content of shale gas. The Niutitang Formation, ~~where~~ Well 4 and 5 ~~are located~~, is located in the footwall of thrust nappe and has a stable structure. It plays an effective role in releasing stress during multi-stage structural transformation, thus protecting the upper overlying Sinian, Cambrian, Upper Ordovician and Lower Silurian shales from being strongly damaged on the rigid base. From the perspective of integrity and stability of source rock development, fracture has a favorable influence on shale enrichment.

5.3. The relationship between sedimentary subphase and gas-bearing

Favorable sedimentary facies zones control the hydrocarbon generation capacity of source rocks, are the material basis of shale gas enrichment, and are closely related to gas-bearing properties. From the successful development examples and experiences of shale gas in Wufeng-Longmaxi Formation in China (Guo et al., 2014), it can be seen that deep-water facies deposits such as deep-water shelf are one of the most important ~~theories in~~ the “ternary enrichment model” theory of shale gas (Guo et al., 2014). The

favorable facies zone model of the Carboniferous platform basin-lower slope facies in the south of Guizhou and the middle of Guangxi has guided the shale gas investigation.

（1） Sedimentary characteristics

The sedimentary environment determines the material basis of shale gas formation. The division scheme of sedimentary environment of Niutitang Formation in the four palaeouplifts in the study area can be divided into two categories: The first type is classified as shelf facies, which can be subdivided into two subfacies: deep shelf and shallow shelf, which is adopted by most scholars. The second category is divided into rifting trough facies, which can be subdivided into aulacogen basin and slope subfacies (Zhai et al., 2017).

In general, southern Shaanxi belongs to passive continental margin deposits on the northern margin of the Upper Yangtze Block. According to the first classification scheme, the Niutitang Formation of Well 1 and Well 2 in southern Shaanxi is mainly shallow shelf sedimentary subfacies, and the high-quality shale segment is deep shelf subfacies. The better gas-bearing member of the two wells is the middle and lower part of Niutitang Formation, and the lithology is dark gray carbonaceous shale, silty shale, silty carbonaceous shale with carbonaceous siltstone and marl. According to the second category , Well 1 is the slope subfacies, and Well 2 is the aulacogen basin facies of the rift trough.

The Niutitang Formation in Shennongjia area is mainly composed of sedimentary shelf facies and slope facies, among which shelf facies can be further divided into deep water shelf subfacies and shallow water shelf subfacies, and slope

facies can be divided into slope foot subfacies (Xie et al., 2017). The Niutitang Formation can be divided into the first, second and third members from the bottom up, corresponding to deep shelf subfacies, shallow shelf subfacies and slope foot subfacies respectively. The first segment of Niutitang Formation with ~~better gas-bearing~~ is characterized by deep grayish-black calc-carbonaceous mudstone, black calc-carbonaceous mudstone, argillaceous siltstone lamination, rich pyrite nodules and pyrite bands. According to the second classification, the sedimentary environment is rifted trough basin subfacies.

Tectonic evolution controls the distribution of sedimentary facies zones in Yi-chang area of western Hubei. In the early Cambrian, influenced by the large-scale transgression of the Yangtze River, the sediments in this area were successively com-posed of tidal flat facies, shallow water facies and deep shelf facies from northeast to southwest (Zhang et al., 2023). Both Well 4 and 5 are deepwater shelf facies, and the former has deeper water. The second segment of Niutitang Formation, lithology of which is gray-black and black carbonaceous shale, is a deep water shelf deposit. According to the second classification, Well 4 is aulacogen basin and Well 5 is slope subfacies (Fig. 8).

The paleogeothermal environment of Niuitang Formation in the Qiannan Depression has low water temperature and dark anoxic deposits, and the organic matter is well preserved. The sedimentary environment of Well 6 and 7 is deep shelf - subdeep sea basin deposition. The second member of Niutitang Formation with good gas-bearing capacity is gray-black mudstone, mixed with gray argillaceous limestone, containing pyrite nodules or bands. A complete trilobite fossil was found in Niutitang

Formation in Well 6. According to the second classification, Well 6 is aulacogen basin, and Well 7 is deep shelf deposition.

（2） The relationship between sedimentary subphase and gas-bearing

The Niutitang Formation in the study area has the characteristics of multi-stage hydrocarbon generation of organic matter. The results show that the Niutitang Formation generally has the characteristics of high organic matter abundance, and the influence of organic matter abundance is usually ignored when analyzing the influencing factors of shale gas content in the Niutitang Formation. According to the analysis of sedimentary facies of 7 wells, all of them belong to rifting trough facies. However, in the case of similar thermal evolution degree and structural preservation conditions, although Hannan palaeouplift and Huangling palaeouplift belong to the same sedimentary zone - West Hubei Trough, due to different sedimentary subfacies, the hydrocarbon generation capacity of shale is affected, and thus the gas content of shale is affected(Fig.9). Although Well 1, 2 and 4 are all located in the same large rifting trough, and the thermal evolution degree of the key factor for the Niutitang Formation is generally less than 3.0%, different sedimentary subfacies lead to differences in their gas-bearing properties. Well 2 and 4 are subfacies of rifting trough basin, while Well 1 is subfacies of rifting trough slope. The sedimentary environment is different, which leads to the lower hydrocarbon generation potential of shale in Well 1 than that in Well 2 and 4, resulting in the difference of gas content. In addition, the stable gas flow of 21×10^4 m^3/d in Well Shanzhenye 1 in Zhenba area, which is adjacent to Well 2, also confirms the controlling effect of sedimentary subfacies relative gas content.

5. Conclusions

(1) Hydrocarbon control by sedimentation. The main reason that the gas content

of Well 1 is lower than that of Well 2 is that the former is slope facies of rifting trough and the latter is deep water facies of rifting trough basin. The difference of hydrocarbon generation potential caused by sedimentary subfacies in the same facies zone is an important factor restricting the gas content of shale.

(2) Thermal ~~evolution degree~~ control zone. The rigid basement on the periphery of the ancient uplift has the effect of "heat insulation and preservation", which makes the thermal ~~evolution degree~~ of the periphery generally low, and most of them have not entered the graphitization stage. However, the differences in the thermal evolution degree of the Niutitang shale on the periphery of different ancient uplift due to the deep burial starting time, deep burial time span and deep burial rate are the key factors restricting the gas content of the shale.

(3) Preservation control the reservoir. As a relatively stable area of the Niutitang Formation around the ancient uplift, the difference in preservation conditions caused by the structural strength, fracture development degree and the coupling relationship with tectonic fractures is the key factor restricting the gas- bearing of shale

(4) The geological conditions of shale gas enrichment at the periphery of palaeouplift, favorable preservation conditions such as lower plate of thrust nappe, moderate thermal evolution degree and deep water facies area of trough are favorable directions for further exploration.

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508 **References:**

509 HAMMES, U., FRBOURG, G, 2012. Haynesville and Bossier mudrocks: a facies and sequence stratigraphic
510 investigation, East Texas and Louisiana，USA. Marine and Petroleum Geology 31, 8-26.

511 Abouelresh, M.O., Slatt, R.M., 2012. Lithofacies and Sequence Stratigraphy of the Barnett Shale in EastCentral
512 Fort Worth Basin, Texas. AAPG Bulletin 96, 1-22.

513 Bruner, K.R., Walker-Milani, M., Smosna, R., 2015. Lithofacies of the Devonian Marcellus Shale in the Eastern
514 Appalachian Basin, U.S. A. Journal of Sedimentary Research 85, 937-954.

515 He, Z.-L., Nie, H.-K., Zhang, Y.-Y., 2016. Analysis of themain controlling factors of shale gas enrichment in the
516 Ordovician Wufeng Formation and Silurian Longmaxi Formation in Sichuan Basin and its peripheral areas.
517 Earth Science Frontiers 23, 8-17.

518 He, Z.-L., Nie, H.-K., Li, S.-J., Liu, G.-X., Ding, J.-H., Bian, R.-K., Lu, Z.-Y., 2021. Differential occurence of
519 shale gas in the Permian Longtan Formation of Upper Yangtze region constrained by plate tectonics in the
520 Tethyan domain. Oil & Gas Geology 42, 1-15.

521 Bao, S.-J., Zhai, G.-Y., Zhou, Z., Yu, S.-F., Chen, K., Wang, Y.-F., Wang, H.,Liu, Y.-M., 2018. The evolution of the
522 Huangling uplift and its control on the accumulation and preservation of shale gas. China Geology 1,
523 346-353.

