Effects of a Mixed Wetting Porous Medium on Gas Flowing and Its Implications for Gas Exploration in Tight Sandstones*

Hui Shi[1], Xiaorong Luo[2], Likuan Zhang[2], Yuhong Lei[2], and Ming Cheng[2]

Search and Discovery Article #42195 (2018)**
Posted April 23, 2018

*Adapted from oral presentation given at AAPG/SEG 2017 International Conference and Exhibition, London, England, October 15-18, 2017

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Abstract

Mixed wetting pores commonly develop in oil and gas sandstone reservoirs and affect the percolation behavior of multiphase flows; thus, these pores represent a key problem that is frequently addressed in studies on hydrocarbon migration and accumulation and oil recovery enhancement. This paper aims to determine the effects of oil-wetting pores on gas migration in a mixed porous medium. We have conducted gas migration experiments in mixed wetting bead models saturated with water in which the beads were composed of oil-wetting and water-wetting beads. Nuclear magnetic resonance is employed to investigate the migration processes and elucidate the mechanisms under which gas flows freely in mixed wetting pores. The experimental results indicate that the likelihood of gas migration driven by buoyancy increases with the fraction of oil-wetting grains in the mixed wetting models as a logarithmic function. Gas migrates spontaneously in mixed pore media with more than 60% oil-wetting beads. Oil-wetting pore throats that are mainly composed of oil-wetting grains also improve the dynamic conditions that favor migration of the gas phase. The connectivity of oil-wetting pore throats in the vertical dimension is critical for the free migration of gas in mixed wetting porous media. Gas can only invade porous media by spontaneous imbibition after sufficient oil-wetting components are available to form a continuous pathway for the nonaqueous phase. Early oil emplacements have been widely identified in low-permeability sandstone reservoirs of various gas plays, and they can lead to wettability alterations of some grain surfaces. The creation of mixed wetting conditions may offset the decreased reservoir quality for late gas migration in terms of nonaqueous fluid flows.

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Theme 8: Tight Gas (Sandstone Reservoirs)

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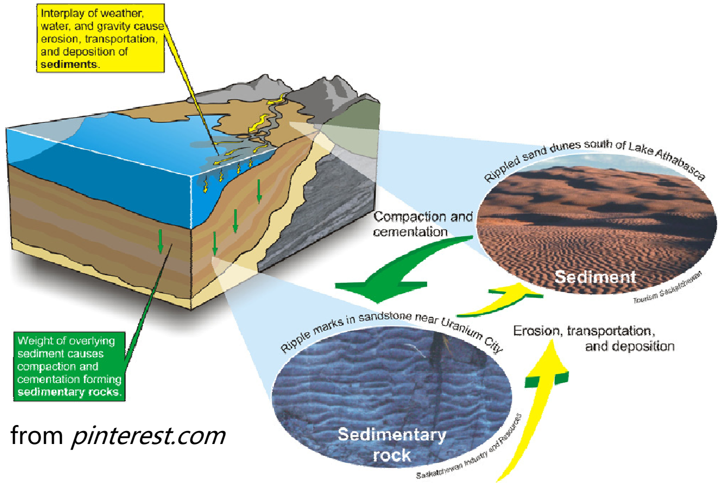
Oct. 2017

OUTLINE

1. Introduction
2. Materials and methods
3. Results
4. Discussion
5. Conclusions

1.Introduction

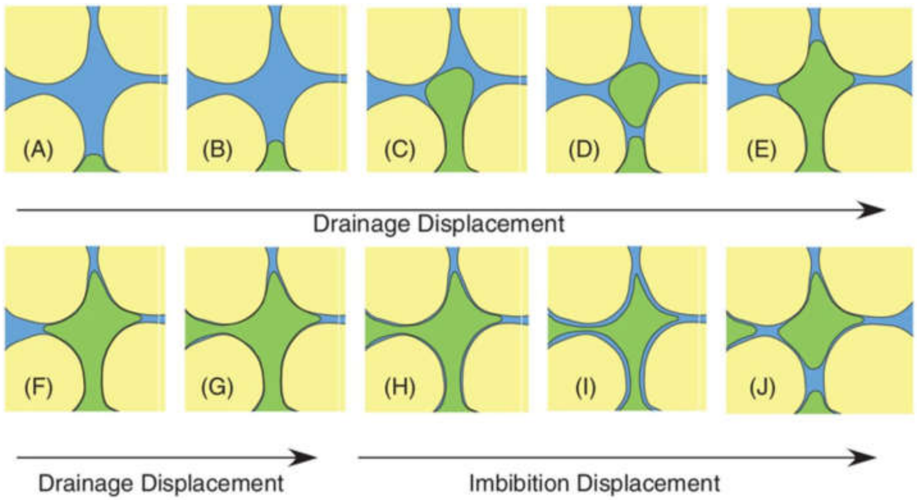
Wettability refers to the relative adhesion of two fluids to a solid surface, and the wettability of a system can range from *strongly water wet to strongly oil wet* depending on the brine-oil interactions with the rock surface.



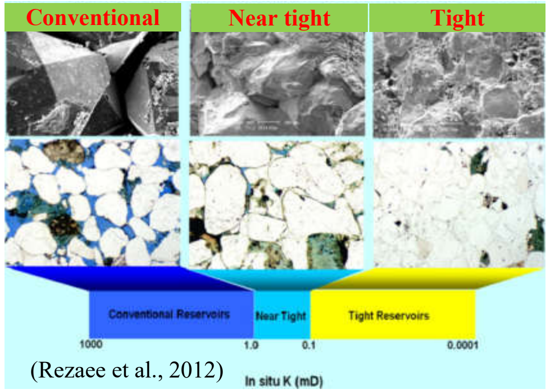
from *pinterest.com*

Original Wettability: Clastic reservoirs that were initially deposited in brine and present rock surfaces adhered with an aqueous film are regarded as *originally strongly water wet*.

