Aspects of Waterflooding

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Projects in Progress at P&SC Group (Led by Morrow N.R.)

• Improved oil recovery by low salinity waterflooding
  - Wyoming reservoirs
  - Reservoirs from North Sea and Middle East
  - Outcrop cores for mechanism studies
  - Fines migration and mineral dissolution of Tensleep and Minnelusa rocks (Micro-CT imagine – joint with ANU)

• Wettability studies
  - Sequential waterflooding
  - Capillary effect, rate effect
  - Spontaneous imbibition at various wettability conditions

• Improved polymer flooding – fly ash augmentation
  - Screening polymer and fly ash
  - Optimal mixture of polymer + fly ash + additives
  - Transport and straining in rock fractures

• Improved gas recovery by wettability alteration
  - Wamsutter tight gas sands (joint with INL)
OUTLINE

• Sample results of improved oil recovery by low salinity waterflooding
  - Wyoming reservoir cores

• Intermittent waterflooding

• Leading mechanism – wettability change

• Summary
### Crude oil properties

<table>
<thead>
<tr>
<th></th>
<th>Minnelusa</th>
<th>Tensleep</th>
<th>Cottonwood Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density, g/ml</strong></td>
<td>0.9065</td>
<td>0.8692</td>
<td>0.89</td>
</tr>
<tr>
<td><strong>Viscosity, cp</strong></td>
<td>56</td>
<td>19</td>
<td>24.3</td>
</tr>
<tr>
<td>n-C&lt;sub&gt;7&lt;/sub&gt; Asp. wt%</td>
<td>9.0</td>
<td>3.2</td>
<td>2.5</td>
</tr>
</tbody>
</table>

### Formation water

<table>
<thead>
<tr>
<th>Comp.</th>
<th>Concentration, mg/L</th>
<th>Minnelusa</th>
<th>Cottonwood</th>
<th>Tensleep</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>29,803</td>
<td>19,000</td>
<td>571</td>
<td></td>
</tr>
<tr>
<td>CaCl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>2,104</td>
<td>8,404</td>
<td>854.7</td>
<td></td>
</tr>
<tr>
<td>Na&lt;sub&gt;2&lt;/sub&gt;SO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>5,903</td>
<td>1,765</td>
<td>1,312</td>
<td></td>
</tr>
<tr>
<td>MgSO&lt;sub&gt;4&lt;/sub&gt;</td>
<td>841</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>MgCl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>-</td>
<td>1,587</td>
<td>145.7</td>
<td></td>
</tr>
<tr>
<td>NaHCO&lt;sub&gt;3&lt;/sub&gt;</td>
<td>-</td>
<td>-</td>
<td>1,312</td>
<td></td>
</tr>
<tr>
<td>TDS</td>
<td>38,651</td>
<td>30,755</td>
<td>3,030</td>
<td></td>
</tr>
</tbody>
</table>

### CBM water

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Concentration, mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>916</td>
</tr>
<tr>
<td>KCl</td>
<td>28.7</td>
</tr>
<tr>
<td>MgCl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>180.4</td>
</tr>
<tr>
<td>CaCl&lt;sub&gt;2&lt;/sub&gt;</td>
<td>191.5</td>
</tr>
<tr>
<td>TDS</td>
<td>1,316.3</td>
</tr>
</tbody>
</table>
Tensleep Reservoir Rock

(After Yin, 2007)
Spontaneous Imbibition of Tensleep cores

**Tensleep 5479B**
- $K_w = 87$ md
- $\phi = 18.67\%$
- 100% mineral oil saturated

**Tensleep crude oil saturated**
Tensleep Reservoir Cores - Low salinity waterflooding at tertiary mode

Initial brine: high salinity
Tensleep Reservoir Cores – waterflooding cases

Initial brine: low salinity
Injection brine: low salinity
Spontaneous imbibition of Tensleep Cores from dry well

<table>
<thead>
<tr>
<th></th>
<th>5514C</th>
<th>5515C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kg, md</td>
<td>51</td>
<td>147</td>
</tr>
<tr>
<td>φ, %</td>
<td>11</td>
<td>14</td>
</tr>
</tbody>
</table>

