Experimental analysis and deliverability calculation of abnormally pressured carbonate gas reservoir considering stress sensitivity

Youyou Cheng1,2, Chunqiu Guo3, Chengqian Tan1, Pengyu Chen3, Haidong Shi3, Yuzhong Xing3

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Abstract
The stress sensitivity of abnormally pressured carbonate gas reservoirs is of great complexity and exerts much influence on gas well deliverability calculation. Fifty core samples from the AD Gas Reservoirs were selected in the experiment to study the effect of abnormally high pressure and fracture on the stress sensitivity of carbonate gas reservoir. The results show that the permeability decline mainly occurs in the abnormally high-pressure stage and is rather small in normal pressure stage. The existence of the fracture could substantially enhance the stress sensitivity. The higher fracture density could induce the stronger stress sensitivity. Furthermore, a mathematical model with the consideration of the variable permeability modulus was established to calculate gas well deliverability in the abnormally pressured carbonate gas reservoir with developed natural fractures. It is revealed that previous method assuming a fixed permeability modulus would lead to an overestimation of the real stress sensitivity and thus underestimating the absolute open flow of the gas well.

Keywords Carbonate gas reservoir · Abnormally high pressure · Fracture · Stress sensitivity · Gas well deliverability

Introduction
As one of the most important gas reservoir types, carbonate gas reservoirs contribute about 45% of the world’s total recoverable gas reserve (Jia et al. 2014; Sun et al. 2016). Most of the carbonate reservoirs discovered in the world are widely developed with a large number of fractures and vugs, which is vital to improve the permeability of gas reservoir. For carbonate gas reservoirs with great burial depths, the compaction from overburden pressure can lead to abnormally high-pressure effect. Due to the significant change of rock and fluids physical property with burial depths, the formation compressibility and flow mechanism of those reservoirs will show intrinsic differences from the normal pressure ones (Chu et al. 1996; Macini et al. 2006; Wu et al. 2014).

During gas field development, the deformation of fractures and vugs caused by formation pressure decrease will drastically reduce the flow capacity in abnormally pressured reservoirs, which is called the stress sensitivity (Gangi 1978). Because the fracture closure in this process is basically irreversible, the stress sensitivity in the carbonate gas reservoir usually leads to a distinct reduction of the permeability. In view of the fact that pressure decline is the main inducement of permeability damage, the stress sensitivity effect can be undoubtedly far more significant and intricate for abnormally pressured gas reservoirs.

The stress sensitivity has been focused on by many researchers for a long time. The permeability and porosity of cores under various confining pressure were tested in the laboratory to characterize the gas reservoir stress sensitivities (Jiang et al. 2000; Davies et al. 2001; Dwi et al. 2007). Yang et al. (2009) tested the stress sensitivity index of carbonate rock under the variable confining pressure and brought the permeability damage rate to evaluate the stress damage. Zhang et al. (2021) launched a pressure depletion simulation experiment to investigate the gas expansion and pore compression effect in high-pressure reservoirs. Currently, there are two different ways, i.e., the
introduced it into the gas well deliverability calculation; an exponential form permeability modulus equation and the relaxation calculation of fractured gas reservoirs. Liu et al. (2016) concluded the pseudo-pressure to further fit the deliverability determination. Ren et al. (2013) introduced the stepwise permeability into the gas well deliverability calculation of fractured gas reservoirs with abnormally high pressure, two essential issues are: (a) how to simulate the stress change under the condition of in situ temperature and pressure; (b) how to obtain more representative fractured cores, so as to accurately evaluate the influence of fractures on permeability damage.

To judge the degree of stress sensitivity, different forms of evaluation indices were introduced, among which the stress sensitivity coefficient, permeability damage rate, and the permeability modulus has received wide approval (Ruistuen et al. 1996; Guo et al. 2010; Zhu 2013). Lan et al. (2005) provided a detailed description and comparison of those indices and suggested that the stress sensitivity coefficient and the permeability damage rate would be more suitable to characterize the degree of stress sensitivity in laboratory. The permeability modulus was more capable when concerned with the gas well deliverability calculation. Nature fractures are considered as the main contributor to the stress sensitivity in the carbonate reservoir in view of its great potential of aperture variation (Duan et al. 1998; Wang et al. 2010; Gland 2010). Zhang et al. (1994) developed a stepwise mode to depict the change of the permeability modulus with respect to stress for cores with fractures. Although some researches have realized that permeability modulus would not stay constant with fractured cores (Pan et al. 2011; Qiao 2012), yet few provide the calculation method to deal with it.

