An Experimental Study on the Permeability Anisotropy of the Paleogene Strata in Zhanhua Sag

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***Abstract* -- To analyse the permeability anisotropy of the Paleogene strata in the Zhanhua sag of the Bohai Bay Basin, 10 groups of 40 sandstone and mudstone samples were selected to conduct four experiments with pressures. The results indicate that horizontal permeability of porous sandstone and mudstone is greater than the vertical permeability at normal atmospheric pressure. Then the permeability anisotropy of sandstone and mudstone is mainly related to its arrangement of particles. The horizontal and vertical permeability of sandstone and mudstone decrease with increased pressure and increase with reduced pressure, but the increased rate of horizontal permeability is greater than that of vertical when the pressure is reduced, and both of them cannot be restored to the same values by increasing the pressure to the previous values. The permeability of sandstone and mudstone are greatly increasing after fracturing, and the mudstone increases more than that of sandstone. When increase or decrease the pressures to the samples with fractures, the permeability parallel to the fractures is greater than that perpendicular to the fractures. However, the permeability changes more dramatically with the pressure perpendicular to the fractures, indicating that fracture permeability is more sensitive to the pressures. In all, the permeability anisotropy of the Paleogene strata in Zhanhua Sag is related to its arrangement of particles, pressures, fractures, and the direction of the pressure and fractures.**

Keywords -- permeability; anisotropy; Zanhua Sag; Paleogene;pressure

I INTRODUCTION

In the continental hydrocarbon basin, sandstone and mudstone are two important transporting pathways in the hydrocarbon accumulation process. The sandstone and mudstone formation permeability reflects the level of transmission of the size. The level of penetration in different directions (anisotropic permeability) not only reflects the quality of the oil and gas transporting properties but also has a significant impact on the Wells arrangement, fracturing design and the development of oil and gas fields [1-4]. In recent years, scholars have performed substantial research on permeability anisotropy, which depends on the internal structure of the rock material [5]. H.Y.Al-Yousef (2005) developed a mathematical analytical formula to calculate the permeability[6], and Yao Jun(2009) studied the reservoir permeability anisotropy through a finite element numerical simulation method[7]. Permeability anisotropy affects not only the flow of oil but also the stress anisotropy [8,9]. Permeability anisotropy of tight sandstone is a function of pressure[10,11],and the anisotropic permeability exerts a greater impact on the yield of the low-permeability reservoir [12]. The permeability of cracked sandstone is greater than the permeability of sandstone without cracks [13,14]. The permeability of mudstone increases with increasing porosity [15,16]. Fracture permeability decreases as a negative exponential function of the effective pressure increase [17]. The permeability parallel to the fault dip is 10 times higher than the permeability along the fault strike [18]. Overall, previous studies have individually considered sandstone, mudstone and fracture permeability anisotropy, but few researchers have performed comparative studies on the permeability anisotropy of sandstone, mudstone formation and fractures. Based on previous research, in this paper, four experiments were designed to study the anisotropic permeability to sandstone, mudstone and fractures in the Zhanhua Sag.

II GEOLOGICAL BACKGROUND AND SAMPLE LOCATIONS

The experimental study of wells is conducted in the Zhanhua Sag, which is located in the northern part of the Jiyang Depression, China (Fig. 1). On the north are the YiNan, YiDong, and ChengDong faults, on the east is KenDong faults, and to the south is the regional stratigraphic uplift overlap transition to ChenJiaZhuang. The stratigraphy mainly developed during the Paleogene, Neogene and Quaternary, and it consists of sand-shale of lacustrine and fluvial deposits（Tab. 1）. The Zhanhua Sag has overall existed in a tensile stress field since the Paleogene. The experimental cores come from the Paleogene strata, mainly in the central and northern Zhanhua Sag, for a total of 10 groups of six wells: the sand-shale core segments of the different layers are examined.

Figure 1. Map of the basin and the well

III LABORATORY METHODS

A. *Equipment*

1)CMS series core auto analyzers

Voltage：110V±0.1 V 50Hz（Fig. 2）.

