Low-Salinity Waterflood with non-Polar Oil: the effects of fines migration excluding the wettability alteration effects

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ABSTRACT

Numerous controversial results on the effect of fines migration on oil recovery with low salinity (LS) waterflood have been reported. However, the current mathematical models do not allow separating the effects of wettability alteration and fines migration from coreflooding tests. We perform LS flooding for non-polar oils, where the rock remains fully water-wet independently of salinity, so the effects can be attributed to fines mobilization and straining only.

Robust characterization of the rock sample and injected and produced fluids allows us to identify and evaluate fines migrations mechanism. Experiments are performed on Berea (400 mDarcy) sandstone. Before the experiments, the plugs are characterized using XRD, XRF, SEM imaging. Then, the first plug is subjected to single-phase water injection with varying salinities from 4 to 0 mass% NaCl. The second sister plugs are used to perform oil drainage and subsequent high salinity (4 g/L) water flooding. Then the oil drainage experiment is repeated and finally low salinity waterflooding is performed. During each experiment, pressure drop across the plugs, fluids' production rate, breakthrough salinities and fines concentrations are measured continuously. Elemental analysis is run on the produced fluids to see if there are any dissolution effects. Next, the fines are separated from the produced fluids from both plugs and SEM-EDX analysis used to identify the composition of the collected fines. Finally, post-experiment SEM are taken. These SEM are registered with the images taken before the experiments to visualize any fines migration. Single phase experiments show at least an order of magnitude drop in permeability. Two-phase experiment show 50% reduction in water permeability and 5% increase in the oil recovery.

INTRODUCTION

Low-salinity effect (LSE) has been found by many researchers that additional amount of oil can be recovered by switching from injecting high-salinity water to low-salinity water [1-3]. There are multiple mechanisms taking place jointly during LSE. An initial mixed-wet condition is always formed when polar compound is present in oil [4-6]. Polar compounds in oil can be adsorbed on clay particles so clay will be oil-wet. Mixed-wet condition is formed when quartz adsorbs water, while clay adsorbs oil [2]. In such case, LSE can increase the percentage of mobile oil. Wettability alteration is considered the main mechanism affecting oil recovery [7] while fines migration has been a controversial topic.

Fines migration, as one of many proposed mechanisms for LSE, explains that fines particles are mobilised when torque balance exerted on these particles is broken during alteration of salinity [8]. These particles then travel in the suspension and some of them will be strained by narrow flow channels that have smaller diameters than particle size. Such pore blockage firstly occurs in high-swept zone, thus redirects water into less-swept zone, therefore, more water is forced to flush low-swept zone than before. Re-distribution of flow channel can increase local swept efficiency thus contribute to improved ultimate recovery. This is also called fines migration and straining.

To model fines migration and straining, Bedrikovetsky, Siqueira [9] proposed a maximum retention function model. Maximum retention model only considers changes in flow conditions that can make particles roll again, such as weakening of electrostatic force due to changing of salinity. To integrate with this model, wettability change should be deactivated. In this paper, we performed a set of low-salinity waterflooding experiments by using paraffinic non-polar oil. So, the results are limited to fines mobilisation and straining only.

EXPERIMENT PROCEDURE

1. ROCK AND FLUID CHARACTERISATION

1.1 Rock and fluid properties

Berea sandstone was selected (porosity 22.6%, Initial permeability = 340 mD). One plug (Berea-1: L = 3.6 cm, D = 2.6 cm) was used for single-phase test with a purpose of confirming fines migration and its impact on permeability. Another plug (Berea-2: L = 3.6 cm, D = 2.6 cm) was used for two-phase test. **Error! Reference source not found.**.

Soltrol 130 (an isoparaffin solvent) was used to prevent occurrence of wettability alteration. The absence of polar-components in soltrol will prevent the formation of initial mixed-wet condition [2].Brines of 8 different salinities (4%, 3%, 2%, 1%, 0.5%, 0.25% and 0 % in mass concentration) were prepared by using de-ionized water.

1.2 Mineral identification

10 gram of Berea core was milled and dried. The powder was analyzed under X-ray diffraction and fluorescence to qualify and quantify existing minerals. Mineralogy of Berea core is presented in
Table *1*.

