Oil Recovery from Bakken Shale by Miscible CO_2 Injection

2015 SCCS Annual Meeting

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Agenda

- Overview of Bakken formation
- CO_2 EOR for unconventional tight oil reservoirs
- Tomographic imaging of multiphase flow
- Experimental set-up & procedures
- Results
- Future work

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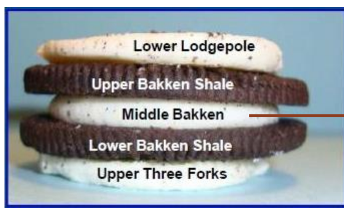
The Bakken Petroleum System

- One of the most productive tight oil plays in North America
- Technically recoverable oil: 7.4 billion STB
- OOIP: 167 billion STB
- Low porosity: 4% to 8%
- Low permeability: 0.001 to 0.01 mD



More laminated zones that are geomechanically weaker

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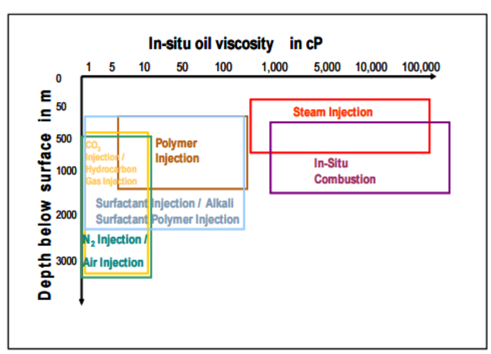
Choice of EOR Technique for Bakken

- Reservoir depth: ~9,000 to 10,500 ft (2,743 to 3,200 m)
- Oil viscosity: 0.15 – 0.45 cP @ Reservoir Conditions
- Light crude oil from 36 to 48 º API
- Reservoir temperature: 150 to 240 ºF
- Reservoir pressure: > 4,000 psi



Source: Poellitzer, et al., 2009 (SPE 120991)

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CO_2 Injection in Tight Oil Reservoirs

- Hoffman (2012): Miscible CO_2 injection
  - 6 – 8% porosity, 2.5 mD permeability
  - 42 º API oil
  - Increased production from 6.02% to 21.58% of OOIP
- Mohanty et al. (2013): Miscible CO_2 huff and puff
  - 8% porosity, 0.01 mD permeability
  - Outperformed primary production for a heterogeneous reservoir

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- Vega et al. (2010): Miscible CO_2 injection into siliceous shale
  - 34% porosity, 1.3 mD permeability
  - Recovered almost all the oil above MMP
- Tovar et al. (2014): Core sample with ultra low permeability
  - Porosity cannot be measured
  - Recovery factor calculated based on assumptions: 18% to 55%

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X-ray Computed Tomography

- Generate cross-sectional images by measuring the attenuation of a beam of X-rays
- Visualize core phenomena that are otherwise undetectable

Linear attenuation coefficient: (Vinegar & Wellington, 1987)

$$\mu = \rho(a + b\,Z^{3.8}/E^{3.2})$$

$$CT = 1000\frac{\mu - \mu_w}{\mu_w}$$

- E > 100 keV: Compton scattering
- E < 100 keV: Photoelectric absorption

Calculation of Porosity and Fluid Saturation

Porosity: (Withjack, 1988)

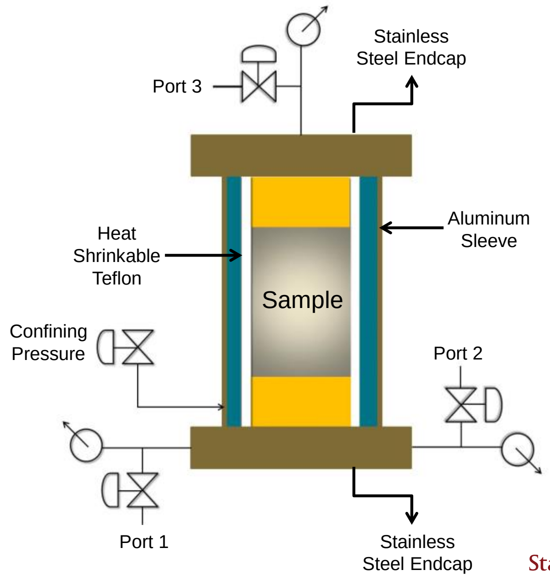
$$\phi = \frac{CT_{or} - CT_{ar}}{CT_{oil} - CT_{air}}$$

CO_2 saturation:

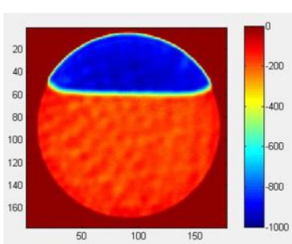
$$S_g = \frac{CT_{or} - CT_{ogr}}{CT_{or} - CT_{gr}}$$

$$S_g = \frac{CT_{or} - CT_{ogr}}{\phi(CT_{oil} - CT_{gas})}$$

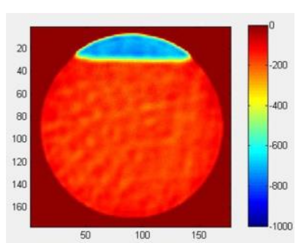
Experimental Set-up



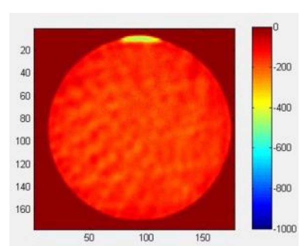
Determination of Miscibility Pressure of CO_2 in Bakken Crude @ 38 ºC



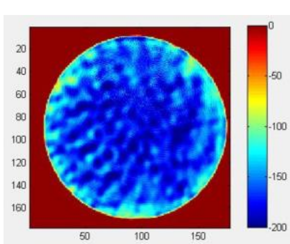
Oil @ ambient P



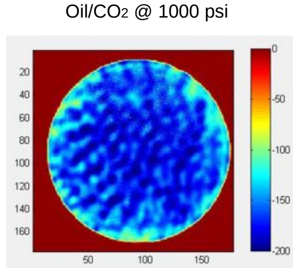
Oil/CO_2 @ 1000 psi



Oil/CO_2 @ 1100 psi



Oil/CO_2 @ 1200 psi



Oil/CO_2 @ 1300 psi

#30 Slice
140 keV / 120 mA
0.625 mm slice thickness

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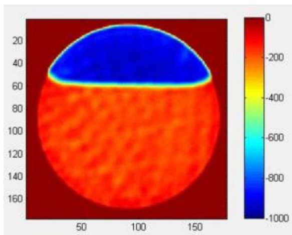
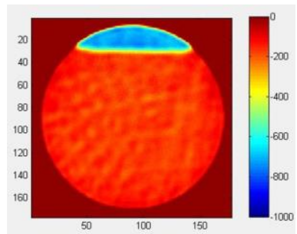


Oil @ ambient P



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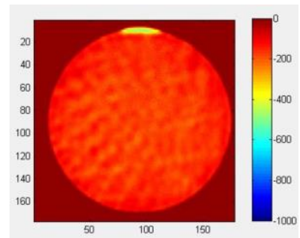

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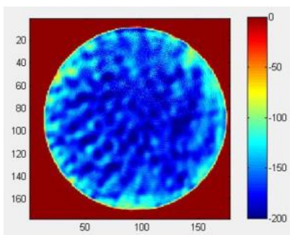

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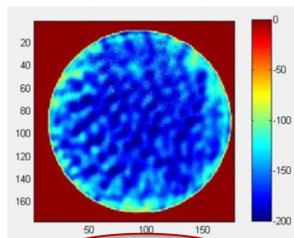

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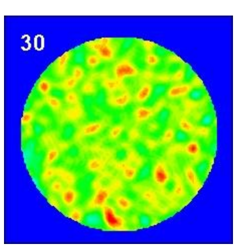
Determination of Porosity



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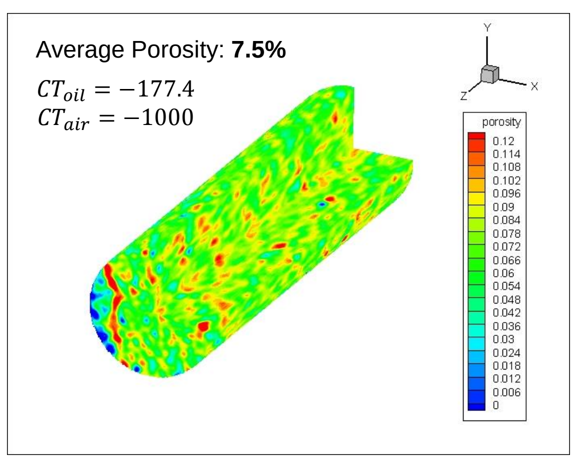

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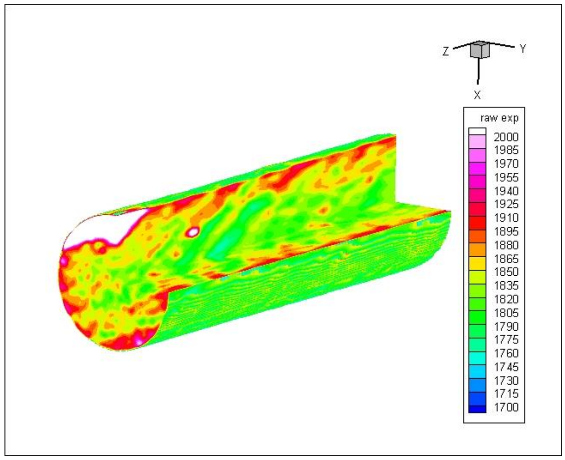
3-D Density Profile

