SmartWater for EOR – Importance on initial wettability at laboratory experiments

John C. Zuta, Research director, NORCE Energy

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NORCE Energy

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  - **EOR/SCAL** — John C. Zuta — Stavanger
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  - **Subsurface characterization, simulation and geomatics** — Roman Berenblyum — Stavanger
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  - **Ullrigg Test Centre** — Gunleik Sandsmark — Stavanger
    - **Driftspersonell** — Steinar Lomeland — Stavanger

EOR - SCAL group

NORCE

- Laboratory investigations of **IOR and EOR** processes from pore to core scale at **semi-reservoir** to **real reservoir conditions**
- Measurement of **petrophysical properties** (Pc, wettability and Kr) at **semi reservoir** to **real reservoir** conditions
- **Interpretation of experimental data** using commercial/in-house reservoir simulation tools
- CCUS – Carbon Capture, Utilization and Storage

Who we are:

- Expertise in petroleum and reservoir engineering, chemistry, and physics
- 26 permanent research staff (including 2 PhDs and 1 post-doc)
- Located in Stavanger and Bergen
- Research director: John C. Zuta: jozu@norceresearch.no
- Chief scientists: Ingebret Fjelde, Arne Stavland, Ying Guo (Senior business developer)

Current research projects

NORCE

- **SmartWater and low salinity EOR**
  - SmartWater compositions
  - Modelling of EOR mechanisms
  - Water treatment for PWRI
- **Conformance control**
  - Silicate for water diversion
  - Polymer based diversion
  - Foam for gas and CO_2 diversion
- **Polymer EOR**
  - Advanced and green polymer
  - Polymer EOR for heavy oil Operational issues
- **CO_2 EOR**
  - Foam for gas and CO_2 diversion
  - CO_2 transport in porous media
  - Carbonated water for EOR

- **CCS – CO_2 injection**
  - Injectivity impairment
  - Polymer resins for remediation of CO_2 wells
- **EOR for heterogeneous carbonates**
  - Middle East carbonates
  - Brazil Pre-Salt reservoirs
- **Core scale modelling**
  - IORCoreSim
  - SENDRA and other alternatives
- **SCAL – special core analyses**
  - Petrophysical and flow properties from rock Imaging with 1D X-ray
  - History matching of SCAL data

- **Innovation/Emerging technologies**
  - In-situ water pressure measurement
  - Nano-fluids for EOR and tracers

The National IOR Centre of Norway

CLIMIT

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Outline

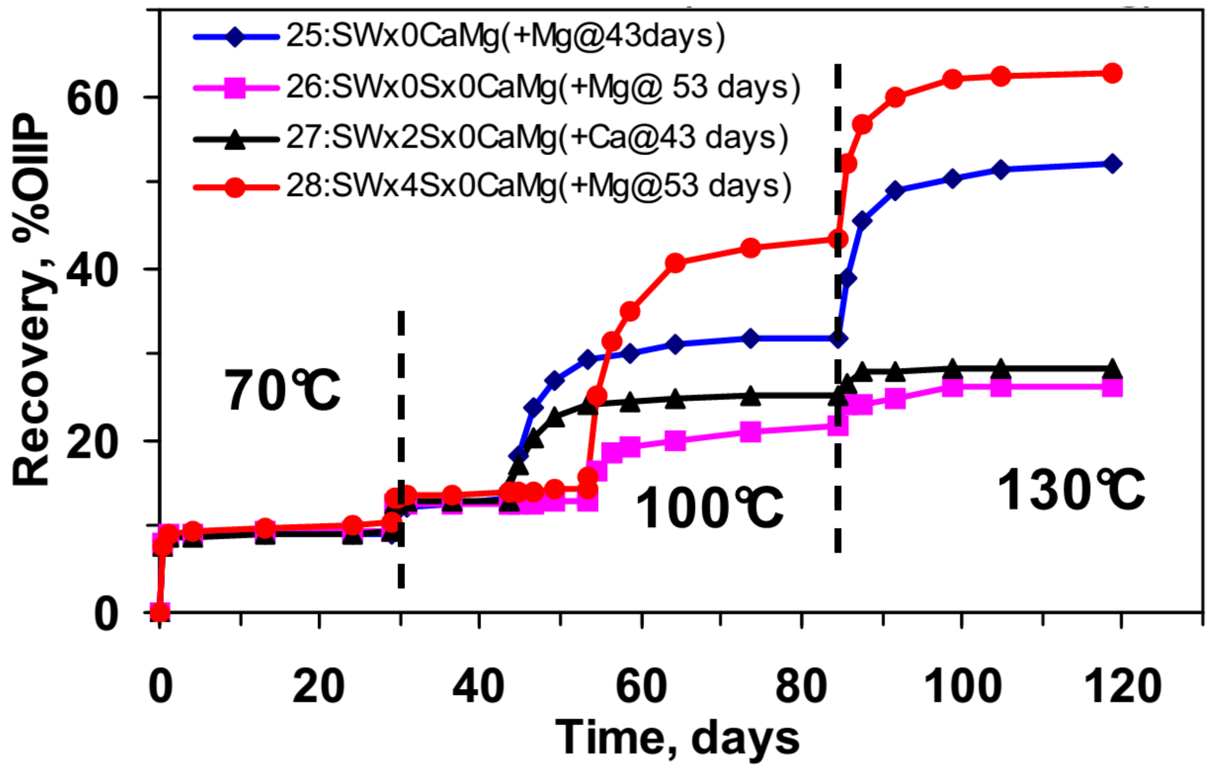
- Background
- Objectives
- Scope of project
- Laboratory experiments
- Modeling of lab experiments labs
- Conclusions

What is Smart water?

- «Smart water» made by adjusting/optimizing the ion composition of injection water
- «Smart water» can improve wetting properties of oil reservoirs and optimize fluid flow/oil recovery in porous media during oil production
- The main advantage is change in wetting properties which can have a positive effect on the capillary pressure and relative permeability curves
  - Wetting dictates:
    - Capillary pressure curve; $P_c = f(S_w)$
    - Relative permeability; k_{ro} and $k_{rw} = f(S_w)$

Smart water in Outcrop Chalk Austad's group – past 20 years

- Potential determining ions; Mg^{2+}, Ca^{2+} and SO_4^{2-} in brine had a significant effect on imbibition rates during oil recovery in Stevns Klint Outcrop Chalk



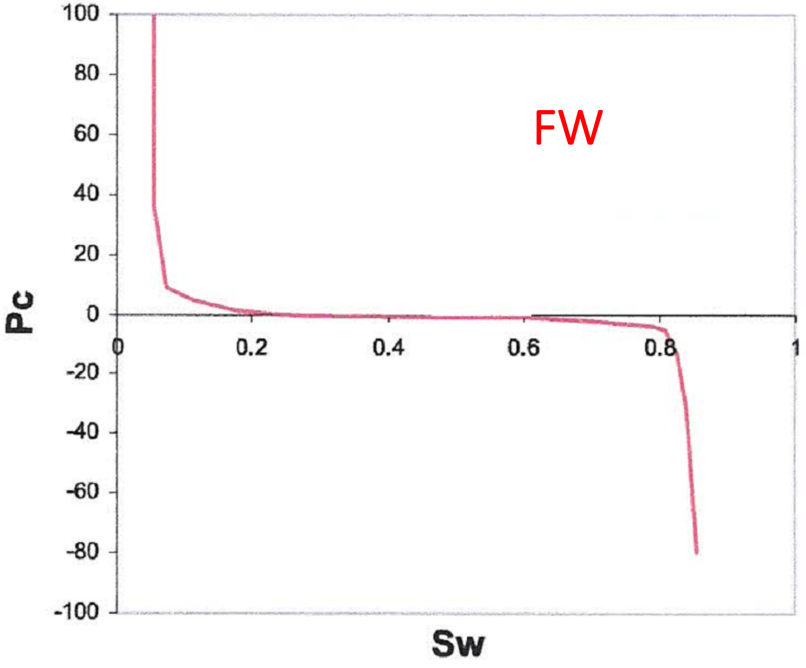
Zhang et al. 2007.Wettability alteration and improved oil recovery by spontaneous imbibition of seawater into chalk: impact of potential of the potential determining ions. Colloids Surf. A Physicohem. Eng. Aspects 301: 199-208

