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STUDY ON CHARACTERISTICS AND ORIGIN OF NANO-PORE AND FISSURES FOR DEEP BURIED CRETACEOUS TIGHT GAS RESERVOIR USING NANOTECHNOLOGY IN KUQA DEPRESSION- TARIM BASIN, CHINA

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Abstract: Although buried over eight thousand meters, there is still developing high production from tight gas reservoir with low porosity and ultra-low permeability in the sandstones of Bashijiqike Formation of Cretaceous in Kelasu area of Kuqa depression. It is an interesting issue for the origin of the ultra-deep reservoirs. This paper aims to present the characteristics and origin of the nano-pore and nano fissures of that ultra-deep reservoirs using field emission scanning electron microscope, laser scanning confocal microscope and other high resolution measure experiments. There are developed two kinds of nano-pores with pore diameters between 40 nanometers to 1000 nanometers, and many nano fissures with width between 10 and 600 nanometers in this sandstone reservoir. Based on their petrophysical properties and microstructure characteristics, the nano pores are connected by those nano fissures that are also as valid pore throats. So, there is valid permeability in sandstones with even very low porosity. The effective combination between nano pores and pore throats is the key factors for high production in this tight gas sandstones. This point can help us to predict gas reservoirs with effective and recoverable reserve in this kind of ultra-deep gas field, also maybe in other similar gas field.

Keywords: micro pore, nano-pore, sandstone reservoir, tectonic compaction, Cretaceous, Tarim Basin

1. INTRODUCTION

The term of ‘deep’ has become increasingly in focus as the future topic of the earth sciences, including “deep sea”, “deep space”, and “subsurface deep”. It is believed that the deep thing must be different from the shallow one in their substance or process, which deserve to be mentioned. In the past decades, gas reservoirs have been drilled over the depth of 8000 meters from the Cretaceous sandstones of Kuqa Depression, Tarim Basin, China (Zhao et al., 2005). These deep buried sandstones reservoir, although having the low porosity (2 % - 6 %) and permeability (0.01 - 0.1×10^{-3} μm^2) with high-temperature (~180 °C) and high-pressure (~150 MPa), is still full of gas resources and will be the alternative reservoirs after the exploration of the shallow buried sandstones later (Lai et al., 2017). It has been reported that this kind of sandstones like that of Kuqa Depression were widely developed in different basins such as Ordos Basin, Songliao Basin, Junggar Basin and Sichuan Basin in China, with recoverable gas resources approximately 8~11×10^{12} m^3 (Windley et al., 2007).

Significant contributions have been made by others in relation to the tectonic evolution, petroleum prospects, source rocks and hydrocarbon accumulations of the Cretaceous play in Kuqa

Depression (Chen et al., 2004; Tang et al., 2004; Huang et al., 2006; Qin et al., 2007; Lai et al., 2017; Windley et al., 2007; Shi et al., 2010; Zeng et al., 2010; Zhu et al., 2015; Guo et al., 2016a; Liu et al., 2016; Zhao & Wang, 2016), but few of them are focused on the reservoir quality, which is one of the critical aspects in understanding the basic elements of the Cretaceous play. The reservoir porosity is less than 10 %, in situ permeability less than 1×10^{-3} μm^2 and pore throat diameter less than 1 mm (Higgs et al., 2007; Zou et al., 2012), which would be a great challenge for exploration. To this kind of tight sandstones in Kuqa Depression (Dai et al., 2012), the reservoir quality is controlled by depositional facies and subsequent modifications from diagenetic alterations according to Chinese literature (Han et al., 2011; Zhang et al., 2014; Zhang et al., 2016; Li et al., 2017). Besides the initial sediments compositions, the subsequent diagenetic modification is one of the most important factors influencing the reservoir quality (Nygård et al., 2004), also controlling their heterogeneity (Schmid et al., 2004). So, to understand the spatial and temporal evolution of diagenesis in sandstones is very significant (Kordi et al., 2011). However, there are still some important issues, relative to reservoir porosity and diagenesis of the sandstones of Kuqa Depression, being relatively poorly explored in those literatures. For example, as gas reservoir, pores are not present in the thin section, even in some common electron scanning microscope. But there is a huge gas reservoir in those sandstones indeed. So, what kinds of pores and how did those porosity be preserved at the depth from 6000 to 8000 meters, and which kind of diagenesis controlled the porosity development, which are really interesting yet unanswered issues. In this regard, there is still existing a blank between the understanding of the origin of the micro pores and its controlling factors, which may should be studied by some new techniques such as electron microscope with resolution of nanometer.