Figure 2. CMS series core auto analyzers

2)Triaxial rock mechanics testing system

The triaxial rock mechanics test system made in United States Terratek company (Fig. 3), which can simulate the temperature and stress of the rock underground, and can test the mechanics, acoustics, and compression properties etc. was used in this paper. Its main technical indicators: axial compression 1.46 × 103kN, confining pressure 140MPa, temperature of 200 □.

Figure 3. Triaxial rock mechanics testing system

B. *Samples*

A total of 10 gorup of 40 samples (including 8 groups of sandstone samples and 2 groups of mudstone samples) from Paleogene strata located in the Middle and northern of Zhanhua Sag were selected for this study. Each group have four samples, two parallel the strata labelled "H"; two perpendicular the strata labelled "V". The samples come form depths of 1904.34m to 4295.50m, and nearly all of them have no cracks except the sample “Y15MH-1”(see TAB. I).

C. *Methods*

Four experiments were carried out in this paper, First, testing the horizontal and vertical permeability of porous sandstone and mudstone at normal atmospheric pressure.

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40 typical sandstone and shale core samples were selected and cut as cylinder with diameter about 25.4mm and lenth about 50.8mm, and were drying and degreasing, and testing the horizontal and vertical permeability of porous sandstone and mudstone at normal atmospheric pressure. Second, testing the horizontal and vertical permeability of sandstone and mudstone by gradually increasing and decreasing pressure, observing and recording the permeability changes with the changing pressure(experimental procedure is as fig. 4). Third, Continue to increase the pressure until the

TABLE I. TABLE OF SAMPLE INFORMATION

NO	Well NO.	Lithology	Depth (m)	Strata	Remark
①	CH110	Feldspathic lithic sandstone	1904.34	Paleogene	No cracks
②	Y3-7-7	Feldspathic lithic sandstone	3111.50	Paleogene	No cracks
②	Y3-7-7	Feldspathic lithic sandstone	3119.94	Paleogene	No cracks
②	Y3-7-7	Feldspathic lithic sandstone	3166.89	Paleogene	No cracks
②	Y3-7-7	Feldspathic lithic sandstone	3353.40	Paleogene	No cracks
③	Y172	Lithic arkose	3528.00	Paleogene	No cracks
④	BS3	Lithic arkose	3542.27	Paleogene	No cracks
⑤	Y151	Lithic arkose	4295.50	Paleogene	No cracks
⑥	L67	Dolomitic mudstone	3309.80	Paleogene	No cracks
②	Y3-7-7	Dolomitic mudstone	3578.87	Paleogene	Sample Y15MH-1 With cracks

samples fractured, then testing the horizontal and vertical permeability of sandstone and mudstone with fractures. Finally, increase and decrease the pressures to the samples with fractures, include two experiments, one is parallel to the fractures with confining pressure (1MPa), the other is perpendicular to the fractures with specified axial compression (0MPa)(Fig. 4).

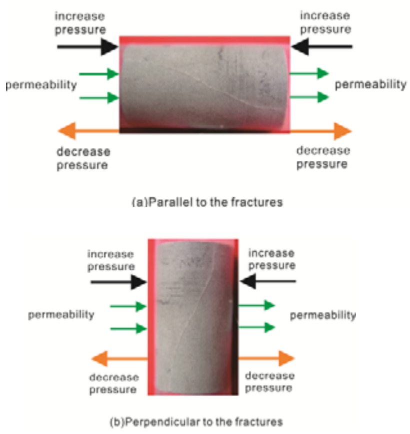

Figure 4. Permeability experiment parallel and perpendicular to the fractures

IV RESULTS

A. Permeability anisotropy experiment on sandstone and mudstone at normal atmospheric pressure

At normal atmospheric pressure, 10 groups of 40 samples were tested in this experiment, including 8 groups of sandstone samples, four of feldspathic lithic sandstone and four of lithic arkose (two groups are argillaceous) and 2 groups of dolomitic mudstone samples (see TAB.II).

