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Experiment on Fracturability of Shale Reservoir in Yingxiongling Area, Qinghai Oilfield

Xiwen Chen, Bin Li, Fusheng Yu

Institute of Safety Environmental Protection and Technical Supervision, Southwest Oil & Gas Field Company, Chengdu, Sichuan, 610000, China

Abstract

The Yingxiongling Area of Qinghai Oilfield is rich in shale oil resources; however, there are still gaps in the analysis of reservoir geological characteristics and the fracturability evaluation system in this region. To address this, a fracturability evaluation model was established through systematic experiments on reservoir engineering geological characteristics, with the results as follows: The reservoir in the Upper Member of Ganchaigou Formation is prominently characterized by interbedded sedimentation of calcareous shale and calcitic dolomite, with an average porosity of 5.7%. The pore size is concentrated in the micron-scale range of 0.001~0.1 μm, and micron-scale pores are well-developed. The mineral composition is dominated by dolomite, calcite, and clay minerals, among which the average content of clay minerals reaches 65%, and the average rock mechanical brittleness index is 41.76%. Natural fractures in the reservoir are poorly developed, and the difference in fracture pressure between limestone intervals and shale intervals is 10.78~16.68 MPa, which is unfavorable for vertical fracture propagation. The shale reservoir fracturability model shows that the average fracturability index is 0.34, indicating low fracturability and difficulty in forming a complex fracture network. Based on the fracturability model and geological characteristics, a reservoir reconstruction mode of "three-dimensional horizontal well pattern + zipper-type volume fracturing" is proposed. By adopting the technologies of close spacing fracturing + limited-entry perforation + large-displacement continuous sanding, the complexity of fractures is further improved to achieve net pressure interlayer breakthrough.

Keywords

Shale Reservoir; Porosity; Rock Fractures; Pressurability Model; Reservoir Stimulation.

1. Introduction

The development of shale oil and gas has extended the lifespan of the petroleum industry while simultaneously increasing global oil and gas reserves, exerting a significant influence on national energy strategic reserve patterns. During the development of shale reservoirs, after identifying the distribution of high-quality reservoirs, it is necessary to conduct a “fracturability evaluation” to assess their development potential. The Huangguamao section of the Qinghai Oilfield is selected as the target study area. This region possesses a strong resource base and demonstrates considerable exploration and development potential. Multiple rounds of resource assessments indicate that the cumulative oil generation has exceeded 100,000 tons[1]. In the Ganchaigou area of the Qinghai Oilfield, shale oil reservoirs in the Yingxiongling region are mainly developed in the upper member of the Ganchaigou Formation. These reservoirs are characterized by high total organic carbon (TOC) content, favorable physical properties, strong lateral distribution stability, and excellent oil and gas-bearing performance[2]. At present, eight horizontal wells have been deployed in the Ganchaigou area of the Qinghai Oilfield, targeting eleven different formations, achieving phased breakthroughs in shale oil exploration and development.

Extensive research has been conducted both domestically and internationally on the geological characteristics and fracturability evaluation of shale reservoirs. For example, Xing Haoting et al[3] studied 578 m of cores from 12 wells in the Yingxiongling area through petrographic, organic geochemical, and reservoir characteristic analyses. Their results show that the interbedded laminated dolomitic limestone and laminated calcareous dolomite represent the most favorable source-reservoir combination model. The sweet spots exhibit good lateral connectivity but strong vertical heterogeneity. Zhao Xing et al[4] investigated the mixed shale oil reservoirs in the upper member of the Lower Ganchaigou Formation in the Yingxiongling area of the Qaidam Basin using scanning electron microscopy, conventional logging, and advanced logging techniques. The results indicate that natural fractures in this area mainly include tectonic fractures, diagenetic fractures, and abnormal overpressure fractures. Tectonic fractures are predominantly high-angle fractures with a high degree of filling. Zhou Xiang et al[5], focusing on the development of shale oil and shale gas, proposed an integrated technology combining measurement, logging, and guidance based on field construction practices, providing technical support for large-scale shale oil and shale gas development in the Qinghai Oilfield. Kuang Lichun et al[6] summarized the major exploration progress and geological understanding of continental shale oil in China and, based on the geological characteristics of different shale oil types, identified key parameters and methods for shale oil characterization.