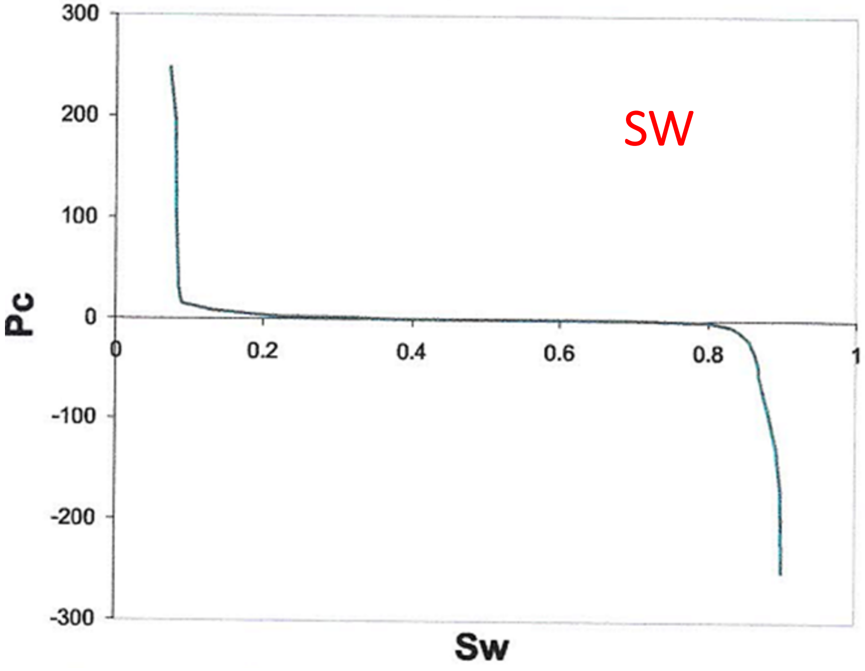
Model brine compositions

Ionic species	FW [mol/l]	SW [mol/l]
Na^+	0.685	0.450
Mg^{2+}	0.025	0.010
Ca^{2+}	0.231	0.013
K^+	0	0.010
Cl^-	1.197	0.528
SO_4^{2-}	0	0.024
HCO_3^-	0	0.002
TDS	**2.138**	**1.037**

Smart water in Valhall core plug (Webb et al. 2005, IPTC 10506)

- Laboratory experiments and representative fluids at 90°C. Additional oil was attributed to wettability alteration
- Oil recoveries with FW and SW:
  - P_c=0, FW: 22.4 % PV and SW: 31% PV
  - P_c= -1 psi, FW: ~ 45% PV and SW: ~ 60% PV





Model brine compositions

Ionic species	FW [mol/L]	SW [mol/L]
Na^+	1.058	0.404
Mg^{2+}	0.0067	0.052
Ca^{2+}	0.018	0.0099
K^+	0.0054	0.0095
Cl^-	0.780	0.148
I^-	0.335	0.335
SO_4^{2-}	0	0.028
HCO_3^-	0	0.0023
TDS	**2.203**	**0.9862**

Single well field case studies

Field name	Lithology	Injected/formation water (Kppm)	Incremental oil recovery	Reference
-	Sandstone	3/220	25-50 %	Webb et al. 2004
Alaska North Slope	Sandstone	0.15 – 1.5/15	13 %	McGuire. 2005
North/West Semlek	Sandstone	10/128	-	Robertson. 2007
Alaska field	Sandstone	2.6/16.64	10 %	Lager. 2008
Omar/Isa field	Sandstone	2.2/90	10-15 %	Vledder. 2010
Endicott field	Sandstone	12	13 %	Seccombe. 2010
Snorre field	Sandstone	0.4/34.0	low	Skrettingland et al. 2011
Saudi Aramco	Carbonate	57.6/210	16-18 %	Yousef et al. 2012
Claire Ridge	Sandstone	14.6	-	Robbana et al. 2012

Motivation

- Evaluate effect of softened seawater (membrane filtered) in chalk
- Optimize softened seawater with "smarter ions"

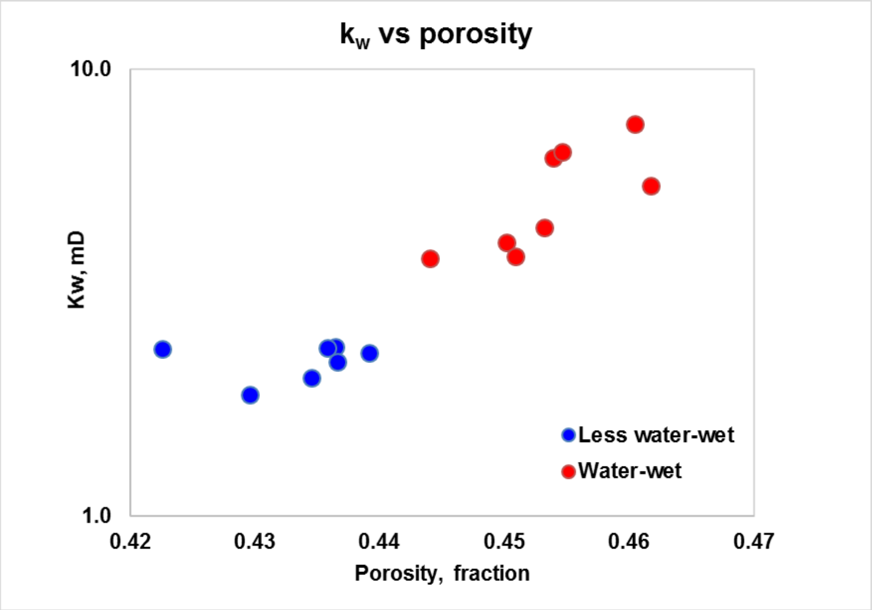
Scope

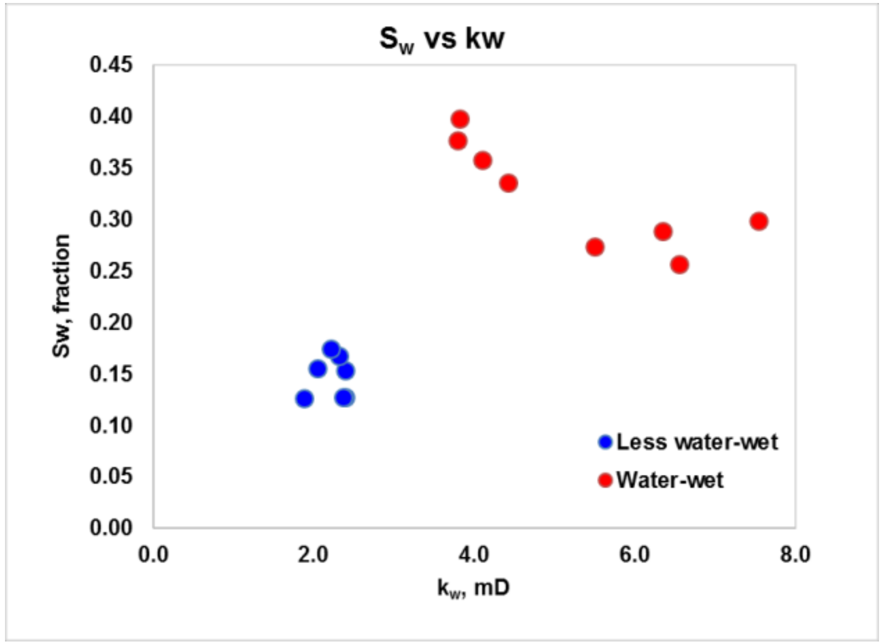
- Brine compositions
  - Baseline seawater (SW)
  - Modified softened seawater (MSSW)
- Type of experiments
  - Spontaneous imbibition
  - Viscous flooding
- **Rock type**
  - Outcrop chalk rock
- **Effect of wettability**
  - Water-wet and less-water wet (mixed wet)
- Interpretation/Simulation of experimental results with IORCoreSim

