

Article

Reservoir Characteristics of Normally Pressured Shales from the Periphery of Sichuan Basin: Insights into the Pore Development Mechanism

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Abstract: Reservoir characteristics and the occurrence mechanism of shale gas outside of the Sichuan Basin are the research hotspots of normally pressured shales in China. Taking shales on the Anchang syncline from the periphery of the Sichuan Basin as an example, X-ray diffraction, organic geochemistry, and rock physical experiments were carried out to analyze the reservoir characteristics and their main geological controls on the normally pressured shales. The mineralogical results show that the studied shales from the Anchang syncline are mainly siliceous shales with a high quartz content (average of 57%). The quartz content of these normally pressured shales is of biological origin, as shown by the positive correlation between the quartz and organic carbon (TOC) contents. The average porosity of the studied shales is about 2.9%, which is lower than shales inside the Sichuan Basin. Organic matter pores are likely the primary storage space of the normally pressured shale gas, as shown by the positive relationship between the TOC content and porosity. However, scanning electron microscopy observations on the studied shales show that the pores in these normally pressured shales are poorly preserved; many pores have been subjected to compression and deformation due to tectonic movements. Compared to shales inside the Sichuan Basin, the effective thickness of shales outside of the Sichuan Basin is thin and the stratum dip is large. Thus, shale gas outside of the Sichuan Basin is apt to escape laterally along the bedding of the strata. After losing a significant amount of shale gas, the gas pressure decreases to normal pressure, which makes it difficult for the pores to resist compaction from the overlying strata. This is probably why most shale gas reservoirs outside of the Sichuan Basin are normally pressured, while the shale strata inside the Sichuan Basin are commonly overpressured. This study provides insights to understand the pore development and hydrocarbon occurrence on normally pressured shales outside of the Sichuan Basin.

Keywords: normally pressured; shale gas; reservoir characteristics; preservation condition; outside of the Sichuan Basin



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1. Introduction

Shale gas is referred to as the natural gas that resides in organic-rich mudstones and shale systems, and occurs in a free state and adsorbed state [1]. During the past decade, China has made great breakthroughs in the exploration and development of shale gas inside the Sichuan Basin. The target formations primarily include the Ordovician Wufeng (O₃W)–Lower Silurian Longmaxi (S₁L) Formations [2,3]. Shale gas from these formations inside the Sichuan Basin is commonly from overpressured shale gas reservoirs (the ratio between the reservoir pressure and hydrostatic pressure is larger than 1.2). Several overpressured shale reservoirs have been discovered inside the Sichuan Basin, including the Jiaoshiba shale gas reservoir, Changning shale gas reservoir, Zhaotong shale gas reservoir, etc. Notably,

the commercial extraction of shale gas from these overpressured shale reservoirs has been achieved [4–6].

Compared to the shale gas reservoirs inside the Sichuan Basin, shales outside of the Sichuan Basin are commonly normally pressured, i.e., the ratio between reservoir pressure and hydrostatic pressure is between 0.8 and 1.2. The distribution area of these normally pressured shales is wide, and the amount of shale gas resources is considerable [7–9]. At the same time, most of the overpressured shale reservoirs are commonly located in tectonically stable zones. Thus, it is relatively easy for overpressured shales to develop inside the Sichuan Basin. However, compared to the overpressured shales inside the Sichuan Basin, the Wufeng–Longmaxi shales outside of the Sichuan Basin are mainly located at strong tectonic deformation zones. These normally pressured shales outside of Sichuan Basin were formed in the sedimentary environments of the shallow-water shelf to deep-water shelf, differing significantly from the overpressured shales [2]. This means that the material basis and preservation condition of normally pressured shales outside of the Sichuan Basin might be worse than the overpressured shales inside the Sichuan Basin [10]. It is also challenging to commercially extract shale gas from the normally pressured shale reservoirs which have experienced multi-stage tectonic movements. However, little research about the reservoir characteristics of normally pressured shales outside of the Sichuan Basin has been published and only a few data exist on the geological background of normally pressured shales. In particular, many kinds of pores, including organic matter-hosted pores, can be well preserved in overpressured shales due to the effective support of fluid pressure [11,12]. However, the role of fluid pressure on the pore systems of normally pressured shales is still very much a subject for debate [13]; the difference in the physical characteristics between the normally pressured and overpressured shales is poorly understood.

Extracting shale gas from the normally pressured shale reservoirs is the focus and difficulty of unconventional reservoirs at present. Most shale gas reservoirs in North America are normally pressured, including the Barnett, Fayetteville, and Marcellus shales [14–17]. In China, the technically recoverable reserve of natural gas from the normally pressured shale reservoirs outside of southern China is estimated to be over $9.08 \times 10^{12} \text{ m}^3$ [13]. Recently, operators have begun turning their attention to the normally pressured shale reservoirs in the periphery of the Sichuan Basin. Several gas wells were drilled in the normally pressured shale reservoirs in Zheng'an, Pengshui, Wulong, and other areas outside of the Sichuan Basin. The initial natural gas production reached $2.0 \times 10^4 \sim 6.4 \times 10^4 \text{ m}^3/\text{d}$ in these normally pressured shale formations after hydraulic fracturing treatments [18]. This indicates that the shale gas from the normally pressured shale reservoirs in the periphery of the Sichuan Basin has considerable potential for geological exploration and industrial development. The physical characteristics of the reservoirs are the basis of the geological evaluation of shales. However, there has been little investigation into the reservoir development characteristics of normally pressured shales. The initial analysis of normally pressured shales has found that their sedimentary environment and preservation conditions are notably different from those of overpressured shales [19,20].

