Minnelusa
Core Analysis and Evaluation Project

Collaborative work of EORI with the Minnelusa Consortium and C&PE faculty members, Professors: Alvarado, Morrow and Piri

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Outline

• Introduction and background:
  – Minnelusa formation
  – A new Minnelusa core

• Objectives

• Core analysis and evaluation protocol

• Results and discussion
  – Porosity and permeability measurements
  – Thin section analysis
  – Tomographic images of the core plugs

  – Oil recovery by spontaneous imbibition of brine
  – Unsteady state (USS) relative permeability measurements
  – Oil viscosity

• Summary

• Future Work

• Acknowledgements
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\(^1,2\)

- Each cycle attempts to fill in the topography left by the last depositional cycle\(^1\)

- Cyclic sedimentation was followed by *erosion* of the Minnelusa surface which was then buried by the transgressive marine *Opeche Shale*\(^1\)
Minnelusa Formation, Cont’d

- Petroleum traps caused by this cyclic sequence
- A, B and C sand units
- Minnelusa is overlain 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

Fig. 1 A, B and C sand units of Minnelusa

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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
A New Minnelusa Core

- Core was collected from a Minnelusa well
- A group of EORI members witnessed the core collection in the field
- 127 ft of core was collected, ~60 ft of which was from Minnelusa (B sand)
- 83 core plugs were taken, 20 of which were sent by the company for cleaning and porosity and permeability measurements

- Core was slabbed and described by the company
- The slabbed part of the core is donated to the Geology and Geophysics Dept. at UW and the rest is donated to EORI
Fig. 3 Comparison of the sonic log for the new well with two Minnelusa representative wells from two different fields.
Objectives

- Improve the geological model of this field by measuring rock properties like porosity and permeability
- Generate Special Core Analysis (SCAL) data for core plugs representative of different observed lithological-facies for this well to improve reservoir descriptions and simulations for this field and other Minnelusa fields
- Evaluate future application of EOR/IOR in this field and other Minnelusa fields
- Provide consortium and the state of Wyoming with a valuable set of data for Minnelusa
Improvement of Reservoir Simulation Forecasts-EOR Scenarios

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

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

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

- EOR lab studies
  - Phase behavior studies for the EOR system
  - Rock-fluid interactions (Core flooding data)

Well completion, perforation, stimulation, hydraulic fractures and history

Dynamic reservoir simulation: history matching and forecasting

Fig. 4 Reservoir modeling and simulation workflow
Chemical Flood Studies Considering the Mineralogy, Water Composition and Field Conditions

- Chemical flooding is the best EOR option for Minnelusa:
  - No CO$_2$ access
  - Small fields
  - Viscous oil

- Some unsuccessful chemical and polymer floods

- Chemical flooding challenges:
  - Conformance control
  - Adverse effects of anhydrite and dolomite on surfactants and polymers
  - Variation in water salinity and hardness between the fields and even sand dunes
Fig. 5 Core analysis protocol

**Phase I**

1. Scanning the core plugs:

2. Cleaning and measuring the porosity and permeability of the un-cleaned cores:
   - 6 cores cleaned with flush technique the rest by extraction.
   - Thin section analysis

3. Selection of core triplicates for different zones:

4. Aging core plugs in crude oil at reservoir temperature:
Phase I, Cont’d

- Steady-state relative permeability measurements:
- Capillary pressure measurements:
- Wettability characterization by spontaneous imbibition

Pore network modeling

- Pc for law salinity and high salinity floods
- AP, ASP and A blends for EOR core flooding tests
- Optimize the use of alkali to reduce precipitation of scales

- Anhydrite dissolution effect on water flooding
- Unsteady-state relative permeability

Fig.5 cont’d. Core analysis protocol
Expected Results

• $\phi$, $k$, $\rho_{\text{grain}}$ and Core Images (Morrow and Piri’s group)

• $K_r$ (USS and SS) $P_c$ and $I_{o-w}$ for different lithological facies (Piri, Alvarado and Morrow’s group)

• Thin section analysis (Peigui)

• Lab results for a chemical system (Alvarado’s group)

• Anhydrite dissolution effect on waterflooding (Morrow’s group)
Porosity and Permeability Measurements

Fig. 6 Core measured porosity (Morrow’s group) shifted to match sonic porosity log vs. depth