Table 1 Mineral composition and percentage of Berea sandstone

Mineral Name	Composition (%wt)
Quartz	84.80 ±8.9
Kaolinite	6.11 ±0.48
Muscovite	4.90 ±0.3
Microcline	4.18 ±0.33

1.3 Pore scale imaging

Scanning Microscope Images were taken on both injection and production sides of Berea-1. Both injection and production faces of the plug were coated with carbon to enhance electron conductivity. SEM 3400I facility at UNSW Australia was used for imaging. Images were taken at 50 different locations on both injection and production faces of the core plug.

2. CORE FLOODING TEST

Both plugs were pre-saturated with 4% (mass concentration) NaCl brine. Wet weight and dry weight were measured to determine pore volume gravimetrically. The experiment was performed at 25^{o}C. The core outlet was open to atmospheric pressure. Initial permeabilities were firstly measured by injecting the same 4% brine at a constant rate. Experiment schematic is shown in **Error! Reference source not found.**.

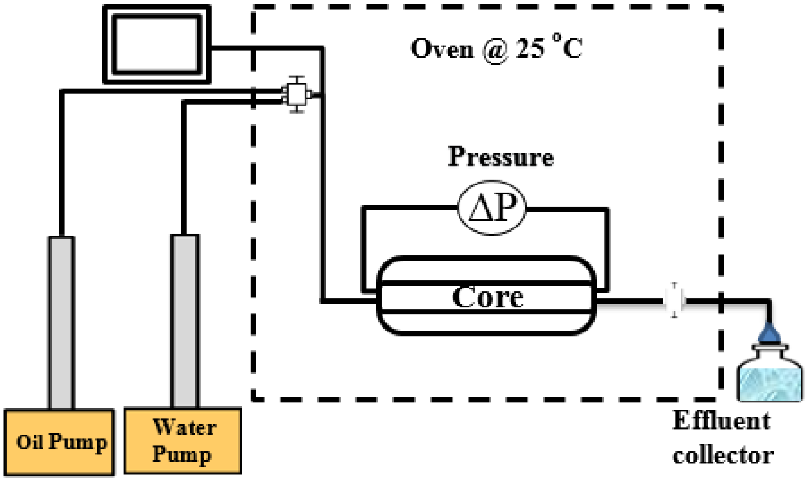

Fig 1 Schematic presentation of experimental apparatus.

2.1 Single-phase corefloodinig with stepwise reduced salinity

Berea-1 plug was subjected to a continuous waterflood (0.25 *ml/min*) with the sequential salinity reduction. The entire process took 3138 pore volumes and 8 stages, starting with 4% brine and ending with de-ironized water. Permeability drop with respect to salinity reduction is showed in **Error! Reference source not found.**. Water samples were collected in small vials with caps for particle concentration and type analyses.

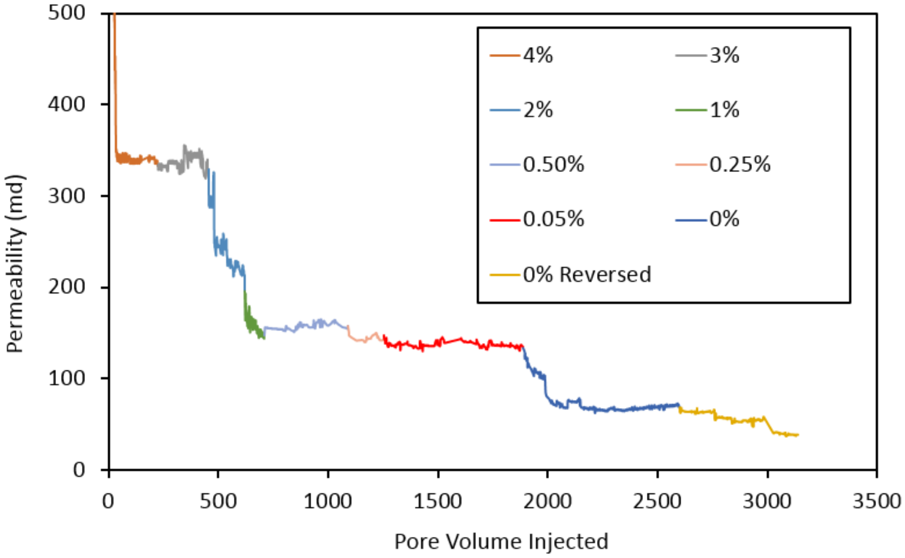

Fig 2 Permeability drop for Berea_1P plug. First permeability drop was noted at 2% NaCl brine. 1% NaCl brine and fresh water also caused permeability reduction

2.2 Two phase waterflooding

4% brine was injected to measure core`s absolute permeability. In the first step, Soltrol was injected at 5cc/min into brine saturated plug to produce connate water saturation (S_{wi}). When steady-state conditions were achieved, the experiment was stopped. In the second step, 4% brine was injected at a rate of 0.25 cc/min to mimic high-salinity waterflooding. This produced residual oil saturation ($S_{or-high}$). Water samples were collected during high salinity water flooding.