Although there is a lot of research on shale gas in the Sichuan Basin, most of it is on the analysis of shales inside the Sichuan Basin, and shales outside of the Sichuan Basin are different from shales inside the basin. There is little research about the reservoir characteristics of normally pressured shales outside of the Sichuan Basin and only a few data exist on the geological background of normally pressured shales. Therefore, this research focuses on shales outside of the Sichuan Basin. Taking the gas shales at the Anchang Syncline from the Periphery of the Sichuan Basin as an example, this paper carries out detailed investigations on the reservoir characteristics and pore development mechanism of the normally pressured shales. Core observations, organic geochemical experiments, and petrophysical measurements were conducted to analyze the mineralogy, pore network structure (pore types and pore sizes), and petrophysical characteristics of gas shales. The characteristic parameters of the reservoir of these normally pressured shales outside of the Sichuan Basin were compared to the overpressured shales inside the

Sichuan Basin. Furthermore, geological factors controlling the reservoir characteristics of the normally pressured shales were also discussed. The aim of this study was to (1) confirm whether there is a difference in the reservoir characteristics of shales from inside and outside the Sichuan Basin and (2) discuss why shale reservoirs outside the basin are normally pressured. Therefore, this paper aims to answer the question of why gas shales outside of the Sichuan Basin are normally pressured whereas shales inside of the basin are overpressured and to provide a better understanding of the occurrence space of hydrocarbons in the complex tectonic deformation area outside of the Sichuan Basin. Furthermore, this research will be interesting for both academics and industry since shale gas resources outside of the Sichuan Basin are the focus of exploration for unconventional natural gas resources in China.

2. Geological Background

The studied area is situated on the Anchang syncline in the southeast of the Sichuan Basin. The Anchang syncline in the Wuling Mountain fold belt is located in Zheng'an County in the north of Guizhou Province (Figure 1). Tectonically, it belongs to the southern edge of the middle-upper Yangtze plate and sits adjacent to the Daozhen syncline in the north [21,22]. Since the metamorphic crystalline basement of the Yangtze plate was formed during the Xuefeng tectonic movement, the northern Guizhou area has experienced the superimposed tectonic movements of the Caledonian, Indosinian, Yanshanian, and Himalayan orogenies. From the Late Ordovician period to the Early Silurian period in geological history, the studied area was surrounded by the uplift of the Sichuan Basin in the north, the uplift of the central Guizhou area in the south, and the uplift of the Xuefeng mountains in the southeast, due to the Caledonian movements. The Wufeng Formation (Late Ordovician) and the Longmaxi Formation (Early Silurian) were deposited in a shallow marine sedimentary environment. At that moment, large-scale transgressions occurred in the study area, resulting in an anoxic environment and the deposition of organic-rich shales [23,24].

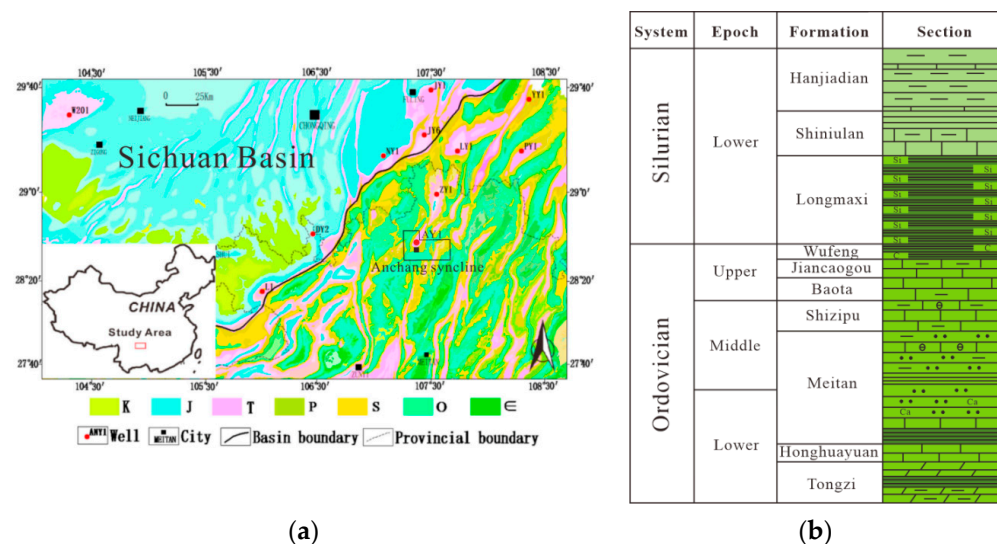


Figure 1. (a) The geological map of the Sichuan Basin and the Anchang Syncline. (b) The integrated stratigraphic column of the Anchang Syncline from Ordovician to Silurian.

Due to the multiple tectonic compression movements from the Late Yanshan to the Himalayas, a narrow and steep syncline, namely the Anchang syncline, was generated in Zheng'an County. Meanwhile, complicated faults developed in this area. This Anchang syncline generally spreads from the northeast to the south and west. Its axial trace is clear and slightly S-shaped, with an axial direction of 20~30° from the northeast to the north. Geologically, the Anchang syncline slopes gently in the southwestern part and is steep in

the northeastern part. The Jurassic-Triassic strata exposures are in the core of the syncline, while the Silurian-Ordovician strata exposures are in the wing of the syncline. Due to the superimposed transformation of Yanshanian tectonic movements, the Anchang syncline formed a fold mainly in the northeast (NE) to the north-northeast (NNE) directions. There are three groups of faults that are in the NE, near the SN, and near the EW directions, and the faults are developed at the syncline core (Figure 2). The target formations at the Anchang syncline are the Wufeng and Longmaxi gas shales, and their burial depths are between 2000 and 3000 m. The distance from the drilling well sites to the outcropping area is 3~5 km. In addition, the stratigraphic dip of the target formations in the eastern part ranges from 25° to 45°, and the dip angle in the western part is 25~35°. The pressure coefficient of the target formations ranges from 1.0 to 1.1, which is a typical normally pressured shale gas reservoir.