One of the essential issues concerned with the stress sensitive gas reservoir is its impact on gas well production. Ostensen (1986) adopted a modified pseudo-pressure with the consideration of stress sensitivity to facilitate the calculation of the gas well deliverability of stress sensitive reservoirs. Oladoyin et al. (2018) estimated the overburden stress and elastic properties of the reservoir rock with reference to the burial depth and discussed their influence on well production behavior. Chu et al. (1996) and Zhang et al. (2021) reported that the compressibility of abnormal pressure gas reservoirs is far more complex to determine and would put great effect on gas reserves and production. Ren et al. (2013) introduced the stepwise permeability into the pseudo-pressure to further fit the deliverability determination of fractured gas reservoirs. Liu et al. (2016) concluded an exponential form permeability modulus equation and introduced it into the gas well deliverability calculation; however, fractures were not considered into the permeability modulus equation.

It might be legitimate to hypothesize that the complexity of the stress sensitivity of fractured gas reservoir would be escalated with the combination of the effect of abnormally high pressure. However, few reports on this issue were exposed, especially on the fracture stress sensitivity measuring under the in situ reservoir condition, and the gas productivity calculation considering changeable permeability modulus. The fracture permeability damage occurs principally in the early stage, so it is essential to conduct the measurement under in situ condition to avoid stress relief. Meanwhile, for abnormally pressured reservoir with fractures, a permeability modulus applicable for stress sensitivity characterization and well deliverability calculation is still lack.

This study is focused on the stress sensitivity effect and its influence on gas well deliverability in abnormally pressured carbonate reservoir with natural fractures. In this article, a series of stress sensitivity experiment was conducted to investigate the in situ permeability variation of carbonate gas reservoirs. Then, the effects of abnormally high pressure and fracture on permeability sensitivity were studied in detail. Finally, a novel gas well deliverability calculation equation considering variational permeability modulus was established, and the influence of permeability sensitivity on gas productivity was discussed.

**Stress sensitivity measurement and evaluation**

Gas reservoir stress sensitivity is determined in the laboratory by measuring the corresponding permeability under a series of confining pressure; the data from the experiment are then analyzed according to relevant evaluation indices to assess the degree of stress sensitivity.

**Core samples**

The experimental cores were collected from the AD Gas Reservoir, Turkmenistan. The initial formation pressure of the gas reservoir is 56.9 – 63.6 MPa, while its buried depths averagely vary from 3400 to 3900 m, which indicates that it is an abnormally pressured gas reservoir. The sedimentary facies are marine carbonate rocks with strong heterogeneity, where fractures are widely developed. Therefore, the main flow media are fractures and pores.

Fifty core samples are involved in the experiment, whose lithology is mainly light brownish gray–gray fine crystalline bioclastic limestones. The physical property of the cores can be characterized as low porosity and low permeability. The porosity is 1.43% – 11.27% in general and 5.13% in average, and permeability 0.14nD – 18.92mD in general and...
0.77mD in average. Fracture density, which can be defined as the fracture numbers per unit length within the core, is introduced to measure the degree of fracture development. Twenty-one out of the total 50 cores show the existence of fractures, whose density varied from 0.91 to 15.42 m⁻¹, and most of which are with a width of < 1 mm (as shown in Fig. 1). The physical properties of core samples with different fracture developing extent are shown in Fig. 2.

**Experimental procedures**

In order to simulate the permeability variation characteristics under in situ temperature and effective stress in abnormally high-pressure gas reservoir, the whole experimental process was carried out in a thermotank; confining pressure was applied to the core to simulate the overlying rock pressure, and nitrogen was driven into the core by injection pump to simulate the formation pressure variation. The formation pressure gradually decreases with the gas reservoir development, while the overlying rock pressure basically remains unchanged. To simulate this pressure changing process during the experiment, we set a constant confining pressure and change the internal pressure of the core to obtain a varying net stress.

