Analysis of Rock Mechanical Parameters of Permian Tight Formations and Related Measures for Fracturing: A Case Study of Jimusaer in XinJiang

Bo Huang[1], Bin Xie[1], Jiaqi Li[1], Xiang Ding [2], Yue Wang[2], Nan Yin [2], Guangqing Zhang[*2]

(1 Engineering Technology Research Institute of Xinjiang Oilfield Company 2 China University of Petroleum-Beijing), Changping, Beijing, 102249, China)

Abstract **- Rock mechanical properties of tight formations are important factors in determining crack patterns and their effect after fracturing. This paper focuses on the formation of horizontal well facture networks and the limitation of fracture height during Permian tight formations fracturing at Jimusaer. Tri-axial stress test was used to analyze the characteristics of rock mechanical parameters, combined with micro-seismic fracture monitoring method. Using these two analysis methods, we developed comprehensive analyses on fracture extending patterns and its influential factors from several aspects, such as studies on layers with high mechanical strength, rock brittleness, stress difference, natural fracture developments and so on. On basis of our work, targeted measures for tight formation fracturing have been further advanced.**

Keywords - Tight formations; Rock mechanics; Measures for Fracturing.

I. INTRODUCTION

In recent years, the exploration of unconventional tight formations continuously goes on deepening， therefore studies and applications on rock mechanical properties of tight formations in fracturing field have drawn increasingly attention. Researchers firstly study the rock mechanical properties of fracturing layers and the interbeds as well as the situ stress's magnitude with its orientation, then simulations are carried on to predict cracks' length, width, height and its extending direction for design, and moreover, to predict output of oil and gas. Finally fracturing parameters, which play extremely important roles in fracturing optimization design and effect evaluation after fracturing, could be determined for design.

Tight oil resources are widely distributed in Chinese major basins. At present, a number of important discoveries in exploration are found at some blocks, and as a result of it, conditions for large-reserves' formation and effective oil exploitation have already formed. In Junggar Basin, significant breakthroughs are made in the process of Changji tight formations' reservoir exploration at Permian Lucaogou Sag of Jimuseaer. However, lots of challenges and issues simultaneously arise, including great differences of oil output after fracturing and high costs for oil exploitation. This paper mainly focus on issues about the formations of horizontal well facture networks and the limitation of fracture height during Permian tight formations' fracturing at Jimusaer. Triaxial stress test was used to analyze the rock mechanical parameters, combined with microseismic fracture monitoring method. According to these two analysis methods, the paper developed a comprehensive analysis on fracturing pattern and its influential factors from several aspects, such as studies on high mechanical strength layer, rock brittleness, stress difference, natural fractures' development and so on. On these basis, targeted measures for tight formations' fracturing would further be put forward, which can provide support for the effective development of tight formations and fracturing optimization design.

II. FRACTURING PRACTICE AND ISSUES RAISED AT PRELIMINARY STAGE

At the target block of the East uplifts in Junggar Basin, SRV(Stimulated reservoir volume) has been conducted in the preliminary exploration practice. More specifically, the idea for SRV is changed from conventional stimulation to SRV, and the fracturing technology also evolves from single layer for each well to multistage fracture of horizontal wells, which represents the gradually increased number of stages and fracturing scale in SRV. When ideas of stimulations are put into use at the target blocks, significant discoveries and technological breakthroughs have been made in tight formation exploration. For example, flowing production rate of horizontal wells differs from that of vertical wells up to about 8 times per day. However, low yield vertical wells of which the daily output per well is less than 10t/d are still great problems. There are still other issues, for example, there is a large difference between production of vertical wells and horizontal wells and only one horizontal well realized the initial production goal of 50t/d, which means effective economic exploitation is hard to achieve.

In the latter part of tight-formation exploration, pilot tests are taken to analyze staged fracturing process around four horizontal wellbores, and the specific test methods include crack monitoring and so on. Through those pilot tests, several specific phenomenon are found, for example, the height and volume of cracks after stimulation are abnormally low, which contributes to another two problems: communication difficulties along longitudinal direction and insufficient SRV. Those problems mentioned above could be the major reasons that lead to a production which doesn't meet the early expectations.

