



GEOINFORMATICS

Original article

<https://doi.org/10.21285/2686-9993-2021-44-4-397-407>



Simulation of tectonic stress field and prediction of fracture distribution in shale reservoir*

Wenlong Ding^a, Weite Zeng^b, Ruyue Wang^c, Kai Jiu^d, Zhe Wang^e, Yaxiong Sun^f, Xinghua Wang^g

^{a,c,f,g}China University of Geosciences, Beijing, China

^bHainan Geological Survey, Haikou, China

^dBeijing Jingneng Petroleum Corporation Limited, Beijing, China

^eShandong Kerui Group Holding Corporation Limited, Dongying, China

Corresponding author: Wenlong Ding, dingwenong2006@126.com

Abstract. In this paper, a finite element-based fracture prediction method for shale reservoirs was proposed using geostress field simulations, uniaxial and triaxial compression deformation tests, and acoustic emission geostress tests. Given the characteristics of tensile and shear fractures mainly developed in organic-rich shales, Griffith and Coulomb – Mohr criteria were used to calculate shale reservoirs' tensile and shear fracture rates. Furthermore, the total fracture rate of shale reservoirs was calculated based on the ratio of tension and shear fractures to the total number of fractures. This method has been effectively applied in predicting fracture distribution in the Lower Silurian Longmaxi Formation shale reservoir in southeastern Chongqing, China. This method provides a new way for shale gas sweet spot optimization. The simulation results have a significant reference value for the design of shale gas horizontal wells and fracturing reconstruction programs.

Keywords: southeastern Chongqing, Longmaxi Formation, shale reservoir, simulation of tectonic stress field, fracture prediction

Funding: this research was supported by the National Natural Science Foundation of China (grant no. 42072173).

For citation: Ding Wenlong, Zeng Weite, Wang Ruyue, Jiu Kai, Wang Zhe, Sun Yaxiong, Wang Xinghua. Simulation of tectonic stress field and prediction of fracture distribution in shale reservoir. *Nauki o Zemle i nedropol'zovanie = Earth sciences and subsoil use*. 2021;44(4):397-407. <https://doi.org/10.21285/2686-9993-2021-44-4-397-407>.

ГЕОИНФОРМАТИКА

Научная статья

УДК 551.243+004.94

Моделирование поля тектонических напряжений и прогноз распределения трещин в сланцевом коллекторе*

Вэньлун Дин^a, Вэйтэ Цзэн^b, Жуюэ Ван^c, Кай Цзю^d, Чжэ Ван^e, Ясюн Сунь^f, Синхуа Ван^g

^{a,c,f,g}Китайский университет геологических наук, г. Пекин, Китай

^bГеологическая служба Хайнаня, г. Хайкоу, Китай

^dПекинская нефтепромышленная корпорация Цзиннэн, г. Пекин, Китай

^eШаньдун Кэжуй Групп Холдинг Лимитед, г. Дунъян, Китай

Автор, ответственный за переписку: Дин Вэньлун, dingwenong2006@126.com

Резюме. Статья представляет способ прогнозирования трещиноватости сланцевых коллекторов, основанный на методе конечных элементов с использованием моделирования поля напряжений, деформационных тестов на одноосное и трехосное сжатие, а также испытаний акустической эмиссии на сжатие. Учитывая характеристики трещин при растяжении и сдвиге, которые в основном возникают в сланцах, богатых органическими веществами, были использованы критерии Гриффита и Кулона – Мора для расчета скоростей роста трещин при растяжении и сдвиге в сланцевых коллекторах. Кроме того, общая скорость роста трещин в сланцевых коллекторах была рассчитана

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* The article was provided by the Earth Science Frontiers journal within the framework of the agreement between the editorial boards of Irkutsk National Research Technical University (Irkutsk, Russia) and China University of Geosciences (Beijing, China) on the exchange of open access scientific papers.

* Статья была предоставлена редакцией журнала Earth Science Frontiers в рамках соглашения между редакциями Иркутского национального исследовательского технического университета (г. Иркутск, Россия) и Китайского университета геологических наук (г. Пекин, Китай) об обмене научными статьями открытого доступа.



на основе отношения трещин растяжения и сдвига к общему количеству трещин. Этот метод был эффективно применен для прогнозирования распределения трещин в сланцевом коллекторе формации Лунмасы нижнего силура на юго-востоке Чунцина, Китай, и он обеспечивает новый способ оптимизации перспективных месторождений сланцевого газа. Результаты моделирования имеют важное значение для проектирования горизонтальных скважин для добычи сланцевого газа и создания программ по реконструкции гидроразрыва пласта.

Ключевые слова: юго-восточный Чунцин, формация Лунмасы, сланцевый пласт, моделирование поля тектонических напряжений, прогноз разрушения

Финансирование: исследование было проведено при поддержке Национального фонда естественных наук Китая (грант № 42072173).

Для цитирования: Дин Вэньлун, Цзэн Вэйтэ, Ван Жуюэ, Цзю Кай, Ван Чжэ, Сунь Ясюн, Ван Синхуа. Моделирование поля тектонических напряжений и прогноз распределения трещин в сланцевом коллекторе // Науки о Земле и недропользование. 2021. Т. 44. № 4. С. 397–407. <https://doi.org/10.21285/2686-9993-2021-44-4-397-407>.

Introduction

For low-porosity and low-permeability shale reservoirs, the nano-scale pores in the matrix have basically no seepage capability. Therefore, fractures not only provide important space for hydrocarbon storage, but also provide efficient channels for hydrocarbon migration [1–3]. The great success of the marine organic-rich shale gas industry in North America shows that natural fractures can promote the large-scale accumulation of hydrocarbons in shale reservoirs [4–6]. Fractures are a key factor in obtaining high yields in shale reservoirs [7–12]. A large number of oil-field data around the world show that the degree of fracture development in tight reservoirs is closely related to productivity [13–16]. For example, the degree of fracture development of Paleozoic marine shale in North America is positively correlated with total gas content and free gas content. The success rate of shale gas exploration in the fractured zone is high. In addition, the natural gas productivity in the organic-rich marine shale reservoirs of the Lower Paleozoic in the Sichuan Basin of China is also positively correlated with the degree of fracture development [17–19].