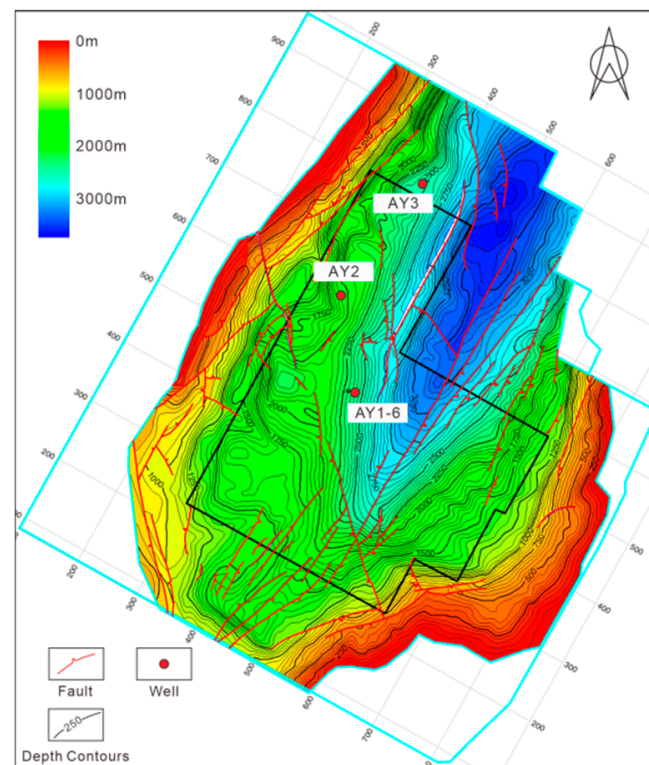


Figure 2. The geological structure about the bottom boundary of the Wufeng–Longmaxi Formation in the Anchang syncline in the northern Guizhou area. AY1-6, AY2, and AY3 are shale gas wells.

3. Sample and Experiments

3.1. Sample Preparation

A total of 50 core samples were collected from the AY1-6, AY2, and AY3 wells drilling through the target formations in the Anchang syncline. All the shale samples were obtained from the productive Ordovician Wufeng–Silurian Longmaxi Formations with a sampling interval of about 1~1.5 m to consider the systematic variability of mineralogy and organic matter characteristics. Fresh core samples were quickly preserved by coating them in several layers of plastic foil and then transferring them to the laboratory for experiments. Cylindrical sample plugs with a diameter of 25.4 mm were wire-electrode cut parallel to the bedding and used for porosity and permeability measurements. Shale samples were also crushed into particles (about 100 mesh, particle size of about 0.15 mm) and prepared for bulk mineralogical composition analysis, total organic carbon (TOC) content, and pore size distribution measurements (low-temperature nitrogen adsorption). All the samples were dried at 105 °C under vacuum for at least eight hours until weight constancy.

3.2. Experiments

3.2.1. X-ray Diffraction Analysis

X-ray diffraction (XRD) was used to determine the mineralogical compositions of the studied samples. XRD analysis was performed on powdered samples to describe bulk mineralogical compositions using a Rigaku SmartLab X-ray diffractometer. The stepwise scanning rate of the X-ray diffractometer was 2° (2θ)/min, and the scanning step width was 0.02° (2θ). The recorded diffractograms were interpreted using commercial software and the typical minerals were semiquantitatively estimated.

3.2.2. Total Organic Carbon Content

TOC content was analyzed in the powdered samples using a LECO carbon/sulfur analyzer instrument. For TOC analysis, powder samples were first treated with dilute hydrochloric acid at about 60°C to remove carbonate. Then, the samples were combusted in oxygen at 1350°C in a combustion oven. The released carbon dioxide was detected by an infrared detector and the TOC content was calculated. The experimental procedure follows the Chinese Oil and Gas Industry Standard (GB/T 19145-2003) [25].

3.2.3. Pore Size Distribution by Low-Temperature Nitrogen Adsorption

The pore size distribution of the shale samples was measured using a Micromeritics ASAP 2020 Surface Area and Porosity Analyzer. Low-temperature N_2 physical adsorption experiments were conducted to record the adsorbed amount of nitrogen at -196.2°C with a relative pressure ranging from 0 to 0.995. The adsorbed data with relative pressure from 0.05 to 0.3 was analyzed for the specific surface area using the Brunauer–Emmett–Teller method, while the adsorption isotherm was interpreted for pore size distribution according to the Barrette–Joyner–Halenda (BJH) theory [26,27].

3.2.4. Porosity and Permeability

The porosity of the cylindrical samples was evaluated according to Boyle's law. The skeletal densities were measured using helium expansion on the studied samples, while the bulk densities were determined using an electrical balance and vernier caliper. Then, the porosity values were calculated from the difference between skeletal density and bulk density.

The permeability of the confined cylindrical samples was measured using the non-steady state technique (pulse-decay permeability). Permeability measurements were performed at a confining pressure between 5 and 20 MPa. After charging a pressure pulse of about 0.5 MPa, the pressure difference between the upstream and downstream reservoirs was recorded with time. Then, the permeability was evaluated using the pressure difference according to the non-steady flow theory. The theory and experimental procedure of pulse-decay permeability have been previously discussed [28,29].

4. Results

4.1. Mineralogy

The drilling cores from the Anchang syncline show that the thickness of the Wufeng Formation is about 5 m. It is mainly comprised of gray-black shales and black carbonaceous shales with a thin layer of siliceous rocks. A thin layer of bioclastic limestone developed in the Guanyinqiao section at the top of the Wufeng Formation. Above the Wufeng Formation (O_3W) is the Longmaxi Formation (S_1L). The lower part of the Longmaxi Formation is primarily comprised of black carbonaceous shales with abundant graptolite (Figure 3), and the upper part is mainly gray mudstones and gray-green argillaceous siltstones. The total thickness of gas shales from the S_1L Formation in the Anchang syncline ranges from 18 to 20 m.

