Article

The Micropore Characteristics and Geological Significance of a Tuffaceous Tight Reservoir Formed by Burial Dissolution: A Case Study of the Carboniferous Tuff in the Santanghu Basin, NW China

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Abstract: As a distinct type of reservoir, tuffaceous tight reservoirs have attracted much attention. However, previous studies on tuffaceous tight reservoirs formed in the burial diagenetic stage are few, particularly regarding the genesis of micropores, which restricts the in-depth exploration of tuffaceous tight oil. According to thin section observation, scanning electron microscopy (SEM) identification, X-ray diffraction (XRD) experiments, elemental analyses, porosity and permeability tests, and pore structure analyses, the micropore characteristics of the Carboniferous tuffaceous tight reservoir formed by burial dissolution in the Santanghu Basin, NW China, are studied. In addition, the cause of the tuff micropore formation and its geological significance are also researched in this paper. The results are as follows: (1) The tuffaceous tight reservoir formed by burial dissolution mainly consists of quartz, feldspar, dolomite, and clay minerals. The reservoir space mainly consists of intergranular pores between minerals, intragranular dissolution pores within feldspars, calcite, dolomite, clay minerals, and locally developed organic matter pores. (2) The formation of micropores in tuff reservoirs formed by burial dissolution is mainly related to the original composition of the tuff. (3) Tuffaceous reservoirs with good physical properties are usually formed at the bottom or top of a large set of source rock. The results of this investigation can provide innovative theoretical evidence for the accumulation mechanism of tuffaceous tight oil formed by burial dissolution. Meanwhile, it can be considered a reference regarding the distribution of and predictions for tuffaceous reservoirs formed by burial dissolution in similar situations in other parts of the world.

Keywords: tight reservoir; tuff; burial dissolution; micropore

1. Introduction

With an increase in unconventional oil and gas exploration and geological research, various unconventional oil and gas reservoirs with special properties have been discovered, and tuffaceous reservoirs have come into people’s view. Geologists took the lead in discovering the tuffaceous tight reservoir in the Santanghu Basin, NW China, obtaining a high-yield industrial oil flow after fracturing. Tuff, a type of transitional rock between pyroclastic and conventional sedimentary rocks, originates from volcanic ash, which is transported across vast distances by wind during volcanic eruptions [1–3].
The tuffaceous tight reservoir developed at the top of the Carboniferous Haerjiawu Formation in the Santanghu Basin [4]. The dissolution phenomenon is obvious according to the observation of its core and thin sections. Its structural evolution history shows that the reservoir has not undergone uplift denudation and weathering leaching and has no conditions of fault communication with the surface. Moreover, the tuff has a high degree of dissolution in the center of the depression and a low degree of dissolution at the edge of the depression.

The research objects within burial dissolution are mainly carbonate rocks, clastic rocks, and volcanic rocks, which refers to the dissolution occurring in the deep burial stage, is mainly related to the maturation of organic matter, and is an important mechanism of the formation of reservoir pores [5,6]. The secondary pores in volcanic rock reservoirs have a more obvious influence on the reservoir physical properties, which is different from sedimentary rock reservoirs. The secondary pores formed by weathering and leaching in the early stage are largely lost after compaction, while the dissolution of the burial stage develops further in the middle and late diagenetic stages, when the pores are essentially unaffected by compaction, making it easier to form effective reservoirs [7,8]. Previously, it was believed that the leaching and dissolution of surface freshwater were decisive factors for the development of secondary pores, and the intensity and scale of the dissolution of reservoirs by acidic fluids in the burial stage were not enough to form large-scale dissolution pores [9]. However, with further research on carbonate reservoirs, it has been gradually realized that burial dissolution plays a crucial role in secondary pore development [10,11]. Acidic fluids have been recognized as playing a leading role in forming high-quality reservoirs such as those found in deep marine carbonate reservoirs like those in the Tarim Basin and the Sichuan Basin [12–14]. There are two main mechanisms for pore formation in the Lucaogou Formation shale oil reservoir in the Jimsar Sag, the Junggar Basin, namely syngenetic–quasi-syngenetic leaching and acid fluid burial, and burial dissolution is the most important genetic mechanism for pores [15]. Similarly, both organic acid and hydrothermal burial dissolution have had constructive effects on the dolomite reservoirs of the Ordovician Majagou Formation in the Ordos Basin [16]. Previous studies show that the reservoir space of the tight volcanic rock reservoir of the Haerjiawu Formation in the Santanghu Basin is dominated by dissolution pores [17]. However, there are few studies on the cause and accumulation characteristics of this tuffaceous tight reservoir formed by burial dissolution. As a special type of tight oil reservoir, it is a replacement field for conventional oil and gas, so this research is of great scientific and practical significance. Therefore, the principal objectives of this study are as follows: (1) to study the micropore characteristics of the Carboniferous tuffaceous tight reservoir formed by burial dissolution in the Santanghu Basin; (2) to analyze the cause of micropore formation; and (3) to discuss the geological significance of the micropores in the tuffaceous tight reservoir formed by burial dissolution.

