Determining the Accumulation Limits of the Physical Properties of Tight Sandstone Reservoirs in Eastern Ordos Basin*

Qing Cao[1,2], Jingzhou Zhao[1,2], Xinshe Liu[3], Aiping Hu[3], Liyong Fan[3], and Huaichang Wang[3]

Search and Discovery Article #51030 (2014)
Posted September 22, 2014

*Adapted from poster presentation given at AAPG International Conference & Exhibition, Istanbul, Turkey, September 14-17, 2014, AAPG © 2014

[1]School of Earth Sciences and Engineering, Xi'an Petroleum University, Xi'an, Shaanxi 710065, China (cao.qing@foxmail.com)
[2]Shaanxi Key laboratory of Petroleum Accumulation, Xi'an, Shaanxi 710065, China
[3]PetroChina Company Limited Changqing Oilfield Branch, Xi'an, Shaanxi 710021, China

Abstract

Focusing on force analysis of natural gas in micropore-throat, this paper researches the upper and lower petrophysical limits of gas accumulation in tight sandstone reservoirs of the Eastern Ordos Basin.

1. Determination of lower limit of pore-throat radius assuming thickness of irreducible water film as the minimum pore-throat radius for gas injecting into tight reservoirs. Based on the irreducible water saturation, it can be calculated the thickness of irreducible water film for tight reservoirs in the study area ranges from 5 nm to 15 nm, with a mean of 10.2 nm. Values of the He 8 Section and Shan 2 Section are 5 nm-17 nm and 4 nm-9 nm respectively.

2. Determination of the upper limit of pore-throat radius calculation the upper limit can be divided into two cases:
   (1) Taking abnormal pressure of source rock into consideration the radius is inversely proportion to abnormal pressure. At the end of the Early Cretaceous, if abnormal pressure was larger than 5 MPa, gas driven by abnormal pressure and buoyancy can inject into all reservoirs with 0.01 μm pore-throat, i.e. all reservoirs with pores-throats which were not sealed by irreducible water. However, the corresponding value of abnormal pressure is 6.5 MPa in current geological conditions.
   (2) Regardless of abnormal pressure, without consideration of hydrodynamic force and abnormal high pressure, when capillary force is equal to buoyancy, the corresponding critical pore-throat radius value can be regarded as the

upper limit of the pore-throat. This value for the tight reservoir of the He 8 Section, Taiyuan Formation and Shan 23 Section, at the end of the Early Cretaceous and present, are 0.61 μm, 1.55 μm and 0.25μm, 0.46μm respectively.

3. Critical petrophysical limit - the relation between median radius and permeability is significant. Therefore, based on the results of correlation fitting between median pore-throat radius and petrophysical parameters, critical petrophysical properties can be predicted with critical pore-throat radius values. For the He 8 Section, lower petrophysical limits of the reservoir are 4% and 0.1×10^{-3} μm^2, upper petrophysical limits, i.e. porosity and permeability, of the reservoir developed at the end of the Early Cretaceous and present are 13%, 1.8×10^{-3} μm^2 and 14%, 2.0×10^{-3} μm^2 respectively. For the Shan 23 Section, the corresponding values are, in order, 2% and 0.01×10^{-3} μm^2, 8% and 1.0×10^{-3} μm^2, 9% and 1.4×10^{-3} μm^2. For the Taiyuan Formation, they are in order, 3.5% and 0.02×10^{-3} μm^2, 11% and 1.1×10^{-3} μm^2, 12% and 2.0×10^{-3} μm^2.