524 Li, H., Liu, A., Luo, S.-Y., Chen, X.-H., Chen, L., 2019. Characteristics of the Cambrian Shuijingtuo shale
525 reservoir on Yichang Slope, western Hubei Province: a case study of well EYY 1. Petroleum Geology &
526 Experiment 41, 76-82.

527 Zhang, J.-F., Zhai, G.-Y., Wang, D.-M., Bao, S.-J., Chen, K., Li, H.-H., Song, T.,Wang, P., Zhou, Z., 2020. Tectonic
528 evolution of the Huangling dome and its control effect on shale gas preservation in the north margin of the
529 Yangtze Block, South China. China Geology 3, 28-37.

Xie, Z., Lu, S.-F., Yu, L., Chen, Y.-P., Wang, M., Chen, F.-W., He, X.-P., 2014. Assessment of Natural Gas Loss from Mudstone Gas Source Rocks — an Example from Jiumenchong Formation of Huangye 1 Well, Lower Cambrian, Southern Guizhou Sag，China. Acta Mineralogica Sinica 34, 137-143.

Xie, X.-N., Hao, F., Lu, Y.-C., He, S., Shi, W.-Z, Jiang, Z.-X., Xiong, Y.-Q.,Zhang, J.-C., 2017. Differential Enrichment Mechanism and Key Technology of Shale Gas in Complex Areas of South China. Earth Science 42, 1045-1056.

Zhang, Y., Huang, D.-J., Zhang, L.-L., Wan, C.-H., Luo, H., Shao, D.-Y., Meng, K.,Yan, J.-P., Zhang, T.-W., 2023. Biogenic silica of the Lower Cambrian Shuijingtuo Formation in Yichang,western Hubei Province-features and influence on shale gas accumulation. Earth Science Frontiers 30, 83-100.

Gao, J., He, S., He, Z.-L., Zhou, Y., Zhao, M.-L., 2014. Genesis of Calcite Vein and Its Implication to Petroleum Preservation in Jingshan Region, Mid-Yangtze. Oil&Gas Geology 35, 33-41.

Hu, D.-F., Zhang, H.-R., Ni, K., Yu, G.-C., 2014. Main Controlling Factors for Gas Preservation Conditions of Marine Shales in Southeastern Margins of the Sichuan Basin. Natural Gas Industry 34, 17-23.

Zhang, G.-W., Dong, Y.-P., Lai, S.-C., Guo, A.-L., Meng, Q.-R., Liu, S.-F., Cheng, S.-Y., Yao, A.-P., Zhang, Z.-Q., Pei, X.-Z., 2004. Mianlue tectonic zone and Mianlue suture zone at the southern margin of the Qinling-Dabie orogenic belt. Science China: Earth Sciences 47, 300-316.

Chen, X.-L., Zhai, G.-Y., Bao, S.-J., Pang, F., Wang, J.-Z., Tong, C.-C., 2018. Shale gas accumulation and gas-bearing properties of Niutitang formation in well Zhendi 1, Zhenba region of southern Shaanxi province. China Mining Magazine 27, 101-106.

He, W., Chen, Y., Lei, Y.-Y., Qian, C., Chen, K., Lin, T., Song, T., 2021. Analyses of the relationship between lithology and shale gas accumulation for the Wufeng Formation to Longmaxi Formation in the west of Hubei Province:A case study of the Erhongdi 1 well. Journal of China Coal Society 46, 1014-1023.

552 Bai, Y.-S., Xiong, C.-Y., Wang, C.-S., Li, X.-B., Liu, A., Zhang, M., 2010. Tectonic Evolution of North Area of
553 Xuefengshan Uplift and Its Relation to Marine Hydrocarbon Formation. Geology and Mineral Resources of
554 South China 96, 68-75.
555 Peng, Z.-Q., Tian, W., Miao, F.-B., Wang, B.-Z, Wang, C.-S., 2019. Geological Features and Favorable Area
556 Prediction of Shale Gas in Lower Cambrian Niutitang Formation of Xuefeng Ancient Uplift and Its Periphery.
557 Earth Science 44, 3512-3528.
558 Zhai, G.-Y., Bao, S.-J., Wang, Y.-F., Chen, K., Wang, S.-J., Zhou, Z., Song, T., Li, H.-H., 2017. Reservoir
559 Accumulation Model at the Edge of Palaeohigh and Significant Discovery of Shale Gas in Yichang
560 Area,Hubei Province. Acta Geoscientica Sinica 38, 441-447.
561 Xu, T., Xu, F., Guo, Y.-H., Wang, N., Xie, Q.-Z., Huang, W., 2019. Organic geochemical characteistics of the
562 Lower Paleozoic shales in Xixiang-Zhenba Area,Southern Shaanxi. Journal of Northeast Petroleum
563 University 43, 59-68.
564 Teng, G.-E, Qin, J.-Z, Zheng, L.-Y., 2008. Hydrocarbon Potential on Excellent Hydrocarbon Source Rock in
565 Southern Guizhou Depression and Its Spacial-Temporal Distribution. Acta Geologica Sinica 82, 366-372.
566 Wang, Y.-M., Dong, D.-Z., Yang, H., He, L., Wang, S.-Q, Huang, J.-L., Pu, B.-L.,Wang, S.-F., 2014. Quantitative
567 characterization of reservoir space in the Lower Silurian Longmaxi shale，southern Sichuan，China. Science
568 China(Earth Sciences) 57, 313-322.
569 Liu, L., He, S., Zhai, G.-Y., Chen, K., Liu, Z.-X.,Wang, Y., Han, Y.-J., Dong, T., 2019. Diagenetic Environment
570 Evolution of Fracture Veins of Shale Core in Second Member of Niutitang Formation in Southern Limb of
571 Huangling Anticline and Its Connection with Shale Gas Preservation. Earth Science 44, 3583-3597.
572 Lee, S.G., Lee, D.H., Kim, Y., Chae, B.G.,Woo, N.C., 2003. Rare Earth Elements as Indicators of Groundwater
573 Environment Changes in a Fractured Rock System:Evidence from Fracture-Filling Calcite. Applied

574 Geochemistry 18, 135-143.

575 Diaz, H.G., Lewis, R., Miller, C., Fuentes, C.C., 2013. Evaluating the Impact of Mineralogy on Reservoir Quality
576 and Completion Quality of Organic Shale Plays. AAPG Rocky Mountain Section Meeting, Salt Lake City,
577 USA.

578 Nie, G.-Q., Li, X.-P., Dan, Y., Liang, B., Zhang, Q.-Y, Li, J.-R., Ji, S.-C., 2021. Burial and thermal history of mud
579 shale in Niutitang formation of lower Cambrian in southern Guizhou depression:A case study of Guidudi well
580 1. Carsologica Sinica 40, 760-767.

581 Dan, Y., Yan, J.-F., Bao, S.-J., Lang, B., Ma, L., Nie, G.-Q., Cao, J.-F., Ji, S.-C., Han, K., 2023. Discovery of
582 Sinian-Cambrian multi-tier shale gas in Guidandi-1 well of southwest margin of Xuefeng uplift. Geology in
583 China 50, 291-292.

584 Ge, M.-N., Chen, K., Chen, X.-L., Wang, C.,Bao, S.-J., 2020. The influence factors of gas-bearing and geological
585 characteristics of Niutitang Formation shale in the southern margin of Xuefeng Mountain ancient uplift: A
586 case of Well Huangdi 1. Geology in China 3, 533-544.

587 Ge, M.-N., Bao, S.-J., He, W., Chen, X.-L., Lin, T., Chen, K., 2018. The discovery of shale gas in Lower Cambrian
588 marine shale gas at Huangdi-1 Well in Huangping region of northern Guizhou. Geology in China 45, 851-852.

589 Guo, X.-S., 2014. Rules of Two-Factor Enrichiment for Marine Shale Gas in Southern China——Understanding
590 from the Longmaxi Formation Shale Gas in Sichuan Basin and Its Surrounding Area. Acta Geologica Sinica
591 88, 1209-1218.

592 Guo, T.-L., Zhang, H.-R., 2014. Formation and enrichment mode of Jiaoshiba shale gas field,Sichuan Basin.
593 Petroleum Exploration and Development 41, 28-36.