The experiment was conducted with the high-temperature and high-pressure core flooding device STL-II, whose maximum working pressure is 200 MPa. The experimental apparatus mainly includes injection pump system, core holder, back pressure regulator, pressure gauge and temperature control system (as shown in Fig. 3). The internal pressure of the core is controlled by back pressure regulator. All the test procedures abide by the industrial standard "Experimental Evaluation Method of Reservoir Sensitivity (SY/T 5358-2002)" and "Core Analysis Method (SY/T 5336-2006)".

The experimental process is as follows:

(a) Setting the confining pressure and the temperature of the thermotank to 124 MPa and 116 °C, respectively; saturating the core with nitrogen until the initial internal pressure of the core reaches 65 MPa.

(b) Reducing the internal pressure gradually with the pressure interval of 5 MPa, measuring the inlet and outlet pressure and collect the inlet and outlet gas volume; recording the injection time and the injection volume of the injection pump, and calculating the air permeability of the core.

The experimental results are shown in Fig. 2.
let pressure and flow rate of at each pressure point to
calculate the core permeability; the minimum internal
pressure value is 10 MPa.
(c) Increasing the internal pressure with the pressure incre-
ment of 5 MPa, the permeability at each step is cal-
culated until the maximum internal pressure reaches
65 MPa.

After the flooding experiment, the core permeability
varying with the net core stress, defined as the confining
pressure minus the internal pressure, was then obtained.
In order to determine the irreversible damage of formation
pressure change to core permeability, 36 of 50 experimental
cores completed the test of internal pressure increase and
decrease process (as shown in Fig. 4a), while the other 14
cores only tested the process of internal pressure decrease
(as shown in Fig. 4b).

**Evaluation indices**

Currently, the stress sensitivity evaluation indices of
reservoir permeability mainly include stress sensitivity
coefficient, permeability damage rate, permeability modu-
lus, etc. If the sequence of pressure rise and fall is both
tested, the concept of “permeability recovery degree” can
be introduced to reflect the irreversible permeability dam-
age caused by the pressure history.

(1) Stress sensitivity coefficient: the definition of stress
sensitivity coefficient $S_s$ can be described with Eq. (1).
It is calculated through the regression of the series
of effective stress and the corresponding permeabil-
ity. This index can comprehensively characterize the
degree of stress sensitivity despite different rock lithol-
ogy (Lan et al. 2005).

\[
S_s = \frac{1 - \left( \frac{K}{K_0} \right)}{\lg \frac{\delta}{\delta_0}}^{1/3}
\]

where $S_s$ is the stress sensitivity coefficient of rocks,
dimensionless; $K$ is the current permeability of rocks,
mD; $K_0$ is the initial permeability of rocks, mD; $\delta$ is the
current effective stress, MPa; $\delta_0$ is the initial effective
stress, MPa; $\lg$ represents a base 10 logarithm.

**Fig. 3** Experimental procedure of high-temperature and high-
pressure core flooding system

**Fig. 4** Typical test results of two different experiment sequences
(2) Permeability damage rate: the permeability damage rate $D_k$ (Eq. (2)) reflects the degree of permeability damage caused by stress variation and is expressed generally in the form of percent. Because permeability variation is closely related to the applied stress, it is necessary to introduce the net permeability damage rate $D_{kn}$ to express the permeability damage degree at unit effective stress (Eq. (3)). This index describes the dynamic features of permeability sensitivity caused by the variation of stress (Li et al. 2014).

$$D_k = \frac{|K - K_0|}{K_0} \times 100\%$$  \hspace{1cm} (2)

$$D_{kn} = \frac{|K - K_0|/K_0}{|\delta - \delta_0|} \times 100\%$$  \hspace{1cm} (3)

(3) Permeability modulus: the permeability modulus $\lambda$ is defined as the permeability variation rate at unit pressure drop. The index is mostly used in well test interpretation and gas well deliverability calculation, so the stress is often converted into the form of formation pressure. The relationship between the permeability variation rate $K/K_0$ and the pressure drop $(p_0-p)$ are usually described in the exponential form as shown in Eq. (4) (Li et al. 2014).

$$\frac{K}{K_0} = e^{-\lambda(p_0-p)}$$  \hspace{1cm} (4)

where $\lambda$ is permeability modulus, dimensionless; $p_0$ is the initial formation pressure, MPa; $p$ is the current formation pressure, MPa.

