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Impact of rock anisotropy on fracture development

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Abstract

Experiments on uniaxial and triaxial rock mechanics and rock acoustic emissions have been conducted for research on the impact of rock anisotropy on the development of the fractures of different directions by taking as an example the ultra-low-permeability sandstone reservoir in the Upper Triassic Yanchang Formation within the Ordos Basin. The experimental results prove the existence of anisotropy of the rock mechanical property in the different directions on the plane, which is the chief reason for the production of impacts on the development of different assemblages of fractures in the geological periods. The rock anisotropy usually restricts the development of one assemblage of conjugate shear fractures. The fractures in the Yanchang Formation within the Ordos Basin are mainly shear fractures that formed under two tectonic actions. Theoretically, here, four assemblages of shear fractures should have developed, but due to the effect of a strong rock anisotropy, in each period one assemblage of fractures chiefly developed. Thus, two assemblages of fractures are usually developed in every part at present.

Keywords: Fracture; Rock anisotropy; Rock mechanical experiments; Acoustic emission experiments

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1. Introduction

Low-permeability reservoirs are an important type of reservoirs within the continental sedimentary basins in China, whose reserves constitute more than one-third of the total of the proven oil and gas resources and 70% of the total of the proven oil and gas reserves since 1995. Their production makes up about 20% of the total annual petroleum production of China and is expected to come up to more than one-third in 2010. Therefore, the exploration and development of the low-permeability reservoirs are of long-term strategic significance to the development of China's oil and gas industry. The sedimentary, diagenetic and tectonic effects give rise to serious anisotropy of the low-permeability reservoirs, in which fractures are developed, affecting the oil and gas development [1–3]. The formation and distribution of fractures are affected by such factors as the lithology, the thickness of a stratum, the geological structure and the stress [3–12]. In addition, the rock anisotropy of mechanical property, caused by sedimentation and diagenesis, is also an important factor [12–14]. The rock anisotropy can even be a dominant factor in controlling the development of fractures, especially in a district with a less tectonic differential stress magnitude [15].

In the recent years, the effect of rock anisotropy on fracture development has aroused increasing attention and it can even be the chief reason for the apparently clustered distribution of fractures in different directions [16,17]. This research is mainly focused on the effect of the vertical rock anisotropy caused by the lithological difference on the

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formation of fractures [18]. But we have no clear idea of the controlling effect of the rock anisotropy on fracture development on the plane. Starting from rock mechanical experiments on the ultra-low-permeability sandstone reservoirs in the Yanchang Formation within the Ordos Basin, and combining the actual different conditions for the development of different assemblages of fractures in the studied area, we analyzed the effect of the rock anisotropy on the development of fractures in different directions.

2. Geological setting

The Upper Triassic Yanchang Formation in the Ordos Basin is a typical place in China, where ultra-low-permeability sandstone reservoirs are distributed. At present, quite a number of large- and medium-sized oil fields have been found in the middle part – the Ansai-Jing'an district and the southwest part – the east Gansu district of the basin. The Yanchang Formation, whose thickness ranges from 1000 to 1500 m, is a gently westward dipping monoclinal structure whose formation angle of dip is less than 1°. The reservoirs here contain mainly fine- and medium-sized lithic arkose which is deposited in the river-controlled delta during the booming construction period and secondarily fine- and medium-sized feldspathic litharenite and arkose. The average grain size of the reservoir debris is 0.174 mm. Among the mineral components of the detrital grain, quartz constitutes 37.4%, feldspar 25.4%, and lithic fragments 18.4%. In the reservoirs, cementing matters constitute 13.6%, most of which are chlorite and laumonite; next are hydromica, calcite, silicon dioxide, etc. They are mainly membrane-porous cementing and next are porous and regenerative cementing modes. The reservoir space contains primarily intergranular porosity and secondary solution pores, but also contains feldspar solution pores, debrital solution pores, zeolite solution pores, solutions pores in the detrital matrix, intercrystal pores, microfractures, etc. The reservoir rock is compact and has a great heterogeneity, but a poor permeability and porosity. The reservoir porosity is generally 10% or so, and its permeability is usually $0.1\text{–}2.0 \times 10^{-3}\ \mu m^2$, both of which show the characteristics of compact ultra-low-permeability reservoirs. Fractures are well developed in the reservoir, which are the effective reservoir space and chief seepage channels in these ultra-low-permeability sandstone reservoirs, and affect the enforcement of development plans and the effect of water flooding.

