



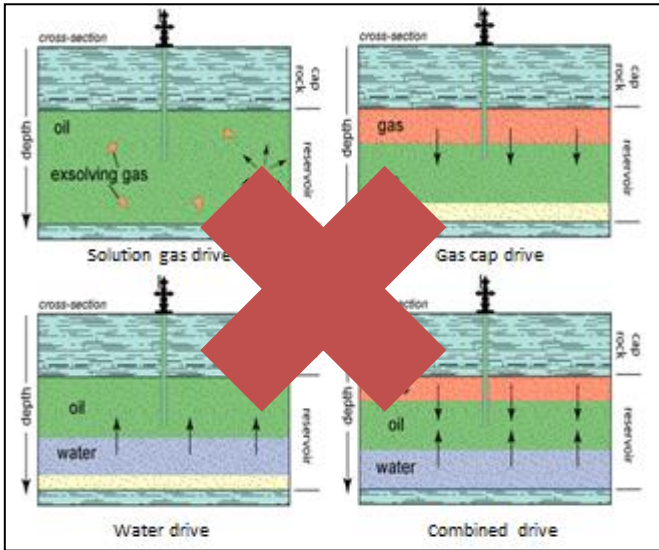
# EVALUATION OF LOW SALINITY BRINE INJECTION IN SANDSTONE RESERVOIR

N. Muchalintamolee, F. Srisuriyachai

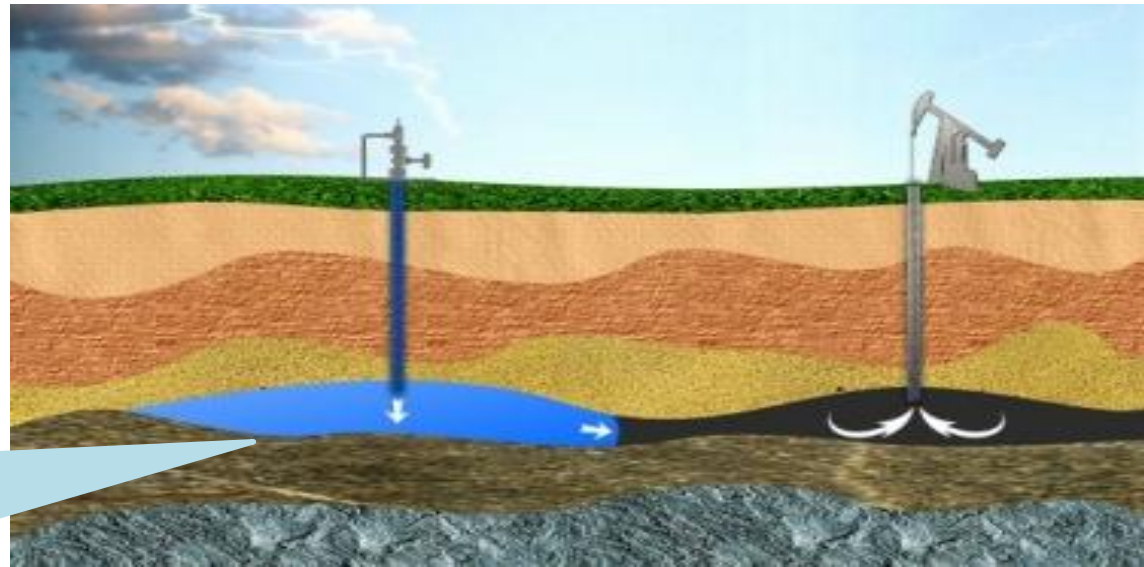
# Outline

- Introduction
- Objectives
- Methodology
- Results and Discussions
- Conclusions

# Introduction



Water injection (so-called waterflooding) is an improved oil recovery technique that is usually implemented when production from natural-stored force is not adequate.



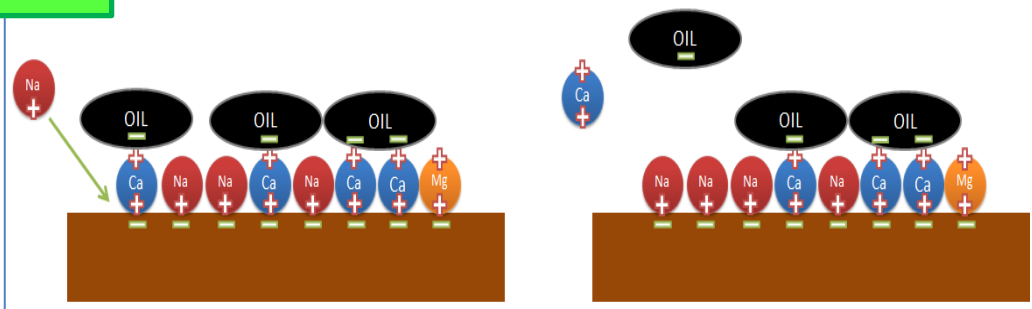
Basically, re-injection of produced water and/or seawater is preferred due to reduction of operating cost.

Hence, injected water usually has high salinity in ordinary waterflooding.

Currently, there are several evidences indicating that injection of low salinity brine (LSB) could yield more benefit than injection of high salinity water.

The benefit of LSB injection could be corresponded to alteration of rock preference toward a more water wetness.

## MIE

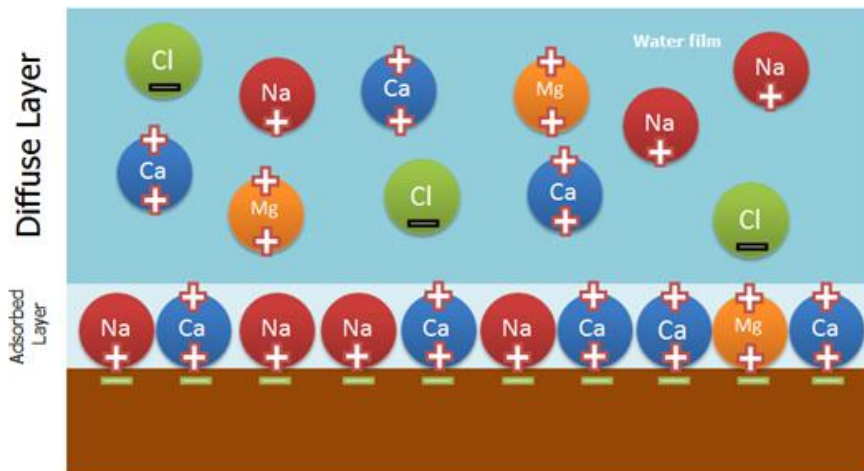


Multicomponent Ion Exchange (MIE) is believed to be the cause of wettability alteration

Divalent cations form a “Bridge” between negatively charge at sandstone surface and polar component in oil hence, oil is adsorbed.

The low concentration of divalent cations in pore water after LSB injection leads to the un equilibrium of ionic environment. Thus, MIE occurs.

## DLE



As a results, divalent cation will be replaced by the imcomplex monovalent cation which causes desorption of adsorbed crude oil.

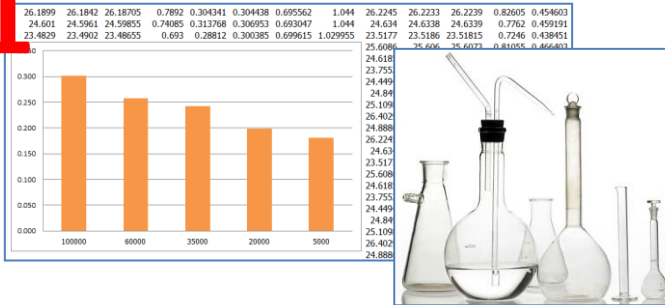
The expansion of Double Layer also promotes the alteration of wettability.

# Objectives

- To evaluate the **additional oil recovery** from wettability alteration by injected low salinity brine compared to ordinary waterflooding.
- To study the effect of **fluid and petrophysical parameters** affecting the effectiveness of LSB injection in **sandstone reservoirs**, including oil viscosity, formation water salinity, initial water saturation, and initial wettability.
- To evaluate effects of **operational parameters** for the LSB injection in **sandstone reservoirs**, including injection slug size, time when starting LSB injection, and injection rate.

