Tuscaloosa Marine Shale Laboratory (TMSL)

Project Number (DE-FE0031575)

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Presentation Outline

• Tuscaloosa Marine Shale Laboratory (TMSL) Team
• Objectives
• Accomplishments in BP3
  - Task 3: Improving TMS Drilling Efficiency and Wellbore Stability
  - Task 4: Improving TMS Formation Evaluation
  - Task 5: Digital Image Correlation
  - Task 6: Foam Generation with Nanoparticles
  - Task 7: Shale Hydrocarbon Phase Solubility
  - Task 8: Socioeconomics of TMS Development
• Organization Chatter
• Bibliography
TMSL Consortium
TMS Background

- **High potential** unconventional play: “An Unproven Unconventional Seven Billion Barrel Oil Resource - the Tuscaloosa Marine Shale (1997)”?

- Limited public shared knowledge.

- **Industry struggle** to develop this formation due to technical and economic issues.

- **Good timing:** availability of data and resources.
Major Goals of TMSL Project

The overall goal of TMSL project is to form a consortium of science and industry partners to address critical gaps in the understanding of TMS with the following objectives:

- To improve drilling and completion efficiency for TMS wells by better understanding the source of wellbore instability issues and proposing innovative cementing solutions.

- To improve formation evaluation using laboratory techniques for the evaluation of mineralogical composition, organic content, and produced water chemistry as well as well log and geophysical analysis.

- To examine the role of geologic discontinuities on fracture growth and deformation behavior using digital image correlation technique.

- To test the application of stable CO₂ foam and super-hydrophobic proppants for improving reservoir stimulation.

- To test the nature of water/hydrocarbon/CO₂ flow in clay and organic-rich formation and the role of kerogen and water/fluid interaction on oil recovery.

- To develop better socio-economic environment for TMS by community engagement.
Wellbore shape is conducted based on TMS well logging data.
Rheology of mud and cement slurries are described using Herschel-Bulkley model (Foroushan et al., 2020).
Simulation time is set as 12000 sec (or 13.586 bbl)
No voids observed as cement/mud density ratio equals to 1.2. Density ratio significantly affects displacement efficiency due to buoyancy effects. As density ratio increases from 1.2 to 1.8, incomplete mud removals happened at 0.11, 0.12, 0.14, and 0.17m to the casing surface.
Denkmann 33-28 H2, Thomas 38H-1, Soterra 6H-1, and Eads_Poitevent_et_al_1 wells were added to the analysis.

Borehole images allowed the identification of several zones affected by natural fractures with possible frac barriers located in between.

These are nearly-vertical or vertical natural fractures with dip magnitudes between 80 and 90 deg.

There is a good agreement between the borehole image and shear-wave splitting analyses. Both show that fractures occur along the E-W direction in the TMS.

Fast shear azimuth plotting indicates that the $S_{hmax}$ is oriented at 100° E-W.
The $S_{\text{hmax}}$ orientation is consistent throughout the TMS.

Most wells fall on the same paleostress line, but Lane 64-1 and Eads Poitevent_et_al_1 wells show a 10° counterclockwise rotation from S to N of the stress field.

We recommend orienting lateral wells perpendicular to the direction shown on the map.
Multi-attribute Analysis

The target log $L(t)$ is predicted from the combination of optimal seismic attributes A, B, C.

The weights $w_1, w_2, w_3$ are calculated by minimizing mean squared predicted error.

$$L(t) = w_0 + w_1 * A(t) + w_2 * B(t) + w_3 * C(t) + ...$$
Task 4.1 Well Log

90% training accuracy
81% validation accuracy
Task 4.1 Well Log

TOC Map
Subtask 4.6 Produced Water Chemistry

Completion of Mineralogical and Geochemical Data Collection and Synthesis

- Historical data from 11 wells that were previously published.
- Historical data from two additional wells.
- Analysis of cuttings from horizontal portion of seven additional wells.


https://scholarsmine.mst.edu/masters_theses/7975/
Subtask 4.6 Produced Water Chemistry