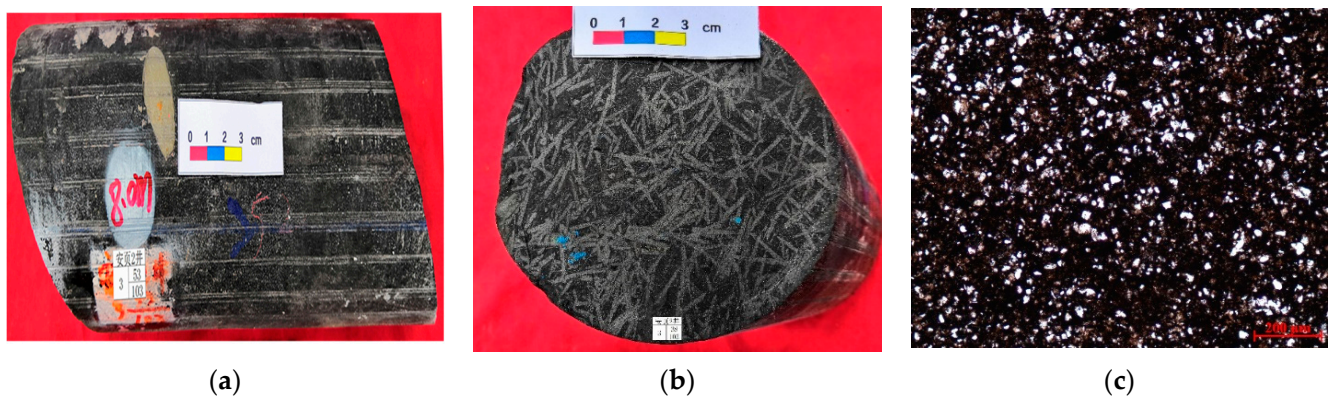


Figure 3. Shale cores of the Wufeng–Longmaxi Formation in the Anchang Syncline. (a) The recovered full-diameter shale core from the Longmaxi Formation, depth = 1964.79 m; (b) abundant graptolites in the shale core; and (c) quartz particles (white) in the shale core observed using a polarizing microscope.

The X-ray diffraction results show that quartz dominates in the shales from the Wufeng–Longmaxi Formation at the Anchang syncline. There is also a certain amount of clay minerals, feldspar, calcite, etc. (Figure 4). The quartz content ranges between 50% and 65.1%, with an average of more than 57%. The clay mineral content of the investigated shales is between 19% and 45%, with an average of 27.5%. The carbonate content is low, ranging from 0.7% to 9.7%. Only minor shale samples near the Guanyinqiao section have a high carbonate content. Shale samples in the Anchang syncline are rich in pyrite with an average content of about 3.5%. The clay minerals are mainly illite/smectite mixed clay, followed by illite and a little chlorite. In general, the quartz content of gas shales from the Wufeng–Longmaxi Formation in the Anchang syncline is higher than gas shales from the Jiaoshiba block, a national demonstration plot for developing shale gas inside the Sichuan Basin. Even the quartz content of these studied shales is a little higher than the siliceous shales in the lower member of Longmaxi Formation in the Jiaoshiba block (about 49% on average) [30,31], which is considered as the preferential section for the effective development of shale gas.

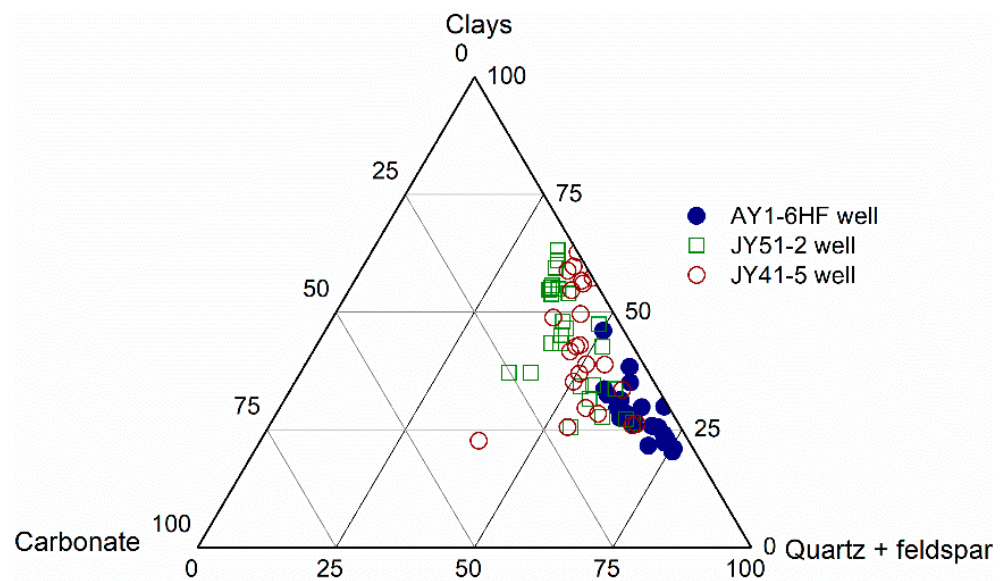


Figure 4. Mineralogical ternary plot of the Wufeng–Longmaxi shales from the Anchang Syncline and the Jiaoshiba Area (data from JY41-5 and JY51-2 wells are collected from [30,31]).

4.2. Organic Matter Characteristics

The organic matter abundance of shales is a key parameter for shale gas generation. The geochemical experiments show that the TOC content of the Wufeng–Longmaxi shales from the Anchang syncline is mainly between 3–6%, with an average of 4.4% (Figure 5). The proportion of samples with a TOC content greater than 5% is more than 50%, indicating that the abundance of organic matter in these samples is high. Vertically, the TOC content in the lower part of the Wufeng–Longmaxi Formation is high. The TOC content decreases slightly from the bottom part to the upper part of the Wufeng–Longmaxi Formation on the Anchang syncline.