On this basis, this paper will focus on the following two topics to analyze the results of rock mechanical experiments:

DOI 10.5013/IJSSST.a.17.49.49

ISSN: 1473-804x online, 1473-8031 print

(1) The formation of volume networks and an adequate stimulation for reservoir in staged fracturing process of horizontal wells.

(2) Whether barriers or bedding planes will limit the extension along height direction of fractures.

TABLE I STILMULATION TREATING PARAMETERS

Well number	Length of frac (m)	Height of frac (m)	Single-stage SRV (ten thousand cube)
Ji 001	136.7~314.8	26.3~93.7	43.4~389.5
Ji 003	138.3~478.0	28.8~114.2	92.0~452.6
Ji 005	188.0~616.5	22.3~138.2	63.7~942.4
Ji 007	128.4~339.5	14.2~178.8	28.0~801.3
average	260.8	63.7	238.8

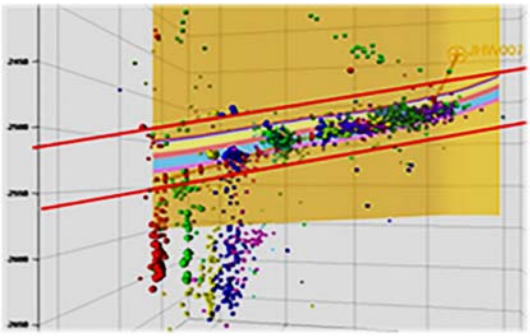


Figure 1. mapping results of fractures

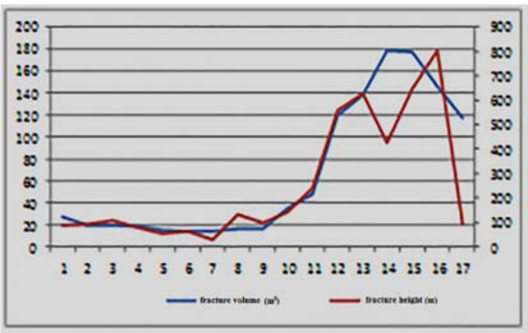


Figure 2. statistical curve of fractures' height

III. Rock Mechanical Experiments and Properties Analysis

In response to the problems mentioned above, triaxial stress test was used to analyze the characteristics of rock mechanical parameters, combined with microseismic crack monitoring method. According to these two methods, comprehensive analyses would then be developed on fracturing pattern and its influencial factors from several aspects, such as studies on layers with high mechanical strength, rock brittleness, stress difference, natural-fracture development and so on.

A. *Layers with high mechanical strength*

Fluorescent mudstone is taken from 2852.9m deep down some well, and the mechanical strength of its rock sample is abnormally high. Considering the influence of high mechanical strength on the extension of cracks' height, researches are mainly conducted on its physical-mechanical properties.

