Tuscaloosa Marine Shale Laboratory (TMSL)

Project Number: DE-FE0031575

Ning Liu, Ph.D.
University of Louisiana at Lafayette

U.S. Department of Energy

National Energy Technology Laboratory

Field Labs-Emerging Plays and DA/ML

Project Review Meeting

October 15, 2020

Presentation Outline

- Tuscaloosa Marine Shale Laboratory (TMSL) Team
- Objectives
- Accomplishments in BP2
    - 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
- Dissemination of Results
- Future Works in BP3

TMSL Consortium

University of Louisiana Lafayette

Missouri S&T

The University of Southern Mississippi

Los Alamos National Laboratory EST. 1943

Department of Energy United States of America

Goodrich Petroleum Corporation

Department of Energy United States of America

ExxonMobil

Berkeley Lab

Helis Oil & Gas

Los Alamos National Laboratory EST. 1943

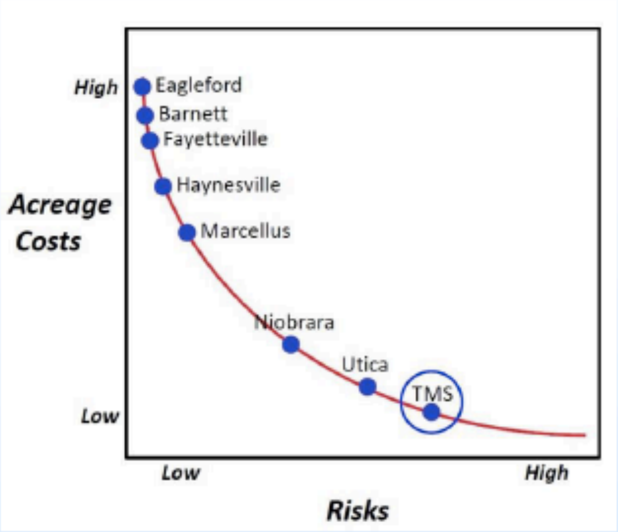
TMS Background

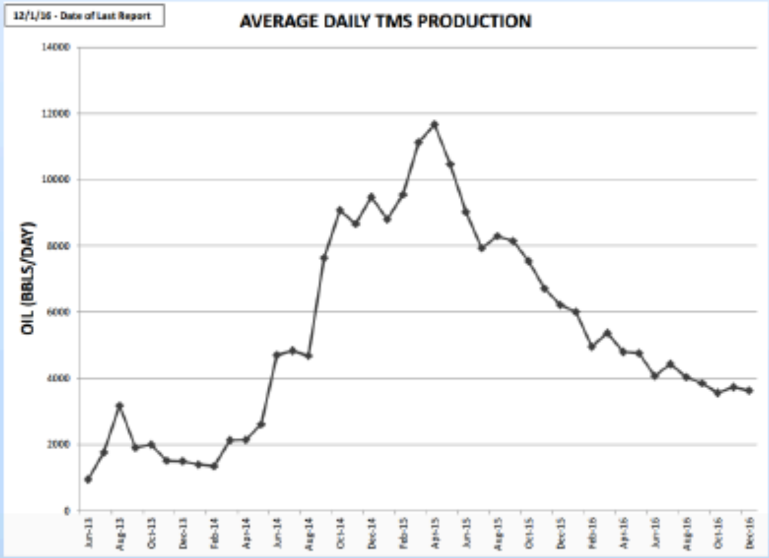
- **High potential** unconventional play: "An Unproven Unconventional Seven Billion Barrel Oil? Resource - the Tuscaloosa Marine Shale (1997)"?

- **Limited public shared knowledge.**

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

- **Good timing:** availability of data and resources.



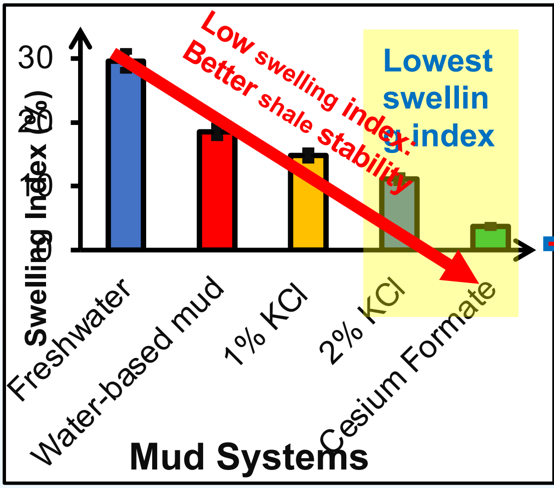


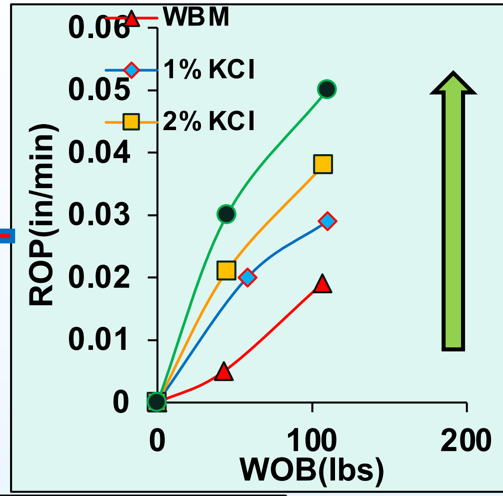
Major Goals of TMSL Project

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 f 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 CO_2 foam and super-hydrophobic proppants for improving reservoir stimulation.
- To test the nature of water/hydrocarbon/CO_2 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.

Task 3: Improving TMS Drilling Efficiency and Wellbore Stability

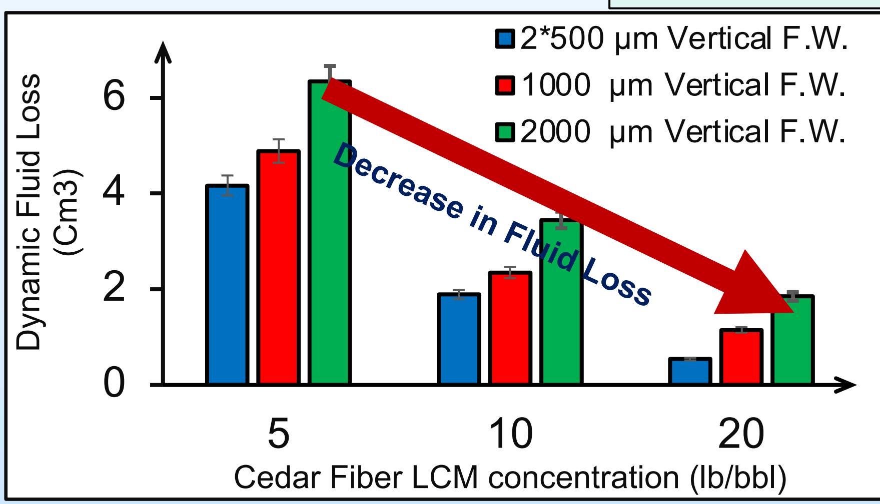




Inhibitive Mud System: **Cesium Formate** and **HPWBMs**

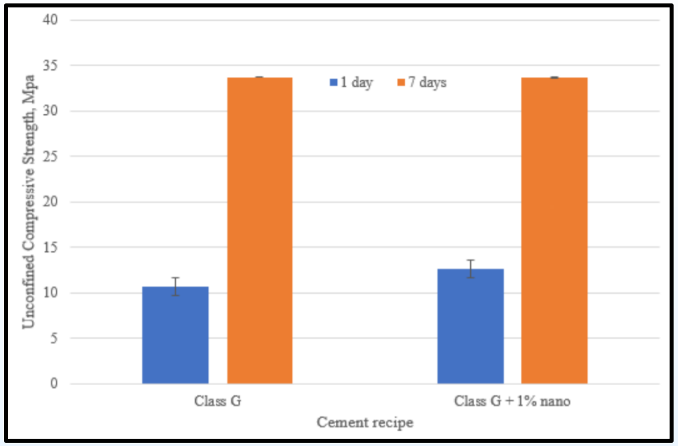
- ✓ Lower friction factor & torque
- ✓ Higher ROP
- ✓ Lower MSE (up to 80%)

- **Better Performance**
- **Better Compatibility (Low Swelling**

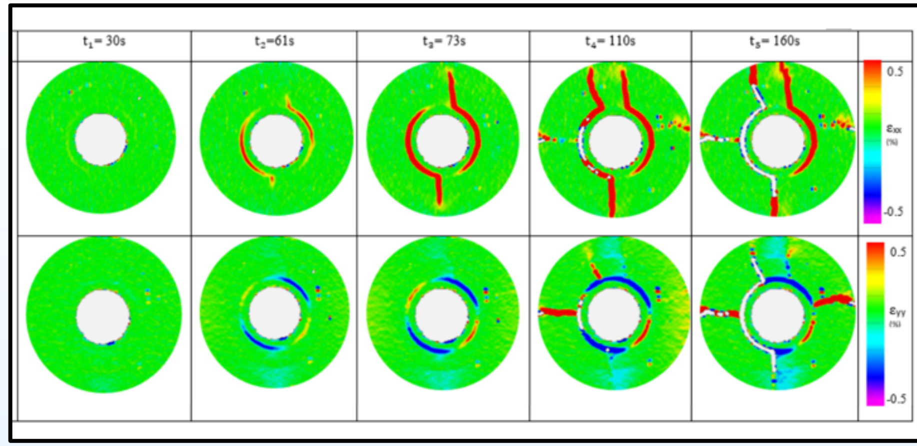


20 lb/bbl Cedar fiber shows most effective ***Sealing*** and ***minimum Lost Circulation***.

Task 3: Improving TMS Drilling Efficiency and Wellbore Stability



Mechanical test



DIC results

Geopolymer and **nano-modified** cement systems have better performances:

- ✓ High UCS
- ✓ Less maximum failure load
- ✓ High deformation before failure

Task 4: Improving TMS Formation Evaluation

Task 4.1: Well Log Analysis

Task 4.2: Geophysical Data Analysis

Task 4.3: Production Data Analysis

Tasks 4.4 & 4.5: Mineralogical Composition & Total Organic Content Evaluation of TMS

Task 4.6: Ionic movement between TMS Cores and Water

Task 4.7: Sedimentologic and Sequence Stratigraphic Study of TMS and Thermal Imaging

Task 4.1: Well Log Analysis

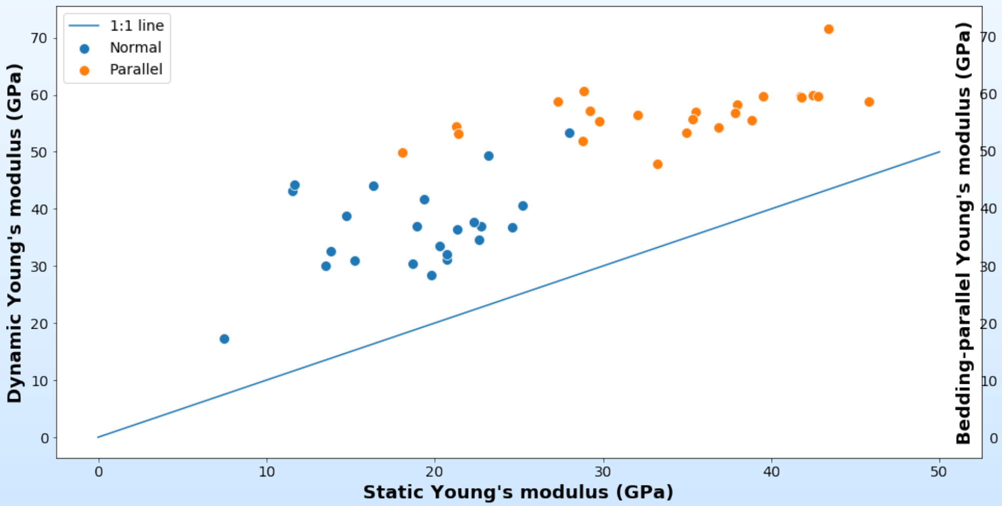
Characterization of Elastic Mechanical Properties of Tuscaloosa Marine Shale From Well Logs Using the VTI Model

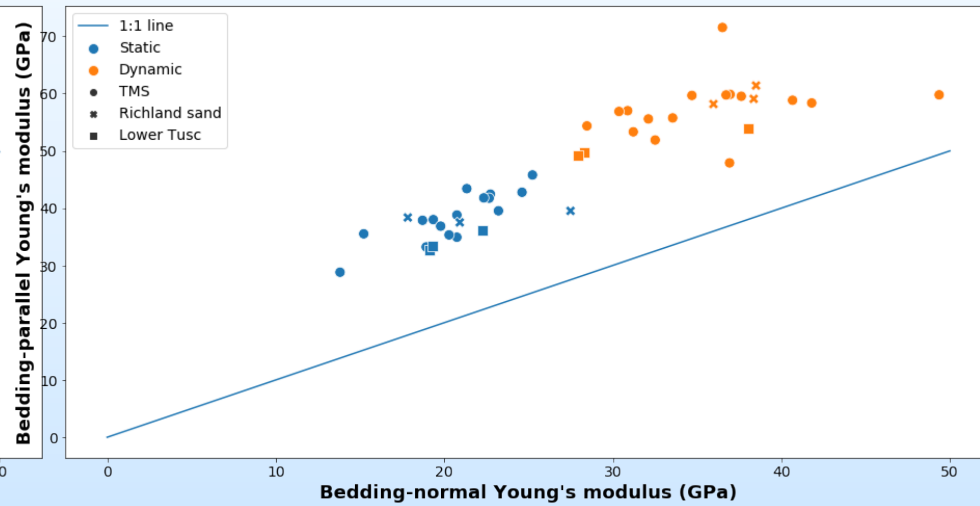
- A VTI model calibrated to core data from two TMS wells was used to estimate the static mechanical properties of the formation
- It was showed that the vertical Poisson's ratio is less than the horizontal Poisson's ratio in the Tuscaloosa Marine Shale
- The proposed model handles the difference between the two ratios by using empirical correlations developed from core data
- The Young's moduli have values between 10.5 and 33 Gpa and the horizontal modulus is constantly higher than the vertical one
- Well A presents close values for the two Poisson's ratios, while Well B is characterized by a difference of 0.1 between the ratios
- The isotropic solution underestimates the min. horiz. stress in both wells and the VTI model converges to the isotropic solution in Well A
- The 20-foot shale interval below TMS may prevent fracture growth

Task 4.1: Well Log Analysis

Experimental Evaluation of Ultrasonic Velocities and Anisotropy in Tuscaloosa Marine Shale Formation

- The experimental evaluation of ultrasonic velocities and anisotropy was performed on 5 Tuscaloosa Marine Shale (TMS) wells.
- TMS velocity data set was compared to the established Vp-Vs relationships.
- Several factors that impact the velocities were examined. The effect of mineralogy, organic content and maturity were studied using the data obtained from XRD and Rock-Eval measurements.