Introduction

At present, petrophysical limits of tight reservoirs are analyzed by the empirical method. However, the results cannot reasonably be explained and defined by the characteristics of tight reservoirs in terms of real accumulating conditions. In order to study the petrophysical limits of gas accumulation in the Paleozoic tight sandstone reservoir, Ordos Basin, on the basis of force analysis of fluid in microscope pore-throat of sandstone, correlation between petrophysical properties (porosity, permeability) and force balance (buoyancy, capillary force, abnormal pressure, hydrodynamic force) can be built. This gives a new idea to investigate the petrophysical limits of gas accumulation in tight reservoir, i.e. with geological conditions of gas accumulation in the Paleozoic tight sandstone gas reservoir of the Ordos Basin. Critical pore-throat radius of gas accumulating in tight sandstone reservoir can be induced based on the real geological parameters. After assuming the thickness of irreducible water film as the lower limit of radius for gas injecting and critical radius, capillary force is equal to buoyancy acts as the upper limit. Then it can be established by fitting relationships between pore-throat radius and petrophysical properties. At last, according to the limit of pore-throat radius, the limit of petrophysical properties can be calculated. Thus, with accurate reconstruction of geological parameters of gas accumulation, tightest degrees of Paleozoic sandstone in the Ordos Basin can be evaluated reasonably. Focusing on force analysis of natural gas in micro pore-throat and synthesizing the irreducible water film, hydropower, buoyancy, capillary pressure, and abnormal high pressure etc., which govern the gas accumulation, this paper researches the upper and lower petrophysical limits of gas accumulation in tight sandstone reservoirs of the Eastern Ordos Basin.

Determination of lower limit of pore-throat radius for tight reservoir

Assuming thickness of irreducible water film as the minimum pore-throat radius for gas injecting into a tight reservoir, based on the irreducible water saturation measured by NMR, it can be calculated that this value is equal to 10 nm. Thickness of irreducible water film for the tight reservoirs in the study area ranges from 5 nm to 15 nm, with a mean of 10.2 nm. The values in the He 8 Section and Shan 2 Section are 5 nm-17 nm and 4 nm-9 nm respectively, which indicate that the thickness of irreducible water film decrease with increasing depth (Table 1 and Figure 1).

Determination of upper limit of pore-throat radius for tight reservoir

On the basis of force analysis of gas in microscope pore-throat, including buoyancy, capillary force, and abnormal pressure, calculation of the upper limit can be divided into two cases:

1. Taking abnormal pressure of source rock into consideration, upward migration of gas is driven by buoyancy and abnormal pressure but inhibited by capillary pressure:

   $$2\sigma/r = Z\times(\rho_w-\rho_g)\times g + P$$

   Where Z is gas column height in m, σ is interfacial tension in 10^{-3} N/m, r is pore-throat radius in micrometers, ρ_w and ρ_g are respectively the density of water and gas in 10^3 kg/m^3, P is abnormal pressure in MPa. Based on the above equation, the following equation can be inferred.

   $$r = 2\sigma/(Z\times(\rho_w-\rho_g)\times g + P)$$

   It can be clearly found that radius is inversely proportion to abnormal pressure if σ, $(\rho_w-\rho_g)$ and Z are all constant, which is to say, for greater abnormal pressure, the pore throat radius which gas can inject, is smaller. So the result is the minimum pore-throat radius is controlled by abnormal pressure and buoyancy. In the study area, at the end of the Early Cretaceous, if abnormal pressure was larger than 5 MPa, gas driven by abnormal pressure and buoyancy, can inject into all reservoirs with 0.01 μm pore-throat, i.e. all reservoirs with pores-throats which were not sealed by irreducible water. However, the corresponding value of abnormal pressure is 6.5 MPa in current geological conditions (Figure 2).

2. Regardless of abnormal pressure:

Without consideration of hydrodyanamic force and abnormal high pressure, when capillary force is equal to buoyancy, the corresponding critical pore-throat radius value can be regarded as the upper limit of the pore-throat. This varies with different gas column height of the gas-bearing section in different periods. Width of the gas zone for the He 8 Section in the Sulige area ranges from 800 m to 1600 m in a south-north direction, calculated width is 1200 m. In the east-west direction of the gas zone, width is mainly 400 m~800 m, calculated width is 600 m. Width of the gas zone in the Shan 2 Section of the Yulin area and Taiyuan Formation of the Shenmu area can be defined by the same way. Formation dip angles of the Late of Early Cretaceous and Current are all nearly 0.5º, formation dip directions are different. Dip direction of Late of Early Cretaceous is south-north, nearly parallel to the trend of the reservoir sandstone. Current dip direction is east-west, vertical to the trend of the reservoir sandstone. Based on the extension length of Late of Early Cretaceous and Current gas zone in the south-north direction and east-west direction, corresponding gas column can be calculated (Table 2).