3. Experimental conditions

Uniaxial and triaxial rock mechanical experiments and acoustic emission experiments on rock samples taken from different directions were performed in order to study the relationship between the differences in the rock mechanical property and the fracture development in a certain part on the plane. The rock samples were taken from ultra-low-permeability sandstone reservoirs in East Gansu of the Upper Triassic Yanchang Formation in the Ordos Basin. Drilling samples were selected from fine sandstones, which are thicker than 20 cm, to guarantee the quantity. First, a corresponding coordinate system of cores was set up, and then, starting in a certain marked direction, samples were taken at an interval of 30° anticlockwise and parallel to the bedding plane. Samples from six directions were selected in a certain part from the top to the bottom. Three samples from the same direction and on the same plane were taken during drilling, and then they were processed into standardized cylindrical test samples of 25 mm × (45–60) mm. When processed, each part had 18 test samples. The real direction of the samples in the current geographic coordinate system was decided based on the geomagnetic orientation of cores in the adjacent sections. According to research done on the geomagnetic orientation of cores in the past, the error was ±10°. The rock mechanical test was conducted on a uniaxial rock mechanical test platform, which is made up of a WGE-600 universal testing machine, a 100 t pressure sensor, a 7V14 program-controlled recorder and an E4800 computer, in the Laboratory of Rock Mechanical Test at Beijing University of Science and Technology, and also on a tri-axial rock mechanical test platform, which is made up of a TYS-500 tri-axial rock testing machine, a 100 t pressure sensor, a 7V14 program-controlled recorder, an E4800 computer, etc., in accordance with the technical standards set in "The Process for Rock Tests by Means of Hydropower and Electric Power (SL264-2001)". According to the burial depth of the Yanchang Formation and the samples' quantity, the confined pressures of the triaxial mechanical test on the rock were 0, 10 and 20 MPa, respectively, without considering the effect of the geotemperature. The acoustic emission tests were conducted with an equipment made up of a 4010-series acoustic emission apparatus, a 300-kN universal pressure machine, a strain transducer and a computer, in the Open Laboratory of the Surface Process of Crustal Deformation under the Ministry of Land and Resources and focused mainly on both the signal quantity of acoustic emissions from the core samples from different directions and the compression strength of the rock in order to know the change of anisotropy of the rock mechanical property on the plane.

4. Analysis of the results

4.1. Rock mechanical experiment

The uniaxial mechanical test on the rock included mainly the parameters of the rock density, the uniaxial compression strength, the elastic modulus, the Poisson ratio, the tension strength, etc. The triaxial mechanical test on the rock, based on the measurement of the axial failure stress, the elastic modulus and Poisson ratio during the action of different confined pressures, calculated such shear strength parameters such as the cohesive force and the angle of the internal friction. Judging from the test results in different confined pressures in X18-01 well, the rock mechanical parameters in different directions were obviously different on the same plane, which reflects a notable anisotropy of the rock mechanical property of different directions on the same plane. The rock shear strength, the cohesive force and the uniaxial compression strength were obviously decreased in the NE–SW direction (45°) and the NNW–SSE direction (345°), but they were increased in the NNE–SSW direction (15°) and the NW–SE direction (315°) (Fig. 1). The degrees of anisotropy (*H*) of the rock shear strength, the cohesive force and the uniaxial compression strength under confined pressures of 10 and 20 MPa in the different directions were 52.1%, 34.5%, 137% and 56.3%, respectively, which reflects the striking anisotropy of parameters such as the rock shear strength, the cohesive force and the compression strength in the different directions on the plane. Here, $H = (K_{\max} - K_{\min})/K$, where H represents the degree of anisotropy, $K_{\max}$, $K_{\min}$ and K, respectively, represent the maximum, minimum and average values of the parameters.

