Field Evaluation of the Caney Shale as an Emerging Unconventional Play, Southern OK

DE-FE0031776

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Progress Report BP3: 10.2021-10.2022

DOE NETL Project Manager: Joe Renk

- TASK 10 Caney Horizontal Well drilling CRL: **Killian**
- TASK 11A Rock characterization: OSU: **Puckette, Grammer, Pashin**
- TASK 11B Rock characterization: OGS: **Seyedolali, Hayman**
- TASK 12A Proppant Embedment, Geochem: OSU **Radonjic**
- TASK 12B Geomechanics: PITT, **Bunger**
- TASK 12C Clay-fluid interactions: OSU ENG, **Bikkina**
- TASK 13A Geomechanics Modeling: LBNL, **Rutqvist**
- TASK 13B Geochemistry Modeling: LBNL, **Doughty**
- TASK 14 Drilling/Completions: OSU ENG, **Hareland**

Acknowledgments

- Caney Team Members:
- Postdocs: Yulun Wang, Fengyang Xiong, Cody Massion, Carl Symcox;
- PhD and MS Graduate Students: Allan Katende, Gabriel Awejori, Margaret Benge, Yunxing Lu, Izabelle Buentello, Ian Cox, Haden Kolmer, Dionne Mayibeki, Chase Watkins, Lauren Brown, Ayush Joshi

- NETL: Joe Renk, Dustin Crandall and Thomas Paronish
- CRL: Brian Killian, Andy Rihn, Adam Haecker, Barry Dean
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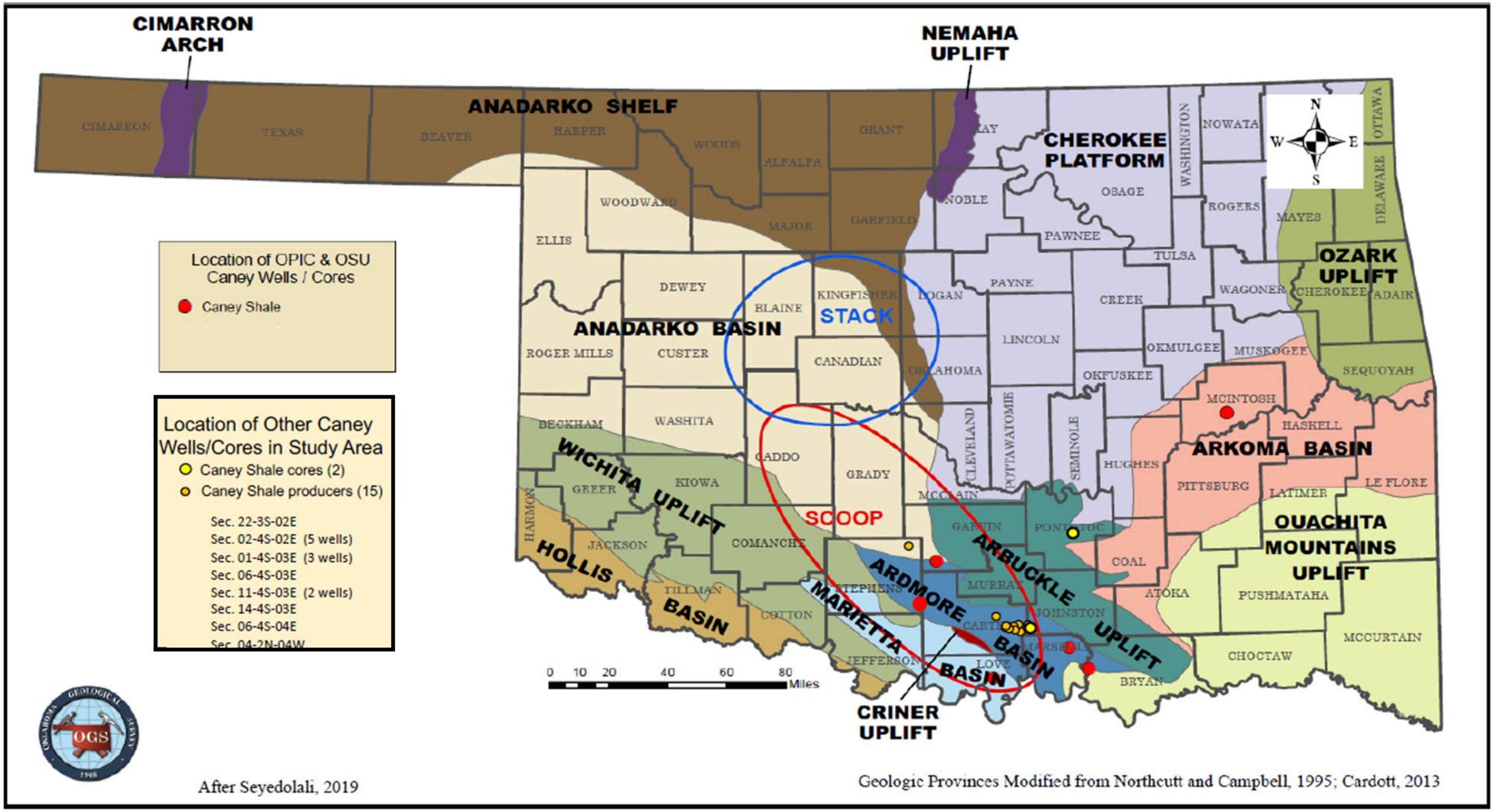
- OSU Microscopy Laboratory staff for their commitment to excellence in training our students and providing technical support.
- Ben Anderson, Corelabs, for support with the AFS system.

Project Background

Key objectives planned for Phase II: BP3 & BP4

- ✓ Drilling, logging and stimulating a horizontal well at the Caney Shale Field Laboratory
- ➢ Geological, geomechanical, petrophysical, and geochemical analysis of well cuttings and produced fluids to further understand reservoir architecture and variability of production streams among hydro-fracture stages and how it might impact fracture conductivity over time.
- ➢ Apply hydraulic fracture-flow simulators for optimizing stimulation of multistage-fractured horizontal wells and verification against laboratory and field data.
- ➢ Prepare a field development plan for Caney Shale that is safe, economically and technically sound.

Project Location



Task 10 Caney Horizontal Well Drilling

Recommendation consists of tapered cluster count for geologic & operational caution due to relatively unknown formation response utilizing modern CMP stage/perfs and volume

- Toe 1/3 of lateral, 240' X 8 Clusters. 29' spaced (1' guns). 4 shots/cluster , 32 holes
- Central 1/3 of lateral, 240' X 9 Clusters. 27' spaced (1' guns). 3 shots/cluster , 27 holes
- Heel 1/3 of lateral, 240' X 10 Clusters. 23' spaced (1' guns). 3 shots/cluster , 30 holes
- 100 bpm, 3+ bpm/perf for limited entry distribution

Design

- Slickwater (68.5%) Linear Gel (31.5%) Hybrid
- Relatively large LG % in attempt to induce downward growth into A3 and possibly A2
- 53.2 bbl/ft
- 1500 gal 15% HCl acid/stage to start job. If able, eliminate acid after 4-5 stages
- Regional southern white 100 mesh (50%) and 40/70 (50%). 40/80 acceptable. 3 ppa max. concentration
  - 3000 lbs/ft. Up to 20% proppant could be lost to embedment
- Additives – standard CLR C CMP WDFD/SCMR, but add
  - 1 gpt Cl- salt based clay stabilizer if FW sourced
  - Dry FR, est. 1.5 ppt necessary
- Pre-job diagnostics indicate slightly over-pressure reservoir

Execution

- 29 of 34 stages were pumped to or near to completion. Stages cut short were more due to service equipment, not design or formation
- 91% of designed proppant placed with 10% excess fluid
- 88 bpm average treating rate and 12100 psi average treating pressure
- All composite Frac plugs successfully drilled out and PBTD tagged
- Well is currently producing