2. Geological Setting

The Santanghu Basin is located in the northeast Xinjiang Region of China and is bordered by Mongolia to the north, the Turpan–Hami Basin to the south, and the Junggar Basin to the west. As a superimposed basin that developed over an Early Paleozoic basement, the Santanghu Basin is sandwiched between the Tianshan and Altai mountains and is composed of three tectonic units: the NE thrust–fold belt, the central depression belt, and the SW thrust–fold belt [18–20]. The central depression belt consists of four uplifts (the Shitoumei, Chahaquan, Fangfangliang, and Weibei Uplifts) and five sags (the Hanshuiquan, Tiaohu, Malang, Naomaohu, and Suluke Sags), among which the M 71 well area in the Malang Sag is the main research area in this paper (Figure 1). The sedimentary strata of the Santanghu Basin are divided into Carboniferous (the Haerjiawu Formation and the Kalagang Formation), Permian (the Lucaogou Formation and the Tiaohu Formation), Triassic, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary from bottom to top, with a cumulative thickness of up to 6500 m. During the Carboniferous and
Permian sedimentation periods, volcanic activity was frequent in the Santanghu Basin and its periphery. The basin was in a compressional environment during the deposition of the Upper Carboniferous Haerjiawu Formation, with thrust faults developing and frequent volcanism. The developed thrust faults were magma passages, forming multiple volcanic active belts. Therefore, a set of volcanic rocks with carbonaceous mudstone, oil shale, and tuffaceous mudstone developed in the basin, which were the main source rocks of the Carboniferous system. The tuffaceous tight reservoir formed by burial dissolution developed in the Haerjiawu Formation has a thickness of about 30 m and is mainly distributed in the upper part of the Haerjiawu Formation in the vertical direction, and the thick immature–low-maturity mudstone of the Kalagang Formation developed at the top. The source rocks of the Haerjiawu Formation have high organic matter abundance and good organic matter types and are in a stage of mature evolution. The oil source correlation indicates that the crude oil in the tuffaceous tight reservoir formed by burial dissolution is from the source rocks of the Haerjiawu Formation [21].

![Figure 1. Location map and regional stratigraphic nomenclature of the Santanghu Basin, NW China (modified according to [4]).](image)