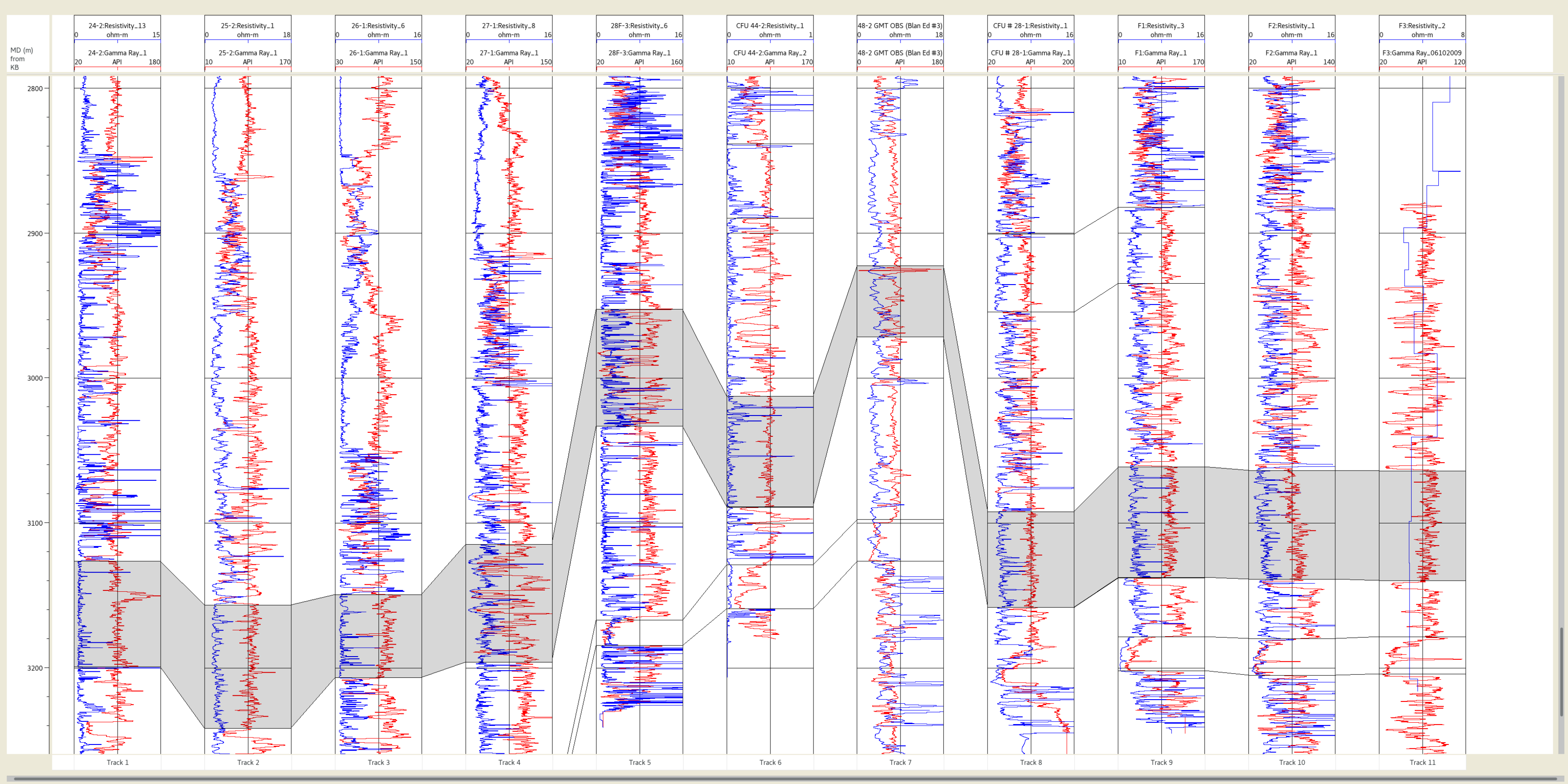


Task 4.1: Well Log Analysis

Significant results

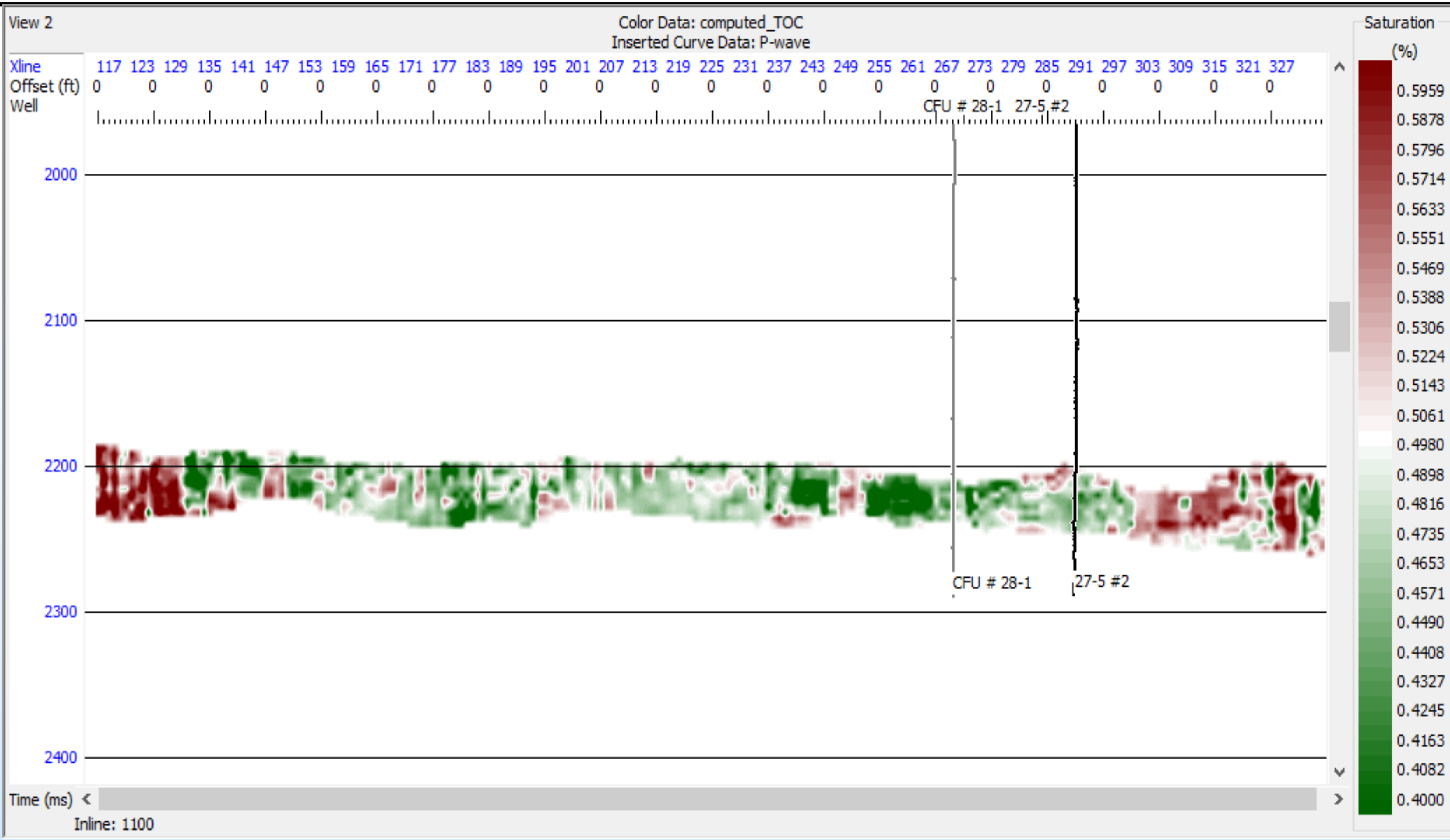
- Static and dynamic results illustrated that horizontal Young's moduli were higher than vertical Young's moduli for all the samples. In addition, vertical Poisson's ratios were lower than horizontal Poisson's ratios for the studied samples.
- The elastic moduli measured from the dynamic method were consistently higher than those measured from the static method. On the other hand, the dynamic Poisson's ratios were either greater or smaller than static Poisson's ratios.

Task 4.2: Geophysical Data Analysis



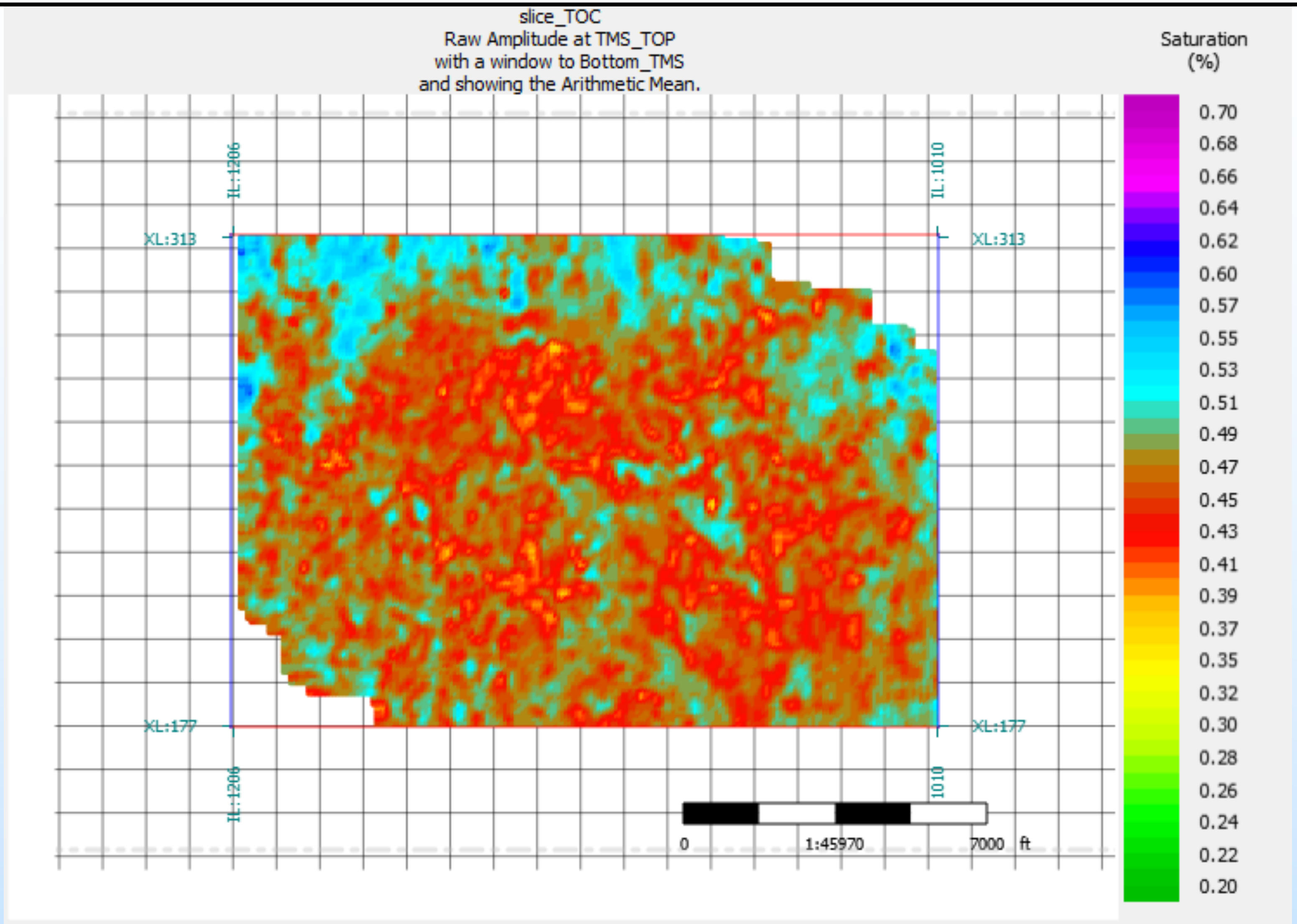
Well log correlation of TMS at Cranfeild