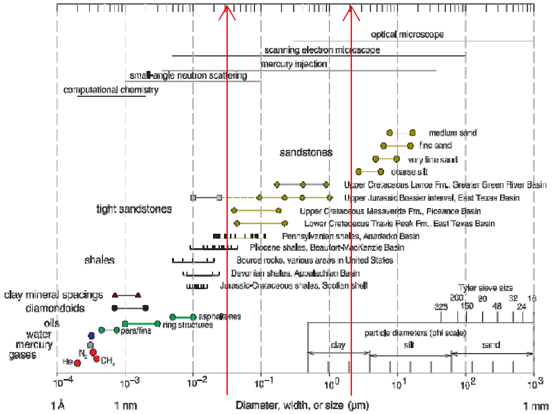
Shanley et al., 2015

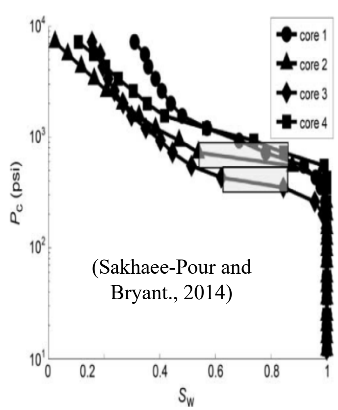


Provided originally strongly water wet: contact angle is 0, and cos is 1; according to capillary pressure formula $Pc=4\sigma\cos\theta/d$, the capillary pressure is the maximal, which means it should overcome the strongest resistance for oil displacing water in the pores with the same pore-throat size.

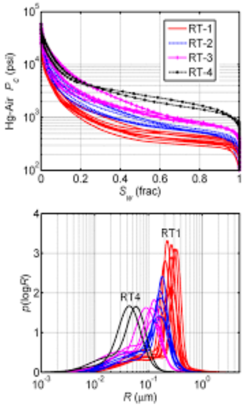


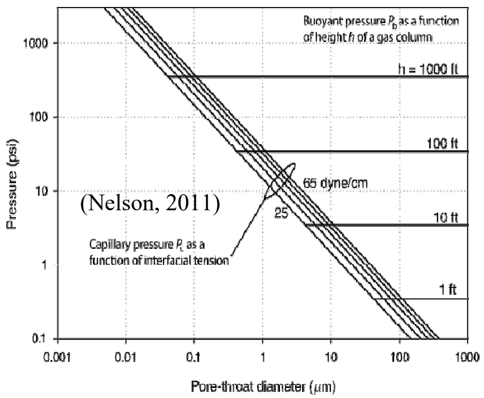
(Rezaee et al., 2012)





(Sakhaee-Pour and Bryant., 2014)

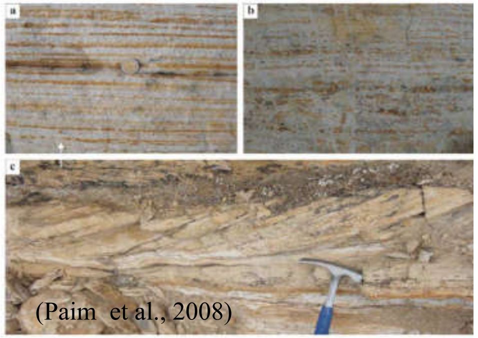


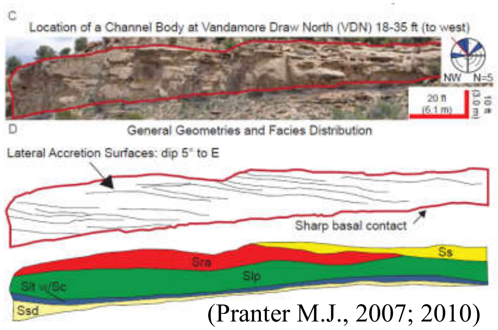


(Nelson, 2011)

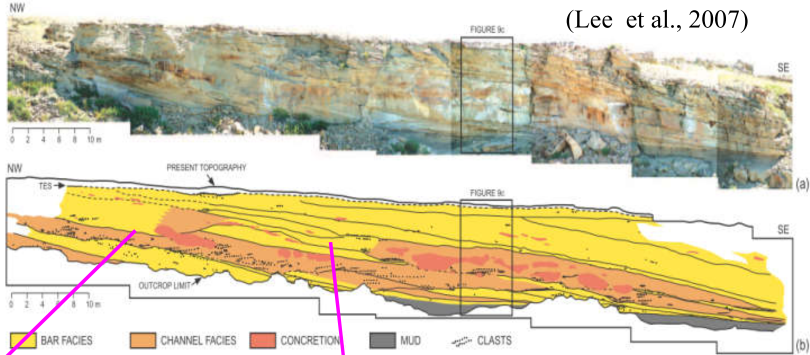
Tight sandstone is similar to conventional sandstone, but with lower permeability (less than 0.1 mD), lower effective porosity and finer pore-throat (diameter below 1 μm), which is historically not economically producible unless stimulated (Law and Spencer, 1993; Holditch, 2006; Nelson, 2011).

Minimum height of a gas stringer is required to over 30 m to exceed the pore throats with a dominated diameter of 1 μm.

