Abstract

Silurian (Niagaran) reefs are significant hydrocarbon reservoirs in the Michigan Basin, having produced over 500 MMBO and 2.9 trillion cubic feet of gas. The creation of static geological models that incorporate sequence stratigraphic interpretations and detailed facies enhance the understanding of the spatial distribution, and possible controlling mechanisms, of reservoir properties. Understanding the relationships between petrophysical properties and the geological controls on the spatial distribution of these flow units are the fundamental inputs for 3D static earth models. The reef reservoir will be subdivided into flow units based on the determination of pore types and most importantly pore throat size distribution. Capillary pressure data (from Mercury Injection Capillary Pressure Tests) and porosity/permeability-r35 analysis will help to identify pore throat size distribution for different depositional facies identified in core. The subdivided flow units will then be cataloged and correlated to geophysical log signatures to help populate the static model where core is not available. The Michigan Geologic Research Team have been participants in the Midwestern Regional Carbon Sequestration Partnership (MRCSP) consortium since 2005 and have provided the Partnership with ongoing data about the potential for safe, efficient, and economically viable Carbon Sequestration in the subsurface strata of Michigan. This ongoing reservoir characterization and static modeling will be used for dynamic fluid flow modeling of the Niagaran Reefs, which are the current targets for the CO$_2$ EOR project currently underway in Otsego County, Michigan.
Selected References


Petrophysical and Stratigraphic Characterization of Michigan Silurian Reefs

Matt Rine
Dave Barnes, William Harrison III, Charlotte Sullivan, Stephen Kaczmarek
Western Michigan University
9/29/2015
1. Build upon previous work on Niagaran “Pinnacle Reef” depositional models
2. Use depositional and diagenetic models to create static 3D models

Huh (1973)
Methodology

Workflow:
1) Create a depositional model for a Southern Trend Reef Complex where **ABUNDANT CORE DATA** exists.
Methodology

Workflow:
1) Create a depositional model for a Southern Trend Reef Complex where **ABUNDANT CORE DATA** exists

2) Cross Trends: Examine applicability of depositional model in Northern Trend where **INTERMEDIATE CORE DATA** exists; similarities/differences
Methodology

Niagaran Reef Trend, Michigan

100% Dolomite  Transition  100% Limestone

Workflow:
1) Create a depositional model for a Southern Trend Reef Complex where **ABUNDANT CORE DATA** exists

2) Cross Trends: Examine applicability of depositional model in Northern Trend where **INTERMEDIATE CORE DATA** exists; similarities/differences

3) Examine diagenetic trends of Northern Trend
Workflow:
1) Create a depositional model for a Southern Trend Reef Complex where **ABUNDANT CORE DATA** exists

2) Cross Trends: Examine applicability of depositional model in Northern Trend where **INTERMEDIATE CORE DATA** exists; similarities/differences

3) Examine diagenetic trends of Northern Trend

**Ultimate Goal:** Use depositional **AND** diagenetic geologic models to populate 3D static models where **LITTLE TO NO CORE DATA** exists
**Geologic Overview**

<table>
<thead>
<tr>
<th>System</th>
<th>Epoch</th>
<th>N.A. Series</th>
<th>Michigan Subsurface Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Devonian</td>
<td>Lower</td>
<td>Ulster.</td>
<td>Bass Islands</td>
</tr>
<tr>
<td></td>
<td>Upper</td>
<td>Cayugan</td>
<td>Salina</td>
</tr>
<tr>
<td>Silurian</td>
<td>Lower</td>
<td>Niagara</td>
<td>Manistique, Burnt Bluff</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cataract</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ordovician</td>
<td>Lower</td>
<td>Cincin.</td>
<td>Richmond</td>
</tr>
</tbody>
</table>

**Cayugan (423-416 Ma):** Michigan Basin shifted north a few degrees; transitioned from humid tropics into arid tropical belt.

**Late Niagaran (427-423 Ma):** Michigan Basin 20-25 degrees south of the equator in tropical to sub-tropical environment.
Geologic Overview

A) Carbonate Platform - shallow, barrier reef environment (patch reefs)

B) Carbonate Slope - gently sloping shelf (pinnacle reefs)

C) Basin Center - little to no carbonate accumulation

Modified from Burgess and Benson (1969)
University of Michigan Depositional Studies:
1) John Huh (1973) - Kalkaska 21 Field, Kalkaska County, Northern Trend

2) Dan Gill (1973) - Belle River Mills Field, St. Clair County, Southern Trend
Geologic Overview

Symmetrical Reef Model

Huh (1973) Northern Trend Depositional Model
Geologic Overview

Symmetrical Reef Model

Gill (1973) Southern Trend Depositional Model
Southern Trend - Columbus III Complex

Columbus III Field Map

LEGEND
- permit: cored well w/ analyses
- permit: core analyses only
- permit: cored well; no analyses
- Oil Well
- Dry Hole
- Brine Disposal Well