Task 4.2: Geophysical Data Analysis



TOC estimation at TMS by using seismic multi-attributes analysis

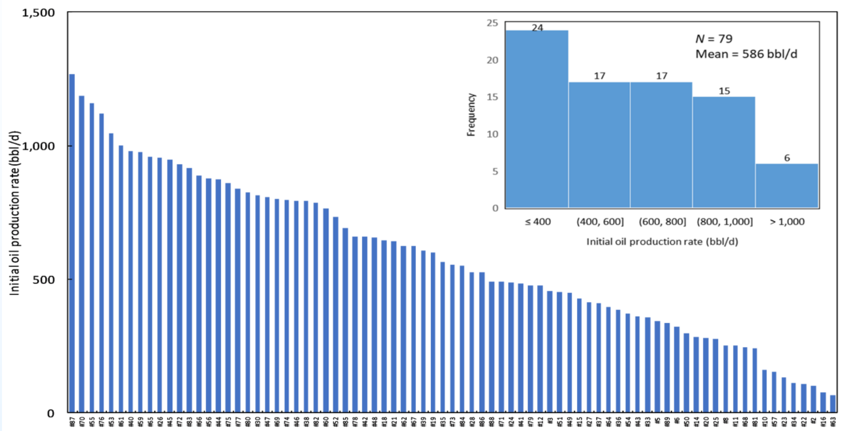
Task 4.2: Geophysical Data Analysis

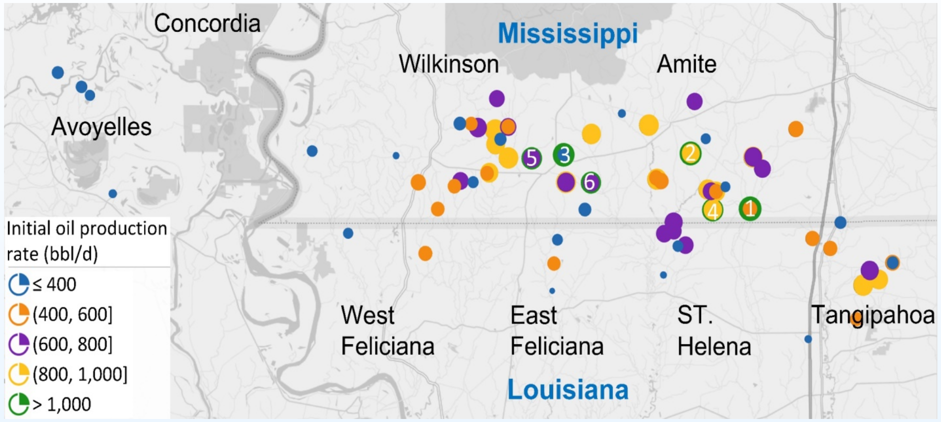


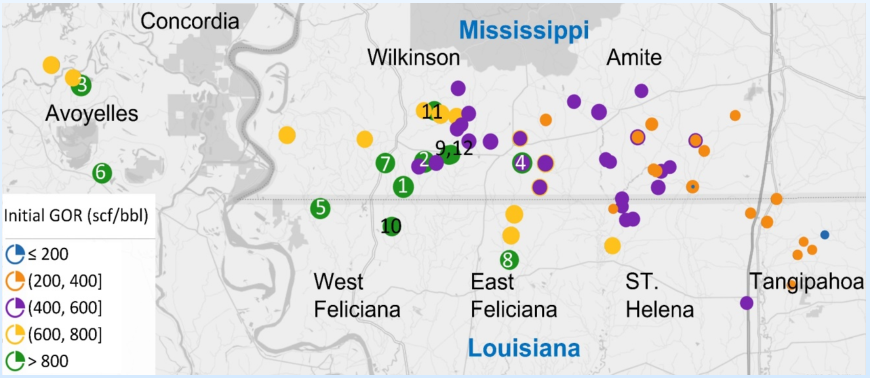
The map view TOC estimation at TMS

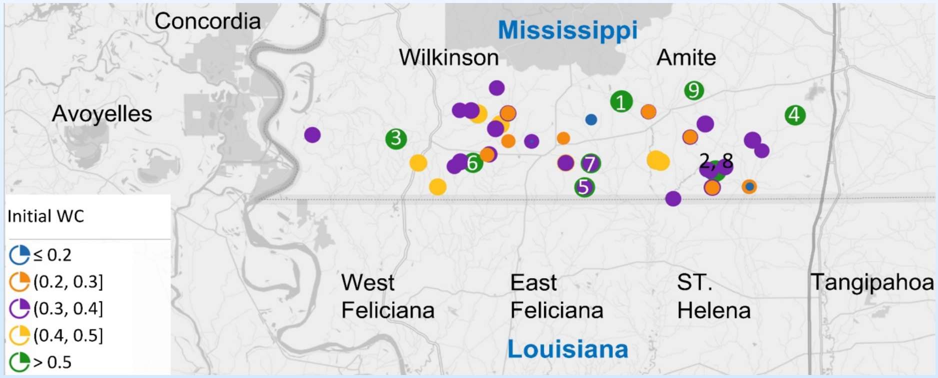
Task 4.3: Production Data Analysis

TMS Initial Production (1st year)



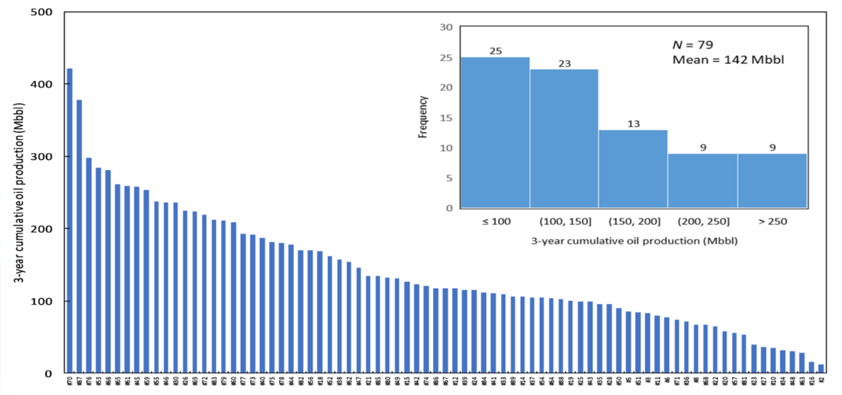


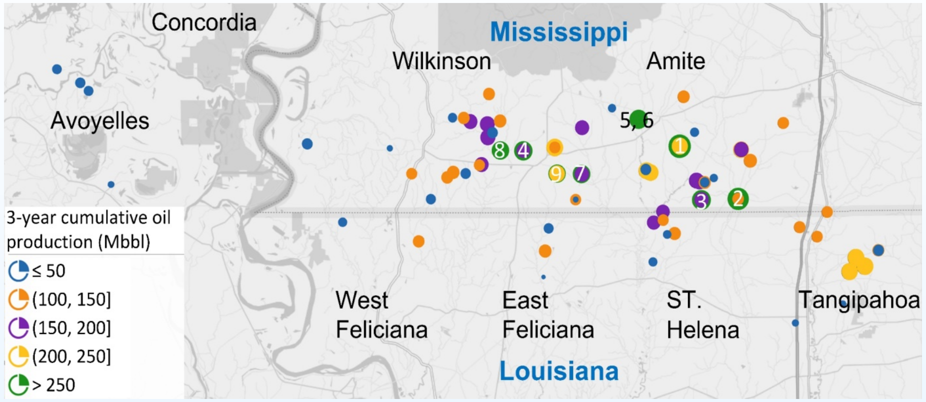


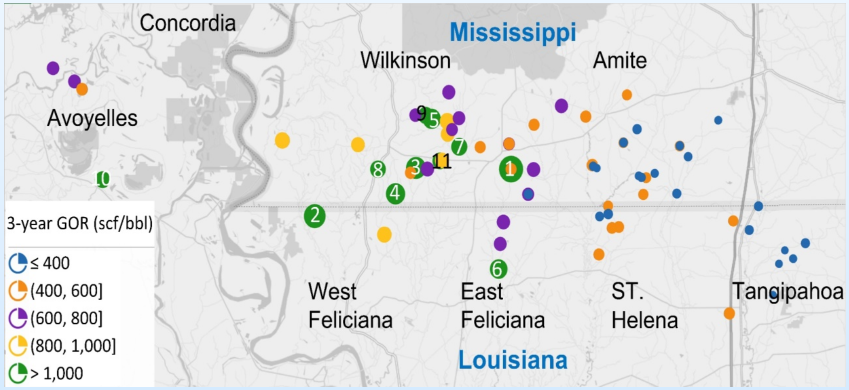


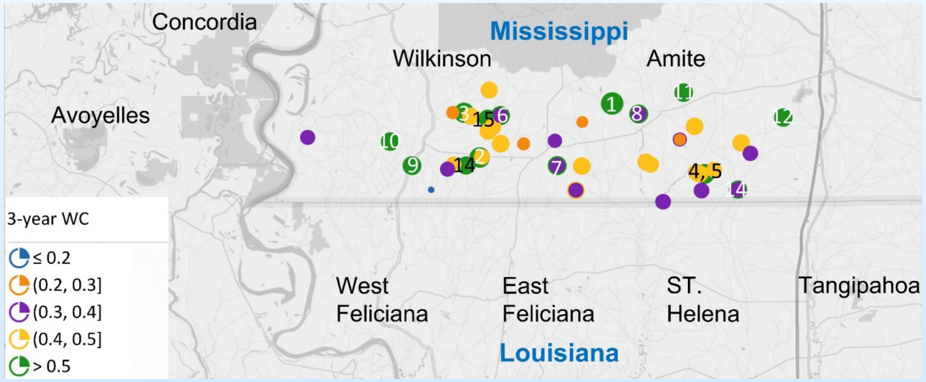
Task 4.3: Production Data Analysis

TMS 3-Year Production



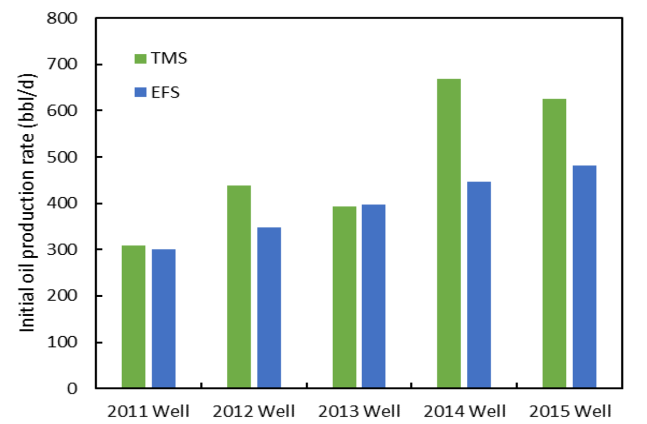


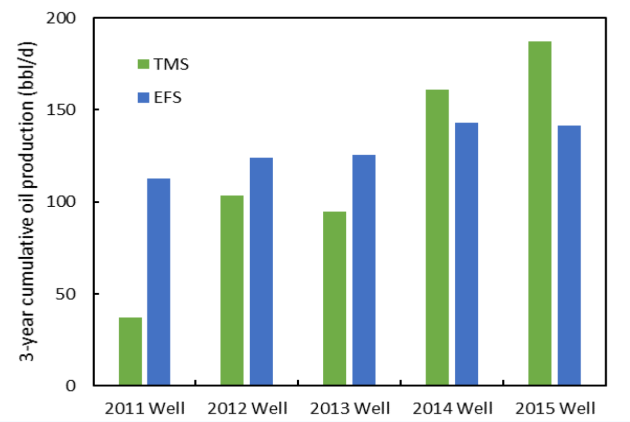


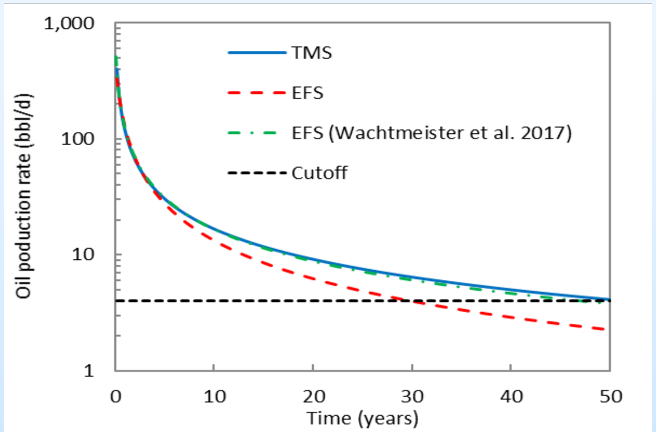


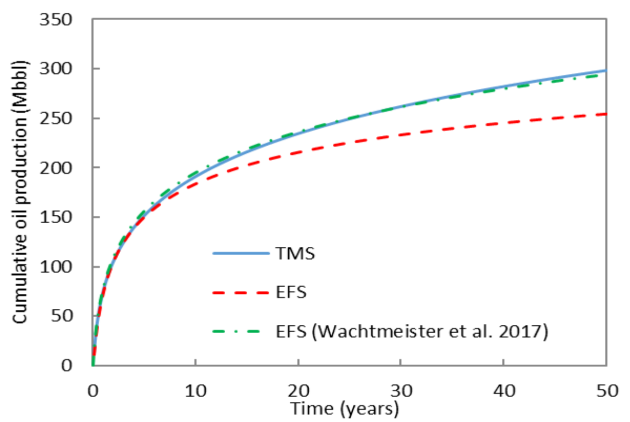
Task 4.3: Production Data Analysis

TMS vs. EFS









Tasks 4.4 & 4.5:
Mineralogical Composition & Total Organic Content Evaluation of TMS

- Obtained new mineralogical and geochemical data from two wells in the TMS. These data were added to the data from 11 wells that were compiled in BP1.
- Fifty-seven new samples of cuttings from seven wells in the TMS have been analyzed for their organic geochemistry, mineralogy, and elemental compositions.
- Evaluated relationships among production data, fracking data, and geochemistry and mineralogy for the TMS. Statistical analysis and contour maps have been created to evaluate trends within these data.

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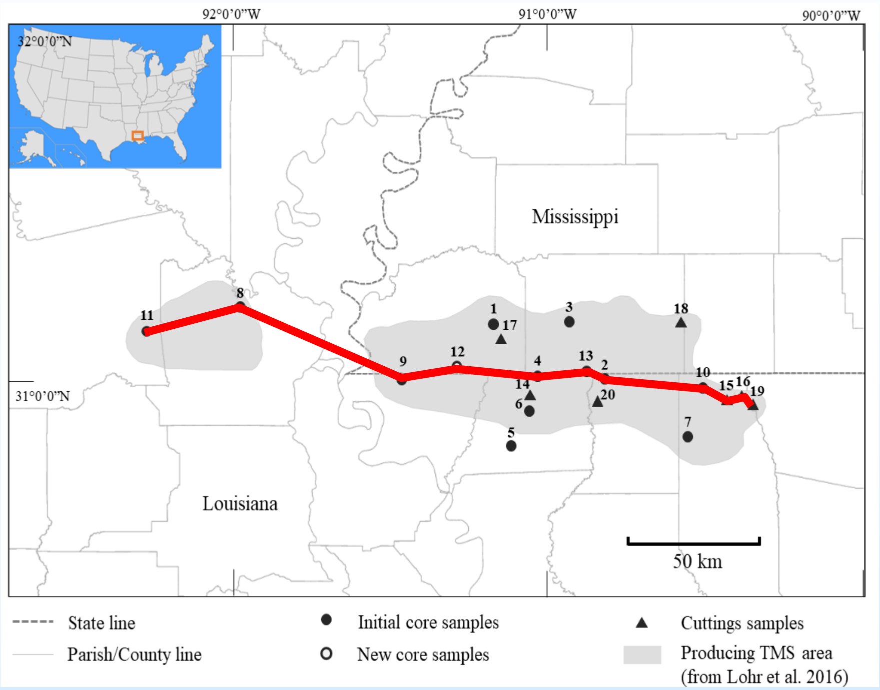
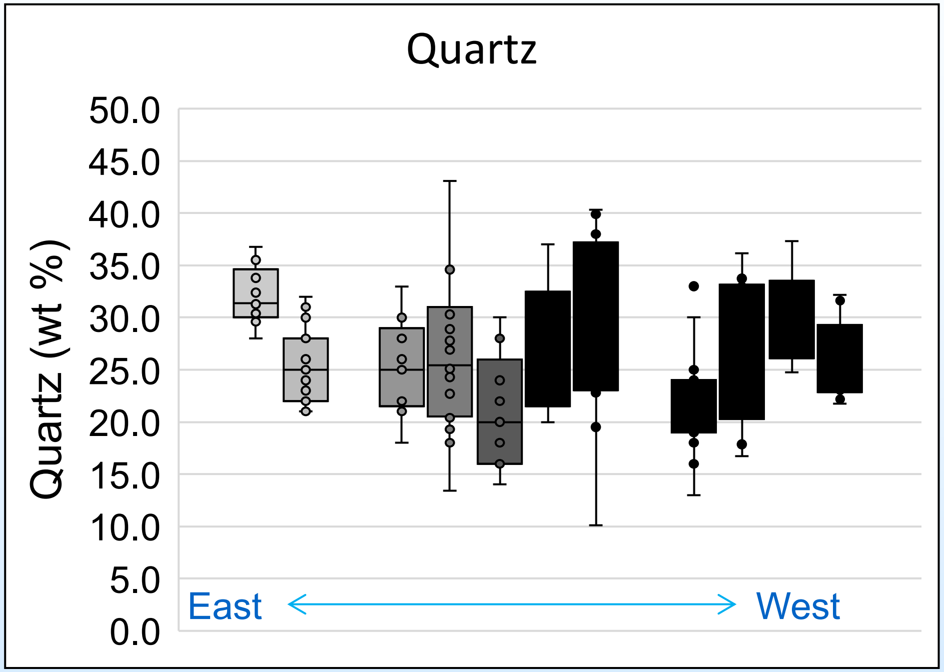
Mineralogical Composition & Total Organic Content Evaluation of TMS