In this paper, a finite element-based fracture prediction method for shale reservoirs was proposed using geostress field simulations, uniaxial and triaxial compression deformation tests, and acoustic emission geostress tests. This technology has achieved good application effects in the prediction of fracture distribution in the Lower Silurian Longmaxi Formation shale reservoir in southeastern Chongqing, China. Moreover, it provides a new way for shale gas sweet spot optimization, and the simulation results have important reference value for the design of shale gas horizontal wells and fracturing reconstruction programs.

Materials and methods

Experiments. In this paper, acoustic emissions and rock mechanics experimental tests were used to obtain the rock mechanical properties and paleostress of the target shale. The tests were completed in the Beijing SGS Rock Physics Laboratory. A GCTS petrophysical testing system was used for rock mechanics testing. The pressure sensor error of this instrument was less than 1 %, the displacement sensor ranges were between ± 50 mm, and the strain accuracy was 0.0001 mm. In addition, the acoustic emission instrument was the SAMOSTM acoustic emission detection system. Its core component is the PCI-8 acoustic emission function card that processes the PCI bus in parallel. It has 8 channels of real-time acoustic emission feature extraction, waveform acquisition and processing capabilities on one board. Modern digital signal processing technology (DSP) is adopted, which is currently the most advanced acoustic emission processing system in the world.

Finite element model. This paper used the finite element method to simulate the tectonic stress field and then predicted the plane distribution of tectonic fractures based on rupture principles. The core technology of this method is to establish an accurate geological model, mechanical model, and calculation model of the simulated area. The measured rock mechanical property parameters and paleostress values were used to calibrate the fake stress field (Fig. 1). The organic-rich shale mainly develops tensile and shear fractures. Therefore, Griffith and Coulomb – Mohr failure criteria were used to calculate the tensile and shear failure rate, respectively. Finally, proposed the comprehensive rupture rate based on the coupling results of tensile and shear ruptures (Fig. 1).

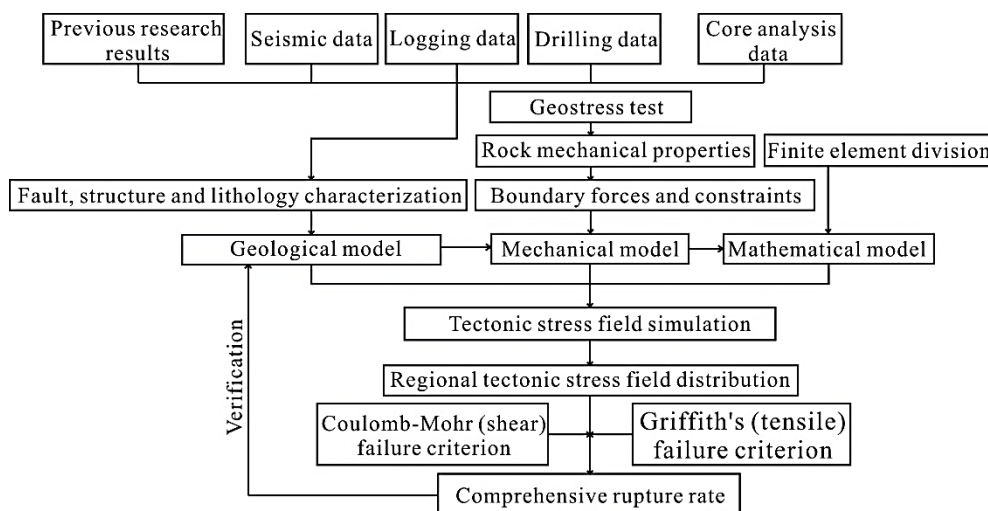


Fig. 1. Work flow of shale fracture prediction based on finite element method

Рис. 1. Последовательность операций по прогнозированию трещиноватости сланцев на основе метода конечных элементов

The geological model of the southeast area of Chongqing is triangularly gridded, which includes 9,965 nodes and 19,670 grid cells (Fig. 2).

$$[f]^e = \begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} N_i u_i + N_j u_j + N_m u_m \\ N_i v_i + N_j v_j + N_m v_m \end{bmatrix} = \begin{bmatrix} N_i & 0 & N_j & 0 & N_m & 0 \\ 0 & N_i & 0 & N_j & 0 & N_m \end{bmatrix} \begin{bmatrix} u_i & v_i & u_j & v_j & u_m & v_m \end{bmatrix}^T. \quad (1)$$

For any triangle mesh element, the displacement u, v of any point (x, y) in the component can be expressed as a matrix form:

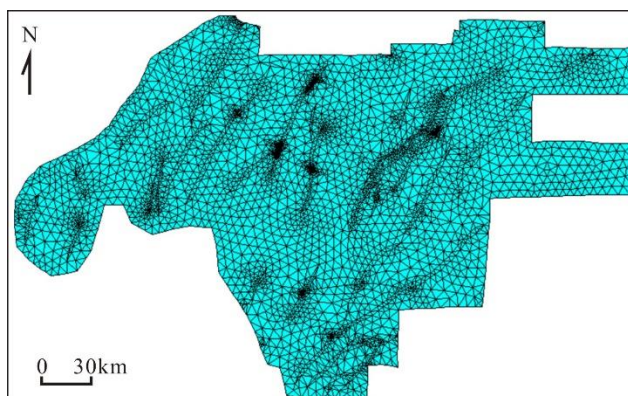


Fig. 2. Grid model of Longmaxi Formation shale in southeastern Chongqing area

Рис. 2. Сеточная модель сланцев формации Лунмасы в юго-восточной части района Чунцин

Equation (1) can be simplified as:

$$[f] = [N][\delta]^e. \quad (2)$$

In the formula, N_i, N_j and N_m are the morphological function or shape function of the element displacement, $[N]$ is the shape function matrix, and $[\delta]^e$ is the nodal displacement component matrix.