# Methodology

1

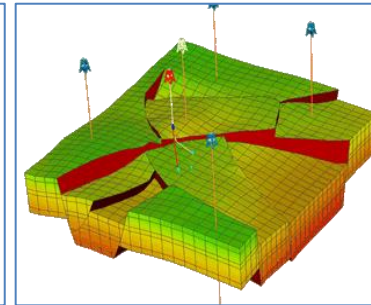


Perform laboratory experiment using Centrifugal machine to estimate the wettability of sandstone surface both before and after LSB injection

n-Dodecane with 2.0 AN of Oleic Acid is used to represent oil

Artificial brine based is prepared base on sea water

Amott-Harvey Wettability index is measured to represent the wettability.



Parameters	Values	Unit
Grid size	70x70x5	Ft
Effective porosity	20	%
Horizontal permeability	30	mD
Vertical permeability	0.1 $k_v$	mD
Top of reservoir	6500	Ft
Datum depth	6600	Ft
Reservoir temperature	143	$^{\circ}$ F
Initial oil saturation	0.7	fraction
Reservoir pressure gradient	0.433	psi/ft

3,150 x 770 x 100 ft in x-, y-, and z-direction, respectively.

45 x 11 x 20 Grid blocks (corner point grid and Cartesian coordinate)

The datum depth is located at the **bottommost** of the reservoir in order to maintain the depth of injection well when different dip angle is considered.

2 High salinity waterflooding is initially simulated as a reference case.

Simulate the model with several interested parameters to evaluate their effect on potential of LSB injection

Discuss the result and summarize the parameters that significantly affect LSB injection

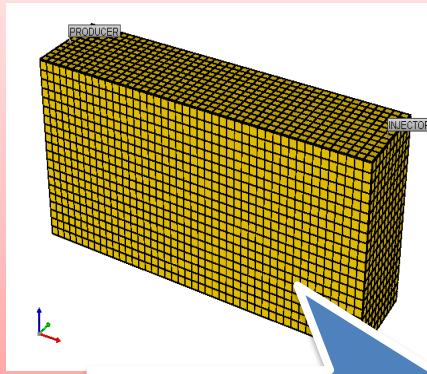


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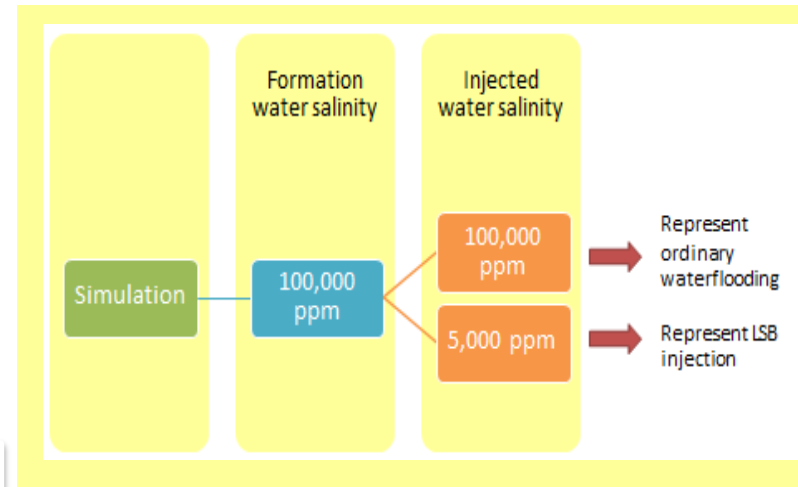
3

# Assumption and Reservoir modeling

Parameters	Values	Unit
Grid size	70×70×5	ft
Effective porosity	20	%
Horizontal permeability	30	mD
Vertical permeability	0.1 $k_h$	mD
Top of reservoir	6,500	ft
Datum depth	6,600	ft
Reservoir temperature	143	°F
Initial oil saturation	0.7	
Reservoir pressure gradient	0.433	psi/ft
Formation water salinity	100,000	ppm
Dip angle	Varied	

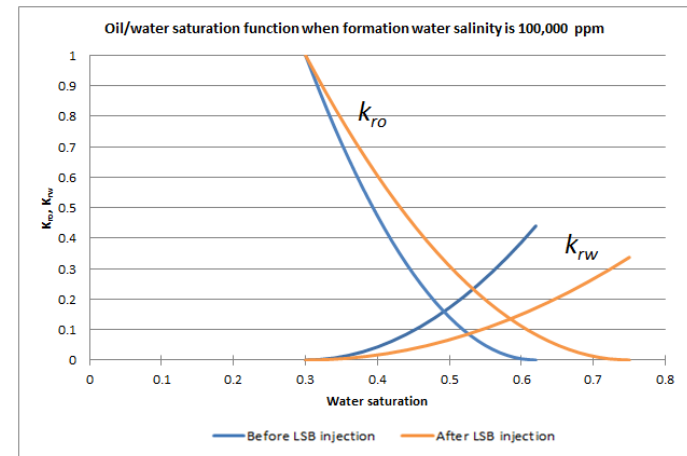


45 x 11 x 20 Grid blocks  
(corner point grid and Cartesian coordinate)



Connate water (ppm)	Before displaced by LSB			After displaced by LSB		
	IWS	1-ROS	$\delta_w$	IWS	1-ROS	$\delta_w$
100,000	0.30	0.62	0.20	0.3	0.75	0.543

Connate water salinity (ppm)		IWS	$k_{ro}$ @IWS	1-ROS	$k_{rw}$ @ (1-ROS)
100,000	Before LSB inj.	0.30	1	0.62	0.44
	After LSB inj.	0.30	1	0.75	0.337



# Assumption and Reservoir modeling

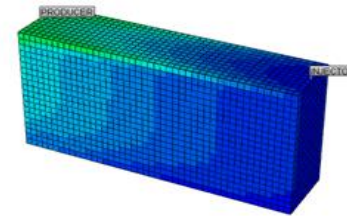
## Reservoir parameters

Formation water salinity	35,000 ppm and 100,000 ppm
Initial Sw	0.35 - 0.5
Oil viscosity	2.0-10.6 cp
Initial wettability	

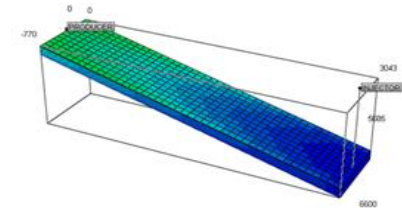
## Operational parameters

LSB slug size	0.10-0.25 PV
Starting time	Start LSB when field So = 0.4-0.6
Injection rate	400-800 stb/d

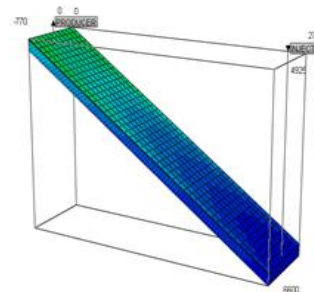
- The production period is set at 30 years to represent the production period of ordinary concession.
- The injection is assumed to implemented since the first day of reservoir exploitation in order to see the effect of LSB clearly.
- 5 Different reservoir inclinations are considered.