The results show that the average horizontal permeability of sandstone is 0.39mD, and the average vertical permeability of the sandstone is 0.0079mD. The horizontal permeability of sandstone is slightly larger than the vertical permeability, and its average permeability ratio is 4.72. The average horizontal permeability of mudstone is 2.03mD, and the average vertical permeability of the

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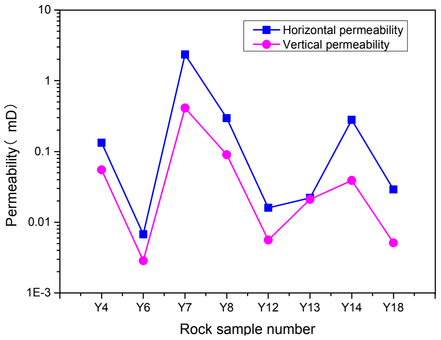
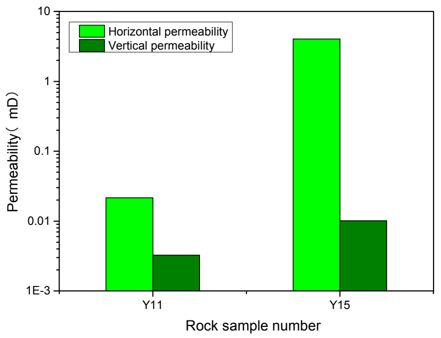
mudstone is 0.0067mD. Clearly, the horizontal permeability of mudstone is much larger than the vertical permeability, and its average permeability ratio average is 220.79. Overall, regardless of sandstone or mudstone, the horizontal permeability is larger than vertical permeability (TAB. III, Fig. 5).



(a)Sandstone



(b)Mudstone

Figure 5. The horizontal and vertical permeability of sandstone and mudstone samples

At normal atmospheric pressure, the permeability anisotropy of sandstone and mudstone is mainly related to its arrangement of particles. When debris particles are deposited, the long axis of the particles is often parallel to the horizontal direction. The experimental samples of Sandstone are all ranging grained sandstones, which resulting in a relatively large number of throats in the horizontal direction and a small number of throats in the perpendicular direction. In addition, porous sandstone easily forms grain seams and grain edge seams in the horizontal direction, and these cracks can communicate with the pores, thus increasing their connectivity. However, microcracks do not develop in the vertical direction, and the pore connectivity is poor. Therefore, the horizontal permeability is larger than vertical permeability.

TABLE II. THE HORIZONTAL AND VERTICAL PERMEABILITY OF SANDSTONE AND MUDSTONE SAMPLES

Well NO.	**Lithology**	**Depth (m)**	**Sample No.**	**Permeability (mD)**	**average permeability (mD)**	**Permeability ratio (H/V)**	**Remark**
CH110	Feldspathic lithic sandstone	1904.34	Y4SH-1	0.205	0.1325	2.41	No cracks
			Y4SH-2	0.06			
			Y4SV-1	0.022	0.055		
			Y4SV-2	0.088			

TABLE II. CONTINUED THE HORIZONTAL AND VERTICAL PERMEABILITY OF SANDSTONE AND MUDSTONE SAMPLES

Well NO.	**Lithology**	**Depth (m)**	**Sample No.**	**Permeability (mD)**	**average permeability (mD)**	**Permeability ratio (H/V)**	**Remark**
Y3-7-7	Feldspathic lithic sandstone	3111.5	Y6SH-1	0.0067	0.00675	2.37	No cracks
			Y6SH-2	0.0068			