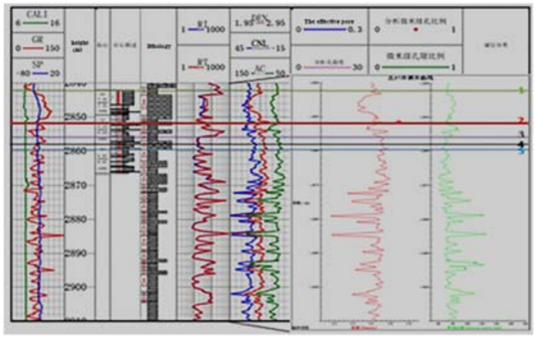


Figure 3. coring locations of layers with high mechanical strength

(a)Before coring

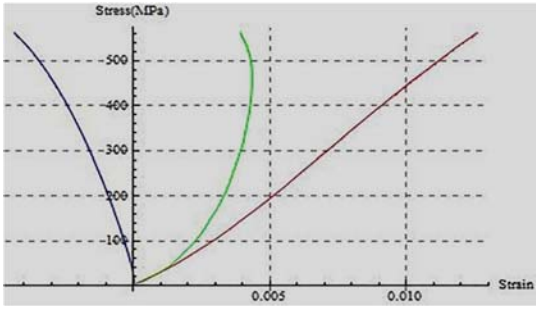
(b) After coring

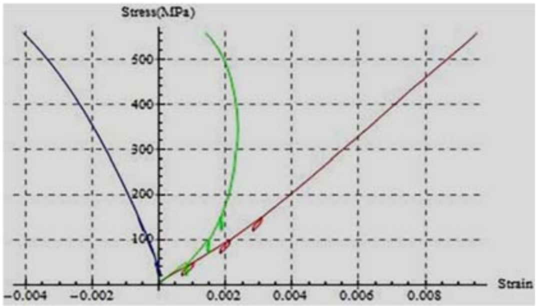
Figure 4. full-size core of layers with high mechanical strength

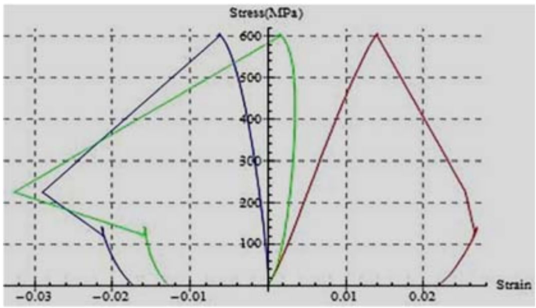
Referring to GB/T 23561 "*Methods for determing physical* [1]*and mechanical properties of coal and rock*[2]" and recommended methods from ISRM, standard specimen is an cylinder with a diameter of 25mm and a height of 50mm.

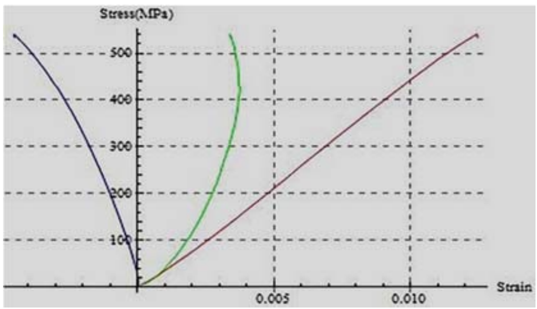
The unevenness of two ends of specimen are both 0.5mm, and scale error is $\pm 0.3mm$ and the perpendicularity error between two ends and axis is $\pm 0.25^{\circ}$. Displacement loading method is chosen to control the loading process, and its loading rate is $10^{-3}S^{-1}$.

Stress-strain curves of the tested rock specimen are shown as follows:









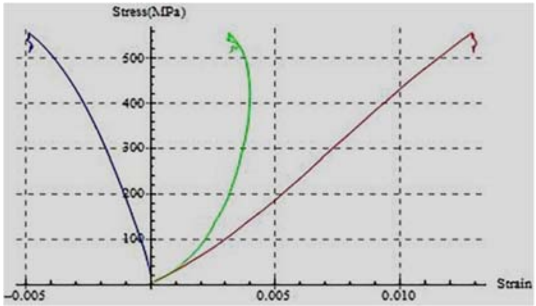


Figure 5. Stress-strain curves of triaxial stress test

Figure 6. standard cores for triaxial stress test

Test results are listed as follows:

TABLE II RESULTS FOR TRIAXIAL COMPRESSION TEST

number of Specimen	Confining pressure /MPa	compressive strength /MPa	tensile strength /MPa	Elastic modulus /GPa	Poisson's ratio
2-1	24	540.9	17.24	45.54	0.31
2-2	28	606.5	28.98	47.76	0.33
2-3	32	559.3	30.64	59.30	0.37
2-4	24	563.7	24.71	47.53	0.29
2-5	28	556.6		46.35	0.32

Compared with the test results of other specimen which are tested under the same conditions of confining pressure, specimens listed above have higher compression strengths, which is twice or triple the value of those specimens under the same conditions of confining pressure. In the meanwhile, higher value of tensile strengths can be found from the listed data.