Critical petrophysical limit of tight reservoir

Mean radius of pore and mean radius of throat have no obvious correlation with permeability. The relationship between median radius and permeability is significant. Based on the results of conventional mercury injection, it can be found that petrophysical fitting trend is relatively poor if median radius is smaller than 0.2 µm and relatively good if median is larger than 0.4 µm. This infers that the median can reflect tighten degree and fit petrophysical parameters of the reservoir (Figure 3).

Finally, on the basis of results from mercury injection experiment, fitting correlation between median pore-throat radius and petrophysical parameters can be built and then critical petrophysical properties can be predicted with critical pore-throat radius values (Figure 4). For the He 8 Section, the lower petrophysical limits of the reservoir are 4% and 0.1×10^{-3} µm^2, upper petrophysical limits, i.e. porosity and permeability, of the reservoir developed at the end of the Early Cretaceous and present are 13%, 1.8×10^{-3} µm^2 and 14%, 2.0×10-3µm2 respectively. For the Shan 23 Section, the corresponding values are, in order, 2% and 0.01×10^{-3} µm^2, 8% and 1.0×10^{-3} µm^2, 9% and 1.4×10^{-3} µm^2. For the Taiyuan Formation, they are in order, 3.5% and 0.02×10^{-3} µm^2, 11% and 1.1×10^{-3} µm^2, 12% and 2.0×10^{-3} µm^2.

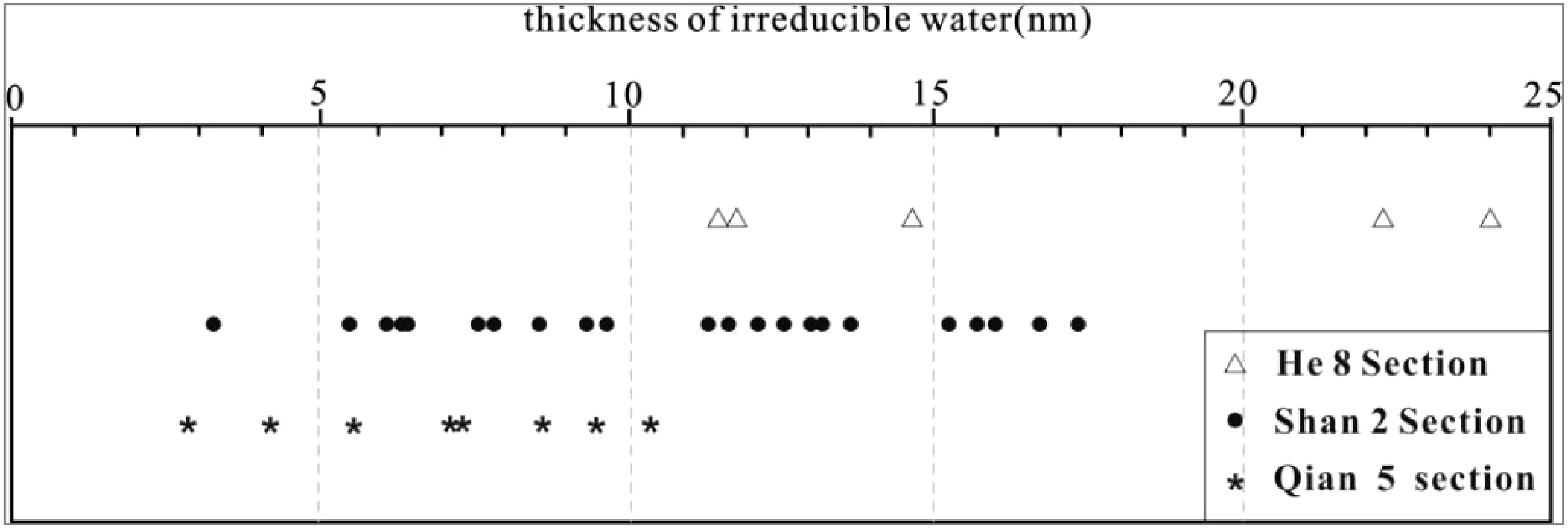

Figure 1. Comparison of irreducible water film thickness in different layers of eastern Ordos Basin.