			Y6SV-1	0.0018	0.00285		
			Y6SV-2	0.0039			
Y3-7-7	Feldspathic lithic sandstone	3119.94	Y7SH-1	3.31	2.355	5.72	No cracks
			Y7SH-2	1.4			
			Y7SV-1	0.572	0.412		
			Y7SV-2	0.252			
Y3-7-7	Feldspathic lithic sandstone	3166.89	Y8SH-1	0.548	0.295	3.28	No cracks
			Y8SH-2	0.042			
			Y8SV-1	0.062	0.09		
			Y8SV-2	0.118			
Y3-7-7	Lithic arkose	3353.4	Y12SH-1	0.018	0.016	2.86	No cracks
			Y12SH-2	0.014			
			Y12SV-1	0.007	0.0056		
			Y12SV-2	0.0042			
Y172	Lithic arkose	3528	Y13SH-1	0.018	0.022	1.05	No cracks
			Y13SH-2	0.026			
			Y13SV-1	0.031	0.021		
			Y13SV-2	0.011			

TABLE II. CONTINUED THE HORIZONTAL AND VERTICAL PERMEABILITY OF SANDSTONE AND MUDSTONE SAMPLES

Well NO.	**Lithology**	**Depth (m)**	**Sample No.**	**Permeability (mD)**	**average permeability (mD)**	**Permeability ratio (H/V)**	**Remark**
BS3	Lithic arkose	3542.27	Y14SH-1	0.036	0.2795	7.17	Lithology uneven
			Y14SH-2	0.523			No cracks
			Y14SV-1	0.05	0.039		
			Y14SV-2	0.028			
Y151	Lithic arkose	4295.5	Y18SH-1	0.033	0.029	5.69	No cracks
			Y18SH-2	0.025			
			Y18SV-1	0.0055	0.0051		
			Y18SV-2	0.0047			
L67	Dolomitic mudstone	3309.8	Y11MH-1	0.031	0.0215	6.62	No cracks
			Y11MH-2	0.012			
			Y11MV-1	0.0028	0.00325		
			Y11MV-2	0.0037			
Y3-7-7	Dolomitic mudstone	3578.87	Y15MH-1	8	4.0475	398.77	With crackes

			Y15MH-2	0.095			No cracks
			Y15MV-1	0.0093	0.01015		
			Y15MV-2	0.011			

TABLE III. COMPARISON OF AVERAGE HORIZONTAL AND VERTICAL PERMEABILITY OF SANDSTONE AND MUDSTONE SAMPLES

Sample	**Horizontal permeability (mD)**	**vertical permeability (mD)**	**Average Permeability ratio (H/V)**
sandstone	0.39	0.0788	4.72
mudstone	2.03	0.0067	220.79

B. Permeability anisotropy experiment on porous sandstone and mudstone under increased and decreased pressures

A total of 10 groups of 40 samples were tested (the samples were the same as in part 3.1). The experimental process of increasing and decreasing the pressure was as follows: the pressure on sandstone samples was gradually increased from 5.52MPa to 40.37MPa in a series of 5 pressure values, and each pressure value was held for 1 to 2 minutes, and then decreased from 40.37MPa to 5.52MPa, and horizontal and vertical permeability were tested at varying pressures. The pressure on the mudstone samples was gradually increased from 5.52MPa to approximately 31.78MPa, and then decreased from the 31.78MPa to 5.52MPa, with each pressure value holding for 1 to 2 minutes. and test horizontal and vertical permeability at varying pressures.

Here, we compared the results under changing pressure and normal atmospheric pressure,then we found that both horizontal and vertical permeability of sandstone samples decreased under increased pressure, and most samples' permeability decreased by more than 80% (see Fig. 6). Under decreased pressure, both horizontal and vertical permeability of the sandstone samples increased, and the rates of permeability increase were predominantly 150% to 400%, with the highest reaching 1,520% (see Fig. 7). Under increased pressure, the difference between horizontal and vertical permeability is small. However, under decreased pressure, the increase rate of horizontal permeability in sandstone is higher than that of vertical permeability (TAB. IV, Fig. 8).