Task 11: Progress, Data Integration and Collaboration

11.0 **Detailed Rock Analysis**

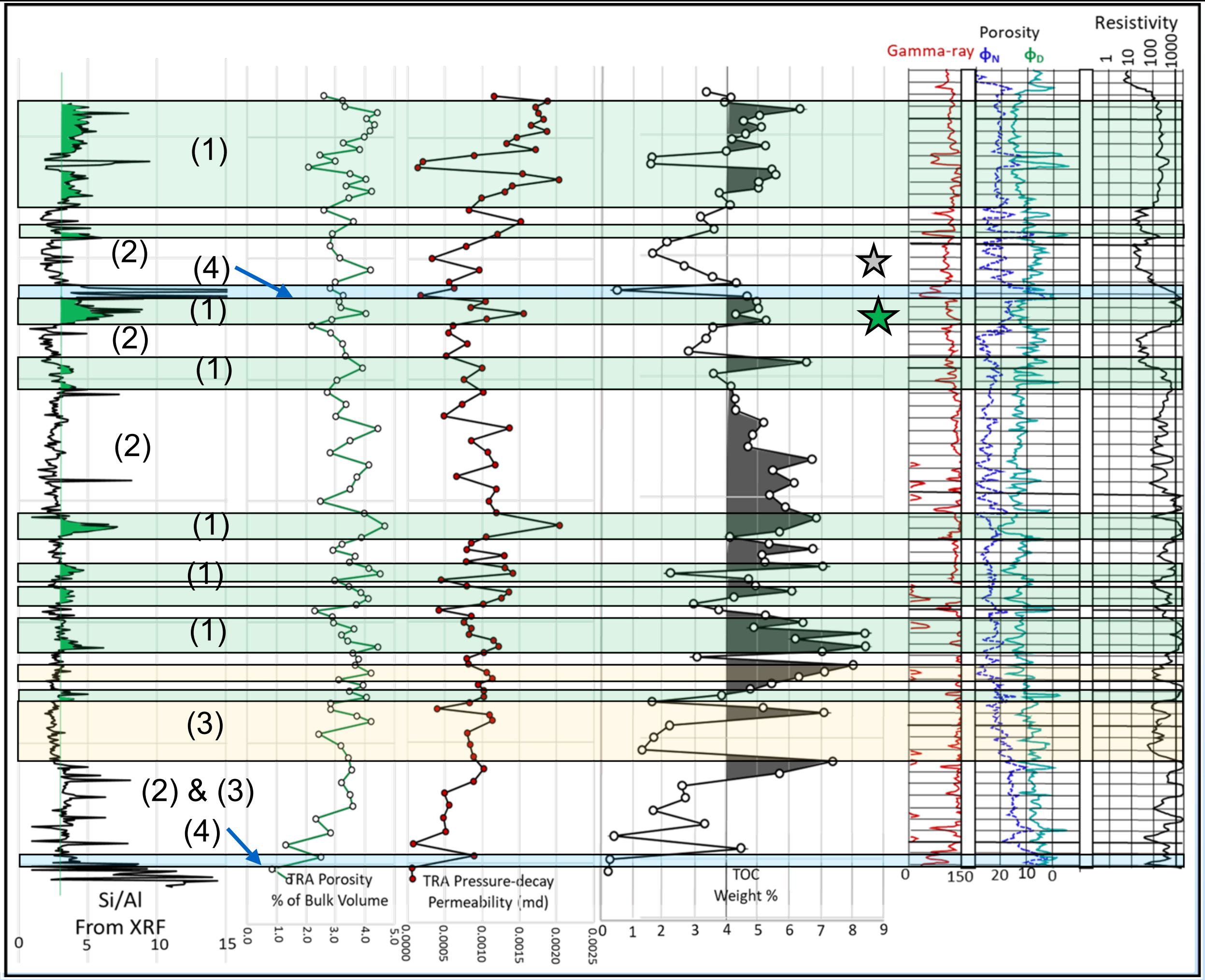
11.1 **Pore architecture characterization** (Grammer and Wang)

- Micro-nano-scale pore-architecture characterization shared with Caney Research Team and presented to our industry partner.
- Shared data on occurrence of intergranular, intragranular and intra-organic matter pores across facies.

11.2 **Petrophysical analysis** (Grammer, Wang, Puckette, Pashin and Seyedolali)

- Intra-OM pore data integrated with Source Rock Analysis (SRA) measurements to demonstrate importance of OM in reservoir intervals and impact on porosity log responses.
- Geological modeling
- Facies, detailed rock analysis from BSE and SEM, and petrophysical properties integrated to establish wireline-log characteristics of reservoir and non-reservoir facies.

Task 11 Progress: Detailed Rock Analysis



TRA porosity, permeability, SRA TOC, and XRF Si/Al correlated to wireline log curves to identify:

(1) reservoirs (green),
(2) clay-rich ductile beds (white),
(3) detrital quartz- and clay-rich intervals (gold);
(4) carbonates (blue).

Reservoirs with higher TOC can have significant organic matter (>4%) and important storage capacity if thermally mature

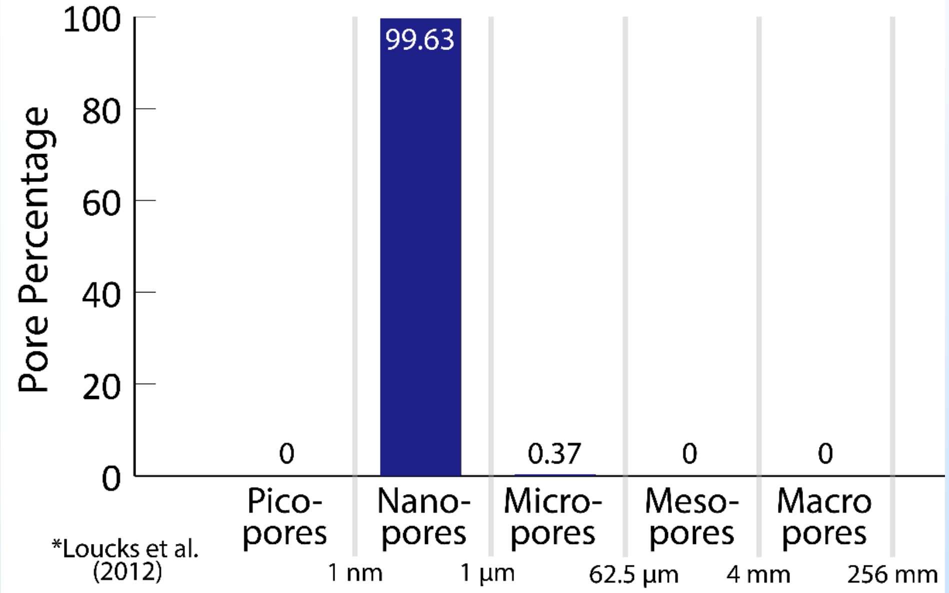
TOC important component when correcting wireline-log density porosity.

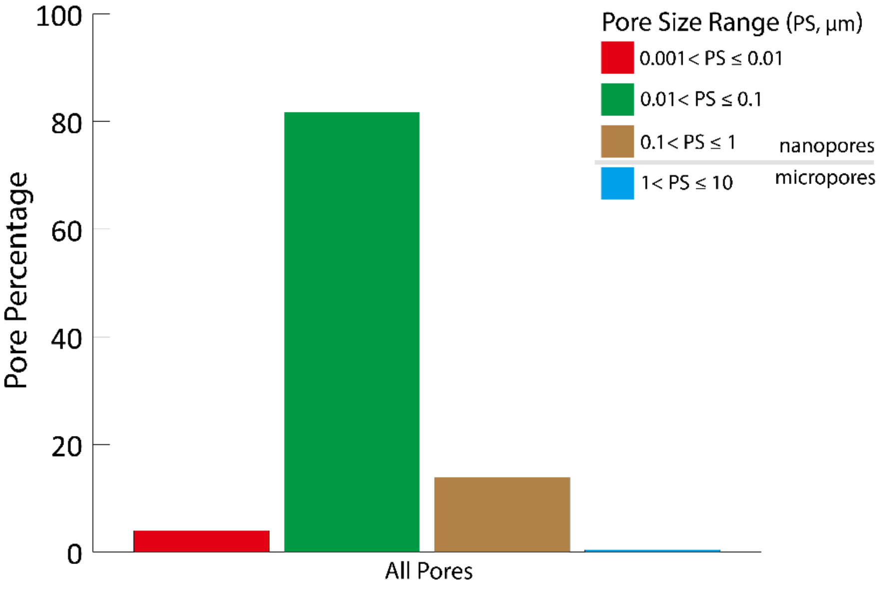
Integrated Rock Analysis and Wireline Logs

- Petrophysics: gamma-ray, $\emptyset_N$ and $\emptyset_D$ (uncorrected), resistivity and PE
- Tight Rock Analysis (TRA)
- Source Rock Analysis (SRA): total organic carbon (TOC)
- Elemental Geochemistry – X-ray fluorescence (XRF)