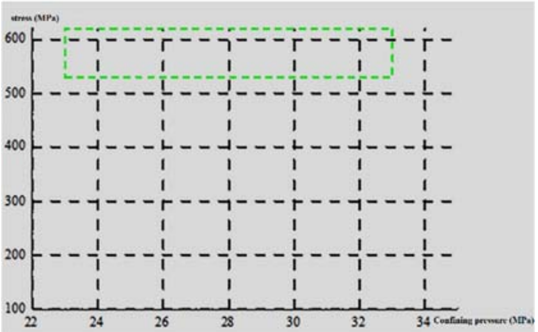


Figure 7. triaxial strength distribution of cores at abnormally hard interbeds

To study the reason why specimens have abnormally high strengths, tests named x-ray diffraction analyses are conducted, and in these test, rock composition are divided into three categories including quartz-dominated minerals, clay-dominated minerals and carbonate-dominated minerals[3]. According to the classification, quartz-dominated minerals include quartz, feldspar and pyrite (Analcime belongs to feldspathoids), and carbonate-dominated minerals consist of calcite, dolomite and siderite. In this part, five standard cores are tested and the test results are listed as follows:

TABLE III X-RAY DIFFRACTION ANALYSIS FOR MINERALS

Number of specimens	Depth /m	Lithology	Quartzs				Carbonates		Clay Minerals
			Quartz	Potassium feldspar	Anorthose	Analcime	Dolomite	Calcite	
2-1	2852.9	Fluore-scent mudstone	3.9	0.3	12.2	0.5	78.6	0	4.5
2-2			3.5	0.6	13.7	0.4	77.6	0	4.2
2-3			3.1	0.5	10.7	2.6	81.1	0	2.0
2-4			2.9	0.3	9.4	3.7	79.2	0.3	4.1
2-5			2.6	0.6	9.3	3.6	81.3	0.3	2.4

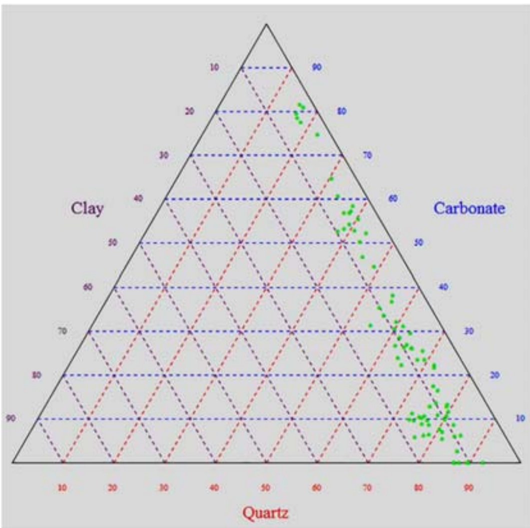


Figure 8. mineral triangle diagram

A mineral triangle is plotted to analyze the specific rock compositions and the data are obviously divided into several parts in the diagram. Clay contents of the five tested specimens are lower than 20% without any exception, and carbonates range from 0 to 81.6% and qurtzs change from 16% to 92%.

A circle is used to underline cores with abnormal value of strength, and carbonates of these cores are higher than those of others. Because dolomite is the major component of carbonates shown in the diagram, it can be speculated that it is the high value of dolomite component that leads to abnormal high strengths.

B. Evaluation of Rock Brittleness

To evaluate the stimulation of reservoirs in the follow-up study, concept of shale brittleness is put into use. B19 and B20 are the most commonly used modes for brittleness evaluation in many references, so a corresponding evaluation[4] for brittleness is developed and compared with another evaluation mode, B7.