(4) Permeability recovery degree: the permeability recovery degree $R_k$ denotes the percent of the permeability damage after stress rise (or drop) to a certain value and then recovery to the original stress to the original permeability, as shown in Eq. (5) (Ye et al. 2014). To better reflect the irreversible damage to permeability, the irreversible permeability damage rate, which can be directly attained by subtracting the permeability recovery degree $R_k$ from 100%, is sometimes used.

$$R_k = \frac{K_i}{K_i} \times 100\%$$  \hspace{1cm} (5)

where $R_k$ is permeability recovery degree, dimensionless; $K_i$ is the original permeability, mD; $K_i'$ is the permeability when recovery to the original stress, mD.

**Results and discussion**

**Initial permeability**

The existence of fractures can essentially alter the relationship between the stress sensitivity coefficient of cores and the initial permeability. For core samples without fractures, the stress sensitivity coefficient reduces with the increase in initial permeability (as shown in Fig. 5a); on the contrary, the stress sensitivity coefficient tends to be increasing with the increase of initial permeability for the samples with fractures (as shown in Fig. 5b). The explanation might lie in the difference of microstructures between the two types of cores. It is the matrix pores that contribute mainly to the permeability of the unfractured reservoirs, and therefore reservoirs with relative low permeability are more sensitive to the stress variation due to the easily deformed potential of micro pores and throats. However, the fracture would dominate the permeability when appears in the cores, so, with higher degree of fracture development, the more permeable cores show stronger stress sensitivity caused by the closure of the fractures.

![Fig. 5](image-url)  \hspace{1cm} The effect of initial permeability on stress sensitivity coefficient
**Abnormally high pressure**

Pressure coefficient, which can be acquired by dividing the formation pressure by the hydrostatic pressure at the same vertical depth, is commonly used to define the abnormally high-pressure degree. Reservoirs are defined as the abnormally pressured ones when their pressure coefficient is larger than 1.2, while the pressure coefficient of normal pressure reservoirs ranges from 0.8 to 1.2.

The relationship between the net permeability damage rates of 3 core samples, with different stress sensitivity degrees, and their pressure coefficients were studied. It can be observed from Fig. 6 that: (a) the net permeability damage rate is rather small in normal pressure stage compared with the abnormally high-pressure stage, revealing that the abnormally high-pressure effect may obviously intensify the stress sensitivity of gas reservoirs; (b) in the abnormal pressured stage, the net permeability damage rate increases sharply as the pressure coefficient increases, which implies that the permeability damage occurs mainly in the early periods of development for abnormally pressured reservoirs; (c) the stronger the stress sensitivity of reservoirs, the larger the net permeability damage rate, especially in the abnormally pressured stage. Therefore, the abnormally high pressure can exert great influence on the stress sensitivity.

**Fracture density**

The effect of fracture developing extent on the stress sensitivity can be clarified by analyzing the relationship of fracture density with stress sensitivity coefficient (as shown in Fig. 7) and permeability recovery degree (as shown in Fig. 8). It is shown in the figures that: (a) the stress sensitivity of the fractured cores is generally stronger than that of the unfractured ones by showing a larger stress sensitivity coefficient and lower permeability recovery degree. The average stress sensitivity coefficient and permeability recovery degree of the unfractured cores are 0.1455 and 78.44%, respectively, while they are 0.4083 and 28.80%, respectively, in the fractured cores. (b) The higher the fracture density, the stronger the stress sensitivity of reservoirs. There exists an obvious rise in the stress sensitivity coefficient and fall in permeability recovery degree with the increase in the fracture density in the figures.


\[ \psi(p) = \int_{p_m}^{p} \frac{\rho_g e^{-\lambda(p_0-p)}}{\mu_g} dp \]  

(8)

where \( p_m \) is the reference pressure, which is generally assigned the value of standard atmospheric pressure, MPa; \( \rho_g \) is the gas density at pressure \( p \), kg/m\(^3\); \( \mu_g \) is the gas viscosity at pressure \( p \), mPa·s.