Task 11 Progress: Pore Systems Analysis

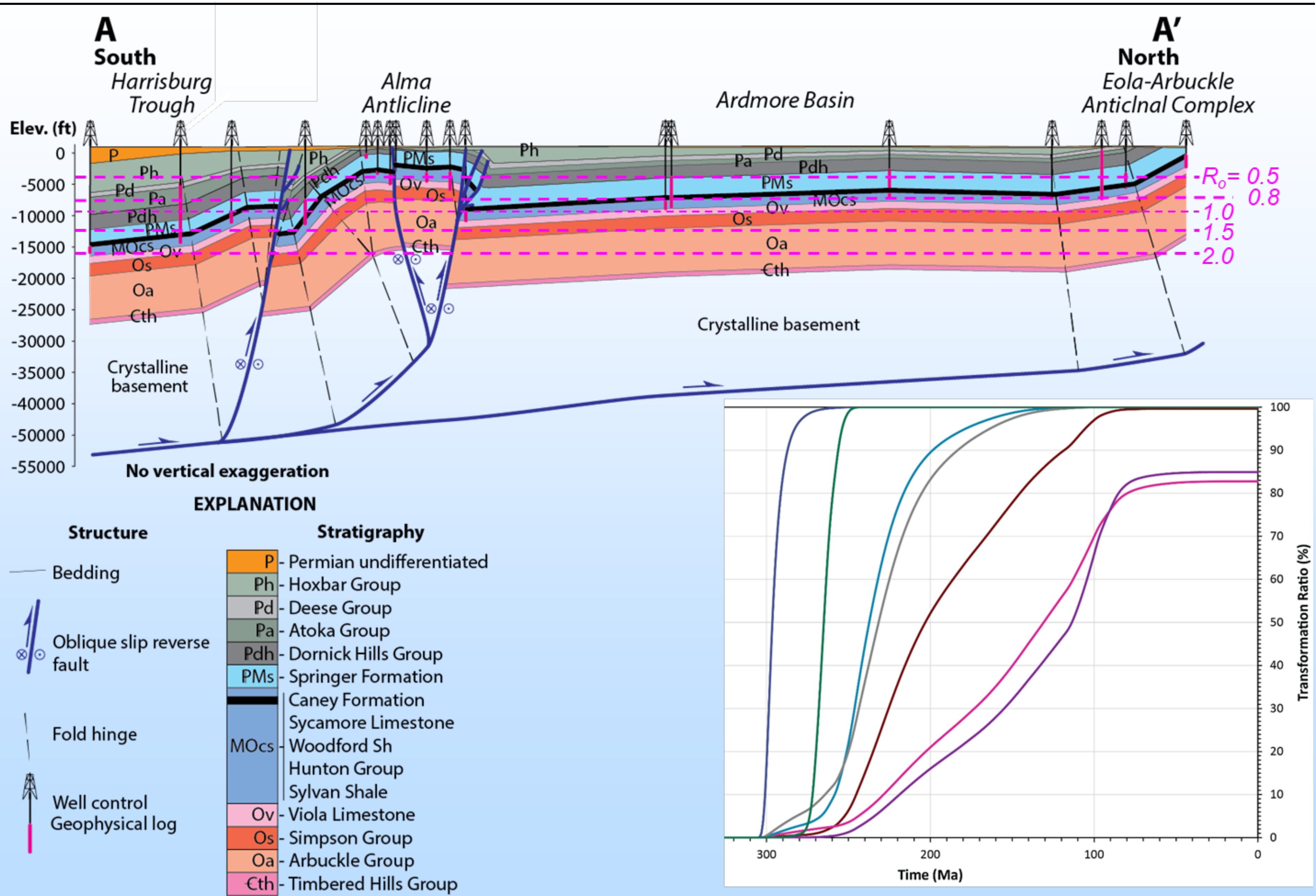
Pore Size (µm)	Max	Min	Mean	Median	25th Percentile	75th Percentile
	5.3	0.002	0.06	0.03	0.02	0.06





- 26,412 pores measured from 3 facies groups, including mudstone (14,241 pores), siltstone (5,351 pores), and carbonate (6,820 pores)
- Nearly all pores are nanopores (i.e., pore size ≤ 1 µm; left bar chart)
- Nearly 80% show a pore size range of 0.01 to 0.1 µm (right bar chart)

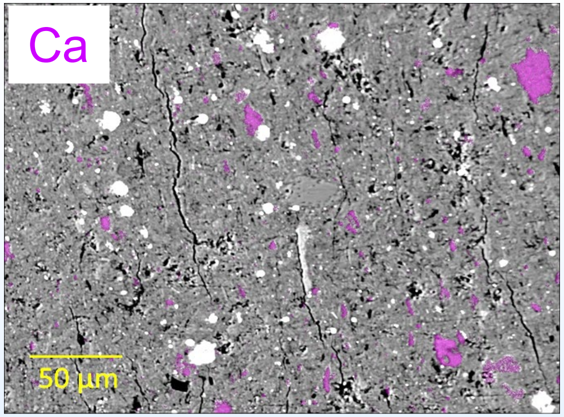
Task 11 Progress: Geological Modeling

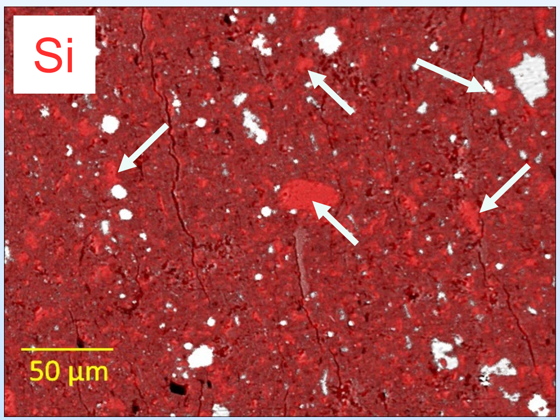


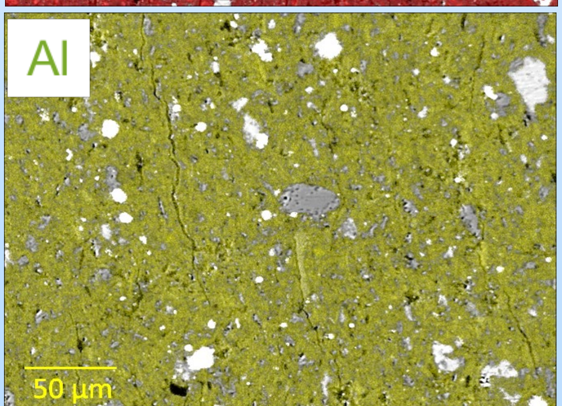
Task 11 Progress: Detailed Rock Analysis

Burrowed mudstone non-reservoir

Bioturbated calcareous siltstone reservoir





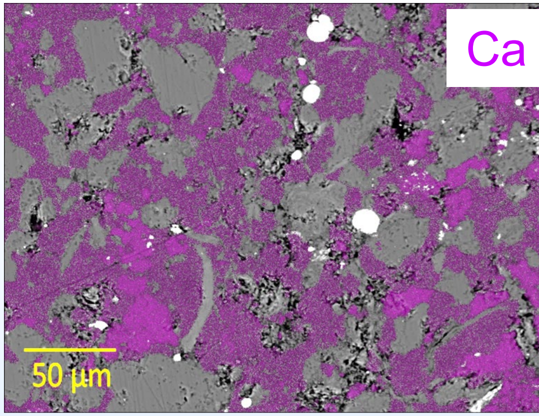


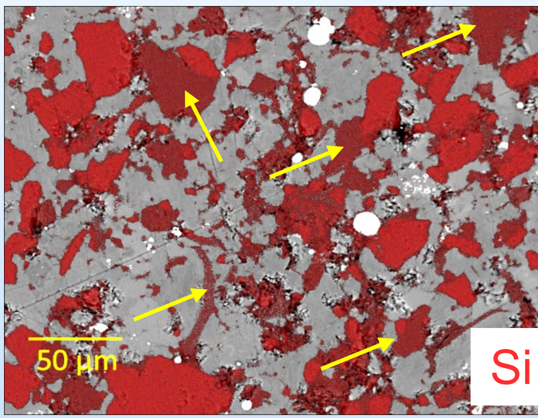
EDS and Backscattered Electron (BSE) imaging elemental mapping shows relative abundance of Al (clay minerals), Si (quartz and clay minerals) and Ca (carbonates) in reservoir and non-reservoir facies.

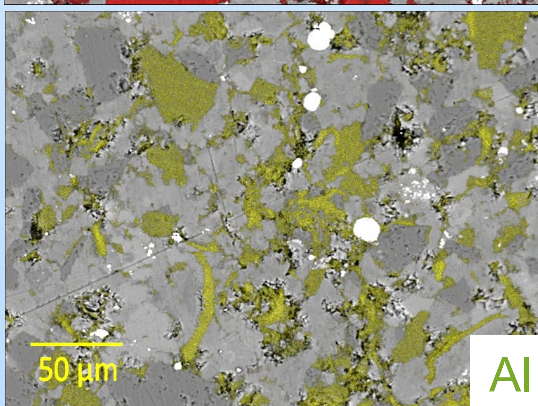
Ca – Calcium in carbonate (calcite) grains and cement (violet)

Si – Silicon in quartz silt (bright red, white arrows left) and aluminosilicate clay minerals (dull red, yellow arrows right)

Al – Aluminum in aluminosilicate clay minerals (yellow green)







Task 11 Key Findings & Future work

- ✓ [11A: 11.2] Petrophysics – log reported density porosity is optimistic and should be corrected for grain density and percent organic matter. Corrected values for porosity are similar to those determined by TRA.
- ✓ [11A: 11.2] Reservoir and seal zones have facies, elemental, rock mechanical, and fracture signatures that can be tied to wireline log responses.
- ✓ [11A: 11.1, 11.2] Facies groups show different fracture distribution, rebound hardness (rock strength), and pore type distribution, suggesting facies stacking creates heterogeneity in these properties at multiple scales.
- ✓ [11B] EPMA of lateral cuttings shows clustering of data indicating similar lithology and depositional environment.