- Constructed from air-saturated CT images
- Alternating layers of high and low density



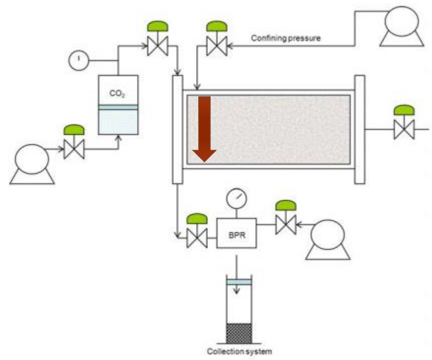
Determination of Permeability

Darcy's Law: $$q = \frac{kA}{\mu}\frac{\Delta P}{L}$$

Average Flow Rate, mL/s	0.000093
Diameter, inch	1
Length, inch	2
Dead Oil Viscosity @ 38 ºC, cP	6.56
ΔP, psi	500
Absolute Permeability, µD	1.8

Countercurrent Injection of CO_2

- Experimental condition: 1300 psi and 38 ºC
- BPR @ 1300 psi
- Dual-energy level CT scan @ 140 keV and 80 keV



Source: Vega, et al., 2010 (SPE 135627)

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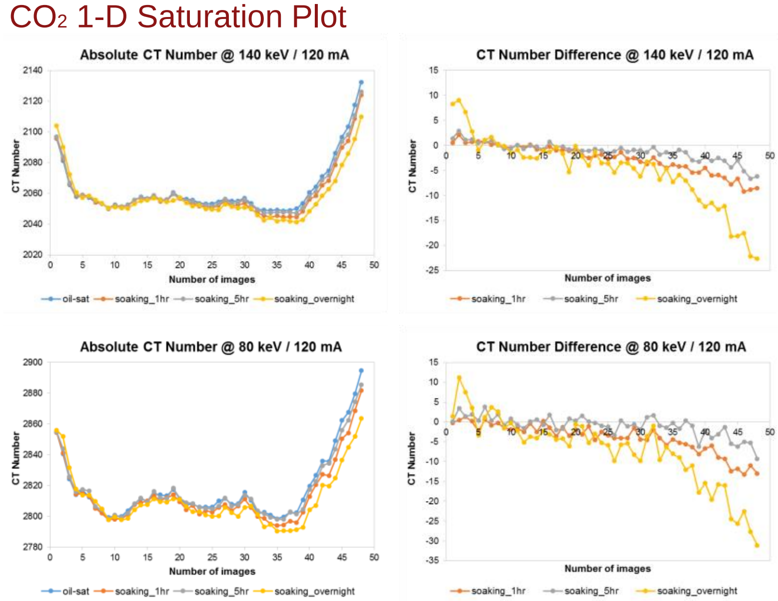
CO_2 1-D Saturation Plot



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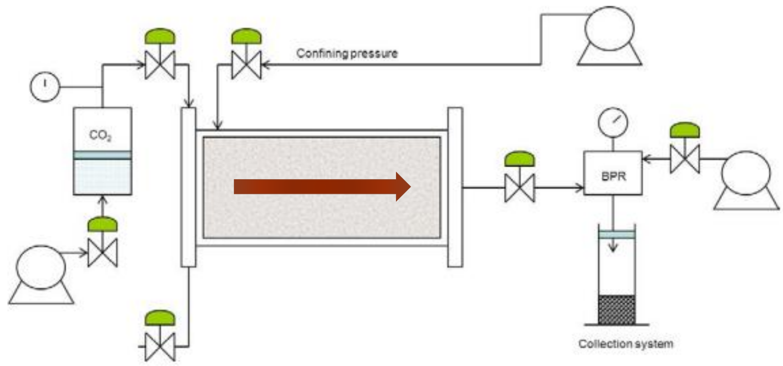
Future Work



Cocurrent Flow

Source: Vega, et al., 2010 (SPE 135627)

Future Work

- Improve on current imaging techniques to better capture saturation front of CO_2
- Continue dual-energy scan at 140 keV and 80 keV
  - Contribution from both Compton scattering and photoelectric absorption
- Use photoelectric dopants, if necessary

Conclusion

- Experimental Condition
  - CO_2 injection pressure @ 1300 psi
  - Back pressure regulator @ 1300 psi
  - Temperature @ 38 ºC
- 7.5% porosity
- 1.8 µD permeability
- This core sample is generally homogeneous with some localized heterogeneities. Alternating layers of high and low density are observed.

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