The aim of this paper is to enrich this blank by deciphering the characteristics of porosity using a microscope in nanometer scale such as field emission scanning electron microscope (FE-SEM),

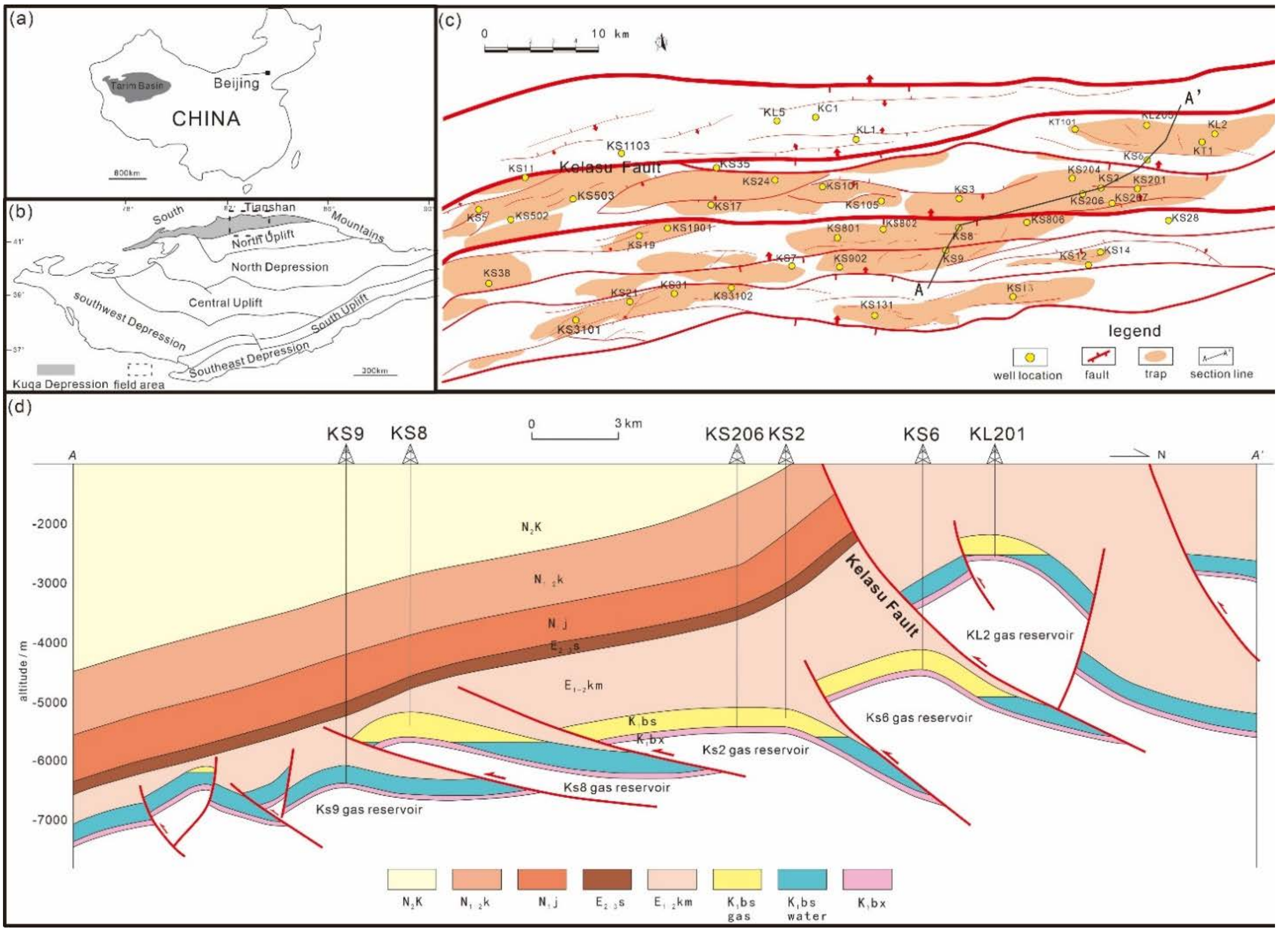

Figure 1. Regional map showing the location of the Kuqa Depression (a, b), and the tectonic elements (after Yin et al.,1998; Wang et al., 2011) and well locations of study area (c) (Modified according to Tang, 2004) and Gas Reservoir Cross-Section (d) (Modified according to Wang, 2018)

back-scattered electron image (BSE) and laser scanning confocal microscope, and analyzing the origin of different porosity by the petrography and geochemical parameters of its porosity. We believe these results will help us to predict the porosity of deep reservoirs in this basin and other similar basins.