- **[11A: 11.1, 11.2] Evaluate micro- and nano-scale composition, fabric and pore network to determine impact on reservoir and seal properties, and wireline log response**
- **[11A: 11.2, 11B] Develop regional depositional model from local interpretations tied to products of characterization study**
- **[11B] Evaluate conodont biostratigraphic option if palynology results unavailable**

Task 12: Progress, Data Integration & Collaboration

Task 12A: Rock-Fluid Characterization – Mileva Radonjic

Subtask 12A.1 Geochemistry and Rock-Fluid Interactions

- Geochemistry data used by LBNL to simulate geochemical reactions
- Collaborate with Oak Ridge National Lab on low-pressure nitrogen sorption and high-pressure methane adsorption

Subtask 12A.2 Proppant Embedment under Reservoir Conditions

- API-19D Test completed in collaboration with ProppantTester
- Composite flowthrough testing of monolayer proppant, AFS
- Micro-rockmechanics and micro-geochemistry of Caney rock

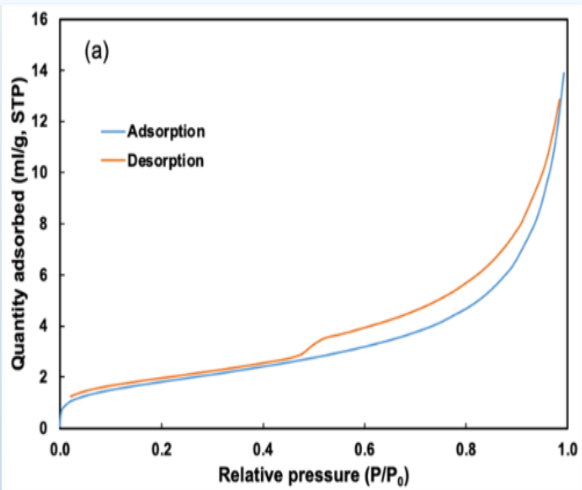
Collaboration and Integration: Experimental data from OSU is shared with LBNL, UPITT, NETL to develop and validate models to be used for the modeling of production, resulting in joint publications, presentations and complementary activities.

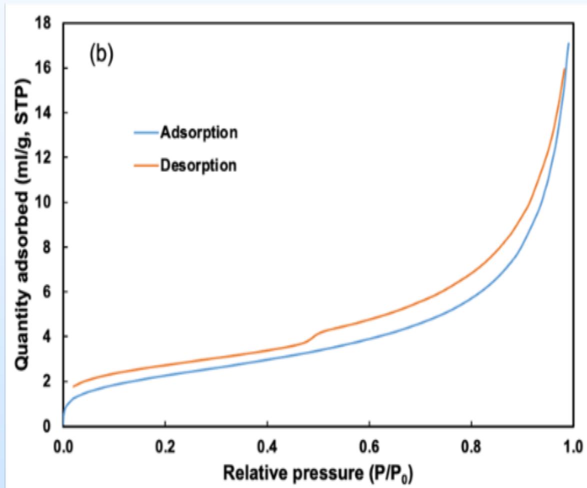
Task 12A.1 Geochemistry & Rock-Fluid Interactions

Pore structure analysis by the BET method

Slit-shape pores

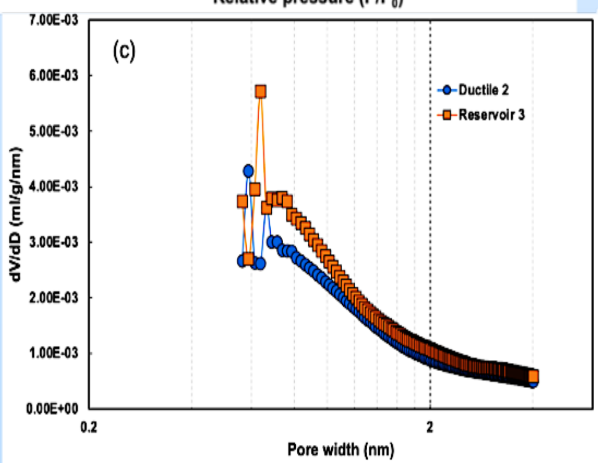
- Ductile 2 and Reservoir 3 includes all micropores, mesopores, macropores
- Reservoir 3 develops more micropores and mesopores than Ductile 2
- The main pore type is a slit-shape

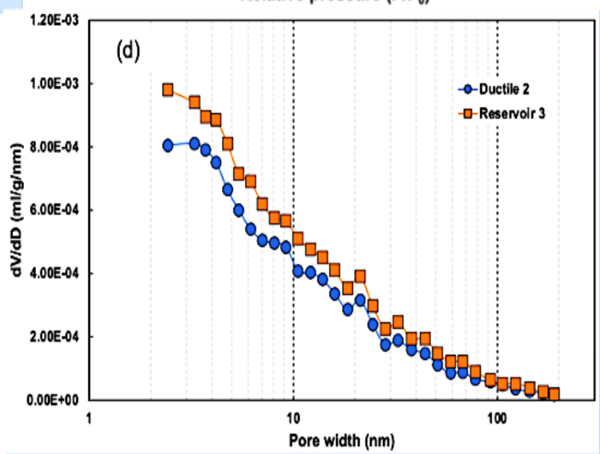




- Low-pressure nitrogen adsorption isotherm of Ductile 2 (a) and Reservoir 3 (b).

Xiong, F., Rother, G., Radonjic*, M., *Insights into controls of mineralogy and pore structure on the density of adsorption phase in shales under supercritical conditions*, Energy & Fuels, 36, 17, 10110–10122, August 22, 2022 https://doi.org/10.1021/acs.energyfuels.2c01847.





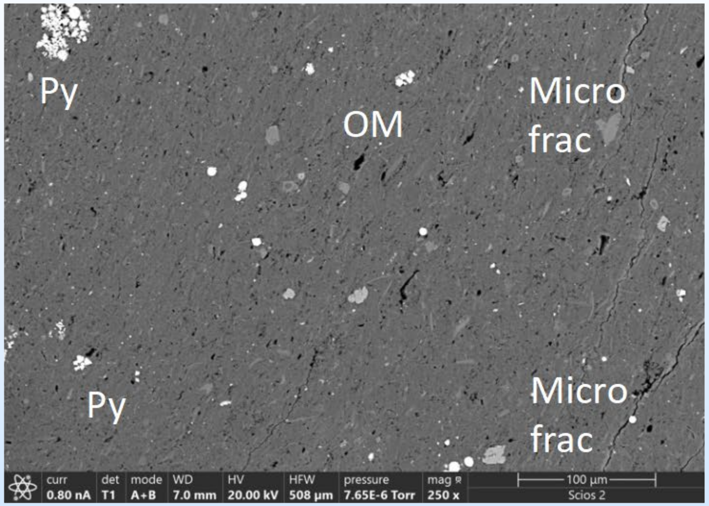
- Pore size distributions of Ductile 2 and Reservoir 3 by the Horvath-Kawazoe (HK) method (c) for micropores and by the Barrett-Joyner-Halenda (BJH) method (d) for mesopores and developed macropores.

Task 12.A1: Rock-fluid Interactions

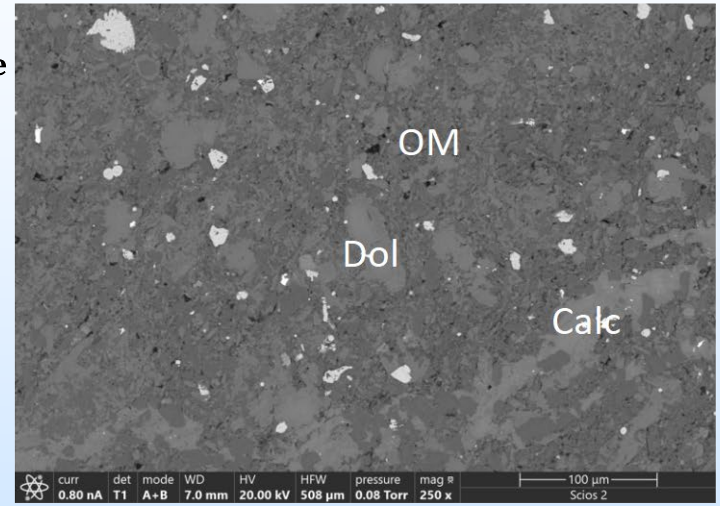
2D Micro-geochemistry of Caney Shale Matrix