The strain of the element is a geometric equation:

$$[\varepsilon] = \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial x} & 0 \\ 0 & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix}. \quad (3)$$

When equation (1) is substituted into equation (3), the strain matrix of the element can be obtained:

$$[\varepsilon] = [B][\delta]^e. \quad (4)$$

In the formula, the conversion matrix $[B]$ is a geometric matrix.

For each element, the maximum principal stress is obtained through coordinate transformation:

$$\begin{vmatrix} \sigma_x - \sigma & \tau_{yx} \\ \tau_{yx} & \sigma_y - \sigma \end{vmatrix} = 0. \quad (5)$$

The maximum principal stress σ_1 and the minimum principal stress σ_3 can be obtained by solving the above formula.



Griffith and Coulomb – Mohr criterions. Under the action of regional tectonic stress, there are two main types of ruptures inside the rock: tensile and shear fractures [8–9].

Shear rupture follows the Coulomb – Mohr criterion, and tensile fracture follows the Griffith criterion [19–21].

The expression of the plane rupture criterion of Griffith theory is:

$$\text{When } \sigma_1 + 3\sigma_3 \geq 0, \text{ the rupture criterion is:} \\ (\sigma_1 - \sigma_3)^2 - 8(\sigma_1 + \sigma_3)\sigma_T = 0. \quad (6)$$

$$\text{When } \sigma_1 + 3\sigma_3 < 0, \text{ the rupture criterion is:} \\ \sigma_3 + \sigma_T = 0. \quad (7)$$

In the formula, σ_1 is the maximum principal stress, MPa; σ_3 is the minimum principal stress, MPa, and σ_T is the tensile stress of the rock, MPa.

The Coulomb – Mohr criterion believes that the shear failure on a plane is related to the combination of the normal stress σ and the shear stress τ . The Coulomb – Mohr shear rupture criterion can be expressed as:

$$|\tau| = C + \sigma \tan \varphi. \quad (8)$$

In the formula, $|\tau|$ is the shear strength of the rock, MPa; σ is the normal stress, MPa; C is the cohesive force, MPa; φ is the internal friction angle, °; $\tan \varphi$ is the internal friction coefficient.

Comprehensive rupture rate. In this paper, the tensile rupture rate I_t and the shear rupture rate I_n were introduced to characterize different types of fractures:

$$I_t = \sigma_T / \sigma_t. \quad (9)$$

In the formula, σ_T is the effective tensile stress, MPa; σ_t is the tensile strength of the rock, MPa. When $I_t \geq 1$, tensile ruptures will occur.

$$I_n = \tau_n / |\tau|. \quad (10)$$

In the formula, τ_n is the effective shear stress, MPa, and $|\tau|$ is the shear strength of the rock, MPa. When $I_n \geq 1$, shear ruptures will occur.

The rupture mode of shale is a comprehensive reflection of tensile and shear stresses [9–10]. Therefore, in order to better quantitatively characterize the development degree of structural fractures in shale reservoirs, a comprehensive fracture coefficient was proposed.

$$I_z = (aI_t + bI_n) / 2. \quad (11)$$

In the formula, a and b are the ratios of tensile and shear fractures respectively. In this paper, $a : b = 3 : 2$. Similarly, when $I_z \geq 1$, the rock reaches a fractured state, and the higher the comprehensive fracture rate value of shale, the greater the fractured degree.

Results

Palaeo-stress based on acoustic emission. In the simulation of in-situ stress, the assignment of reasonable rock mechanics parameter attributes of the geological model of the target layer is essential. Furthermore, the assigned geological model is converted to a mechanical model. According to regional tectonic movement and acoustic emission tests, it is believed that during the Yanshan period, the tectonic activity in south-eastern Chongqing was the strongest (148.8 MPa maximum tectonic stress); followed by the Himalayan movement (122.5 MPa maximum tectonic stress) (Table 1).

Rock mechanics parameters. The faults in the study area were divided into first-order, second-order, and third-order faults. At the same time, the fold areas were split into slot folds, battlement folds, and barrier folds. The rock mechanics test results of different types of shales in the Longmaxi Formation in the study area are shown in Table 2.

Mechanical properties of fault and fold zones. The fault zone was defined as a "weak zone" whose elastic modulus was 50–70 % of the ordinary sedimentary strata. At the same time, the Poisson's ratio was more extensive than that of the ordinary sedimentary strata, and the differences between them were between 0.02 and 0.1. The folding zone was identified as a "tough zone", and its elastic modulus was 1.5 to 3 times that of the normal sedimentary formation. At the same time, the Poisson's ratio was smaller than the normal sedimentary formation, and the differences between them were between 0.01 and 0.15 (Table 3).

Table 1. Measurement results of acoustic emission stress of Longmaxi Formation in Well Y1
Таблица 1. Результаты измерения напряжения акустической эмиссии формации Лунмасси в скважине Y1

Well	Depth, m	Formation	Effective value of σ_1 , MPa	Number of tectonic activities
Y1 well	0–325.5	Longmaxi Formation	23.1, 40.8, 57.4, 91, 122.5, 148.8	6



Table 2. Rock mechanics test results of different types of shales in the Longmaxi Formation in the study area

Таблица 2. Результаты испытаний механики горных пород различных типов сланцев в формации Лунмасы в районе исследования