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Figures and Tables:

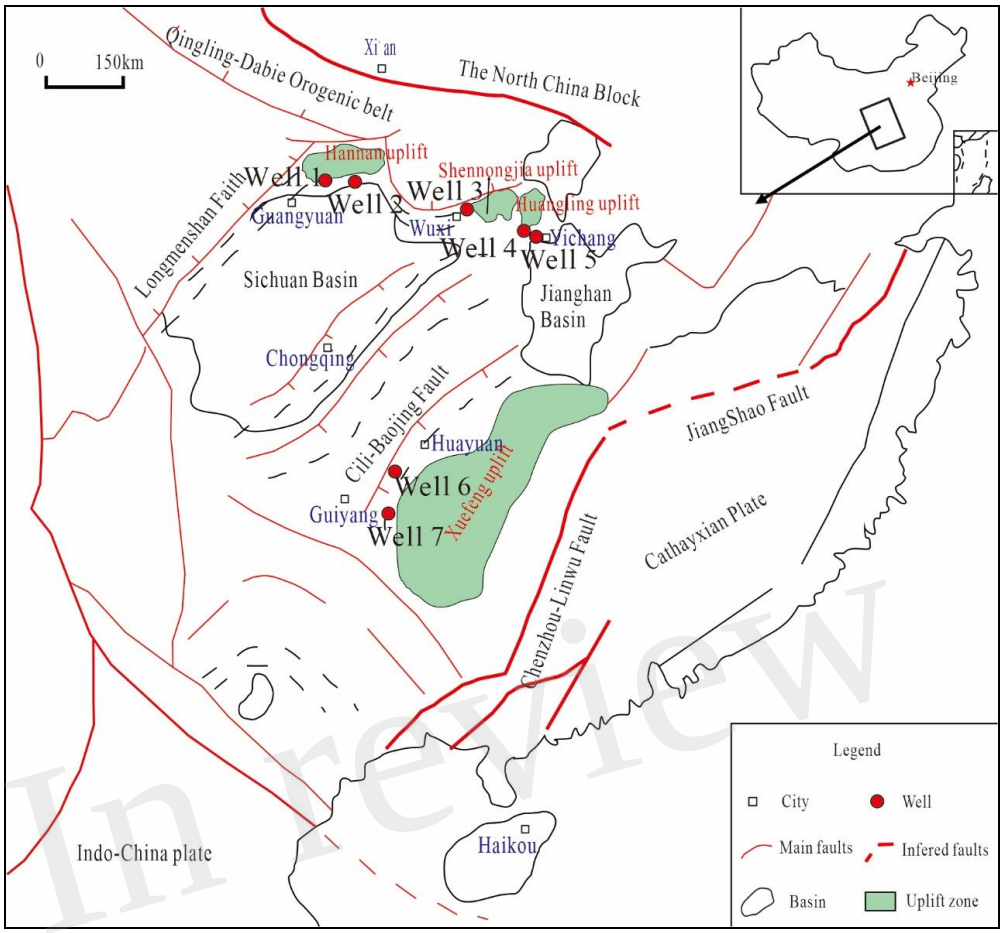

Fig.1. Study area and drilling structure location.

Well 1 and 2 belong to the periphery of Hannan Palaeohigh, Well 3 belong to the periphery of Shennongjia Palaeohigh, Well 4 and 5 belong to the periphery of Huangling Palaeohigh, and Well 6 and 7 belong to the periphery of Xuefeng Palaeohigh.

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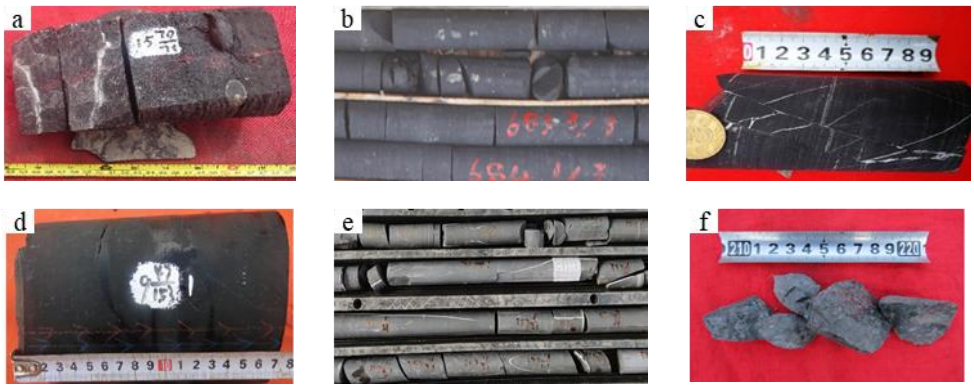

603 Fig.2 Core fractures of Niutitang Formation in different drilling wells.

604 (a) Core fracture of Niutitang Formation in Well 1, along with bedding fracture, are partially filled;

605 (b) The core fracture of Niutitang Formation in Well 2, along with the bedding joint, is not filled;

606 (c) The cracks of Niutitang Formation in Well 3 are filled with calcite, and the filling degree is

607 high; (d) The core crack of Niutitang Formation in Well 4 is open and not filled; (e) Niutitang

608 Formation of Well 6 has high Angle shear fracture and high filling degree; (f) Core fracture of

609 Niutitang Formation, Well 7, Slip cracks, core breakage.

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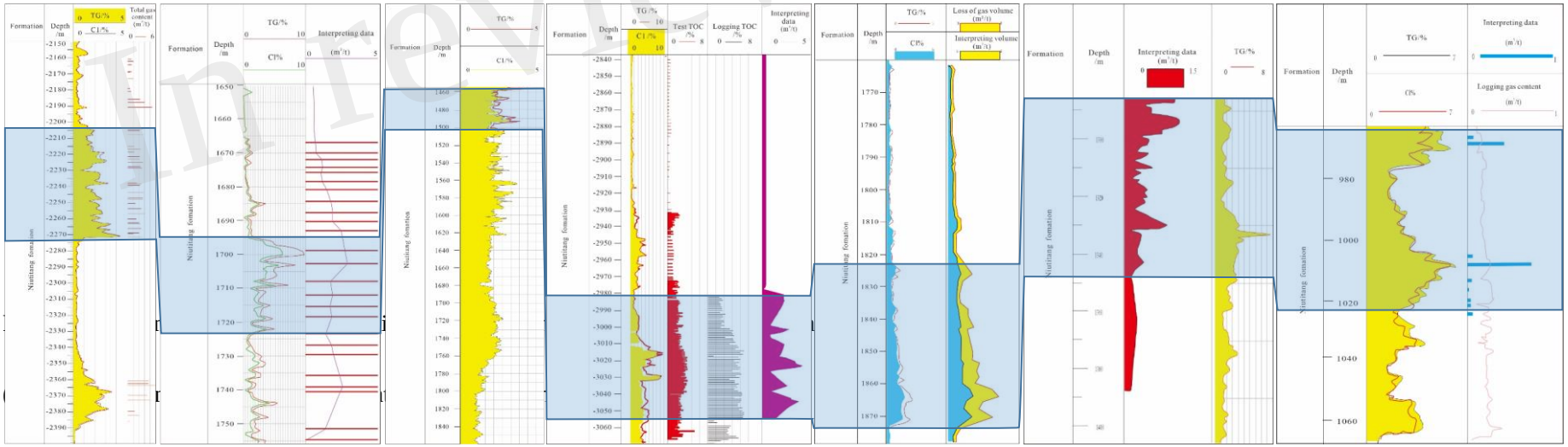

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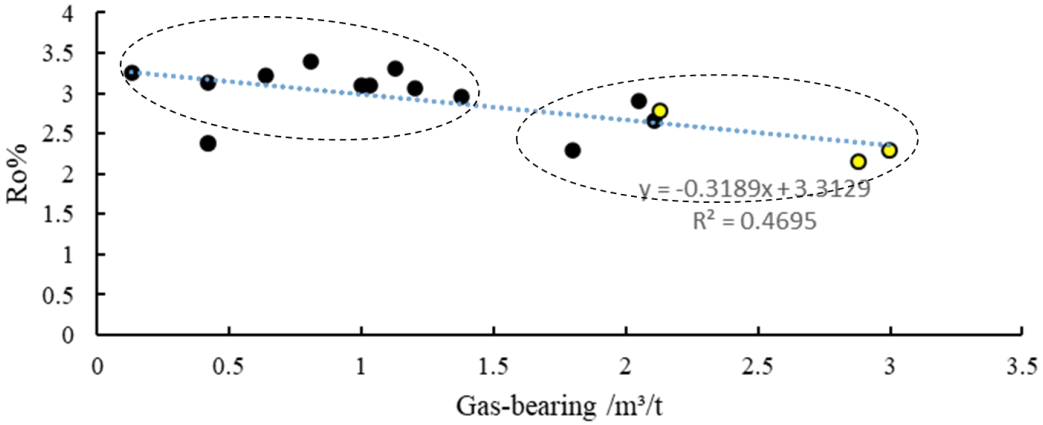