	Sea Water (ppm)	Modified (softened) sea water (ppm)
Na^+	10,345	8,848
K^+	391	358
Mg^{2+}	1,094	29.6
Ca^{2+}	521	37.2
Cl^-	18,648	14,074
HCO_3^-	122	58
SO_4^{2-}	2,305	19
TDS	**33,426**	**23,423**

Preparation of plugs

- **Outcrop chalk**: Stevns Klint (Denmark)
  - Diameter: 3.8 cm; Length: 7.0 cm
- **Cleaning and saturation**
  - FW
    - Measure PV and k_a (S_w=1)
- **Drainage to S_{wi}**
  - Confined porous plate method with N_2-gas
    - Water-wet: ~ 25-40 %
    - Less water-wet: ~ 10-20%
- **Ageing**
  - Continuous injection with STO at 90^{o}C
    - Water-wet: 48 hrs at 7 cm/day
    - Less water-wet: 80 hrs at 1 cm/hr
  - Measure k_o (S_{wi}) and resistivity index





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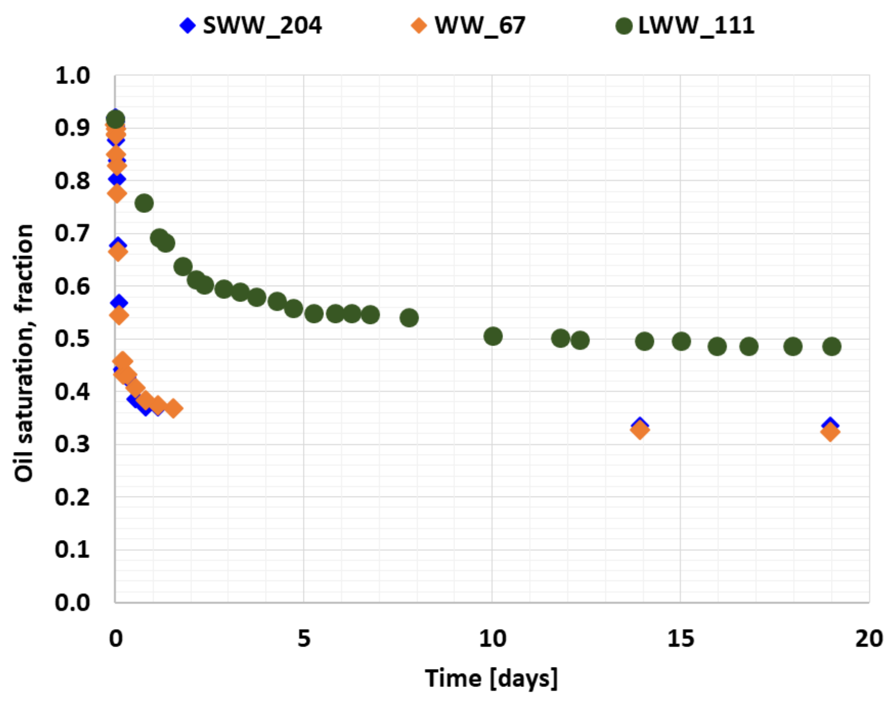
Wettability characterization with FW @ reservoir temperature

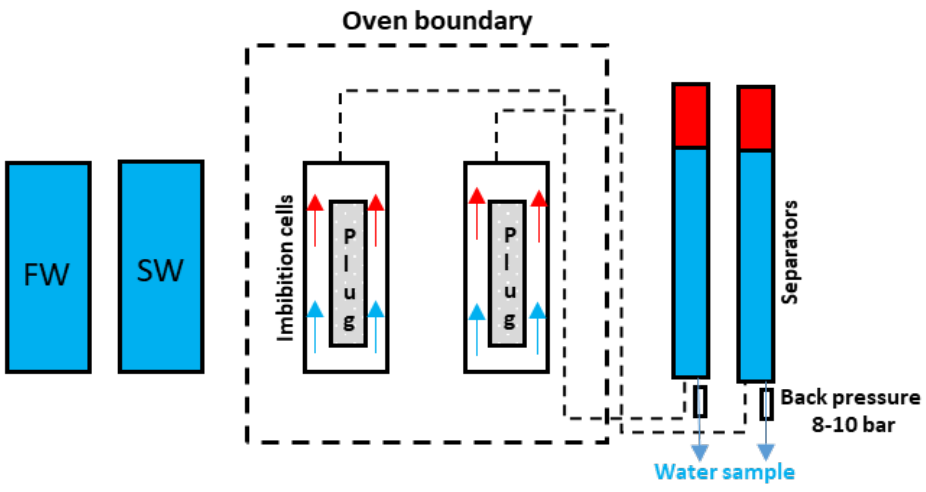
- Basic Amott-Harvey wettability test at reservoir temperature:
  - Start with plugs at S_{wi}
  - Amott A – Spontaneous imbibition of water (V_{AA})
  - Amott B – Forced imbibition of water with flooding (V_{AB})

    - $I_w = V_{AA} / (V_{AA}+V_{AB})$



Plug id	S_{wi}	Wett.	S_{or} (End of Spont. Imb.)	S_{orw} (End of Viscous Flood)	S_{orw} (Based on ion-exchange titrations)	I_w
			From Produced Volumes			
204	0.079	SWW	0.33	0.33	0.33	1.0
67	0.093	WW	0.32	0.32	0.34	1.0
111	0.082	LWW*	0.49	0.29	0.29	0.65

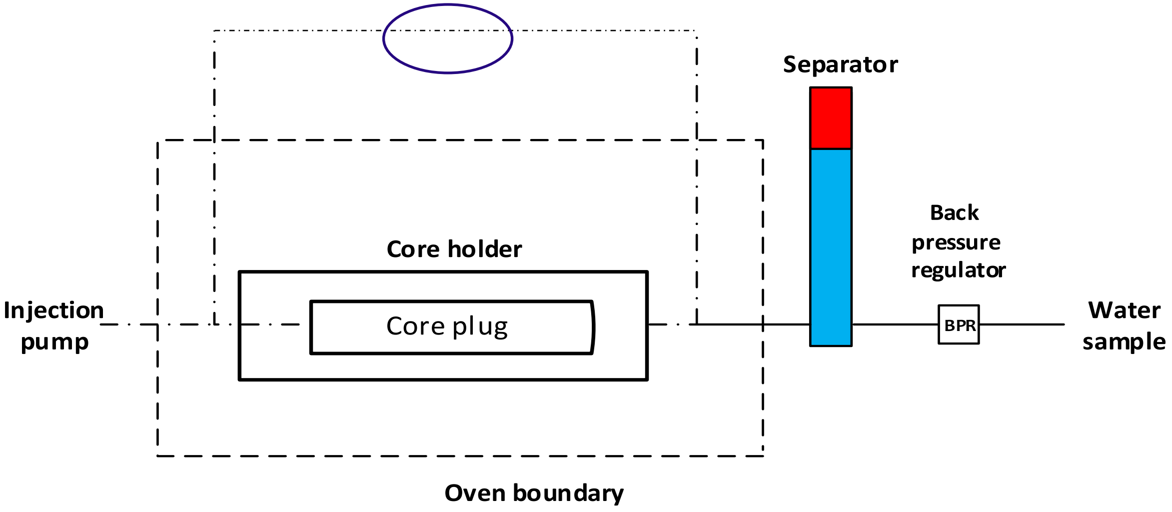
Spontaneous imbibition @ reservoir temperature