**Permeability modulus**

It is vital to determine the permeability modulus for the gas well deliverability calculation of stress sensitive reservoirs. According to Eq. (4), the permeability modulus \( \lambda \) can be referred to as the slope of the correlation between \( \ln(K/K_0) \) and \( (p_0-p) \). However, for the abnormally pressured gas reservoirs, especially those with nature fractures, the regression using linear relation generally gives a poor performance. It implies that the permeability modulus \( \lambda \) would not stay a constant value here. Therefore, the variable \( \delta \) called the permeability modulus variation factor is developed in this article. It is defined as the variation of the permeability modulus under unit pressure change, as shown in Eq. (9).

\[ \delta = \frac{d\lambda}{dp} \]  

(9)

Integrating Eq. (9) with respect to \( p \) yields:

\[ \lambda = \lambda_0 - \delta(p_0-p) \]  

(10)

Substituting Eq. (10) into Eq. (4) yields:

\[ K = K_0 \cdot e^{[-\lambda(p_0-p)+\delta(p_0-p)^2]} \]  

(11)

\[ \ln \left( \frac{K}{K_0} \right) = -\lambda(p_0-p) + \delta(p_0-p)^2 \]  

(12)

With the consideration of the variation of permeability modulus, the relationship between \( \ln \left( \frac{K}{K_0} \right) \) and \( (p_0-p) \) becomes binomial, which was also supported by the regression results shown in Fig. 9. Yet, the core 1–16, whose fracture density is 0, showed a constant permeability modulus and observed a linear matching.

Further study of the relationship of permeability modulus \( \lambda \) and permeability modulus variation factor \( \delta \) with fracture developing extent can be conducted. Both parameters are showing a positive correlation with the fracture density (as shown in Fig. 10), reflecting that the more intensive the fractures, the stronger the stress sensitivity and the higher changing rate of it. Moreover, quantitative relations of permeability modulus and permeability
A modulus variation factor with fracture density can be established through the regressions obtained in Fig. 10. For reservoirs incapable to measure stress sensitivity, the approximate permeability modulus $\lambda$ and the permeability modulus variation factor $\delta$ could be directly determined with the relations shown in Eqs. (13) and (14).

$$
\lambda = 0.0006L_f^2 - 0.0012L_f + 0.0805 \quad (13)
$$

$$
\delta = 7.0 \times 10^{-6}L_f^2 - 2.0 \times 10^{-5}L_f + 0.0008 \quad (14)
$$

where $L_f$ is the fracture density, m$^{-1}$.

Example of field application

B-5 is a gas well in the AD Gas Filed. The basic parameters are: net pay thickness $h = 64.6$ m, average porosity $\phi = 9.2\%$, well radius $r_w = 1.106$ m, formation temperature $T = 388$ K, gas specific gravity $\gamma_g = 0.67$, initial permeability $K_0 = 53.44$ mD, and skin factor $S = 3.06$. The productivity test results are shown in Table 1. Fractures are extensively developed in the pay formation and the fracture density measured within the rock sample is 13.13 m$^{-1}$. In view of no stress sensitivity data available for this well, the permeability modulus $\lambda$ and the permeability modulus variation factor $\delta$ can be estimated using the relations above.
variation factor $\delta$ can be obtained to be 0.1682 and 0.0017, respectively, using Eqs. (13) and (14).

The deliverability of Well B-5 was calculated under three different assumptions: (a) assuming $\lambda=0$ (no stress sensitivity), the AOF calculated is $502.23 \times 10^4 \text{m}^3/\text{d}$; (b) assuming $\lambda=0.1682$ (constant permeability modulus), the AOF calculated is $423.85 \times 10^4 \text{m}^3/\text{d}$; (c) assuming $\lambda_0=0.1682$, $\delta=0.0017$ (variable permeability modulus), the AOF calculated is $442.99 \times 10^4 \text{m}^3/\text{d}$ (as shown in Fig. 11). It is unquestionable that stress sensitivity can exert a significant influence on gas well productivity, the AOFs with consideration of stress sensitivity are accounting for merely 84.4% (constant $\lambda$) and 88.2% (variable $\lambda$) of the AOF without sensitivity. In addition, the neglecting of permeability modulus variation factor would cause an underestimation of the AOF, the AOF shows a rise about 4.5%, compared to the constant stress sensitivity situation.

### Gas productivity results discussion

With pseudo-pressure defined in Eq. (8), the gas well deliverability calculation referring to abnormally high pressure and stress sensitivity could basically be settled. Nevertheless, fractures can fundamentally change the extent and behavior of the stress sensitivity. With the introduction of permeability modulus variation factor, a binomial relationship between $\ln(K/K_0)$ and $(p_0-p)$ was developed in this article. To extend this study, quantitative relations of permeability modulus and permeability modulus variation factor with fracture density were given. It provides an approach for fracture stress sensitivity assessment and facilitates the gas well deliverability calculation of the fractured reservoirs.

