

# A Surface Complexation Model of Alkaline-SmartWater Electrokinetic Interactions in Carbonates

Moataz Abu-Al-Saud\*, Amani Al-Ghamdi, Subhash Ayirala, and Mohammed Al-Otaibi

Saudi Aramco, EXPEC Advanced Research Center, Dhahran, Saudi Arabia

**Abstract.** Understanding the effect of injection water chemistry is becoming crucial, as it has been recently shown to have a major impact on oil recovery processes in carbonate formations. Various studies have concluded that surface charge alteration is the primary mechanism behind the observed change of wettability towards water-wet due to SmartWater injection in carbonates. Therefore, understanding the surface charges at brine/calcite and brine/crude oil interfaces becomes essential to optimize the injection water compositions for enhanced oil recovery (EOR) in carbonate formations. In this work, the physicochemical interactions of different brine recipes with and without alkali in carbonates are evaluated using Surface Complexation Model (SCM). First, the zeta-potential of brine/calcite and brine/crude oil interfaces are determined for Smart Water, NaCl, and Na<sub>2</sub>SO<sub>4</sub> brines at fixed salinity. The high salinity seawater is also included to provide the baseline for comparison. Then, two types of Alkali (NaOH and Na<sub>2</sub>CO<sub>3</sub>) are added at 0.1 wt% concentration to the different brine recipes to verify their effects on the computed zeta-potential values in the SCM framework. The SCM results are compared with experimental data of zeta-potentials obtained with calcite in brine and crude oil in brine suspensions using the same brines and the two alkali concentrations. The SCM results follow the same trends observed in experimental data to reasonably match the zeta-potential values at the calcite/brine interface. Generally, the addition of alkaline drives the zeta-potentials towards more negative values. This trend towards negative zeta-potential is confirmed for the Smart Water recipe with the impact being more pronounced for Na<sub>2</sub>CO<sub>3</sub> due to the presence of divalent anion carbonate (CO<sub>3</sub>)<sup>-2</sup>. Some discrepancy in the zeta-potential magnitude between the SCM results and experiments is observed at the brine/crude oil interface with the addition of alkali. This discrepancy can be attributed to neglecting the reaction of carboxylic acid groups in the crude oil with strong alkali as NaOH and Na<sub>2</sub>CO<sub>3</sub>. The novelty of this work is that it clearly validates the SCM results with experimental zeta-potential data to determine the physicochemical interaction of alkaline chemicals with SmartWater in carbonates. These modeling results provide new insights on defining optimal SmartWater compositions to synergize with alkaline chemicals to further improve oil recovery in carbonate reservoirs.

## 1. Introduction

Water ionic composition in the waterflooding process plays a crucial role in oil recovery for carbonate formations [1]. The chemistry of injected water strongly affects the reservoir wettability, which has been proven and observed in numerous laboratory and field studies for both carbonates and sandstones [2-4]. Modifying the water chemistry to alter the rock wettability is known as SmartWater or low salinity [5]. However, the root causes of this wettability alteration effect, which takes place at the pore-level, remain poorly understood especially for carbonates [6]. This lack of fundamental understanding of root causes of wettability alteration has resulted in conflicting studies, where some studies have observed an increase in oil recovery while other cases have not shown an increment in oil recovery [7]. Various pore-scale mechanisms have been proposed to delineate the wettability alteration process in carbonates. Some of these plausible mechanisms include electric double layer [4],

in-situ soap generation (saponification effect) [8], and multi-ion exchange [9]. The surface charges of carbonate/brine and crude oil/brine are altered in such pore-scale processes, which affects the zeta-potential measurements used in understanding the rock wettability [10,11].

Recently, the synergy between tailored water salinity and enhanced oil recovery (EOR) has gained a lot of attraction [12]. For polymer EOR, it has been shown that the use of tailored salinity (SmartWater) reduces the polymer consumption used to increase the injected water viscosity [13]. For surfactant-based EOR, it has been observed that decreasing the water salinity increases the effect of surfactant on crude oil/brine through efficiently reducing the interfacial tension [14]. It is well-known that surfactants are adsorbed on carbonate rock surfaces. Therefore, a large amount of chemical surfactant is consumed before the chemical reaches the crude oil/brine

\* Corresponding author: [moataz.abualsaud@aramco.com](mailto:moataz.abualsaud@aramco.com)

interface. To minimize surfactant adsorption on carbonate rock surfaces, alkaline is added to the injected water [15]. The alkaline chemical reacts with both crude oil/brine and calcite/brine interfaces. The reaction of alkali and naphthenic acid in crude oil generates in-situ soap that locally reduces the interfacial tension of the crude oil/brine interface. For the calcite surface, the adsorption of alkali changes the electric charges balance on the calcite/brine interface which alters the carbonate wettability towards more water-wet state [15]. Therefore, understanding the electrokinetics of brine with alkaline chemicals in carbonates is crucial to define the optimal water compositions for improving oil recovery.