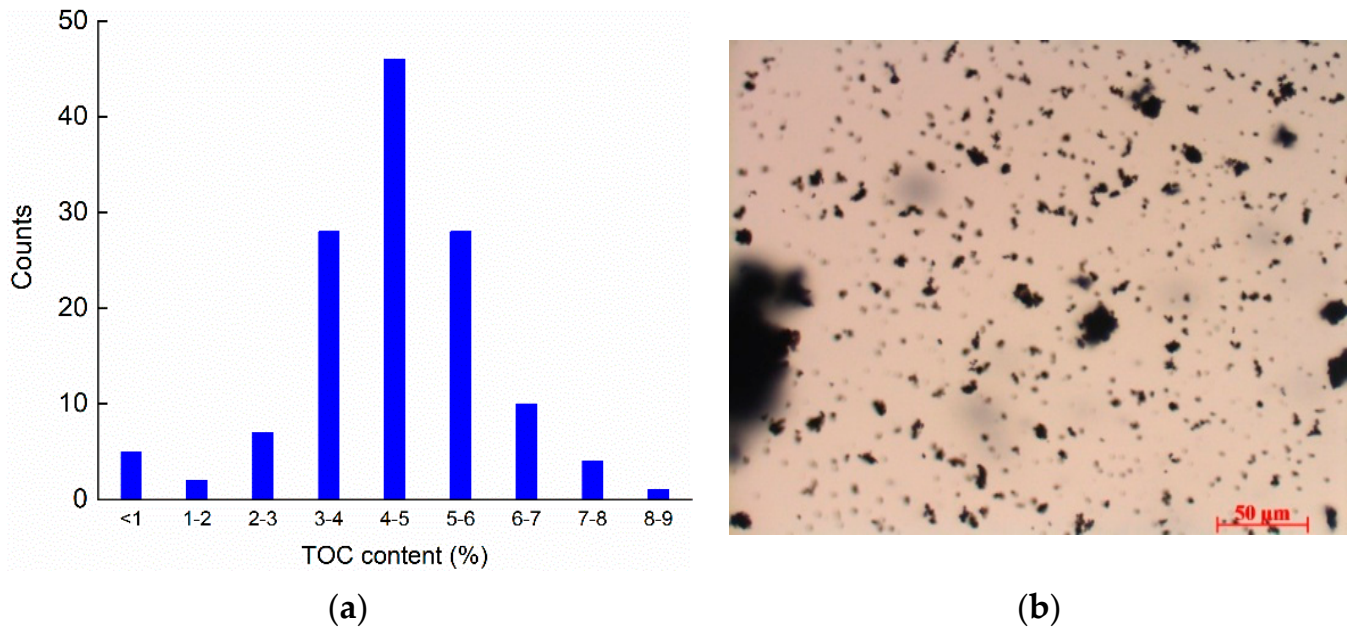


Figure 5. Organic matter characteristics of the investigated gas shales on the Anchang Syncline: (a) Histogram of the TOC content and (b) amorphous macerals of the sapropel (black) in shales at the Anchang syncline, observed using an optical microscope under transmitted light.

The type of organic matter in the shales from the Anchang Syncline is dominated by type I. The macerals are mainly sapropel (>85%), and the vitrinite is less than 5% (normal vitrinite). The inertinite content in the studied shales is in the range of 1~6% (Figure 5). No exinite was observed in the macerals of these shales. The bitumen reflectivity ranges from 2.6% to 3.1%, indicating that the investigated gas shales on the Anchang syncline are at the over-matured stage.

4.3. Pore Types from SEM

Scanning electron microscopy (SEM) observation shows that the pore types of the investigated gas shales on the Anchang syncline mainly include organic matter (OM) pores, pores of inorganic matter minerals, and fractures (Figure 6). The pore diameters of the organic matter pores measure dozens of nanometers on the SEM images (Figure 6a,d). However, the diameters of these organic matter pores are relatively smaller than gas shales from the Jiaoshiba block inside the Sichuan Basin [30,31]. The pore shapes of the investigated shales on the Anchang syncline are mostly oval and irregularly polyhedral. The inorganic matter pores are mainly interparticle pores of clay minerals. There are also some intercrystalline pores in the pyrite framboids and a few dissolution pores in the carbonates (Figure 6c,f). In addition, there are microfractures in these shales. The fractures are either between the clay minerals and rigid framework minerals (Figure 6b) or in the organic matter particles (Figure 6e). The microfractures, though limited in extension length, are important for free gas storage and migration.

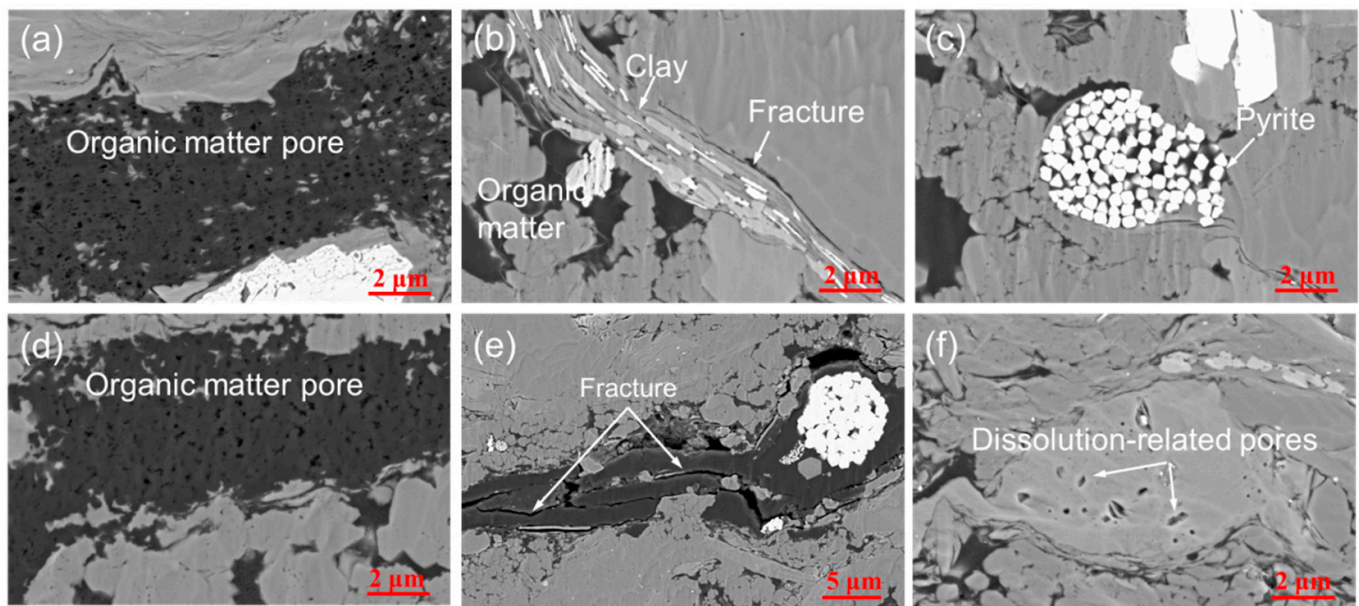


Figure 6. Pore types of shales in Wufeng–Longmaxi Formation of the Anchang Syncline. (a) Organic matter pores; (b) Fracture between clay minerals and framework minerals; (c) Intercrystalline pores in the pyrite framboid; (d) Organic matter pores; (e) Fractures in organic matter particles; (f) Dissolution-related pores in carbonates.