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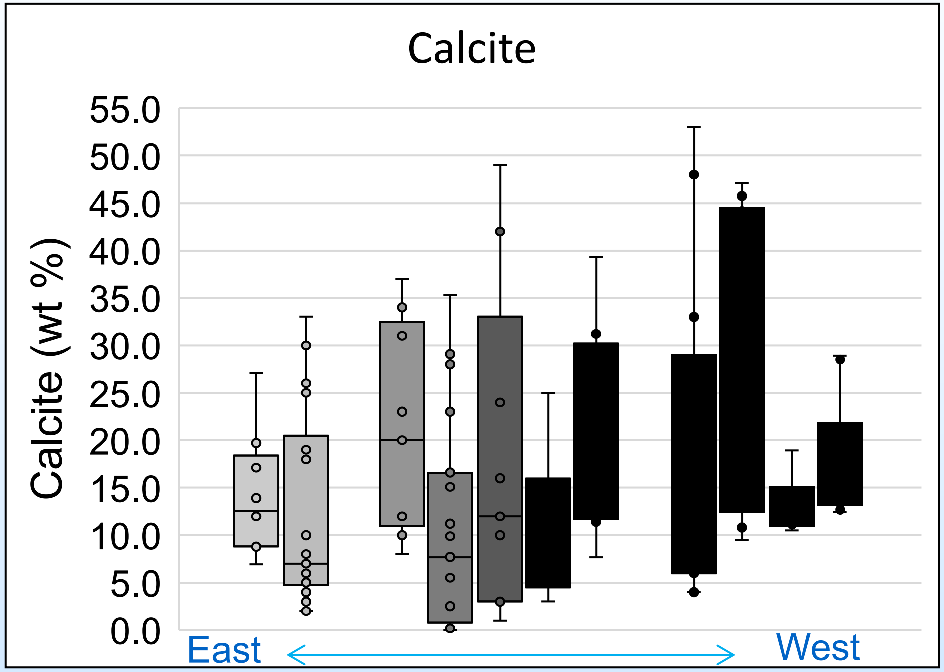
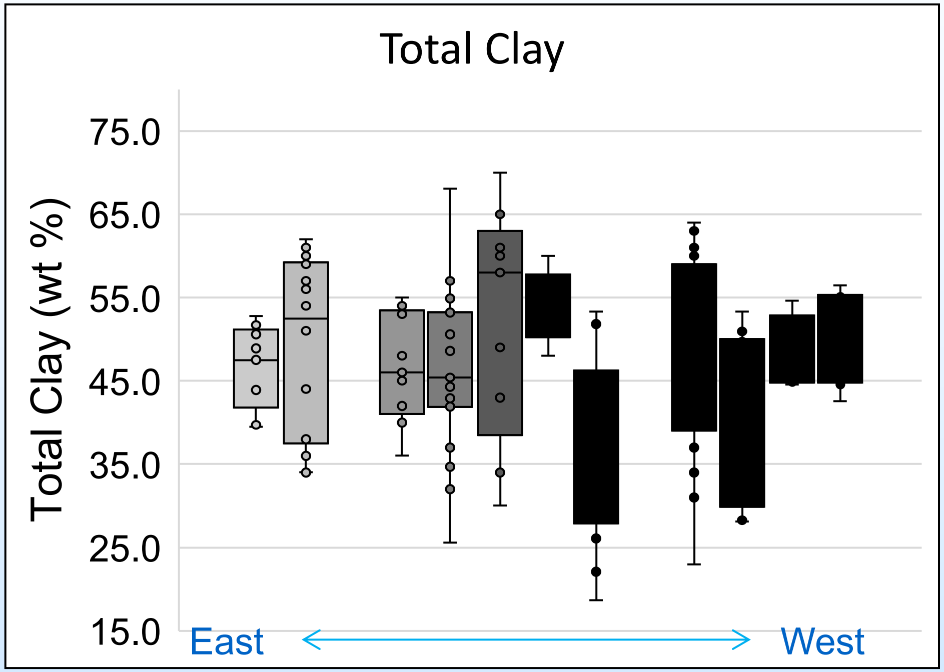
Mineralogical Composition & Total Organic Content Evaluation of TMS



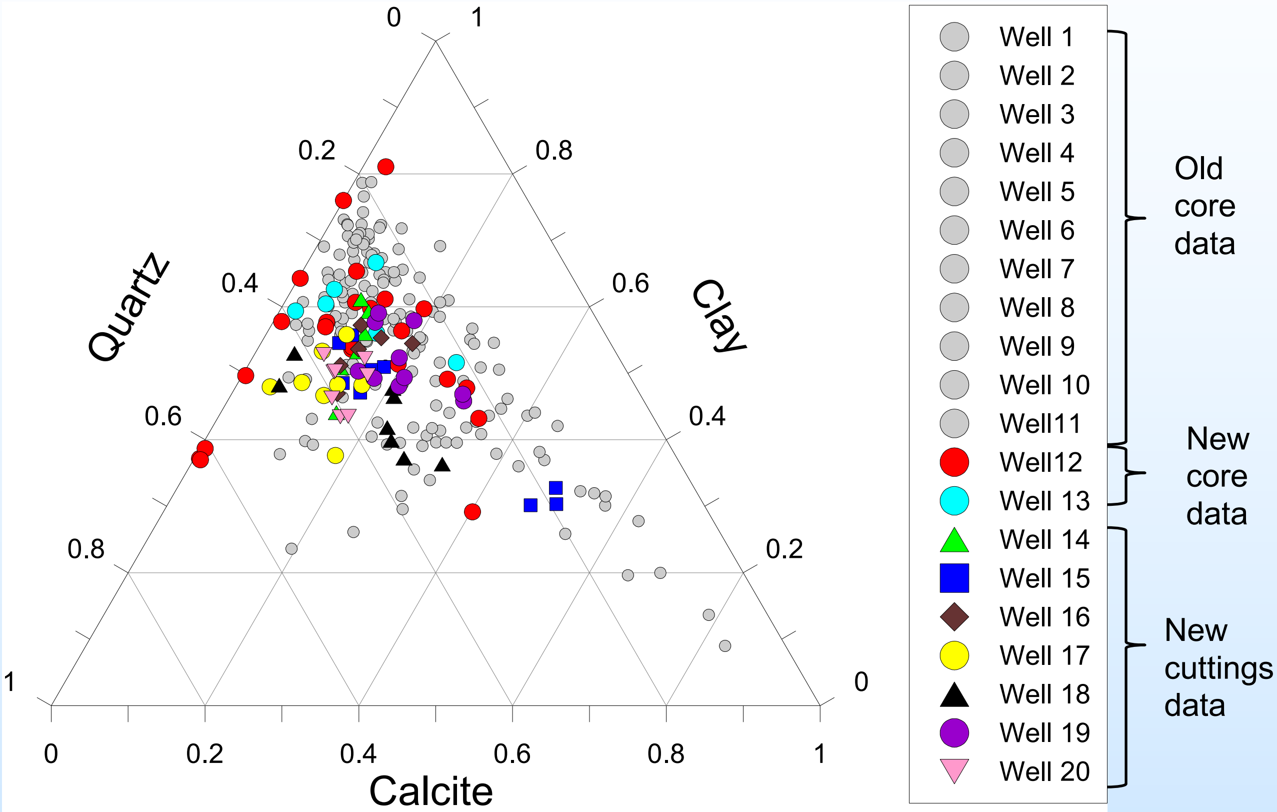


Tasks 4.4 & 4.5:

Mineralogical Composition & Total Organic Content Evaluation of TMS

Mineralogy

- 20 to 40% quartz
- 45 to 70% clay minerals
- 0 to 20% calcite with some excursions to higher values.

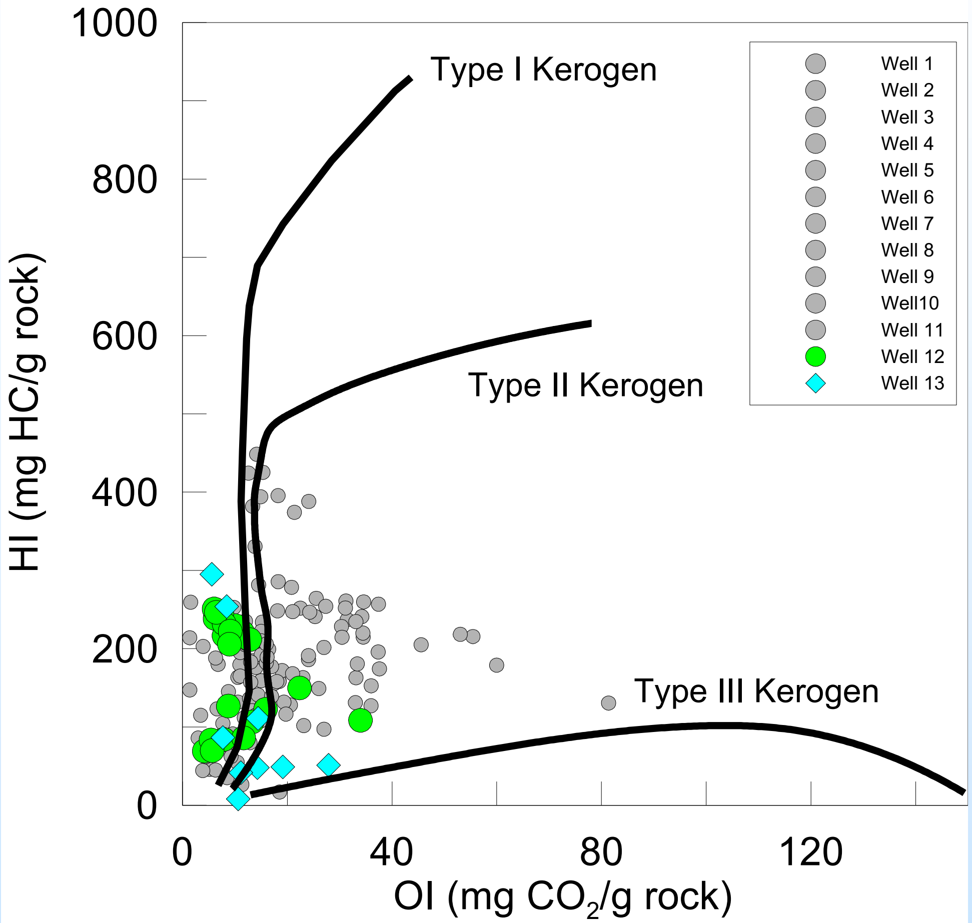


Tasks 4.4 & 4.5:

Mineralogical Composition & Total Organic Content Evaluation of TMS

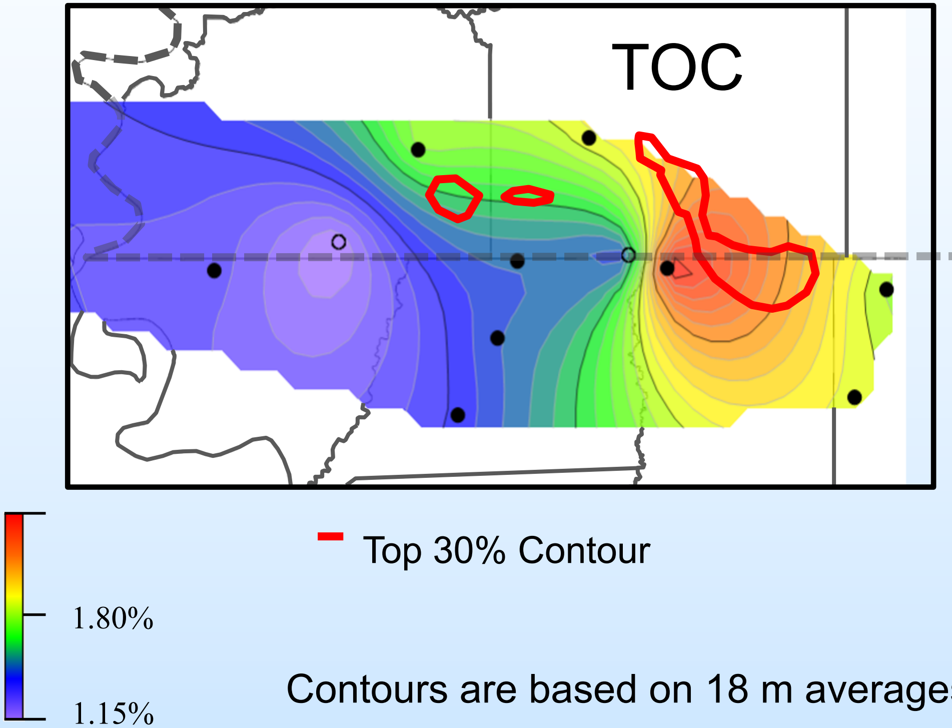
Pseudo-Van Krevelen diagram

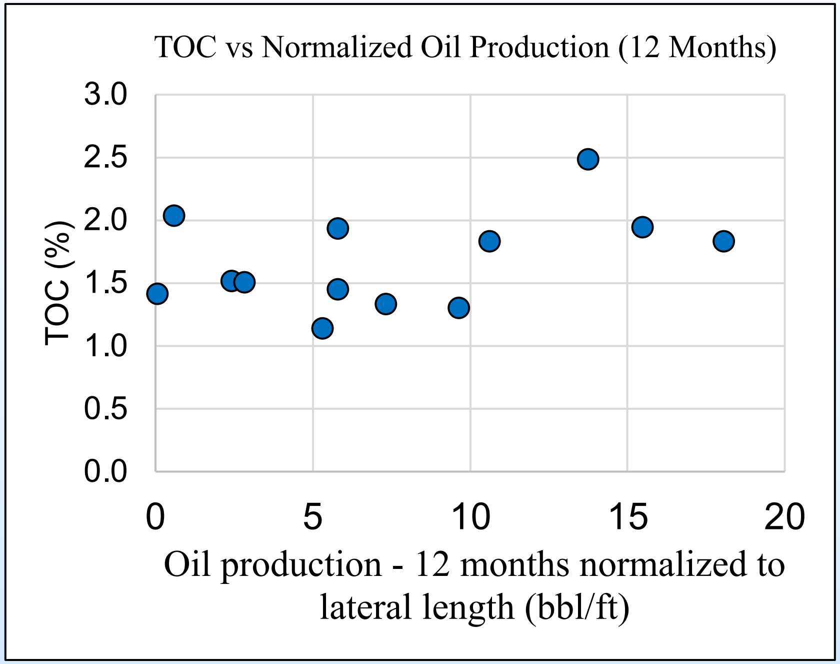
- ➢ TMS kerogen is mixed Type II and Type III, but there tends to be more Type II near the base.