2. GEOLOGICAL BACKGROUND

Kuqa Depression is a 400 km long and 20 - 65 km wide foreland fold-thrust unit with an area of 28.500 km^2 (Figure 1), lying between the South Tian Shan to the north and the Tarim Basin to the south (Allen et al., 1991).

A great many literatures of Kuqa depression have been addressed on the origin, the structural characteristics, the sedimentary facies, the hydrocarbon resources and so on (Guo et al., 2016b; Tang et al., 2016; Zhang et al., 2016). Kuqa depression was formed as a result of the collision of Tarim to Junggar "Plate" at late Permian. Then due to the crust isostatic adjustment of the Tianshan Orogen, the continental sediments of Triassic to early Cretaceous were deposited in this fault depression (Figure 2). Later, a regional unconformity was formed over the Early Cretaceous strata as a result of the neotectonic deformation caused by India-Asia collision of middle to late Cretaceous, also called Himalayan Orogeny (Yin, 2006). After that, along with the uplift and the southward thrusting of South Tianshan, a series of coarse terrigenous sediments were deposited in this foreland depression since Oligocene up to Quaternary (Yin et al., 1998; Yang & Liu, 2002; Li et al., 2004; Charreau et al., 2005). Meanwhile, the tectonic units were formed as followings: Northern Slope, Kelasu Anticline Belt, Baicheng Sag and Qiulitage Anticline Belt (Lu et al., 1994; Zhou et al., 2001; Lin et al., 2002; Jia, 2003; Wang et al., 2011; Xiao et al., 2012).

As a sequences of a series of south-directed thrust faults, many east-west striking anticlines and synclines have been formed during Neogene (Huang et al., 2008; Qi et al., 2009). Because of one large thrust fault-Kelasu Fault (Figure 1c), the Cretaceous sandstones have been split into two blocks, one part in the hanging wall with another in the footwall. Hydrocarbon exploration was started in the hanging wall firstly, because the burial depth of Cretaceous sandstones was just 3500 – 4000 m. The famous gas field named KL 2, which is the source of natural gas for West-East Pipeline Project in China, is located in the hanging wall (Yu et al., 2017). Meanwhile, the exploration to Cretaceous sandstones of the footwall has just begun since the last ten years ago, for the great burial depths of 6000 – 8000 m, which is our study target, Bashijiqike Formation (K_1bs) (Figure 2).

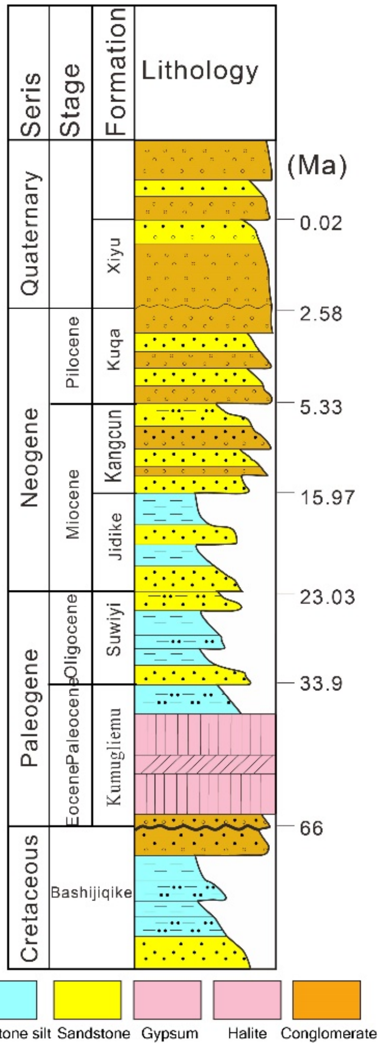

Figure 2. Lithostratigraphic column showing the ages and simplified lithology of different formations of the strata deposited in study area. The studied sandstones are in the Bashijiqike Formation of Cretaceous