According to the gas well deliverability calculation results, the AOF increased when permeability modulus variation factor was brought in. The explanation might be that the stress sensitivity of the fracture system was mistaken as that of the whole reservoir when permeability modulus was considered as a constant. This would consequently lead to an overestimation of the real permeability sensitivity.

In addition, besides fracture density, there exist other important factors to affect the stress sensitivity of fractures, such as the fracture width and fracture length. Therefore, this study could be further extended for the characterization of the permeability modulus in fractured gas reservoirs.

### Conclusions

In this paper, stress sensitivity of abnormally high-pressure carbonate gas reservoir has been investigated via experimental approach. The stress sensitivity coefficient, permeability damage rate and permeability modulus of 50 cores have been measured in the high-temperature and high-pressure core flooding experiment. The effects of fracture and abnormally high pressure on the permeability damage are discussed. With the introduction of various permeability modulus into the pseudo-pressure formula, a novel gas well deliverability equation is established to gain a more accurate gas well deliverability calculation of the fractured reservoirs.

### Table 1 Productivity test results of Well B-5

| No. | Test time (h) | Chokes (mm) | $P_R$ (MPa) | $p_{wf}$ (MPa) | $q_{sc}$ ($10^4 \text{m}^3/\text{d}$) |
|-----|---------------|-------------|--------------|-----------------|----------------------------------|
| 1   | 8             | 9.5         | 47.579       | 46.131          | 683.609.21                       |
| 2   | 8             | 11.1        | 45.839       | 784.880.43      |                                  |
| 3   | 8             | 12.7        | 45.468       | 885.361.79      |                                  |
| 4   | 8             | 14.3        | 44.929       | 1,047.550.46    |                                  |
AOF for abnormally high-pressure carbonate gas reservoirs. Based on these studies, the following conclusions can be drawn as follows:

(1) The stress sensitivity coefficient reduces with the increase in initial permeability in the cores without fractures, while it tends to be increasing with the increase of initial permeability for the samples with fractures.

(2) The abnormally high pressure can exert great influence on the stress sensitivity. The net permeability damage rate increases sharply as the pressure coefficient increases in the abnormal pressured stage, while in the normal pressure stage it is weakened distinctly.

(3) The existence of the fracture could substantially enhance the stress sensitivity. Cores with fractures show not only a larger stress sensitivity coefficient but also a lower permeability recovery degree. With the existence of fracture, the permeability modulus turns to be a variable and can be described as the function of the permeability modulus variation factor.

(4) The regression relations of permeability modulus and permeability modulus variation factor with fracture density are given and thus facilitate the gas well deliverability calculation of the fractured reservoirs. The variation of the permeability modulus should be considered in the calculation of gas well deliverability in the abnormally pressured reservoir with the development of natural fractures; otherwise, the AOF of the gas well would be underestimated.

Authors contribution Corresponding author is TL, and the all authors name order is YC, CG, CT, PC, HS, and YX. YC and PC were involved in writing—original draft. CG, HS, and YX were involved in Experiments. CT was involved in investigation.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

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References

Chu WC, Kazemi H, Buettner RE, Stouffer TL (1996) Gas reservoir performance in abnormally high pressure carbonates. In: Gas technology conference. Calgary, Alberta, Canada, pp 1–5

Davies JP, Davies DK (2001) Stress-dependent permeability: characterization and modeling. SPE J 6(02):224–235

Duan YT, Meng YF, Luo PY, Su W (1998) Stress sensitivity of naturally fractured- porous reservoir with dual-porosity. In: SPE international conference and exhibition, Beijing, China, pp 1–5

Dwi H, Sandra N, David C (2007) The effect of pressure depletion on geomechanical stress and fracture behavior in Gunung Kembang field. In: Indonesian petroleum association

Gangi AF (1978) Variation of whole and fractured porous rock permeability with confining pressure. In: International Journal of rock mechanics and mining science & geomechanics abstracts, 15

Gland N, Dautriot J, Dimanov A, Raphanel J (2010) Stress path dependent hydromechanical behavior of heterogeneous carbonate rock. EPJ web of conferences, 6

Guo P, Zhang J, Du JF XuYG, Wu GS (2007) Study on core stress sensitivity for gas reservoir with two experimental methods. J Southwest Pet Univ 29:7–9

