Investigation of Water-Sensitivity Damage for Tight Low-Permeability Sandstone Reservoirs

Lufeng Zhang, Fujian Zhou, Shicheng Zhang, Yuechun Wang, Jie Wang, and Jin Wang

State Key Laboratory of Petroleum Resources and Prospecting and The Unconventional Natural Gas Institute, China University of Petroleum, Beijing 102249, China

ABSTRACT: Tight sandstone reservoir has been characterized by low permeability and porosity, developed micro-nanopore throats, strong capillary forces, and high content of clay minerals. It is vulnerable to damage caused by water sensitivity during the processes of reservoir development, which significantly impedes the hydrocarbon production. Hence, it is important to analyze the damage mechanism of water sensitivity to avoid the production decrease. However, the conventional steady-state method is time-consuming and inaccurate for evaluating the water-sensitivity damage in tight low-permeability reservoirs. Aiming at this problem, this paper introduced pressure transmission test (PTT), a time-saving and accurate method, to quantitatively evaluate the degree of damage by water sensitivity. Moreover, lithofacies analysis methods, consisting of computed tomography (CT) scanning, scanning electron microscopy (SEM), and X-ray diffraction (XRD), are also used to evaluate the reservoir properties, which can provide a basis for analyzing the potential damage factors. The CT scanning results show that the developed micropore throat in the target reservoir has poor connectivity. The XRD results indicate that the target reservoir mainly consists of a mixed-layer illite/smectite and smectite, which is consistent with the observation by SEM experiments. The results of PTT show that the ultimate average damage rate of water sensitivity is approximately 62.94%, attributed to the medium-strong water sensitivity. Compared with the conventional steady-state method measuring the outlet flow of the core, this method can reduce the experimental errors merely by recording the pressure data varying with time. Moreover, it is also applicable for evaluating other types of formation sensitivity damage, such as alkali and acid sensitivity damage for low-permeability reservoirs.

1. INTRODUCTION

With the characteristics of low permeability, low porosity, and strong capillary force, tight sandstone reservoirs are vulnerable to water-sensitivity damage caused by the invasion of extraneous fluids during the process of reservoir development. The contact of extraneous fluids with the formation may cause hydration, expansion, dispersion, and migration of clay minerals, resulting in the decrease of formation permeability. Investigation of water-sensitivity damage can be traced back to the 1940s, when Johnston and Beeson (1945) performed water-sensitivity damage experiments on 1200 core samples and illustrated permeability impairment of clay-bearing reservoirs by injecting low-salinity water. Since then, it has gone through three stages of defining migration and dispersion mechanisms, theoretical analysis, and controlling technology research. According to previous studies, water-sensitive damage can be classified into three categories. In the first one, the phenomenon of smectite hydration and expansion will occur when smectite contacts with external water, leading to the decrease of pore radius and permeability. In the second, the migration of kaolinite and hairlike illite will induce the blockage of pores and throat. In the third, chlorite is prone to become a colloidal precipitate after acidification.

At present, the evaluation of formation-sensitivity damage in tight low-permeability reservoirs is mainly based on the core flow experiment. The formation sensitivity is reflected by measuring the change of core permeability before and after the displacement of the working fluid, and the sensitivity index (the ratio of permeability variation to initial value of the permeability) is used to evaluate the sensitivity. After extensive research, a large number of scholars conducted studies on the formation sensitivity based on conventional core flow experiments. To study the effects of water-sensitive damage on the seepage characteristics of microscopic water flooding, Zhu et al. used the sandstone model made by the reservoir core to carry out three types of water flooding experiments in single, double, and combined models. Liu studied the rules of water-sensitivity damage of carbonate rocks. Han and Liao studied the mechanism of water sensitivity by analyzing the reservoir rock composition, physical properties, and pore structure. Zhu introduced nuclear magnetic resonance technology to analyze the rate of damage of water sensitivity in sandstone reservoir. Leng et al. combined core flow experiments with core computed tomography (CT) scanning techniques to carry out the quantitative evaluation of the water-sensitivity damage.