There are several electrokinetic studies involving zeta-potentials that have reported the synergy effect of water salinity, crude oil, and alkaline in carbonates for crude oil/brine [17, 18] and calcite/brine interfaces [15, 16]. To the best of our knowledge, the role of individual ions in different brine compositions in the presence of alkaline chemicals for both the calcite/brine and crude oil/brine interfaces has not been previously studied using a surface chemistry model and lab measurements. In this work, we study the electrokinetics of with various brine recipes interacting with crude oil and calcite with and without alkali chemicals using a surface complexation model (SCM). We validate the modeling results with zeta-potentials of calcite/brine and crude oil/brine interfaces measured in the lab.

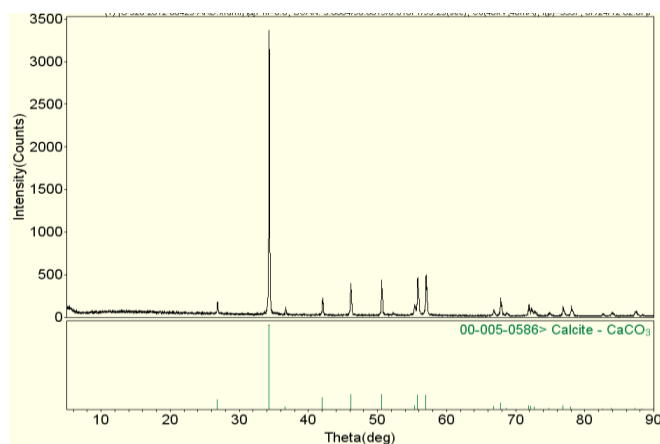
The outline of this work is as follows; a brief summary of the experimental setup for zeta-potential measurement is presented in section 2, followed by the surface complexation model (SCM). Then, the results of the SCM and lab measurements are shown in section 3. The conclusion and summary are included in section 4.

## 2. Materials and Methods

### 2.1. Experiment

#### *Rock sample:*

Pure calcium carbonate is used to represent the calcite rock sample. The purity of the calcite disk sample is measured using x-ray diffraction (XRD), which is composed of 99 wt. % of  $\text{CaCO}_3$  as shown in **Figure 1**. The calcite purity confirms that there are no mineral impurities interfering with the ion adsorption on the calcite surface. The calcite disk is manually grinded using a granite mill for 30 minutes at atmospheric conditions far from contaminants to avoid surface impurities.



**Figure 1:** X-ray diffraction (XRD) diffractograms of calcite disk with reference patterns of pure calcite compound. The x-ray wavelength is 1.54 Å.

#### *Brine and Crude Oil Properties:*

Synthetic brine ionic compositions are prepared by adding different salts to deionized water. The ionic composition of the considered brine samples is listed in **Table 1**. The crude oil properties are shown in **Table 2**.

#### *Alkaline chemicals:*

Two types of Alkali ( $\text{NaOH}$  and  $\text{Na}_2\text{CO}_3$ ) are added at 0.1 wt% concentration (1000 ppm) relevant to each brine recipe. Typically, alkali chemicals increase the brine pH level, which causes calcium and magnesium ions to precipitate as  $\text{Ca}(\text{OH})_2$  and  $\text{Mg}(\text{OH})_2$  respectively. Therefore, the addition of alkali to seawater is not considered to avoid precipitation, as seawater contains a high ionic concentration of hardness ions such as  $\text{Mg}^{2+}$  and  $\text{Ca}^{2+}$ . **Table 3** lists the equilibrium pH level of different brines including alkali chemicals. The brine pH is measured after reaching equilibrium with alkaline and calcite suspensions without manually adjusting the pH level.

#### *Zeta-potential measurement:*

The measurement of zeta-potential is conducted using phase analysis light scattering technique (zeta PALS) applied to calcite in brine and crude oil emulsion in brine samples. 0.2 g of grinded pure calcite particles were thoroughly mixed with 50  $\text{cm}^3$  of different brines for a minimum of 48 hours to ensure suspension and equilibrium are achieved. The ratio of solid/liquid and liquid/liquid is fixed throughout the experiment to guarantee consistency in the reported values. The brine pH level is not manually adjusted. The oil droplets and calcite particles size distribution in different brines is determined using optical microscopy, similar to the approach in [19]. The average calcite particle size distribution is estimated to be around 10  $\mu\text{m}$ , while the average oil droplet size is between 14-35  $\mu\text{m}$ . Sonification is used to avoid calcite particle aggregation or crude oil coalescence in brine suspensions. The zeta-potential values are determined using Smoluchowski approximation based on the electrophoretic mobility of brine suspensions. Each zeta-potential measurement is

repeated three times to ensure consistent results. The measurement variation for each reported zeta-potential value is within 3 mV. Additional details on the sample preparation and experimental zeta-potential measurement procedures can be found in [19].