3. The Samples and Method

The samples used in this study were all taken from the core of drilling in the target layer of the study area. The experimental methods mainly included conventional thin section and casting thin section analysis, fluid inclusion, scanning electron microscopy, and major element and whole-rock X-ray diffraction, and there were 10, 10, 5, 8, 12, and 8 analysis samples, respectively, for each. These experiments were carried out in the laboratory of the Beijing Research Institute of Uranium Geology. In addition, the porosity, permeability, and high-pressure mercury injection data used in this study are previous results cited by the authors [21]. A Leica DM4500P microscope with 12 V and 100 W halogen and mercury lamps was used to observe the fluid inclusion type and optical characteristics. The instrument used for SEM was the TESCAN GAIA3 with an accelerating voltage of 15 kV, and the samples needed to be plated with platinum before observation to increase the conductivity and clarity. The XRD instrument was a Panalytical X’ PRO X-ray diffractometer with a voltage of 40 kV, a current of 40 mA, and a scanning speed of 4°/min. The tuff samples were crushed to a diameter of less than 40 mm with an agate mortar; then, the mineral type was identified from the diffraction pattern, and its relative abundance was semi-quantitatively analyzed. The major elements of the tuff were analyzed using an X-ray fluorescence spectrometer.
4. Reservoir Space of the Tuffaceous Tight Reservoir Formed by Burial Dissolution

4.1. Micropore Types and Characteristics

Through the observation of the core and casting thin sections, it is found that the dissolution pores of the tuffaceous tight reservoir formed by burial dissolution are very or relatively well developed (Figure 2a–d). In addition, a small number of tectonic fractures have developed, which are filled with calcite and other minerals, and the dissolution phenomenon can also be seen in the fractures. An intragranular dissolution phenomenon can be seen in some particles, characterized by a small number of oil fluid inclusions developed in the tuff. The fluid inclusions are distributed in groups and show blue-white fluorescence (Figure 2e,f). The higher the content of feldspar in the sample, the more developed the intragranular dissolution phenomenon is. There are also oil inclusions in bands or groups, showing blue-white fluorescence in the calcite veins (Figure 2g,h).

Figure 2. Petrographic characteristics of tuffaceous tight reservoirs formed by burial dissolution through thin section and core sample observation. (a) Dissolution pores are obvious in the core sample. Well M73, 2249 m. (b) Dissolution pores are obvious, and residual oil is easily observed in the core sample. Well M73, 2248.5–2248.66 m. (c) Dissolution pores in observation of casting thin section. Well M73, 2249 m. (d) Dissolution pores can be clearly and easily observed in casting thin section. Well M71, 2785.12–2785.26 m. (e,f) Oil fluid inclusions are developed in the tuff, and the fluid inclusions are distributed in groups, with blue-white fluorescence. (e) was observed under polarized light, and (f) was observed under fluorescence. Well M361, 3159.14 m. (g,h) Oil inclusions in groups, showing blue-white fluorescence in the calcite veins. (g) was observed under polarized light, and (h) was observed under fluorescence. Well M73, 2249 m.

SEM is the most direct and effective method for observing the microscopic pores of rocks. According to the SEM observations, there is mainly microcrystalline quartz (Figure 3a) (the elemental composition of this mineral is mainly Si and O according to SEM energy spectrum analysis), feldspar (Figure 3b) (the elemental composition of this mineral is mainly Si, O, Al, and Na), dolomite (Figure 3c) (the elemental composition of this mineral is mainly O, Ca, Mg, and Fe), clay minerals (mainly chlorite; the elemental composition of these minerals is mainly O, Fe, Si, Al, and Mg), etc., in the tuffaceous tight reservoir formed by burial dissolution. The intergranular pores of the microcrystalline particles are well developed (Figure 3a–c), followed by intragranular dissolution pores within the feldspars (Figure 3d) and a small number of dissolution pores within calcite, dolomite, and clay minerals (Figure 3e). In addition, there are locally developed organic matter pores (Figure 3f) (the elemental composition of the minerals where the dissolution pores are located is mainly C). The pores in the tuff are generally small, but there are many and their connectivity is good.
In general, the micropores in tuffaceous tight reservoirs formed by burial dissolution can be divided into three types: the first type is intergranular pores between microcrystalline minerals, the second type is intragranular dissolution pores within minerals, and the third type is organic matter pores. Among them, the first and second types are the main pore types and oil and gas storage spaces. The dissolution pores can communicate with many independent small pores, which is of great significance to improving the permeability of the reservoir and contributes greatly to the physical properties of the reservoir. The pores within clay minerals, especially the interleaf pores of chlorite, are beneficial to the reservoir, but their number is limited. Organic matter pores refer to the pores caused by a reduction in the volume of organic matter in the process of hydrocarbon generation [22]. The organic matter content of tuffaceous tight reservoirs formed by burial dissolution is not high, and the development of organic pores is very limited, which is of little significance to improving the physical properties of reservoirs.