In summary, due to the high core permeability of conventional oil and gas reservoirs, it is feasible to analyze the reservoir water-sensitivity damage through the traditional steady-state...
method; however, for the tight low-permeability reservoirs (shale, tight sandstone, bedrock, etc.), the steady-state core flow method is not applicable as it is time-consuming and inefficient.

In response, unsteady-state methods, including pressure attenuation method, pressure transmission method, and periodic oscillation method, are usually applied in measuring the core permeability of a tight low-permeability reservoir. Pressure attenuation method proposed by You and Kang et al. was used to evaluate the formation-sensitivity damage of in Daniudi Gas Field.19,20 However, this method takes a long time to complete, making it vulnerable to external environmental impact. Periodic oscillation method was first proposed by Kranz et al. who referred to the measurement of thermal diffusivity and measured the permeability of low-permeability rocks.21 Fischer et al. further elaborated the theoretical background, experimental design, and data processing of the periodic oscillation method.22 Unfortunately, this method requires a high performance from the instrument and has a high cost. Therefore, this paper introduced the pressure characteristics of transmission test of saving time and cost-effectiveness to measure the core permeability. This method was first proposed by Brace et al. in 1968 and the semianalytical solution of the method is also given.23 But it is assumed that the rock porosity is zero, which is quite different from the actual core. Lin adopted a numerical method to analyze the model proposed by Brace and proposed to replace the semianalytical solution of Brace with the numerical solution; however, the calculation time of the numerical solution was too long for convenience.24 Hsieh et al. gave an analytical solution to the Brace model, which is a breakthrough in this method.25 Dicker et al. proposed a general solution to the method based on Hsieh’s results and Brace’s model; this method is widely applied in the petroleum industry.26

In this paper, based on the previous research studies on pressure transmission method, an analytical model was derived to calculate the core permeability. Furthermore, considering the low permeability of the target reservoir, microscopic lithofacies analysis and macroscopic pressure transmission experiments were performed to investigate the water-sensitivity damage.

2. RESULTS AND DISCUSSION

2.1. Analysis of Potential Damage Factors. The characteristics of the pore microstructure of the reservoir are one of the intrinsic causes of formation-sensitivity damage. Understanding the pore microstructure can help analyze the potential damage factors of the reservoirs. In this study, a multislice spiral CT scanner was applied to investigate the spatial distribution of pores in the whole core. The CT scan date was processed by MATLAB, and the three-dimensional visualization of the core can be obtained through the commercial software Tecplot. It can be seen from Figure 1 that the three cores have only a few pores. Furthermore, since the CT scan is shown as slices along the axial direction of the core, the average porosity of each slice can be analyzed to quantitatively describe the porosity distribution of the core. Figure 2 shows the distribution of the average porosity along the axial direction (from left to right are cores of 7, 14, and 20).

Figure 1. Core images of CT scan (from left to right are cores of 7, 14, and 20).

Figure 2. Distribution of average porosity along the axial direction (from left to right are cores of 7, 14, and 20).
SEM) and X-ray diffraction (XRD) experiments were performed on the fragments of target core samples. The SEM in Figure 3 shows that the main constituents of clay minerals in the target reservoir are mixed-layer illite/smectite, which is mainly distributed in or near the center of the pore throats and increases the structural complexity of the pore throats. In addition, intergranular pores and intragranular pores are developed in the core, and the connectivity of the pore throat is poor.

According to the principle of Stokes settlement experiment, the clay minerals with particle size less than 4 μm in the core powder were extracted by sedimentation. The total amount of clay minerals and the relative contents of various clay minerals were obtained by X-ray diffraction analysis. As can be seen from Table 1, the target reservoir has a high content of clay mineral of up to 38.9%. It mainly consists of a mixed-layer illite/smectite and smectite, which is consistent with the observation by the SEM experiments. Therefore, when clay minerals are exposed to...
extraneous fluids, on the one hand, the swelling of the clay minerals leads to an increase of irreducible water. On the other hand, the expanding clay minerals plug the pores and greatly decrease the radius of the pores, causing serious damage to the reservoirs.