**Table 1.** The composition of different synthetic brines used in this study.

Brine samples (concentration mg/L)				
	Seawater	SmartWater	NaCl	Na <sub>2</sub> SO <sub>4</sub>
<b>Ions</b>				
Na <sup>+</sup>	18,300	1824	2266	1865
Cl <sup>-</sup>	32,200	3220	3495	-
Ca <sup>2+</sup>	650	65	-	-
Mg <sup>2+</sup>	2,110	211	-	-
SO <sub>4</sub> <sup>2-</sup>	4,290	429	-	3896
HCO <sub>3</sub> <sup>-</sup>	120	-	-	-
Total dissolved Solids, ppm	57,670	5,761	5,761	5,761
pH	7.45	7.4	6.3	6.11

**Table 2.** Crude Oil Properties

API	27.1
Acid Number mg KOH/g	0.47
Base Number mg KOH/g	0.04
Saturates (%)	50.6
Asphaltenes (%)	1.6
Resins (%)	20.7
Aromatics (%)	27.1

**Table 3.** Equilibrium pH values of calcite suspension in different electrolytes containing alkali.

Type of electrolyte	pH CaCO <sub>3</sub>	pH CaCO <sub>3</sub> (NaOH 0.1 wt.%)	pH CaCO <sub>3</sub> (Na <sub>2</sub> CO <sub>3</sub> 0.1 wt.%)
Na <sub>2</sub> SO <sub>4</sub>	9.85	12	10
NaCl	9.4	11.33	10
SmartWater	8.6	11.7	10
Seawater	7.45	-	-

## 2.2 Surface Complexation Model

The surface complexation model (SCM) describes the equilibrium state of ion adsorption based on specified surface reactions. The surface reactions of ions give rise to surface electric charges. For calcite/brine/crude-oil system, the adsorption of ions on crude-oil/brine and calcite/brine interfaces determine the surface charges and the corresponding zeta-potentials. The SCM has been employed to gain insight on the effect of electrokinetics on wettability in the context of brine chemistry in carbonates [20,21,24,25]. Brady *et al.* [21] used SCM

based on surface reactions proposed in [22,23] to predict zeta-potentials for both rock/brine and brine/crude-oil interfaces in sandstone and carbonate rocks. However, the SCM has not been validated with experimental zeta-potential measurements. Mahani *et al.* [24] studied the electrokinetics of carbonate-based rocks with different water salinities using SCM. The SCM results were qualitatively validated with different carbonate/brine zeta-potential measurements. Song *et al.* [25] applied SCM and reported quantitative agreement with experimental zeta-potential measurements of synthetic calcite and multiple brine recipes. The SCM surface reactions are based on the model proposed in [26], which includes different SCM reactions compared to the models in [21,24]. The SCM work of Song *et al.* [25] has been recently extended to include surface reactions of organic and inorganic impurities occurring in natural carbonates [27]. In this work, we use SCM with surface reactions similar to the approach in [25] to predict zeta-potentials for pure calcite and different brine recipes with and without alkali chemicals. In addition, we determine brine/crude oil zeta-potentials by modeling SCM reactions at the brine/crude oil interface. **Tables 4 and 5** list the surface reactions and the corresponding equilibrium constants for both calcite and crude oil surfaces. The non-integer surface charge values of  $> CaOH^{-0.75}$  and  $> CO_3H^{+0.75}$  hydrated calcite sites is due to the structure of calcite crystal. The ionic bonding between Ca and O atoms from  $(CO_3)^{2-}$  gives an effective charge of +1/3 for Ca atoms [26]. In this model, a charge of +1/4 is assumed for Ca atoms, following the approach in [25,26]. The crude oil surface reactions are similar to the models used in [20,21,28]. The SCM equations are solved using PHREEQC software [29], whereby the double layer model is specified. In the model, the concentration of adsorbed surfaces complexes (adsorbed ions) determines the total surface charge as follows:

$$\sigma = \frac{F}{SA} \sum Z_i c_i \quad (1)$$

where  $\sigma$  is the surface charge density (C/m<sup>2</sup>), F is the Faraday constant (96493.5 C/mol), S is the surface material mass (g), A is the specific surface area (m<sup>2</sup>/g), Z<sub>i</sub> is the ionic electric charge, and c<sub>i</sub> is the adsorbed ion concentration (mol). The surface charge and surface-potential are related through the Gouy-Chapman model [29]:

$$\sigma = (8000\epsilon_o\epsilon_wRTI)^{1/2} \sinh\left(\frac{\nu F\Psi}{2RT}\right), \quad (2)$$

where  $\epsilon_o$  is the vacuum permittivity  $\left(\frac{C^2}{m}\right)$ ,  $\epsilon_w$  is the water relative permittivity,  $\Psi$  is the surface-potential (V), R is the gas constant  $\left(\frac{J}{mol K}\right)$ , T is the temperature (K), I is the brine ionic strength (mol/l), and  $\nu$  is the electrolyte ionic charge which is assumed to be unity in PHREEQC [29]. The bulk concentration of ions interacts with the adsorbed ions at the surface due to coulombic forces. Hence, the apparent equilibrium constants are considered to include the effect of bulk concentration of the ions. The apparent

and intrinsic equilibrium constants (listed in Tables 4 and 5) are described through the Boltzmann distribution [29]:

$$K_{app} = K_{int} \exp\left(\frac{Z_c F \Psi_s}{RT}\right), \quad (3)$$

where  $Z_c$  is the net change of the surface charge at the surface due to surface reaction. The zeta-potential  $\zeta$  can be approximated from the surface-potential based on the linearized Debye-Huckel theory [25], which is valid for  $|\Psi| \leq 25$  mV [30]:

$$\zeta = \psi \exp(-\kappa d_s), \quad (4)$$

where  $\kappa$  is the inverse Debye length-scale, and  $d_s$  is the slipping plane distance from the outer Helmholtz plane. For brines with ionic-strength of 0.1 mol/l (the considered brine recipes except for sea water), the slipping distance  $d_s$  is 0.33 nm [25, 26], while the Debye length  $\kappa^{-1}$  is 0.97 nm. For the seawater case (ionic strength of 1.1 mol/l),  $d_s$  is 0.1 nm ( $d_s = 0.1/c^{0.5}$  [26]), while  $\kappa_{sw}^{-1}$  is 0.29 nm. The site density for calcite surface is 4.95 sites/nm<sup>2</sup> [26, 27], while the crude oil surface has a site density of 0.47 sites/nm<sup>2</sup> [28]. The calcite specific surface area is 1 m<sup>2</sup>/g [26], while the crude oil specific area is 0.5 m<sup>2</sup>/g [28]. Additional details of the above SCM equations are elaborated in [29,31].

**Table 4.** Surface Complexation Reactions and Parameters for the Calcite Surface.

Calcite Surface Reaction	Equilibrium Constant ( $\log_{10} K_{int}$ )
$>CaOH^{-0.75} + H^+ \leftrightarrow >CaOH_2^{+0.25}$	0.4
$>CO_3H^{+0.75} + OH^- \leftrightarrow >CO_3^{-0.25} + H_2O$	0.5
$>CaOH^{-0.75} + Ca^{2+} \leftrightarrow >CaOH..Ca^{+1.25}$	1.53
$>CaOH^{-0.75} + Mg^{2+} \leftrightarrow >CaOH..Mg^{+1.25}$	1.15
$>CO_3H^{+0.75} + SO_4^{2-} \leftrightarrow >CO_3H..SO_4^{-1.25}$	1.5
$>CO_3H^{+0.75} + CO_3^{2-} \leftrightarrow >CO_3H..CO_3^{-1.25}$	2.23
$>CO_3H^{+0.75} + HCO_3^- \leftrightarrow >CO_3H..HCO_3^{-0.25}$	0.09
$>CaOH^{-0.75} + Na^+ \leftrightarrow >CaOH..Na^{+0.25}$	0.22
$>CO_3H^{+0.75} + Cl^- \leftrightarrow >CO_3H..Cl^{-0.25}$	0.65

**Table 5.** Surface Complexation Reactions and Parameters for the Crude Oil Surface.

Crude Oil Surface Reaction	Equilibrium Constant ( $\log_{10} K_{int}$ )
$-COOH \leftrightarrow -COO^- + H^+$	6
$-N + H^+ \leftrightarrow -NH^+$	4
$-COOH + Ca^{+2} \leftrightarrow -COOCa^+ + H^+$	-4
$-COOH + Mg^{+2} \leftrightarrow -COOMg^+ + H^+$	-4.3
$-COOH + Na^+ \leftrightarrow -COONa + H^+$	-4

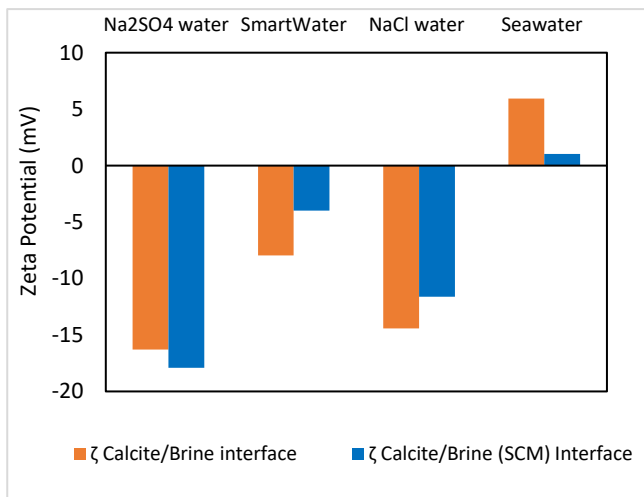
### 3. Results and Discussion

Figures 2 to 7 compare the SCM and experimental measurements of the zeta-potential values for different brine recipes with and without alkali. First, the zeta-potentials for brine/calcite interface are analyzed, followed by the brine/crude oil interface. The intrinsic