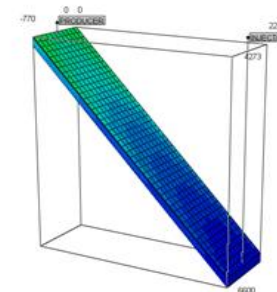
a) 0°



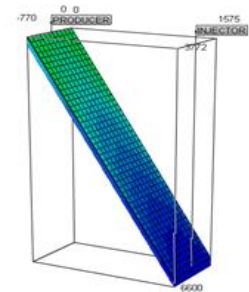
b) 15°



c) 30°



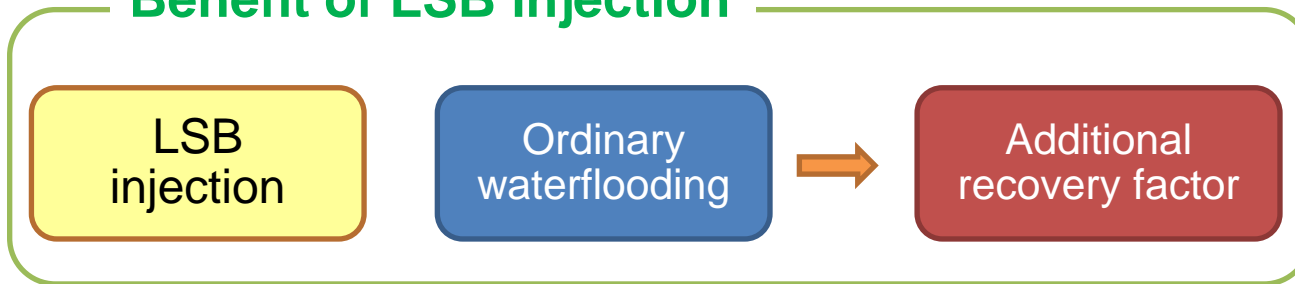
d) 45°



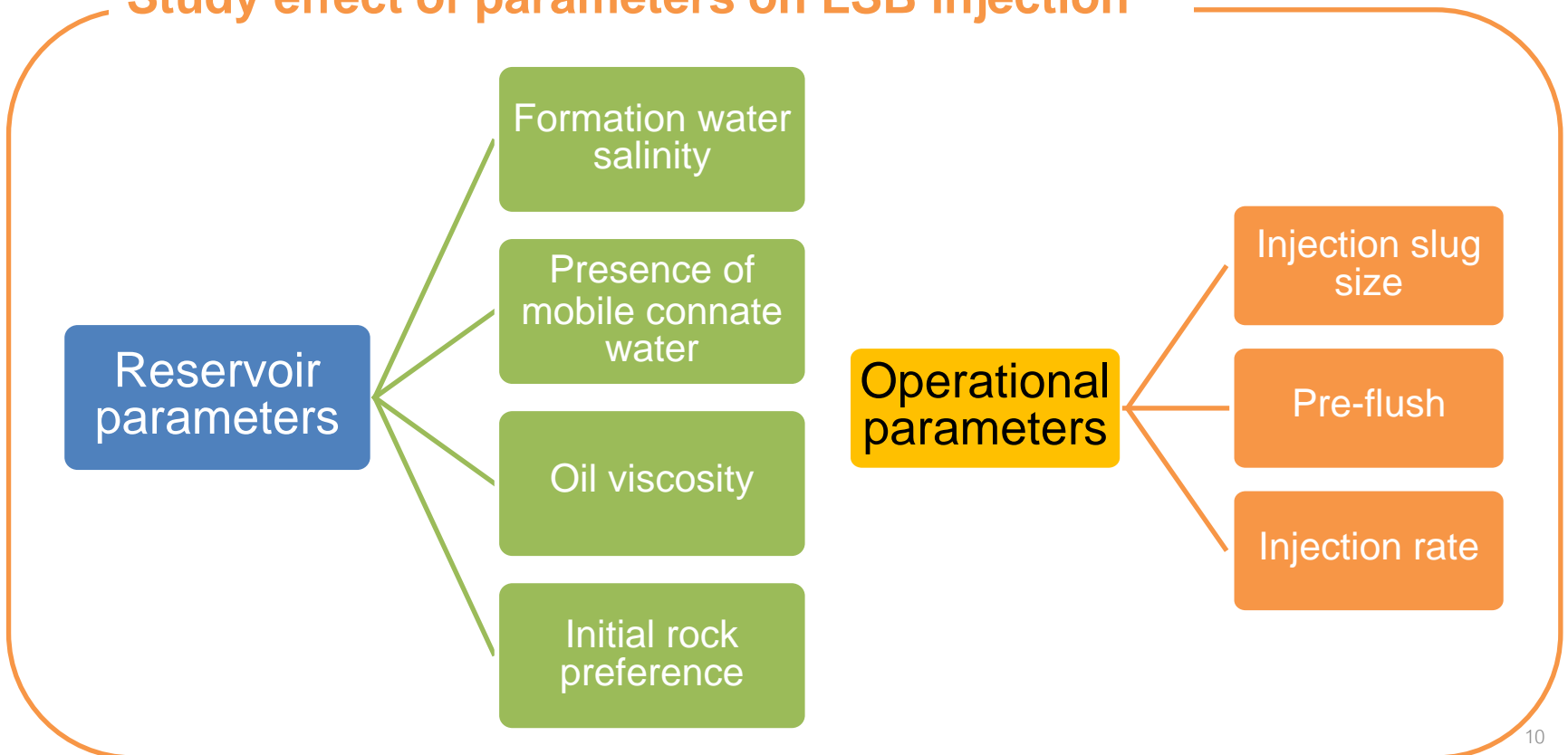
e) 60°

# **RESULTS AND DISCUSSION**

## Benefit of LSB injection



## Study effect of parameters on LSB injection



## Benefit of LSB injection

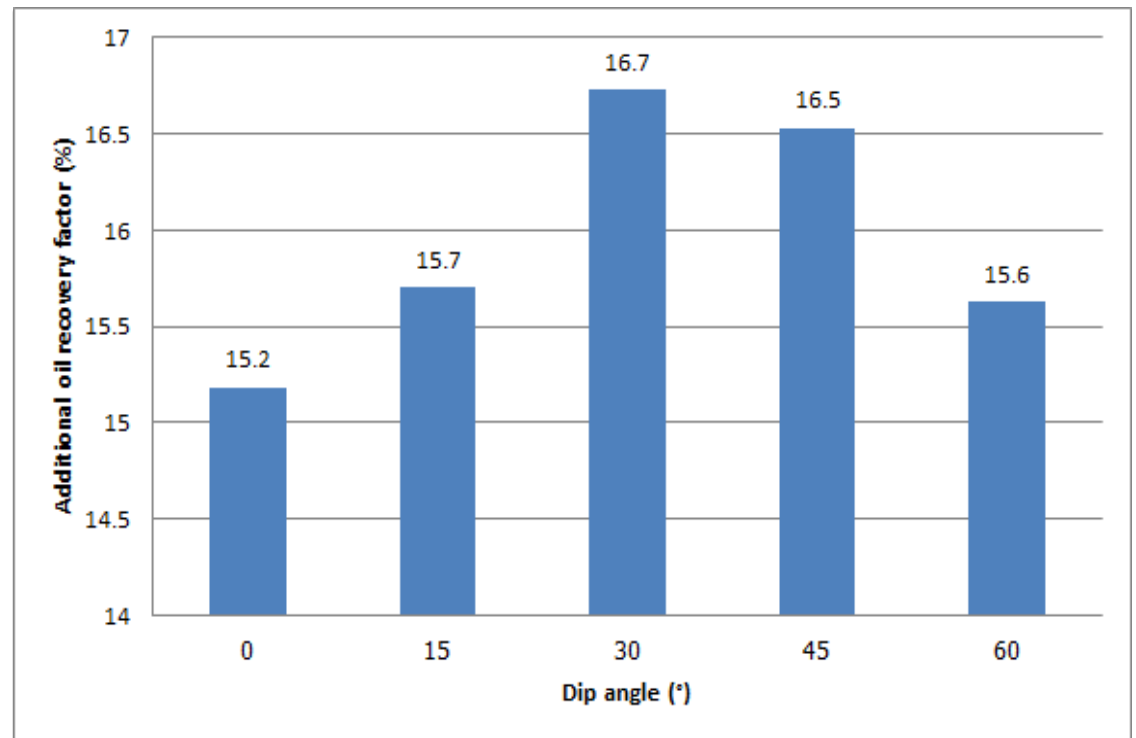
LSB injection

Ordinary  
waterflooding



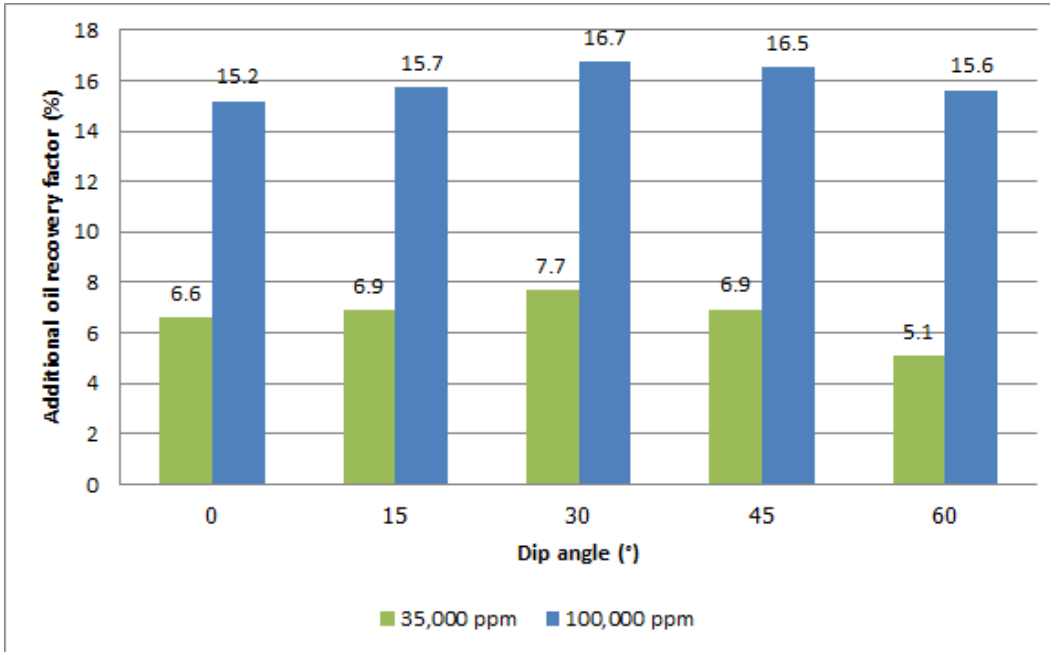
Additional  
recovery factor

- LSB injection could yield **15.2% to 16.7%** of additional oil recovery compared to ordinary waterflooding in several inclined reservoirs.



Reservoir parameters

Formation water salinity



The presence of **formation water with low salinity** would yield **lower benefit** of LSB injection.

A new salinity occurs at different location as a result of salt diffusion.

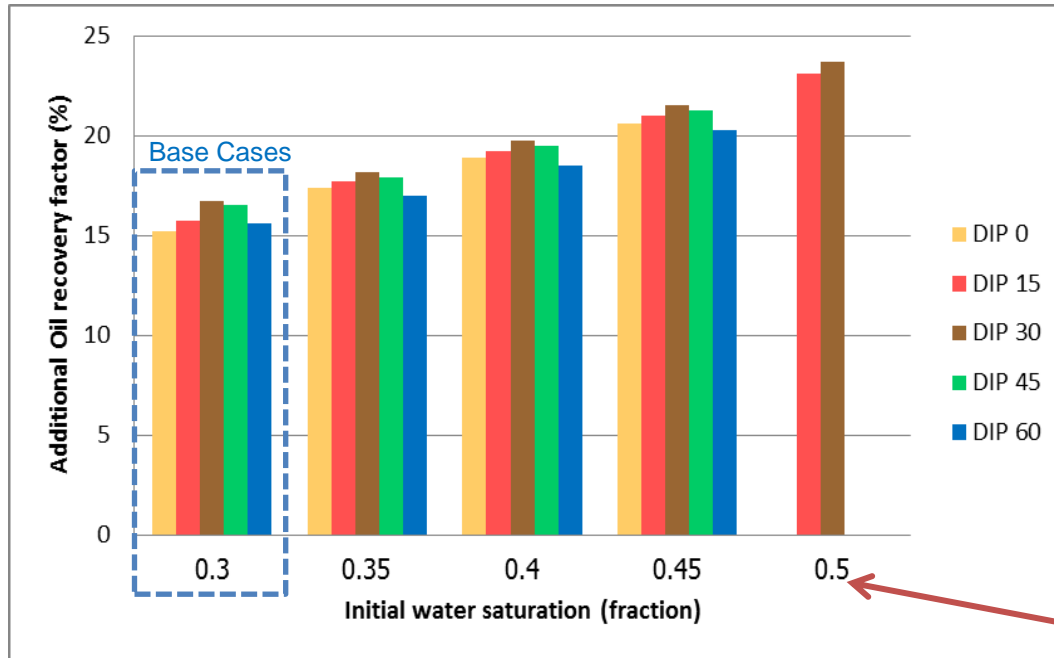
$$\text{Rate of diffusion} \propto \Delta \text{ concentration}$$

Thus, the higher the formation water salinity, the greater the benefit of LSB injection.