In summary, there is currently no unified standard for the fracturability evaluation of shale reservoirs worldwide. Therefore, this study focuses on the Yingxiongling shale reservoir in the Qinghai Oilfield, conducting geological characteristic experiments and establishing a fracturability evaluation model. By deriving a fracturability index, this study aims to propose suitable reservoir stimulation methods for shale reservoirs in this region, thereby providing ideas and data support for future reservoir stimulation and hydraulic fracturing design.

2. Geological Characteristics of the Upper Member of the Ganchaigou Formation in the Yingxiongling Shale Reservoir

2.1. Physical Properties

Table 1. Comparative Analysis of Typical Shale Oil Reservoir Characteristics in China

Category		Yingtan Shale Oil	Jilin Oilfield	Changqing Oilfield	Daqing Shale Oil	Da'anzhai, Central Sichuan	Ganchaigou, Qinghai
Reservoir Properties	Reservoir Depth (m)	Reservoir Lithology	Calcareous shale	Mudstone, shale	Oil shale interbedded with mudstone and siltstone	Silty mudstone, shale	Shale–limestone interbeds
	Porosity (%)	1200~4300	1750~2600	700~2900	2000~2500	2500~3500	2337~2348
		5%~14%	2%~15%	0.5%~2.1%	2%~4%	5.9%	5.7%
Flow Capacity	Permeability (mD)	0.001~0.002	0.16~0.32	<0.01	0.011~1.62	0.001~0.01	0.01~ 0.48

Based on literature investigations and field data from the Qinghai Oilfield, a comparative analysis was conducted between the shale reservoirs of this oilfield and the engineering geological characteristics of five typical shale reservoirs in China[7–11]. The results are shown in Table 1. The shale reservoirs in the Qinghai Oilfield mainly consist of interbedded calcareous shale and dolomite, whereas the shale reservoirs in the other five oilfields are primarily composed of sandstone, shale, and mudstone. The permeability of the shale reservoir in this oilfield ranges from 0.01 to 0.48 mD, with an average porosity of 5.7%.

2.2. Porosity and Fracture Network Characteristics

A nuclear magnetic resonance (NMR) analyzer was used to conduct three pore-size distribution measurements on core samples from Well No. 1 in the upper member of the Ganchaigou Formation. The results obtained from the three samples show a high degree of consistency. The pore-size distribution characteristics are shown in Figure 1, and the fracture network characteristics are illustrated in Figures 2–3.

The pore-size distribution curve exhibits a bimodal pattern, with pores mainly distributed within the 0.001–0.1 μm range. The primary peak occurs at approximately 0.035 μm, while the secondary peak corresponds to the pore-size interval of 0.02–0.035 μm, forming a bimodal distribution characteristic. This indicates that storage-type pores and seepage-type pores coexist within the reservoir. Intercrystalline pores in clay minerals and intergranular pores constitute the dominant pore structures, followed by organic pores and microfractures.