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615 Fig.4 Relationship between Ro and gas content

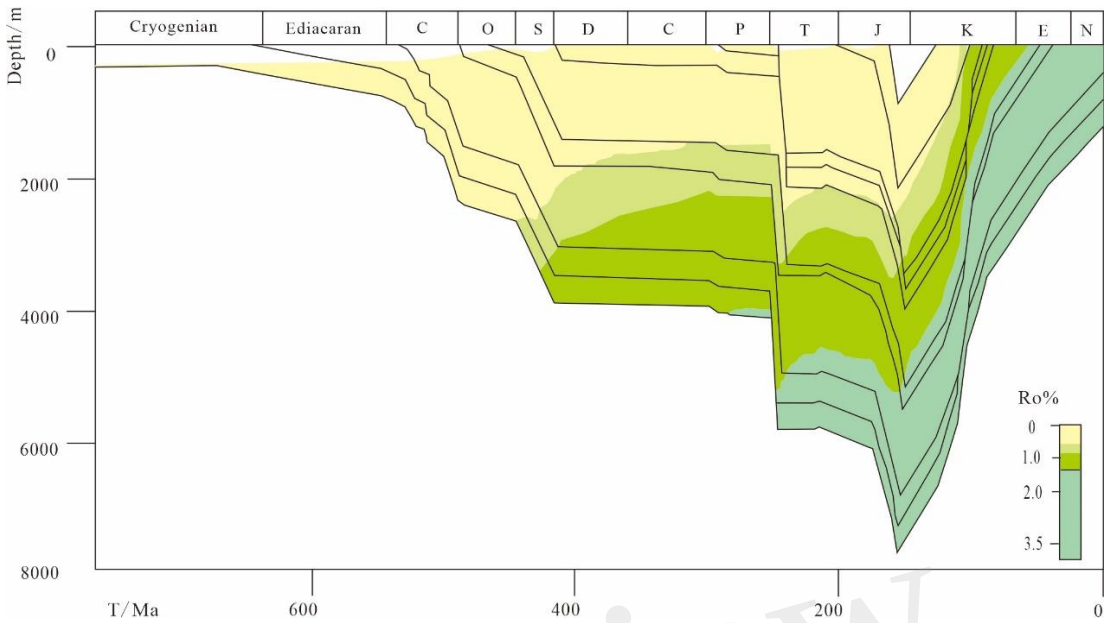

Fig.5 History of sedimentary burial in Huangling palaeouplift

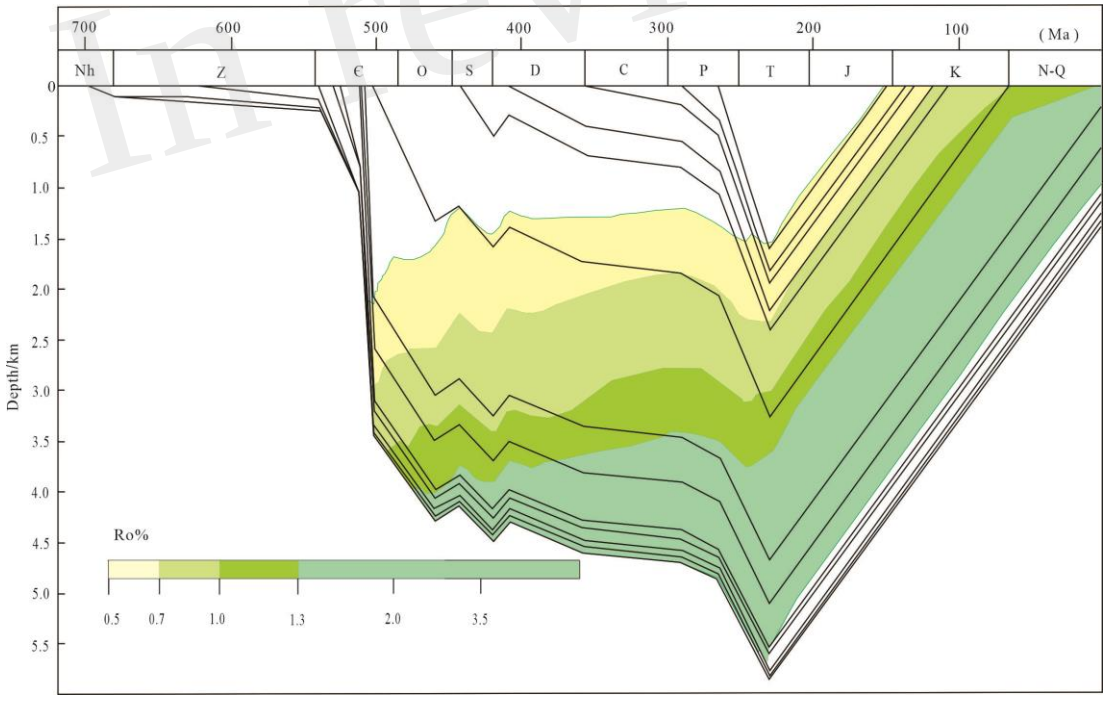

Fig.6 History of sedimentary burial in Xuefeng palaeouplift

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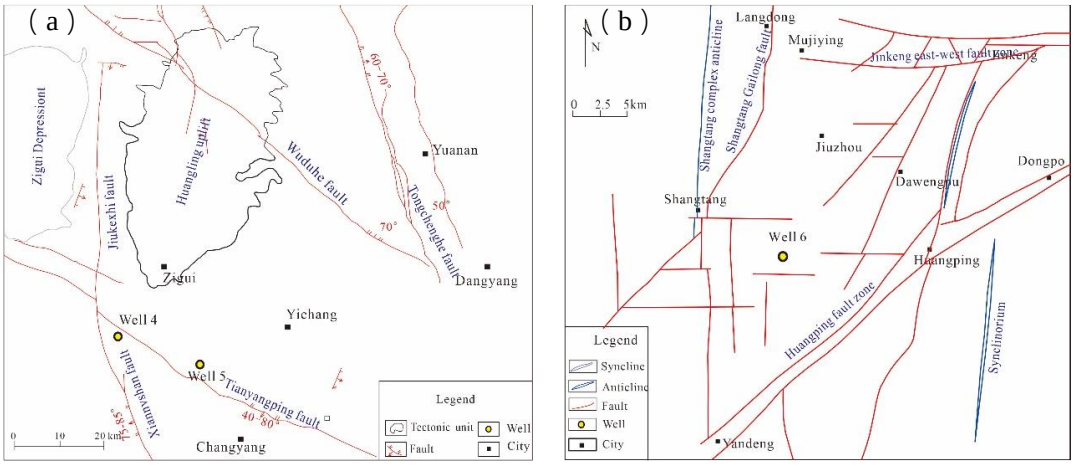

622 Fig.7 Distribution of major faults.

623 (**a**) periphery of Huangling Uplift. (**b**) periphery of Xuefeng Uplift.