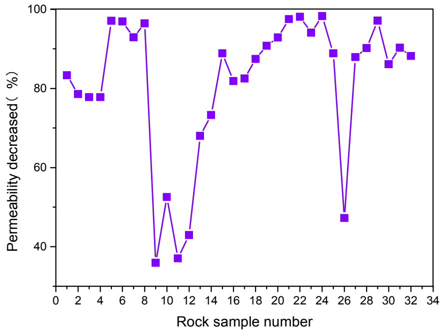


Figure 6. Sandstone permeability decrease with increased pressure

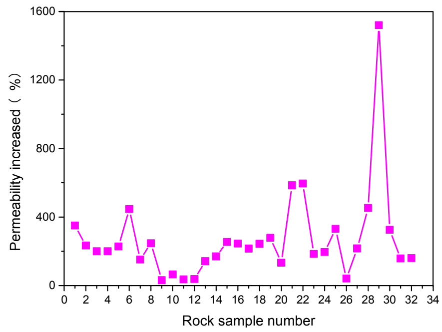


Figure 7. Sandstone permeability increase with decreased pressure

TABLE IV. AVERAGE HORIZONTAL AND VERTICAL PERMEABILITY OF SANDSTONE SAMPLES

samples / **Item**	**horizontal permeability**	**vertical permeability**
Average permeability decrease (%)	79.42	83.03
Average permeability increase (%)	345.17	196.96

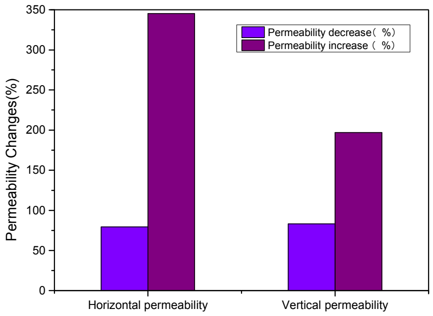


Figure 8. Comparison of average horizontal and vertical permeability of sandstone samples

Under increased pressure, both the horizontal and vertical permeability of the mudstone samples decreased by more than 90% (see Fig. 9). Under decreased pressure, both the horizontal and vertical permeability of the mudstone samples increased, mostly by approximately 150% -400% (see Fig. 10). Under increased pressure, the difference between the horizontal and vertical permeability decrease is small. However, under increased pressure, the increase rate of horizontal permeability is higher than that of vertical permeability (TAB.V, Fig. 11).

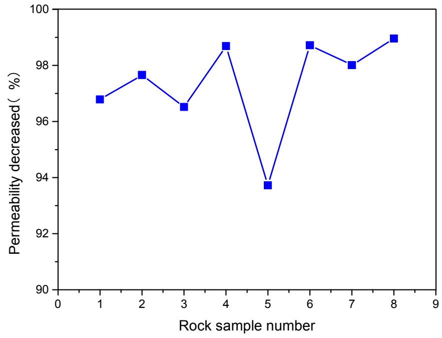


Figure 9. Mudstone permeability decrease with increased pressure

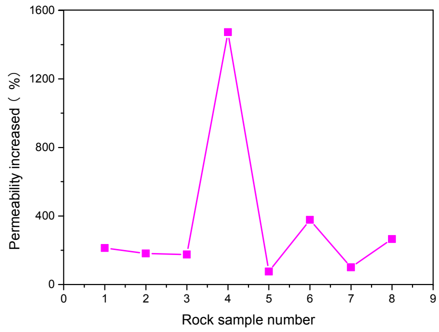


Figure 10. Mudstone permeability increase with decreased pressure

TABLE V. AVERAGE HORIZONTAL AND VERTICAL PERMEABILITY OF MUDSTONE SAMPLES

samples / Item	horizontal permeability	vertical permeability	remark
Average permeability decrease (%)	96.72	98.04	Samples Y11MV-2 permeability increased rate is abnormal; remove value
Average permeability increase (%)	211.80	180.39	