Tensleep oil saturated cores

Oil recovery, OOIP% vs Imbibition time, Days
Tensleep Reservoir Core 5520C - Low salinity waterflooding (no effect)

Core from dry well

Initial brine: high salinity
Tensleep Core H4
Effluent Analysis

**Tensleep H4**
- $K_v = 7.03 \text{md}$
- $\phi = 0.55\%$
- connate 1316 ppm NaCl solution
Dolomite crystals from suspension of crushed Tensleep rock

Micro-CT: Tensleep rock before and after flooded by brine

Green color: dissolved during flooding
Minnelusa Reservoir Rock

(After Yin, 2009)
Spontaneous Imbibition of Minnelusa cores

Minnelusa 5246-9299
Swi = 19.34%

Minnelusa 5246-9301
Swi = 20.28%
Minnelusa Core 5036-8094: Low salinity effect

Initial Brine: Minnelusa (38,651 ppm)
Minnelusa Core 5246-9309: Injection rate effect

5246-9309
$K_g = 292 \text{ md}$
$\phi = 20.68\%$
$S_{wi} = 22.75\%$

Initial Brine: Minnelusa (38,651 ppm)
Injection Brine: CBM (1,316 ppm)
Minnelusa Core 5036-8095: Injection rate effect

Recovery, % OOIP
Pressure Drop, psi

50368095
K_g=182md
Ø=18.44%
S_wi=11.37%

Recovery
Pressure

Injected Brine, PV

Connate Brine: Minnelusa (38,651 ppm)
Injection Brine: CBM (1,316 ppm)
Brine Permeability of Minnelusa Core 5036-8041
(saturated with 2,000 ppm NaCl and displaced with the same brine)

5036-8041
$K_g = 64 \text{md}$
$\phi = 5.75\%$

Brine Permeability, md

Brine Injected, PV
Cottonwood Creek Reservoir Rock

(after Yin, 2003)
Spontaneous Imbibition of Cottonwood Cores

Cottonwood 5672
$K_w = 8.6 \text{ md}$
$\phi = 11.37\%$
$S_{wi} = 34.45\%$

Cottonwood brine (30,755 ppm) 20 times dilution (1537 ppm)

Cottonwood 5772
$K_w = 3.9 \text{ md}$
$\phi = 9.02\%$
$S_{wi} = 47.95\%$

Cottonwood brine (30,755 ppm) 20 times dilution (1537 ppm)
Coreflood Results of Cores 5800 A and 5800B

Cottonwood 5800A
$S_{wi}$=48.89%

Cottonwood 5800B
$S_{wi}$=36.27%

Initial brine: high salinity
Sequential Waterflooding
(Nina’s talk)

Intermittent Waterflooding
Carbonate Cores: Intermittent waterflooding

Carbonate C1
K_w = 28.4 md
S_{wi} = 21.9%

Initial brine: high salinity

Brine Injected, PV

Pressure drop, psi

Oil Recovery, %OOIP

4 day intermission

20 times diluted seawater

Initial brine: high salinity
Sandstone Cores: Intermittent waterflooding

Initial brine: high salinity
Sandstone Core: Intermittent waterflooding

Sandstone Core E10

Oil recovery, %OOIP

Brine Injected (PV)

No salinity change
Revisited: Suggested mechanisms for low salinity waterflooding

- Osmotic pressure
- Salinity shock
- Saponification
- Limited release of mixed-wet particles
- Emulsification/snap-off
- Particle-stabilized interfaces/lamellae
- Multi-component ion exchange
- Surfactant-like behavior
- Wettability alteration (more water-wet)
- Wettability alteration (less water-wet)
- Viscosity ratio

(after Buckley, 2009)
Summary

• Laboratory tests show that Wyoming reservoir rocks appear to be weakly water-wet. Both sandstones and dolomite have mostly responded positively to low salinity waterflooding in tertiary mode.

• Fines migration and mineral dissolution are important features of Tensleep and Minnelusa rocks during low salinity waterflooding;

• Intermittent and sequential waterflooding without salinity change indicate that water/oil re-distribution associated with wettability change and capillarity during waterflooding play key roles in improved oil recovery.

• The dominant mechanisms for improved oil recovery by low salinity waterflooding vary depending on the rock, the oil, the brine and their interactions.
Thanks You!