4.4. Pore Size Distribution by Low-Temperature Nitrogen Adsorption

Low-temperature nitrogen adsorption experiments were conducted to characterize the pore size distributions of gas shales from the Anchang syncline. The nitrogen adsorption-desorption isotherms of these shales are approximately type IV (Figure 7), according to the International Union of Pure and Applied Chemistry (IUPAC) classification [26]. The single-layer adsorption, multi-layer adsorption, capillary condensation, and external surface adsorption of nitrogen successively occur on the pores of these shales when the relative pressure increases from 0 to 1. These are the characteristics of typical mesoporous materials with certain fractures [26]. Nitrogen adsorption isotherms and desorption isotherms of the studied shales are separated when the relative pressures (P/P_0) are higher than 0.42, i.e., there are hysteresis loops in these isotherms. The hysteresis loops of the studied shales from the Anchang syncline mainly belong to the H3 type but also have a certain characteristic of the H2 type. These indicate that there are slit pores and ink-bottled pores in the samples. The pore size distributions of the studied shales, evaluated using the nitrogen adsorption data, are illustrated in Figure 7. The studied shales have wide pore size distributions, ranging from about 2 nm to more than 200 nm. The peak pore size is biased to the left, indicating that these shales are dominated by pores with a small diameter.

The Brunauer–Emmett–Teller equation was utilized to calculate the specific surface area using nitrogen adsorption data [26]. The specific surface areas (SSA) of the investigated gas shales from the Anchang syncline are between 20 and 25 m²/g, with an average of about 23 m²/g. The total pore volume (PV) of these shales varies from 0.025 to 0.035 cm³/g, with an average of 0.028 cm³/g. Compared to the Wufeng–Longmaxi Formation of the Jiaoshiba area in the Sichuan Basin [30,31], the SSA and PV of gas shales in the Anchang syncline are larger, which further indicates that pores with a small size are fairly developed in the investigated gas shales from the Anchang syncline.

4.5. Porosity and Permeability of Shales

The porosity of the investigated shale samples from the Anchang syncline ranges from 1.1% to 6.5%, with an average of about 2.9%. The porosity of these investigated shales at the Anchang syncline is lower than that from the Jiaoshiba block inside the Sichuan Basin

(3.3% on average) [30,31]. The permeability of shale cores perpendicular to the bedding ranges from $0.0008 \times 10^{-3} \mu\text{m}^2$ to $0.0088 \times 10^{-3} \mu\text{m}^2$, and the average permeability is about $0.0028 \times 10^{-3} \mu\text{m}^2$. Vertically, shales at the bottom of the Longmaxi Formation have the largest porosity and permeability, followed by shales at the Wufeng Formation. In general, shales at the top of the Wufeng–Longmaxi Formation of the Anchang syncline have poor physical properties.

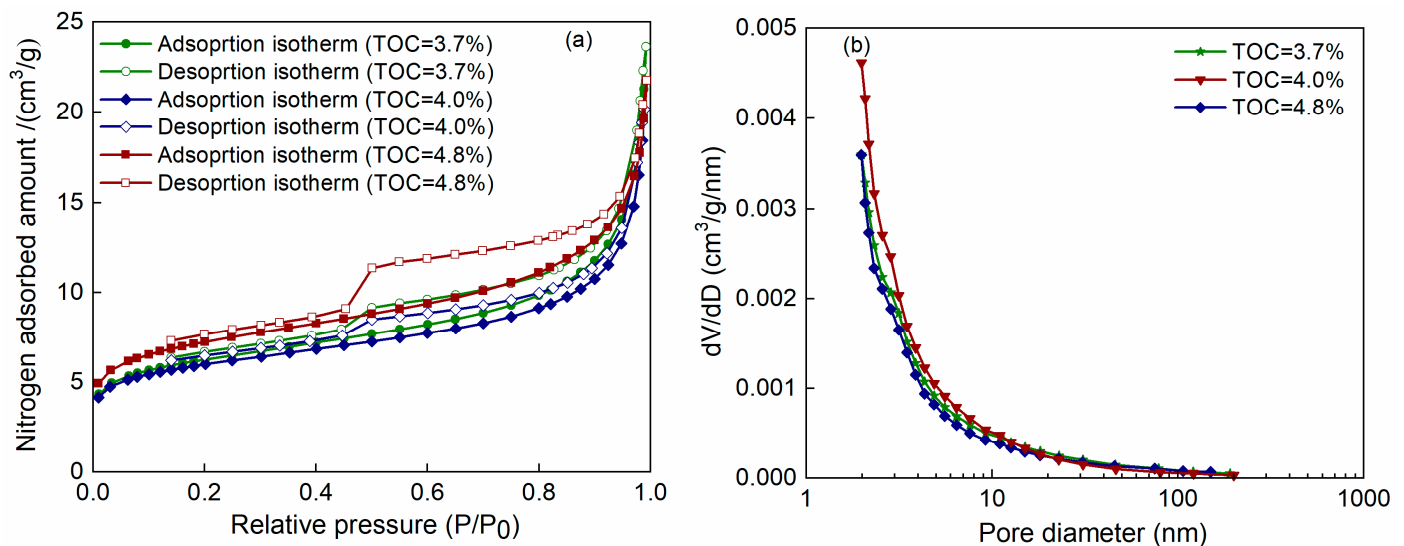


Figure 7. (a) The N₂ adsorption-desorption isotherms of the investigated gas shales at the Anchang syncline and (b) pore size distribution of shales determined by nitrogen adsorption isotherms.