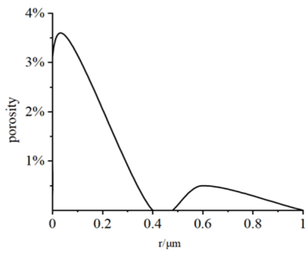

Fig 1. Pore Size Distribution Map of Core from Well No. 1

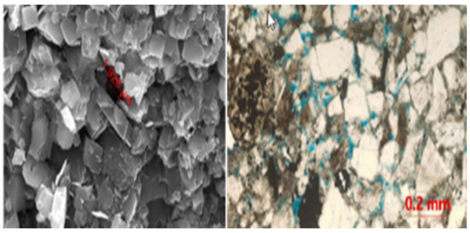

Fig 2. Calcite dissolution pores and micro-pores

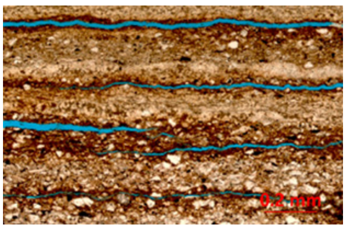

Fig 3. Calcite and micro-fractures

2.3. Mineral Composition Characteristics

Based on core thin-section observations and X-ray diffraction (XRD) analysis, the mineral composition and content characteristics of shale reservoir samples from four wells in the upper member of the Ganchaigou Formation in the Yingxiongling structural belt, Qinghai, were investigated. The analytical results are shown in Figure 4. The rock mineral assemblage is mainly composed of dolomite, calcite, and clay minerals, while the proportions of quartz and feldspar are relatively low. In some local intervals, small amounts of anhydrite, glauberite, and pyrite are also observed.

Specifically, the calcite content ranges from 4.6% to 83.6%, with an average value of 19.8%; the dolomite content varies between 7.6% and 90.2%, with an average of 27.3%; the quartz content ranges from 4.7% to 65.2%, averaging 18.4%; and the feldspar content fluctuates between 4.2% and 23.1%, with an average value of 18.8%. The composition of clay minerals is shown in Figure

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5, where illite dominates the clay mineral assemblage (62.6%), followed by illite/smectite mixed layers (28.2%) and smectite (9.2%), with the mixed-layer ratio ranging from 5% to 7%. Statistical results indicate that the content of brittle minerals (the sum of carbonate minerals and terrigenous clastic minerals) generally exceeds 65%. Comprehensive analysis suggests that the relatively high clay mineral content in the shale reservoir of the upper member of the Ganchaigou Formation plays an inhibitory role in the development of the reservoir fracture network system.

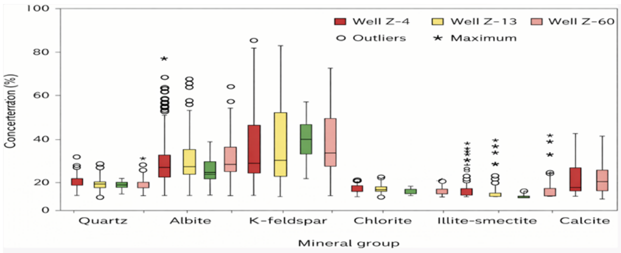

Fig 4. Distribution Map of Mineral Contents in Core of Shale Reservoirs from Different Wells in Ganchaigou

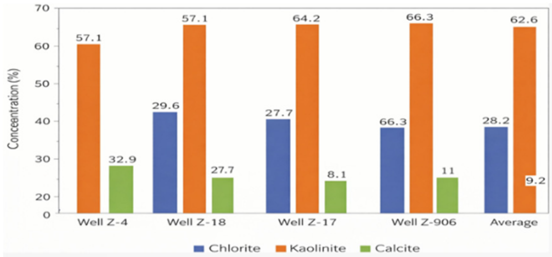

Fig 5. Comparison Chart of Clay Mineral Contents in Core of Shale Reservoirs from Different Wells in Ganchaigou

2.4. Rock Mechanical Characteristics

A RTR–1000 dynamic triaxial rock mechanics testing system (as shown in Figure 6a) was used to perform triaxial compressive tests (as shown in Figure 6) on core samples from six wells in the shale reservoir of the upper member of the Ganchaigou Formation (core samples shown in Figure 6b).