2.2. Analysis of Water-Sensitivity Damage. As can be seen from Figure 4, the applied upstream pressure remains stable and the corresponding downstream pressure increases from the initial pressure with time until it reaches a peak and remains steady during water-sensitivity damage experiments. In addition, it takes very long for the pressure downstream to reach an equilibrium when the salinity of the experimental fluids decreases. Especially, the stable time of deionized water is approximately twice that of the mimicked formation water. This indicates that the core samples suffer serious water-sensitivity damage, resulting in significant reduction of seepage capacity.

There is also an obvious phenomenon that the final stable downstream pressure is always slightly lower than the applied upstream pressure during the damage experiments. The internal reason is that the low-permeability rock behaves like a semipermeable membrane, resulting in an osmotic effect.27,28

According to the definition of dimensionless pressure, it can be concluded that the dimensionless pressure will keep steady when the downstream pressure reaches an equilibrium. Hence, this paper only focuses on the increasing stage of the downstream pressure. Figure 5 shows the dimensionless pressure versus time before and after every damage of two core samples. The slope ($\xi$) and fitting coefficient ($R^2$) were acquired by the linear fitting method. It can be seen that all fitting coefficients were above 0.97, which shows an excellent linear fitting. According to eq 15, the permeabilities of the core samples before and after every damage can be obtained.

As can be seen from Figure 6, with the reduction of the salinity of the working fluid, core permeability decreases and damage rate increases. Due to the invasion of water, the permeabilities of the core samples suffer significant reduction. The degree of ultimate water-sensitivity damage of the two core samples is $63.09$ and $62.79\%$, respectively, which fall into the category of medium-strong sensitivity. Therefore, to avoid the reduction of permeability as a result of the decrease of production, it is necessary to prevent the water-sensitivity damage during the development of reservoirs. Furthermore, different kinds of surfactants, which can alter the wettability of rock and reduce the interfacial tension, have been widely applied in the field to mitigate the water-sensitivity damage. Clay stabilizer, which can inhibit the expansion and migration of clay minerals, also has been used in the field application.

3. CONCLUSIONS

In this paper, microscopic lithofacies analysis and macroscopic pressure transmission were combined to study the water sensitivity of the formation damage for tight low-permeability reservoir. Based on the experimental results and theoretical analysis, the following conclusions are obtained:

1. The formation of target reservoir is tight, and its average permeability and porosity are $0.05$ md and $5\%$, respectively. The clay minerals of target reservoir mainly consist of mixed-layer illite/smectite.
2. The results of pressure transmission tests show that the ultimate average damage rate of water sensitivity is approximately $60\%$, which falls into the category of medium-strong sensitivity.
3. This method is also applicable to evaluate other types of formation-sensitivity damage, such as alkali and acid sensitivity damages of low-permeability reservoirs.

4. PRINCIPLE OF PRESSURE TRANSMISSION TEST

4.1. Permeability Model. Figure 7 shows the physical model of the pressure transmission instrument. Obviously, it is a one-dimensional saturated seepage model along the vertical direction. Therefore, a mathematical model, which describes the permeability of tight sandstone reservoirs, was established.27,28

In this model, the fluids flowed across the top of the core sample at a constant upstream pressure ($P_m$) while the downstream pressure of the reservoir beneath the core sample is initially
The coefficients $C_1$ and $C_2$ in eq 8 are determined from the boundary conditions. To solve the coefficients $C_1$ and $C_2$, the boundary conditions must be transformed into a Laplace form.

boundary conditions:

\[
\begin{cases}
    P(0, s) = \frac{P_m}{s} \\
    \frac{dP(L, s)}{dx} = -\frac{CV\mu}{kA} (sP - P_o)
\end{cases}
\]