Data Synthesis

![Triangular plot showing data synthesis for various wells with labels Well 1 to Well 20, categorized as old core data, new core data, and new cuttings data.](image)
# Subtask 4.6 Produced Water Chemistry

## Comparison with previous work

<table>
<thead>
<tr>
<th>Source of sampling</th>
<th>Depth range</th>
<th>n samples</th>
<th>Avg. Quartz (wt%)</th>
<th>Avg. Calcite (wt%)</th>
<th>Avg. Total clay (wt%)</th>
<th>Avg. TOC (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lu et al. (2015)</td>
<td>3337-3361 m (within HRZ)</td>
<td>7- XRD 6- TOC</td>
<td>9.98</td>
<td>13.02</td>
<td>52.96</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>3283-3361 m (total TMS)</td>
<td>14- XRD 13- TOC</td>
<td>12.14</td>
<td>9.14</td>
<td>55.69</td>
<td>1.39</td>
</tr>
<tr>
<td>Besov et al. (2017)</td>
<td>N/A</td>
<td>12 FTIR &amp; TOC</td>
<td>7</td>
<td>11</td>
<td>63</td>
<td>1.6</td>
</tr>
<tr>
<td>Lowery et al. (2017)</td>
<td>3361.3-3319.3 m (within HRZ)</td>
<td>65- TOC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.78</td>
</tr>
<tr>
<td></td>
<td>3276.6-3361.3 m (total TMS)</td>
<td>135- TOC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.43</td>
</tr>
<tr>
<td>Enomoto et al. (2017)</td>
<td>70 wells in TMS (cuttings and core)</td>
<td>Various</td>
<td>96 (within HRZ) - XRD &amp; TOC</td>
<td>36</td>
<td>4</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>116 (TMS outside of HRZ) - XRD &amp; TOC</td>
<td>32</td>
<td>16</td>
<td>44</td>
</tr>
<tr>
<td>Borrok et al. (2019)</td>
<td>11 wells in TMS (core)</td>
<td>Various (all within HRZ)</td>
<td>161- XRD 136- TOC</td>
<td>22.8</td>
<td>17.2</td>
<td>47.6</td>
</tr>
<tr>
<td>Lohr 2020 (data from Enomoto et al. (2017) &amp; Hackley et al. (2020))</td>
<td>Various within 3002-4215 m</td>
<td>154 from 37 wells- TOC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.03 (within HRZ)</td>
</tr>
<tr>
<td>This study</td>
<td>21 wells Basal 20 m</td>
<td>241</td>
<td>25.2</td>
<td>16.8</td>
<td>47.0</td>
<td>1.58</td>
</tr>
</tbody>
</table>
Task 5.4 Creep Test with DIC

- **Trial Experiments**: single uniaxial compressional compliance creep test with one loading stress on Mancos shale in parallel and perpendicular sample and multistage uniaxial compressional compliance creep test with multiple step loading stress on plastic pipe.

- **Test Conducted**: multistage compressional compliance creep test for the TMS sample

- **Procedure**: Each loading stage was for 5 hours, First stage is with 70% of UCS load, Load increment was 20% of UCS for perpendicular sample and 10% of UCS for parallel sample until failure of the specimen

- **Sample Selection**: samples based on the different mineralogy (high clay content with low carbonate and rich carbonate with low clay content)
Task 5.4 Creep Test with DIC
Using the Power Law equation and DIC measurement, we were able to generate linear regression of all the stress level of the previous specimen.

B is decreasing at higher stress level while n is decreasing and increasing based on some stress level.

B and n value can help predict the creep value over time.
Task 4.7 Shale Swelling with DIC

- New DIC setup enabled study shale and helped observe non-uniform deformation with clay-rich laminae showing localization of high strains.
- Different clay-rich laminations swell at different times and swelling laminas stimulated growth of other swelling laminations.
1. It was found that the rate of expansion in the period from the initial immersion to 5hr is the highest compared to the later strain development for all specimens exposed to the DI water and brines.