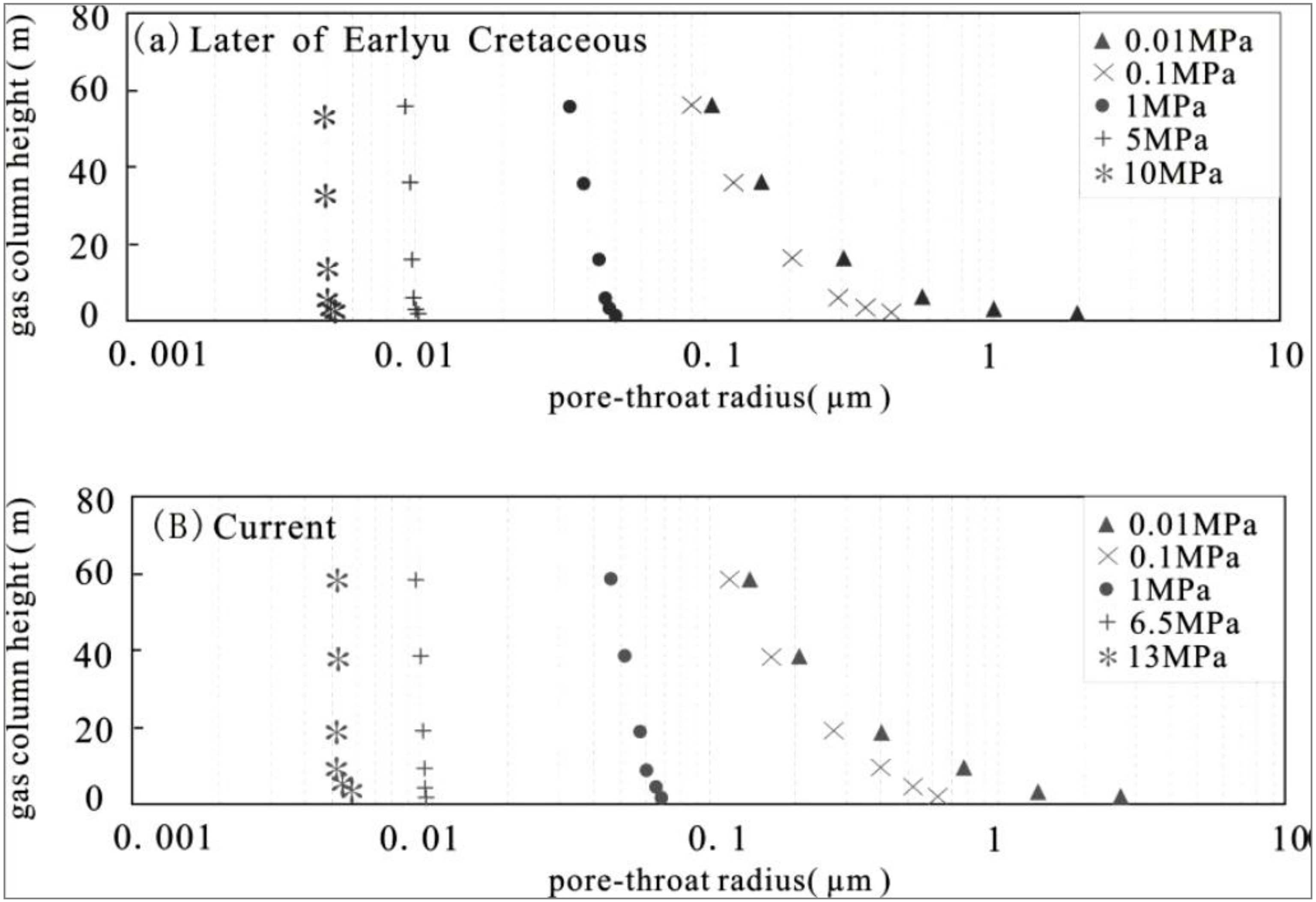

Figure 2. The comparison of overpressure, gas column height, and pore-throat radius in different epochs.