Niagara Complex Facies Distribution:
- 0 = Regional Inter-Reef
- 1 = Flank
- 2 = Windward Reef Talus
- 3 = Reef Core Complex
- 4 = Leeward Proximal Reef Apron
- 5 = Leeward Distal Reef Apron
Niagara Complex Facies Distribution:
- 0 = Regional Inter-Reef
- 1 = Flank
- 2 = Windward Reef Talus
- 3 = Reef Core Complex
- 4 = Leeward Proximal Reef Apron
- 5 = Leeward Distal Reef Apron
## Southern Trend - Columbus III Complex

### 2: Windward Reef Talus

<table>
<thead>
<tr>
<th>Lithostrat. Nomenclature</th>
<th>Depositional Facies Nomenclature</th>
<th>Core Photo</th>
<th>Gamma Ray</th>
<th>SNP</th>
<th>Core Porosity</th>
<th>Core Permeability (mD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown Niagaran</td>
<td>Reef Rubble Conglomerate</td>
<td>![Core Photo]</td>
<td><img src="#" alt="Gamma Ray" /></td>
<td><img src="#" alt="SNP" /></td>
<td><img src="#" alt="Core Porosity" /></td>
<td><img src="#" alt="Core Permeability" /></td>
</tr>
<tr>
<td>A0 Carbonate</td>
<td></td>
<td>![Core Photo]</td>
<td><img src="#" alt="Gamma Ray" /></td>
<td><img src="#" alt="SNP" /></td>
<td><img src="#" alt="Core Porosity" /></td>
<td><img src="#" alt="Core Permeability" /></td>
</tr>
<tr>
<td>A1 Carbonate</td>
<td>Supratidal Thrombolite</td>
<td>![Core Photo]</td>
<td><img src="#" alt="Gamma Ray" /></td>
<td><img src="#" alt="SNP" /></td>
<td><img src="#" alt="Core Porosity" /></td>
<td><img src="#" alt="Core Permeability" /></td>
</tr>
<tr>
<td>A2 Evaporite</td>
<td>A2 Anhydrite</td>
<td>![Core Photo]</td>
<td><img src="#" alt="Gamma Ray" /></td>
<td><img src="#" alt="SNP" /></td>
<td><img src="#" alt="Core Porosity" /></td>
<td><img src="#" alt="Core Permeability" /></td>
</tr>
</tbody>
</table>
Niagara Complex Facies Distribution:
0 = Regional Inter-Reef
1 = Flank
2 = Windward Reef Talus
3 = Reef Core Complex
4 = Leeward Proximal Reef Apron
5 = Leeward Distal Reef Apron

LEGEND
- Oil Well
- Dry Hole
- Brine Disposal Well
- Permit: cored well w/ analyses
- Permit: core analyses only
- Permit: cored well; no analyses

Paleo-wind Direction

82°40'30"W
82°39'30"W

42°54'00"N
42°53'30"N

0 1,750 FEET
Stage 1 - **Niagara Reef Complex**: Shallowing upward genetic package

A) Bioherm (deeper water)

B) Reef Core; contemporaneous Reef Apron and Reef Rubble (above FWB)

C) Stromatolitic Cap; contemporaneous Stromatolitic Rubble (intertidal to supratidal)
Stage 1 - **Niagara Reef Complex**: Shallowing upward genetic package

A) Bioherm (deeper water)
B) Reef Core; contemporaneous Reef Apron and Reef Rubble (above FWB)
C) Stromatolitic Cap; contemporaneous Stromatolitic Rubble (intertidal to supratidal)

Stage 2 - **A-1 Evaporite/A-1 Carbonate**

**Regression**: Deposition of A-1 Evaporite; Reef Complex flanks = anhydrite, Basin Center = salt

**Transgression**: Deposition of A-1 Carbonate; Distal (carbonate mudstones) in inter-reef areas; Peritidal deposits (stromatolites, thrombolites) on topographic highs of Niagara Complex
Stage 1 - **Niagara Reef Complex**: Shallowing upward genetic package

A) Bioherm (deeper water)
B) Reef Core; contemporaneous Reef Apron and Reef Rubble (above FWB)
C) Stromatolitic Cap; contemporaneous Stromatolitic Rubble (intertidal to supratidal)

Stage 2 - **A-1 Evaporite/A-1 Carbonate**

**Regression**: Deposition of A-1 Evaporite; Reef Complex flanks = anhydrite, Basin Center = salt

**Transgression**: Deposition of A-1 Carbonate; Distal (carbonate mudstones) in inter-reef areas; Peritidal deposits (stromatolites, thrombolites) on topographic highs of Niagara Complex

Stage 3 - **A-2 Evaporite/A-2 Carbonate**: Complete encompassing of Niagara-Lower Salina Complex
**RED** = No Flow Depositional Facies (tight mudstones/evaporites)

**YELLOW** = Intermediate to Low Reservoir Quality Depositional/Diagenetic Facies (Genetic Package 2 rocks; peritidal dolostones, intercrystalline porosity)