Lithology	Density ρ_0 , g·cm ⁻³	Tensile strength σ_t , MPa	Compressive strength σ_c , MPa	Elastic modulus E , GPa	Poisson's ratio μ	Cohesion C , MPa	Internal friction angle φ , °
Black shale	2.715	16.67	100.95	52.83	0.266	22.33	34.53
Dark gray shale	2.657	5.95	149.6	59.75	0.255	27.71	34.56
Argillaceous siltstone	2.688	12.23	102.75	65.82	0.286	3.84	56.36
Calcareous shale	2.655	6.79	132.87	42.87	0.205	16.42	49.01
Siliceous shale	2.747	9.06	101.83	54.06	0.261	12.42	58.11

Table 3. Assignment of rock mechanics parameters in the fault and fold zones in the study area

Таблица 3. Определение параметров механики горных пород в разломной и складчатой зонах исследуемой территории

Geological unit type		Elastic modulus, MPa	Poisson's ratio
Fault zone	First-order fault	21,435	0.332
	Second-order fault	32,436	0.317
	Third-order fault	36,981	0.305
Fold zone	Slotted fold	102,180–137,460	0.2–0.211
	Battlement fold	85,660–102,180	0.211–0.248
	Barrier fold	65,740–85,660	0.248–0.256

Discussion

Tectonic stress field distribution. It can be seen from the simulation results of the tectonic stress field (Fig. 3) that the maximum principal stresses of the Longmaxi Formation shale reservoir in southeastern Chongqing were concentrated between -217.404 and -4.109 MPa. Positive values were defined as tensile stress, and negative values were defined as compressive stress. The maximum principal stress inside the

fault zone was lower than that of ordinary sedimentary strata, and the stress intensity values were mainly distributed between -46.768 and -4.19 MPa. For areas with underdeveloped faults, the maximum principal stress value distribution ranged from -103.647 to -46.768 MPa.

The rocks inside the fold zone are severely deformed, especially the rocks at the shaft and turning ends of the folds are more severely deformed. The stress in these structural parts will

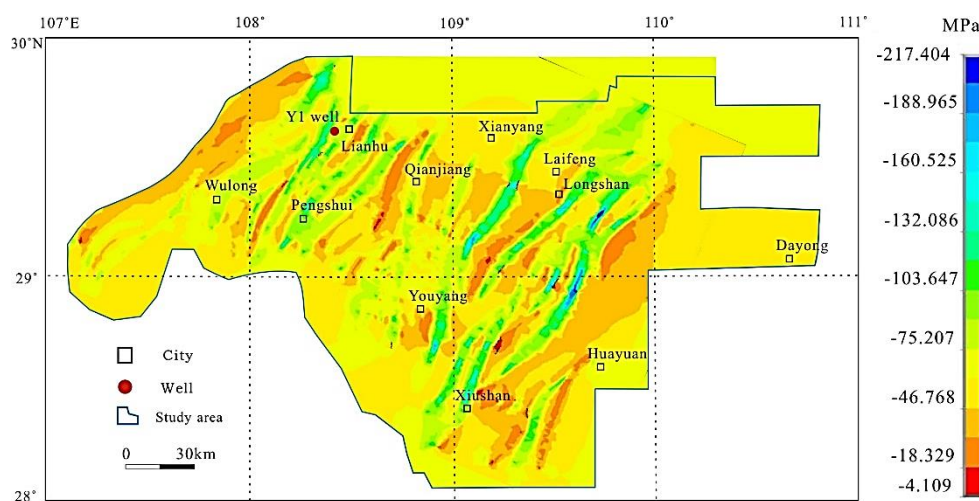


Fig. 3. Distribution of maximum principal stress of Longmaxi Formation shale in southeastern Chongqing area

Рис. 3. Распределение максимумов основных нормальных напряжений в сланцах формации Лунмасы в юго-восточной части района Чунцин



be highly concentrated under the premise that there is no fault damage and cannot release the stress. Suppose the fold is clamped by reverse faults, such as the southwestern Huayuan and Pengshui west-trending fault fold belt, or the fault-related folds adjacent to the fault, such as Longshan and Xiushan areas. In that case, the maximum principal stress value will be higher. In addition, the closer the fold is to the fault, the more obvious the stress gradient changes. In addition to the fold mentioned above belts, the fault belt's end and the fault's turning end are also the transition areas from the broken rocks inside the fault belt to continuous strata. The rocks in these areas are at the edge of ruptures. Therefore, the stress value is higher. The maximum principal stress distribution in these areas ranges from -217.404 to -103.647 MPa.

The shear stresses of the target shale reservoir in the study area ranged from -4.707 to 49.222 MPa (Fig. 4). Among them, positive values were defined as left-handed and defined negative values as right-handed. The structures of the study area showed obvious strike-slip characteristics, and the NNE-trending "S"-shaped faults and folds had the attributes of counter-clockwise rotation and twisting. It can see from

Figure 4 that the shear stress value in the study area is mainly positive, reflecting the counter-clockwise left-handed shear stress field in the Himalayan period in southeast Chongqing. The simulation results are consistent with the compression-torsional strike-slip structural deformation characteristics shown in the Himalayan period in the study area.

Prediction of fracture distribution. In this paper, the degrees of fracture development in shale reservoirs were divided into five levels (Table 4).

According to Figure 5, there are widely distributed fractures of grade I–IV in the eastern part of the study area, and the fracture development coefficients are mainly 1.4–4. Among them, the sizeable trough-shaped fold axis in the northern part of Huayuan is an area with highly developed fractures (level IV), and the fracture development coefficient has even reached above 4 (the formation was severely broken). The southern (Xiushan, south of Huayuan) and northwestern (Lianhu area) areas are favorable areas for level II and level I fractures, respectively. The western part (Wulong, Pengshui) mainly develops first-level fractures, and the fracture development coefficients are between 1–1.4.