Next, same oil was injected at 5 cc/min to re-produce irreducible water saturation (S_{wi}). Values of S_{wi} and k_{ro} were compared with first drainage step (Table 2). Finally, de-ionized water was injected to mimic low-salinity flooding and produce residual oil saturation (S_{or-low}). Pressure and production data were recorded continuously. The values of S_{wi} and k_{rowi} are similar in both oil injection stages, suggesting that same oil saturation was achieved before the high-salinity and low-salinity waterfloods (Table 2).

Table 2 end-point saturation, relative permeability and core exponent

	Stage	S_{wi}	$K_{ro}(S_{wi})$	S_{or}	$K_{rw}(S_{or})$
Berea-2	High-salinity injection	0.311	0.66	0.385	0.09
	Low-salinity injection	0.314	0.66	0.362	0.05

3. POST EXPERIMENT CHARACTERIZATION

After core flooding, cores were dried and SEM imaging was repeated. Spectrex PC-2000 Laser Particle Counter was used to quantify particles suspended in each produced water sample. A special filter membrane device was used to filter particles suspended in water samples. According to our known mineralogy information, polytetrafluoroethylene (PTFE) membrane was selected because PTFE material only contains carbon(C) and florin(F) elements that are not included in both sandstones. The filtration method adopted in this paper is described in details by Guo, Hussain [10].

4. RESULTS

4.1 SINGLE-PHASE RESULTS

The permeability profile of Berea plug and Obernkirchener plug is shown in **Error! Reference source not found.**. There is an order of magnitude permeability drop from 4% brine injection to de-ionized water injection. **Error! Reference source not found.** shows the particle concentration of Berea_1P plug along with pore volume injected. The first sample shows significantly high concentration of particles. In general, particle production seems to be associated with permeability drop. As described above, all four stages that showed permeability drop (2%, 1%, fresh water and fresh water reversed flow) showed particle concentration. Conductivity plot shows the reduction of concentration of sodium ion, which can be further interpreted as the reduction of salinity.

Particles released from the core was filtered on PTFE membranes and then identified by Energy Dispersive Spectrum (EDS) technique. The particles were mainly quartz and kaolinite. Quartz were relatively larger in terms of size that it was usually visible under 500-micron scale. By contrast, kaolinite particles were so small that they were only visible under 10-micron scale. A statistics analysis (**Error! Reference source not found.**) shows that for Berea-1 plug, quartz was produced in each stage, while the boost of kaolinite production is only during fresh water injection.

Error! Reference source not found. shows the initial condition of a pore at the inlet face before water flooding. A few fines are highlighted by red circles which disappeared after water flooding. **Error! Reference source not found.** shows migration of a big chunk of clay near the exit of an existing pore after experiment. This may block the pore and force water to flow through another pore.

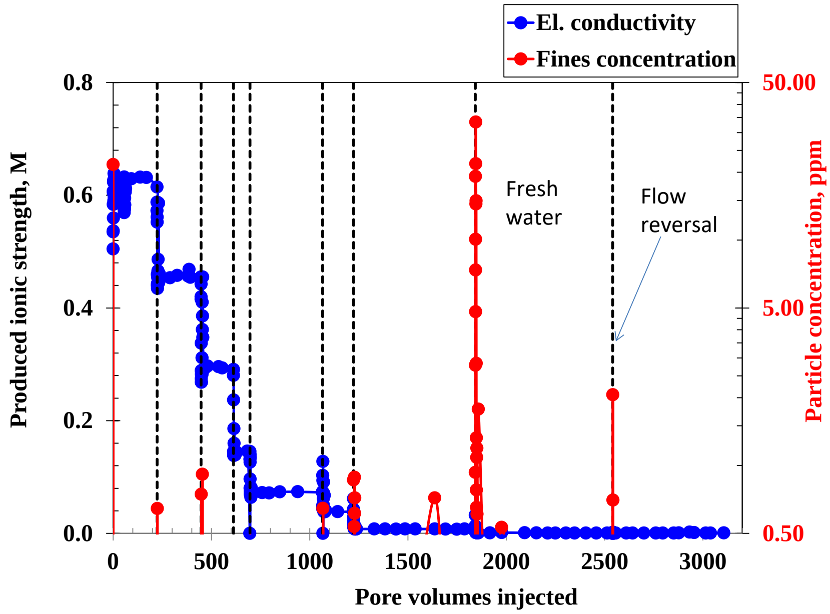

Fig 3 Result of particle concentration- a large number of particles were produced during fresh water flooding. Reversed flow can re-mobilize strained fines during previous stages.