2. The ionic strength of the fluid significantly affects the rate of swelling and its progression. It was determined that the increase of KCl and NaCl concentration from 2 to 6% might reduce the shale swelling by 39 and 43%.

3. It was assessed that once a high strain region is formed in the samples immersed in DI water and NaCl brine, the hydration of a shale matrix in its immediate vicinity is initiated, which leads to a moderate strain development and formation of the new fractures. Whereas in the samples immersed in KCl brine, the high strain sites either propagate independently or coalescence with fractures extended from other regions.

4. The induced fractures significantly affect the water intake by the shale. Thus, the rapid increase of shale swelling can be attributed to the formation of new fractures in the specimen.
Subtask 6.1c CO$_2$ foam Leak-off tests

\[ V = V_{sl} + m \times \sqrt{t} \]

\[ C_w = 0.0328 \times \frac{m}{A_c} \]

$V$ is the total leakoff volume, $cm^3$, $V_{sl}$ is the spurt leakoff volume before the steady leak off, $cm^3$, $t$ is the time elapsed, min, $A_c$ is the cross-sectional area of the core, $cm^3$, $C_w$ is the leak-off coefficient, $\frac{ft}{\sqrt{min}}$. 

Schematic experimental setup for foam leak off test
### Comparison of leakoff coefficients

<table>
<thead>
<tr>
<th>Fluid configuration</th>
<th>Leakoff coefficients (ft/√min)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dynamic $C_w$</td>
<td>Static $C_w$</td>
<td>$C_\text{wgas}$</td>
</tr>
<tr>
<td>Pure water, 1300psi, 18mL/min</td>
<td>0.264</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>10% quality, 5% NaCl, 5000ppm NP, 1300psi, 18mL/min</td>
<td>$C_\text{wgas}$</td>
<td>0.17156</td>
<td>$C_\text{wliquid}$</td>
</tr>
</tbody>
</table>
Subtask 6.3c: fracture conductivity using super-hydrophobic proppants and regular proppants.

Time and stress dependent fracture conductivity for water-wet proppants.

Time and stress dependent fracture conductivity for oil-wet proppants.
Subtask 6.3c: fracture conductivity using super-hydrophobic proppants and regular proppants.

Comparison of fracture conductivity decline with confining pressure for samples with oil-wet proppants (C1 to C5) and samples with water-wet proppants (C6 and C7).
Fracking with scCO$_2$ coupled with horizontal drilling has resulted in tremendous production increases in unconventional shale reservoirs over the short term (months).

- Averaged over time however EOR is limited to the recovery of less than approximately 10% of the in-situ energy reserve.
- New Huff-N-Puff “green” gas extraction techniques are currently proposed for unconventional reservoir EOR. However they require significant operational downtimes.

- In this exploratory research, the feasibility and efficiency of enhanced in-situ hydrocarbon extraction using scCO$_2$ solvent + modifiers is discussed.
- Our experimental extraction results on oil shale samples at reservoir P-T conditions indicate that new CO$_2$ solvent mixtures can potentially increase fluid-rock interactions along fracture surfaces.
- If correct this may bring more efficiency to the production of O&G from “water sensitive” unconventional shale plays (TMS and EF) and significantly contribute to “greener” FE production over the next 30 year transition to alternate energy solutions.
Enhanced In-situ Hydrocarbon Extraction Experiments

NB: Eagle Ford core (7wt% TOC) was used in this study for analytical reasons. Both EF and TMS plays are of Upper Cretaceous shallow marine origin that were deposited during transgressions of
Enhanced *In-situ* Hydrocarbon Extraction: 
**Results**

- 2019: Completed 17 tests using different co-solvent mixtures at P=34MPa, T=80C.
- 2020: Effluent and solvent were reanalyzed for each test using GCMS and XRF, gXRD and ELMS to determine TOC, bulk composition and mineralogy.