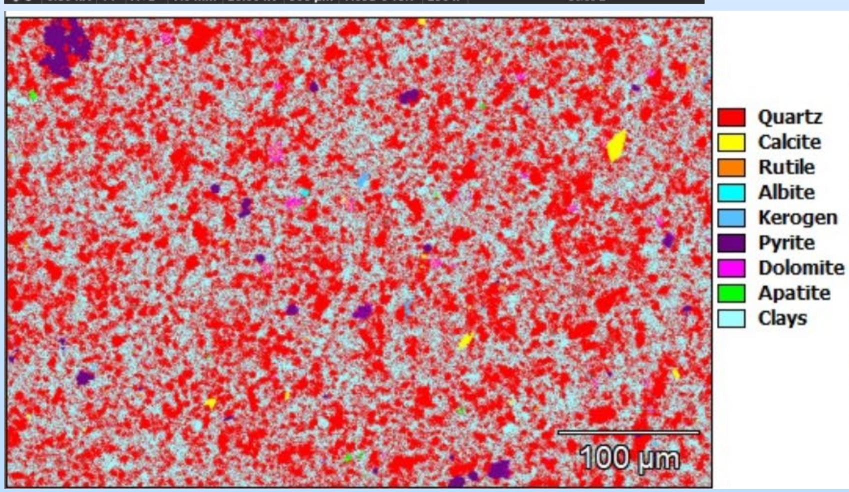
- Ductile 2, uniformity, dispersive quartz in clay matrix, lower brittleness
- Reservoir 3, heterogeneity, Quartz, carbonate, clays compacted, high brittleness

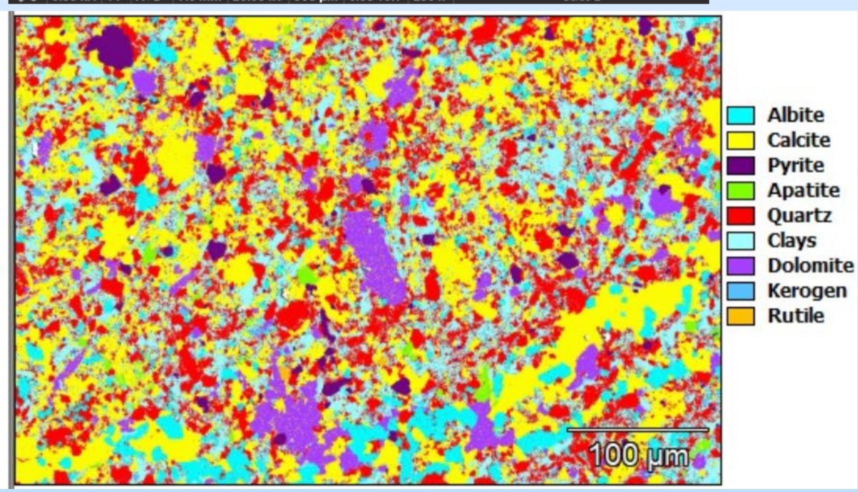
Ductile 2 | **Reservoir 3**



Dol: Dolomite
Calc: Calcite
Py: Pyrite
OM: Organic Matter
Frac: Fracture



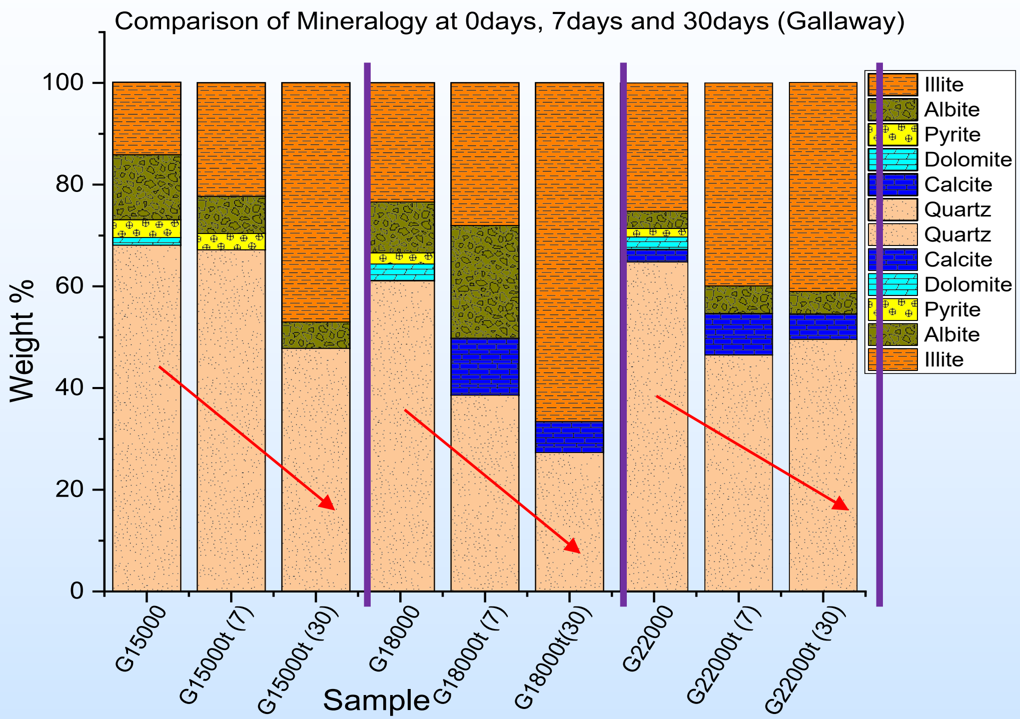


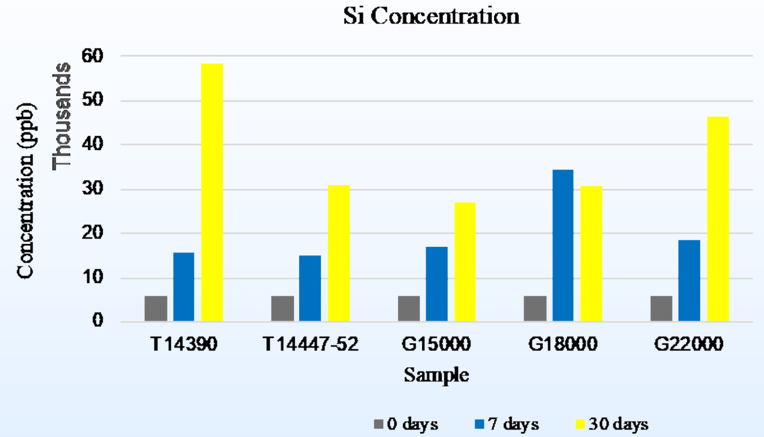


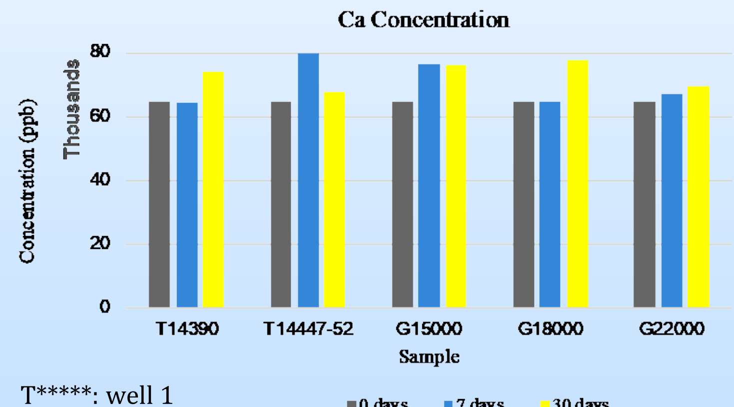
SEM/EDS micrographs of Caney Shale Ductile 2 and Reservoir 3 showing microstructural and heterogeneous differences

Task 12A.1: Rock-fluid Interactions

Geochemistry of Rock-Fracturing Fluid Reactions







- Rock-fluid reactions show dissolution of pyrite & carbonates and increase in clay composition
- Dissolution of pyrite causes temporal acidity resulting in dissolution of carbonates thus the marginal increases in Ca concentrations
- Increased Si, due to dissolution of biogenic silica

T*****: well 1
G*****: well 2 no reaction
G*****t(7): well 2, 7days reaction
G*****t(30): well 2, 30days reaction

Nomencleture:

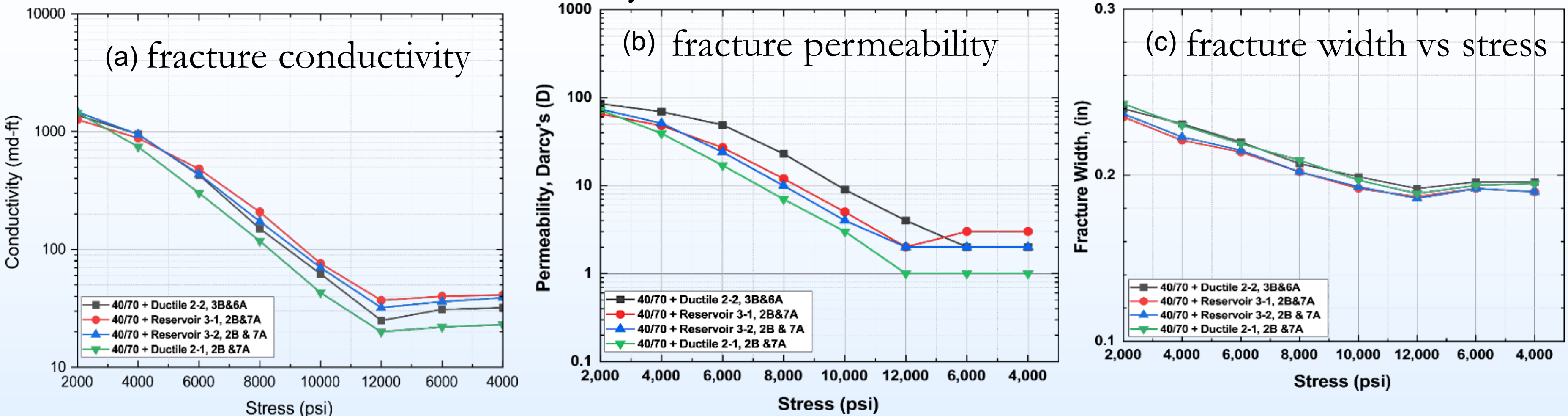
SDG –Spray-Dried Gallaway
GPG –Ground-Powder Gallaway
SDT – Spray-Dried Tomaney
GPT –Ground-Powder Tomaney

SDG –Spray-Dried well 2
GPG –Ground-Powder well 2
SDT – Spray-Dried well 1
GPT –Ground-Powder well 1

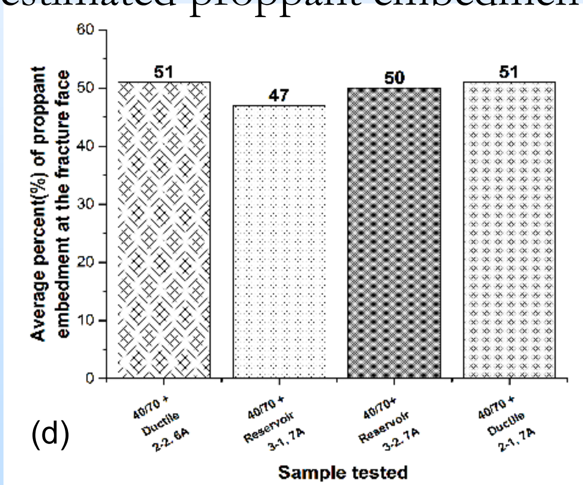
Awejori, G.A., Doughty, C., Xiong, F., Spycher, N. Paronish, T., Radonjic*, M., *Integrated Experimental and Modeling Study of Geochemical Reactions of Simple Fracturing Fluids with Caney Shale*, Energy & Fuels, 36, 17, 10064–10081, August 22, 2022, https://doi.org/10.1021/acs.energyfuels.2c01739.

Task 12A.2 Proppant Embedment & Fracture K

API-19D Fracture Conductivity Test



estimated proppant embedment



Fracture conductivity and permeability of Ductile 2 drop (over one order of magnitude) further than Reservoir 3 under stress ~12,000 psi (~83 MPa)

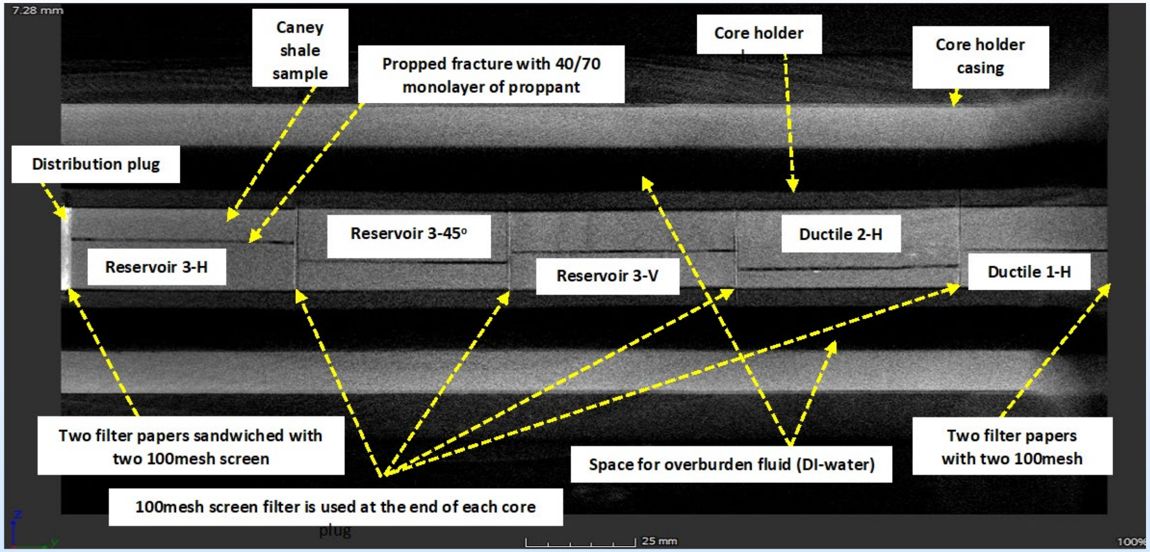
Average **fracture width** of both Ductile 2 and Reservoir 3 drops around 20.8%

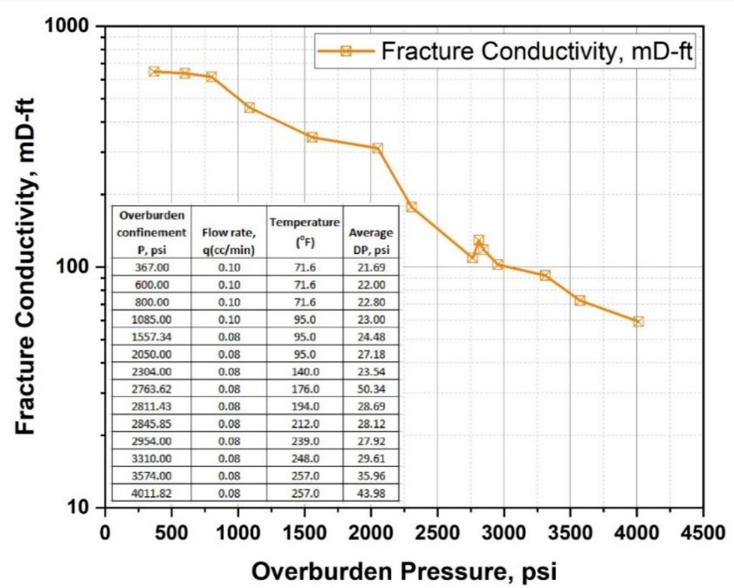
Ductile 2 shows more **proppant embedment** on fracture surface than Reservoir 3

Katende, A, Connell, . L. O', Rich, A. , Rutqvist, J. and Radonjic*, M., *A comprehensive review of proppant embedment in shale reservoirs: Experimentation, modeling and future prospects*. Journal of Natural Gas Science and Engineering, 95, 104143. November 2021. *https://doi.org/10.1016/j.jngse.2021.104143*.

Task 12A.2 Proppant Embedment & Fracture K

Automated Core Flooding using a Monolayer Proppant in Fractured Multi-composite core (five plugs 2x1inch)





Overburden confinement P, psi	Flow rate, q(cc/min)	Temperature (°F)	Average DP, psi
367.00	0.10	71.6	21.69
600.00	0.10	71.6	22.00
800.00	0.10	71.6	22.80
1085.00	0.10	95.0	23.00
1557.34	0.08	95.0	24.48
2050.00	0.08	95.0	27.18
2304.00	0.08	140.0	23.54
2763.62	0.08	176.0	50.34
2811.43	0.08	194.0	28.69
2845.85	0.08	212.0	28.12
2954.00	0.08	239.0	27.92
3310.00	0.08	248.0	29.61
3574.00	0.08	257.0	35.96
4011.82	0.08	257.0	43.98

CT scan image of the composite Caney shale sample (five ductile/brittle 1x2 inch plugs) inserted in a carbon composite core holder (12x4 inch).

Fracture conductivity vs overburden pressure coupling temperatures and pressures.

- Fracture conductivity decreases with an increase in confinement stress
- Reduced fracture permeability is caused by proppant embedment and proppant crushing

Katende, A., Rutqvist, J., Benge, M., Seyedolali, A., Bunger, A., Puckette, J.O., and Radonjic*, M., *Convergence of micro-geochemistry and micro-geomechanics towards understanding proppant shale rock interaction: A Caney shale case study in southern Oklahoma, USA*. Journal of Natural Gas Science and Engineering 96, 104296. December 2021. https://doi.org/10.1016/j.jngse.2021.104296.