Applying boundary condition 9 to eq 8 to get a simultaneous solution, the coefficients $C_1$ and $C_2$ can be obtained as follows

\[
\begin{align*}
    C_1 &= \frac{(P_m + P_o)\sqrt{s/\eta} e^{-\sqrt{s/\eta} L}}{\sqrt{s/\eta} e^{-\sqrt{s/\eta} L} + \sqrt{s/\eta} e^{\sqrt{s/\eta} L}} + \frac{CV\mu}{kA}s(sP - P_o) \\
    C_2 &= \frac{\sqrt{s/\eta} e^{\sqrt{s/\eta} L}(P_m + P_o) + CV\mu s(sP - P_o)}{\sqrt{s/\eta} e^{-\sqrt{s/\eta} L} + \sqrt{s/\eta} e^{\sqrt{s/\eta} L}}
\end{align*}
\]

\[
P(x, s) = \frac{(P_m + P_o)\sqrt{s/\eta} e^{-\sqrt{s/\eta} L} + \sqrt{s/\eta} e^{\sqrt{s/\eta} L}}{\sqrt{s/\eta} e^{-\sqrt{s/\eta} L} + \sqrt{s/\eta} e^{\sqrt{s/\eta} L}} e^{-\sqrt{s/\eta} L} + \frac{CV\mu}{kA}s(sP - P_o) \\
    e^{-\sqrt{s/\eta} L} - \frac{P_o}{s}
\]

For eq 11, refer to Carslaw et al. and Van Oort et al. (1994). 29,30

A solution to the equation that satisfies the boundary and initial conditions was found and can be expressed as follows

\[
\frac{P(x, t) - P_o}{(P_m - P_o)} = 1 - 2 \sum_{n=1}^{\infty} \exp(-\phi_n \eta L^2) \\
    \sin(x\phi_n L)/(\cos \phi_n \sin \phi_n + \phi_n)
\]

where the parameter $\phi_n$ are the roots of the following equation

\[
\phi_n \tan \phi_n = AL\phi/V
\]

The parameter $\phi_n$ is greatly dependent on the ratio of the pore volume of the rock sample and the volume of the downstream reservoir; when the above ratio is small, the equation can be simplified as follows

\[
\frac{P(L, t) - P_o}{(P_m - P_o)} = 1 - \exp(-Akt/\mu CV L)
\]

where $P(L, t)$ is the downstream pressure as a function of time, and its value is equal to the pressure of the rock sample at $x = L$ MPa; $L$ is the height of the rock sample, cm. $(P(L, t) - P_o)/(P_m - P_o)$ is defined as dimensionless pressure.

---

### Table 2. Information about Core Samples Used in This Study

| Sample Name | Dimensions (cm × cm × cm) | Permeability (md) | Porosity - Gas (%) | Experimental Types |
|-------------|---------------------------|-------------------|--------------------|-------------------|
| M1-1#       | 3.6 × 3.6 × 0.65          | 0.0479            | 4.2                | water sensitivity damage |
| M1-2#       | 3.6 × 3.6 × 0.65          | 0.0432            | 4.1                | water sensitivity damage |
| M1-1frag    | fragments                |                   |                    | SEM, XRD           |
| M1-2        |                          |                   |                    |                   |
| M1-7#       | 2.51 × 7.26              | 0.0686            | 2.3/3.0            | CT scan           |
| M1-14#      | 2.51 × 6.96              | 0.0481            | 4.9/5.7            |                   |
| M1-20#      | 2.51 × 6.77              | 0.0527            | 5.0/5.5            |                   |

The parameter $\phi_n$ is the permeability of the rock sample, md; $\eta$ is the viscosity of the working fluid, MPa s; $\phi$ is the porosity of the rock sample, dimensionless; $C$ is the compression coefficient of the working fluid, MPa$^{-1}$; $P_o$ is the initial downstream pressure, MPa; $P_m$ is the initial upstream pressure, MPa; $A$ is the cross-sectional area of the rock sample, cm$^2$; and $V$ is the volume of the downstream container, cm$^3$.  