## Reservoir parameters

Presence of mobile connate water

Simulation is based on the assumption that critical water saturation is 30%, Four  $S_{wi}$  that beyond critical saturation were observed.



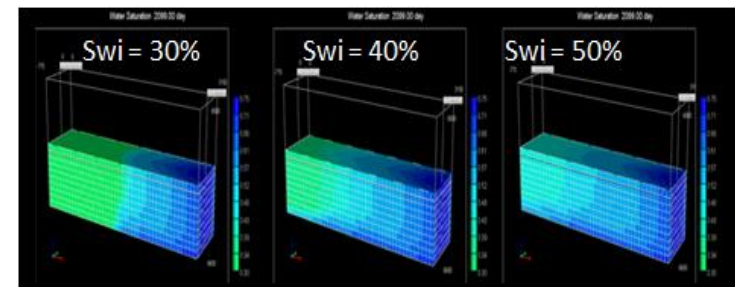
High  $S_{wi}$  → High  $k_{rw}$  → High  $i$

Mobile connate water can flow along with oil.

Flood front is advanced closer to production well, yielding higher sweep efficiency.

Production period is short due to excessive amount of water.

The presence of **mobile connate water** would yield **higher benefit** of LSB injection. **However**, too high  $S_{wi}$  would promote early water breakthrough.



# Reservoir parameters

# Oil viscosity

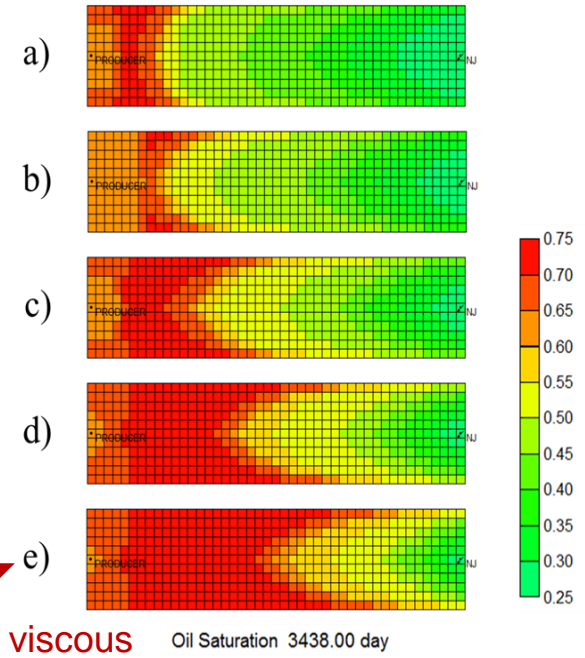
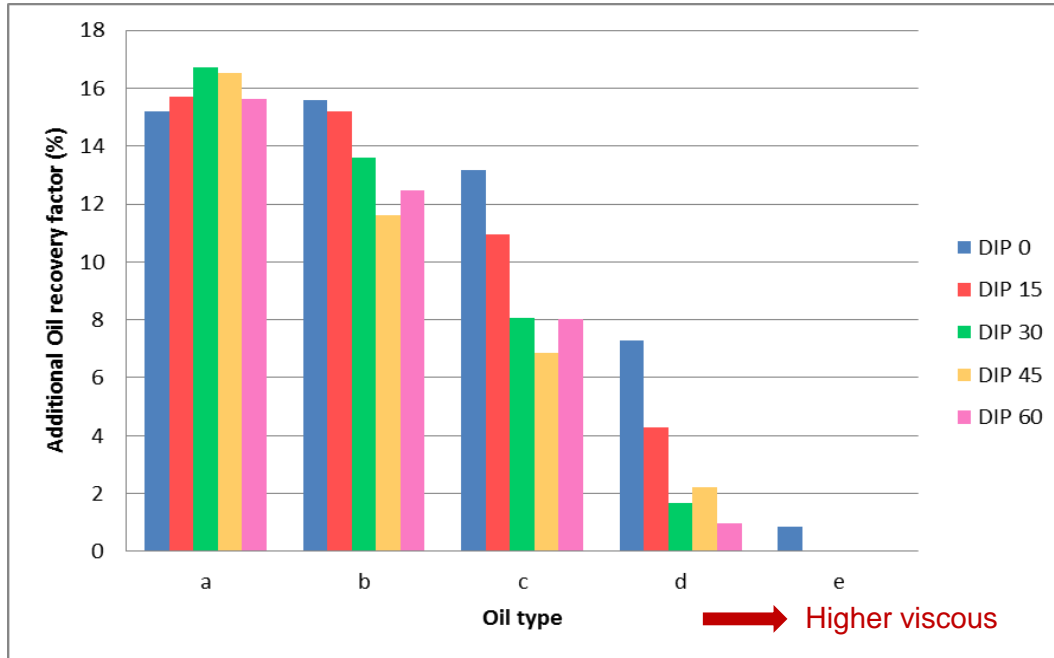
RF at every dip angle is reduced when oil is more viscous.  
**Less displacement efficiency!**

LSB injection

Recovery mechanisms

- Immiscible Displacement
- Wettability alteration

The desorbed oil is not well-displaced by the LSB slug due to the high contrast of their viscosities.