Task 12A Key Findings & Future work

Task 12.1: Geochemistry of Rock-fluid Interactions

- ✓ Ductile 2 low compositional and textural heterogeneity, compared to Reservoir 3.
- ✓ The Ductile 2 based on composition is expected to have a lower brittleness than Reservoir 3.
- ✓ Rock-fracturing fluid reactions lead to significant dissolution of quartz/feldspar, an increase in clays, reduction of pyrite, based on XRD,
- ✓ High fluid pH reduces rates of carbonate dissolution, but pyrite dissolution and iron oxidation remain significant

Task 12.2: Rock-proppant Interactions

- ✓ Fracture conductivity is primarily driven by fracture closure pressure (exp. API, AFS)
- ✓ Fracture conductivity is affected by the rock composition, both mineralogy and organic content as well as microstructure and pore architecture.

BP4: Integration of data within Task 12 and with Tasks 11, 12B, 13A,B

Task 12.A 1: Rock-fluid Interactions

- ➢ **Complete the comparison of heterogeneity between Ductile 2 and Reservoir 3.**
- ➢ **Continue to compare the 3D characteristics of Ductile 2 and Reservoir 3.**
- ➢ **Assist modeling of current experiments to help in forecasting**
- ➢ **Start core flooding experiments**

Task 12.A 2: Rock-proppant Interactions

- ➢ **Complete nano indentation.**
- ➢ **Investigate proppant embedment from fracturing fluid softened shale**

Task 12: Progress, Data Integration & Collaboration

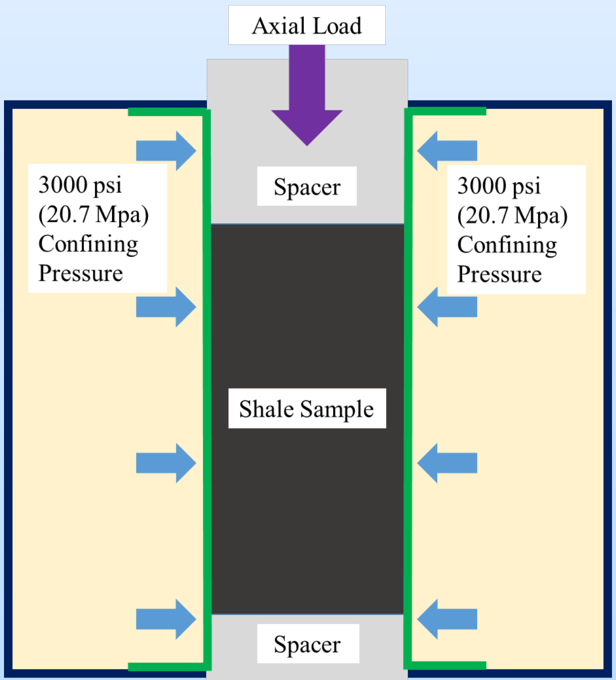
Task 12B: Geomechanical Characterization – Andrew Bunger

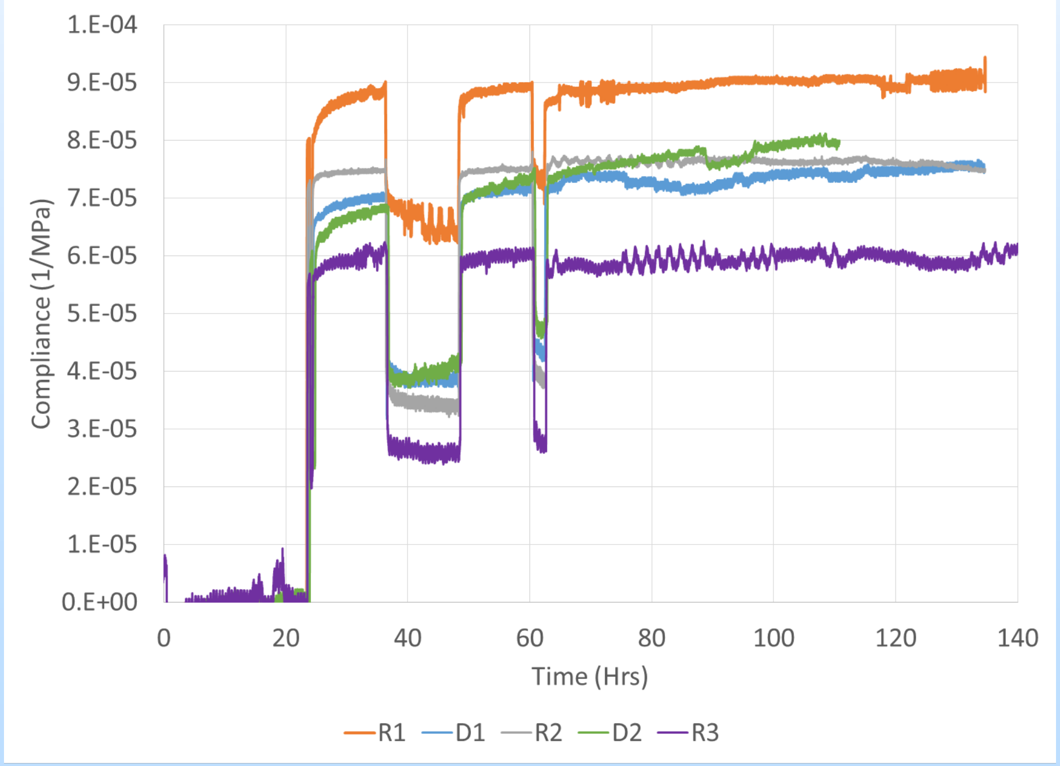
- **Triaxial data** used in drilling simulation (previous BP)
- **Creep and triaxial data** used by LBNL to simulate formation creep and proppant embedment (see Benge et al, 2021)
- Additional laboratory data will be shared with group to predict behavior and simulate creep

- **Completed all testing of vertical samples** (drilled perpendicular to bedding planes)
  - Unconfined: compressive, tensile, fracture toughness
  - Confined (90 °C): triaxial compressive, creep testing
- **Initial testing of horizontal samples** (drilled parallel to bedding planes)
  - Creep testing at 90 °C
  - Will be duplicated for repeatability
- Continued development of geomechanical model
  - Benchmarked against laboratory creep test data

Task 12B: Geomechanical Characterization

- Characterization complete for vertical and horizontal samples
  - Only remaining is creep of 45° samples
- Initial trends from creep testing
  - Ductile zones more prone to creep deformation
  - Reservoir 3 shows almost no creep
  - Accounting for differences in elastic strain and applied stress allows all zones to be compared