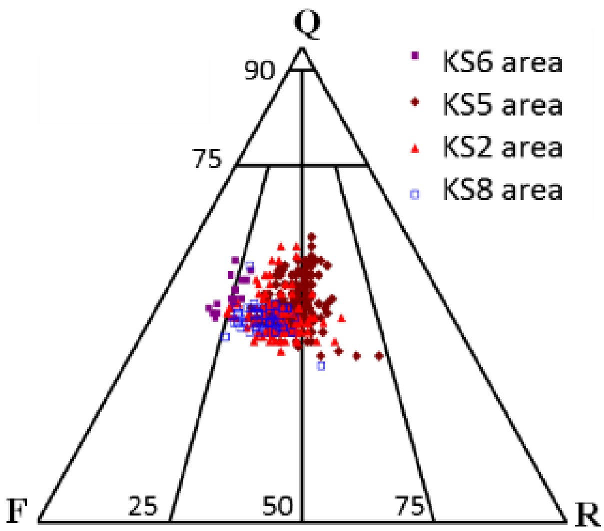

Figure 3. Ternary diagram showing content of different framework grains in Bashijiqike sandstones. Q = quartz; F = feldspar; R = rock fragment. Nighty one samples from six wells of four different areas

3. PETROGRAPHY AND PHYSICAL PROPERTY

3.1. Petrography characteristics

Most Cretaceous sandstones are mainly grain supported, moderately to well sorted lithical arkoses and feldspathical litharenite (Figure 3), according to the classification scheme of Folk (Wang et al., 2018). The average content of each kind of debris are quartz (42.55 %), feldspar (28.05 %) and rock fragments (29.4 %). Generally, quartz ranges from 32 % to 58 %; feldspar is in the range between 12 % and 32 %; rock fragments are in the range between 17 % and 40 %, mainly with metamorphic and volcanic rock fragments.

3.2. Physical property

The porosity of those core samples is in the range from 0.34 % to 12.55 %, and the permeability are in the range from 0.005 mD to 9.678 mD (Figure 4). The porosity and permeability are various for each well in our study area, and the average physical property of Bashijiqike sandstones of well KS6 are much better than those of other wells. Generally, the Bashijiqike sandstones are the gas reservoirs with porosity less than 10 % and in situ permeability less than 1 md, so, we have to define this kind of sandstone as tight gas reservoir according to some literature (Dai et al., 2012; Zou et al., 2012).

From the plot of the permeability and porosity, some anomalous value of wells in KS5 and KS8 area, with some low porosity but high permeability. In addition, based on the results of the mercury intrusion experiment, the mean value of the pore throat radius of wells in KS8 area is 0.0358 μm according to the mercury intrusion pore size distribution, with 0.1787 μm of wells in KS5 area and 0.018 μm of wells in KS2 and KS6 area. The micro pore throat, radius between ten nanometers and a hundred nanometers, is the dominated pore throat type in the study area, occupying seventy percent of all pore throat (Figure 5). The reason for this will be mentioned in the later discussion.

3.3. Characteristics of nano pore and pore throat

According to the literatures, the macro pores of Bashijiqike sandstones can be divided into primary pores and secondary pores by the origin. They also can be divided into macro and micro pores by their diameter (Sun et al., 2018). In this article, we only talk about the micro pores and fissures, especially those

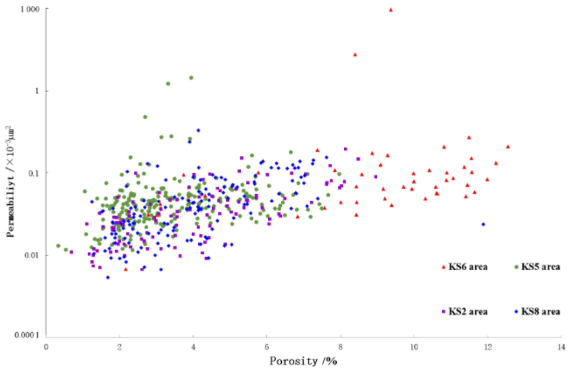

Figure 4. Plot of porosity and permeability of Bashijiqike sandstones of Cretaceous in our study area. All the data are from core samples, including 50 samples of KS6 area, 104 samples of KS5 area, 56 samples of KS2 area and 137 samples of KS8 area