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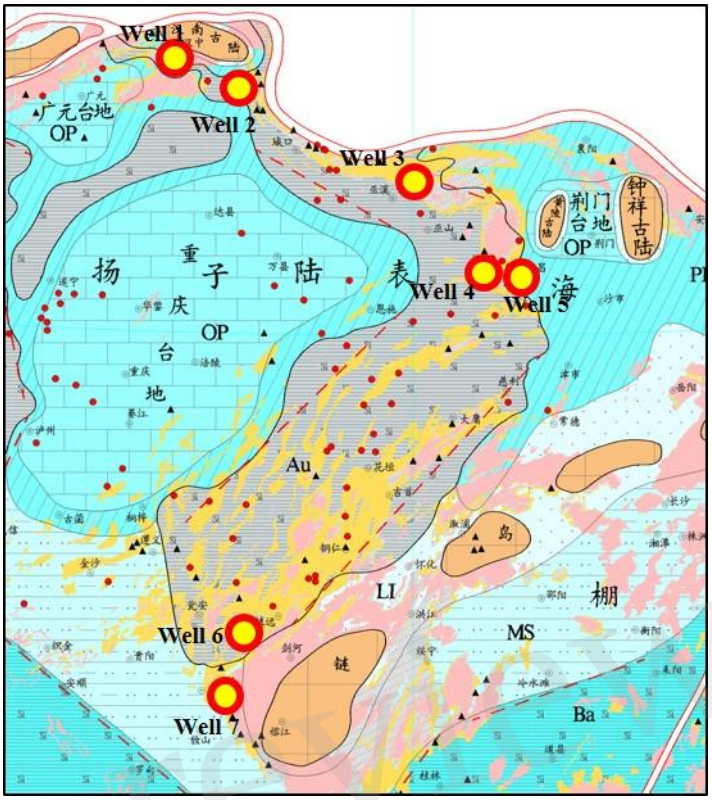

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627 Fig.8 Sedimentary facies of Niutitang Formation in the study area (modified by Zhai Gangyi)

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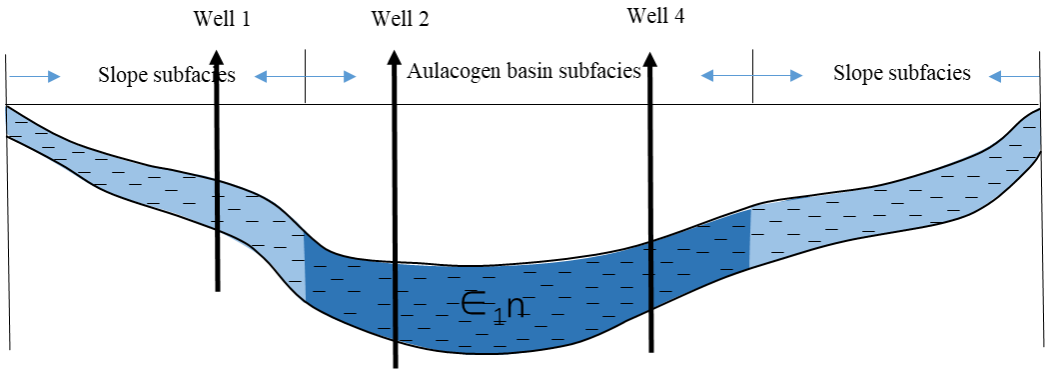

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630 Fig.9 Schematic diagram in the Aulacogen basin sedimentary subfacies of Niutitang formation

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632 **Tables:**

633 Table 1 Information of 7 wells

Well number	Geographical position	Tectonic position	Well type	Formation	Depth m	Start drilling formation	Completed formation	Hydrocarbon indication
1	Nanzheng, Shaanxi	Between Hannan Uplift and Micang Mountain uplift	Parameter well	Niutitang Formation	2150-2380	Permian	Nanhuan (Nantuo Formation)	Gas showing
2	Zhenba,Shaanxi	Southeastern margin of Micang Mountain uplift	Survey well	Niutitang Formation	1670-1750	Silurian	Sinian (Dengying Formation)	gas show strong
3	Shennongjia, Hubei	Northern wing of Shennongjia complex anticline	Survey well	Niutitang Formation	1454-1852	Silurian	Sinian (Dengying Formation)	No gas show
4	Changyang, Hubei	South margin of Huangling uplift	Parameter well	Niutitang Formation	2600-3069	Cambrian	Nanhuan (Nantuo Formation)	Industrial gas flow
5	Dianjun,Hubei Province	South margin of Huangling uplift	Parameter well	Niutitang Formation	1787-1871	Cretaceous	Nanhuan (Nantuo Formation)	Industrial gas flow
6	Huangping, Guizhou	Southwest margin of Xuefeng uplift	Survey well	Niutitang Formation	1286-1406	Cambrian	Nanhuan (Nantuo Formation)	Gas showing
7	Danzhai, Guizhou	Southwest margin of Xuefeng uplift	Survey well	Niutitang Formation	960-1070	Cambrian	Sinian (Doushantuo Formation)	Gas showing

634

Table 2 Basic geological parameters of 7 wells

Well number	Fault/structure	Lithology	Thickness /m	TOC /%	R_0 /%	Gas content m^3/t	Production $*10^4/d$	Brittle mineral /%	Porosity /%	permeability /mD	Fracture
1	Less/ weak deformation	Black carbonaceous shale	103.5	0.52-3.02/1.5	2.48-4.36/3.0	0.2-4.4	inproductivity	52.7-74.1	0.02-5.17/2.01	0.00053-0.0041/0.0008	rich
2	Less/ weak deformation	Dark grey siliceous carbonaceous shale interspersed with carbonaceous siltstone	90	0.88-8.61/3.37	2.04-3.14/2.66	0.77-3.39	inproductivity	40.6-64.8/53.6	/	/	rich
3	Many/ strong structure	Gray-black calcareous silty mudstone interbedded with argillaceous limestone	397.86	0.49-4.14/1.96	3.02-3.25	0.0002-0.13/0.032	inproductivity	20-74/50	1.45-8.04/3.33	0.0005-0.004/0.0015	are mostly filled
4	Less/Structural stability	Shale, mixed with argillaceous limestone and argillaceous siltstone	468.5	0.04-3.88/2.01	2.0-2.77	0.26-4.48	7.83	55-75	2.01-3.61/2.88	0.00031-0.00078/0.00054	rich
5	Less/Structural stability and simple	Gray-black gray shale with dark gray argillaceous limestone	86	0.43-10.45/2.62	2.06-2.66/2.29	0.58-5.48	6.02	45-75	1.48-2.5	/	rich
6	Many/ Strong structure	Black carbonaceous shale	119.95	0.60-8.89/3.55	1.43-2.81/2.37	0.09~1.31/0.42	inproductivity	37~68/51	0.2 ~ 1.8/0.51	0.0001-0.01/0.001	Slip fracture
7	Many/ Strong structure	Black carbonaceous mudstone	105	0. 25-8.72/3.55	3.26-4.4	0.06~1.97	inproductivity	35.1-51.8/43.5	0.65-1.21	0.001-0.012	are mostly filled

Note: "/" represents the average value.

