Minnelusa Consortium

EORI Collaboration in Solving the Challenges of Minnelusa

Prepared for EOR Commission and Technical Advisory Board Meeting

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Outline

• Introduction to Minnelusa Formation
• Challenges of Production from Minnelusa
• Lab Protocol for Minnelusa Cores
• Reservoir Modeling and Simulation: Workflow and challenges
• Static model and reservoir simulation of an example Minnelusa field
• Summary
• Acknowledgments
Minnelusa Formation

- Pennsylvanian-Permian (Wolfcampian) in age\(^1\)
- **Sandstone (eolian)-carbonate cycles** caused by several episodes of off-shore *progradation of eolian sand dunes* into the evaporitic carbonate sedimentary province of the ancient Lusk Embayment\(^1,2\)
- Cyclic sedimentation was followed by *erosion* of the Minnelusa surface which was then buried by the transgressive marine *Opeche Shale*\(^1\)
- Each cycle attempts to fill in the topography left by the last depositional cycle\(^1\)
Minnelusa Formation, Cont’d

• A, B and C sand units
• Petroleum traps caused by this cyclic sequence\(^3\)
• Minnelusa is covered by 30-40 ft. of Opeche shale and is encased by a thick layer of dolomite (80 ft.) beneath the sand that becomes thinner towards west\(^1,2\)
Minnelusa Formation, B-Sand Unit

- B unit consists of intertidal and subtidal carbonates overlain by sheet and dune sandstones\(^1\)
- The B-dolomite is overlain by a thin-bedded silty sandstone which is usually well cemented with anhydrite and dolomite\(^1,5\)
- Interdunal dolomitic sandstone separates dunes\(^5\)

Fig.2 Interbedded dolomite within the B sand unit\(^4\)
Production from Minnelusa Formation

- 319 fields
- 129 fields > 1MMBBLO
- Small reservoirs (average of 4 wells per field) with average field production of 3.7 MMBO (2006)
- About 20% of the fields have an active water drive
- Active water drive fields have the best production statistics (average 500 barrels/acre-ft)
- Mainly produce form A, B and C sand units
- Oil API gravity (measured for 35 fields) = 18-40
Challenges of Oil Production from Minnelusa Formation

- Small fields
- Conformance problems:
  - Regions of dolomitic sand and layers of thin dolomite
  - Faults or hydraulic fractures causing bad material balance
  - Some wells close to water contact or perforated in the W/O transition zone
  - Bad microscopic sweep efficiency caused by low API of oil
- Lack of rock and fluid properties data:
  - Electrical properties
  - Relative permeability
  - Capillary pressure
  - PVT
- Chemical or CO$_2$ flooding data using Minnelusa cores:
  - Effect of anhydrite and dolomite on chemicals$^8$
Possible Conformance Control Problems in Minnelusa

Fig. 3 Various conformance problems  (Sydansk and Zeron, 2011)
Main Conformance Concerns in Minnelusa

- Wellbore problems
- Heterogeneity
- Water production
- Wide range of API gravity (18-40)

\[
f_w = \frac{1}{1 + \left( \frac{k_o}{k_w} \right) \left( \frac{\mu_w}{\mu_o} \right)}
\]

Fig. 4 Effect of mobility ratio caused by viscosity variations on break-through

\[
M = \left( \frac{k_{rw}}{\mu_w} \right) \frac{s_{or}}{\left( \frac{k_{ro}}{\mu_o} \right) s_{iw}}
\]
Lab Protocol for Minnelusa Cores

• Core cleaning
• Measuring general core properties:
  – Porosity
  – Air and water permeability
• Core aging using crude oil at reservoir temperature
• Core flooding using Minnelusa crude and brine
• Steady state relative permeability measurements

• Capillary pressure measurements (both imbibition and drainage)
• Rock electrical properties (formation factor, cementation exponent, resistivity index, saturation exponent, and brine resistivity)
• Core flooding using EOR/IOR and conformance control agents
Reservoir Modeling and Simulation Work Flow

Well headings and tops, core porosity and permeability, well logs (Gamma, sonic etc.) and seismic

- Horizons, layers and grids.
- Porosity, permeability and saturation distribution models

Dynamic reservoir simulation: history matching and forecasting

Rock and fluid properties:
- Special core analysis (SCAL): relative permeability, capillary pressure etc.
- PVT: black oil or compositional

- Properties of chemicals and CO2
- Core flooding information

Well completion, perforation, stimulation, hydraulic fractures and history

Fig. 5 Reservoir modeling and simulation workflow
Challenges of Reservoir Simulation in Minnelusa Formation

- Capturing dunes in a static model as a control volume
- Layering
- Rock and fluid properties
- Hydraulic connection between the dunes and also between the dunes and aquifers
- Water/oil transition zones

- Lack of accurate production and injection data especially before 1978 and BHP data for production wells
Static Model Example of a Minnelusa Field

Petrel Model: Well Log Cross Section

Fig. 6 Well log cross section for an example Minnelusa Field
Static Model Example of a Minnelusa Field
Core-Sonic and Porosity-Permeability Correlations

Fig. 7 Core-sonic and porosity-permeability correlations for an example Minnelusa Field

- Core porosity vs. Sonic porosity:
  \[ y = 1.0385x + 0.5402 \]
  \[ R^2 = 0.7734 \]

- Core porosity vs. Permeability:
  \[ y = 0.0547e^{0.3785x} \]
  \[ R^2 = 0.8749 \]
Static Model Example of a Minnelusa Field
Calculated Water Saturation