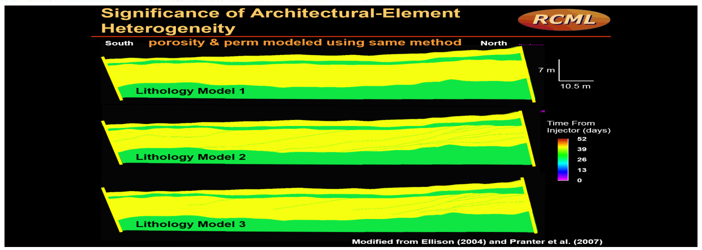

(Paim et al., 2008)

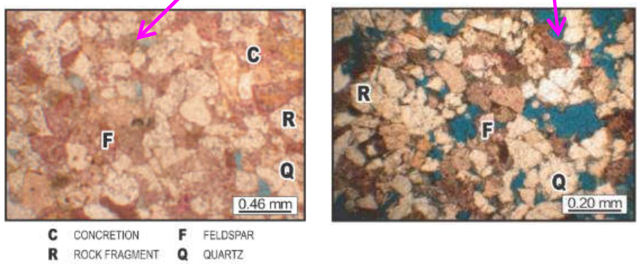


(Pranter M.J., 2007; 2010)

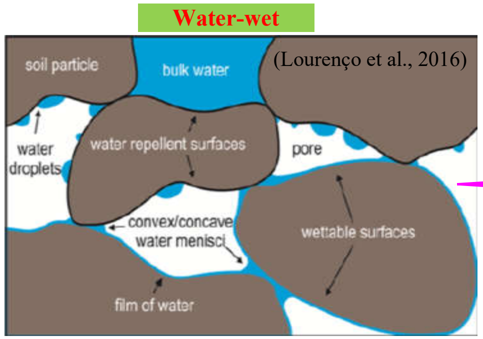


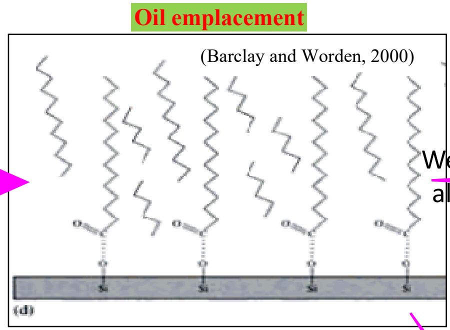
(Lee et al., 2007)



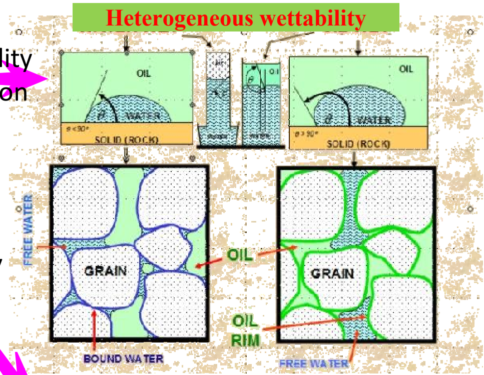


Reservoir heterogeneity makes it hard for fluvial sand bodies to form vertical dimensions that exceed 30 m as shown by outcrops and interpreted cross sections because of barriers and interlayers composed of finer-grained sediments or cemented rocks (Nelson, 2011).





Wettability alteration

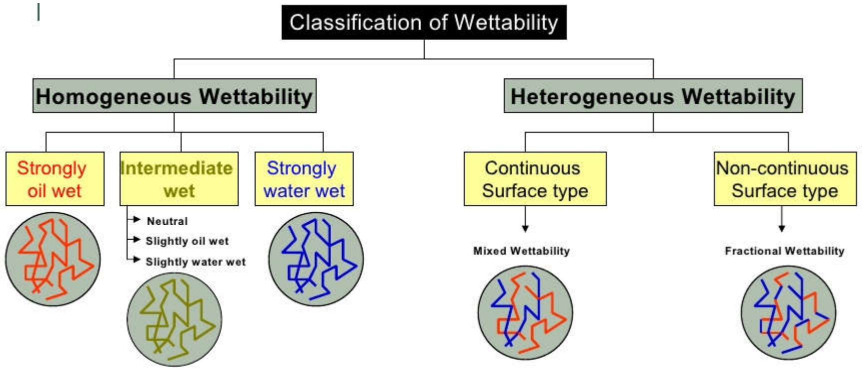


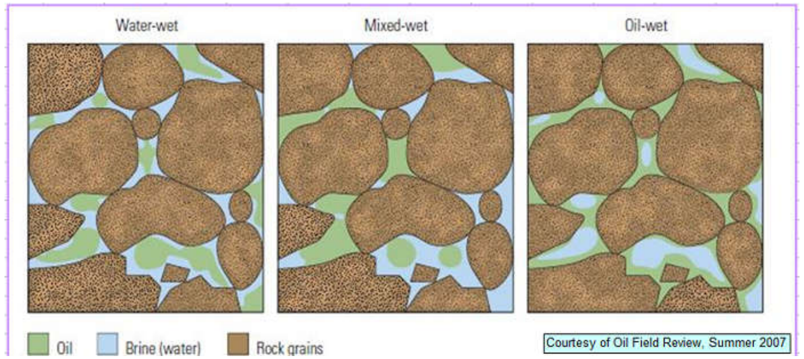
Wettability alteration

The interfacially active polar compounds will destroy the water film that is stabilized by a double layer of electrostatic forces and react with the rock's surface to produce an oil-wet lining in the large pores *after oil has displaced the brine*. Some surfaces of grains show oil wettability and other surfaces keep water-wet.