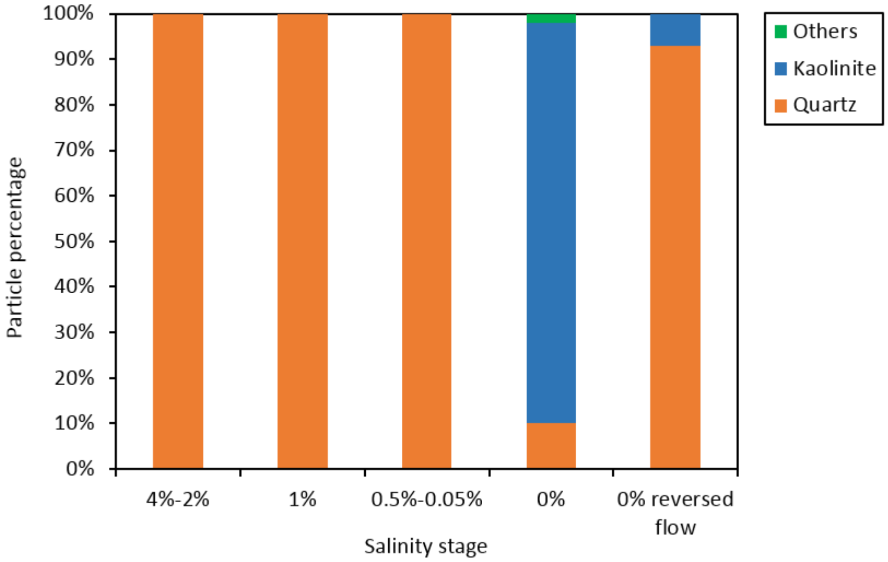

Fig 4 Percentage of produced quartz, kaolinite from SEM/EDS analysis.

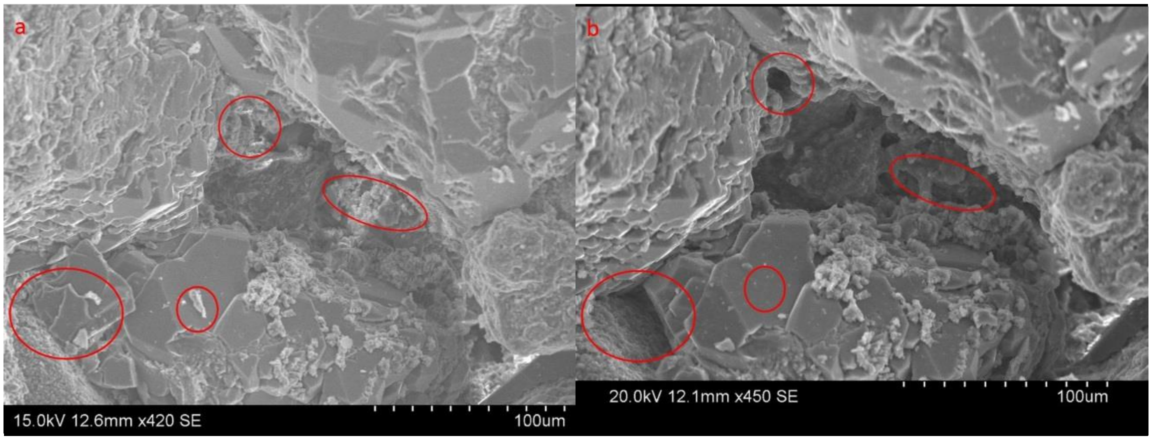

Fig 5 shows fines in four locations on inlet face are initially attached on grain surfaces (a) and migration of these fines after water flooding created extra pore volume (b).