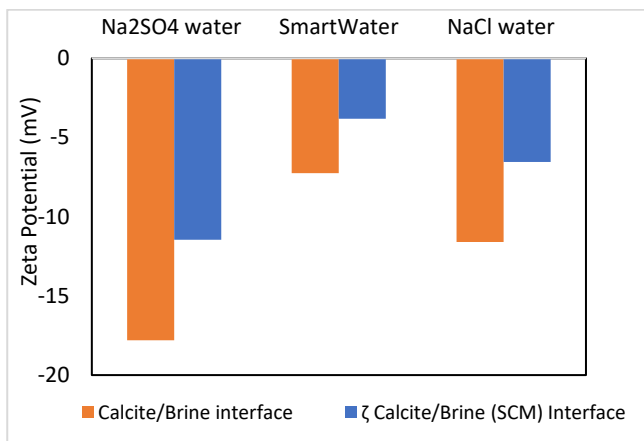
equilibrium constants are varied in the SCM to match the measured zeta-potentials. The number of fitting parameters is equal to the number of surface reaction equations (nine equations for calcite/brine interface, and five equations for the crude oil/brine interface). The site density and specific surface area of the considered surfaces are fixed (see Section 2.2). For the brine/calcite interface (Figures 2-4), the SCM results follow the trends observed in experimental data, and quantitatively agree with the lab zeta-potential measurements especially for NaCl, SmartWater, and Na<sub>2</sub>SO<sub>4</sub> brines. For the seawater case without alkali, the SCM underestimates the zeta-potential as can be seen in Figure 2. When NaOH alkaline is added to the brine recipes, the change in zeta-potential values of calcite/brine interface is almost negligible and in agreement with the experimental zeta-potential measurements as illustrated in Figure 3 (within 2.5 mV difference). The addition of (OH)<sup>-</sup> ions increases the negative charge, and decreases the adsorption of H<sup>+</sup> protons while adding Na<sup>+</sup> ions increase the charge positivity resulting in an insignificant total change in the surface charge. For the Na<sub>2</sub>CO<sub>3</sub> alkaline, the SCM calcite/brine zeta-potentials decrease for the considered brine recipes as displayed in Figure 4. This decrease in zeta-potential values is mainly due to the presence of divalent anion carbonate (CO<sub>3</sub>)<sup>-2</sup>, which forms a surface complex on the calcite surface with a -1.25 charge as illustrated in reaction 6 in Table 3. Calcite precipitation/dissolution has not been considered in SCM, which is likely to contribute to the slight discrepancy observed in the SmartWater recipe case in Figure 4. The intrinsic equilibrium constants (fitting parameters) in Table 4 are in agreement with the work of Song et al. [25] except for the Cl<sup>-</sup> ion which has the largest discrepancy. The SCM confirms that the total surface charge and zeta-potential of calcite/brine interface strongly depend on the divalent ions (Ca<sup>2+</sup>, Mg<sup>2+</sup>, CO<sub>3</sub><sup>2-</sup>, and SO<sub>4</sub><sup>2-</sup>) due to large intrinsic equilibrium constants compared to the other ions. The SCM predicts that the most effective ion in pushing the calcite surface charge to a negative value is the divalent anion carbonate (CO<sub>3</sub>)<sup>-2</sup>, which has the largest equilibrium constant.

For the crude oil/brine interface cases, the SCM zeta-potential results qualitatively match the experimental observations. The predicted zeta-potentials are in general negatively charged as shown in Figure 5, which agree with the experimental results. The equilibrium constants in Table 5 agree with the values reported in the literature [21,28] (the discrepancy in the equilibrium constants are within a value of one for each reaction). At pH > 7 (greater than the isoelectric point for crude oil/brine interface with a similar acid number [32]), the carboxylic acids in crude oil are not completely protonated (reaction 1 in Table 5). Also, the protonation of nitrogen bases (reaction 2 in Table 5) is not sufficient to switch the crude oil surface to a positive charge. When alkali is added to the brine recipe (Figures 6 and 7), the variation in SCM zeta-potentials is less than 2 mV. The zeta-potentials slightly increase in the positive side, especially for NaOH alkaline. This slight increase is not expected as the protonation activity decreases with the increase of the brine pH level.