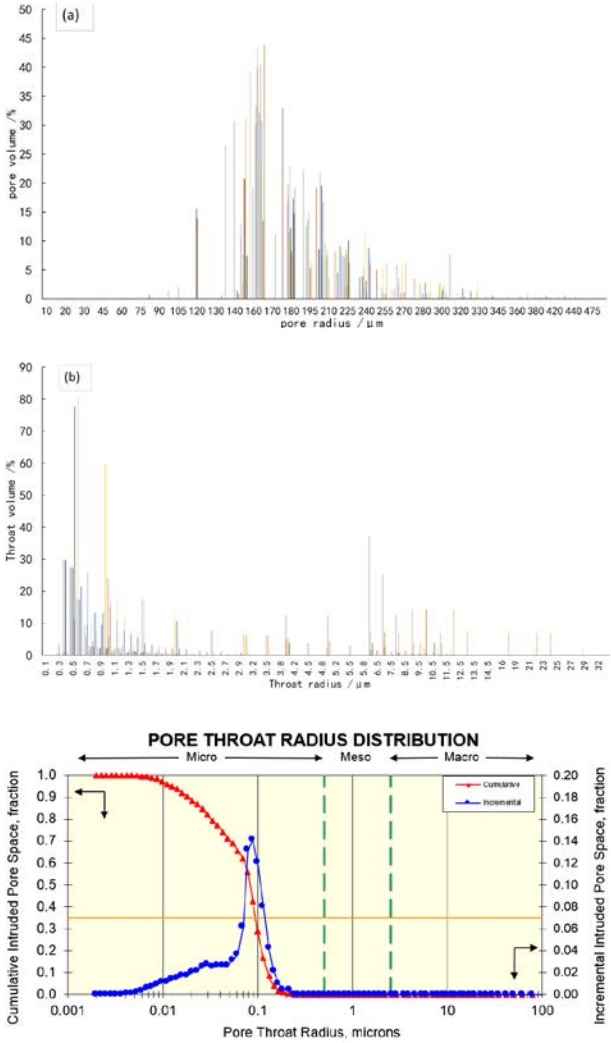

Figure 5. Mercury injection results of the wells in study area. (a). Pore radius and its value distribution of the reservoir; (b) Throat radius and its value distribution of the reservoir. The bottom chart shows the pore throat radius distribution including some micro pore throat, which is the dominated pore throat according to the cumulative curve

pores and fissures of nanometers. Based on the high-resolution image of different experiment facility, we can investigate those tiny pores and fissures directly (Figure 6).