4.2. Micropore Structure and Reservoir Physical Properties

In order to solve the problems of the complex microscopic pore structure and strong heterogeneity in tight reservoirs, pores, throats, and pore throat connectivity can be used to reflect the microscopic pore structure [23]. Pore structure refers to the number, size, geometry, distribution, and connectivity of pores and throats in rocks and represents the reservoir performance and seepage characteristics [24]. In this paper, the pore structure was studied using the mercury injection method. The pore structure parameters obtained using the mercury injection method can be divided into three categories: parameters reflecting the pore throat size, such as the maximum pore throat radius, the average pore throat radius, and the saturation median pore throat radius; parameters that reflect the sorting ability of the pore throat, such as skewness and the sorting coefficient; and parameters that reflect pore throat connectivity, such as displacement pressure, saturation median pressure, maximum mercury saturation, mercury removal efficiency, etc. The middle
section of the mercury injection curves of the tuffaceous tight reservoir formed by burial dissolution of the Haerjiawu Formation have a large span and are gentle (Figure 4), indicating that the pore distribution in the core is concentrated. The mercury injection data show that the average pore throat radius is mainly distributed in the range of 0.08–0.30 µm, the sorting coefficient is mainly distributed in the range of 1.8–2.2, and the displacement pressure is mainly distributed in the range of 0.7–2.7 MPa, which indicates that the pore structure of the tuffaceous tight reservoir formed by burial dissolution is good [21].

![Mercury injection curve characteristics of tuffaceous tight reservoir caused by buried dissolution, showing that the pore structure is good.](image)

**Figure 4.** Mercury injection curve characteristics of tuffaceous tight reservoir caused by buried dissolution, showing that the pore structure is good. (a) Well M71, 2782.78 m. (b) Well M71, 2783.17 m (According to [21]).

After analyzing the physical properties of the tuffaceous tight reservoir formed by burial dissolution in the M71 well in the Haerjiawu Formation, it is found that the porosity is mostly greater than 10% and the permeability is greater than 0.5 mD. However, the porosity and permeability of tuff without dissolution are mostly less than 10% and less than 0.1 mD [21]. It can be seen that the physical properties of the tuffaceous tight reservoir have become better due to burial dissolution, which has greatly improved its ability to store oil and gas.

5. Discussion

5.1. Cause of the Formation of Micropores in Tuff

During the burial process of tuff, with changes in the water medium conditions, strong devitrification will occur. The formation process of devitrification includes a series of geochemical processes such as the dissolution and precipitation of original materials, recrystallization, the migration and transformation of ions, etc., and the volume of new minerals shrinks when they are formed, thus forming a large number of micropores between different minerals [25,26]. The minerals formed by devitrification continue to dissolve under the action of acidic fluid, and dissolution pores form. The formation of pores in tuffaceous tight reservoirs is mainly related to their own devitrification. During the devitrification of the original material, a large number of minerals such as quartz and feldspar are formed, resulting in the formation of a large number of pores among the tiny particles, and some easily soluble minerals continue to dissolve, forming intragranular dissolution pores. Therefore, the difference in the dissolution type and dissolution degree of tuff is closely related to the composition of the original material, which determines the difference of the degree of devitrification and then affects the type and size of the pores.