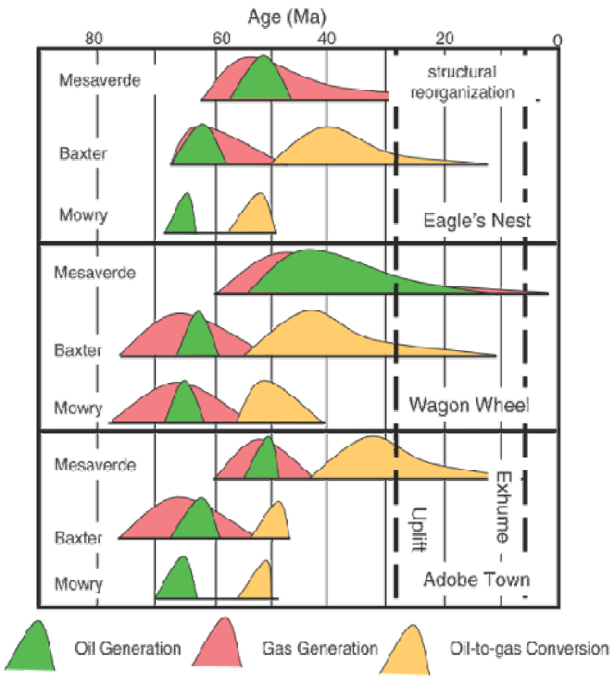
Mixed wettability: when oil containing interfacially active polar organic compounds invades a water-wet rock saturated with brine, the rock will exhibit mixed wettability (Salathiel, 1973; Anderson, 1986; Freer et al., 2003).

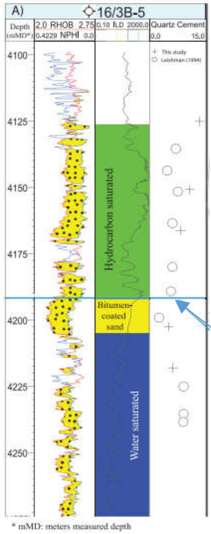
Oil generally cannot invade into smaller pores that are occupied by water; thus, these pores retain a waterwetted condition.

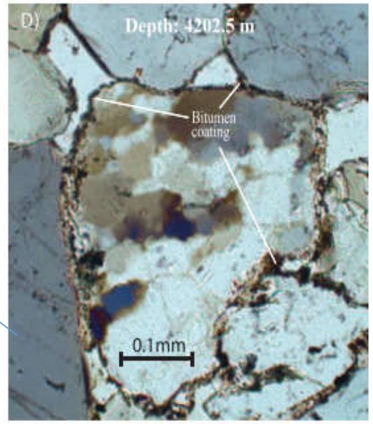




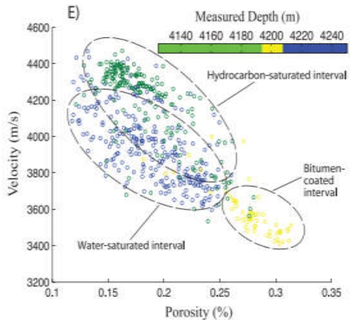
As the content of oil-wet framework grains increases in clastic reservoir, **the resistance of oil charging into the pores saturated with water decreases**, and the oil-wet pores can even imbibe oil under certain mixed wetted conditions, thereby displacing water without anexternal force.







(Shanley and Cluff, 2015)

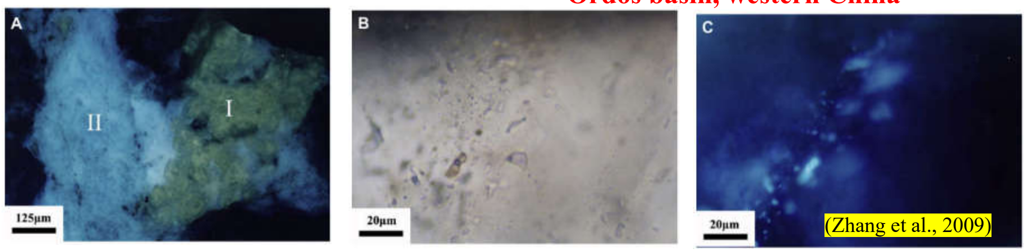


(Maast et al., 2011)

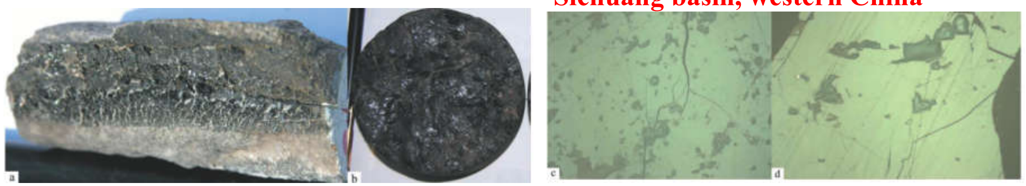
Early oil emplacement: Many tight-gas basins of the western United States experienced an earlier phase of petroeum charge.

Migrabitumen has been identified in gas sandstones of the Sichuan Basin, Ordos Basin and Tarim Basin, which are the main gas producing basins in China.

Ordos basin, western China

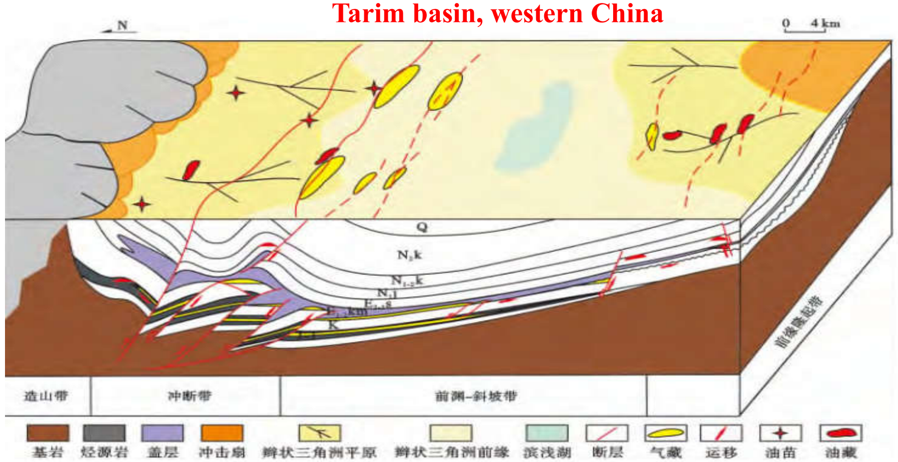


Sichuang basin, western China



Pore bitumen and oil inclusions are identified in the tight gas sandstones.