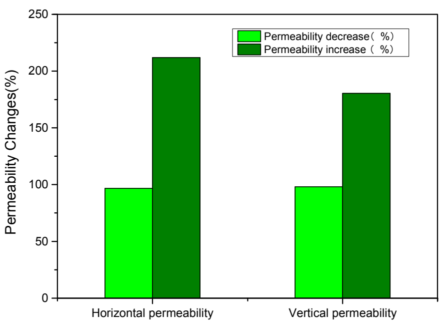


Figure 11. Comparison of average horizontal and vertical permeability of mudstone samples

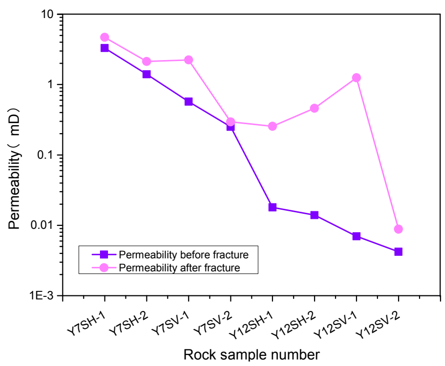
Overall, under increasing pressure (relative to the process of settlement), both the horizontal and vertical permeability of sandstone and mudstone decreased; under decreaed pressure (as opposed to uplift and erosion processes), both the horizontal and vertical permeability of sandstone and mudstone increased. However, the horizontal permeability increased more than the vertical permeability, and both of them cannot be restored to the same values by increasing the pressure to the previous values.

C. Permeability anisotropy experiment of sandstone and mudstone with fractures under increased and decreased pressures

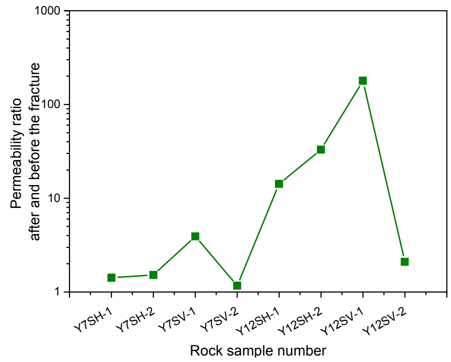
Eight sandstone samples and eight mudstone samples were tested before and after the fracture The permeability before fracture was tested in part 3.2, so we need to test the horizontal and vertical permeability after fracture. Four samples of sandstone and mudstone were used for the fracture experiment under low confining pressure, and the remaining four samples were used for the fracture experiment under high confining pressure.

The experimental process under low confining pressure was as follows: Under low confining pressure, increase or decrease the pressure along the single direction of the principal axis until the sample fracture, and record the fracture strength. Then, under1MPa confining pressure conditions, gradually increase and decrease pressure for the sandstone and mudstone samples with fractures, and test the horizontal and vertical permeability permeability change during the process of pressures change.

The experimental process under high confining pressure was as follows. At a high confining pressure of 10 MPa, increase or decreases the pressure along the single direction of the principal axis until the sample fracture, and records the fracture strength. Then under 2MPa confining pressure conditions, gradually increase and decrease pressure on the sandstone and mudstone samples with fractures, and test the permeability change during the process of pressures change.