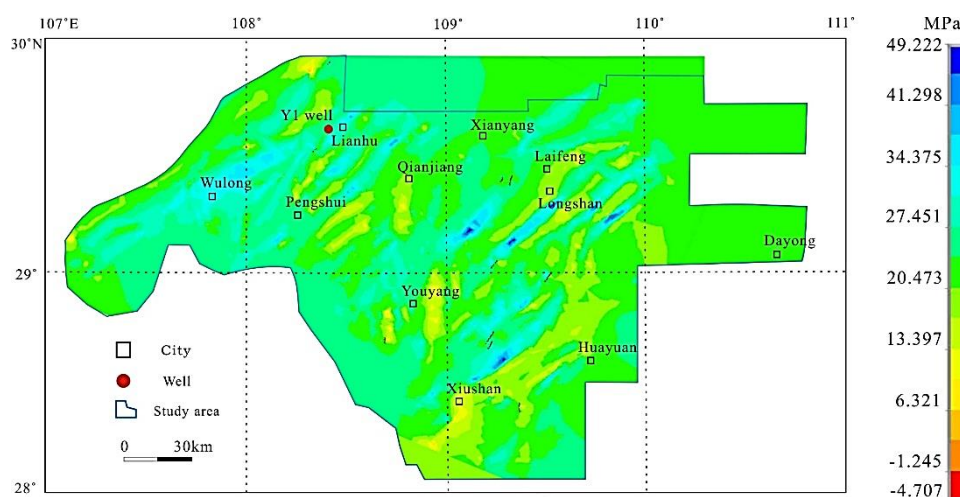


Fig. 4 Distribution of shear stress of Longmaxi Formation shale in southeastern Chongqing area

Рис. 4. Распределение напряжений сдвига в сланцах формации Лунмаси в юго-восточной части района Чунцин

Table 4. Criteria for the development of fractures in shale reservoirs

Таблица 4. Критерии развития трещин в сланцевых коллекторах

Fracture development	X	I	II	III	IV
I_z	$I_z < 1$	$1 \leq I_z < 2$	$2 \leq I_z < 3$	$3 \leq I_z < 4$	$I_z \geq 4$
Fracture description	Undeveloped	Relatively developed	Developed	Well developed	Extremely developed

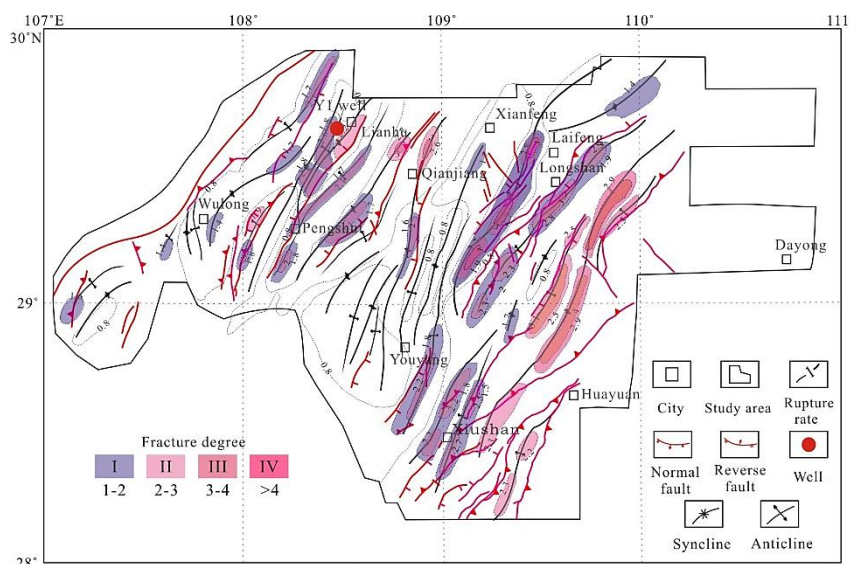


Fig. 5. Distribution of fracture development coefficient in Longmaxi Formation shale in southeastern Chongqing area

Рис. 5. Распределение коэффициента развития трещин в сланцах формации Лунмасы в юго-восточной части района Чунцин

The areas with high TOC content and brittle mineral content in Longmaxi Formation shale reservoirs are mainly located in the deposition center of black shale, namely Lianhu-Qianjiang and South Longshan areas. With the same comprehensive fracture coefficient, shale fractures with high TOC content and brittle mineral content are more developed. The eastern and southern parts of the study area have the most developed fractures, especially in the areas adjacent to the faults and the relatively strong-deformed grooved fold shafts, where some normal tensile faults have appeared. The southern part of the study area is the development zone of sandy shelf facies shale. The rock elastic modulus is high, and Poisson's ratio is low. It is prone to develop fractured under the action of external forces.

Conclusions

(1) The core of the numerical simulation method of the tectonic stress field lies in the establishment of the accurate geological model, mechanical model, and mathematical model. Given the particularity of shale reservoirs, the geological model must be used as the basis during the simulation process, and shale types and

rock mechanical properties must be classified according to rock facies.

(2) For the interior of the fold belt in the study area, especially the shale reservoir near the axis of the fold and the turning end, has suffered severe structural deformation, which is a highly concentrated area of stress. The end of the fault zone and the turning end are the continuous transition area from the broken shale inside the fault zone to the ordinary sedimentary strata, which is at the edge of rupture and has high-stress values. The black carbonaceous, siliceous, and calcareous shale of shallow sea shelf facies with stable distribution and weak structural deformation in the deposition center have high elastic modulus and low Poisson's ratio. These brittle shales are prone to develop structural fractures.

(3) The quantitative prediction of shale fracture distribution cannot be based on a single factor as the criterion. Otherwise, it will cause one-sided and limited results. The total fracture rate that affects the development of fractures in shale reservoirs should be considered as much as possible. This study found that fracture development areas are mostly concentrated in high-stress areas with severe structural deformation.

References

1. Jarvie D. M., Hill R. J., Ruble T. E., Pollastro R. M. Unconventional shale-gas systems: the Mississippian Barnett Shale of north-central Texas as one model for thermo-

genic shale-gas assessment. *AAPG Bulletin*. 2007;91(4): 475-499. <https://doi.org/10.1306/12190606068>.