Measurements:

- Oil production
- Saturation control (end of viscous flooding)
- Water analysis; pH. Na^+. K^+. Mg^{2+}. Ca^{2+}. Cl^- and SO_4^{2-}

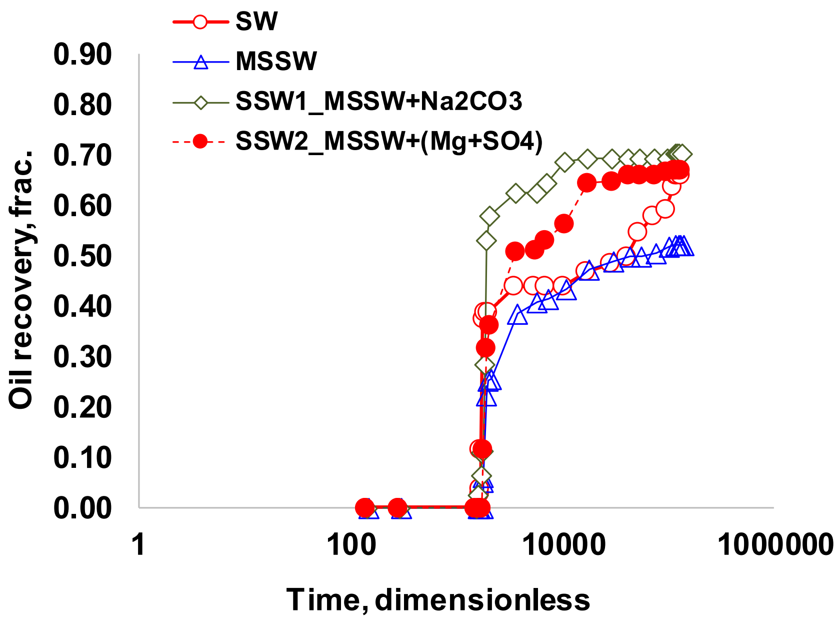
Viscous flooding



Measurements:

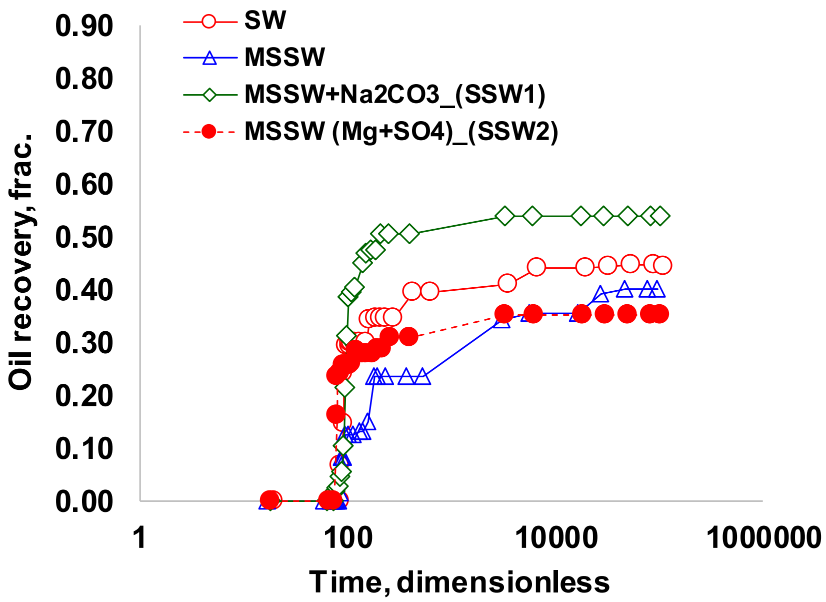
- Rates:
    - 1 PV/day and bump rates: 0.1 and 0.2 ml/min
- Oil productions / differential pressures
- Saturation control – ion exchange
- Water analysis; pH. Na^+. K^+. Mg^{2+}. Ca^{2+}. Cl^- and SO_4^{2-}

Spontaneous imbibition
Less water-wet vs water-wet plugs



Brine type	k_w mD	S_{wi} frac	$k_{ro}(S_{wi})$	S_w	Oil recovery
SW	2.0	0.19	0.95	0.73	0.66
MSSW	2.4	0.17	0.77	0.60	0.52
SSW1	2.3	0.16	0.79	0.75	0.70
SSW2	2.2	0.14	0.79	0.72	0.67

Trend for improved oil: SSW1>SSW2>SW>MSSW

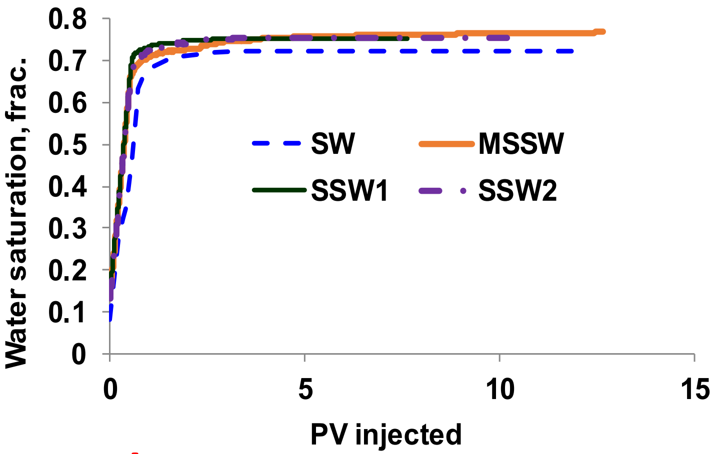


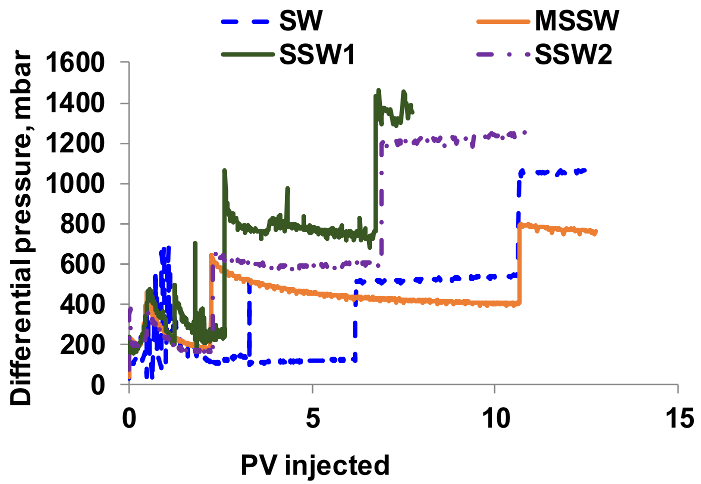
Brine type	k_w mD	S_{wi} frac	$k_{ro}(S_{wi})$	S_w	Oil recovery
SW	7.7	0.26	0.59	0.59	0.45
MSSW	5.5	0.27	0.18	0.56	0.40
SSW1	6.7	0.28	0.57	0.67	0.54
SSW2	6.5	0.30	0.24	0.54	0.35