4.2. Rock acoustic emission experiments

Results of the rock samples test showed that the acoustic emission (AE) type is Type I. It contains a closure stage, a linear elastic stage, a steady expansion stage and a non-steady expansion stage of fractures and a rock cracking stage [19]. Generally speaking, the maximum stress of the Mesozoic sandstone in the closure stage of the cracks does not exceed 6.7% of the uniaxial compression strength, σ_c, and the stress of a steady expansion stage of the cracks at the initial point is 77% of the uniaxial compression strength, σ_c. Thus all the samples were compared with the signal quantity of acoustic emissions from the external initial stress that came up to 77% of the uniaxial compression strength, σ_c (Table 1). In this case, the signal quantity of acoustic emissions from the external initial stress that rises to 6.7% of the uniaxial compression strength, σ_c (13 MPa) was taken as the total of AE signals during the closure stage of the rocks, while the signal quantity of acoustic emissions that range from 6.7% to 77% of the uniaxial compression strength, σ_c (150 MPa) were taken as the total of AE signals during a linear elasticity stage.

The experimental results obtained from six different directions from Z40 well in east Gansu demonstrated that the samples assuming a direction of 60° (or 240°) and 150° (or 330°) in different stages have a maximum quantity of AE signals (Fig. 2), which reflects that the cracks assuming these two directions are the majority. Therefore, the rock strength in these two directions is relatively low (Fig. 3). Rock crack usually occurs across a soft surface, on which the resistance is the minimum and the stress is concentrated. So, the direction in which the strength of the rocks is the least and the cracks are the most numerous is where it is easiest for the fractures to form.

5. Discussion

5.1. Anisotropy of the rock mechanical property and its influential factors

In order to demonstrate the anisotropy of the rock mechanical property on a plane, properly speaking, all the samples taken from six directions should be on the