2. Curtis J. B. Fractured shale-gas systems. *AAPG*



Bulletin. 2002;86(11):1921-1938. <https://doi.org/10.1306/61EEDDBE-173E-11D7-8645000102C1865D>.

3. Ross D. J. K., Bustin R. M. Shale gas potential of the Lower Jurassic Gordondale Member, northeastern British Columbia, Canada. *Bulletin of Canadian Petroleum Geology*. 2007;55(1):51-75. <https://doi.org/10.2113/gscpgbull.55.1.51>.

4. Gale J. F. W., Reed R. M., Holder J. Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments. *AAPG Bulletin*. 2007;91(4):603-622. <https://doi.org/10.1306/11010606061>.

5. Hill D. G., Lombardi T. E., Martin J. P. *Fractured gas shale potential in New York*. Available from: <https://treichlerlawoffice.com/radiation/HillNY.pdf> [Accessed 20th August 2021].

6. Zeng W., Zhang J., Ding W., Zhao S., Zhang Y., Liu Z., et al. Fracture development in Paleozoic shale of Chongqing area (South China). Part one: Fracture characteristics and comparative analysis of main controlling factors. *Journal of Asian Earth Sciences*. 2013;75(5):251-266. <https://doi.org/10.1016/j.jseaes.2013.07.014>.

7. Ding W., Zhu D., Cai J., Gong M., Chen F. Analysis of the Developmental characteristics and major regulating factors of fractures in marine-continental transitional shale-gas reservoirs: a case study of the Carboniferous-Permian strata in the southeastern Ordos Basin, central China. *Marine and Petroleum Geology*. 2013;45:121-133. <https://doi.org/10.1016/j.marpetgeo.2013.04.022>.

8. Jiu K., Ding W., Huang W., Zhang Y., Zhao S., Hu L. Fractures of lacustrine shale reservoirs, the Zhanhua Depression in the Bohai Bay Basin, eastern China. *Marine and Petroleum Geology*. 2013;48:113-123. <https://doi.org/10.1016/j.marpetgeo.2013.08.009>.

9. Jiu K., Ding W., Huang W., You S., Zhang Y., Zeng W. Simulation of paleotectonic stress fields within Paleogene shale reservoirs and prediction of favorable zones for fracture development within the Zhanhua Depression, Bohai Bay Basin, east China. *Journal of Petroleum Science and Engineering*. 2013;110:119-131. <https://doi.org/10.1016/j.petrol.2013.09.002>.

10. Ding W., Fan T., Yu B., Huang X., Liu C. Ordovician carbonate reservoir fracture characteristics and fracture distribution forecasting in the Tazhong Area of Tarim Basin, Northwest China. *Journal of Petroleum Science and Engineering*. 2012;86-87:62-70. <https://doi.org/10.1016/j.petrol.2012.03.006>.

11. Atkinson B., Meredith P. Experimental fracture mechanics data for rocks and minerals. In: Atkinson B. K. (ed.). *Fracture mechanics of rock*. London: Academic Press; 1987. p.76-80.

12. Bewick R. P., Kaiser P. K., Bawden W. F. DEM simulation of direct shear: 2. Grain boundary and mineral grain strength component influence on shear rupture. *Rock Mechanics and Rock Engineering*. 2014;47:1673-1692. <https://doi.org/10.1007/s00603-013-0494-4>.

13. Jaeger J. C., Cook N. G. W. *Fundamentals of rock mechanics*. London: Chapman and Hall; 1976. 612 p.

14. Lama R. D., Vutukuri V. S. Handbook on mechanical properties of rocks. Vol. II. In: *Trans tech publications*. Clausthal; 1978. p.58-60.

15. Liu J., Ding W., Yang H., Wang R., Yin S., Li A., et al. 3D geomechanical modeling and numerical simulation of in-situ stress fields in shale reservoirs: a case study of the lower Cambrian Niutitang formation in the Cen'gong block, South China. *Tectonophysics*. 2017;712-713:663-683. <https://doi.org/10.1016/j.tecto.2017.06.030>.

16. Liu J., Ding W., Wang R., Yang H., Wang X., Li A. Methodology for quantitative prediction of fracture sealing with a case study of the lower Cambrian Niutitang Formation in the Cen'gong block in South China. *Journal of Petroleum Science and Engineering*. 2018;160:565-581. <https://doi.org/10.1016/j.petrol.2017.10.046>.

17. Mahmoodi S., Abbasi M., Sharifi M. New fluid flow model for hydraulic fractured wells with non-uniform fracture geometry and permeability. *Journal of Natural Gas Science and Engineering*. 2019;68:102914. <https://doi.org/10.1016/j.jngse.2019.102914>.

18. Oluwadebi A. G., Taylor K. G., Ma L. A case study on 3D characterisation of pore structure in a tight sandstone gas reservoir: the Collyhurst Sandstone, East Irish Sea Basin, northern England. *Journal of Natural Gas Science and Engineering*. 2019;68:102917. <https://doi.org/10.1016/j.jngse.2019.102917>.

19. Salamon M. D. G. Energy considerations in rock mechanics: fundamental results. *Journal of the Southern African Institute of Mining and Metallurgy*. 1984;84(8):233-246.

20. Wang R., Hu Z., Sun C., Liu Z., Zhang C., Gao B., et al. Comparative analysis of shale reservoir characteristics in the Wufeng-Longmaxi (O₃W-S₁) and Niutitang (Є₁n) Formations: a case study of wells JY1 and TX1 in southeastern Sichuan Basin and its periphery, southwestern China. *Interpretation*. 2018;6(4):SN31-SN45. <https://doi.org/10.1190/int-2018-0024.1>.

21. Yang R., Jin Z., van Loon A. J., Han Z., Fan A. Climatic and tectonic controls of lacustrine hyperpycnite origination in the Late Triassic Ordos Basin, central China: implications for unconventional petroleum development. *AAPG Bulletin*. 2017;101(1):95-117. <https://doi.org/10.1306/06101615095>.