Tasks 4.4 & 4.5:
Mineralogical Composition & Total Organic Content Evaluation of TMS

Relationship with production





Contours are based on 18 m averages for wells only.

Task 4.6: Ionic movement between TMS Cores and Water

The objective of this study is the screening of the clay stabilizers such as KCl, and NaCl inorganic brines and providing the baseline for the Tuscaloosa Marine shale treatment utilizing well-established methodologies such as capillary suction time (CST) and roller oven (RO) tests. This work provides an innovative insight into selecting the efficient stabilizer for this clay-rich formation, which is essential to minimize the formation damage and improve recovery mechanisms. Two wells have been studied such as CB and BG.

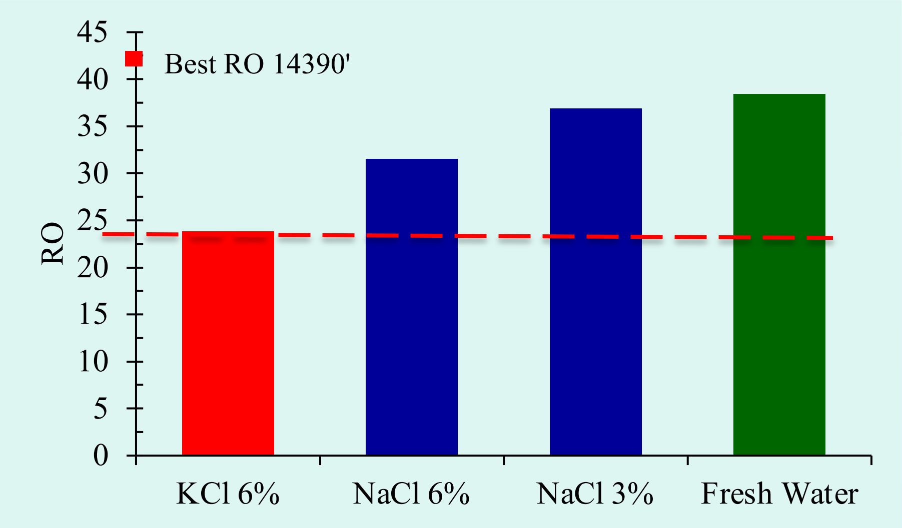


Figure 5: Capillary Suction Time Test Results for BG Well Specimen

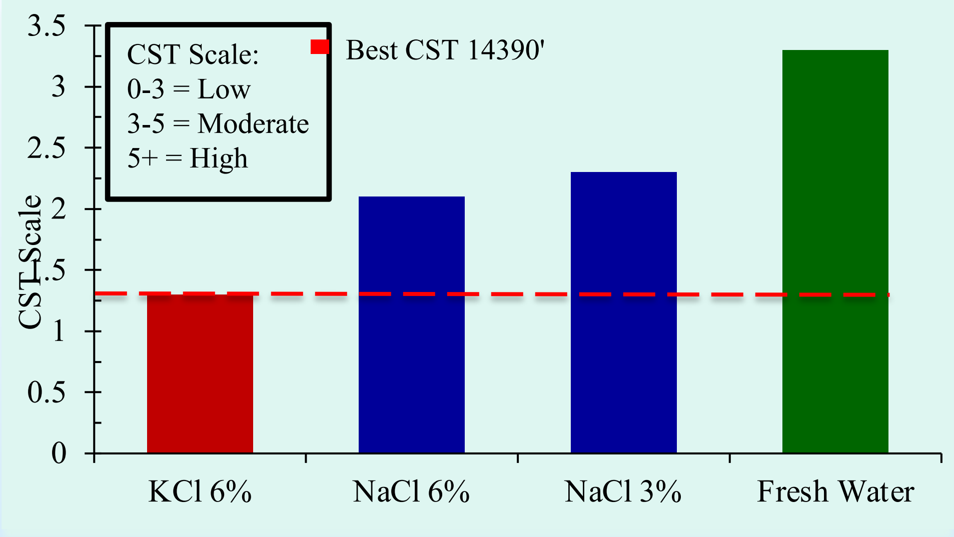


Figure 6: Roller Oven Test Results for BG Well Specimen

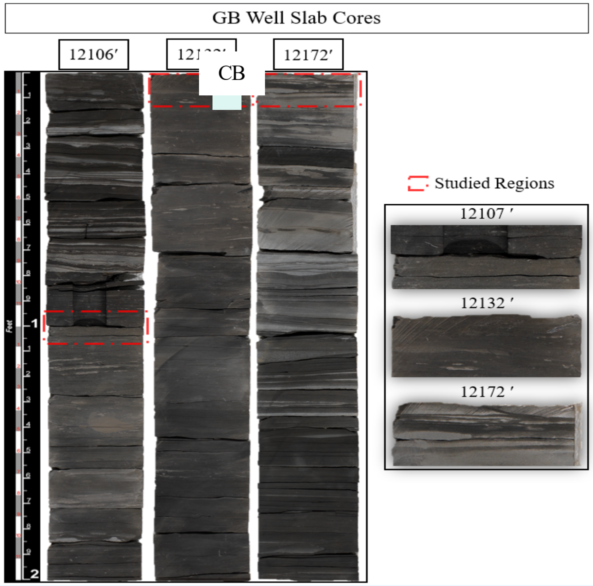


Figure 7: Evaluation of Tuscaloosa Marine Shale Stability Using Capillary Suction Time and Roller Oven Tests

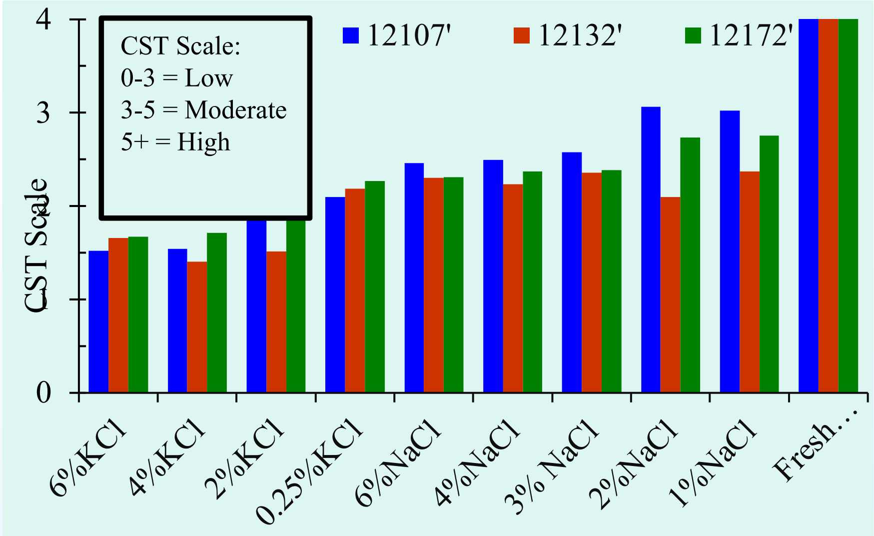


Figure 8: Capillary Suction Time Results for CB Well Specimens

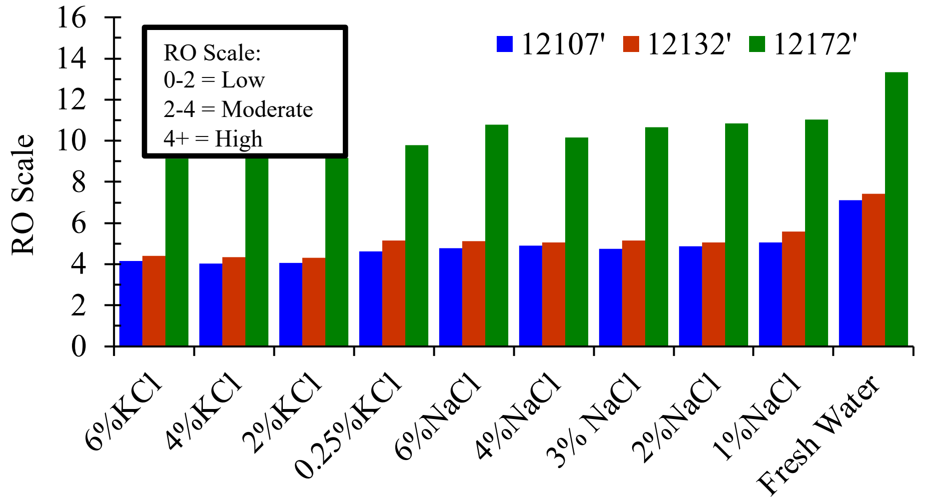


Figure 9: Roller Oven Test Results for CB Well Specimen

The overall performance of Potassium Chloride delivered encouraging results in stabilization of the Tuscaloosa marine shale. Based on that, the conclusions can be drawn, such as:

1. The evaluation showed that in the TMS studied cases, all grades of KCl surpassed NaCl brines based on CST and RO tests
2. Escalating the ionic strength of the drilling fluid cannot be assumed to correspond to better shale stabilization results of the TMS specimens.
3. The highest destabilization results were established on the depth 12172′ from CB well, where the concentration of the Illite & Mica is significantly dominating compared to other identified clay groups, and nearly 30% higher compared to 12107′ and 12132′.
4. In some cases, when the total clay in TMS exceeds 50%, the low grade of NaCl brine follows the freshwater pattern providing almost no contribution to the shale inhibition.

Task 4.7: Sedimentologic and Sequence Stratigraphic Study of TMS and Thermal Imaging

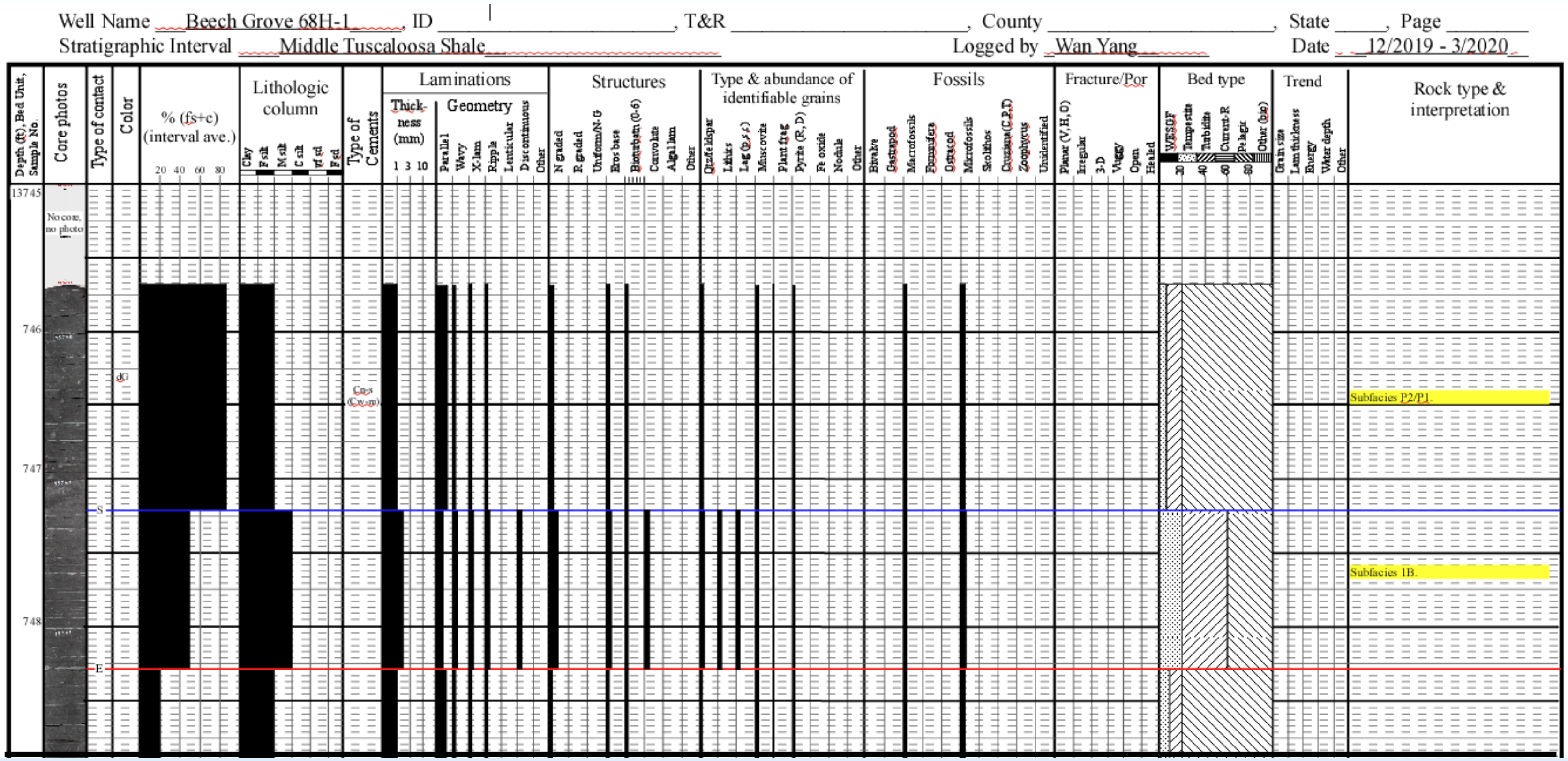
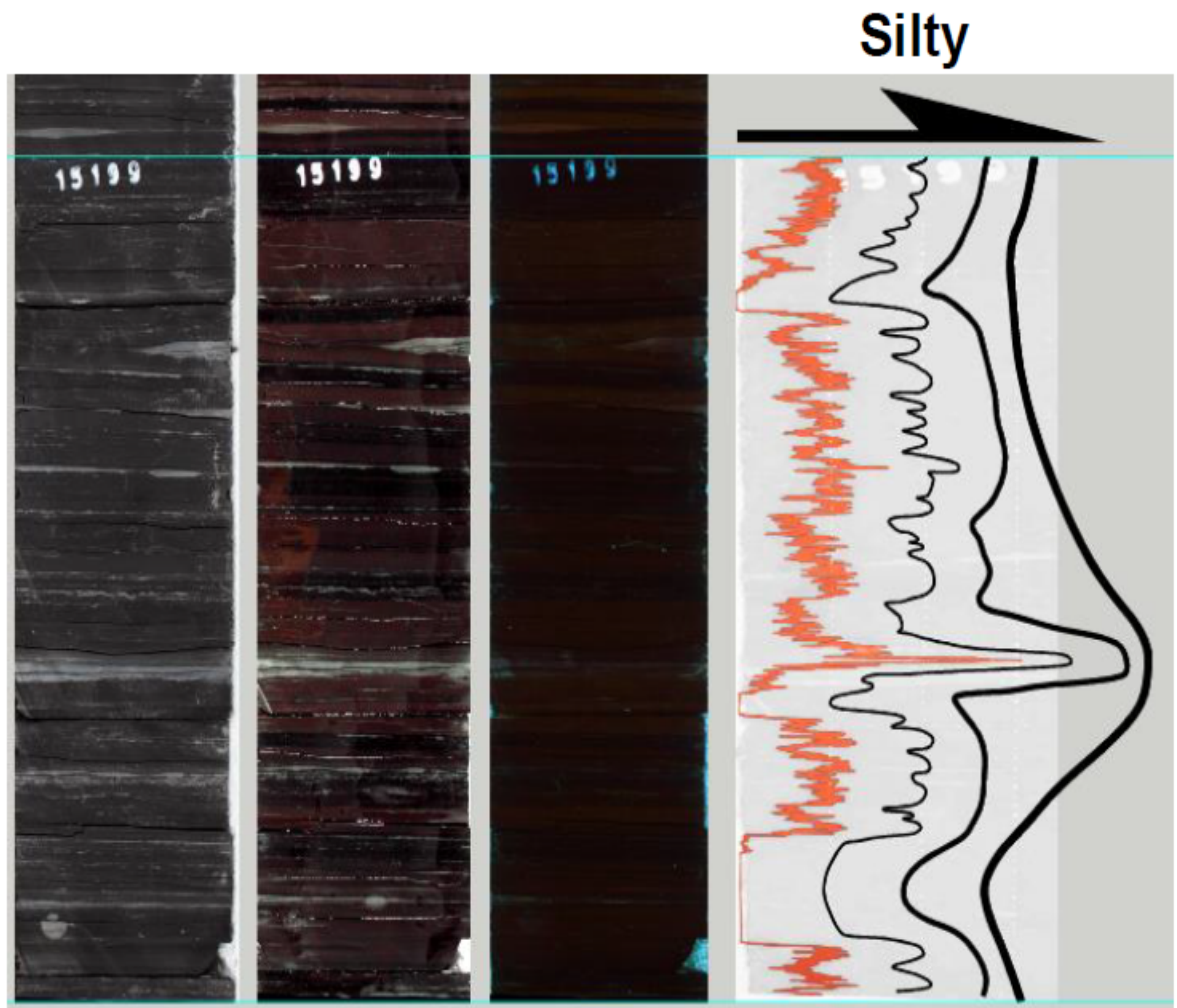