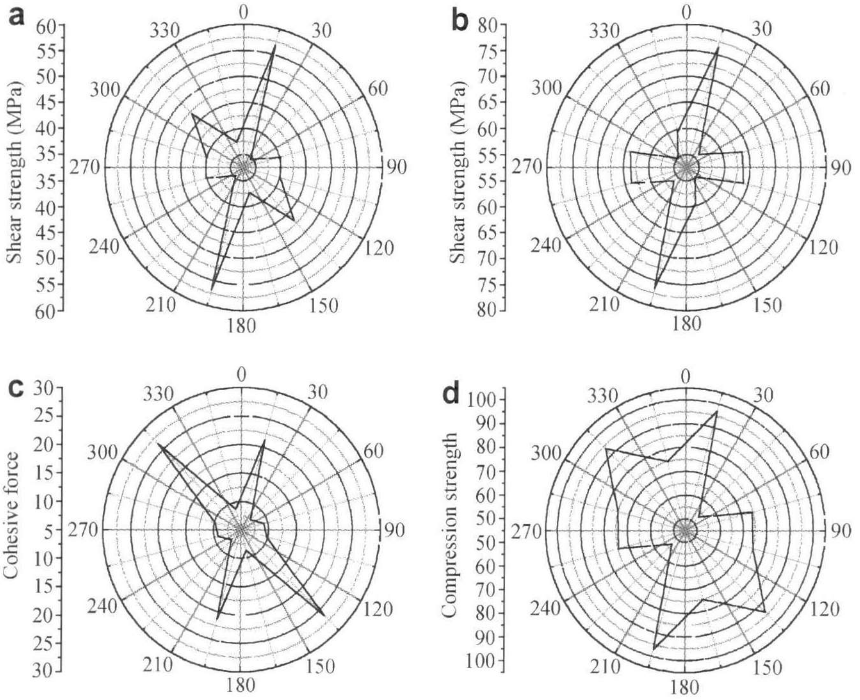

Fig. 1. Cohesive force, shear strength and compression strength of the rock samples assuming different directions under different confined pressures in X18-01 well (the depth of the samples is 1520.2–1520.5 m). (a) Rock shear strength under a 10-MPa compression pressure; (b) rock shear strength under a 20-MPa compression pressure; (c) rock cohesive force and (d) rock uniaxial compression strength.

Table 1
Comparison of the total amount of AE signals of acoustic emissions (AE) signaling signals from various core samples in different stages in well Z40 well

No. of samples	The total amount of AE signals from the external initial stress that rises to 77% of the uniaxial compression strength, σ_c (150 MPa)	The total amount of AE signals from the external initial stress that rises to 6.7% of the uniaxial compression strength σ_c (13 MPa)	The total amount of AE signals received when the external initial stress rises from 6.7% to 77% of the uniaxial compression strength σ_c (13–150 MPa)
ZF4-1c	350	243	107
ZF4-2c	450	140	310
ZF4-3c	1588	1194	394
ZF4-4c	550	331	219
ZF4-5c	731	315	415
ZF4-6c	744	208	536

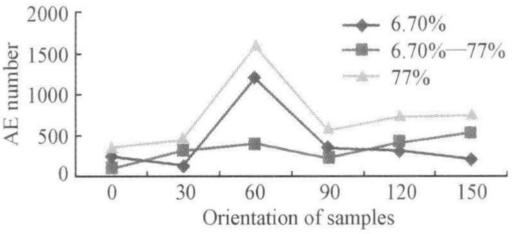

Fig. 2. The amount of acoustic emission signals from the samples taken from different directions in Z40 well at different stages (the depth of the samples is 1626.0–1626.4 m).

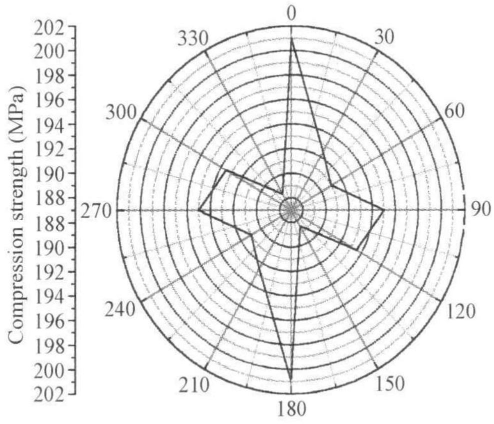

Fig. 3. The rock compression strength of the samples taken from different directions in Z40 well (the samples here are the same as those in Fig. 2).

same plane. But, restricted by the cores, three or four samples taken in the same direction were ensured to be on the same plane during sampling. However, samples taken from different directions were not on the same plane. Although they are in the same layer, they are vertically 20–30 cm apart. Thus, samples taken from the different directions actually show a certain difference. In the present conditions, however, this difference has been lowered to a minimum, so the results of the tests should be preferably representative.

In the traditional rock mechanical analysis, the strata are usually simplified as of longitudinal anisotropy, while horizontally the strata are seen as of isotropy. Li et al., by conducting rock mechanical tests on an elastic modulus, the Poisson ratio and the uniaxial compression strength in the different directions on a plane, proved that the rock mechanical property had an anisotropy on the plane, by judging that the degree of anisotropy would be great in some geological conditions, so they could not be simplified as isotropy on the plane [20]. This uniaxial and triaxial rock mechanical test also proved the apparent anisotropic features of the rock mechanical property in the ultra-low-permeability sandstone reservoirs on a plane.

