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Effect of exposure time and crude oil composition on low-salinity water flooding

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A B S T R A C T

Rational and systematic approaches to the application of low-salinity water flooding have been slow to develop, due in part to a lack of understanding of the physics concerning oil/brine/rock interactions and uncertainty in assessments of wetting behavior of the rock. This paper provides insight into some of the factors controlling rock wettability during low-salinity water injection. A series of core flood experiments were performed on three crude oil samples with different resin and asphaltene concentrations. Three brine salinities of 122,000, 10,000, and 500 ppm were tested. Oil recovery, upstream pressure, and effluent pH were continuously monitored during the experiments. This study confirms that wettability alteration, during low-salinity water flooding, is sensitive to the heavy fractions of crude oil. Crude oils with a lower concentration of heavy ends are less responsive to low-salinity water injection. Additionally, this study indicates that the desorption of polar components is a time-dependent process, and sufficient exposure time between invaded low-salinity water and an in-situ oil/brine/rock system is required to ensure the complete transition from one wetting state to the next.

These results add new experimental evidence to the literature that will assist in understanding the complex mechanism of wettability alteration in low-salinity water flooding.

1. Background

The effect of low-salinity water flooding (LSWF) on oil recovery is not a new finding. In 1959, Martin [1] conducted laboratory tests for heavy oil recovery by fresh water injection and observed an increase in ultimate oil recovery. He suggested that clay swelling and in-situ emulsification as being responsible for the enhanced recovery. A similar result was reported in another study by Bernard [2] in 1967 in which he conducted laboratory tests involving the displacement of mineral oil by low-salinity water (LSW) containing 1000 ppm NaCl. He observed that water-sensitive cores (those with high clay content) produce more oil with low-salinity water injection. Field application of low-salinity water injection dates back to the 1970s, when production data shows unintentionally improved recovery from low-salinity water flooding. There are a number of field examples in the Powder River Basin in Wyoming, which was flooded with water containing as low as 1000 ppm water salinity [3].

Historically, little attention has been paid to the impact of brine salinity on waterflood microscopic displacement efficiency or the possibility of additional recovery by engineering the brine's ionic composition. Injected water salinity has only been a concern with regard to scaling, reservoir souring, and optimizing the performance of surfactant flooding. In the 1990s, Norman Morrow and his coworkers at the University of Wyoming [4–8] conducted pioneering laboratory studies on the improved recovery of crude oil by lowering the salinity of injected water. Using experimental data, they investigated the influence of brine composition on oil recovery and found that injecting sufficiently low-salinity brine could potentially improve oil recovery. Since then, this effect has been followed and investigated by other researchers who have tried to identify, reproduce, and explain the physical and chemical mechanisms behind the low salinity effect (LSE). Recently, this method has been tested in a field pilot, with Seccombe et al. [9,10] reporting positive results from a single well test using a reactive tracer. The field data showed that low-salinity water injection reduced the residual oil saturation near the wellbore [11].

2. Mechanism

Through numerous studies, it has been proven that low salinity has the potential to improve oil recovery in formations with sufficient clay content. However, the mechanism is still

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Nomenclature

Abbreviations

CEC	cation exchange capacity
SARA	saturate, aromatic, resin, and asphaltene
S	saturation
PV	pore volume
PPM	parts per million
OOIP	original oil in place
MIE	multi-component ion exchange
LSWF	low-salinity water flooding
LSW	low-salinity water
LSE	low salinity effect
BN	base number
AN	acid number
IFT	interfacial tension

List of Symbols: Parameters

L	length, ft.
K	permeability
md	millidarcy
D	diameter, in.
g	gram
mg	milligram

Subscripts

ab	absolute
or	residual oil
wi	initial water

unknown—there is no comprehensive explanation to describe exactly how the process works (i.e., the mechanisms that give rise to oil recovery, the effect of crude oil composition and clay mineralogy, and the composition of the formation and injected brine). This lack of understanding is one of the primary challenges for reservoir screening and extending the LSWF from the laboratory to field application. Various hypotheses have been postulated to explain the low salinity effect; however, none have been fully accepted or explain all of the experimental observations and laboratory results.

In Table 1, some of the proposed mechanisms have been reviewed. These models are not completely independent, and some of them overlap. The reported counterevidence studies are also presented for each model.

2.1. Wettability alterations

It has been known for decades that the ionic strength of the fluid flowing in a rock does impact the measured rock permeability [27–29]. The different wetting states of crude oil, water, and rock cause significant variations in oil recovery during laboratory water flooding experiments. The wetting state (wettability) of porous media can be modified in a number of ways. For example, wettability can be altered in the laboratory scale by changing crude oil's

Table 1
Overview of low-salinity water flooding mechanisms.

Osmosis Buckley et al. [12] In this model, Clay particles act as a membrane in the pore throats. Osmosis between low-salinity injected water and high salinity connate water generate extra pressure that potentially helps to mobilize additional oil out of the pores	**Alkaline flooding behavior** McGuire et al. [14] Carbonate dissolution and cation exchange during low-salinity water flooding cause a rise in the pH of the aqueous phase. This will activate a saponification reaction of acidic components of crude oil and in-situ generation of surfactant, lowering the interfacial tension between water and oil and further reducing residual oil saturation (in a way similar to alkaline flooding)
Counterevidence This mechanism is based on the salinity gradient between injected and connate brine, regardless of the type of oil in-situ. Core flood experiment using mineral oil (oil without polar components) did not show any additional oil recovery [13]	*Counterevidence* A pH increase is not reported in all the experiments, and it is not usually as high as alkaline flooding [21,27]. The experimental results by Lager et al. [15] showed no direct correlation between brine pH and additional oil recovery
Multi-component ion exchange (MIE) Lager et al. [15] This mechanism explains desorption of both positively and negatively charged organic compounds from the surface of the clay when low-salinity brine is injected. Ion exchange occurs between crude oil polar components and divalent cations, leading to the removal of organic polar compounds at the clay surface and an increase in rock water-wetness	**Mineral dissolution** Pu et al. [18] Injected low-salinity water partially dissolves anhydrite, which causes an increase in the sulphate ion content of the liquid phase. Sulphate ions create an acidic pH, which in turn changes the wetting properties of the rock from a weak water-wet to a stronger water-wet surface
Counterevidence Some experimental results showed that the presence of divalent cations in the injected brine is not a critical parameter, and the low salinity effect has been reported without Ca2+ and Mg2+ [7,14,16–17]	*Counterevidence* This mechanism has only been studied in carbonate rocks and was not tested in sandstone cores. Based on this mechanism, the presence of clay is not a necessary component for the low salinity effect, which contradicts numerous studies [7,19–21]
Salting in Austad et al. [26] During the injection of low salinity water, the solubility of organic polar compounds in the water increases and causes these components to detach from the clay surface and promote the water-wetness of the rock	**Fines migration** Tang et al. [19,22] Clay particles detach from the surface of the grains when exposed to low-salinity water. The detachment of these particles mobilizes the oil droplets from the clay surface and results in oil recovery enhancement
Counterevidence Further studies by Austad et al. [21] on the adsorption and desorption of hydrocarbon on the surface of kaolinite showed no correlation between the desorption process and the injected brine's salinity condition	*Counterevidence* A number of experimental studies [23–25] reported incremental oil recovery without fine particle production. Zhang et al. [25] and Nasralla et al. [24] did not observe fine production in all of the LSE experiments. Lager et al. [15] argued that fine clay production is more likely to be induced by LSE, not be the cause of it