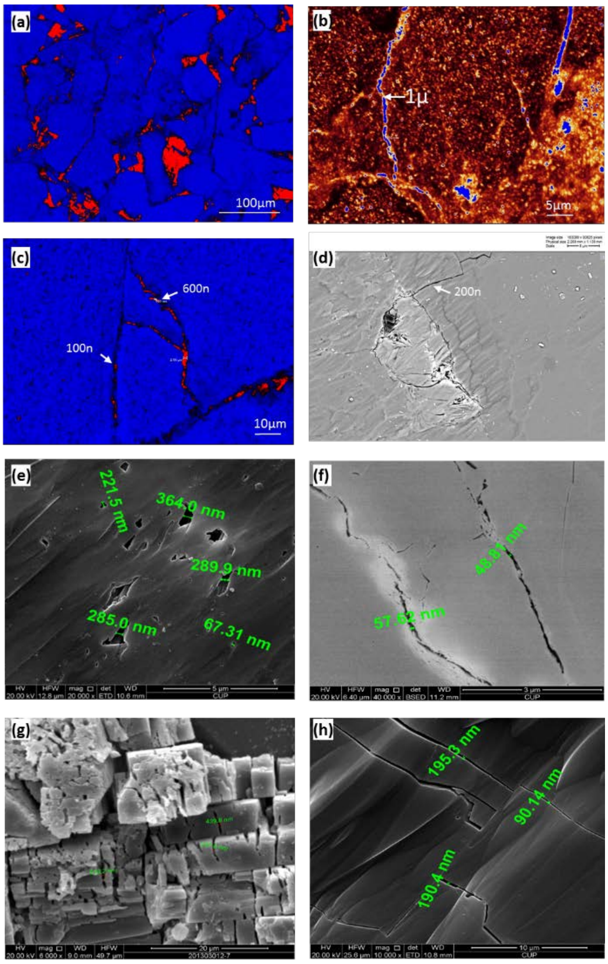

Figure 6. Photos of micro pores and fissures in study area. (a) Micro pore throat connecting the intergranular pores, laser scanning confocal microscope image, KS802 well, 7326.95m. (b) Micro pores and micro fissures of reservoirs, the fissures are also the pore throat with width of one micrometers or smaller, laser scanning confocal microscope image, KS201 well, 6511.26 m. (c) Fissures of nanometer in reservoirs, such as 100 nanometers, laser scanning confocal microscope image, KS201 well, 6509.67 m. (d) Nano fissures connecting micro pores, the width of the fissure is about 200 nanometers, field emission scanning electron microscope image, KS207 well, 6875.24 m. (e) Nano pores in reservoirs, the diameter of nano pores are 60 to 400 nanometers, field emission scanning electron microscope image, KS207 well, 6875.24 m. (f) Nano pores in reservoirs, fissure width is only 40-60 nanometers, back-scattered electron image, KS207 well, 6866 m. (g) A lot of nano pores with width between 50 nanometers to 500 nanometers, field emission scanning electron microscope image, KS8 well, 6736.45 m. (h) Nano fissures with width between 90 nanometers to 200 nanometers, field emission scanning electron microscope image, KS207 well, 6804.41 m

3.4. Micro pores and nano pores

The diameters of macro pores are larger than 10 μm according to the literatures. The diameters of the micro pores are smaller than 10 μm, but larger than 1 μm. The micro pores are all intergranular pores with both primary and secondary origin, as like macro pores. The primary micro intergranular pores have clear boundary and the shape of this kind of pores are triangle or irregular polygon (Figure 6a). The boundary of the secondary micro intergranular pores is very obscure and without particular shapes (Figure 6b, d). What we concerned is the nano pores, and their diameters are smaller than 1 μm (Figure 6e, g). Most nano pores are formed by the intragranular dissolution, exactly feeble dissolution. The results of this dissolution lead many tiny nano pores with diameters between tens to hundreds of nanometers. And the shape is also dominated by irregular polygons. These nano pores cannot be detected by common equipment, but could be seen under the high-resolution equipment such as field emission scanning electron microscope (FE-SEM).

3.5. Nano pore throat

The key influence factors of the permeability are the pore throat. In our study area, most pore throat is the fissures with different width according to the literatures (Sun et al., 2018). Their origin is including three types: compaction, tectonic compression and dissolution. Generally, the pore throat formed by compaction are often with micrometers width (Figure 6a-b), and the formed near the edge of the grains. After compaction, the remaining spaces between the adjacent grains generate a linear throat and finally become the pathway connecting the pores in its end. The pore throat formed by tectonic compression could be both very wide and very narrow. In the high-resolution image, we could see some narrow pore throat with width of tens to hundreds of nanometers (Figure 6d, h). Their two sides are sharp and clean, without any authigenic mineral. And their length is not very large, only in micrometers grade or millimeters grade. But this length is enough for them to connecting some micro pores and nano pores (Figure 6d). The last kinds of throat formed by dissolution have unsharp sides because of the dis-thorough dissolution, and the width of this throat will be changing along their extension direction (Figure 6c, f).