Trend for improved oil: SSW1>SW>MSSW>SSW2

Viscous flooding
Less water-wet vs water-wet

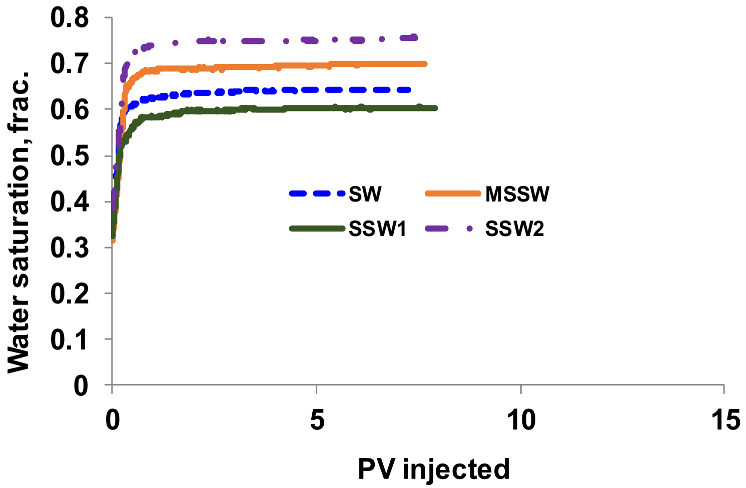
Less water-wet

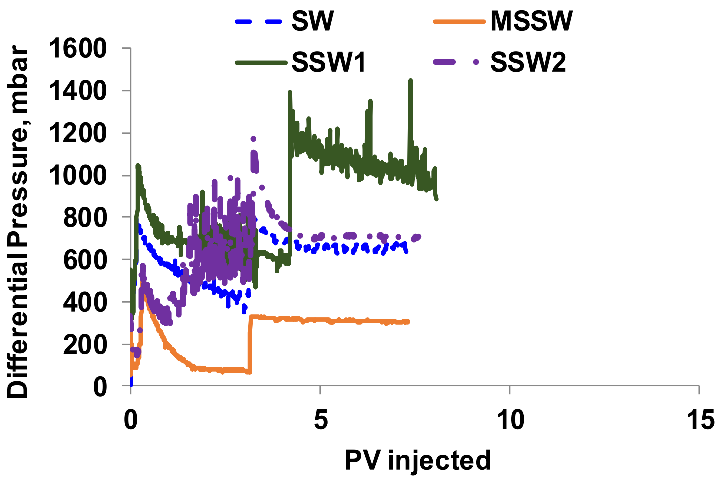




Brine type	k_w mD	S_{wi} frac	k_{ro}	k_{rw}	S_w	Oil recovery frac
SW	4.0	0.09	0.66	0.12	0.77	0.62
MSSW	2.6	0.13	0.98	0.25	0.77	0.64
SSW1	1.9	0.13	0.95	0.12	0.77	0.63
SSW2	2.5	0.13	0.69	0.15	0.72	0.64

Water-wet





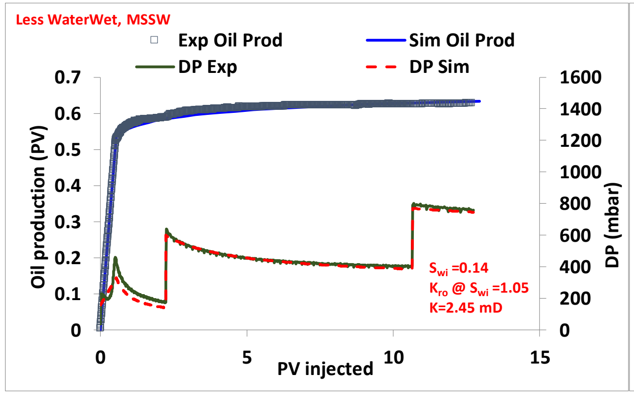
Brine type	k_w mD	S_{wi} frac	k_{ro}	k_{rw}	S_w	Oil recovery frac
SW	4.1	0.34	0.55	0.10	0.65	0.36
MSSW	4.4	0.29	0.75	0.18	0.65	0.48
SSW1	3.9	0.30	0.90	0.07	0.59	0.33
SSW2	3.8	0.36	1.25	0.10	0.71	0.51

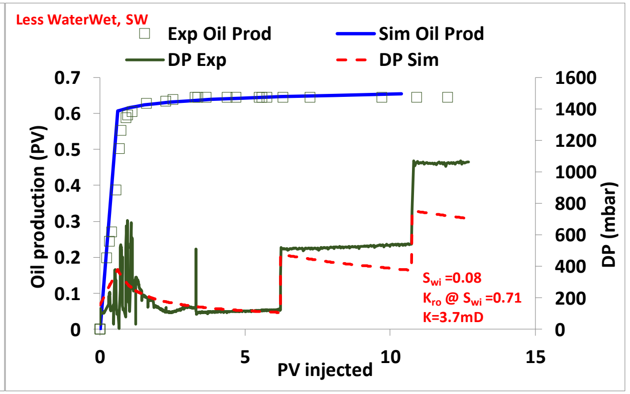
Interpretation of experimental data

- Spontaneous imbibition and viscous flooding lab experiments were interpreted by history matching the experimental data with the IORCoreSim simulator
- IORCoreSim is being developed within the National IOR Centre with special emphasis for simulation of laboratory core experiments
- The following simulator options are important for this project:
    - Geochemical model: Allows simulation of brine/rock interactions including precipitation and dissolution of ions.
    - Interpolation model for relative permeability and capillary pressure. This allows making saturation functions dependent on some property or the presence of a selected component.
    - Spontaneous imbibition boundary conditions: Allows simulations of spontaneous imbibition experiments. It also has the possibility to include diffusive component exchange across the rock fluid boundary.

Viscous floods – Oil production and differential pressure data (less water wet vs water wet)