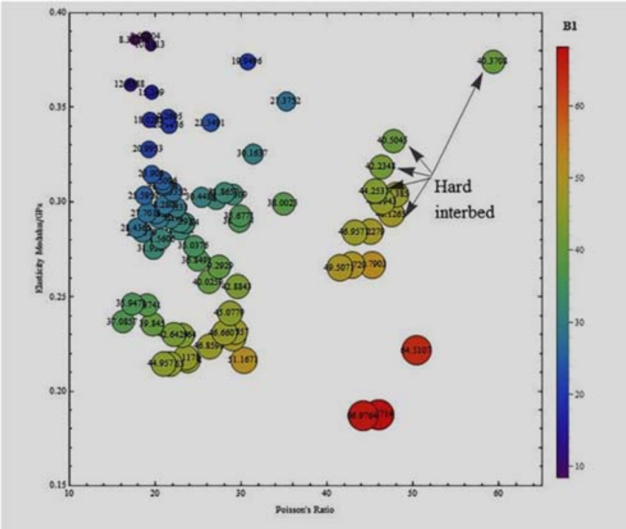


Figure 9.brittleness distribution of B19

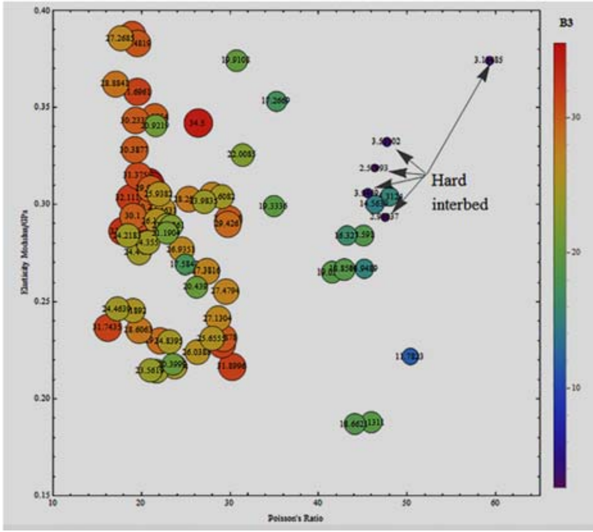


Figure 10. brittleness distribution of B20

The brittleness values of B19 are generally lower than that of B7 and the hard interbeds have medium brittleness values and higher elastic moduli.

TABLE IV EVALUATION MODES FOR BRITTLENESS

Formulations	Explanations	Test methods
$B_1=(H_m-H)/K$	Differences between macro-hardness H and micro-hardness H_m	Hardness Test[5]
$B_2=q\sigma_c$	q is the percentage of fragment smaller than 0.60mm, $\sigma_c$represents compressive strength	Protodyakonov Test[6]
$B_3=(\tau_p-\tau_r)/\tau_p$	Functional relationship of peak strength τ_p and residual strengthτ_r	Stress-strain test[7]
$B_4=\varepsilon_r/\varepsilon_t$	ratio of recoverable strain ε_r and total strain ε_t	Stress-strain test
$B_5=W_r/W_t$	ratio of recoverable strain energy W_r and total strain energy W_t	Stress-strain test
$B_6=\sigma_c/\sigma_t$	ratio of compressive strength σ_c and tensile strength σ_t	Strength ratio[8]
$B_7=(\sigma_c-\sigma_t)/(\sigma_c+\sigma_t)$	Functional relationship of compressive strength σ_c and tensile strength σ_t	Strength ratio
$B_8=\sin\varphi$	φ represents internal friction angle	Mohr's circle[8]
$B_9=45^0+\varphi/2$	Functional relationship of rupture angle on internal friction angle φ	Stress-strain test
$B_{10}=H/K_{1c}$	ratio of hardness H and fracture toughness K_{1c}	Hardness test and Toughness test[9]
$B_{11}=\varepsilon_{1l}\times 100\%$	ε_{1l} represents the unrecoverable axial strain when specimen breaks	Stress-strain test
$B_{12}=HE/K_{1C}^2$	E represents elasticity modulus	Test for ceramic materials[10]
$B_{13}=S_{20}$	$S_{20}$is the percentage of fragment smaller than 11.2 mm	impact testing[11]
$B_{14}=(\varepsilon_p-\varepsilon_r)/\varepsilon_p$	Functional relationship of peak strain ε_p and residual strain ε_r	Stress-strain test