Список источников

1. Jarvie D. M., Hill R. J., Ruble T. E., Pollastro R. M. Unconventional shale-gas systems: the Mississippian Barnett Shale of north-central Texas as one model for thermogenic shale-gas assessment // *AAPG Bulletin*. 2007. Vol. 91. Iss. 4. P. 475-499. <https://doi.org/10.1306/12190606068>.

2. Curtis J. B. Fractured shale-gas systems // *AAPG Bulletin*. 2002. Vol. 86. Iss. 11. P. 1921-1938. <https://doi.org/10.1306/61EEDDBE-173E-11D7-8645000102C1865D>.

3. Ross D. J. K., Bustin R. M. Shale gas potential of the Lower Jurassic Gordondale Member, northeastern British Columbia, Canada // *Bulletin of Canadian Petroleum Geology*. 2007. Vol. 55. Iss. 1. P. 51-75. <https://doi.org/10.2113/gscpgbull.55.1.51>.

4. Gale J. F. W., Reed R. M., Holder J. Natural fractures in the Barnett Shale and their importance for hydraulic fracture treatments // *AAPG Bulletin*. 2007. Vol. 91. Iss. 4.



P. 603–622. <https://doi.org/10.1306/11010606061>.

5. Hill D. G., Lombardi T. E., Martin J. P. Fractured gas shale potential in New York. [Электронный ресурс]. URL: <https://treichlerlawoffice.com/radiation/HillNY.pdf> (20.08.2021).

6. Zeng W., Zhang J., Ding W., Zhao S., Zhang Y., Liu Z., et al. Fracture development in Paleozoic shale of Chongqing area (South China). Part one: Fracture characteristics and comparative analysis of main controlling factors // *Journal of Asian Earth Sciences*. 2013. Vol. 75. Iss. 5. P. 251–266. <https://doi.org/10.1016/j.jseaes.2013.07.014>.

7. Ding W., Zhu D., Cai J., Gong M., Chen F. Analysis of the Developmental characteristics and major regulating factors of fractures in marine-continental transitional shale-gas reservoirs: a case study of the Carboniferous-Permian strata in the southeastern Ordos Basin, central China // *Marine and Petroleum Geology*. 2013. Vol. 45. P. 121–133. <https://doi.org/10.1016/j.marpetgeo.2013.04.022>.

8. Jiu K., Ding W., Huang W., Zhang Y., Zhao S., Hu L. Fractures of lacustrine shale reservoirs, the Zhanhua Depression in the Bohai Bay Basin, eastern China // *Marine and Petroleum Geology*. 2013. Vol. 48. P. 113–123. <https://doi.org/10.1016/j.marpetgeo.2013.08.009>.

9. Jiu K., Ding W., Huang W., You S., Zhang Y., Zeng W. Simulation of paleotectonic stress fields within Paleogene shale reservoirs and prediction of favorable zones for fracture development within the Zhanhua Depression, Bohai Bay Basin, east China // *Journal of Petroleum Science and Engineering*. 2013. Vol. 110. P. 119–131. <https://doi.org/10.1016/j.petrol.2013.09.002>.

10. Ding W., Fan T., Yu B., Huang X., Liu C. Ordovician carbonate reservoir fracture characteristics and fracture distribution forecasting in the Tazhong Area of Tarim Basin, Northwest China // *Journal of Petroleum Science and Engineering*. 2012. Vol. 86–87. P. 62–70. <https://doi.org/10.1016/j.petrol.2012.03.006>.

11. Atkinson B., Meredith P. Experimental fracture mechanics data for rocks and minerals // *Fracture mechanics of rock* / B. K. Atkinson. London: Academic Press, 1987. P. 76–80.

12. Bewick R. P., Kaiser P. K., Bawden W. F. DEM simulation of direct shear: 2. Grain boundary and mineral grain strength component influence on shear rupture // *Rock Mechanics and Rock Engineering*. 2014. Vol. 47. P. 1673–1692. <https://doi.org/10.1007/s00603-013-0494-4>.

13. Jaeger J. C., Cook N. G. W. Fundamentals of rock mechanics. London: Chapman and Hall, 1976. 612 p.

14. Lama R. D., Vutukuri V. S. Handbook on mechanical properties of rocks. Vol. II // Trans tech publications. Clausthal, 1978. P. 58–60.

15. Liu J., Ding W., Yang H., Wang R., Yin S., Li A., et al. 3D geomechanical modeling and numerical simulation of in-situ stress fields in shale reservoirs: a case study of the lower Cambrian Niutitang formation in the Cen'gong block, South China // *Tectonophysics*. 2017. Vol. 712–713. P. 663–683. <https://doi.org/10.1016/j.tecto.2017.06.030>.

16. Liu J., Ding W., Wang R., Yang H., Wang X., Li A. Methodology for quantitative prediction of fracture sealing with a case study of the lower Cambrian Niutitang Formation in the Cen'gong block in South China // *Journal of Petroleum Science and Engineering*. 2018. Vol. 160. P. 565–581. <https://doi.org/10.1016/j.petrol.2017.10.046>.

17. Mahmoodi S., Abbasi M., Sharifi M. New fluid flow model for hydraulic fractured wells with non-uniform fracture geometry and permeability // *Journal of Natural Gas Science and Engineering*. 2019. Vol. 68. P. 102914. <https://doi.org/10.1016/j.jngse.2019.102914>.

18. Oluwadebi A. G., Taylor K. G., Ma L. A case study on 3D characterisation of pore structure in a tight sandstone gas reservoir: the Collyhurst Sandstone, East Irish Sea Basin, northern England // *Journal of Natural Gas Science and Engineering*. 2019. Vol. 68. P. 102917. <https://doi.org/10.1016/j.jngse.2019.102917>.