The experimental results presented in Figure 7 indicate that the reservoir has an average elastic modulus of 3.54×10^4 MPa and a Poisson's ratio of 0.24, suggesting that the shale reservoir exhibits certain plastic characteristics.

a RTR—1000

b Core Samples Before and After the Experiment

Fig 6. Triaxial Compression Test of Core

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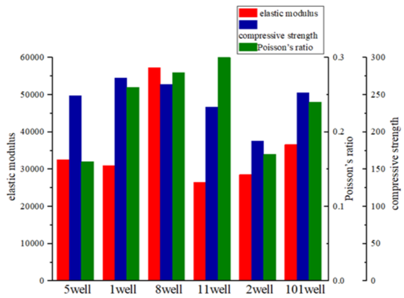

Fig 7. Rock Mechanical Experiment Results of Shale Reservoirs in the Upper Section of Ganchaigou Formation

2.5. In-Situ Stress Characteristics

Numerical tests of in-situ stress were conducted on core samples from six wells in the shale reservoir of the upper member of the Ganchaigou Formation in the Yingxiongling area, Qinghai. The experimental data are presented in Table 2. The results show that the difference between the two principal horizontal stresses of the core samples ranges from 10.78 to 16.68 MPa, with the vertical stress at an intermediate magnitude. This stress state is favorable for the formation of T-shaped fractures.

For reservoir intervals where shale and dolomitic marl are interbedded, the fracture pressure of the dolomitic marl formation differs from that of the shale formation by approximately 7 MPa. This pressure difference can inhibit the vertical propagation of fractures.

Table 2. Comparison of In-Situ Stress Magnitude Experimental Data in the Upper Section of the Ganchaigou

Well No.	Lithology	Principal Stresses (MPa)			In-Situ Stress (MPa)
		Maximum	Minimum	Vertical	
1	Shale	67.03	51.94	61.28	92.59
2	Shale	110.67	99.88	106.47	116.49
3	Shale	89.64	74.67	77.04	90.17
4	Shale	112.08	95.4	106.56	101.64
5	Shale	113.04	97.8	107.52	99.78
	Limestone	94.20	81.50	89.62	104.89
6	Shale	79.56	66.6	75.24	105.78

2.6. Brittleness Characteristics

According to the calculation method of the rock mechanical brittleness index for shale, Equation (1) was used to calculate the brittleness index of rock samples from six wells in the upper member of the Ganchaigou Formation in the Yingxiongling area, Qinghai. The corresponding results are shown in Figure 8.

Analysis of the data in Figure 8 indicates that the average brittleness index of the shale in the upper member of the Ganchaigou Formation is 41.76%, which falls within a relatively favorable brittleness category.

$$B = \left\{\left[\frac{(E_s - E_{min})}{(E_{max} - E_{min})} + \frac{(v_{max} - v_s)}{(v_{max} - v_{min})}\right]/2\right\} \times 100 \tag{1}$$

Where:B is the rock mechanical brittleness index of shale;E_s is the static Young's modulus of the sample;E_{min} is the lower limit of the static Young's modulus of shale (taken as 0.7×10^4 MPa);E_{max} is the upper limit of the static Young's modulus of shale (taken as 5.5×10^4 MPa);ν_{max} is the upper limit of the static Poisson's ratio of shale (taken as 0.4);ν_s is the static Poisson's ratio of the sample;ν_{min} is the lower limit of the static Poisson's ratio of shale (taken as 0.1).

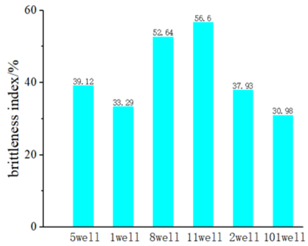

Fig 8. Rock Mechanical Brittleness Index of Reservoirs in the Upper Section of the Ganchaigou Formation

To investigate the brittleness characteristics of shale reservoirs in the Qinghai Oilfield, a comparative study was conducted between the shale reservoirs in this area and other typical shale oil reservoirs in China. The comparison results are shown in Table 3.The brittle mineral content of the shale reservoir in the Qinghai Oilfield exceeds 60%, which is higher than that of other shale oil reservoirs, indicating that this shale reservoir has high hardness and strong resistance to deformation. In addition, the rock mechanical brittleness index in this area is 41.76%, which is higher than that of other typical regions, suggesting that fractures in this area have good stimulation potential.