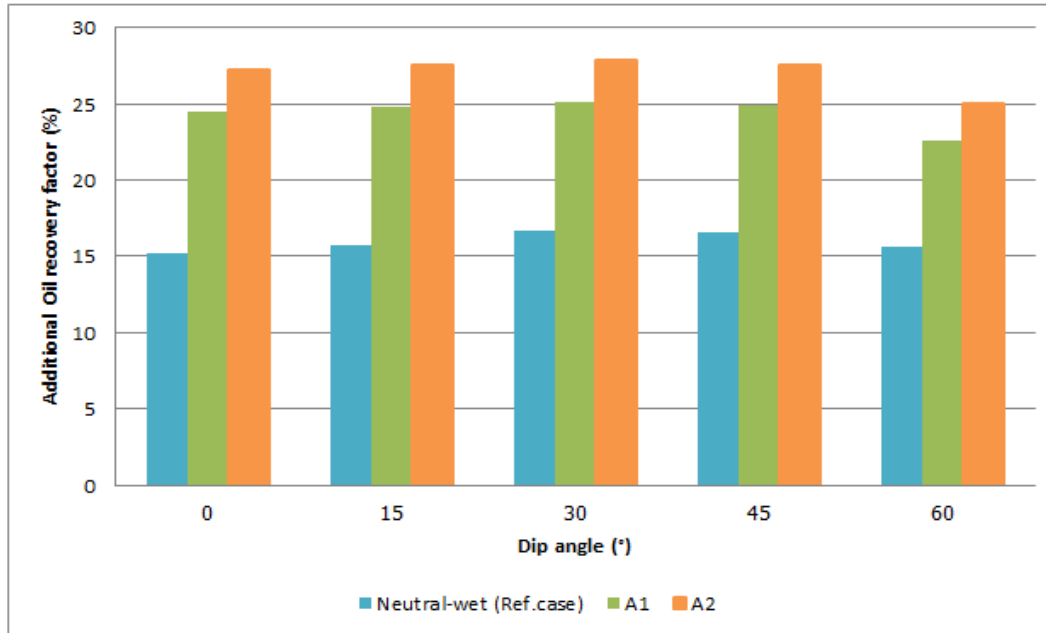


Additional oil recovery from LSB injection tend to **decrease** as oil is **highly viscous**.

Reservoir parameters

Initial rock preference

Previously, initial wettability of reservoir rock is based on core samples from laboratory, neutral-wet.



2 different wetting conditions are simulated and labeled as Type A1 and A2 which are **increased in oil wetness**.

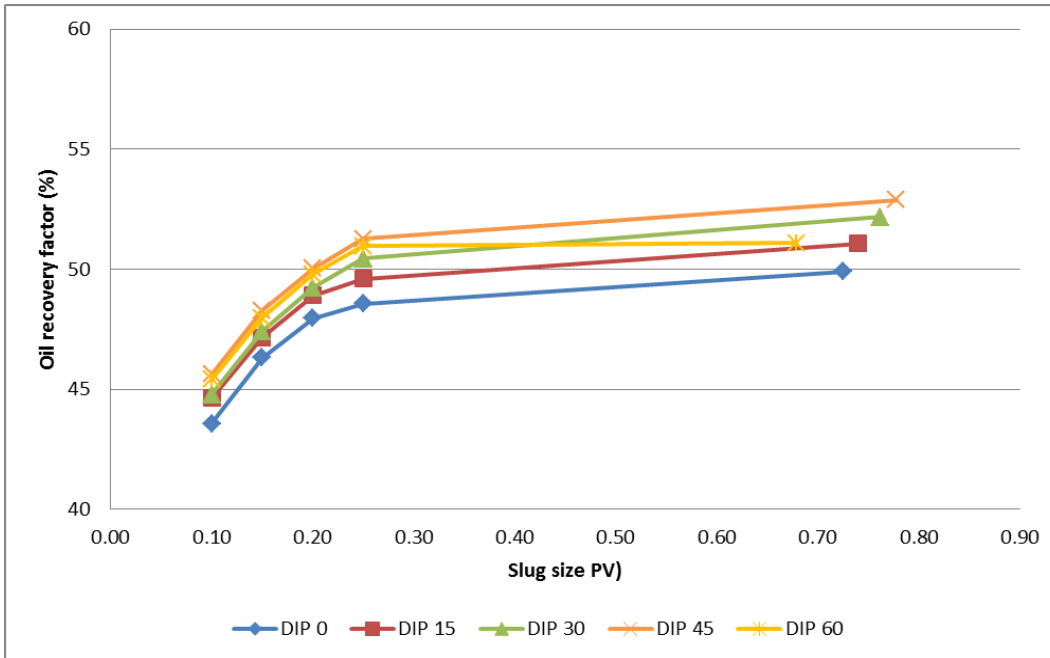
A **more oil-wet condition** of reservoir rock yields **larger portion of additional oil recovery**.

There is a larger amount of trapped oil that will be affected by wettability alteration.

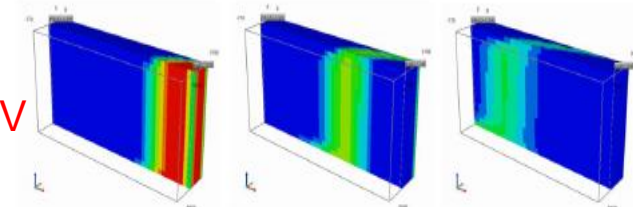
Operational parameters

Injection slug size

0.10 PV, 0.15 PV, 0.20 PV, and 0.25 PV  
(Chased by water containing the same salinity as formation water )

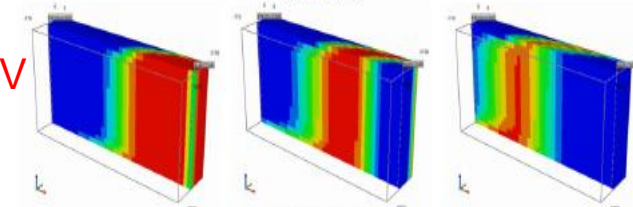


0.10 PV



a) 0.10 PV of LSB

0.25 PV



b) 0.25 PV of LSB

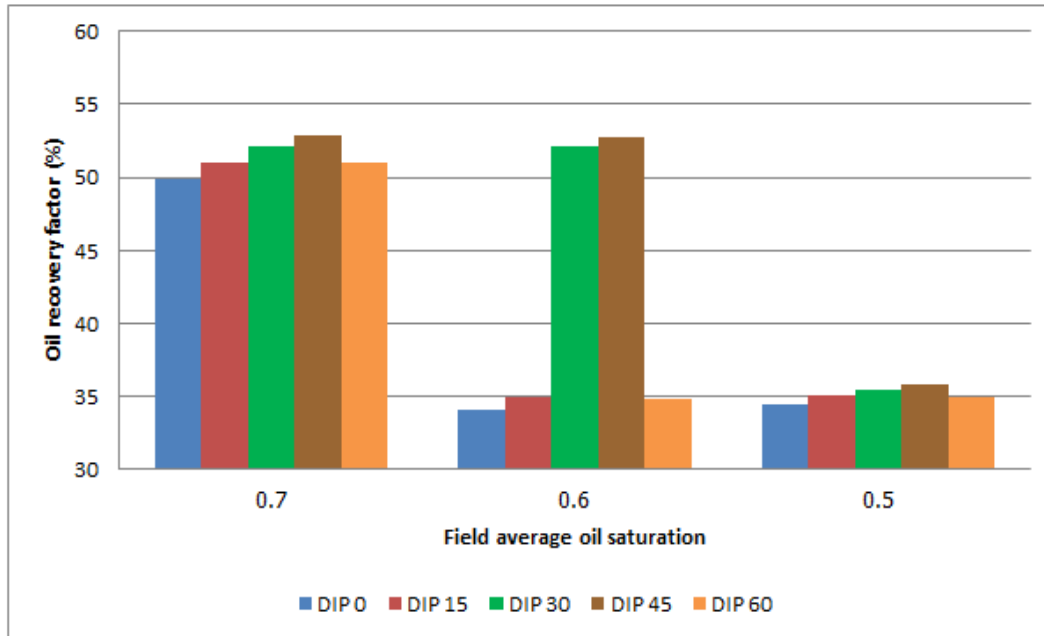
Oil recovery is **not significantly improved** when slug size **exceeds 0.25 PV**.