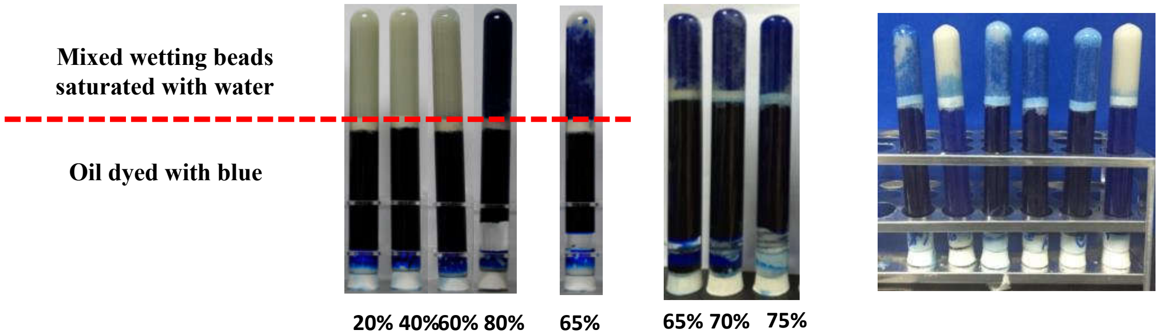
Tarim basin, western China



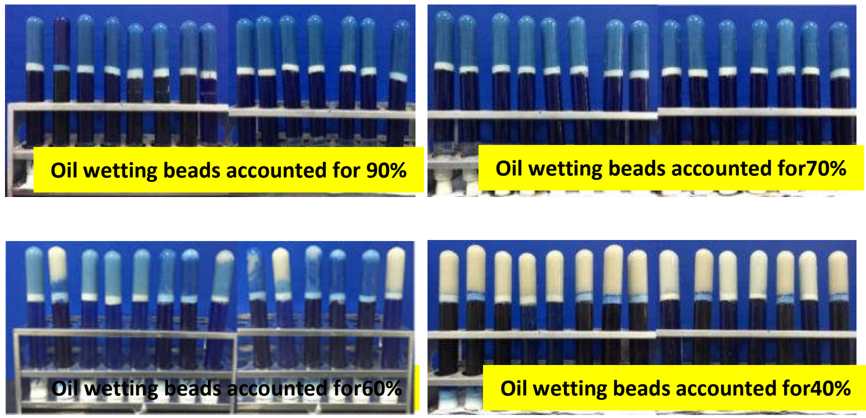
(Zhao et al., 2015)

These all implied that **there should be pervasive conditions for the occurrence of mixed wetting sandstones with water-wetting and oil-wetting pore throats in low-permeability gas reservoirs**.

➢ Oil inbibition experiment



Qi et al. (2015) systematically conducted oil imbibition experiments using glass tubes with mixedwetting glass beads and suggested that when the pore throats are dominated by oil-wetting grains and connected to form a complete pathway, oil can continuously imbibe via the porous media. Mixed wetting conditions that show an increased percentage of oil-wetted grains can significantly reduce the oil migration resistance and greatly improve the flow properties of oil phase.



There is a probability of oil migration upward, when the proportion of oil-wet beads above 40%.

Whether the oil wettability result in spontaneous inbibition for gas or not?

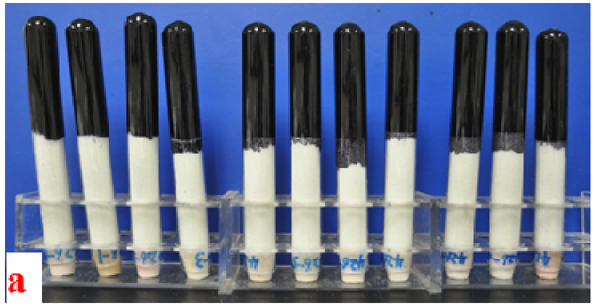
we designed and conducted gas migration experiments in a closed brinegas-bead system to (1) determine the effects of oil-wetting pore throats on gas flow; (2) establish a model of mixed wettability and likelihood of spontaneous gas migration; and (3) identify the mechanism of gas migration and accumulation in the mixed wetting porous medium of a low-permeability sandstone reservoir.