Table 3. Comparison of Brittleness Characteristics in Typical Shale Oil Reservoirs

Region / Reservoir	Brittle Mineral Content (%)	Brittleness Index (%)
Jimusar	30~40	32.15
Changqing Oilfield	>70	36.34
Daqing Shale Oil	average40	39.85
Qinghai Oilfield	>60	41.76

3. Fracturability Evaluation of the Shale Reservoir in the Upper Member of the Ganchaigou Formation, Yingxiongling

3.1. Fracturability Evaluation Model

For the convenience of calculation and experimentation, the core brittleness index B dimensionless fracture toughness index K_n, in-situ stress difference coefficient K_h, and natural fracture influence index F_θ were selected as evaluation factors for the fracturability index.

Among them, the core brittleness index B and the in-situ stress difference coefficient K_h were obtained directly through brittleness tests and in-situ stress measurements. Through rock mechanics and fracture toughness experiments, the Mode I fracture toughness K_1 and Mode II fracture toughness K_2 of the core samples were obtained. Then, combined with Equation (3), the dimensionless fracture toughness index K_n can be calculated.

$$K_n = \frac{K_{1\mathrm{C}} + K_{2\mathrm{C}}}{2} \tag{2}$$

The calculation formulas for $K_{1\mathrm{C}}$ and $K_{2\mathrm{C}}$ are shown in Equations (3) and (4):

$$K_{\mathrm{IC}} = \frac{K_{1\max} - K_1}{K_{1\max} - K_{1\min}} \tag{3}$$

$$K_{2\mathrm{C}} = \frac{K_{2\max} - K_2}{K_{2\max} - K_{2\min}} \tag{4}$$

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The fracture dip angles of multiple core samples were obtained using a CT scanner, and the average value was taken as the natural fracture dip angle θ. Based on the interaction theory between hydraulic fractures and natural fractures, the calculation formula for the natural fracture influence index F_θ is shown in Equation 5.

$$F_\theta = 1 - K_h \cdot sin^2\theta \tag{5}$$

Using the weighting superposition method, the calculation formula for the fracturability index F_n of the shale reservoir is derived, as shown in Equation (6).

$$F_n = B[aK_n + b(1 - K_h) + cF_\theta] \tag{6}$$

In the formula: a represents the dimensionless fracture toughness index K_n; b represents the coefficient of ground stress difference K_h; c represents the weight coefficient of the natural fracture influence index F_θ.

3.2. Verification of the Fracturability Model

Through core experiments, the brittleness index, dimensionless fracture toughness, in-situ stress difference coefficient, and natural fracture influence index were obtained for four shale reservoir wells in the Yingxiongling area of the Qinghai Oilfield. Using Equation (6), a fracturability evaluation analysis was conducted for these four wells. Combined with the actual field conditions of the shale reservoir, the reliability of the fracturability evaluation model was verified. The calculation results are shown in Table 4.

Table 4. Results of Pressurability Evaluation for Shale Oil Reservoirs in the Upper Section of Ganchaigou

Well No.	Brittleness Index	Dimensionless Fracture Toughness	In-Situ Stress Difference Coefficient	Natural Fracture Influence Index	Fracturability Index
1	0.47	0.49	0.23	0.63	0.31
2	0.49	0.40	0.09	0.78	0.35
3	0.50	0.50	0.16	0.74	0.39
4	0.43	0.50	0.13	0.72	0.32

It can be seen from Table 4 that the fracturability indices of the four wells are 0.31, 0.35, 0.39, and 0.32, respectively. The fracturability indices are relatively low, indicating that the shale reservoirs in this area have difficulty forming complex fracture networks and exhibit low recovery efficiency. This result is consistent with the actual field conditions in the Yingxiongling area of the Qinghai Oilfield, which verifies the reliability of the fracturability evaluation model used in this study.Therefore, appropriate technological measures are required to increase fracture complexity, thereby improving the stimulation effectiveness and the fracturability index.