**RESULTS:**

1. HC liquid effluent extracted at P-T is proportional to the TOC extracted from the shale.
2. The addition of cosolvents THF + PropOH to scCO$_2$ enhances HC extraction*.
Enhanced In-situ Hydrocarbon Extraction: GC Effluent Analyses

GB-1: CO₂ Only

- nC-15
- TOC extract = 6.3 wt%

GB4-HHB3: scCO₂ + [5% AA]

- nC-15
- TOC extract = 7.0 wt%

GB3-HOBY: scCO₂ + [5% MeOH]

- nC-15
- TOC extract = 8.7 wt%

GB14-HOBX: Stage 1/4

- scCO₂ + [5% THF + 2.5% PropOH]
- TOC extract = 15.5 wt%
Results to date indicate that:

- scCO₂ + cosolvent modifiers [THF+PropOH] effectively enhance in-situ HC extraction by a factor of 2.5 over scCO₂ only extraction.

- Over 95% of the HC extraction occurs within the first 3 pore volumes (PV) equivalent to ≈16wt% of the shale TOC.

- This is likely due to the fact that co-solvent extraction may be limited to the fraction of kerogen (± bitumen) present in the shale.
Enhanced In-situ Hydrocarbon Extraction: Conclusions

1. We have verified that the addition of THF + PropOH to scCO₂ results in substantial HC extraction enhancement.

2. The GC analyses confirm that this is due to the extraction of heavier hydrocarbons ($15 \leq nC \leq 28$).

3. The HC extraction seems limited to 30 vol% and ≤ 3 pore volumes.

4. We hypothesize that the TOC extracted is limited to the amount of kerogen (±bitumen) present.

- In the next month we hope to conduct 3-5 repeat experiments to verify our results.

- This will also require verifying our hypothesis that kerogen was the main phase extracted by analyzing post-test solid residues and liquid effluents to ID extracted hydrocarbon phase(s).
Enhanced In-situ Hydrocarbon Extraction: Summary

- The overarching goal of this study was to investigate the potential for enhancing the in-situ extraction of liquid hydrocarbon (HC) reserves from water-sensitive unconventional oil shale reservoirs (e.g., TMS and EF).

- As a working hypothesis we postulated that this goal could be achieved by using scCO₂ co-solvent mixtures that act as chemical modifiers during fracking.

- During an 18 month Laboratory closure due to the Covid-19 Pandemic we were unable to complete microfluidics testing – however we used that time to (i) rerun all post-extraction hydrocarbon analyses ($C_{TOT}$, TOC, $\delta^{13}C$) in triplicate for the residue solid samples, and (ii) reprocess all gas chromatography analyses of the effluent extracts for each test.

- Our results confirm our hypothesis that at unconventional oil shale reservoir conditions ($P=5000$psi; $T=80^\circC$), the addition of tetrahydrofuran (THF) and isopropanol (PropOH) to supercritical CO₂ fluids can potentially result in a substantial enhancement of current EOR extraction techniques.
Task 8.5 TMSL Consortium Meeting

- TMSL consortium Meeting was held in Lafayette, LA on August 2-3, 2021.
- The meeting will be an in-person event in Lafayette with remote access.
Appendix
TMSL Collaboratory Team:
Multi-Disciplinary, Multi-Institutional, EPSCoR Region

DOE Project Manager (Bruce Brown)

University of Louisiana at Lafayette (UL Lafayette)

- Missouri S&T: David Borrok
- Missouri S&T: Wan Yang

The University of Oklahoma (OU): Saeed Salehi

Los Alamos National Laboratory (LANL): Gilles Bussod

University of Southern Mississippi (USM): Chad Miller

Ning Liu

Rafael Hernandez

Boyun Guo

Rui Zhang
Bibliography

Thesis and Dissertation

Conference Publications
5. Wu, Y. and Salehi, S. A Numerical and Experimental Study On Cement Integrity Based On a Novel Method. ARMA 54th us rock mechanics/geomechanics symposium, June 28-July 1, 2020 at the virtual meeting.