**GREEN** = Good Reservoir Quality Depositional/Diagenetic Facies (Genetic Package 1 rocks; reef boundstones, wackestones, conglomerates, intercrystalline AND touching vug porosity)
RED = No Flow Depositional Facies (tight mudstones/evaporites)

YELLOW = Intermediate to Low Reservoir Quality Depositional/Diagenetic Facies (Genetic Package 2 rocks; peritidal dolostones, intercrystalline porosity)

GREEN = Good Reservoir Quality Depositional/Diagenetic Facies (Genetic Package 1 rocks; reef boundstones, wackestones, conglomerates, intercrystalline AND touching vug porosity)

YELLOW = Salt plugged reservoir (Intermediate to Low Reservoir Quality)
Salt plugging does not result in no-flow barriers

Still need to be incorporated into static reservoir models
Diagenesis & Reservoir Quality

3 to 1 vertical exaggeration
Petrophysical properties interpolated from 29 whole core core analyses
Diagenesis & Reservoir Quality

### Model Validation:

<table>
<thead>
<tr>
<th>PETREL VOLUME CALCULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Net Volume</strong> [<em>10^6ft3</em>]</td>
</tr>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td><strong>Petrel 3D Grid</strong></td>
</tr>
<tr>
<td><strong>BWGS Estimates</strong></td>
</tr>
</tbody>
</table>

*Oil-gas contact: -2420; Water-oil contact: -2500
A 10% water saturation was used for the oil interval

Near exact match
Important to recognize:

1) The Columbus III Field has sufficient core analysis data to create a petrophysical model.

2) Control points come from core porosity-permeability; No need for log-derived petrophysical properties.

This is not the case for core-limited Northern Trend Fields.
Research Objective:
Test the validity of the depositional model built for a Southern Trend Reef Complex (Columbus III) on a Northern Trend Reef Complex (Kalkaska 21)
- 3rd order sequence boundaries
- complex geometries
- diagenesis
Kalkaska 21 and 28 Fields are a composite of 4 Niagara-Lower Salina Reef Complexes which have coalesced.

Observations made using 11 cores (bolded permit #s) and wire-line logs.
Depositional Model Validation

Kalkaska 21 Field Stratigraphic Cross Section - Stage 1: Niagara Reef Complex

Key Observations:

1) The depositional model accurately predicts Niagara facies distribution in the K-21 field
Key Observations:

1) The depositional model accurately predicts Niagara facies distribution in the K-21 field.

2) **Limestone** is observed in Reef Apron only; acts as NO FLOW baffle.
Depositional Model Validation

Kalkaska 21 Field Stratigraphic Cross Section - Stage 1: Niagara Reef Complex

Key Observations:

1) The depositional model accurately predicts Niagara facies distribution in the K-21 field

2) **Limestone** is observed in Reef Apron only; acts as NO FLOW baffle

3) K-21 field originally treated as separate reservoir pools; not full communication
Depositional Model Validation

Kalkaska 21 Field Stratigraphic Cross Section - Stage 1: Niagara Reef Complex

Leeward Distal Reef Apron

Leeward Proximal Reef Apron

Windward Reef Talus/Leeeward Distal Reef Apron

Leeward Proximal Reef Apron

Leeward Flank

Leeward Proximal Reef Core Complex

Windward Flank

Kalkaska 28 Field

POOL D

POOL C

POOL B

POOL A

Pressure Decline with Production for the Kalkaska 21 Field

Reservoir discovery pressure 3574 PSI @ -5591 ft subsea

Kalkaska 21 Field Map

Kalkaska 21 Field

POOL A

POOL D

POOL C

POOL B

Kalkaska 28 Field

POOL D

POOL C

POOL B

Kalkaska 21 Field

POOL A

POOL D

POOL C

POOL B

Kalkaska 27 Field
The application of this depositional model helps to better understand the performance of this field.

Q: Is Limestone predictable?
Regional Diagenetic Trends

Niagaran Reef Trend, Michigan

Northern Trend Reefs gradationally transition from 100% **Dolomite** to 100% **Limestone** in the basinward direction.

Southern Trend Reefs are 100% **Dolomite**

*Calculated using wire-line log cutoffs for Sequence 1 Niagara Rocks ONLY*
Regional Diagenetic Trends

**Fundamental Observation:**
It has been observed that limestone lithologies in Niagara-Salina Reef complexes have little to no reservoir quality.
Next Phase

Medium to Low Core Density
Next Phase

CO2 Storage Fields:
- Actively Storing CO2
- Upcoming Target
- Current WMU Collaboration

% Dolomite
- 100%
- 80%
- 60%
- 40%
- 20%

Otsego County

1 core
2 cores
3 cores
Summary

1) Niagara-Lower Salina Reef Complexes are **asymmetrical** and facies distributions are predictable both vertically and laterally.

2) 3rd order sequence boundaries are observable in both the Northern and Southern Silurian Reef Trends.

3) Diagenesis is different across Trends, however **regional trends of dolomitization** are observed and very important for reservoir modeling.

**Conclusion:** Geological studies can most definitely optimize CO2 Storage and EOR operations.
Thank You and Safe Travels