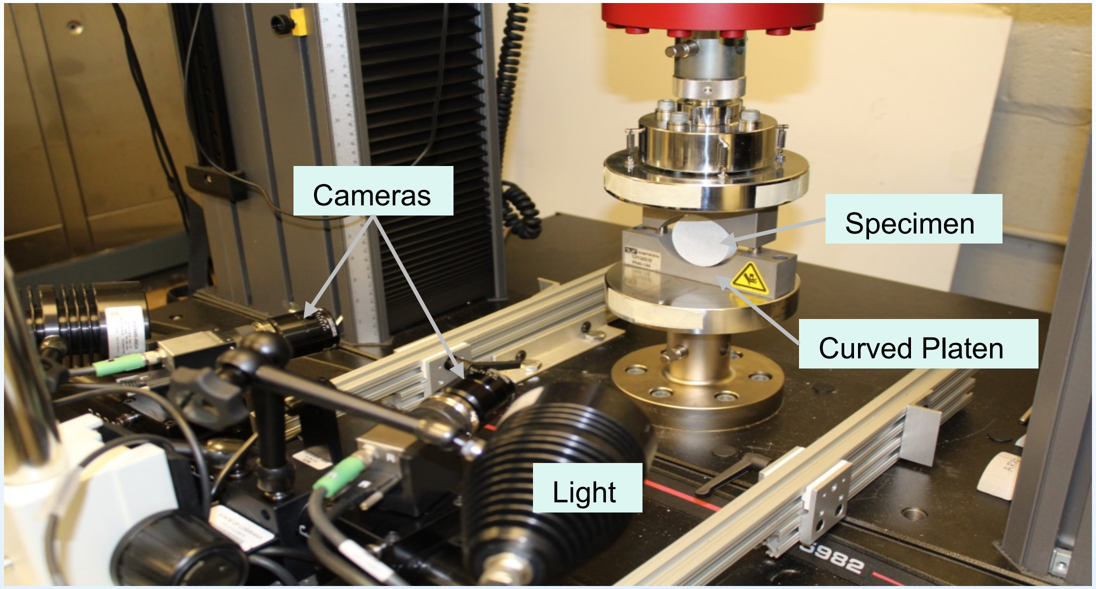
Figure 1. A portion of the log form of Well Beech Grove 68H-1, showing the key observations and preliminary interpretations of depositional processes, environments, and sequence stratigraphy. This is a proto type of a core-based template that can be expanded with data from other researchers.

Figure 2. Core photos (left panel) and corresponding scratch curve (red) and three order of stratigraphic hierarchy based on thickness and lithology from Well Lane 64-1. The scratch curve and data from core logs can be used to qualitatively and quantitatively analyze such hierarchy.

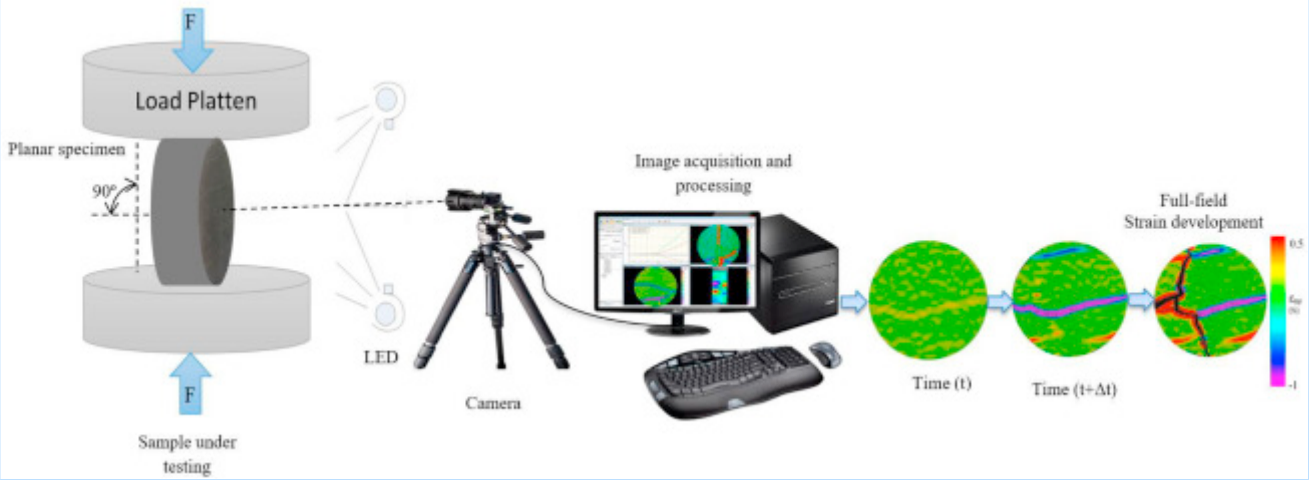


Lamina → lamina set → bed → bed set → facies association → depositional systems → sequences

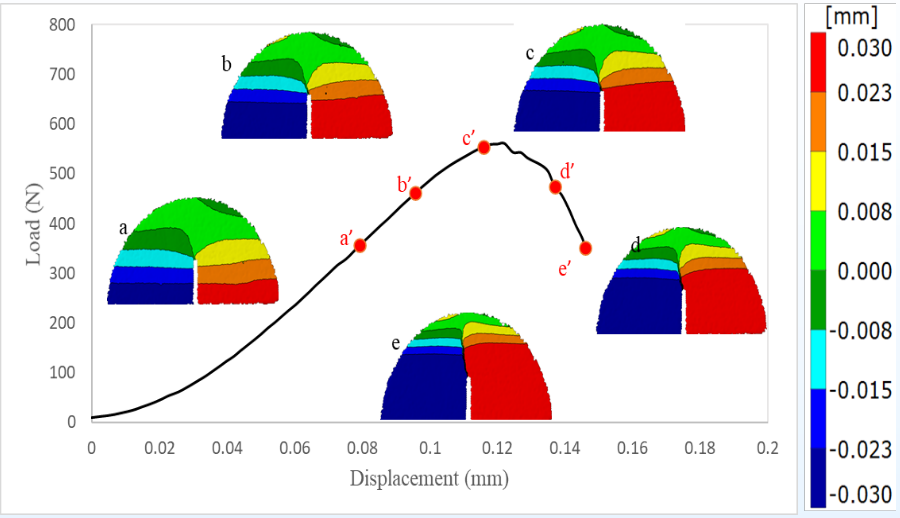
Task 5: Development of Digital Image Correlation System and Techniques



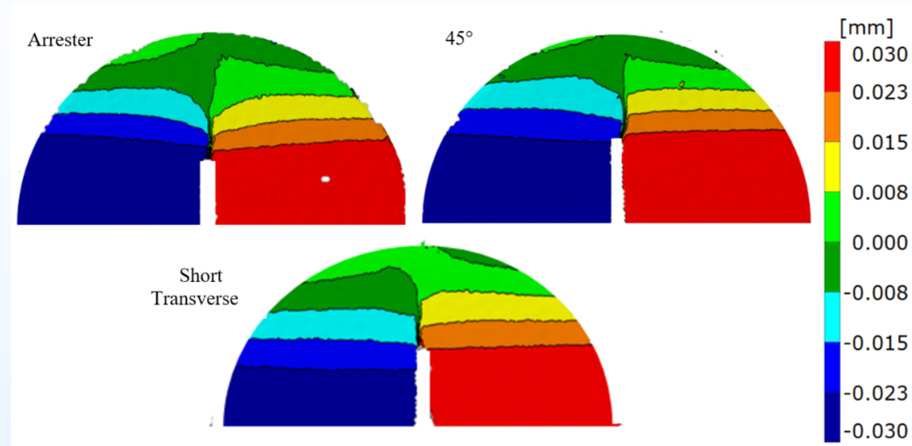
- Two 12 MP digital cameras
- Blue LED lights
- Instron 5982 (100 KN load cell)
- Images processed using DIC software
- Displacement and strain information over entire specimen surface



Fracture Toughness



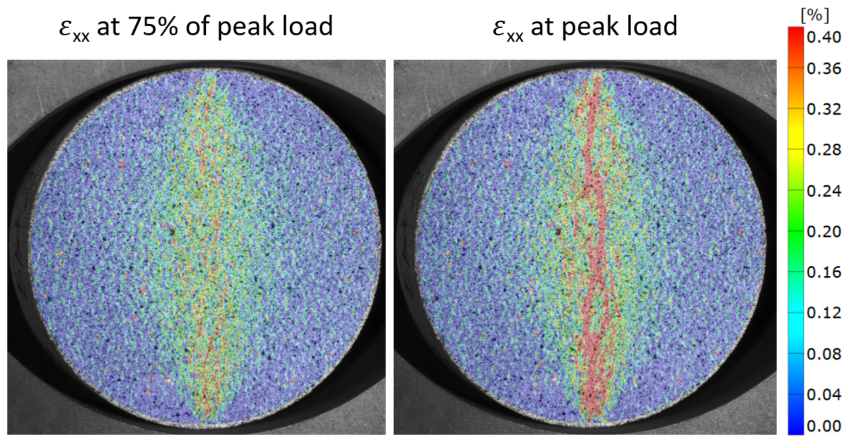
Development of Fracture Process Zone (FPZ) during testing



Fully developed FPZ for various crack orientations

- Displacement fields obtained by the DIC were used to measure fracture toughness
- FPZ development was tracked and measured. Average FPZ size for Berea Sandstone is 4.9±1.1 mm and for Mancos Shale average FPZ size is 2.3±0.9 mm
- Effect of different notch orientations with respect to bedding on fracture toughness was investigated

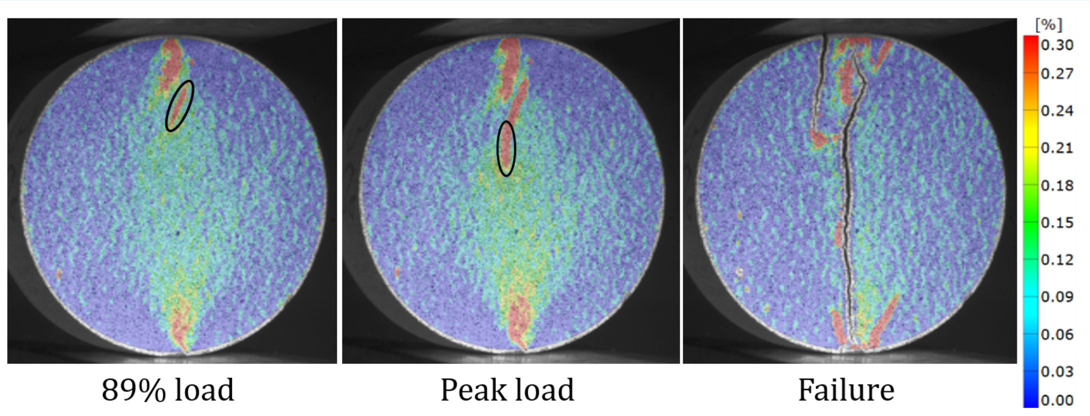
Brazilian Disc Test



Horizontal strain in Berea Sandstone with bedding planes at 90° with loading axis

Berea Sandstone

- Multiple cracks get initiated during BDT and participate in fracture process
- Failure is tensile and fracture grows along bedding direction
- Bedding planes are planes of weakness and tensile strength is function of bedding plane orientation



Horizontal strain in Mancos Shale with bedding planes at 30° with loading axis

Mancos shale

- Single crack dominates the fracture process
- The cracks originate along bedding planes and then grow towards loading axis when growing
- Bedding planes are planes of weakness and their orientation affects tensile strength.