Figure 1.JPEG

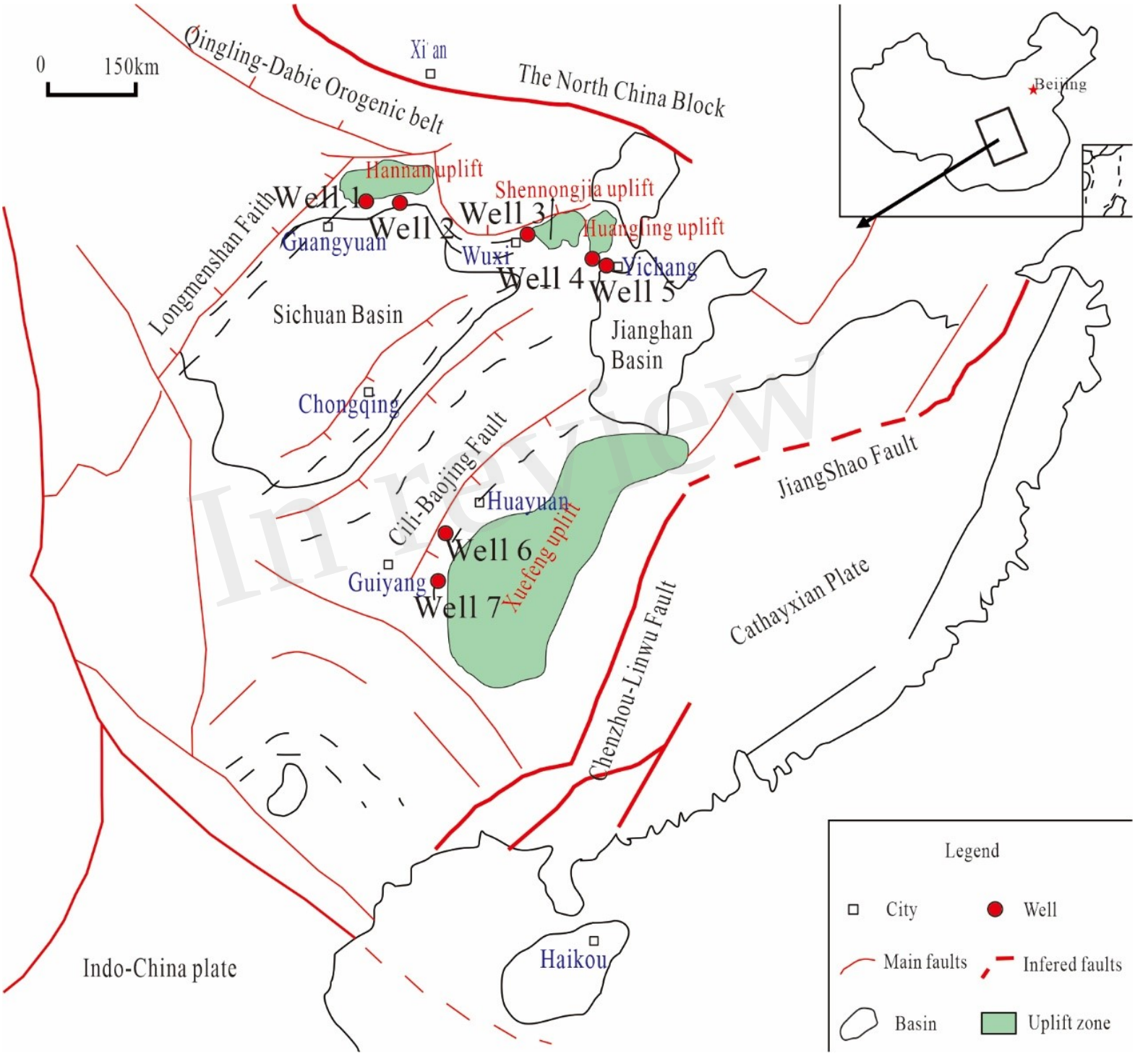


Figure 2.JPEG

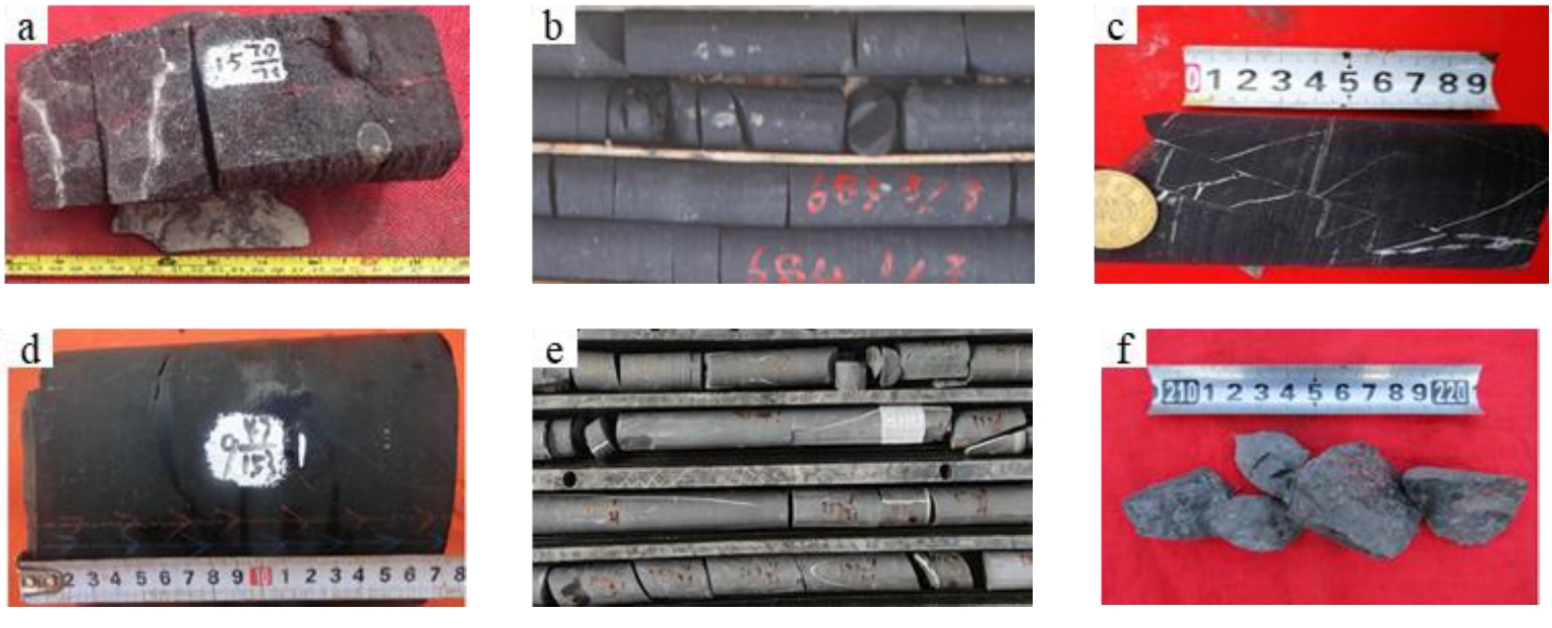


Figure 3.JPEG

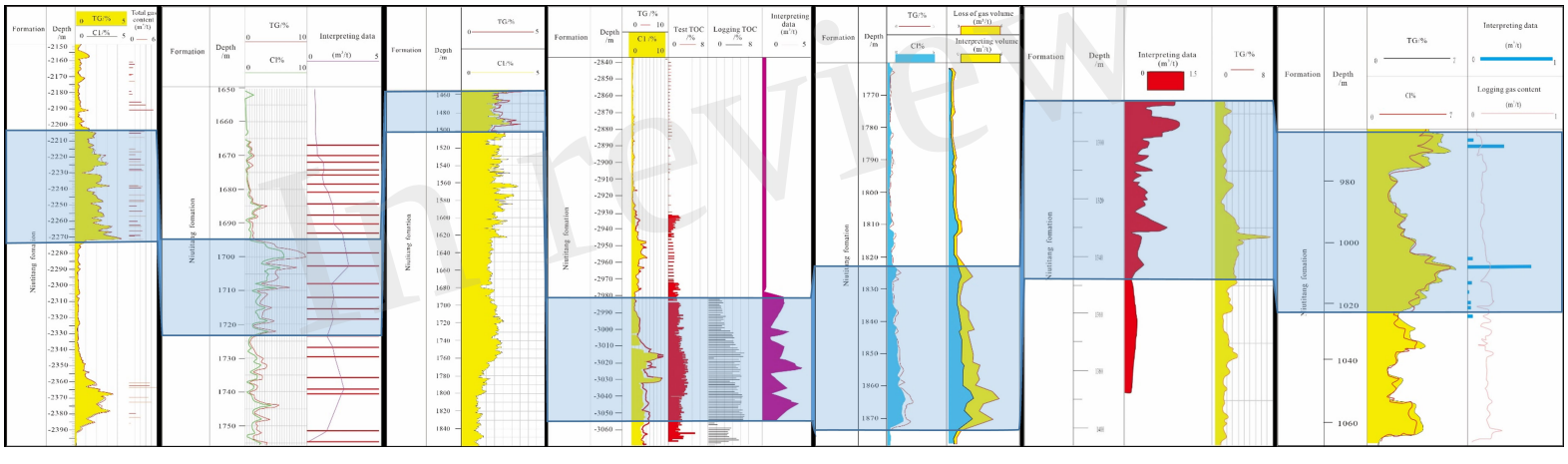