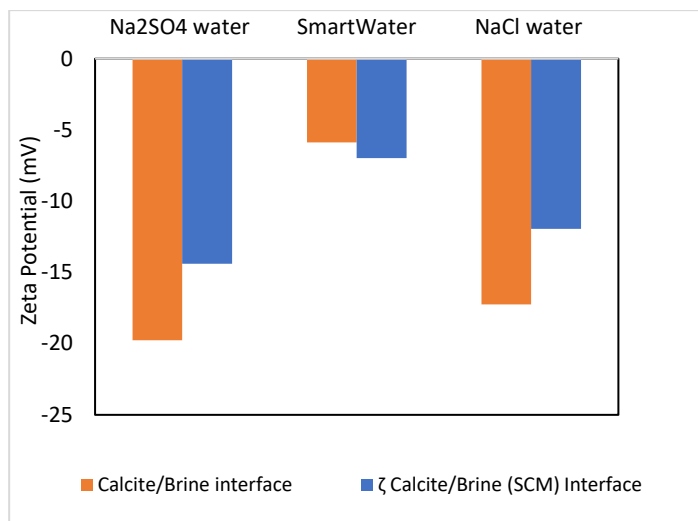
However, the reactions in SCM predict that the adsorption of  $Mg^{2+}$  and  $Ca^{2+}$  (reactions 3 and 4) slightly compensates for the decrease in  $H^+$ , which results in a small increase in the zeta-potential. Based on the model predictions of calcite/brine and brine/crude oil zeta-potentials, the  $Na_2SO_4$  brine with  $Na_2CO_3$  alkaline provides the largest interface negative charges (**Figures 4 and 7**). The modeling results support the conclusion drawn from the experiments that the  $Na_2SO_4$  brine with  $Na_2CO_3$  alkaline is the preferable brine recipe to synergize with anionic surfactants due to its large negative zeta-potential. This large negative zeta-potential increases the water-wetness towards carbonate reservoir [16] and reduces the anionic surfactant retention [15]. Further improvement and refinement in the SCM will be considered as this is a starting point for ongoing research in electrokinetic modeling. Such improvements include using an SCM triple-layer model, non-linear diffuse double layer model to infer zeta-potential from the surface-potential, and adding dissolution/precipitation reactions for the calcite/brine interface. Also, including the crude oil chemistry (acid/base numbers) to be part of the surface site density [33] of nitrogen base and carboxylate groups will improve the SCM for the crude oil/brine interface.



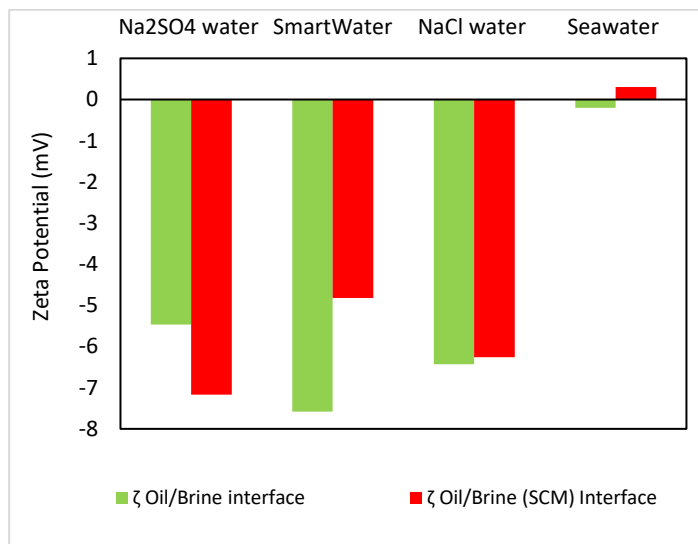
**Figure 2:** Experimental and SCM  $\zeta$ - potential values at the calcite/brine interface



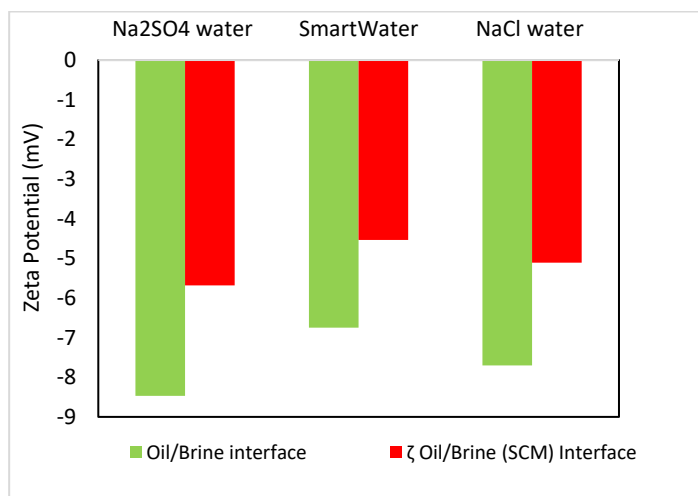
**Figure 3:** Experimental and SCM  $\zeta$ - potential values at the calcite/brine interface. Brine is containing 0.1 wt.% NaOH.



**Figure 4:** Experimental and SCM  $\zeta$ - potential values at the calcite/brine interface. Brine is containing 0.1 wt.%  $Na_2CO_3$ .

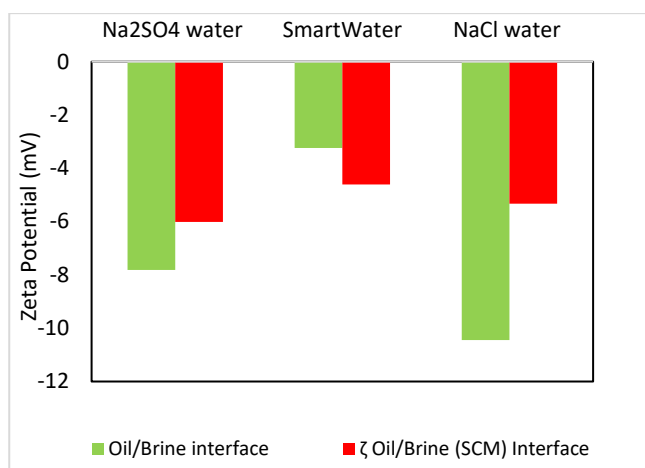


**Figure 5:** Experimental and SCM  $\zeta$ - potential values at the oil/brine interface.



**Figure 6:** Experimental and SCM  $\zeta$ - potential values at the oil/brine interface. Brine is containing 0.1 wt.% NaOH.