19. Salamon M. D. G. Energy considerations in rock mechanics: fundamental results // *Journal of the Southern African Institute of Mining and Metallurgy*. 1984. Vol. 84. Iss. 8. P. 233–246.

20. Wang R., Hu Z., Sun C., Liu Z., Zhang C., Gao B., et al. Comparative analysis of shale reservoir characteristics in the Wufeng-Longmaxi (O₃w-S₁l) and Niutitang (Є₁n) Formations: a case study of wells JY1 and TX1 in southeastern Sichuan Basin and its periphery, southwestern China // *Interpretation*. 2018. Vol. 6. Iss. 4. P. SN31–SN45. <https://doi.org/10.1190/int-2018-0024.1>.

21. Yang R., Jin Z., van Loon A. J., Han Z., Fan A. Climatic and tectonic controls of lacustrine hyperpycnite origination in the Late Triassic Ordos Basin, central China: implications for unconventional petroleum development // *AAPG Bulletin*. 2017. Vol. 101. Iss. 1. P. 95–117. <https://doi.org/10.1306/06101615095>.

Information about the authors / Информация об авторах



Wenlong Ding, PhD, professor, doctoral supervisor, major in petroleum geology, and has long been engaged in teaching and research on petroleum structure analysis and oil and gas control, formation mechanism and quantitative characterization of unconventional oil and gas reservoir fractures, and evaluation of engineering sweet spots.

Вэньлун Дин – доктор философии, профессор, научный руководитель докторских диссертаций, специалист в области нефтяной геологии, долгое время занимался преподаванием и исследованиями в области анализа структуры нефти и контроля нефти и газа, механизма образования и количественной характеристики необычных трещин в нефтегазовых коллекторах, а также оценки перспективных месторождений.

**Wenlong Ding,**

Dr. Sci. (Geol. & Mineral.), Professor,
School of Energy Resources,
Key Laboratory for Marine Reservoir Evolution and Hydrocarbon Abundance Mechanism, Ministry of Education,
Key Laboratory for Shale Gas Exploration and Assessment, Ministry of Land and Resources,
China University of Geosciences,
Beijing, China,
dingwenong2006@126.com,
<https://orcid.org/0000-0003-3669-3905>.

Дин Вэньлун,

доктор геолого-минералогических наук, профессор,
Школа Энергетических Ресурсов,
Главная лаборатория эволюции морских резервуаров и механизма распространения углеводородов,
Министерство образования,
Главная лаборатория по разведке и оценке запасов сланцевого газа, Министерство земли и ресурсов,
Китайский университет геологических наук,
г. Пекин, Китай,
dingwenong2006@126.com,
<https://orcid.org/0000-0003-3669-3905>.

Weite Zeng,

Hainan Geological Survey,
Haikou, China.

Цзэн Вэйтэ,

Геологическая служба Хайнана,
г. Хайкоу, Китай.

Ruyue Wang,

School of Energy Resources,
Key Laboratory for Marine Reservoir Evolution and Hydrocarbon Abundance Mechanism, Ministry of Education,
Key Laboratory for Shale Gas Exploration and Assessment, Ministry of Land and Resources,
China University of Geosciences,
Beijing, China.

Ван Жуюэ,

Школа Энергетических Ресурсов,
Главная лаборатория эволюции морских резервуаров и механизма распространения углеводородов,
Министерство образования,
Главная лаборатория по разведке и оценке запасов сланцевого газа, Министерство земли и ресурсов,
Китайский университет геологических наук,
г. Пекин, Китай.

Kai Jiu,

Beijing Jingneng Petroleum Corporation Limited,
Beijing, China.

Цзю Кай,

Пекинская нефтепромысловая корпорация Цзиннэн,
г. Пекин, Китай.

Zhe Wang,

Shandong Kerui Group Holding Corporation Limited,
Dongying, China.

Ван Чжэ,

Шаньдун Кэжуй Групп Холдинг Лимитед,
г. Дуньин, Китай.

Yaxiong Sun,

School of Energy Resources,
Key Laboratory for Marine Reservoir Evolution and Hydrocarbon Abundance Mechanism, Ministry of Education,
Key Laboratory for Shale Gas Exploration and Assessment, Ministry of Land and Resources,
China University of Geosciences,
Beijing, China.



Сунь Ясюн,

Школа Энергетических Ресурсов,
Главная лаборатория эволюции морских резервуаров и механизма распространения углеводородов,
Министерство образования,
Главная лаборатория по разведке и оценке запасов сланцевого газа, Министерство земли и ресурсов,
Китайский университет геологических наук,
г. Пекин, Китай.

Xinghua Wang,

School of Energy Resources,
Key Laboratory for Marine Reservoir Evolution and Hydrocarbon Abundance Mechanism, Ministry of Education,
Key Laboratory for Shale Gas Exploration and Assessment, Ministry of Land and Resources,
China University of Geosciences,
Beijing, China.

Ван Синхуа,

Школа Энергетических Ресурсов,
Главная лаборатория эволюции морских резервуаров и механизма распространения углеводородов,
Министерство образования,
Главная лаборатория по разведке и оценке запасов сланцевого газа, Министерство земли и ресурсов,
Китайский университет геологических наук,
г. Пекин, Китай.

Contribution of the authors / Вклад авторов

The authors contributed equally to this article.

Все авторы сделали эквивалентный вклад в подготовку публикации.

Conflict of interests / Конфликт интересов

The authors declare no conflicts of interests.

Авторы заявляют об отсутствии конфликта интересов.

The final manuscript has been read and approved by all the co-authors.

Все авторы прочитали и одобрили окончательный вариант рукописи.

Information about the article / Информация о статье

The article was submitted 03.09.2021; approved after reviewing 06.10.2021; accepted for publication 12.11.2021.

Статья поступила в редакцию 03.09.2021; одобрена после рецензирования 06.10.2021; принята к публикации 12.11.2021.