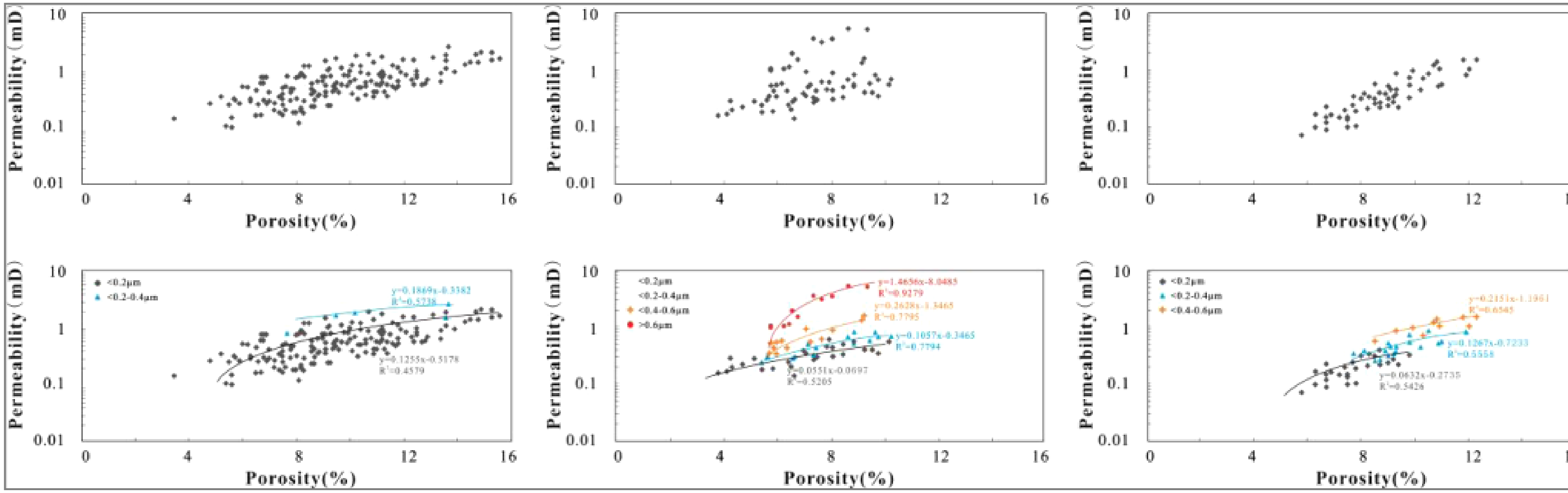

Figure 3. The relationship between porosity and permeability and its median pore-throat size in different formations.