**Figure 7:** Experimental and SCM  $\zeta$ - potential values at oil/brine interface. Brine is containing 0.1 wt.% Na<sub>2</sub>CO<sub>3</sub>.

#### 4. Conclusions

This work explores the electrokinetic interactions of different brine recipes with and without alkali in carbonates using Surface Complexation Model (SCM). Various SCM calculations of brine/calcite and crude oil/brine zeta-potentials are conducted to evaluate the synergy between different brine recipes and alkali chemicals. The proposed SCM predicts zeta-potential results that are consistent with the experimental measurements for choosing the Na<sub>2</sub>SO<sub>4</sub> brine with Na<sub>2</sub>CO<sub>3</sub> alkaline to be the most suitable alkaline-based recipe due to its large negative zeta-potentials. In alkaline/surfactant EOR process, the negative electrokinetic calcite charge repels the anionic surfactant causing a reduction in surfactant retention. The modeling of zeta-potential results quantitatively agree with the experiments for the calcite/brine interface. For the crude oil/brine interface, the SCM zeta-potential results reasonably match the experimental measurements. Further correlation of the carboxylic acid group and nitrogen base crude oil active surface sites with the acid/base number is required [33] to quantitatively predict accurate zeta-potentials and gain additional insights on the electrokinetics of crude oil surfaces.

#### Acknowledgements

The authors thank Hussain Saleem and Dong kyu Cha, Saudi Aramco for their help with zeta-potential measurements.

#### References

1. T. Austad, S. Strand, E. Høgenesen, P. Zhang. "Seawater as IOR fluid in fractured chalk". In *SPE international symposium on oilfield chemistry* 2005 Jan 1. Society of Petroleum Engineers.
2. A. Yousef, S. Al-Saleh, A. Al-Kaabi, M. Al-Jawfi. "Laboratory investigation of the impact of injection-

water salinity and ionic content on oil recovery from carbonate reservoirs". *SPE Reservoir Evaluation & Engineering*. 2011 Oct 1;14(05):578-93.

3. A. Yousef, J. Liu, G. Blanchard, S. Al-Saleh, T. Al-Zahrani, R. Al-Zahrani, H. Al-Tammar, N. Al-Mulhim. "Smart waterflooding: industry". In *SPE Annual Technical Conference and Exhibition* 2012 Jan 1. Society of Petroleum Engineers.
4. D. Ligthelm, J. Gronsveld, J. Hofman, N. Brussee, F. Marcelis, H. Van der Linde. "Novel Waterflooding Strategy by Manipulation Of Injection Brine Composition". In *EUROPEC/EAGE conference and exhibition* 2009 Jan 1. Society of Petroleum Engineers.
5. N. Morrow, J. Buckley. "Improved oil recovery by low-salinity waterflooding". *Journal of Petroleum Technology*. 2011 May 1;63(05):106-12.
6. H. Mahani, A. Keya, S. Berg, W. Bartels, R. Nasralla, W. Rossen. "Insights into the mechanism of wettability alteration by low-salinity flooding (LSF) in carbonates". *Energy & Fuels*. 2015 Mar 3;29(3):1352-67.
7. M. Jackson, D. Al-Mahrouqi, J. Vinogradov. "Zeta-potential in oil-water-carbonate systems and its impact on oil recovery during controlled salinity water-flooding". *Scientific reports*. 2016 Nov 23;6:37363.
8. P. McGuire, J. Chatham, F. Paskvan, D. Sommer, F. Carini. "Low salinity oil recovery: An exciting new EOR opportunity for Alaska's North Slope". In *SPE western regional meeting* 2005 Jan 1. Society of Petroleum Engineers.
9. A. Lager, K. Webb, C. Black, M. Singleton, K. Sorbie. "Low salinity oil recovery-an experimental investigation-1". *Petrophysics*. 2008 Feb 1;49(01).
10. D. Al Mahrouqi, J. Vinogradov, M. Jackson. "Zeta-potential of artificial and natural calcite in aqueous solution". *Advances in colloid and interface science*. 2017 Feb 1;240:60-76.
11. M. Jackson, J. Vinogradov, G. Hamon, M. Chamerois. "Evidence, mechanisms and improved understanding of controlled salinity waterflooding part 1: Sandstones". *Fuel*. 2016 Dec 1;185:772-93.
12. S. Ayirala, A. Yousef. "A state-of-the-art review to develop injection-water-chemistry requirement guidelines for IOR/EOR projects". *SPE Production & Operations*. 2015 Feb 1;30(01):26-42.
13. S. Ayirala, E. Uehara-Nagamine, A. Matzakos, R. Chin, P. Doe, P. Van den Hoek. "A designer water process for offshore low salinity and polymer flooding applications". In *SPE Improved Oil Recovery Symposium* 2010 Jan 1. Society of Petroleum Engineers.
14. W. Alameri, T. Teklu, R. Graves, H. Kazemi, A. AlSumaiti. "Low-salinity water-alternate-surfactant in Low-permeability Carbonate Reservoirs". In *IOR 2015-18th European Symposium on Improved Oil Recovery* 2015 Apr 14.
15. G. Hirasaki, C. Miller, M. Puerto. "Recent advances in surfactant EOR". *SPE Journal*. 2011 Dec 1;16(04):889-907.