0.25 PV slug seem to be a slug size that large enough to provide wettability alteration effect to the most part of the reservoir.

Operational parameters

Starting time of LSB injection



Hence, waterflooding prior to LSB injection *may* not yield any benefit.

Oil RF is slightly different when average field oil saturation < 60%.

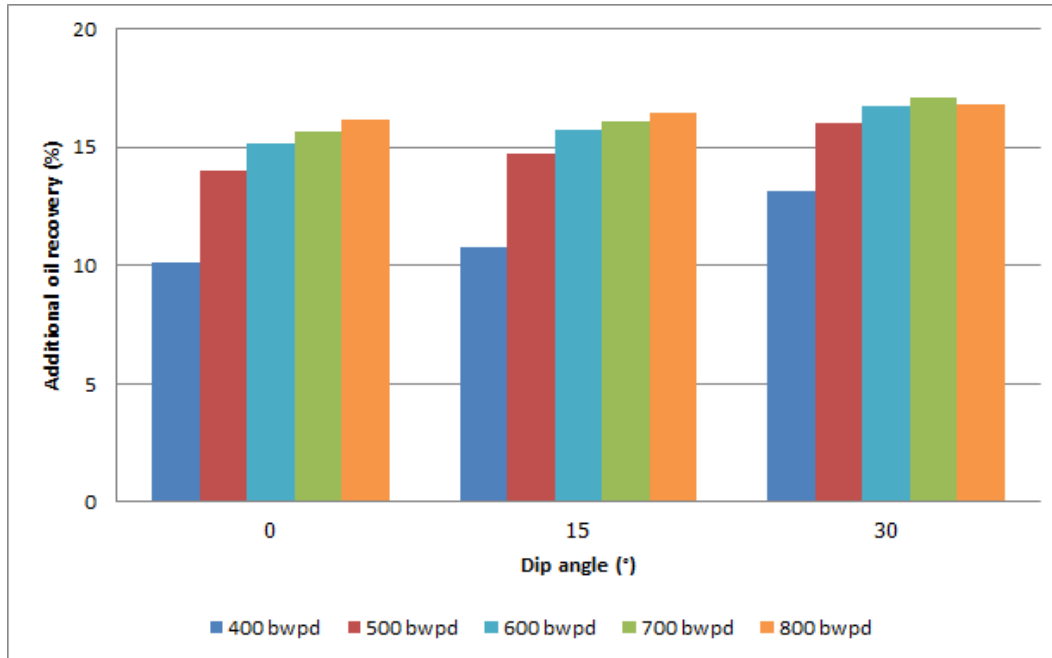


Large amount of water is already injected into reservoir prior to LSB injection and hence, excessive water production is encountered.

Operational parameters

Injection rate

According to well constraints, injected water cannot be maintained at the maximum desired rate when reservoir  $> 30^\circ$ . Hence, result is considered only;  $0^\circ$ ,  $15^\circ$ , and  $30^\circ$  dip-angled reservoir.



Theoretically, oil recovery should be improved as injection rate is lower when water is displacing oil in updip direction.

Range of injection rate used in this study is excessively low and thus, displacement mechanism of desorbed-oil is not adequate.

Simulation results show similar trend for each inclination. **Benefit of LSB injection is increased** as **rate of injection increases**.

Injection rate is believed to affect wettability alteration time however, effect of injection rate on retention time is excluded.

# Conclusions

- The benefit of LSB injection is evaluated by comparing oil recovery factor of LSB injection (5,000 ppm injected brine) to waterflooding (flooding with water having same salinity as formation water of 100,000 ppm).
- Simulation shows that **15.2 to 16.7% of additional oil recovery is obtained**. Alteration of rock preference toward more water-wet condition is believed to be a major mechanism.
- Subsequently, influences of each reservoir parameter and operational parameter on effectiveness of LSB injection process are investigated order to achieve the **preliminary screening criteria** for designing LSB injection in sandstone reservoir.

## Reservoir parameters

Salinity contrast  $\uparrow$  yields effectiveness of LSB injection  $\uparrow$

Benefit  $\uparrow$  when  $S_{wi} \uparrow$  : the mix of formation and injected brine could occur abruptly .

Formation Water Salinity	The salinity of formation water plays a major role in oil recovery mechanism of LSB injection.
Mobile connate water	Mobile connate water significantly affects the effectiveness of LSB injection due to <b>excessive water</b> production.
Oil Viscosity	The higher oil viscosity leads to the <b>inefficiency of displacement</b> mechanism. Released oil is not well-displaced
Initial Wettability	The <b>benefit</b> from LSB injection is maximized <b>in oil-wet reservoir</b> since there is more trapped oil is attached

## Operational parameters

LSB Slug Size	The recovery from LSB injection is directly proportional to the slug size until the optimal slug size is reached.
Starting Time of Injection	Waterflooding preflush <b>does not yield any additional recovery</b> in LSB injection since it accelerates the excessive water production
Injection Rate	Injection rate mainly affect the performance of LSB injection through the immiscible displacement mechanism.

*Questions ?*

*Thank you*

*for your attention*

Q & A

**THANK YOU FOR YOUR ATTENTION**


# Backup



# Recommendation


Wettability measurement is conducted using centrifugal machine.

Coreflood equipment should be used instead since the residual saturation would be measured precisely.




The number of grid blocks used in reservoir simulation model is limited by academic license .

The result might not be as precise as the simulation model with larger number of grid blocks.




The interpolated relative permeability is based on the SALT component

The new CMG version is already enhanced the LSB injection through the ion exchange function.



This study only focuses the sandstone reservoir.

Carbonate reservoir would yield different results.



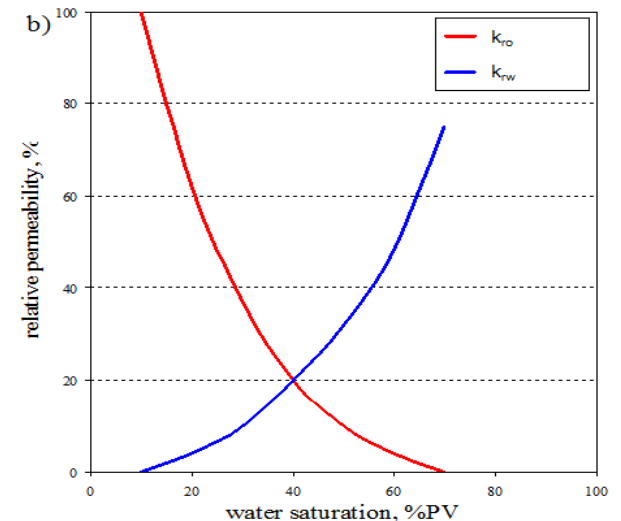
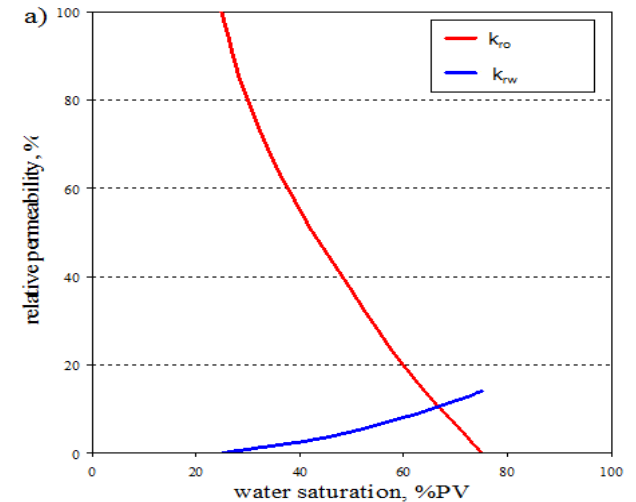
Assume clean sandstone

Should study the sensitivity of shale content.