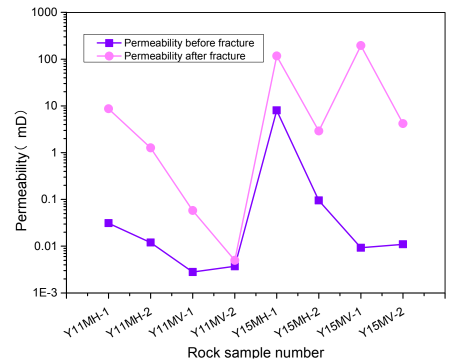


(a) Permeability before and after fracture

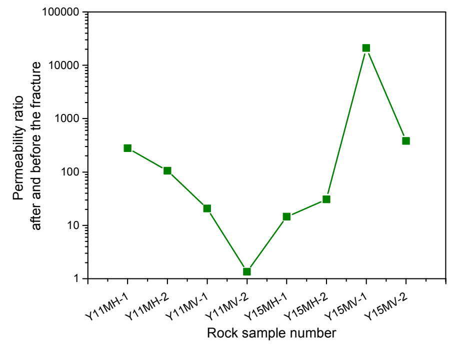


(b) Permeability ratio after and before the fracture

Figure 12. Permeability after and before the sandstone fracture



(a) Permeability before and after fracture



(b)Permeability ratio after and before the fracture

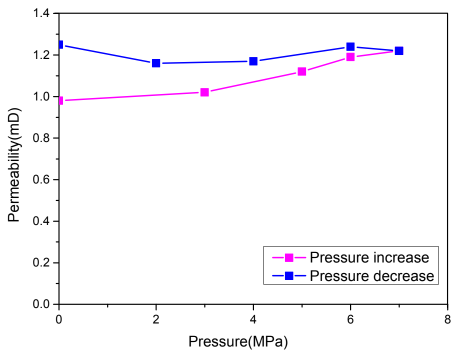
Figure 13. Permeability after and before the mudstone fracture

The experimental results show that both the horizontal and vertical permeability of the fractured sandstone and mudstone is much higher than that of the porous sandstone and mudstone. The permeability of fractured sandstone is predominantly 1.17-33 times the permeability of porous sandstone, and the highest value is 178.57 times(see Fig. 12).The permeability of fractured mudstone is predominantly 1.35-381.36 times the permeability porous mudstone, and the highest is 21000 times(see Fig. 13). Comparing the permeability of fractured and porous sandstone and mudstone, the permeability values after fracture are greatly increased, overall, and the permeability of the mudstone samples increased more than the permeability of the sandstone samples. Under this condition, the anisotropy of permeability is related to the fractures.

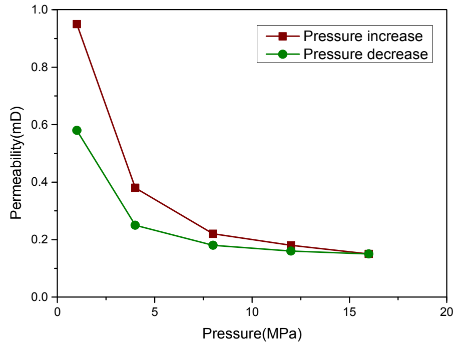
D. Permeability experiment parallel and perpendicular to the fractures

6 samples of three groups were tested in the experiment, including 2 groups of sandstone samples, 4 in all, and 1 group of mudstone samples, 2 in all. First, under1MPa confining pressure parallel to the fractures , the permeability was tested with increasing and decreasing pressure, and then under 0MPa cofining pressure perpendicular to the fractures,the permeability was tested with increasing and decreasing pressure(see Fig. 4).

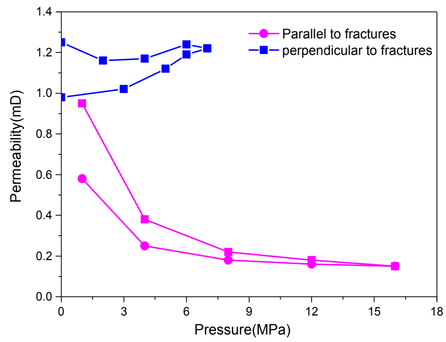
The experimental results show that at a certain confining pressure and under the condition of increasing the pressure parallel to the fractures, in the initial stage, the



(a) parallel to fracture



(b) perpendicular to fracture



(c) Comparison

Figure 14. Permeability of Sandstone parallel and perpendicular to the fractures while increasing and decreasing the pressure

permeability of sandstone with fractures decreases with increasing pressure: as the pressure continues to increase, the permeability will also increase. Under the condition of decreasing the pressure parallel to the crack, permeability of sandstone decreased with decreasing pressure but could not return to the original permeability (Fig. 14a). However, under the condition of increasing the pressure perpendicular to the fractures, permeability of sandstone with fractures decreases rapidly with increasing pressure, and increases with decreasing pressure but also cannot return to the original permeability (Fig. 14b). Comparing the processes of increasing and decreasing pressure parallel and perpendicular to fractures, we found the permeability is higher under pressure parallel to the fractures than that of perpendicular. However, the permeability perpendicular to the fracures is more sensitive to the pressures (Fig. 14c).