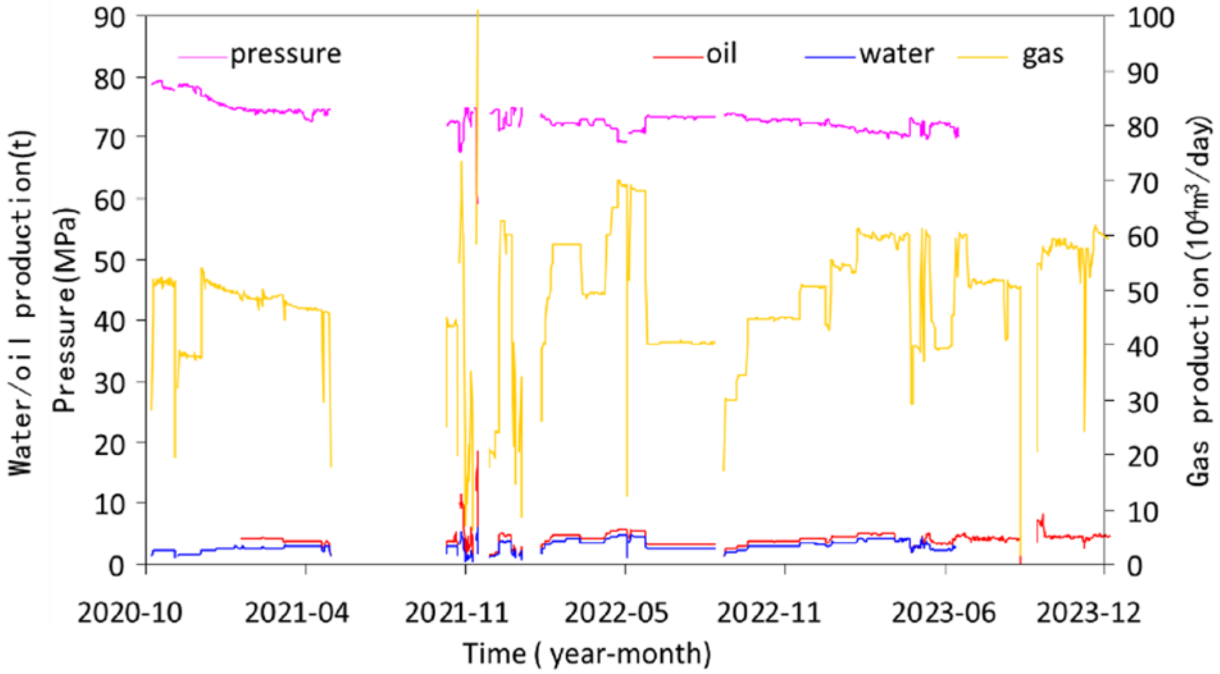

Figure 7. Production curves of BZ 301 well since the year of 2020 to the year of 2023. The same geological background with KS area

4. DISCUSSION

4.1. The influence of the nano pores and pore throats on rock physical property and the production

From the physical property part, we can see the same samples with low porosity and high permeability, especially in KS8 and KS5 area. The correlation between their permeability and porosity is not very well. Indeed, in the study area, this phenomenon exists in other boreholes of study area as well. We believe that the reason of the permeability increase is the development of those fissures, especially those nano fissures, as we say, nano pore throat. Because we can see in the mercury injection experiment results, the valid size of the pore throat often lying at the content from 15 to 100 nanometers, which are just the nano fissures as we seeing in the scanning electron microscope (Figure 6). And these pore throats of different origin can connect different size pores, such as macro pores, micro pores and nano pores. In this physical property of the tight gas reservoir, the production curves could maintain three years (Figure 7). The fundamental factor is the matrix pores are all connected by the pore throats. The matrix pores are including the nano pores, and the pore throats are mainly the nano pore throats. Due to nano fissures, the matrix nano pores can become effective pores. So that, the production was always very invariable for a long time. So, we agree that contributions of nano pores and nano pore throats in the matrix are important factors affecting tight gas reservoir physical property and production.

4.2. The distribution of the nano pores and nano pore throats

The final application of the above progress is to predict the valid reservoir according to their distribution. So, the next question we should concern is how do they distributed, especially for the nano pore throats. As we explained before, the reason for the nano pore throats is including compaction, tectonic compression and dissolution. Firstly, the compaction is not very good to the tight gas reservoirs, so we should select the area underwent weak compaction. Secondly, the tectonic compression, which is the sword double edged, can increase the nano fissures and also can decrease the intergranular pores. Therefore, we shall research the balance time of the tectonic compression. Thirdly, the dissolution is always the beneficial factor. This dissolution is the later dissolution in the diagenesis evolution of the tight sandstones. And according to the literatures, this dissolution should be formed by the organic acid released from the adjacent source rocks. So, the favorable area for the distribution of nano pores and nano pore throats may lying in the area with certain tectonic compression and dissolution and without intensely compaction.

5. CONCLUSION

Tight gas sandstones formed in the Bashijiqike

Formation of Cretaceous in Kuqa Depression of Tarim Basin is mainly the grain supported, moderately to well sorted lithical arkoses and feldspathical litharenite. This tight gas sandstones area known as low porosity but relatively high permeability.

Based on the field emission scanning electron microscope (FE-SEM), back-scattered electron image (BSE), mercury injection experiment and laser scanning confocal microscope, we can measure the nano pores and nano pore throats with tiny diameters directly. These nano pores can be divided into two types according to their origin and characteristics, and the nano pore throats can be divided into three types.

The contribution of the nano pores and nano pore fissures is very important for the tight gas sandstones physical property and production, because the nano pore fissures can effectively connect the nano pores and macro pores in the matrix of the reservoir. So, the next exploration should concern, mainly, the compaction, tectonic compression and partly, dissolution, which are the controlling factors for the nano pores and nano pore throats.

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