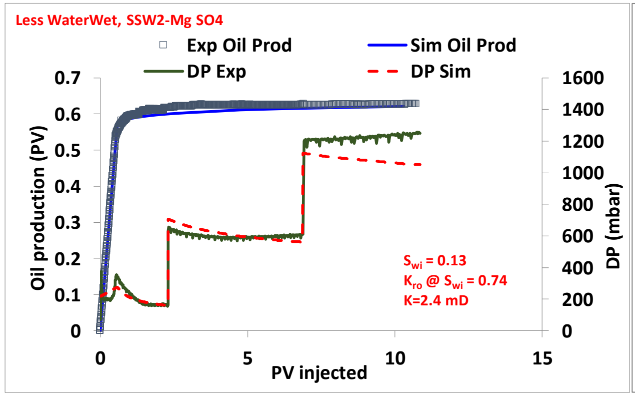
Less water-wet

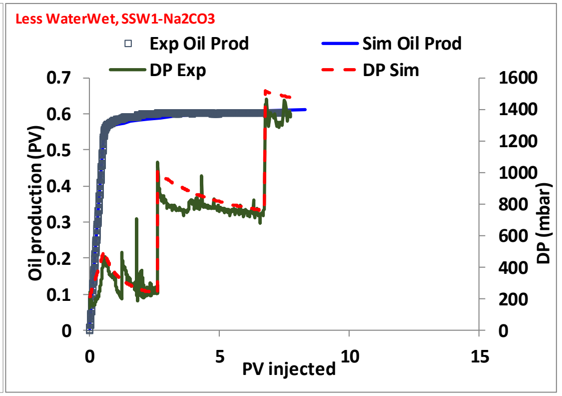




(a) MSSW brine

(b) SW brine

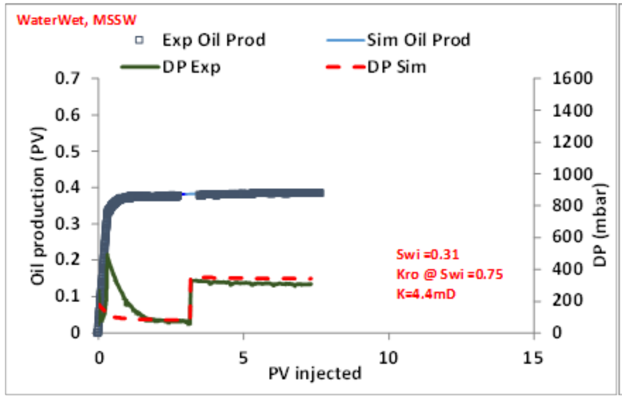


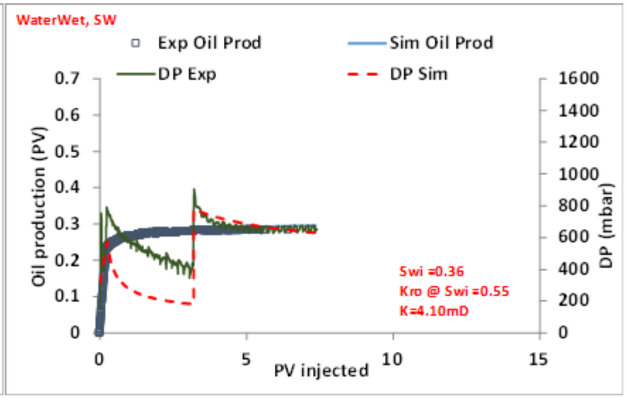


(c) SSW2 brine

(d) SSW1 brine

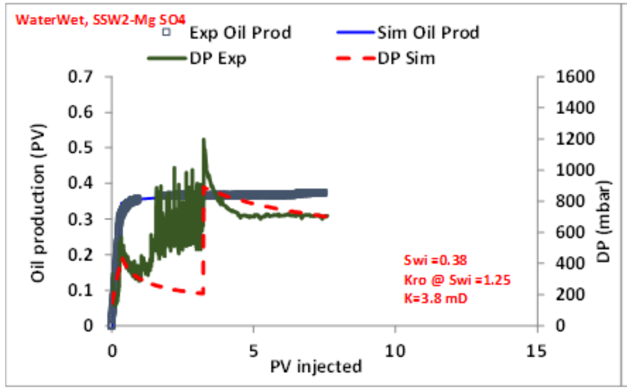
water-wet

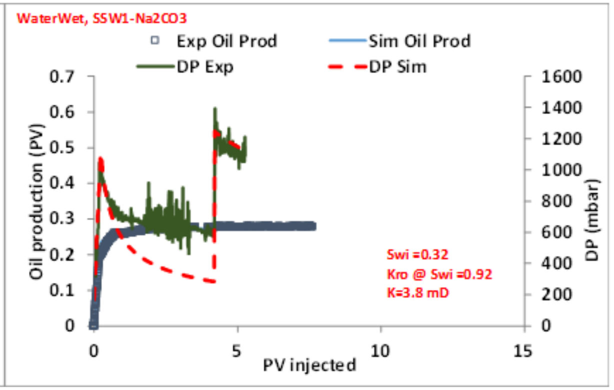




(a) MSSW brine

(b) SW brine



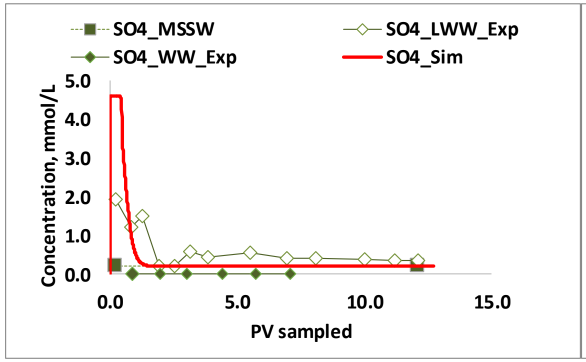


(c) SSW2 brine

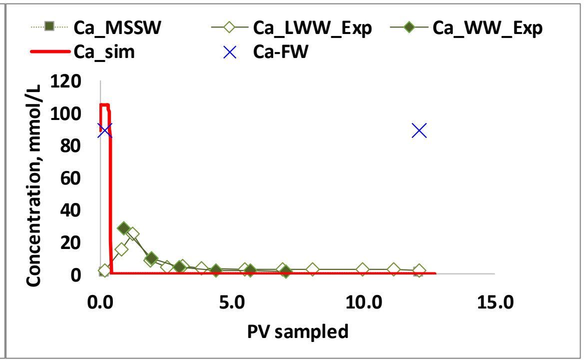
(d) SSW1 brine

Viscous floods – ion concentrations data MSSW vs SW Brines

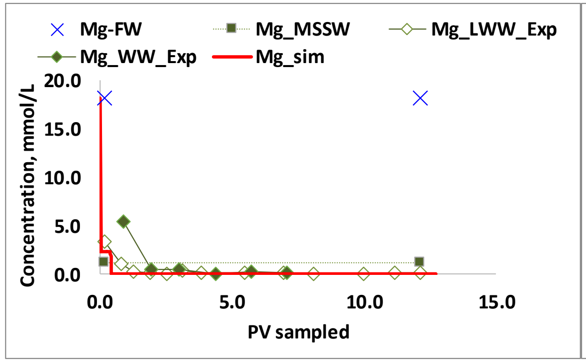