Figure 4.JPEG

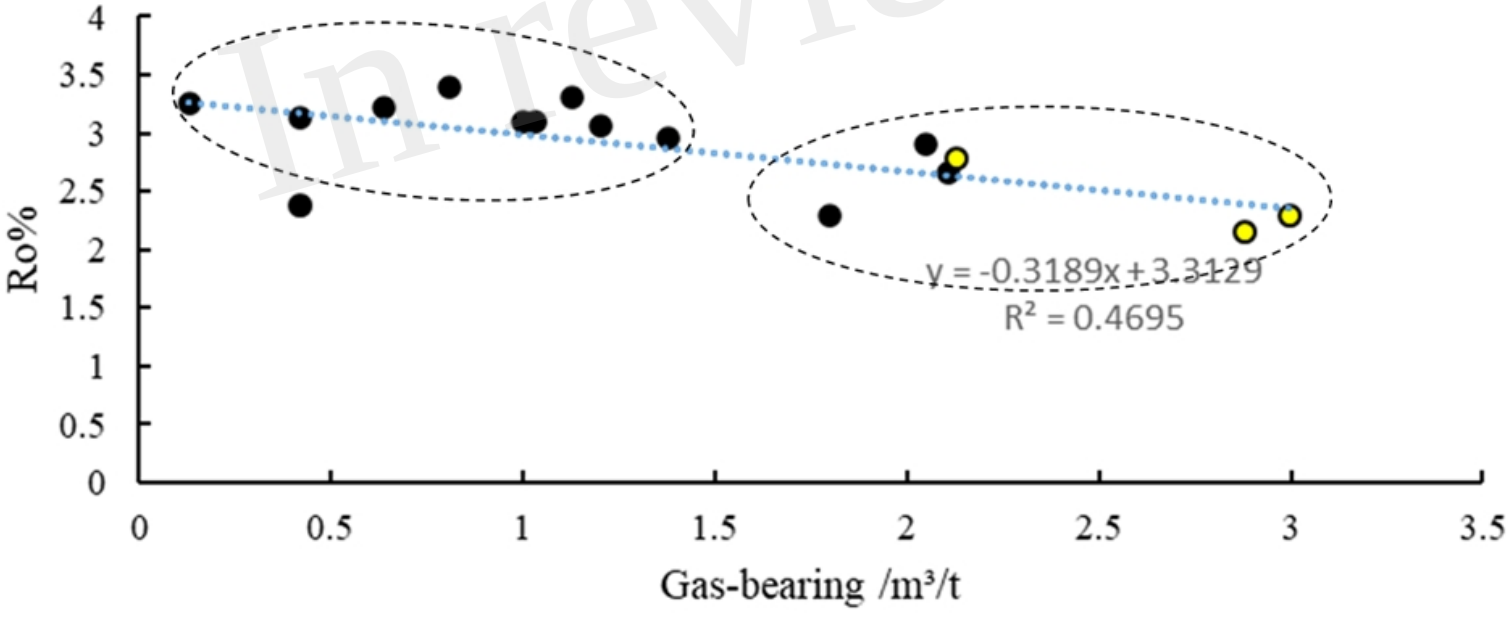


Figure 5.JPEG

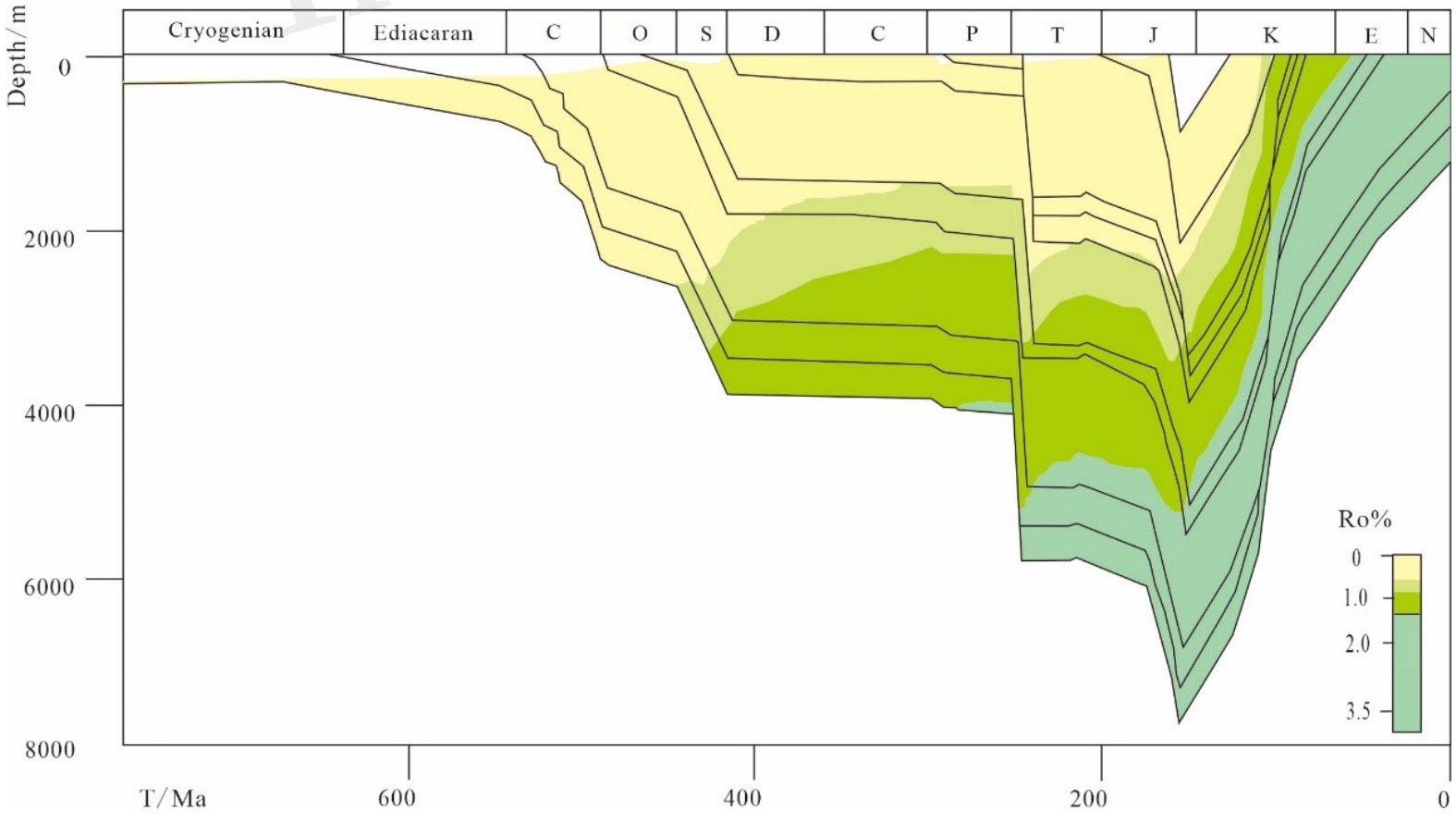


Figure 6.JPEG

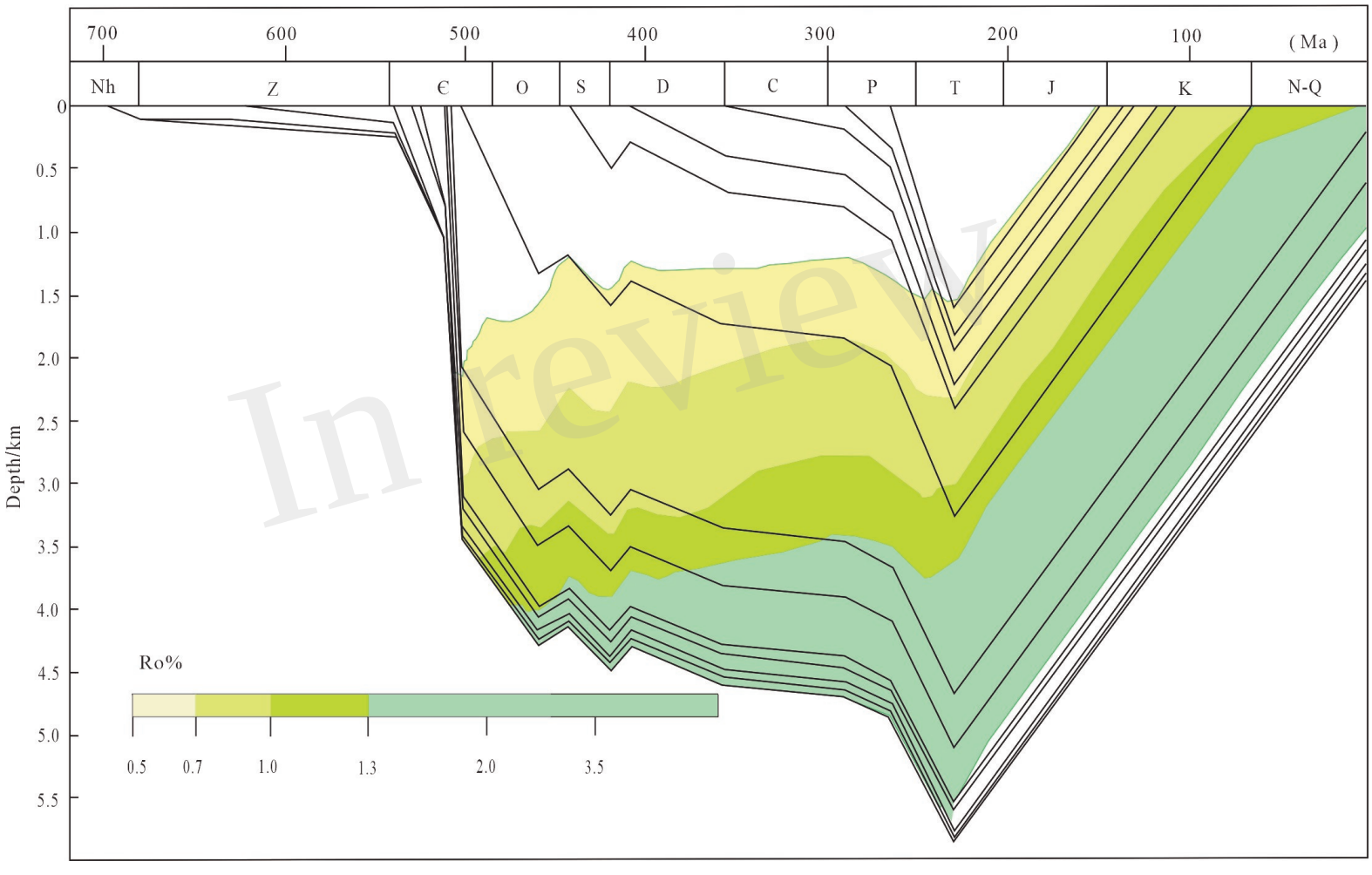