# Rule of thumb

Property	Water-wet	Oil-wet
Irreducible water saturation	Usually greater than 20 to 25 % PV	Generally less than 15% PV
Cross over saturation	Greater than 50% water saturation	Less than 50% water saturation
Relative permeability at ROS	Generally less than 30%	Greater than 50% and can approach 100%

Craig Jr., F.F. The Reservoir Engineering Aspects of Waterflooding. Dallas, Texas: Millet the Printer, 1971.



# Laboratory Experiment



Artificial brine:  
To represent formation water

Amott-Harvey wettability index measurement

Connate water (ppm)	Before displaced by LSB			After displaced by LSB		
	IWS	1-ROS	$\delta_w$	IWS	1-ROS	$\delta_w$
35,000	0.30	0.70	0.40	0.3	0.75	0.60
100,000	0.30	0.62	0.20	0.3	0.75	0.543

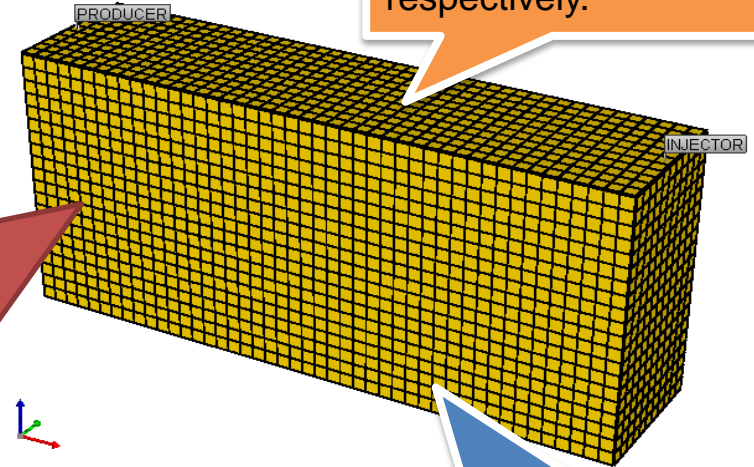
Connate water salinity (ppm)		IWS	$K_{ro}$ @IWS	1-ROS	$K_{rw}$ @(1-ROS)
35,000	Before LSB inj.	0.30	1	0.70	0.38
	After LSB inj.	0.30	1	0.75	0.32
100,000	Before LSB inj.	0.30	1	0.62	0.44
	After LSB inj.	0.30	1	0.75	0.337

$$I = \delta_w - \delta_o$$

# Reservoir Model Construction

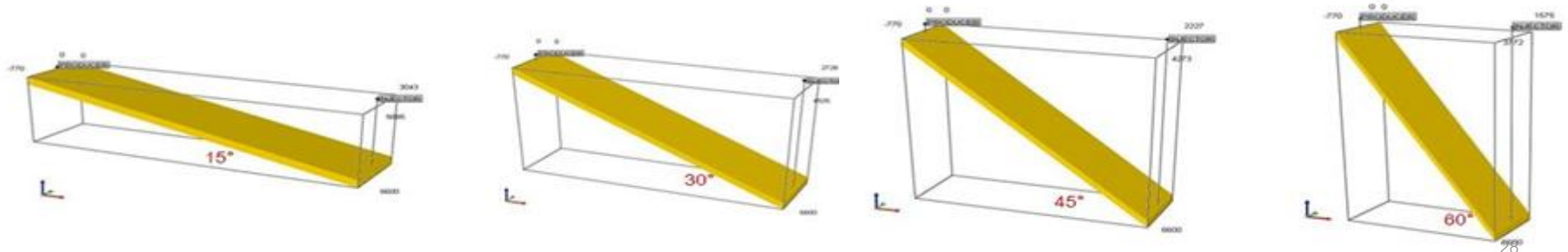
Parameters	Values	Unit
Grid size	70x70x5	Ft
Effective porosity	20	%
Horizontal permeability	30	mD
Vertical permeability	0.1 $k_v$	mD
Top of reservoir	6500	Ft
Datum depth	6600	Ft
Reservoir temperature	143	°F
Initial oil saturation	0.7	fraction
Reservoir pressure gradient	0.433	psi/ft

3,150 x 770 x 100 ft in x-, y-, and z-direction, respectively.

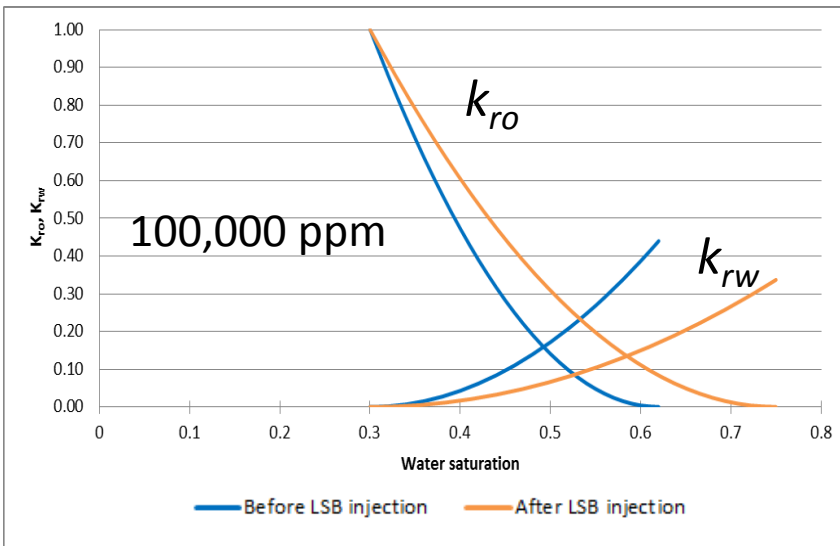
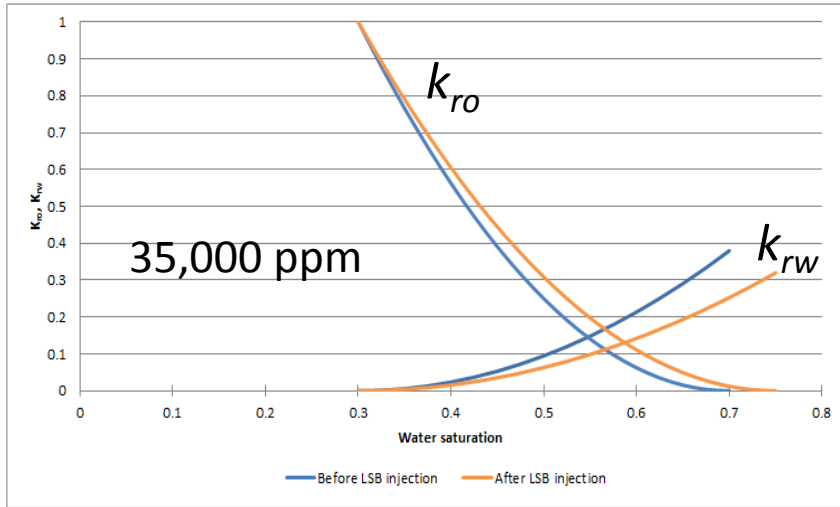


45 x 11 x 20 Grid blocks (corner point grid and Cartesian coordinate)

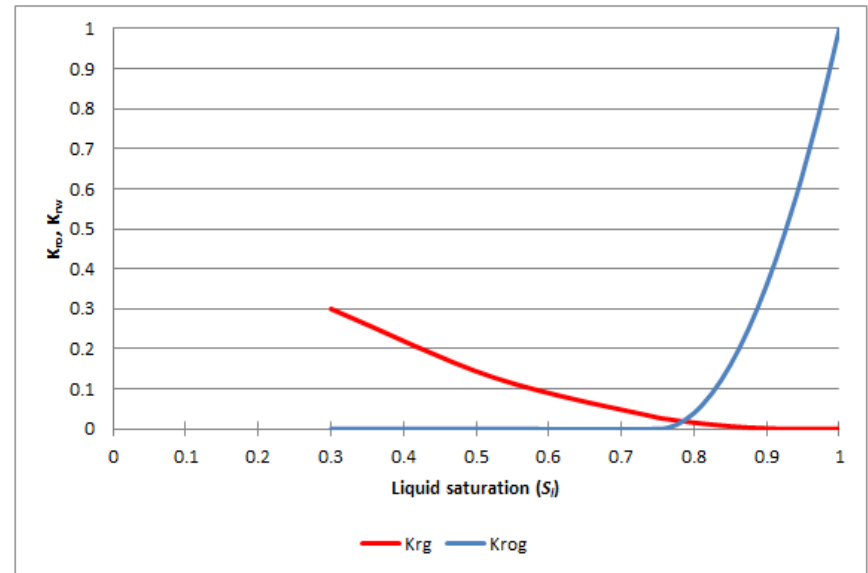
The datum depth is located at the **bottommost** of the reservoir in order to maintain the depth of injection well when different dip angle is considered.