4.2 Model Solving. Based on the given boundary conditions and initial conditions, the diffusion eq 1 was solved by the method of Laplace Transform.

First, transform the diffusion eq 1 to the Laplace space

\[
\frac{\partial^2 P}{\partial x^2} = \frac{sP}{\eta} = -\frac{P_o}{\eta}
\]

It is obvious that eq 7 is a second-order nonhomogeneous equation, so its general solution is

\[
P(x, s) = C_1 e^{\sqrt{s/\eta} L} + C_2 e^{-\sqrt{s/\eta} L} - \frac{P_o}{s}
\]
Taking the natural logarithm of eq 14, and the expression of permeability can be obtained

\[ k = -\frac{\xi CVL}{A} \]  

where \( \xi \) is the slope of the curve of dimensionless pressure with time.

5. MATERIALS AND SETUP

5.1. Core Preparation. The whole-diameter core samples in the experiments are from Tarim sandstone reservoir located in northwest China at the depth of 6000–6900 m. The formation temperature is above 140 \(^\circ\)C and the pressure gradient is 1.17 MPa/100 m. They were cut and polished to fit the special core holder for pressure transmission test, and the fragments collected by cutting process were used for XRD and SEM experiments. In addition, the core sample used in the CT scan experiments was drilled from the same whole diameter core samples. Table 2 lists the experiments performed on these core samples in this paper.

The preparation steps of the experimental core are as follows:

1. The whole diameter rock plug (18 cm in length and 6.25 cm in diameter) is exposed to the vapor of toluene for cleaning and then dried in an oven.
2. In the laboratory, the whole diameter rock sample is cut into a 3.6 cm \( \times \) 3.6 cm \( \times \) 10 cm square prism core with a wire cut machine.
3. The previously processed core column is put into a heat-resistant plastic tube (polycarbonate or acrylic) with an outer diameter of 6.35 cm, an inner diameter of 5.84 cm, and a length of 20.32 cm. The geometric center of the processed square prism core and the center of the heat-resistant plastic tube are overlapped and then the epoxy resin and the hardener is thoroughly mixed in a ratio of 1:1 and poured into a heat-resistant plastic tube.
4. Place the whole system on the horizontal platform and let it stand still for 24 h.
5. Put the whole system in an oven and bake at 110 \(^\circ\)C for 1 h to ensure that the processed square prism core is glued together with the epoxy resin.
6. Slice the encapsulated core into some disks with a thickness of 0.65 cm as shown in Figure 8.

5.2. Experimental Fluids Preparation. In this paper, the mimicked formation brine is prepared as the basic fluid to measure the initial permeability of the core sample. It contains 2 wt % potassium chloride, 5.5 wt % sodium chloride, 0.45 wt % magnesium chloride, and 0.55 wt % calcium chloride. Its density, viscosity, and salinity are 1.06 g/cm\(^3\), 1.08 MPa·s, and 80 000 mg/L, respectively. The mimicked formation brine diluted to 75, 50, and 25% by deionized water was used in water-sensitivity damage test.

5.3. Pressure Transmission Test Setup. The pressure transmission test setup used in this experiment is shown in Figure 9. It is mainly composed of two ISCO high pressure, a vacuum pump, four intermediate containers, a special core holder, a nitrogen bottle, incubator, and data acquisition system. A test fluid flowed across the top of the epoxy-encapsulated core sample at a constant upstream pressure. In a small sealed chamber beneath the core sample, on the downstream side, the
fluid pressure build-up was recorded. The cell, containers, and all-important fluid lines were placed in an incubator.