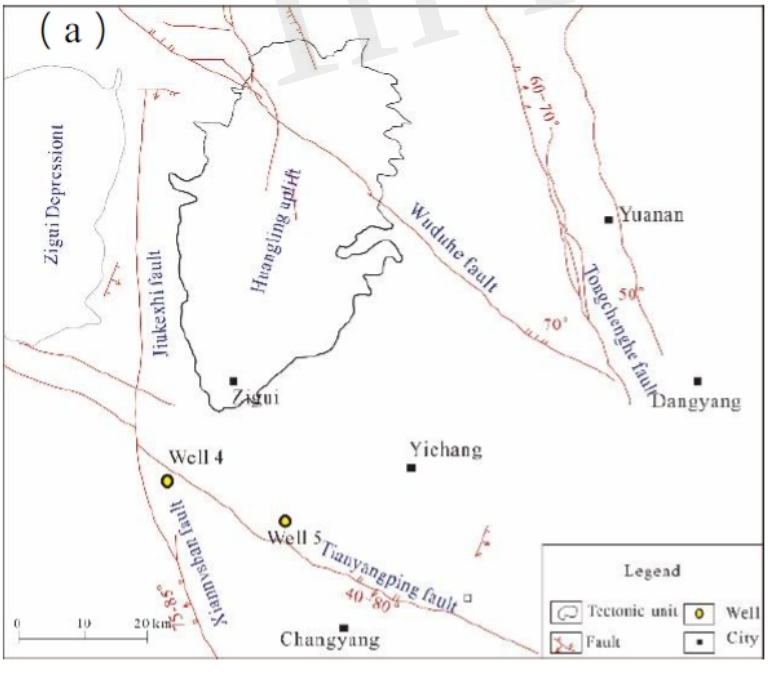


Figure 7.JPEG



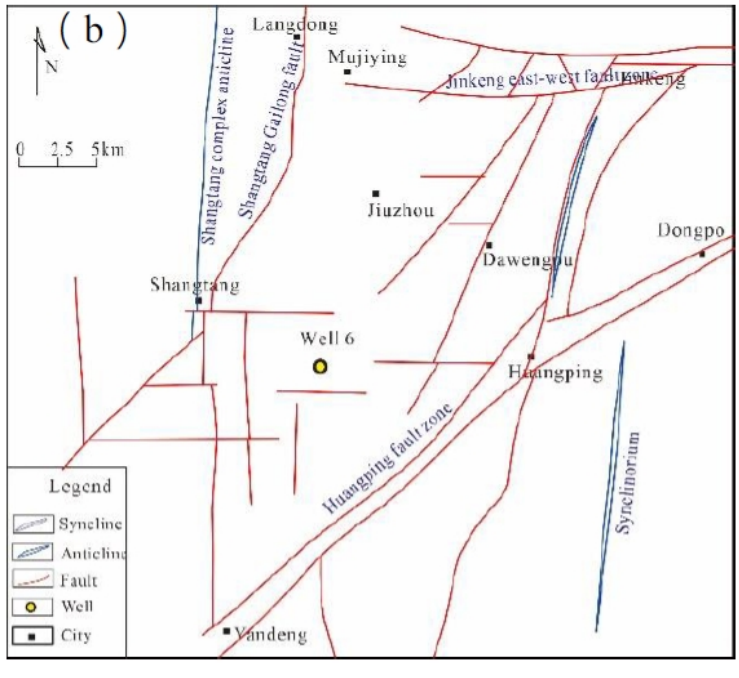


Figure 8.JPEG

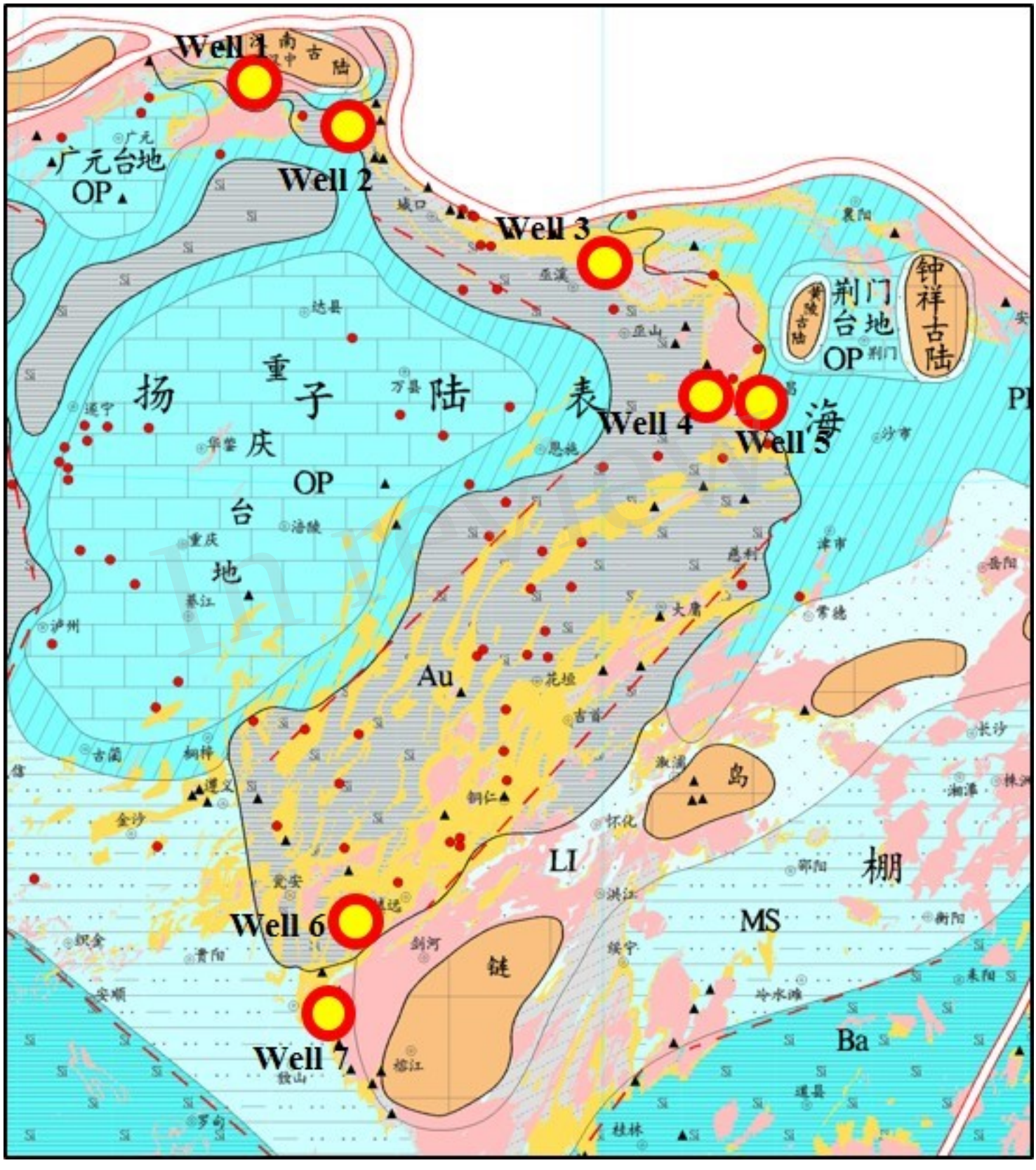


Figure 9.JPEG