4. Reservoir Stimulation Strategy for the Shale Reservoir in the Upper Member of the Ganchaigou Formation, Yingxiongling

To address the problem that the shale reservoir in the upper member of the Ganchaigou Formation in the Yingxiongling area of the Qinghai Oilfield is difficult to form complex fracture networks, resulting in low production parameters and limited recovery efficiency, a reservoir stimulation strategy was proposed. Based on a review of relevant shale reservoir stimulation literature and considering the geological conditions of the Yingxiongling area in the Qinghai Oilfield, the three-dimensional horizontal well pattern combined with zipper-style volumetric fracturing was selected as the method for shale reservoir stimulation[12–15].

Targeting the shale reservoir in the upper member of the Ganchaigou Formation in the Yingxiongling area, volumetric fracturing experiments have already been carried out on four shale oil wells. With the continuous improvement in the understanding of the engineering geological characteristics of the shale reservoir, the construction parameters and stimulation technologies have been gradually optimized. For the stimulated wells, the average sand ratio reached 21%, the total fluid volume was 631 m^3, the total sand volume was 42 m^3, with an oil production rate of 0.02 m^3/d and a gas production rate of 2833 m^3/d.Although certain progress has been achieved in the stimulation of the shale reservoir in the upper member of the Ganchaigou Formation in Yingxiongling, several difficulties still remain. Based on the reservoir geological characteristics and the comprehensive fracturability evaluation obtained in this study, the following stimulation strategies for the shale reservoir are proposed. From the characteristics of whole-rock minerals and clay minerals, it can be observed that the reservoir contains few swelling minerals, while the brittle mineral content in Yingxiongling, Qinghai exceeds 65%, with a relatively high average brittleness index, indicating that the shale reservoir possesses favorable conditions for large-scale hydraulic fracturing.However, due to the interbedding of shale and limestone in the reservoir, the rock mechanical properties and in-situ stress characteristics indicate that vertical fracture propagation is restricted. Therefore, increasing the net pressure within fractures can be considered to achieve interlayer fracture breakthrough. To realize this objective, a stimulation process combining dense cluster spacing, limited-entry perforation, high pumping rate, and high-intensity continuous sand injection is recommended to further enhance fracture complexity.

5. Conclusion

(1) A series of core geological experiments indicate that the upper member of the Ganchaigou Formation in the Yingxiongling area of the Qinghai Oilfield is mainly composed of interbedded calcareous shale and dolomitic marl. The average porosity is 5.7%, and the pores are mainly concentrated in the 0.001–0.1 μm range, with micron-scale pores developed. The mineral composition is dominated by dolomite, calcite, and clay minerals, with an average clay mineral content of 65%, and the average rock mechanical brittleness index is 41.76%. The development of natural fractures in the reservoir is relatively limited, and the fracture pressure difference between limestone and shale intervals ranges from 10.78 to 16.68 MPa, which is unfavorable for vertical fracture propagation.

(2) Taking the brittleness index, dimensionless fracture toughness, in-situ stress difference coefficient, and natural fracture influence index as evaluation factors, a fracturability mathematical model for the shale reservoir was derived using the weighting superposition method. Using this model, the fracturability indices of four shale reservoir wells in the Yingxiongling area of the Qinghai Oilfield were calculated. The results show that these four wells have difficulty forming complex fracture networks, which is consistent with the actual fracture conditions observed in the field, thereby verifying the applicability of the fracturability model.

(3) To address the difficulty in forming complex fracture networks in the shale reservoir of the Yingxiongling area in the Qinghai Oilfield, a three-dimensional horizontal well pattern combined with zipper-style volumetric fracturing is proposed for reservoir stimulation. To achieve interlayer breakthrough through increased net pressure within fractures, a stimulation process combining dense cluster spacing, limited-entry perforation, high pumping rate, and high-intensity continuous sand injection is recommended to further enhance fracture complexity.

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