From the data on the whole-rock mineral composition from X-ray diffraction, the quartz content of the tuffaceous tight reservoir formed by burial dissolution is extremely high, up to 50–90%, followed by feldspar, calcite, dolomite, and zeolite (Figure 5). In addition, only a few samples have a relatively low quartz content, but the contents of carbonate minerals (calcite and dolomite) and zeolite are high in these samples, which still causes a higher dissolution of tuff and more developed pores. In the major element
composition, the SiO$_2$ content is the highest, followed by Al$_2$O$_3$, indicating that the original volcanic ash is mainly felsic. There is a negative correlation between SiO$_2$ and Al$_2$O$_3$ (Figure 6a) and a negative correlation between SiO$_2$ and CaO (Figure 6b).

Figure 5. The relative content of different minerals of the tuffaceous tight reservoirs formed by burial dissolution from XRD analysis.

![Figure 5](image)

Figure 6. Correlation between major elements in the tuffaceous tight reservoirs formed by burial dissolution. (a) There is a negative correlation between SiO$_2$ and Al$_2$O$_3$ content. (b) There is a negative correlation between SiO$_2$ and CaO content.

Organic acid is the main fluid for the formation of secondary dissolution pores in tuff in the burial diagenetic stage. Unstable material such as volcanic ash, vitreous, feldspar porphyry, and crystalline chips in tuff will dissolve in acidic media and produce a large number of secondary dissolution pores [27,28]. It is believed that buried acidic fluids are mainly derived from (1) organic matter thermal evolution in source rocks and the organic–inorganic oxidation between hydrocarbons with minerals and water; (2) organic and inorganic oxidation in the transport layer during crude oil migration; and (3) organic acidic fluids formed by the biodegradation of crude oil in the reservoir [29]. The buried dissolution of volcanic rocks mainly includes two mechanisms: non-selective dissolution, that is, the dissolution of all the easily soluble mineral components, and selective dissolution, meaning that the cracks or pores are mainly diffused along the original pore system [30]. The Carboniferous tuffaceous tight reservoir formed by burial dissolution is adjacent to the source rock. The large amount of organic acids produced by the source rock provides favorable conditions for dissolution, and the oil and gas entering the reservoir in the later stage also promote dissolution.
5.2. Geological Significance of the Micropores in the Tuffaceous Tight Reservoir Formed by Burial Dissolution

The tuffaceous tight reservoir formed by burial dissolution mainly lies beneath a large set of source rock in the study area, and the tuff has the conditions for organic acid dissolution. The source rock produces a large amount of organic acids in the immature to low-maturity stage, and the organic acids and formation water are discharged downward during the compaction process, which dissolve the tuffaceous minerals. After oil and gas enter the reservoir, the tuff minerals are also selectively dissolved. The degree of dissolution depends on the original material composition and the upper source rock. Under the action of paleo-fluid, a large number of intergranular dissolution pores and intragranular dissolution pores formed in the tuff, and the physical properties of the tight reservoir became better, which was conducive to oil and gas accumulation. The tuff’s obvious dissolution characteristics are mainly due to the dissolution and transformation by a large amount of organic acids produced in the early maturity of the overlying thick source rock, which made the physical properties of the reservoir better. Due to the limited amount of organic acid, a thin layer of source rock has a weak dissolution effect on the adjacent tuff. Therefore, reservoirs with good physical properties are often developed at the bottom or top of a large set of source rock.

6. Conclusions

(1) The tuffaceous tight reservoir formed by burial dissolution mainly consists of microcrystalline quartz, feldspar, dolomite, clay minerals, etc. The reservoir space mainly consists of intergranular pores between minerals, followed by intragranular dissolution pores within feldspar, calcite, dolomite, and clay minerals. A small number of organic matter pores are also developed.

(2) The micropore formation in tuffaceous tight reservoirs formed by burial dissolution is mainly related to the original composition of the tuff and then to the characteristics of the paleo-fluid (oil and gas/water) during burial dissolution, which affects the devitrification degree and the devitrification products of the tuff and ultimately determines the type of pores and the porosity.

(3) Tuffaceous tight reservoirs formed by burial dissolution with good physical properties are usually located at the bottom or top of a large set of source rock, where there is a favorable exploration horizon.

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