### 5.4. Experimental Procedure
The simulation process of water-sensitivity damage evaluation are as follows:

1. connect the instruments, load the working fluid into the intermediate container, put the core sample saturated with the mimicked formation water in a special core holder, and vacuum the upstream and downstream of core holder simultaneously for 60 min;
2. inject formation water to the downstream of the rock sample at a set pressure (0.1 MPa) and record the downstream initial pressure as $P_o$ after the downstream pressure is stabilized;
3. stabilize the downstream pressure and inject the formation water upstream with a flow pressure of $P_w = 0.48$ MPa; maintain the flow at a flow pressure of $P_{w0}$;
4. monitor the downstream pressure $P_{d0}$ changes with time;
5. drawn the semilog plot between dimensionless pressure and time, and then find the slope $\xi$ of the curve and calculate the initial permeability $k_i$ with eq 15;
6. repeat the above experimental steps, and sequentially damage the core with the mimicked formation brine diluted to 75, 50, and 25% and deionized water;
7. based on similar method, the permeabilities ($k_i$) after different working fluids damage are calculated by eq 15;
8. according to the evaluation criteria of water-sensitivity damage in China petroleum industry standard, the water- sensitivity damage index was defined by the following equation

$$\lambda_d = (k_0 - k_{\text{min}})/k_0 \times 100\%$$

### REFERENCES

(1) Yang, S.; Wei, J. Fundamentals of Petrophysics, 2nd ed.; Springer: Berlin, 2017, pp 239–295.

(2) Civan, F. Reservoir Formation Damage, 3rd ed.; Gulf Professional Publishing: Waltham, 2015, pp 1–25.

(3) Liang, T.; Gu, F.; Yao, E.; Zhang, L.; Yang, K.; Liu, G.; Zhou, F. Formation damage due to drilling and fracturing fluids and its solution for tight naturally fractured sandstone reservoirs. *Geoﬂuids* 2017, 2017, 1–9.

(4) Lufeng, Z.; Fujian, Z.; Shicheng, Z.; zhun, L.; Jin, W.; Yuechun, W. Evaluation of permeability damage caused by drilling and fracturing fluids in tight low permeability sandstone reservoirs. *J. Pet. Sci. Eng.* 2019, 175, 1122–1135.

(5) Zhang, L.; Zhou, F.; Mou, J.; Xu, G.; Zhang, S.; Li, Z. A new method to improve long-term fracture conductivity in acid fracturing under high closure stress. *J. Pet. Sci. Eng.* 2018, 171, 760–770.

(6) Johnston, N.; Beeson, C. M. Water permeability of reservoir sands. *Trans. AIME* 1945, 160, 43–55.

(7) Zhang, L.; Zhou, F.; Pournik, M.; Liang, T.; Wang, J.; Wang, Y. An integrated method to evaluate formation damage due to water and alkali sensitivity in Dongping bedrock reservoir. *SPE Reservoir Eval. Eng.*, SPE-197058-PA, accepted.

(8) Kleijn, W. B.; Oster, J. D. A model of clay swelling and tectoid formation. *Clays Clay Miner.* 1982, 30, 383–390.

(9) Mohan, K. K.; Fogler, H. S. Colloiddally induced smectitic fines migration: existence of microquakes. *AIChE J.* 1997, 43, 565–576.

(10) Zhang, L.; Zhou, F.; Wang, J.; Mou, J.; Zhang, S. An Experimental Investigation of Long-Term Acid Propped Fracturing Conductivity in Deep Carbonate Reservoirs. 52nd US Rock Mechanics/Geomechanics Symposium, 2018.

(11) Tolmacheva, K. I.; Boronin, S. A.; Osiptsov, A. A. Formation damage and cleanup in the vicinity of flooding wells: Multi-fluid suspension flow model and calibration on lab data. *J. Pet. Sci. Eng.* 2019, 178, 408–418.

(12) Ghasemian, J.; Riahi, S.; Ayatollahi, S.; Mokhtari, R. Effect of salinity and ion type on formation damage due to inorganic scale deposition and introducing optimum salinity. *J. Pet. Sci. Eng.* 2019, 177, 270–281.