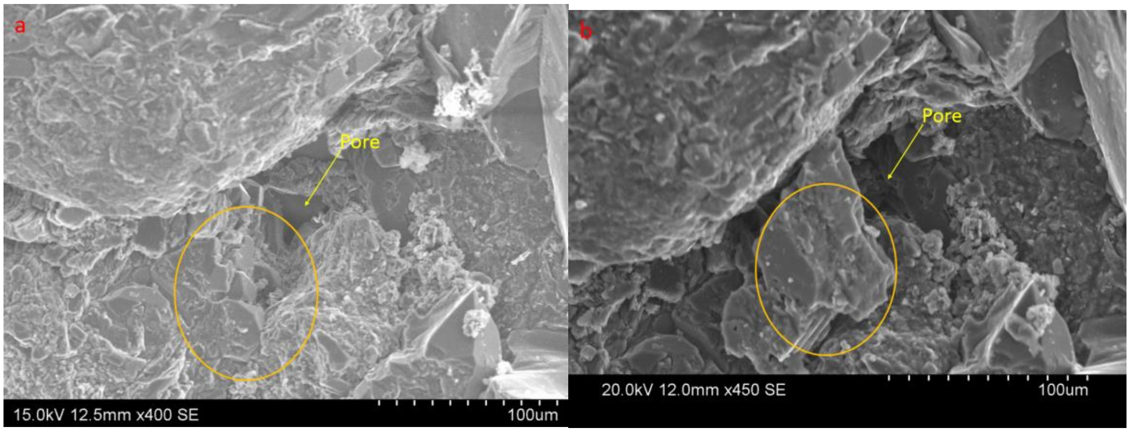

Fig 6 shows one position near a pore on outlet face before water injection (a) and a big chunk of particles migrated and blocked the outlet of this pore(b).

4.2 TWO-PHASE RESULTS

Cumulative oil production curve for high-salinity and low-salinity injections is shown in **Error! Reference source not found.**. Oil recovery in low-salinity water flooding is 2.5% more than high salinity flooding. Pressure drop for Berea sandstone increased from 3.5psi for high-salinity injection to 6 psi for low-salinity injection which was used to measure end point water permeability (Table 2**Error! Reference source not found.**). The results show that water permeability was reduced to half after low salinity water injection.

Error! Reference source not found. Error! Reference source not found.shows the number of fines produced with high salinity water were negligible compared with that with low salinity water. Also, concentration graph shows that fines production occurs in early stage of low-salinity injection. EDS results (**Error! Reference source not found.**) for two phase flow test matches single phase flow results where clay is mobilized only during low salinity water flooding. High concentration of particles, mainly kaolinite is produced near low-salinity water break through (**Error! Reference source not found.** and **Error! Reference source not found.**). The quantity of particles on membranes may somewhat represent their quantity in water.

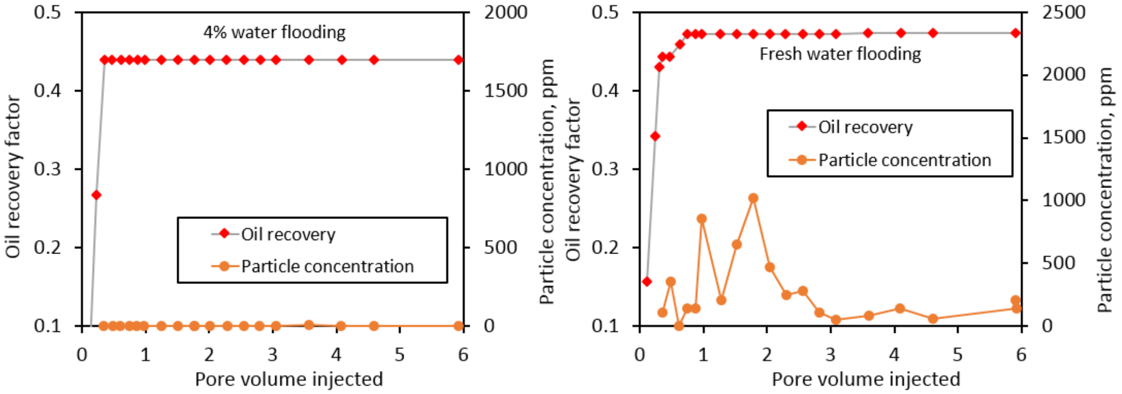

Fig 7 Oil recovery and particle concentration from effluent for both high-salinity water and fresh water