2. Materials and methods

60 mesh beads used to imitate framework grains

Glass test tube with dimensions 25mm inner diameter and 200 mm length to simulate a closed system

Dyed brine with nigrosin to track the flow of water



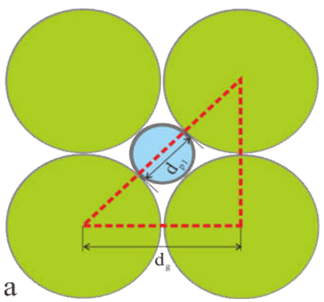
A NMR core analyzer was used to obtain the porosity and water saturation values of mixed wetting porous media

Dichlorodimethylsilane solution with a concentration of 2.5%, which can be used as surfactant to oil-wettability

Other apparatus

3. Results

3.1 Breakthrough gas column height

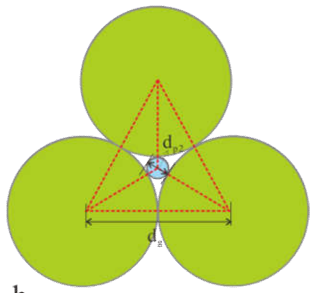


a

Cubic packing scheme

$$d_p = (\sqrt{2} - 1) \cdot d_g = 0.414 \cdot d_g$$

60 mesh beads， d_g=250 μm, so the pore-throat diameter is 103.5 μm; the theoretical porosity is approximately 50%.



b

Cubic packing scheme

$$d_p = (\sin 45^{\circ} - 0.5) \cdot d_g = 0.155 \cdot d_g$$

60 mesh beads， d_g=250 μm, so the pore-throat diameter is 38.75 μm; the theoretical porosity is approximately 25%.

Id	Component /g		Mixed degree	Porosity
	Upper	Lower		
B-0	50 g WW beads	50g WW beads	0%	48.73%
B-1	45 g WW beads+5 g OW beads	50g WW beads	10%	48.76%
B-2	40 g WW beads+10 g OW beads	50g WW beads	20%	47.64%
B-3	35 g WW beads+15 g OW beads	50g WW beads	30%	47.94%
B-4	30 g WW beads+20 g OW beads	50g WW beads	40%	46.21%
B-5	25 g WW beads+25 g OW beads	50g WW beads	50%	46.79%
B-6	20 g WW beads+30 g OW beads	50g WW beads	60%	46.58%
B-7	15 g WW beads+30 g OW beads	50g WW beads	70%	46.91%
B-8	10 g WW beads+40 g OW beads	50g WW beads	80%	44.12%
B-9	5 g WW beads+45 g OW beads	50g WW beads	90%	40.24%
B-10	50 g OW beads	50g WW beads	100%	41.00%

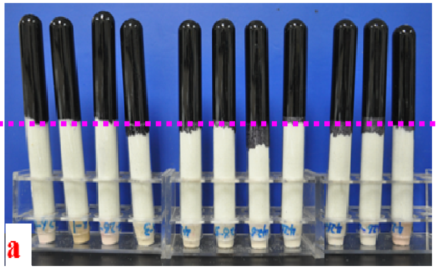
Porosity values measured by NMR imply that most glass beads are packed with the cubic scheme, and the maximal pore-throat diameter is about 103.5 μm

$$\left.\begin{aligned} \mathrm{Pc} &= \frac{4\sigma\cos\theta}{d} \\ \mathrm{Pb} &= (\rho_w - \rho_g)gh \end{aligned}\right\} \quad \mathrm{h} = \frac{4\sigma\cos\theta}{(\rho_w - \rho_g)gd}$$

g=9.8N/Kg, ρ_w=990Kg/m³, ρ_g=1.169Kg/m³, $\cos\theta$=1， d=103.5μm， σ=0.07N/m

h=279.2 mm

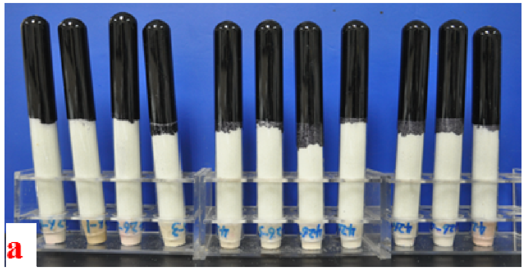
we can estimate that the minimum height of a gas stringer required to break through the capillary pressure for a strongly water-wetting pore-throat system with a maximum porethroat size of 103.5 μm should be 279.2 mm.



Strongly water-wet beads saturated with blue water after vacuum treatment to clear air

Strongly water-wet beads saturated with air, then the tube was stoppered with rubber after compaction

Note that: all the gas column heights were approximately 90 mm (less than 279.2 mm).



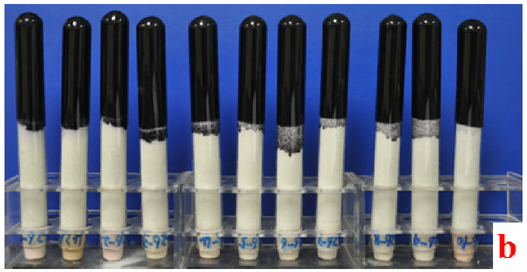
0 hour

24 hour

48 hour

72 hour

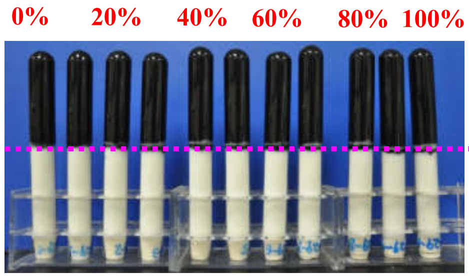
96 hour



120 hour

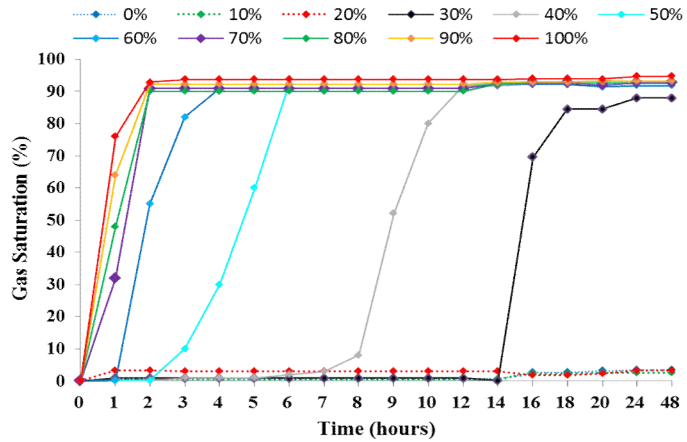
Result: After 144 h, gas migration was not observed in any of the tubes (Fig. 2b), which suggested that as long as 50 g of strongly waterwetting beads were saturated with water in the upper part of tube, gas could not break through the capillary pressure.