At a certain confining pressure, when increasing the

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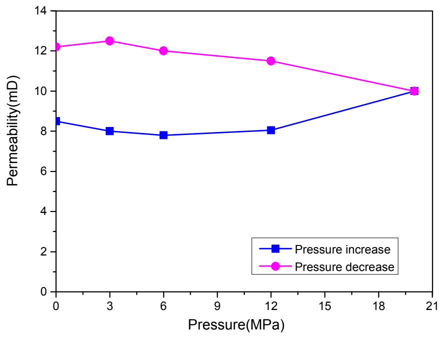
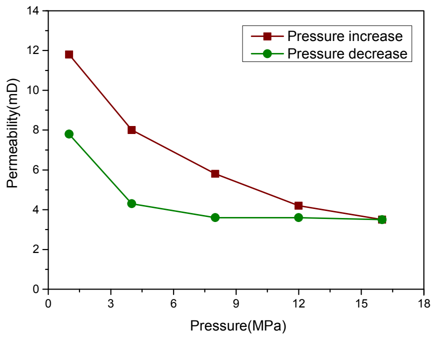
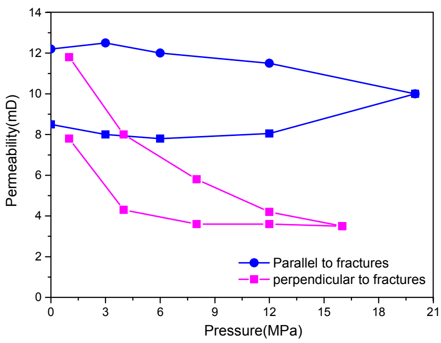
pressure parallel to the fractures, the permeability of mudstone with fractures decreases slowly with increasing pressure. As the pressure decreases, the permeability continued to decrease until the confining pressure was relatively low (less than 3MPa), at which point the permeability increases slowly (Fig. 15a). However, when decreasing the pressure perpendicular to the fractures, the permeability of mudstone with fractures decreases rapidly with increasing pressure and increases with decreasing pressure , but can not return to the original permeability (Fig. 15b).



(a) parallel to fracture



(b) perpendicular to fracture



(c) Comparison

Figure 15. Permeability of mudstone parallel and perpendicular to the fractures while increasing and decreasing the pressure

Upon the comparation results of increasing and decreasing pressure parallel and perpendicular to sandstone and mudstone fractures, we found the permeability is higher under pressure parallel to the fractures than that of perpendicular. However, permeability perpendicular to fractures is more sensitive to the pressures(Fig. 14c, 15c).

V Conclusions

At normal atmospheric pressure, the permeability anisotropy of sandstone and mudstone is mainly related to its arrangement of particles, and the horizontal permeability of sandstone and mudstone is larger than the vertical permeability. Under increasing pressure (relative to the process of settlement), both the horizontal and vertical permeability of sandstone and mudstone decrease, and under decreasing pressure (as opposed to uplift and erosion processes), both the horizontal and vertical permeability of sandstone and mudstone increase. With the pressure increases until the samples fracture, both the horizontal and vertical permeability of the fractured sandstone and mudstone is much higher than that of the porous sandstone and mudstone, the anisotropy of permeability is related to fractures. When increase and decrease the pressures to the samples with fractures, we found that permeability is higher under the pressure parallel to the fractures than that perpendicular to. However, permeability perpendicular to fractures is more sensitive to the pressures. In all, the permeability anisotropy of the Paleogene strata in Zhanhua Sag is related to its arrangement of particles, pressures, fractures, and the direction of the pressure and fractures. In the exploitation process of oil and gas, all of the above factors should be considered seriously.

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