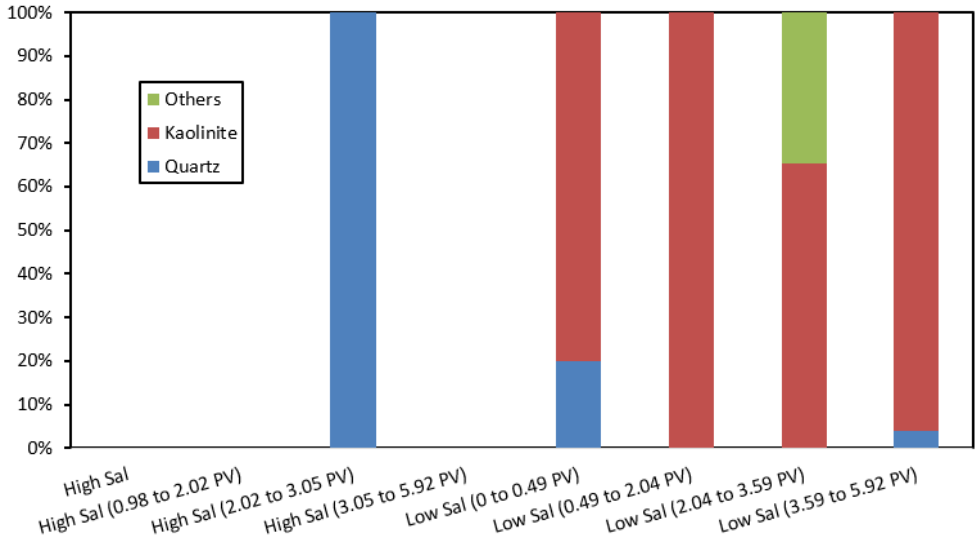

Fig 8 Percentage of different type of particle identified under SEM/EDS.

CONCLUSION

Wettability alteration was avoided by using non-polar oil. SEM images and particle identification give direct evidence of fines migration. This correlates well with the data on fines concentration, which is significant during fresh water flooding and negligible during HS flooding. The core contains no swelling clays; hence water swelling effect is excluded. Fines production is found to be associated with absolute permeability reduction for single-phase experiment (10 times) and water relative permeability reduction for water-oil displacement experiment (2 times). The produced fine particles during our test are mostly kaolinite. There is also some decrease in residual oil saturation (almost 3%) during the LS waterflood in comparison with the high-salinity waterflood. As there is no wettability alteration, improved recovery was due to fines migration induced flow diversion.

Reference

1. Yildiz, H.O. and N.R. Morrow, *Effect of brine composition on recovery of Moutray crude oil by waterflooding.* Journal of Petroleum science and Engineering, 1996. **14**(3-4): p. 159-168.
2. Tang, G.-Q. and N.R. Morrow, *Influence of brine composition and fines migration on crude oil/brine/rock interactions and oil recovery*. Journal of Petroleum Science and Engineering, 1999. **24**(2): p. 99-111.
3. Fogden, A., et al., *Mobilization of fine particles during flooding of sandstones and possible relations to enhanced oil recovery.* Energy & Fuels, 2011. **25**(4): p. 1605-1616.
4. Buckley, J., K. Takamura, and N. Morrow, *Influence of electrical surface charges on the wetting properties of crude oils.* SPE Reservoir Engineering, 1989. **4**(03): p. 332-340.
5. Fogden, A. and E.V. Lebedeva, *Changes in Wettability State Due to Waterfloodin.* Petrophysics, 2012. **53**(06): p. 420-429.
6. Sharma, M. and P. Filoco, *Effect of brine salinity and crude-oil properties on oil recovery and residual saturations.* SPE Journal, 1998. **5**(03): p. 293-300.
7. Al-Shalabi, E.W. and K. Sepehrnoori, *A comprehensive review of low salinity/engineered water injections and their applications in sandstone and carbonate rocks.* Journal of Petroleum Science and Engineering, 2016. **139**: p. 137-161.
8. Hussain, F., et al., *An experimental study of improved oil recovery through fines-assisted waterflooding.* Journal of Petroleum Science and Engineering, 2013. **109**: p. 187-197.
9. Bedrikovetsky, P., et al., *Modified particle detachment model for colloidal transport in porous media.* Transport in porous media, 2011. **86**(2): p. 353-383.
10. Guo, Z., F. Hussain, and Y. Cinar, *Permeability variation associated with fines production from anthracite coal during water injection.* International Journal of Coal Geology, 2015. **147**: p. 46-57.