Guo JJ, Zhang LH, Tu Z (2010) Stress sensitivity and its influence on productivity in gas reservoirs with abnormally high pressure. Spec Oil Gas Reserv 17:79–81

Jia AL, Yan HJ, Guo JL, He D, Wei T (2014) Characteristics and experiences of the development of various giant gas fields all over the world. Nat Gas Ind 34(10):33–46

Jiang HJ, Yan JN, Li R (2000) Experimental study on fractured reservoir stress-sensitivity. Pet Drill Technol 28:32–33

Lan L, Kang YL, Chen YJ, Yang J, Chen JM (2005) Discussion on evaluation methods for stress sensitivities of low permeability and tight sandstone reservoirs. Drill Fluid Complet Fluid 22:1–4

Li DQ, Kang YL, You LJ (2014) Experimental study on permeability stress sensitivity of carbonate rocks. Nat Gas Geosci 25:409–413

Liu X, Shen R, Zhang H (2016) The new analysis method of permeability stress-sensitivity and simulation. In: IADC/SPE Asia Pacific drilling technology conference. Singapore, pp 22–24

Macini P, Ezio M, Salomoni VA, Schreffer BA (2006) Casing influence while measuring in situ reservoir compaction. J Pet Sci Eng 50:40–54

Oladoyin K, Kovács F, István S (2018) Formation susceptibility to wellbore instability and sand production in the Pannonian Basin, Hungary. In: The 52nd US rock mechanics/geomechanics symposium, Seattle, Washington, USA, pp 17–20

Ostensen R (1986) The effect of stress-independent permeability on gas production and well testing. SPE Form Eval 6:227–235

Pan WY, Lun ZM, Wang WH, Hua L (2011) Experimental study on stress sensitivity of abnormally high pressure gas reservoir. Pet Geol Exp 33:211–214

Peng XD, Lu Y, Liu X, Duan C, Li Z, Liu S, Tong L (2015) Rock stress sensitivity and its influence on productivity of overpressured gas
reservoir: a case study in Yinggehai Basin, China. Int J Oil Gas Coal Eng 3:33–40
Qiao LP (2012) Determination of Biot’s effective stress coefficient for permeability of Nikanassin Sandstone. J Can Pet Technol 51:193–197
Ren JJ, Guo P, Wang SP, Bo B, Wang Z, Zhao Z (2013) A new method for calculating the productivity of abnormally high-pressure gas reservoirs considering variable permeability modulus. Nat Gas Ind 33:52–56
Ruistuen H, Teufel LW, Rhett D (1996) Influence of reservoir stress path on deformation and permeability of weakly cemented sandstone reservoirs. In: SPE annual technical conference & exhibition. Denver, USA
Sun YP, Lu JL, Liu H, Wan Y, Tang H, Zhang J (2016) Study on the development laws of large-scale carbonate gas reservoirs at home and abroad. Nat Gas Explor Dev 40:59–64
Wang JZ, Yao J, Zhang K, Hao ZJ (2010) Variable permeability modulus and pressure sensitivity of dual-porosity medium. J China Univ Pet 34:80–83
Wu K, Li X, Yang P, Zhang S (2014) The establishment of a novel deliverability equation of abnormal pressure gas reservoirs considering a variable threshold pressure drop. Petrol Sci Technol 32:15–21
Yang Z, Sun JS, Zhang J, Zhang X, Wang C (2009) Experimental study on stress sensitivity of fractured carbonate reservoirs. Drill Fluid Complet Fluid 26:5–9
Ye T (2014) Experimental study on stress sensitivity of naturally fractured reservoirs. In: SPE annual technical conference and exhibition. Amsterdam, the Netherlands, pp 27–29
Zhang MY, Ambastha AK (1994) New insights in pressure-transient analysis for stress-sensitive reservoirs. In: SPE annual technical conference and exhibition. New Orleans, LA, USA
Zhang JZ, Gao TR (2021) Compressibility of abnormal pressure gas reservoirs and its effect on reserves. ACS Omega 6:26221–26230
Zhu SY (2013) Experiment research of tight sandstone gas reservoir stress sensitivity based on the capillary bundle mode. In: SPE annual technical conference and exhibition. New Orleans, Louisiana, USA, pp 1–11

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