MSSW BRINE



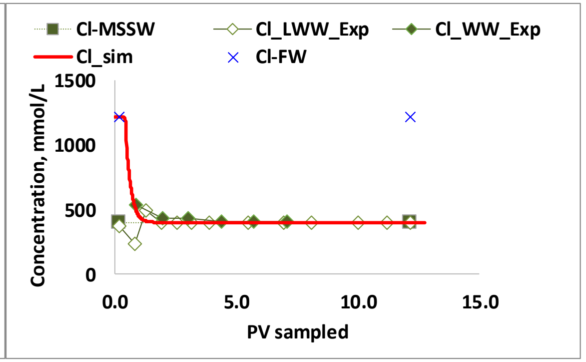
(a) Sulphate profile



(b) Calcium profile

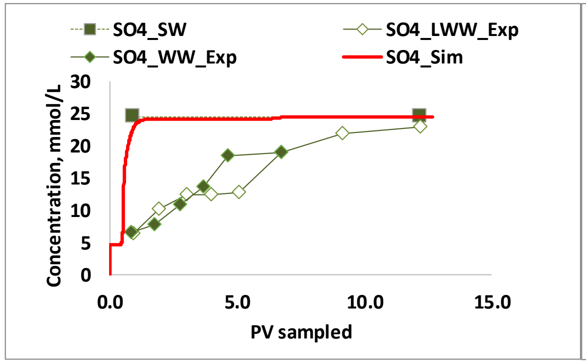


(c) Magnesium profile

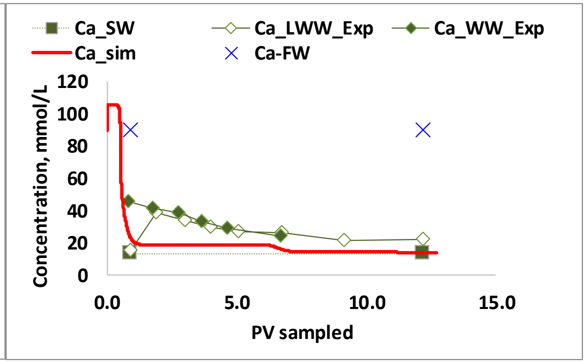


(d) Chloride profile

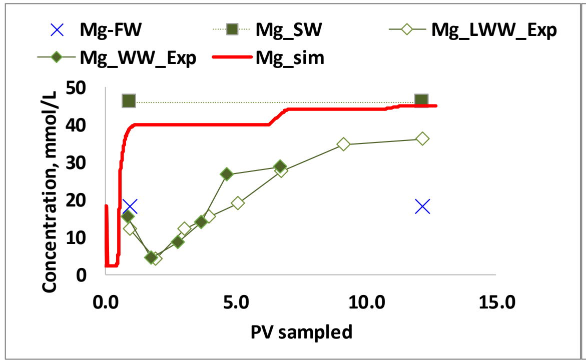
SW BRINE



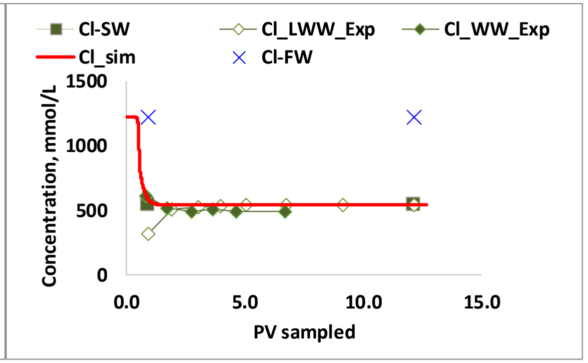
(a) Sulphate profiles



(b) Calcium profiles



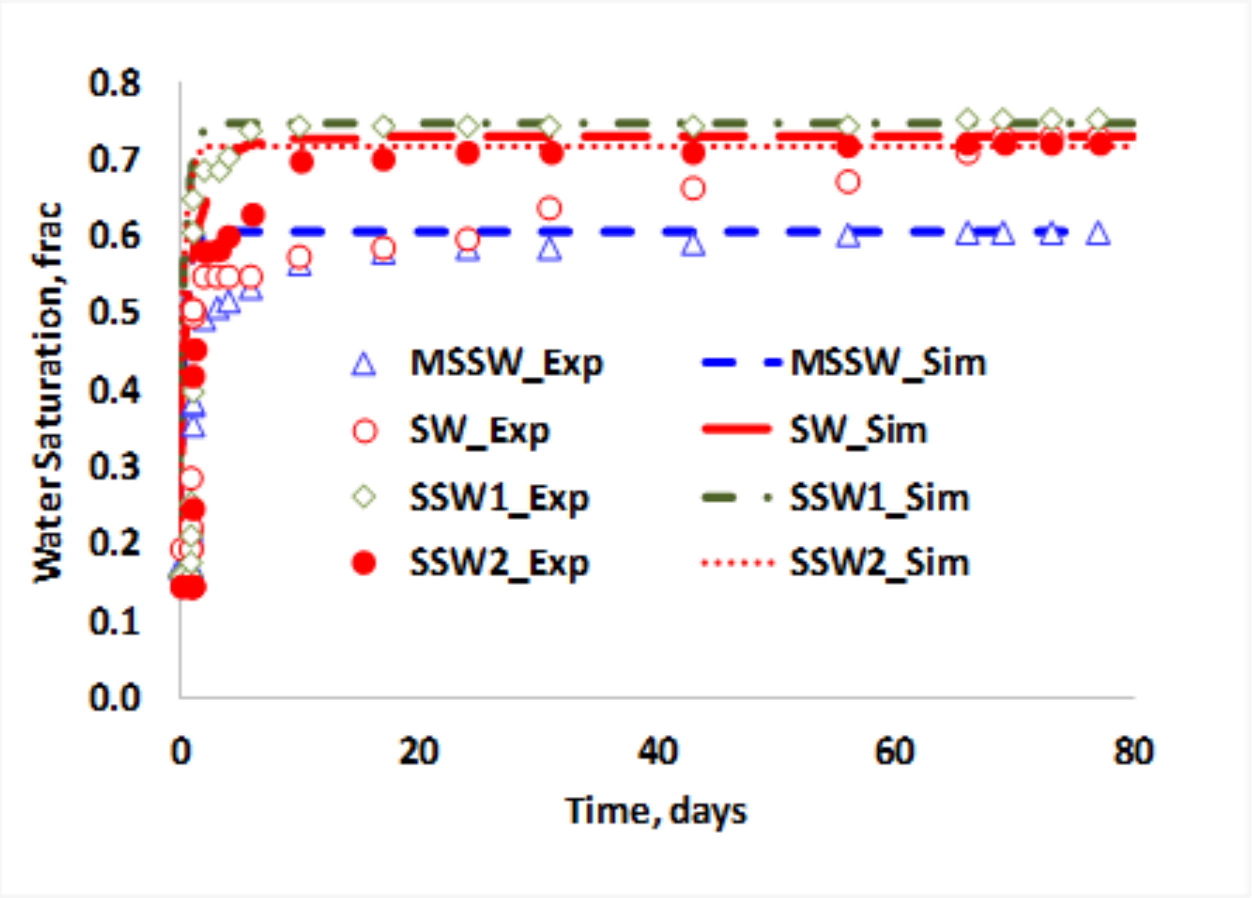
(c) Magnesium profile



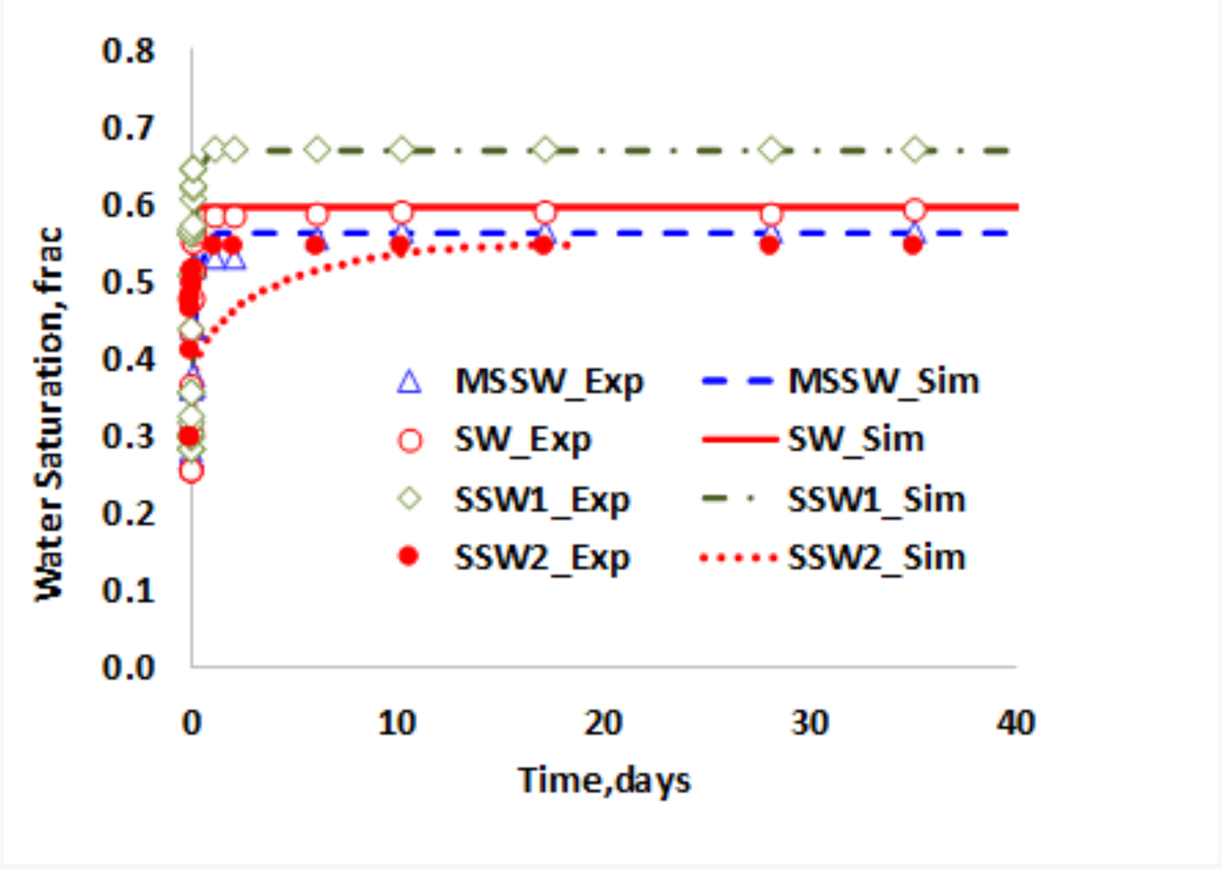
(d) Chloride profile

Spontaneous imbibition – oil production profiles (Less water-wet vs water-wet)