5. Discussion

5.1. Effect of Organic and Inorganic Minerals on Pore Development of Shales

The investigated gas shales from the Anchang syncline commonly contain more than 60% of siliceous minerals (quartz and feldspar), which indicates that these shales belong to the typical siliceous shale lithofacies. The siliceous mineral content is even higher than the siliceous shales deposited in the deep-water shelf of the Jiaoshiba area inside the Sichuan Basin. The siliceous minerals content of gas shales collected in two commercially developed wells (JY 51-2 and JY 41-5) drilled in the Jiaoshiba area ranged from 33.5% to 68.4% (average 45.5%) [30,31]. According to the field practice in the Jiaoshiba area, siliceous shales generally have the characteristics of high TOC content, porosity, gas content, and brittleness index, which are favorable for hydraulic fracturing treatments [32–34]. In addition, the siliceous minerals of gas shales on the Jiaoshiba block are biological in origin, mainly formed by hydrocarbon-generating organisms such as algae and bacteria [35]. The biogenic quartz can be verified by the positive correlation between the TOC content and the quartz content of gas shales (Figure 8a). The correlation between the quartz content and TOC content of shales at the Anchang syncline is in line with gas shales at the Jiaoshiba block, which indirectly indicates that the siliceous minerals of shales at the Anchang syncline are also mainly biological in origin.

The Jiaoshiba block and Anchang syncline are located in the interior and exterior of the Sichuan Basin, respectively. Though the sedimentary environment of the Wufeng–Longmaxi Formation shales in the Jiaoshiba block is primarily a deep-water shelf environment and the northern Guizhou area gradually evolved into a shallow-water shelf environment, the source of the siliceous minerals of the Wufeng–Longmaxi Formation shales is likely similar. Thus, the total porosity of the investigated shales at the Anchang syncline is positively correlated with TOC content (Figure 8b), which is consistent with the results of shales in the Jiaoshiba area. This further verifies the previous understanding of the pore development of shales: over-matured shales with a high TOC content usually have high porosity. However, with the same TOC content, the total porosities of gas shales

on the Anchang syncline (outside of the Sichuan Basin) are lower than that of shales from the Jiaoshiba area (inside the Sichuan Basin). This is mainly related to the difference in the preservation condition of shale formations in these areas which will be discussed in the following section.

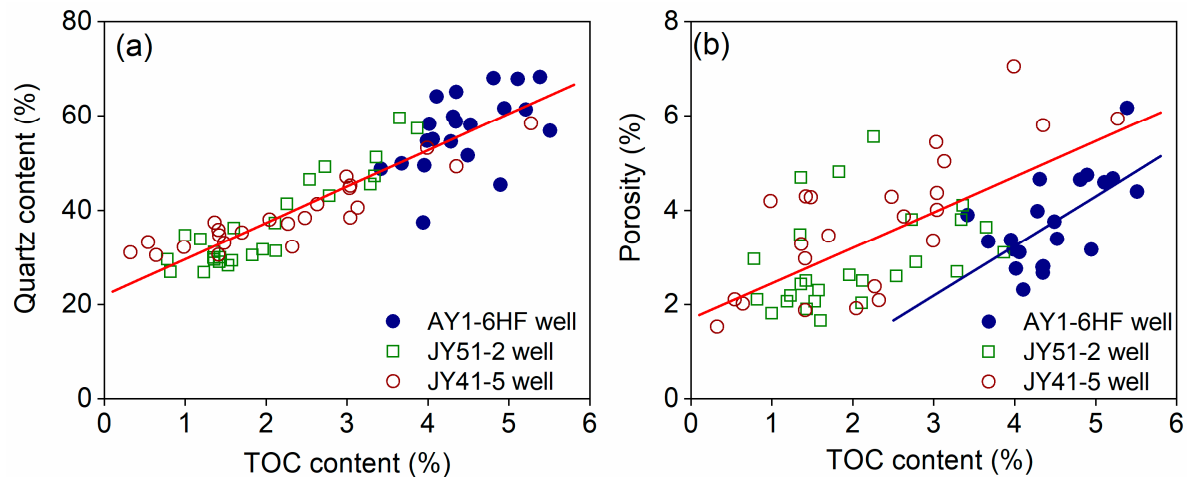


Figure 8. The correlation between TOC content and the (a) quartz content and (b) porosity of Wufeng–Longmaxi shales at the Anchang Syncline (data from JY41-5 and JY51-2 wells are collected from [30,31]).

The Anchang syncline, situated in the periphery of the Sichuan Basin, has experienced much more complicated tectonic movements than the stable zones inside the Sichuan Basin. The natural crustal stress caused by tectonic movements is apt to fracture the formations and create pores, which leads to shales at the Anchang syncline not only having organic matter pores but also containing abundant inorganic mineral-related pores. In order to quantitatively evaluate the contributions of different minerals (organic matter and inorganic matter) to the porosity of the investigated gas shales, the layered petrophysical model, developed in our previous study, was used to divide the shales into three main minerals: organic matter minerals, skeleton minerals (quartz, feldspar, and carbonates), and clays [30]. Combined with the mineral components on a mass-fraction base, the porosity detected by helium pycnometry, and the bulk density of rock, the porosity of different types of minerals was evaluated. The evaluation results show that the contributions of organic matter, skeleton minerals, and clays to the porosity of the investigated shale are about 48–72%, 2.5–3.74%, and 24.2–50%, respectively. This indicates that the main contributor to the total porosity of shales at the Anchang syncline is organic matter, followed by clay minerals.

5.2. Effect of Preservation Conditions on the Normally Pressured Shale Reservoir

Although the porosity of shales on the Anchang syncline is mainly due to organic matter, the diameter of organic matter pores in the Anchang syncline is obviously smaller than that from the Jiaoshiba area [30,31]. The pore morphology of the shales at the Anchang syncline is also much more irregular rather than circular or elliptical. These are probably related to the destructive effect of the poor preservation conditions during the tectonic uplifts in the Anchang syncline. The initial uplift time of the Wufeng–Longmaxi Formation at the Anchang syncline was about 120–145 Ma, which is much earlier than that of the Jiaoshiba area (about 100 Ma) [36]. Furthermore, compared to shales in the Jiaoshiba area inside the Sichuan Basin, the denudation time is much longer, and the denudation degree is much more serious at Anchang syncline [37]. The thickness of the O₃W-S₁L shale formation at Anchang syncline is about 25 m, which is much lower than that in the Jiaoshiba area (80–100 m), and even lower than the high-quality siliceous shales in the lower part of the O₃W-S₁L shale formation in the Jiaoshiba area (about 40 m) [30]. Thus, shales at the

Anchang syncline in the periphery of the Sichuan Basin are severely affected by tectonic movements. The earlier uplift of shale outside of the Sichuan Basin brought about more severe denudation to shale formations. Therefore, the thickness of shale formation is obviously thinner, and the preservation condition of natural gas becomes worse outside of the Sichuan Basin.

