Canadian Bakken IOR/CO$_2$ Pilot Projects

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Executive Summary

1) Waterflooding has had a lot of success
   ✓ very low permeability situations with multi-frac horizontal injectors

2) A Gas (CO₂) flooding pilot was successful in very low permeability reservoir
   ($k_{\text{air}} \sim 0.1 \text{md}$)

3) Both waterflooding and CO₂ flooding is influenced by flooding induced fractures
Executive Summary

4) Injectivity behavior indicates waterflood induced fractures and natural fractures

5) Flooding success depends upon
   • Matrix permeability
   • Dispersion of water or CO₂ injection
   • Imbibition
   • Induced fracture length
   • Level of pressure depletion
• Executive Summary
• Objective
• Field Cases (public data only)
  – CO₂ flooding in low permeability rock \( \sim 0.13\text{mD} \) with horizontal wells
  – Waterfloods in low permeability rock \( K_{a_{\text{max}}} < 0.06 \text{mD} \) with hz multifract wells (Viewfield Bakken)
• Why are the waterflood and CO₂ floods successful?
• Conclusions

Permeability Classification Permeability (mD)
- Very low: < 0.01
- Low: 0.01 – 1
- Average: 1 – 100
- High: 100 – 10000
- Very high: > 10000

_sinclair/viewfield waterfloods +CO₂_
Mobility, a Critical Driving Parameter

Range of most miscible Floods assuming 0.3-10cp

Is it possible to gas flood this area? \( \mu_{\text{oil}} \sim 0.3 \text{cp} \)
Resource Pyramid

Top-tier resource, very high permeability, tier 1

Medium permeability, tier 2

Low permeability, tier 3

Very low permeability, tier 4

Increasing development costs and uncertainty

Enhancing oil recovery from tight oil plays
The Bakken Formation was deposited in the more central and deeper portion of the Williston Basin.

Source: USGS
Bakken Formation

- 9,723 Wells in the Bakken Formation
- 320 new injectors since January 2011
  - 148 of the new injectors are in the 'tight Bakken' area highlighted

148 of the new water injectors are in the ‘tight Bakken’ area highlighted started injection since 2011
New Horizontal Multi-fractured Wells; Red Highlighted Wells are Injectors

148 new water injectors are in the ‘tight Bakken’ area highlighted started injection since 2011

9,723 Wells in the Bakken Formation
• Waterfloods in low permeability rock with hz multifract wells
• CO$_2$ flood with Horizontal CO$_2$ injector

DALY SINCLAIR FIELD
Play Development
Daly Sinclair Field

- **Horizontal well** development:
  - Required due to thin nature of play.
  - East-west horizontal tracks
    - Follows regional stress field;
  - 3 to 4 wells per section;
  - Leg length ~ 1 mile on surface (one section in length);
- Multi-stage fracs:
  - 4 to 28 intervals per leg.
  - Example: 5.3 tonne 20/40 sand, 17.5 m³ fluid

>200 hz multifrac wells

6 miles

~400 m or yards between wells
rapid growth; 1300 wells last 10 yrs change in oil rate~4000 STB/d

Bakken-Torquay Production

Sinclair discovery & horizontal development
Interbedded siltstone and shale, massive shale and occasionally Brecciated; most rock permeability $K_{ave} \sim 0.1$ mD, $K_{max} \sim 30$ md in streaks oil-water capillary transition zone which results in a mobile water saturation and free water production.
### Reservoir Properties (Three-Forks-Formation)

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pb (kPa)</strong></td>
<td>1920</td>
</tr>
<tr>
<td><strong>GOR (sm3/sm3)</strong></td>
<td>6.4</td>
</tr>
<tr>
<td><strong>Permeability (md)</strong></td>
<td></td>
</tr>
<tr>
<td>- Upper Three Forks</td>
<td>0.13</td>
</tr>
<tr>
<td>- Lower Three Forks</td>
<td>0.002</td>
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<tr>
<td><strong>Porosity (fraction)</strong></td>
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<tr>
<td>- Upper Three Forks</td>
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<tr>
<td>- Lower Three Forks</td>
<td>0.037</td>
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<tr>
<td><strong>Density (API)</strong></td>
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<tr>
<td><strong>Bo (sm3/sm3)</strong></td>
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<td><strong>Viso (cp)</strong></td>
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<tr>
<td><strong>Gas gravity</strong></td>
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</tr>
<tr>
<td><strong>Swi (%)</strong></td>
<td>29</td>
</tr>
<tr>
<td><strong>Sor (%)</strong></td>
<td>31</td>
</tr>
</tbody>
</table>

- Air permeability $K_{\text{air ave}} = 0.13$
- $K_{\text{max}} \approx 30 \text{ md streaks}$

**Ultimate primary recovery ~13% from**

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**SINCLAIR LYLETON ‘A’ POOL
WATERFLOOD FEASIBILITY STUDY**

Prepared for:
Tundra Oil and Gas Ltd.

May 2005
Waterflood Response Unit 1 minus CO₂ pilot area

Waterflood injectors are hz hydraulically fractured

Great waterflood response in low permeability rock

Low produced Water volumes

~300 M spacing
World Stress Map

Stress trend

Orientation of Induced Hydraulic Fractures and Stress field

Figure 14: Limiting fracture configurations from a horizontal well: on the left, multiple transverse fractures; on the right, a longitudinal fracture.

from how to decide between horizontal transverse, horizontal longitudinal and vertical fractured completion; SPE 134424; M.J. Economides + A.N. Martin
Schematic Picture of Horizontal multi-frac well in East West orientation with stress field in NE+SW trend
Great waterflood response in low permeability rock

Low produced water volumes

Waterflood injectors are hydraulically fractured

Waterflood Response Unit 1 minus CO2 pilot area

K=0.13 mD

SHOULDN’T BREAKTHROUGH WITH HYDRAULIC FRACTURES?
Vertical Injector vs. Horizontal Injector
Horizontal Injector – Both CO2 and Water

Horizontal CO2 injector starts
Highlighted Area Production (CO2 injection and surrounding production)

Horizontal water injector starts
Highlighted Area Production
(CO2 injection and surrounding production)
CO₂ Produced and Retention

CO₂ INJECTION AND % PRODUCTION VS TIME

CO₂ INJECTED

CO₂ PRODUCED

CUMULATIVE CO₂ PRODUCED

CO₂ (MCF/DAY)

CUM CO₂ PRODUCED (%)
Vertical Injector vs. Horizontal Injector
**Simple Mental Model**

- Simple planar fracture system
  - Very high permeability fracture

**More Realistic Model**

- Complex fracture system
  - Substantial pressure drop within fracture system
  - Cross fractures
  - Pressure/rate dependent
Conclusions

1. Low permeability waterfloods with injectors with hydraulic fractures are increasing reserves
2. Low permeability CO$_2$ floods have had some success increasing reserves
3. Managing the fracture system and the matrix flow is key