$B_{15} = (\sigma_c \sigma_t)/2$	Functional relationship of compressive strength σ_c and tensile strength σ_t	Stress-strain test
$B_{16} = \sqrt{\sigma_c \sigma_t}/2$	Functional relationship of compressive strength σ_c and tensile strength σ_t	Stress-strain test
$B_{17} = P_{inc}/P_{dec}$	ratio of loading increment P_{inc} and loading decrementP_{dec}	penetration test[11]
$B_{18} = F_{max}/P$	Ratio of loading F_{max} and penetrating depth P	penetration test
$B_{19} = (E + \bar{\upsilon})/2$	Average of normalized elasticity modulus E and Poisson's ratio $\bar{\upsilon}$	Stress-strain test
$B_{20} = (W_{qtz} + W_{card})/W_{total}$	ratio of Brittleness mineral content $W_{qtz} + W_{card}$ and total mineral content W_{total}	Mineral composition analysis[12]

A homogeneous distribution is found of mode B20 which defines brittleness by the value of quartz component, so the brittleness is directly decided by quartz's value.

It can be summarized from the experimental data that quartz content is 20.9% and index of brittleness ranges from 24% to 58% with an average of 41%, which reflects a medium brittle feature. Comparisons are made among those evaluation modes mentioned above, and for the same cores large differences of brittleness values exist among different evaluation modes together with different change trends. Brittleness evaluation modes used above are built for shale without any consideration about the special situation of tight-formation reservoirs in Changji, and it may be the major factor that leads to the phenomena described above.

C. *stress difference evaluation*

At present, difference of the in-situ stresses for sandstone is about 6 or 7MPa and that for mudstone is some 4MPa via experimental data analysis.

AE is short for acoustic emission and DSA is short for differential strain analysis.

TABLE V STATISTICAL RESULTS FOR STRESS DIFFERENCE TESTS

NO.	Lithology	The maximum horizontal in-situ stress (MPa)		The minimum horizontal in-situ stress(MPa)		Horizontal stress differences (MPa)	
1	mudstone	57.1(AE)	56.84(DSA)	53.51(AE)	52.63(DSA)	3.9(AE)	4.21(DSA)
2	dolomitic siltstone	57.05(AE)		49.45(AE)		7.6(AE)	
3	limy siltstone	60.139(AE)		53.684(AE)		6.466(AE)	

D. *Natural Fractures*

According to results of core observation and image logging, summaries can be made as follows: it is obvious that fractures of tight formations are poorly developed from a general view in Jimusaer, and the observed fractures are mainly medium-angles or high-angles and less than 1 m, and the last point is that differences of fracture development exists among tested wells. The specified data for those phenomena described above are listed as follows:

TABLE VI NATURAL FRACTURES FROM IMAGE LOGGING FOR DEVELOPMENT OF FRACTURES IN LUCAOGOU FORMATION

NO.	Depth (m)	Thickness （m）	Number of frac	Density of frac (numbers per meter)
1	3593.7~3630.62	36.92	6	0.1625
2	3115.2~3153.4	38.2	6	0.1571
3	2917.58~2955.4	37.82	6	0.1586
4	2829.39~2871.97	42.58	4	0.0939
5	3517.86~3568.04	50.18	14	0.2790
6	3558.23~3594.75	36.52	2	0.0548
7	3651.76~3691.57	39.81	4	0.1005
8	4117~4150	33	30	0.9091
9	2707.64~2749.24	41.6	4	0.0962
10	3765~4885	1120	210	0.1875
11	3226~4126	900	319	0.3544
12	3958~4878.5	920.5	177	0.1923
JHW016_H	3404.5-4675.68	1271.18	246	0.1935

Figure 11. CT scanning of a full-size core

Only one natural crack is found in one full-sized core among results of CT scanning results for some cores, which means the natural fractures are poorly developed from a general view.

IV. Measures for Tight Formation Fracturing

It can be found from the analyses above that the brittleness evaluation for Permian tight formations at Jimusaer is worse than medium. Stress differences also are in medium-class value and overall natural fractures are poorly developed. The existence of high stress intensity layer can be found via those analyses as well. From a general view, fracturing has difficulties in cracks extending through strata and forming net works. Considering the previous construction periodicals, suggestions are developed as followings:

(1) In the fracture stimulation, low-viscosity liquid such as quick water is used for complicated network near the wellbore, and at the distant end, high-viscosity liquid is used for fracturing long fractures.