In addition, the Jiaoshiba block is located in the interior of the Sichuan Basin. The tectonic deformation of this area is gentle, and the stratigraphic dip of the O₃W-S₁L shale formation is small (generally 0~10°). Thus, the sealing conditions for shale gas are superior. The Anchang syncline is located in the periphery of the Sichuan Basin. The Wufeng–Longmaxi Formation shale at the Anchang syncline has been subjected to intense tectonic movements. The dip angle of the targeted shale formation at the Anchang syncline reaches 20~45°, which is much higher than that in the Jiaoshiba block inside the Sichuan Basin. Shale gas easily escapes along the bedding plane of the formations due to the high formation dip. Core test results show that when the effective stress is 20 MPa, the permeability coefficient of shales with parallel bedding fractures reaches $1 \times 10^{-3} \mu\text{m}^2$ at the Anchang syncline, while the permeability coefficient of shale matrix is only about $0.2 \times 10^{-6} \mu\text{m}^2$ (Figure 9). The permeability of shales with parallel bedding fractures is significantly higher than the shale matrix [38,39]. Therefore, the lateral loss of natural gas along the bedding fractures of the shale formations is much more serious than the vertical loss of the shale gas [40,41]. When the stratigraphic dip of the O₃W-S₁L shale formation is large, the bedding fractures act as the main dissipation channels of shale gas on the core scale, reducing the self-sealing property of the shale gas reservoir [42,43]. After significant amounts of shale gases escape along the bedding fractures, the gas pressure of the shale formation decreases, and the shale gas reservoir gradually becomes normally pressured. Under the compaction of the overlying strata, the low pore pressure cannot protect pores from collapse [44,45]. Consequently, the pore structure of gas shales at the Anchang syncline is further compacted. Therefore, although both the provenance of minerals and the TOC content of shales outside of the Sichuan Basin are similar to the interior of the Sichuan Basin, the preservation conditions for shale gas are unfavorable outside of the Sichuan Basin. After significant amounts of shale gases escape, the reservoir pressure decreases to be normally pressured, and the pore structure of the shale reservoir becomes worse.

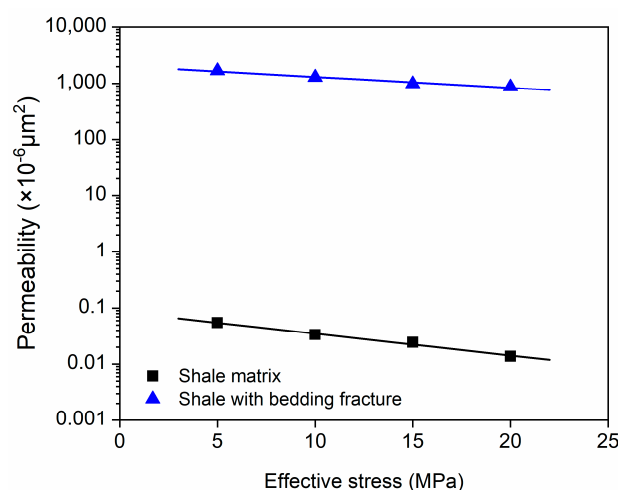


Figure 9. Variation of permeability with effective stress for Wufeng–Longmaxi shales at the Anchang syncline.

6. Conclusions

Based on the observations presented here for shale samples outside of the Sichuan Basin, the following conclusions can be drawn:

- (1) Shales from the O₃W-S₁L Formation of the Anchang syncline are mainly siliceous lithofacies with high quartz contents and TOC contents. The quartz content of these shales ranges between 50% and 65.1%, with an average of more than 57%, while the

TOC contents of the studied shales are mainly between 3–6%, with an average of 4.4%. The quartz of these shales in the studied area outside of the Sichuan Basin is of biogenic origin.

- (2) The total porosity of shales in the studied area outside of the Sichuan Basin is low, with an average value of about 2.9%. Organic matter pores create the main space for the normally pressured shale gas, which is verified by the relationship between the TOC content and porosity of these shales. Organic matter contributes about 48–72% to the porosity, while clays contribute about 24.2–50% to the porosity of the investigated shales. However, the organic matter pores are poorly preserved or compressed due to severe tectonic movements at the Anchang syncline. Pore sizes of the organic matter pores of the normally pressured shales at the Anchang syncline are small, while the inorganic matter-related pores are mainly polygonal pores or narrow slit pores.
- (3) Tectonic movement significantly affects the shale gas reservoir characteristics and gas pressure in the periphery of the Sichuan Basin. Compared with the interior Sichuan Basin, shale formations at the Anchang syncline are uplifted earlier and denuded seriously. Compared to shales inside the Sichuan Basin, the effective thickness of shale formation outside of Sichuan Basin is thinner (23–25 m, compared to 40 m inside Sichuan Basin) and the dip angle of the shale formation is larger (20–45°, compared to 5° inside Sichuan Basin). The thin formation thickness and high dip angle lead to the significant dissipation of natural gas along the bedding plane of the shale formation.
- (4) The O₃W-S₁L shales on the Anchang syncline outside the Sichuan Basin have similar provenance to that of the interior Sichuan Basin. Both the TOC contents and the brittle minerals contents of shales outside of the Sichuan Basin are close to that of shales inside the Sichuan Basin. However, the preservation conditions for shale gas at the periphery of the Sichuan Basin are unfavorable. The severe shale gas leaking leads to reservoir pressure decreasing to that of normal pressure. This is probably why shale gas outside of the Sichuan Basin is normally pressured.

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