Less water-wet

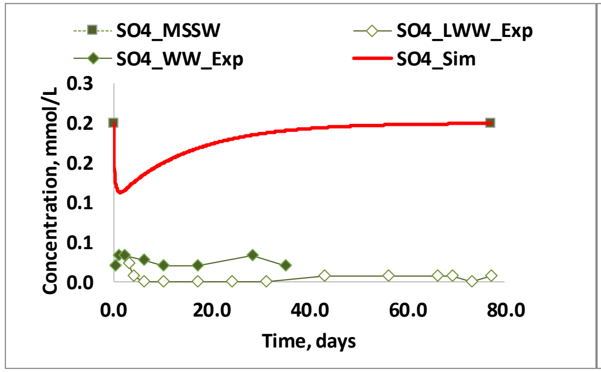


Water-wet

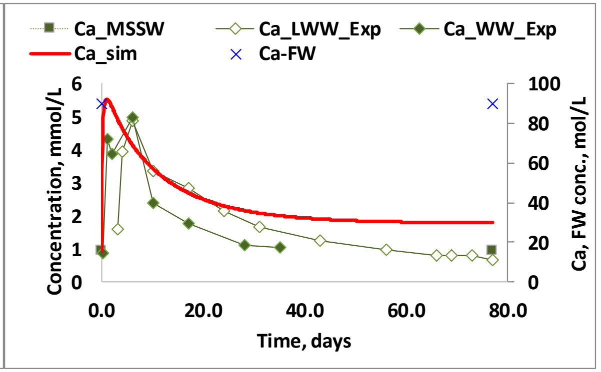


Spontaneous imbibition – ion concentration data MSSW vs SW brines

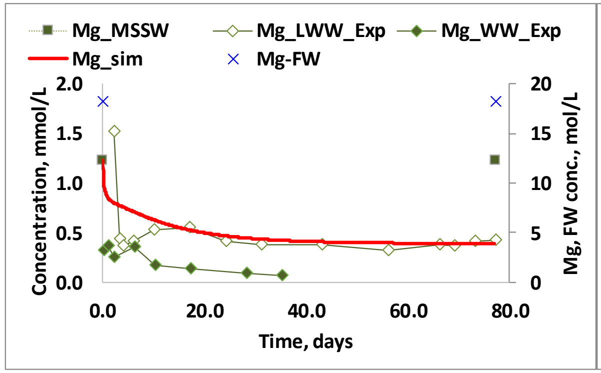
MSSW BRINE



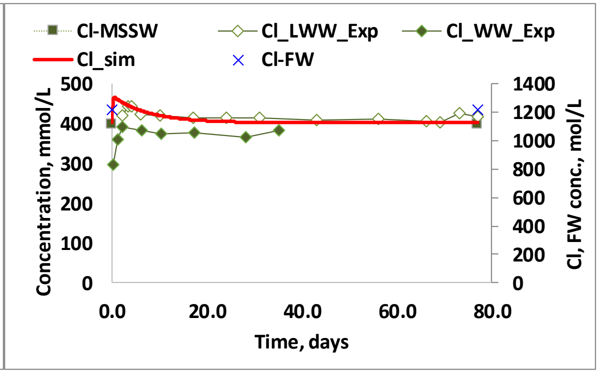
(a) *Sulphate profiles*



(b) *Calcium profiles*

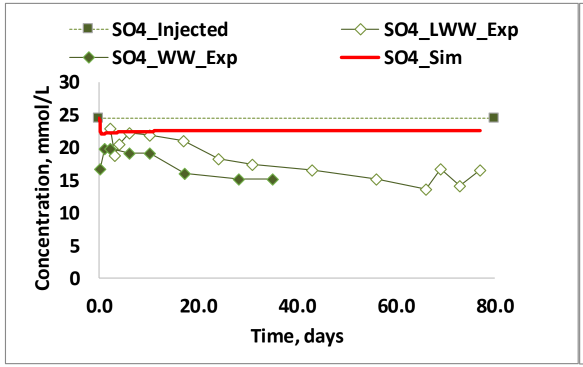


(a) *Magnesium profiles*

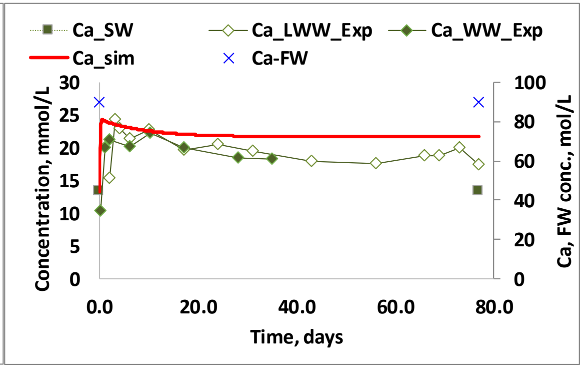


(b) *Chloride profiles*

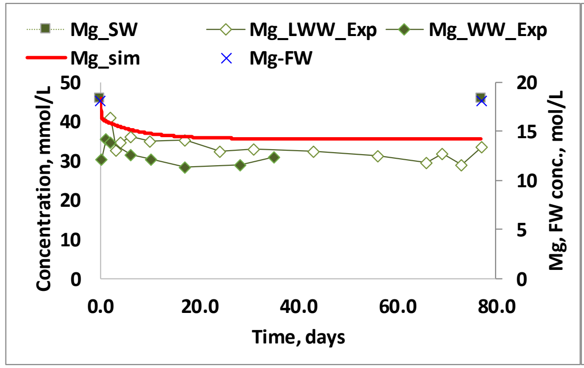
SW BRINE



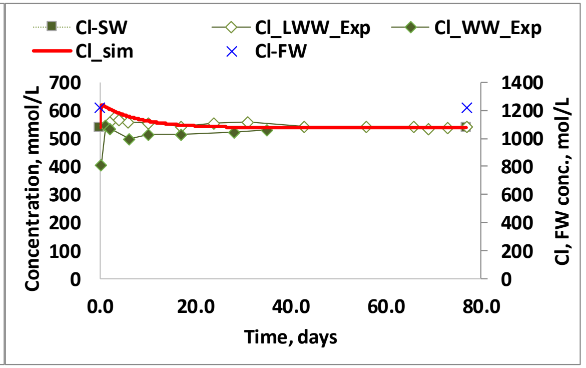
(a) *Sulphate profiles*



(b) *Calcium profiles*



(c) *Magnesium Profile*



(d) *Chloride profile*

Conclusions

- Spontaneous imbibition and viscous flooding experiments have been used to investigate the effect of brine compositions on oil recovery in Stevns outcrop chalk plugs at reservoir temperature
- Different suggested mechanisms have been investigated by simulating the surface charge, sulphate adsorption and dissolution of calcite for different seawater-like brine compositions interactions with chalk
- Results indicate that recovery of oil with the different brines under spontaneous imbibition at less water-wet conditions showed the same trend as the calculated surface charge from surface complexation simulations with calcite i.e. SSW1>SSW2>SW>MSSW. This suggests that the surface charge is the determining criteria for spontaneous imbibition under less water wet conditions
- The recovery by viscous flooding were approximately the same for the different brines indicating that the less water wetting state of the plug was optimal under viscous flooding and the different brine compositions had little or no effect
- During spontaneous imbibition experiments at more water-wet conditions, the trend for improved oil recovery was SSW1>SW>MSSW>SSW2. This trend was reversed under viscous flooding. This is consistent with literature which recommends a more water-wet system is not optimal for ultimate oil recovery in viscous floods
- The results from this work suggest that optimized water composition may give significant enhanced oil production from chalk reservoirs, but wettability is one key parameter to consider for the water composition design (viscous flooding versus spontaneous imbibition

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Thank you

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