Fig. 7 Permeability-porosity correlation for the new well (Morrow’s group)

\[ y = 0.11e^{0.365x} \]
\[ R^2 = 0.6693 \]
Comparison With Other Minnelusa Core Data

Fig. 8 Comparison between the core permeabilities measured for this field and other Minnelusa wells (Minnelusa data provided and plotted by Geoff Thyne)
Thin Section Analysis

Anhydrite cemented SS (#1-110, $k_{He}=0.225$ mD, $\phi=7.7\%$)

Anhydrite nodules (#1-83)

Fig. 9 Thin section analysis done by Peigui Yin: The LHS image shows the anhydrite cemented SS and the RHS image shows the anhydrite nodules observed in some core plugs. Black spots are oil stained dolomite cement.
Thin Section Analysis, cont’d

Dolomite cement (#1-64, $k_{He}=0.069$ mD, $\phi=3.5\%$)  

Sandy dolomite (#1-63)

Fig. 10 Thin section analysis done by Peigui Yin: The LHS image shows the sandstone with dolomite cement and the RHS image shows the sandy dolomite observed in some core plugs.
Thin Section Analysis, cont’d

Permeable SS (#1-74, $k_{He} = 280.5$ mD, $\phi = 23.7\%$)

Fig. 11 Thin section analysis done by Peigui Yin: A permeable SS observed in some of the core plugs
Fig. 12 Sonic versus core porosity values for the core taken from the new well.
Tomographic Images of the Cores

1-78 ($k_{\text{Air}}=327 \text{ mD}, \phi=18.1 \%)$

1-107b ($k_{\text{Air}}=177 \text{ mD}, \phi=16 \%)$

1-86b ($k_{\text{Air}}=99.6 \text{ mD}, \phi=16.4 \%)$

1-94 ($k_{\text{Air}}=74.9 \text{ mD}, \phi=11.8 \%)$

1-117 ($k_{\text{Air}}=5.17 \text{ mD}, \phi=11.9 \%)$

1-82b ($k_{\text{Air}}=3.76 \text{ mD}, \phi=8.2 \%)$

Fig.13 Tomographic images of the core plugs (Piri’s group)
Porosity-CT Number Correlation

Fig. 14 Permeability-porosity and porosity-average CT# correlations for 20 core plugs with measured properties
Spontaneous Imbibition of Water - Core #86b

- $\phi_{\text{Helium}} = 18.5\%$
- $\phi_{\text{Brine}} = 16.4\%$
- $k_{\text{Helium}} = 117.4\ mD$
- $k_{\text{Brine}} = 111.5\ mD$
- $S_{\text{wi}} = 20.54\%$

Fig. 15 Tomographic image of the 1-86b core (Piri’s group)

Fig. 16 Oil recovery by spontaneous imbibition of brine for Core 1-86b at 95 °C (Morrow’s group). The core was aged for 10 days in brine and then 30 days in crude oil.
USS Relative Permeability Measurement for Core # 1-85b

- Crude oil from a different field with $\mu=83$ cp at 48 °C was used
- Core was not aged, WF started as soon as the connate water was established
- $K_{Air} = 54.26$ mD
- $K_{water} = 28$ mD
- $\phi = 12.71\%$

Fig.17 a- USS relative permeability curves (Alvarado’s group). b- Tomographic image of the 1-85b core (Piri’s group)
Dissolution During the Flood-Core # 1-76

$K_{\text{Air}} = 183 \text{ mD}$

$\phi = 16.5\%$

Fig. 18 Anhydrite-cemented channel opening during a chemical flood experiment (Alvarado’s group)
Crude Oil Viscosity Versus Shear and Temperature

Fig. 19 Crude oil viscosity versus shear and temperature (Alvarado’s group)
Summary

• Cores were scanned
• Un-cleaned cores were cleaned and their porosity, permeability and grain density was measured
• Core triplicates selected based on porosity, permeability, grain density and core image from the 20 cleaned cores
• Groups received the first cleaned cores and some uncleaned cores

• Thin section analysis
• Oil viscosity vs. shear and temperature measured
• First set of USS relative permeability and spontaneous imbibition recovery were measured
Future Work

• SARA analysis
• SCAL and spontaneous imbibition measurements for cores from different lithological facies
• Pore network modeling
• Anhydrite dissolution studies
• Chemical flood
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