Fig. 8 Water saturation logs calculated for an example Minnelusa Field
Static Model Procedure for a Minnelusa Field

- Porosity, permeability and saturation logs were generated.
- Logs were upscaled using arithmetic average method for porosity and saturation and geometric average methods for permeability.
- Properties were distributed using sequential Gaussian simulation and ordinary krigging.
Static Model Example of a Minnelusa Field
Porosity Distribution

Fig. 9 Porosity distribution of an example Minnelusa Field
Static Model Example of a Minnelusa Field

Permeability Distribution

Fig. 10 Permeability distribution of an example Minnelusa Field
Static Model Example of a Minnelusa Field
Hydrocarbon Pore Volume Distribution

Fig. 11 Hydrocarbon pore volume distribution of an example Minnelusa Field
Reservoir Simulation Example of a Minnelusa Field
Oil, Gas, Water and Rock Properties Used to Generate PVT Curves

- Oil viscosity (API= 24.6):\(^{11}\)
  - 47.2 @ 23 °C
  - 7.5 @ 75 °C
  - <14.7 @ 65 °C

- GOR:
  - 10 in DST data
  - 40-60 in reported production data after 1985
  - 26, estimated as initial GOR using the production data

- Average TDS for water= 35000 ppm
- Gas specific gravity= 0.66
- \(C_R: 3.9E-6 \) 1/psi
- \(P_i= 3100 \) psi (estimated form pressure BU test of DST)
Reservoir Simulation Example of a Minnelusa Field

Water, Oil and Gas Properties Calculated by the Simulator

- \( B_w \): 1.0067 RBBL/STB
- \( C_w \): 2.8E-6 1/psi
- \( \mu_w \): 0.45 cP
- \( \rho_o \): 56.75 lb/ft\(^3\)
- \( \rho_w \): 62.808 lb/ft\(^3\)
- \( \rho_g \): 0.0507 lb/ft\(^3\)
- \( P_b = 438.8 \) psi

### Table 1. Calculated gas properties used for history matching of an example Minnelusa Field

<table>
<thead>
<tr>
<th>( P, ) psia</th>
<th>Gas FVF, RBBL/MSCF</th>
<th>Gas viscosity, cP</th>
</tr>
</thead>
<tbody>
<tr>
<td>145.04</td>
<td>20.77</td>
<td>0.0124</td>
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<tr>
<td>536.64</td>
<td>5.40</td>
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<td>928.24</td>
<td>3.02</td>
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<td>1319.8</td>
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<td>1711.4</td>
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<td>3277.9</td>
<td>0.82</td>
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<td>3669.5</td>
<td>0.74</td>
<td>0.0234</td>
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<td>4061.1</td>
<td>0.69</td>
<td>0.0249</td>
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<tr>
<td>4452.7</td>
<td>0.65</td>
<td>0.0265</td>
</tr>
<tr>
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<td>0.62</td>
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<td>5627.5</td>
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<td>7585.5</td>
<td>0.49</td>
<td>0.0368</td>
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Reservoir Simulation Example of a Minnelusa Field
W/O Relative Permeability and Oil PVT Data Generated by the Simulator

Table 2. Calculated oil PVT table used for history matching of an example Minnelusa Field

<table>
<thead>
<tr>
<th>Rs, MCF/STB</th>
<th>P, psia</th>
<th>FVF, RBBL/STBBL</th>
<th>Viscosity, cp</th>
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</thead>
<tbody>
<tr>
<td>0.0013562</td>
<td>47.22</td>
<td>1.0329</td>
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<td>438.82</td>
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<tr>
<td>6704.4</td>
<td>1.0463</td>
<td>23.97</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 12 Relative permeability and capillary pressure curves used for history matching of an example Minnelusa Field
Reservoir Simulation Example of a Minnelusa Field
History Matching Approach

• History matching:
  – Primary history matching
  – Static model improvement
  – Shut-in and hydraulic fracture simulation
  – Water-flood history matching

• Primary production history matching:
  – Total rate constraint during the primary to adjust relative permeability curves
  – Improve the model (aquifers) using oil rate as constraint
Reservoir Simulation Example of a Minnelusa Field
Field Primary Production History Matching

Fig. 13 Field oil and water history matching of an example Minnelusa Field
Reservoir Simulation Example of a Minnelusa Field
Pressure Distribution (July 1970)
Reservoir Simulation Example of a Minnelusa Field Pressure Distribution (Dec. 1970)
Reservoir Simulation Example of a Minnelusa Field Pressure Distribution (July 1971)
Reservoir Simulation Example of a Minnelusa Field
Pressure Distribution (Dec. 1971)
Reservoir Simulation Example of a Minnelusa Field
Pressure Distribution (July 1972)
Reservoir Simulation Example of a Minnelusa Field
Pressure Distribution (Dec. 1972)
Reservoir Simulation Example of a Minnelusa Field
Pressure Distribution (Dec. 1973)
Reservoir Simulation Example of a Minnelusa Field
Pressure Distribution (Dec. 1974)
Reservoir Simulation Example of a Minnelusa Field
Pressure Distribution (Aug. 1975)
Summary

- EORI is focused on challenges during production from Minnelusa formation through the consortium.
- Conformance problems specially wellbore problems, heterogeneity, water production and unfavorable mobility ratio will be considered in Minnelusa.
- EORI is equipped with labs capable of studying general and special core analysis and application of EOR/IOR techniques in Minnelusa.
- EORI is capable of reservoir modeling and simulation of Minnelusa fields which helps understand the challenges and improve future activities.
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• Merit Energy
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• Schlumberger SIS center
• WOGCC
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