# Relative Permeability Curve



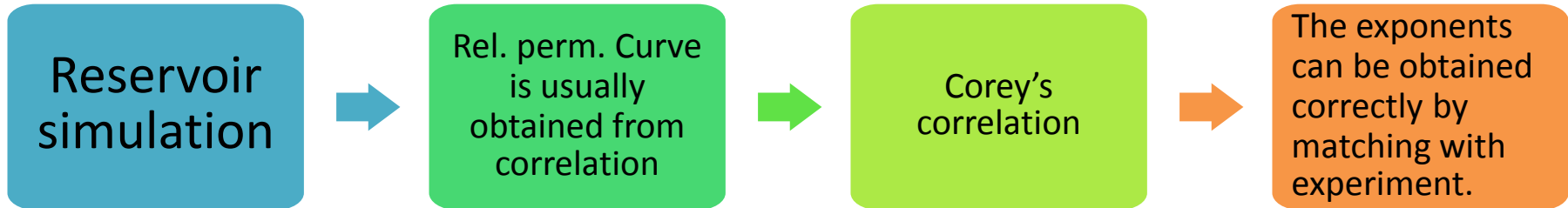
Gas/liquid relative permeability curve is obtained from the STARS Tutorial 2012.



The end-point data obtaining from experiment is used for generating the water/oil relative permeability curves

# Corey's correlation

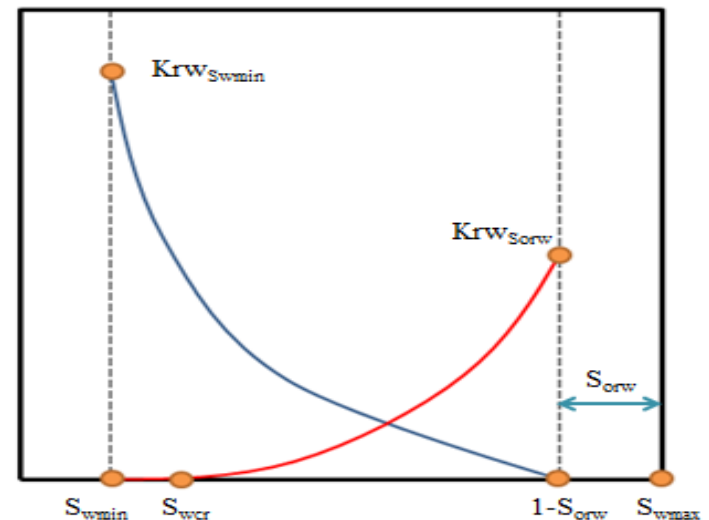
A **power law** which refers to the relationship between **rel. perm.** and  $S_w$ .



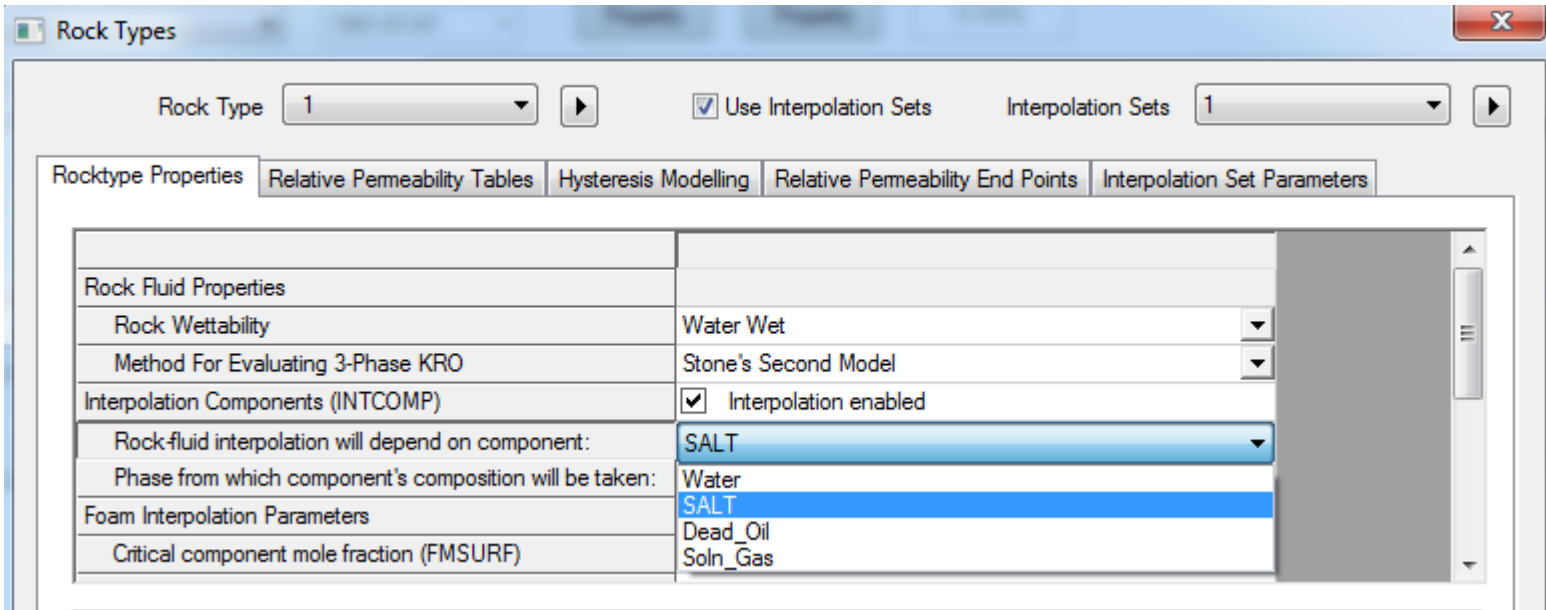
- Corey's correlation is generally used in reservoir simulator.
- In the use of Corey's correlation, the relative permeability to oil and water is calculated by following equations:

$$k_{ro}(S_w) = k_{ro@S_{wmin}} \left[ \frac{S_{wmax} - S_{orw} - S_w}{S_{wmax} - S_{orw} - S_{wi}} \right]^{C_o}$$

$$k_{rw}(S_w) = k_{rw@S_{orw}} \left[ \frac{S_w - S_{wcr}}{S_{wmax} - S_{orw} - S_{wcr}} \right]^{C_w}$$



# Rel. perm interpolation



The interpolation function (INTCOMP) of STARS is based on a **component** mole fraction.

#	Component	Mole Fraction
1	Water	0.9985
2	SALT	0.0015
3	Dead_Oil	0.
4	Soln_Gas	0.
	Total:	1.

Thus, we must create SALT component to represent the salinity instead of input the salinity directly. Salinity will be converted into the mole fraction basis.

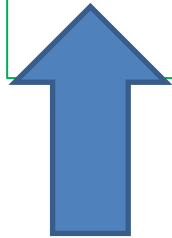
# Pressure and temperature

- For pressure, normal pressure gradient is assumed. (**0.433 psi/ft**)

$$6600 \times 0.433 = 2857.8 \text{ psi}$$

- Geothermal gradient of **1°F/100 ft** is assumed.

$$77 + \left[ \left( \frac{6600}{100} \right) \times 1 \right] = 143 \text{ } ^\circ\text{F}$$



Surface temp. = 77°F (25°C)