Task 6: Investigation of CO_2 Foam Generation with Nanoparticles

$$\tau = K\gamma^n$$

$$\begin{cases} \tau_w = \dfrac{d\Delta p}{4L} \\ \gamma_{wa} = \dfrac{8v}{d} \end{cases}$$

$$\mu_a = \frac{\tau_w}{\gamma_{wi}} = K\gamma^{n-1}$$

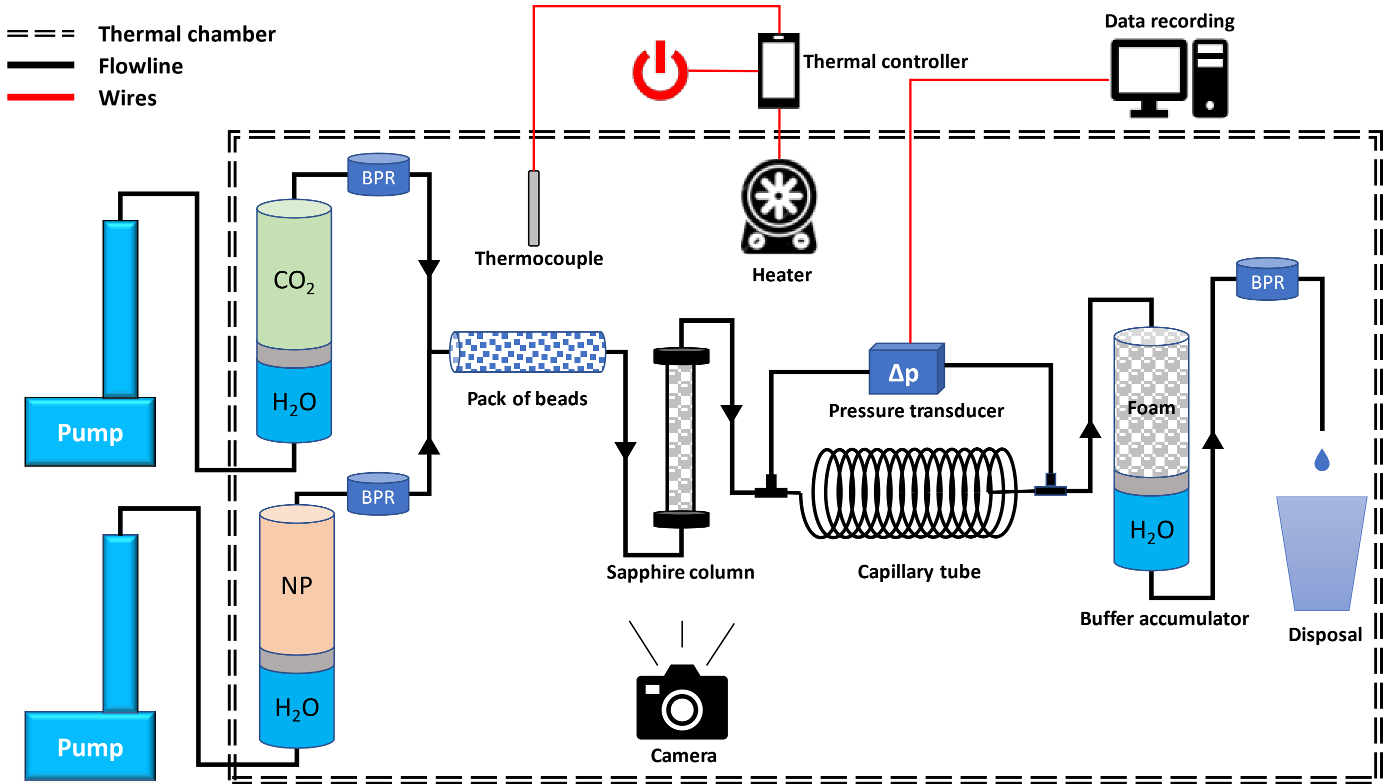
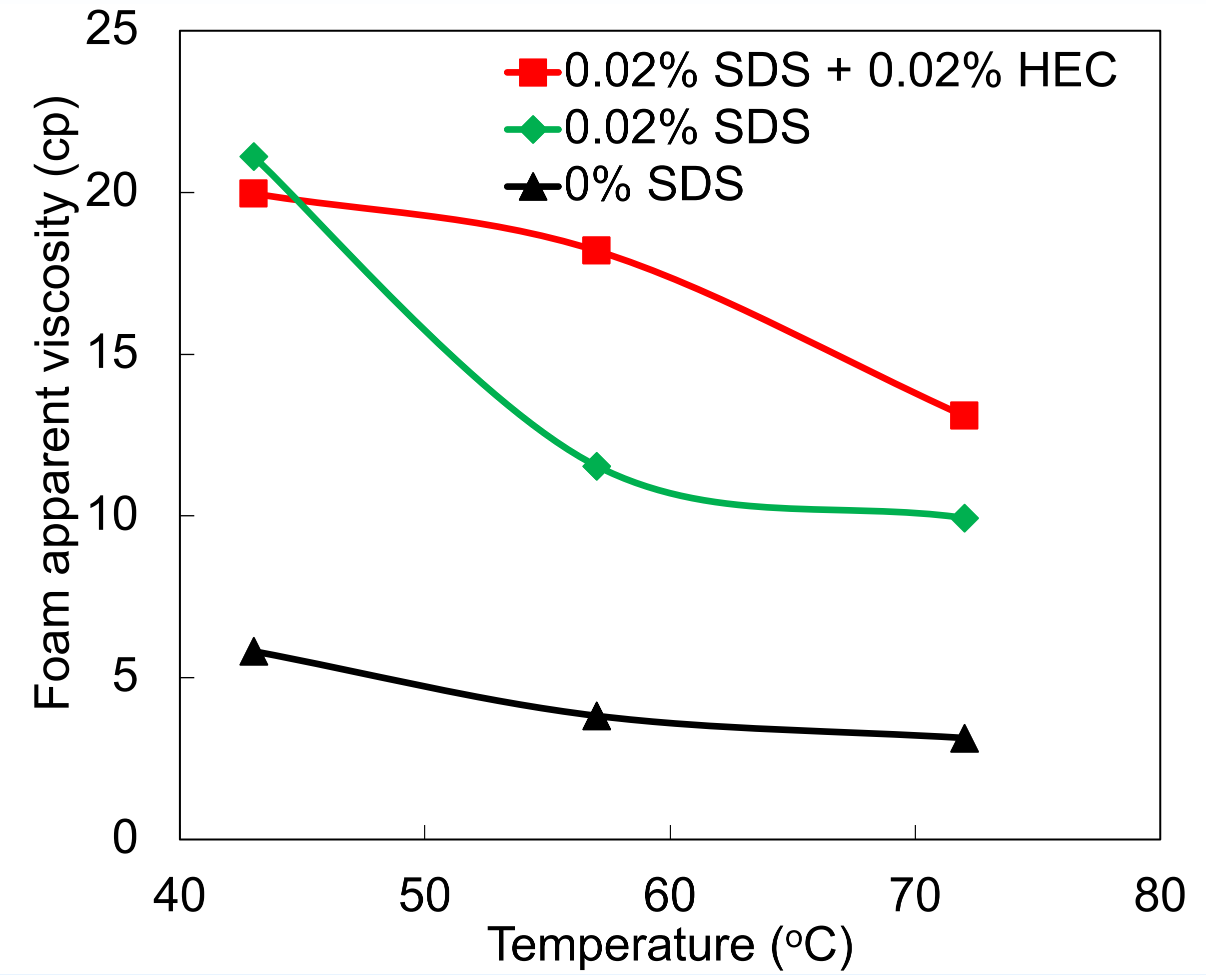


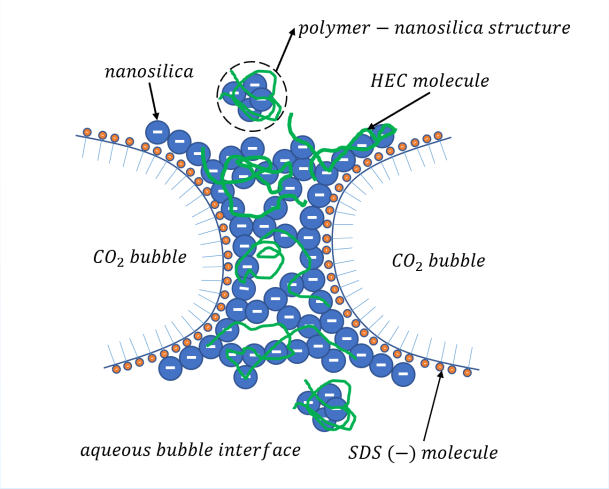
Illustration of experiment setup

Task 6: Investigation of CO_2 Foam Generation with Nanoparticles

- Rheology of Nanosilica-Surfactant-stabilized CO_2 foam
  - Effect of surfactant type
  - Effect of surfactant concentration
  - Effect of temperature
- Rheology of Nanosilica-Surfactant-Polymer-stabilized CO_2 foam
  - Effect of HEC polymer concentration
  - Effect of temperature

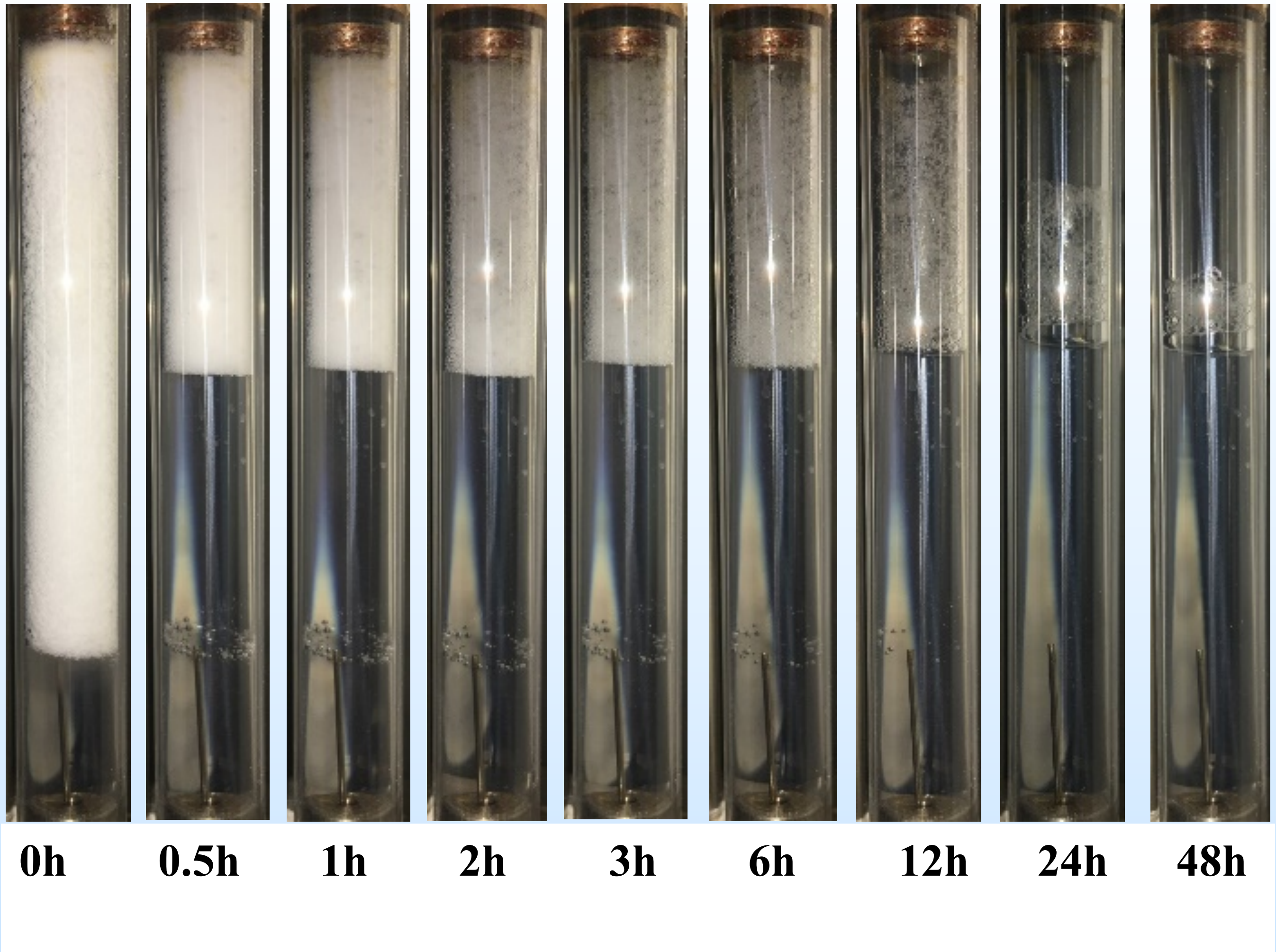
Nanosilica-Surfactant-Polymer-stabilized CO_2 Foam