16. G. Hirasaki G, D. Zhang. "Surface chemistry of oil recovery from fractured, oil-wet, carbonate formations". *Spe Journal*. 2004 Jun 1;9(02):151-62.
17. Q. Liu, M. Dong, X. Yue, J. Hou. "Synergy of alkali and surfactant in emulsification of heavy oil in brine". *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2006 Feb 1;273(1-3):219-28.
18. K. Chan, D. Shah. (1981) "The Physico-Chemical Conditions Necessary to Produce Ultralow Interfacial Tension at the Oil/Brine Interface". In: Shah D.O. (eds) *Surface Phenomena in Enhanced Oil Recovery*. Springer, Boston, MA
19. M. Alotaibi, A. Yousef. "The role of individual and combined ions in waterflooding carbonate reservoirs: electrokinetic study". *SPE Reservoir Evaluation & Engineering*. 2017 Feb 1;20(01):77-86.
20. Q. Xie, A. Sari, W. Pu, Y. Chen, P. Brady, N. Al Maskari, A. Saeedi. "pH effect on wettability of oil/brine/carbonate system: Implications for low salinity water flooding". *Journal of Petroleum Science and Engineering*. 2018 Sep 1;168:419-25.
21. P. Brady, J. Krumhansl, P. Mariner. "Surface complexation modeling for improved oil recovery". In *SPE improved oil recovery symposium 2012* Jan 1. Society of Petroleum Engineers.
22. P. Van Cappellen, L. Charlet, W. Stumm, P. Wersin. "A surface complexation model of the carbonate mineral-aqueous solution interface". *Geochimica et Cosmochimica Acta*. 1993 Aug 1;57(15):3505-18.
23. O. Pokrovsky, J. Schott, F. Thomas. "Dolomite surface speciation and reactivity in aquatic systems". *Geochimica et Cosmochimica Acta*. 1999 Oct 1;63(19-20):3133-43.
24. H. Mahani, A. Keya, S. Berg, R. Nasralla. "Electrokinetics of carbonate/brine interface in low-salinity waterflooding: effect of brine salinity, composition, rock type, and pH on  $\zeta$ -potential and a surface-complexation model". *SPE Journal*. 2017 Feb 1;22(01):53-68.
25. J. Song, Y. Zeng, L. Wang, X. Duan, M. Puerto, W. Chapman, S. Biswal, G. Hirasaki. "Surface complexation modeling of calcite zeta-potential measurements in brines with mixed potential determining ions ( $\text{Ca}^{2+}$ ,  $\text{CO}_3^{2-}$ ,  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$ ) for characterizing carbonate wettability". *Journal of colloid and interface science*. 2017 Nov 15;506:169-79.
26. F. Heberling, T. Trainor, J. Lützenkirchen, P. Eng, M. Denecke, D. Bosbach. "Structure and reactivity of the calcite-water interface". *Journal of colloid and interface science*. 2011 Feb 15;354(2):843-57.
27. J. Song, S. Rezaee, L. Zhang, Z. Zhang, M. Puerto, O. Wani, F. Vargas, S. Alhassan, S. Biswal, G. Hirasaki. "Characterizing the Influence of Organic Carboxylic Acids and Inorganic Silica Impurities on the Surface Charge of Natural Carbonates Using an Extended Surface Complexation Model". *Energy & Fuels*. 2019 Jan 11;33(2):957-67.
28. T. Takeya, M. Shimokawara, Y. Elakneswaran, T. Nawa, S. Takahashi. "Predicting the electrokinetic properties of the crude oil/brine interface for enhanced oil recovery in low salinity water flooding". *Fuel*. 2019 Jan 1;235:822-31.
29. D. Parkhurst, C. Appelo. "Description of input and examples for PHREEQC version 3: a computer program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations". *US Geological Survey*; 2013.
30. J. Israelachvili. "Intermolecular and surface forces". *Academic press*; 2011 Jul 22.
31. D. Dzombak, F. Morel. "Surface complexation modeling: hydrous ferric oxide". *John Wiley & Sons*; 1990 Mar 16.
32. J. Buckley, K. Takamura, N. Morrow. "Influence of electrical surface charges on the wetting properties of crude oils". *SPE Reservoir Engineering*. 1989. 4(03):332-340.
33. M. Bonto, A. Eftekhari, H. Nick. "An overview of the oil-brine interfacial behavior and a new surface complexation model". *Scientific reports*. 2019 Apr 15;9(1):6072.