There are lots of factors that impact the rock mechanical property, including the components, textures, structures, porosity, permeability and pore fluids of the rocks [21–23]. Sedimentation and fierce diagenesis, which give rise to factors that cause a difference in the texture and the structure of compact sandstones, including the directional array of mineral particles, the porous connectivity and permeability under the effect of the tectonic stress and the distribution of micro fractures in the rocks, are the prime reason for the anisotropy of the rock mechanical property in different directions on the plane. In a sedimentary process, the arrays of mineral grains, controlled by the direction of water flow are different in orientation. Because of the strong diagenesis that formed the ultra-low-permeability sandstone reservoirs in this district, the secondary pores and clay minerals that were generated made the porous structures of the rocks and the distribution of liquids complex and inhomogeneous, thus causing a greater difference in the rock textures and structures in different directions. Under fierce compaction and tectonic compression, the mineral particles would turn from a point contact to a lineal contact. In this process, micro fractures such as intragranular and grain boundary fractures have been generated, this would worsen the inhomogeneity within the rocks, thereby forming an anisotropy of the rock mechanical property on the same plane.

5.2. Influence of the anisotropy of the rock mechanical property on the development of fractures in different directions

The anisotropy of the rock mechanical property in the ultra-low-permeability sandstone reservoirs provides a proof of rock mechanics for a rational interpretation of the difference in the development of fractures in the different directions in the studied area. It mainly controls the development of fractures in different directions, and usually restricts the development of one assemblage of conjugate shear fractures but does not restrict that of the other, thereby causing a discordance in the development between the two assemblages of conjugate shear fractures. The difference in the rock micro textures and structures in different directions leads to an inhomogeneity of the internal stress within the rocks. It is easier for fractures to appear on rocks in the direction that has a minimum strength.

According to the study of the outcrops, cores and slices, fractures in the Upper Triassic Yanchang Formation in east Gansu within the Ordos Basin are mainly those high-angle shear fractures that are nearly vertical to the rock strata that were formed under the effect of the tectonic stress field during the Yanshan and Himalayan periods [15]. In the Yanshan period (135 Myr), under the effect of a horizontal compression stress in the NWW–SEE direction, theoretically, two assemblages of shear fractures that assume the E–W and NW–SE directions could have formed, but the strong anisotropy restricted the development of fractures in the E–W direction and promoted the development of fractures in the NW–SE direction. In the Himalayan period (65–23.5 Myr), under the effect of a horizontal compression stress in the NNE–SSW direction, theoretically, there could have formed two assemblages of shear fractures that assume the S–N and NE–SW directions could have formed, but the strong anisotropy was a hindrance to the development of fractures in the S–N direction and promoted the development of fractures in the NE–SW direction. Thus, in the east Gansu at present, two assemblages of fractures in the NE–SW direction (preferred orientation of 50°–60°) and the NW–SE direction (preferred orientation of 320°–330°) have chiefly developed, while fractures in the E–W and S–N directions develop relatively poorly [15].

6. Conclusions

The difference in the rock textures and structures, which was dominated by sedimentation and diagenesis, gives the ultra-low-permeability sandstone reservoirs an apparent anisotropy of the rock mechanical property in the different directions, forming an important factor that affects the development of the fractures assuming different directions. When the tectonic differential stress has a low value in particular, the anisotropy of the rock mechanical property on the plane even could become the main factor for controlling the expansion, the direction and the channels of the fractures. The rock strength that assumes the NE–SW direction (60°–240°) and the NW–SE direction (330°–150°) in east Gansu within the Ordos Basin is apparently lower than that in other directions. Thus, under the horizontal tectonic compressive stress during the Yanshan and Himalayan periods, two assemblages of fractures that assume the NE–SW and NW–SE directions were well developed, while fractures that assume E–W and S–N directions were developed relatively poorly.

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