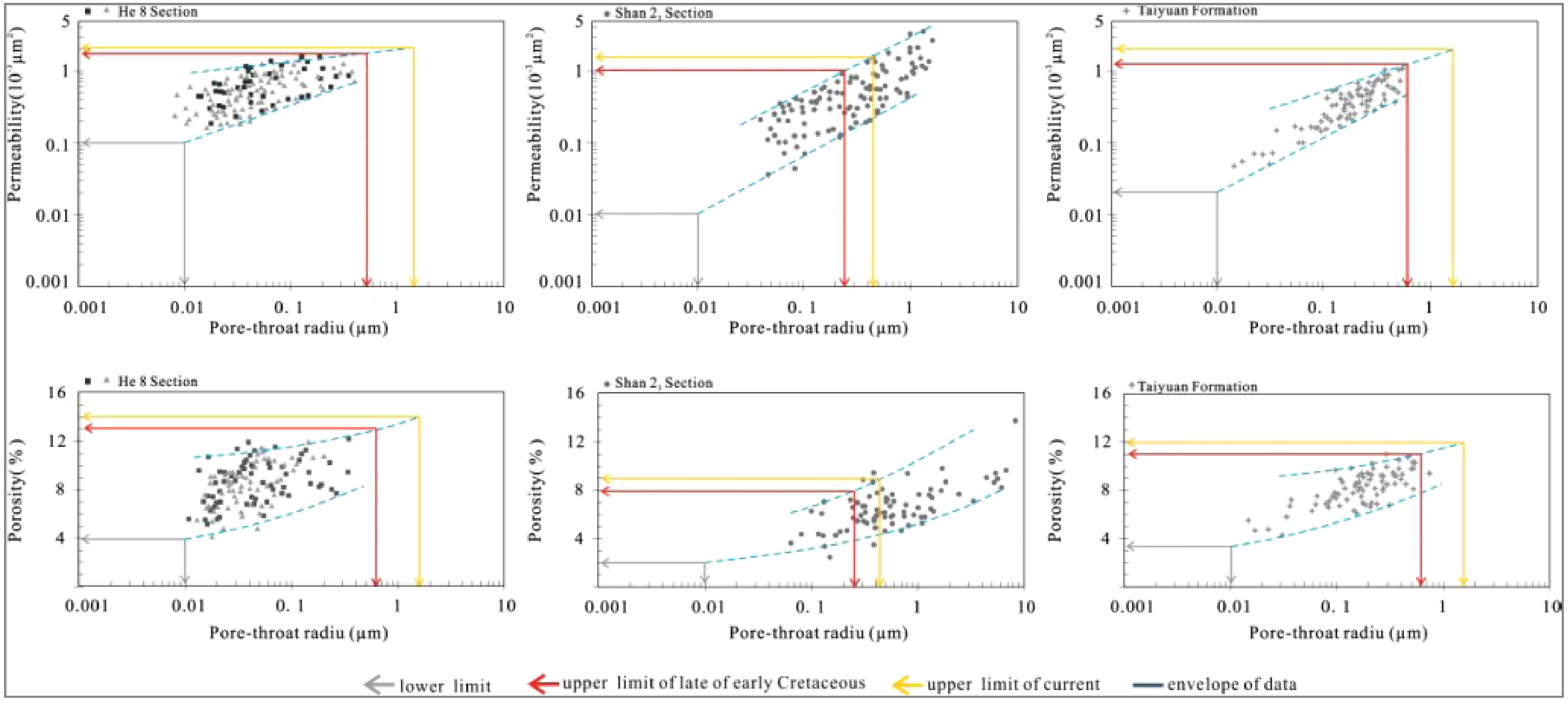

Figure 4. The consequence of physical properties limit in tight sandstone in different epochs.

Section	Number	Pore（%）			Saturation of irreducible water（%）			Thickness of irreducible water film（nm）		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Qian 5 Section	5	10.7	15.5	13.1	35.9	68.6	53.8	11.5	24.1	18.9
He 8 Section	50	3.1	16.7	7.8	34.1	83.2	64.4	4.2	22.1	10.8
Shan 2 Section	9	3.6	12.4	8.6	15.4	71.1	42.2	3.1	10.5	7.2

Table 1. Irreducible water film parameters and calculation results in different layers.

section	Late of Early Cretaceous			Current		
	Width of gas zone（m）	Height of gas column（m）	pore-throat radius（μm）	Width of gas zone（m）	Height of gas column（m）	pore-throat radius（μm）
He 8 Section	1200	10	0.61	600	5	1.55
Shan 2 Section	3000	26	0.25	2000	17	0.46
Taiyuan FM	1200	10	0.61	600	5	1.55

Table 2. The comparison of critical pore-throat radius in different epochs.