(13) Zhu, Y.; Li, Q.; Wang, X. Study on formation damage during water injection development for Yan 10 formation of Maling Oilfield North Third District. *Oil Gas Geol.* 2006, 27, 263–268.

(14) Liu, D.; Kang, Y.; He, J.; Lei, M.; Shu, Z. Laboratory investigation of water sensitivity of carbonate reservoirs and discussion of its mechanism. *Nat. Gas Ind.* 2007, 27, 32–34.

(15) Han, D.; Dong, P.; Shi, N. Reservoir water sensitivity experiment and its formation mechanism. *Pet. Geol. Oilﬁeld Dev. Daqing* 2008, 27, 14–17.

(16) Liao, J.; Tang, H.; Zhu, X.; Li, G.; Zhao, F.; Lin, D. Experimental study on water sensitivity and damage mechanism of ultra-low permeability sandstone reservoirs - A case study of Xifeng Oilfield Yanchang 8 formation in Ordos Basin. *Oil Gas Geol.* 2012, 36, 27–33.

(17) Zhu, Q. Study on water sensitive damage of tight sandstone reservoirs by nuclear magnetic resonance. *Petrochem. Ind. Appl.* 2014, 33, 25–27.

(18) Leng, Z.; Ma, D.; Lv, W.; Liu, Q.; Jia, N. Application of CT scanning technique in water damage assessment. *Spec. Oil Gas Reservoirs* 2015, 22, 100–103.

(19) You, L.; Kang, Y.; Du, X. A Method for Determining Damage of Dense Core. China Patent CN200910058286, 2012.

(20) Kang, Y.; Zhang, X.; You, L.; Du, X. A new method to evaluate fluid sensitivity of tight reservoir: pressure decay analysis. *Drill. Fluid Completion Fluid* 2013, 30, 81–84.

(21) Kranz, R. L.; Saltzman, J. S.; Blacic, J. D. Hydraulic diffusivity measurements on laboratory rock samples using an oscillating pore pressure method. *Int. J. Rock. Mech. Min. Sci. Geomech. Abstr.* 1990, 27, 345–352.

(22) Fischer, G. J. The determination of permeability and storage capacity: Pore pressure oscillation method. *Int. Geophys.* 1992, 51, 187–211.

(23) Brace, W.; Walsh, J. B.; Frangos, W. T. Permeability of granite under high pressure. *J. Geophys. Res.* 1968, 73, 2225–2236.

(24) Lin, C.; Pirie, G; Trimmer, D. A. Low permeability rocks: Laboratory measurements and three-dimensional microstructural analysis. *J. Geophys. Res.* 1986, 91, 2173–2181.

(25) Hsieh, P. A.; Tracy, J. V.; Neuzil, C. E.; Bredehoeft, J. D.; Silliman, S. E. A transient laboratory method for determining the hydraulic properties of ‘tight-rocks—I. Theory. *Int. J. Rock. Mech. Min. Sci. Geomech. Abstr.* 1981, 18, 245–252.
(26) Dicker, A. I.; Smits, R. M. A Practical Approach for Determining Permeability from Laboratory Pressure-Pulse Decay Measurements; Society of Petroleum Engineers, 1988.

(27) Jung, C. M. Measurement of Fluid Properties in Organic-rich Shales. Doctoral Dissertation, University of Texas at Austin, 2015.

(28) Al-bazali, T. M. Experimental Study of the Membrane Behavior of Shale during Interaction with Water-based and Oil-based Muds. Doctoral Dissertation, University of Texas at Austin: 2005.

(29) Carslaw, H. S.; Jaeger, J. C. Conduction of Heat in Solids, 2nd ed.; Clarendon Press: Oxford, 1959; pp 142–148.

(30) Van Oort, E. A Novel Technique for the Investigation of Drilling Fluid Induced Borehole Instability in Shales; Society of Petroleum Engineers, 1994.