(2) Increasing the ratio of low-viscosity fracturing liquid.

(3) Increasing the delivery volume for fracturing to decrease the influence of layer with high stress strength on the extension of fracture height.

(4) Improving the stimulation scales and bulk volume.

Previous study on measures for fracturing only stays in qualitative stage, and further study can be done to quantifying parameters for fracturing stimulation.

V. Conclusions and Suggestions

(1) The interbed of mud-sandstone shows higher elastic moduli between 45.54 GPa and 59.3GPa. Similarly, higher triaxial compressive strengths of the interbed of mud-sandstone range from 540.9MPa to 606.5MPa and Poisson's ratios change from 0.29 to 0.27. In the meantime, the interlayer of mud-sandstone also has apparently high values of compression strengths and tension strengths which are about twice or triple strengths of conventional specimens under same confining pressures. Those conclusions above are available in the experimental data, and via analyzing mineral composition of specimens, it can be concluded that a high content of dolomite can lead to a high strength feature.

(2) Two brittleness evaluation modes B19 and B20, which are suitable for shale in a general way, are applied to analyze the distribution of abnormal hard interlayer. The analysis result shows that big differences are existing between these two evaluation modes which means the modes' correlation is really low and that is because the two modes are created for shale. Therefore, the further study needs to focus on developing brittleness evaluation modes for tight oil reservoir.

(3) Previous study on measures for fracturing only stays in qualitative stage, and the correlation between related rock mechanical properties and the extensions of fractures need to be further studied to quantifying parameters for fracturing design.

Conflict of Interest

The author confirms that this article content has no conflict of interest.

References

[1] Industry standard editorial committee of the People's Republic of China. GB/T23561–2009 Coal and rock physical and mechanical properties measurement method [S]. Beijing: China standard press, 1988.

[2] Bieniawski, Z.T. and M.J. Bernede. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials: Part 1. Suggested method for determining deformability of rock materials in uniaxial compression. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1979. 16(2): p. 138-140.

[3] Rickman R ,Mullen M ,Petre E, et al. A practical use of shale petrophysics for stimulation design optimization : all shale plays are not clones of the Barnett Shale[R]. SPE 115258, 2008.

[4] Li Q H,Chen M,Jin Y, etal. the indoor evaluation method and improvement of shale Brittle [J]. Journal of rock mechanics and engineering, 2012, (8):1680-1685.

[5] Honda H, Sanada Y. Hardness of coal[J]. Fuel, 1956, 35 : 451.

[6] Protodyakonov M M. Mechanical properties and drill-ability of rocks[C] Proceedings of the 5th Symposium on Rock Mechanics. Twin Cities, USA : University of Minnesota Press, 1963 : 103–118.

[7] Bishop A W. Progressive failure with special reference to the mechanism causing it[M]. Oslo: Proceedings of the Geotechnical Conference, 1967 : 142–150.

[8] Hucka V, Das B. Brittleness determination of rocks by different methods[J]. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 1974, 11(10) : 389–392.

[9] Lawn B R, MARSHALL D B. Hardness, toughness and brittleness : an indentation analysis[J]. Journal of American Ceramic Society , 1979, 62(7/8) : 347–350.

[10] Quinn J B, QUINN G D. Indentation brittleness of ceramics : a fresh approach[J]. Journal of Materials Science, 1997, 32(16) : 4 331–4 346.

[11] Copur H, BILGIN N, TUNCDEMIR H, et al. A set of indices based on indentation test for assessment of rock cutting performance

and rock properties[J]. Journal of the South African Institute of Mining and Metallurgy, 2003, 103(9) : 589–600.

[12] Rickman R, Mullen M, Petre E, et al. A practical use of shale petrophysics for stimulation design optimization : all shale plays are not clones of the Barnett Shale[R]. SPE 115258, 2008.