3.2 Gas migration in mixed wetting porous models



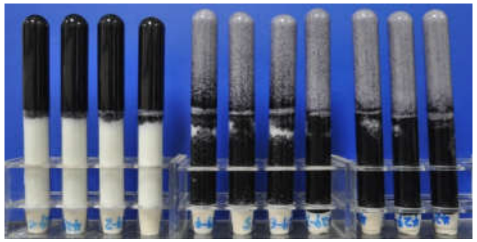
Strongly water-wet beads mixed with strongly oil-wet beads in various proportions, saturated with blue water after vacuum treatment to clear air

Strongly water-wet beads saturated with air, then the tube was stoppered with rubber after compaction

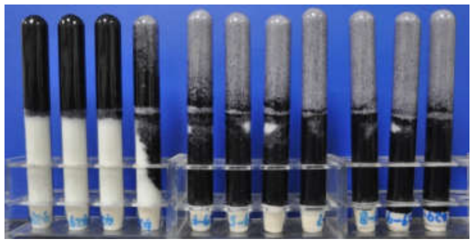


0hour

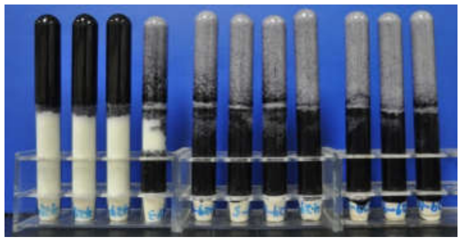
1hour



4hour



8hour



24hour

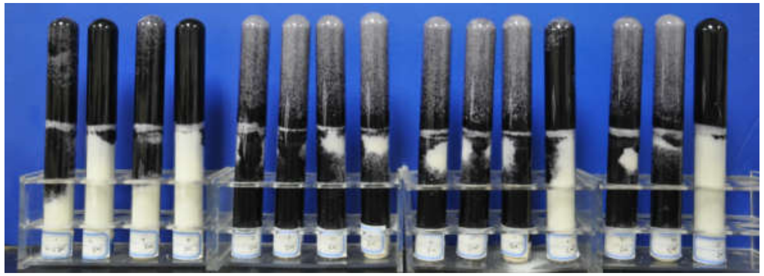
Gas started to flow upward and completely invaded the upper mixed wetting porous media with oil-wetting bead contents of 70–100% after only two hours; the gas and water states in the porous media with only 0–20% oil-wetting beads did not exhibit any changes.

Question: It was unclear whether gas surely could flow into the mixed wetting pores as the content of oil-wetting beads approached 30%

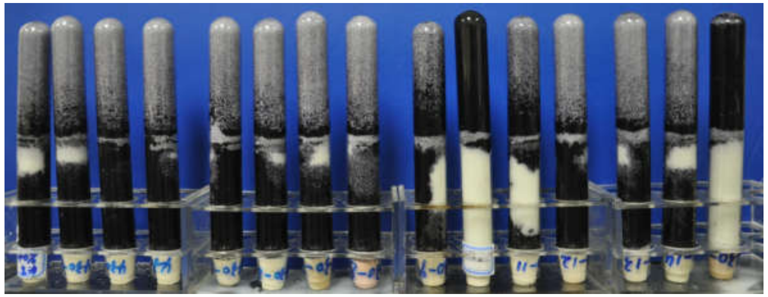
3.3 Gas migration probability in mixed wetting models

10% strongly oil-wetting beads——migration probability（1/15）

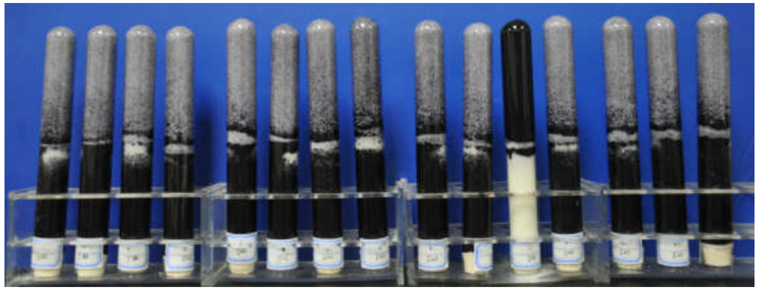
20% strongly oil-wetting beads——migration probability（12/15）



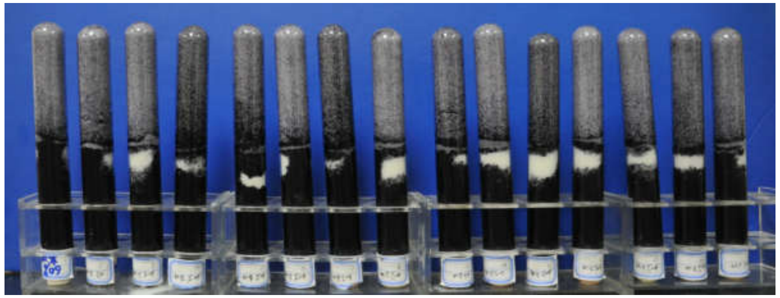
40% strongly oil-wetting beads——migration probability（13/15）