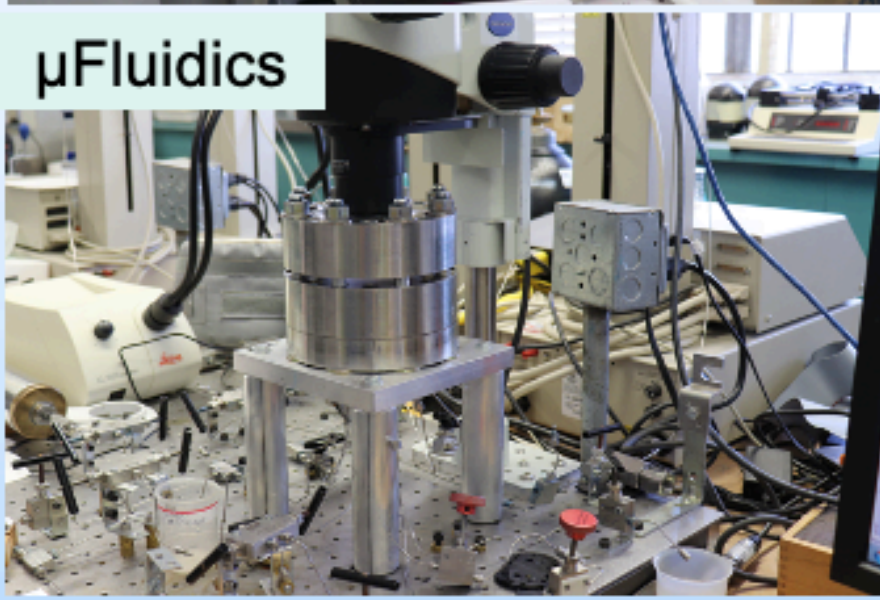


NP-SDS-HEC-stabilized interface

Nanosilica-Surfactant-Stabilized CO_2 Foam Stability at 43°C



Task 7: Shale Hydrocarbon Phase Solubility



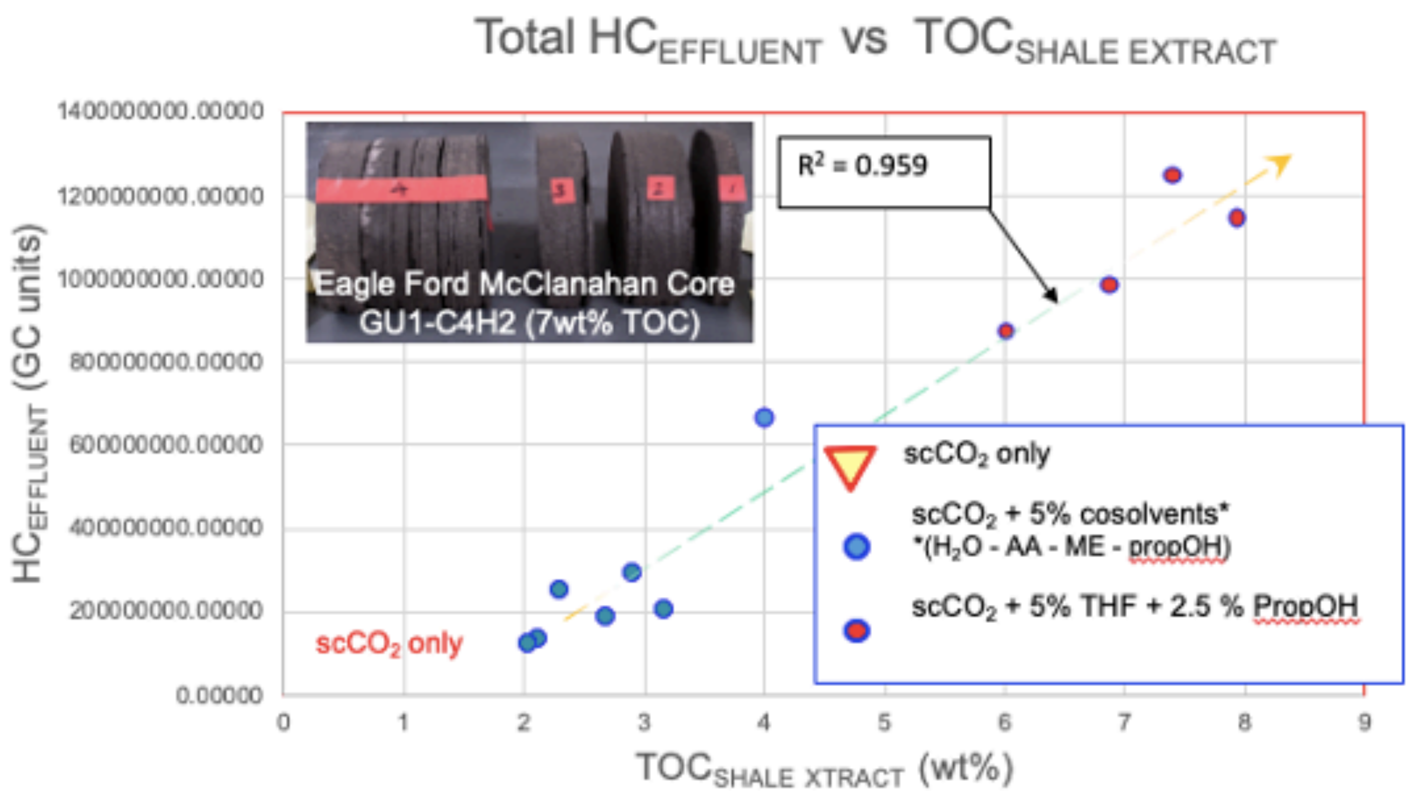
BP 2: 2019-2020
HC Extraction Study

Hydrocarbon Extraction (HCX) Lab

1. SFX SC Fluid Dual Extraction System
   - D-series ISCO pumps
   - SFX ™ 220 Controller
   - Extractor Pressure Chamber
   - Temperature Contoller
   - Restrictor
   - Effluent Collection Vials

2. Test Conditions
   - T = 80° C
   - Pc = 34 MPa
   - 10 ml cartridges
   - 2g oil shale sample powder
   - $scCO_2$ + modifiers

TMSL TASK 7
BP 2 Extraction Results



Using GC measurements on effluent and EL mass spec measurements on the solid residue, we confirmed that the HC fluid extracted during testing is proportional to the TOC (wt%) extracted from the EF shale.

N.B.: Analysis of GC results on TOC extraction to look at extract speciation for different co-solvents has been delayed due to lab closure.

BP2 Results: The addition of small amounts of THF+PropOH to $scCO_2$ fluid results in a 6wt% increase in HC extraction compared to other cosolvents (3 pore volumes).

Task 8: Evaluation of the Major Needs/Socioeconomics for the development of TMS Region

Subtask 8.3. Evaluation of workforce training programs in Louisiana and Mississippi for the oil and gas industry

- The inventory and interviews of existing workforce training programs in the TMS region found that by reaching out to adjacent communities, the region has a significant workforce training capacity.

- Benchmarking against more developed shale regions found the broader TMS region had competitive training programs following similar curriculums.

- The skills competency model and skills transferability matrix identified construction as a closely aligned industry.

- Improving local hiring opportunities will be challenging, and workforce training is important. However, improving K-12 education and soft skills will be even more important as those are the foundations of workforce development.

Subtask 8.4. Business assistance and diversification programs in Louisiana and Mississippi for the oil and gas industry

- The TMS region has many business assistance programs, but limited technical assistance for the oil and gas industry when benchmarked to more developed shale regions.

- Communicating with executives of economic development organizations in established shale regions could be beneficial for the TMS when production increases.

Dissemination

Peer-Reviewed Journal Publications

1. Ahmadov J. and Mokhtari M., **2020**, Experimental evaluation of Ultrasonic velocities and Anisotropy in the Tuscaloosa Marine Shale, *Interpretation*, https://doi.org/10.1190/int-2019-0268.1

2. Mlella M., Ma M., Zhang R. and Mokhtari M., **2020**, Machine Learning for Geophysical Characterization of Brittleness: Tuscaloosa Marine Shale Case Study, *Interpretation*, https://doi.org/10.1190/int-2019-0194.1

3. Guo, B., Shaibu, R., & Hou, X., **2020**, Crack Propagation Hypothesis and a Model To Calculate the Optimum Water-Soaking Period in Shale Gas/Oil Wells for Maximizing Well Productivity, SPE Drilling & Completion, https://doi:10.2118/201203-PA

4. Huang, Z.; Guo, B.; Shaibu, R., **2020**, Lab-Supported Hypothesis and Mathematical Modeling of Crack Development in the Fluid-Soaking Process of Multi-Fractured Horizontal Wells in Shale Gas Reservoirs. *Energies 13*, 1035. https://doi.org/10.3390/en13051035

5. Hoffmann A.A., Borrok D.,**2020**, The geochemistry of produced waters from the Tuscaloosa Marine Shale, USA, *Applied Geochemistry*, https://doi.org/10.1016/j.apgeochem.2020.104568.

6. Kimanzi, R., Wu, Y., Salehi, S., Mokhtari, M., and Khalifeh, M., **2020**, Experimental Evaluation of Geopolymer, Nano-Modified, and Neat Class H Cement by Using Diametrically Compressive Tests, ASME. *J. Energy Resour. Technol*. doi: https://doi.org/10.1115/1.4046702

7. Zhang, H., Nath, F., Parrikar, P. and Mokhtari, M., **2020**, Analyzing the Validity of Brazilian Testing Using Digital Image Correlation and Numerical Simulation Techniques, *Energies*, *13*(6), 1441; https://doi.org/10.3390/en13061441

8. Wu Y., Patel H., Salehi S., Mokhtari M., **2020**, Experimental and Finite Element Modelling Evaluation of Cement Integrity under Diametric Compression, *Journal of Petroleum Science and Engineering*, Vol. 188, https://doi.org/10.1016/j.petrol.2019.106844.

9. Borrok, D.M., Yang, W., Wei, M., and Mokhtari, M., **2019**. Heterogeneity of the Mineralogy and Organic Content of the Tuscaloosa Marine Shale, *Marine and Petroleum Geology,* Vol. 109, p.717-73. https://doi.org/10.1016/j.marpetgeo.2019.06.056

10. Guo, B., and Yang, X. **2019**. Use of a New Analytical Model to Match Production Data and Identify Opportunities to Maximize Well Productivity in the Tuscaloosa Marine Shale Reservoir. *SPE Production & Operations*, https://doi.org/10.2118/198892-PA

11. Yang, X., and Guo, B. **2019**. Statistical analyses of reservoir and fracturing parameters for a multifractured shale oil reservoir in Mississippi. *Energy Sci Eng*. DOI: https://doi.org/10.1002/ese3.537

12. Yang, X., Guo, B., and Mokhtari, M. **2019**. Productivity analysis of multi-fractured shale oil wells accounting for the low-velocity non-Darcy effect, *Journal of Petroleum Science and Engineering*, doi: https://doi.org/10.1016/j.petrol.2019.106427

Dissemination

Thesis and Dissertation

1. Ruse C., 2020, *Characterization of Elastic Mechanical Properties of Tuscaloosa Marine Shale from Well Logs using the VTI Method*, M.Sc. Thesis, University of Louisiana at Lafayette, (Adviser: Dr. Mehdi Mokhtari)

2. Kramarov V., 2020, *Fracture Toughness Determination and Strain analysis of anisotropic rocks using Semicircular Bend Test and Digital Image Correlation*, M.Sc. Thesis, University of Louisiana at Lafayette, (Adviser: Dr. Mehdi Mokhtari)

3. Mlella M., 2020, Geophysical Characterization of Unconventional reservoir Properties using Machine Learning Techniques, a Case study from Tuscaloosa Marine Shale, M.Sc. Thesis, University of Louisiana at Lafayette, (Adviser: Dr. Rui Zhang)

4. Konate N., 2020, *Experimental Investigation of Shale-Drilling Fluid Interaction and Implications on Drilling Efficiency*, M.Sc. Thesis, University of Oklahoma (Adviser: Dr. Saeed Salehi)

5. Kimanzi, R., 2019. *Experimental Investigation of the cement bond integrity by application of digital image correlation (DIC) technique*, *M.Sc. Thesis*, University of Oklahoma. (Adviser: Dr. S. Salehi)

6. Nippes, V., 2019. *Production Behavior and Decline Curve Analysis of Tuscaloosa Marine Shale Wells in Wilkinson and Amite Counties* Mississippi, *M.Sc. Thesis*, University of Louisiana at Lafayette. (Adviser: Dr. M. Mokhtari)

Conference Publications

1. Chavez N.A., Chuprin M., Mokhtari M., Nath F., 2020, Evaluation of Tuscaloosa Marine Shale stability using Capillary suction time and Roller Oven Tests, Unconventional Recourses Technology Conference (URTeC), Houston, Texas, July 20-22

2. Mokhtari M., Parrikar P., Saidzade A., 2020, Microscopic Measurement of Shale Swelling: Impact Of Salinity, Unconventional Recourses Technology Conference (URTeC), Houston, Texas, July 20-22

3. Mokhtari M., Ezeakacha C., 2020, Storage and Flow Properties of an Oil-Prone/Clay-Rich Shale Play: Tuscaloosa Marine Shale, *Unconventional Recourses Technology Conference (URTeC)*, Houston, Texas, July 20-22

4. Saidzade A., Parrikar P., Mokhtari M., 2020, Experimental Investigation of Main Factors Affecting Spontaneous Imbibition in Shales, *Unconventional Recourses Technology Conference (URTeC)*, Houston, Texas, July 20-22

5. Miller C., 2020, Economic and Workforce Development in Rural Shale-Based Economies, *Unconventional Recourses Technology Conference (URTeC)*, Houston, Texas, July 20-22

Future Works in BP3

Task 3, Improving TMS Drilling and Wellbore Stability

- Simulation of Mud Displacement by Cement in Irregular Enlarged Wellbores
- Casing/Cement Bonding Simulation

Task 4, Improving TMS Formation Evaluation

4.1 Characterize TMS natural fractures using image logs and sonic logs.

4.2 -- The permeability of TMS via laboratory analyses will be conducted

-- Develop a machine learning method to estimate TOC of the TMS from seismic and seismic associated datasets.

4.4 &4.5 -- Complete solvent extractions to remove free oil from TMS cuttings samples and re-analyze the treated samples using Rock Eval pyrolysis at UL Lafayette.

-- Conduct lab experiments to better understand the interactions of fracking fluids with the TMS substrate under high T and P conditions.

4.6 -- Imbibition studies will be focused and expanded on various facies of several TMS wells

-- screening of various salts such as formate-based fluids for the stability of the TMS.

4.7 Thermographic investigation on approximately 20 TMS core samples to analyze the thermal conductivity of various components in TMS

Task 5, Development of Digital Image Correlation (DIC) System and Techniques

- Investigate creep behavior of TMS using digital image correlation technique.
- Using the high-speed camera to better capture the fracture initiation during Brazilian testing.

Task 6, Investigation of CO2 Foam Generation with Nanoparticles

- Design and build a coreflooding system to estimate the nanoparticle-stabilized CO_2 foam leak-off rate.
- Measurement of Fracture Permeability in TMS Cores

Future Works in BP3

Task 7, Shale Hydrocarbon Phase Solubility

- characterization of supercritical fluid extractions (SFE) tests using dynamic high PT reactor experiments on scCO_2 with co-solvents propanol and tetrahydrofuran (THF).
- The initiation of hydrocarbon microfluidics extraction using scCO2 with PropOH + THF modifiers to determine their relation to HC breakdown and kerogen stability.
- The analysis & summary of hydrocarbon phase stability test results & properties gained from testing: potential applications to in-situ fossil fuel yield during deep reservoir fracking.

Task 8, Evaluation of the major needs/socioeconomics for the development of TMS region

- Organize a multi-disciplinary training event

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