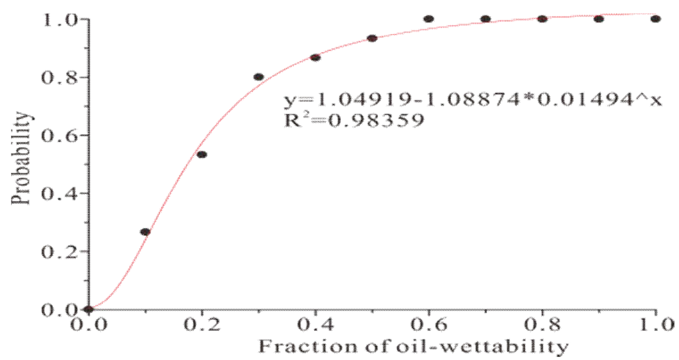


50% strongly oil-wetting beads——migration probability（14/15）



60% strongly oil-wetting beads——migration probability（15/15）

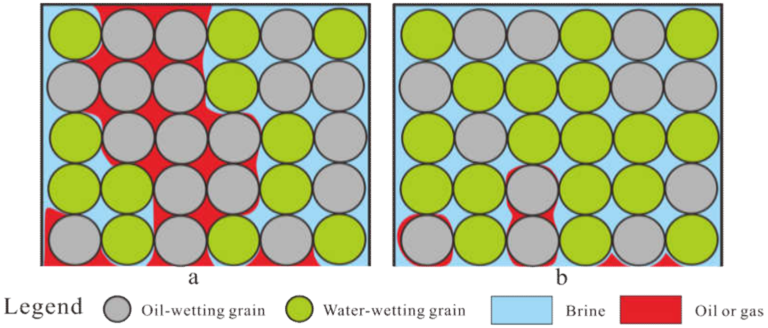




Result: The data are regressed to a standard power function between the mixed degree and probability, and the fit of regression reached 0.99 (Fig. 6f), which indicates that there may be a probability for gas to promote migration when the porous media are mixed wetting, and this probability increases with the content of oil-wetting beads in the mixed wetting porous media. When the content exceeds 60%, gas invariably flows into the mixed wetting pores

4. Discussion

4.1 Mechanisms of gas migration in mixed wetting pores



When the content of strongly oil-wetting beads in the mixed porous medium exceeds 60%, most of the pore throats are surrounded with oil-wetting grains, and the overall wettability of the porous models are preferentially oil-wetting. Thus, *there is a strong likelihood that these oil-wetting pores and throats will constitute a continuous pathway for the nonaqueous phase*. Gas in the lower part of the tube flows upward along this pathway and invades the mixed wetting bead model saturated with blue water

4.2 Implications for gas exploration in low-permeability reservoirs

Id	Component /g		Mixed degree	Porosity
	Upper	Lower		
B-0	50 g WW beads	50g WW beads	0%	48.73%
B-1	45 g WW beads+5 g OW beads	50g WW beads	10%	48.76%
B-2	40 g WW beads+10 g OW beads	50g WW beads	20%	47.64%
B-3	35 g WW beads+15 g OW beads	50g WW beads	30%	47.94%
B-4	30 g WW beads+20 g OW beads	50g WW beads	40%	46.21%
B-5	25 g WW beads+25 g OW beads	50g WW beads	50%	46.79%
B-6	20 g WW beads+30 g OW beads	50g WW beads	60%	46.58%
B-7	15 g WW beads+30 g OW beads	50g WW beads	70%	46.91%
B-8	10 g WW beads+40 g OW beads	50g WW beads	80%	44.12%
B-9	5 g WW beads+45 g OW beads	50g WW beads	90%	40.24%
B-10	50 g OW beads	50g WW beads	100%	41.00%

The probability forming a continuous pathway for the upward migration gas increases with the fraction of oil-wetting pore throats. When the content of oil-wetting grains reaches 60%, the probability of gas migrating freely in the mixed wetting pore system can approach 100%. With regard to low-permeability sandstone reservoirs, *wettability alterations and their effects on the dynamics of gas migration and accumulation should be considered* when developing a gas exploration strategy.

5. Conclusions

According to the experimental results, the following conclusions can be drawn.

(1) Experiments demonstrating gas migration in mixed porous media with different mixed degrees of oil-wetting grains have been conducted to determine the effects of oil-wetting pore throats on gas flow. Oil wettability has a positive influence on gas migration.

(2) An empirical relationship has been established to illustrate the relationship between the likelihood of gas migration and the degree of mixing wettability. The likelihood of gas migration significantly increases along with the fraction of oil-wetting grains in the mixed wetting porous medium. When the content of oil-wetting beads exceeds 60%, the probability equals 100%. It suggests that gas will migrate spontaneously in mixed pore media with more than 60% oil-wetting beads.

(3) An oil-wetting pore throat that is primarily surrounded by oil-wetting grains can spontaneously imbibe the nonaqueous phase (wetting phase) to decrease the surface energy. When the fraction of oil-wetting grains reaches 60% in a mixed wetting porous system, the oil-wetting pores and throats are certain to constitute a continuous imbibition pathway for upward gas migration. But there is a forming probability for the continuous imbibition pathway when the oil-wetting grain fraction below 60% and the probability decreases with reducing fraction of oil-wetting grain in the mixed wetting pore system.

(4) Reservoir wettability should offset the effect of decreased porosity and permeability on gas migration. Petroleum emplacements are common for low-permeability gas plays prior to gas charging, and the early oil can result in a mixed wetting reservoir, which prevents later cementation and improves the migration dynamics for late gas. Therefore, gas exploration in low-permeability sandstone reservoirs should consider the wettability alteration conditions when predicting gas distributions.

Thank you for your attention!