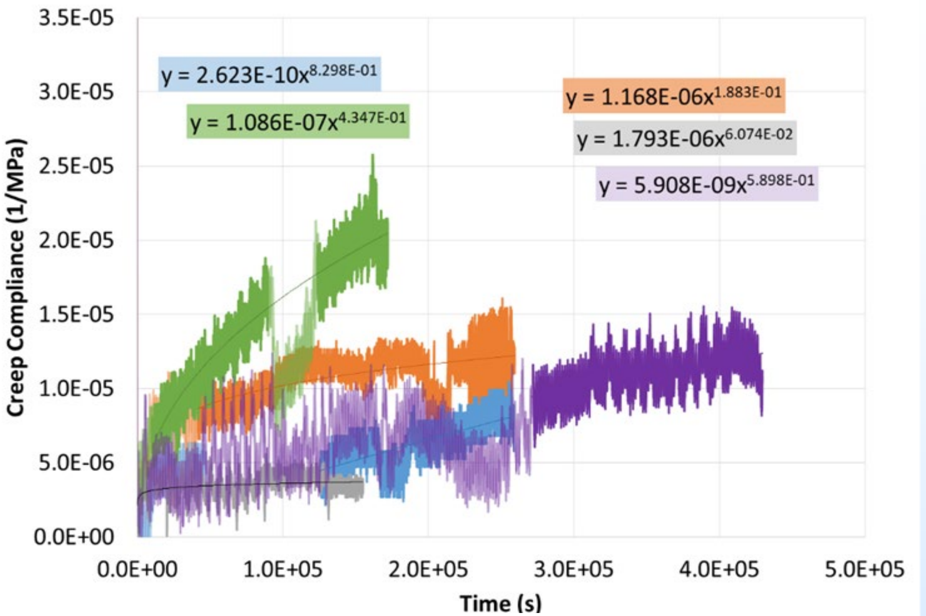


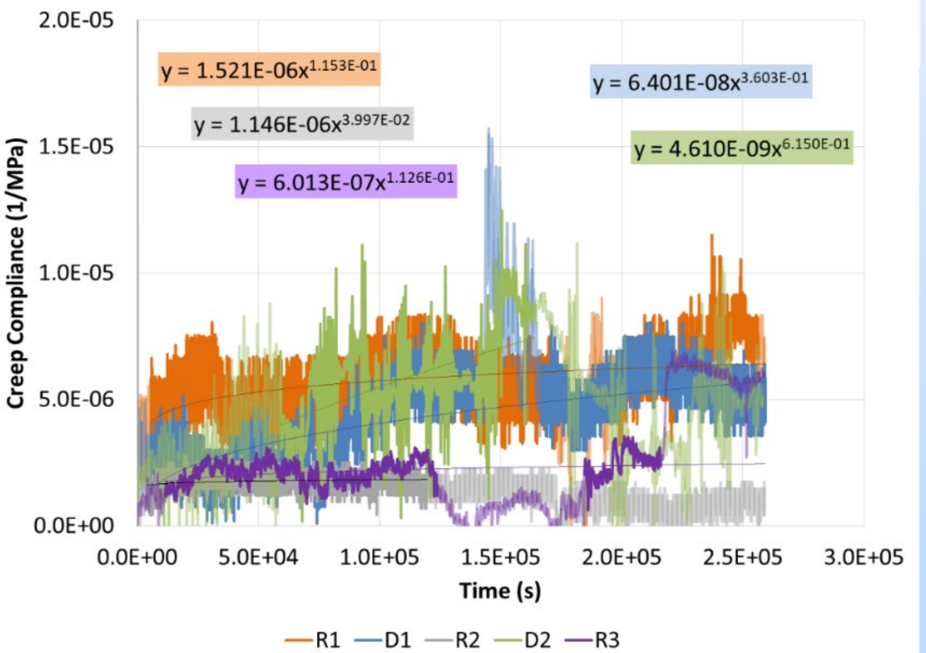


Task 12B: Geomechanical Properties

- **Creep testing** completed for vertical (drilled perpendicular to bedding planes) and horizontal samples (drilled parallel to bedding planes)
  - Both data sets show similar magnitude of creep compliance
  - Ductile zones more prone to creep

- **Horizontal samples** show significantly lower magnitude of creep compliance
  - Implies most of creep occurs in bedding planes





Creep compliance of vertical samples (above)
and horizontal samples (below)

Task 12B Key Findings & Future work

Task 12B: Summary Characterization of Geomechanical Properties

- ✓ Ductile zones significantly more prone to long-term creep deformation
- ✓ Creep mostly occurs in bedding planes
- ✓ Benge, M., Katende, A., Rutqvist, J., Radonjic, M., and Bunger, A. 2022. "Creep Properties of Shale and Predicted Impact on Proppant Embedment for Caney Shale, Oklahoma". Rock Mechanics and Rock Engineering. (Submitted to Rock Mechanics and Rock Engineering)

Task 12B: Future work for Characterization of Geomechanical Properties

- ➢ Complete creep testing of 45° samples
- ➢ Continue development of in-situ FEA model

Progress, Data Integration & Collaboration

Task 12C: Microfluidics Experiments and Fluids Evaluation

Accomplishments to Date: Prem Bikkina

– Swelling potential of Illite and Illite-Smectite clays have been quantified upon exposure to model and field fluids obtained from Continental Resources.

– Fluid properties measurements including density, viscosity, and interfacial tension of model fluids and field fluids obtained from Continental Resources have been conducted.

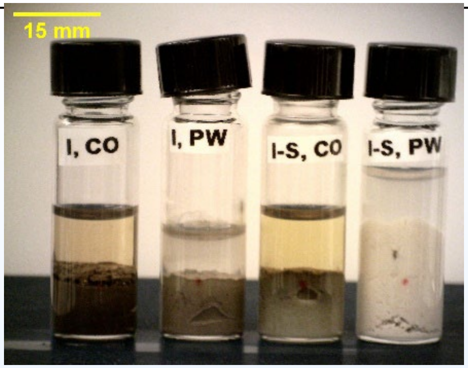
– Advancing and receding contact angle data for DI water-air, brine-air, n-Decane-air, produced water-air, crude oil-air, brine-n-Decane systems, and crude oil-produced water systems have been measured in the untreated and Illite-coated microfluidic channels.

TASK 12C: Microfluidics Experiments & Fluids Evaluation

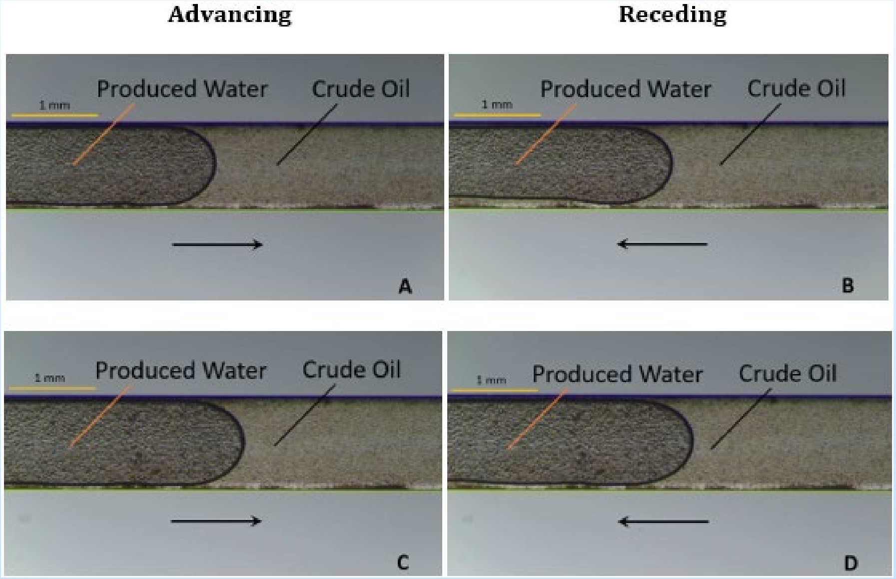
❖ Quantified Illite and Illite-Smectite clays swelling potentials.

❖ Measured model and Caney shale fluid properties.

❖ Quantified wettability of Illite clay-coated surfaces when exposed to model and Caney shale fluids.

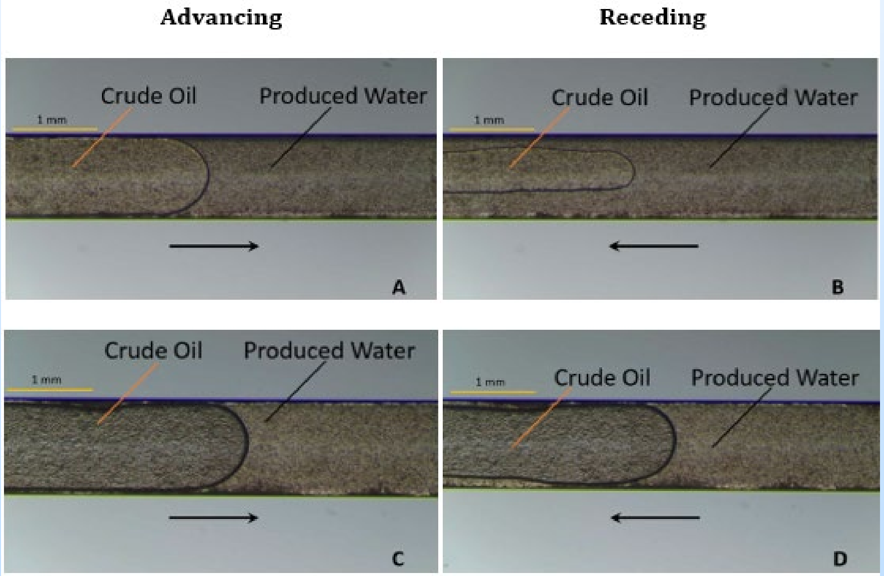


Illite (I) and Illite-Smectite (I-S) swelling after 24 hrs. Red dots represent the original heights of the clays



Before (A&B) and after (C&D) aging wettability results in Illite-coated microfluidic channel contacted **by Crude Oil first**.

➢ *Arrow direction indicates the fluid flow/interface movement direction.*



Before (A&B) and after (C&D) aging wettability results in Illite-coated microfluidic channel contacted **by Produced Water first**.

Task 12C Key Findings & Future work

BP3 Summary :

- ✓ Illite clay has negligible swelling upon contact with Caney Crude oil and Produced water, however, Illite-Smectite (30:70 wt.%) clay has significant swelling with the Produced water.
- ✓ Wettability experiments in untreated and Illite clay coated microfluidic channels indicated that wetting state of the surface is determined by the liquid (i.e., aqueous or non-aqueous) that first contacts the surface, except for the case of 30k ppm brine contacted the microfluidic channel first which can be attributed to the effect of salinity.
- ✓ Bhattacherjee, R. and Bikkina, P.K., 2022. Preparation of illite coated geomaterial microfluidic surfaces: Effect of salinity and heat treatment. Journal of Petroleum Science and Engineering, 216, p.110805.

Next Steps for BP 4

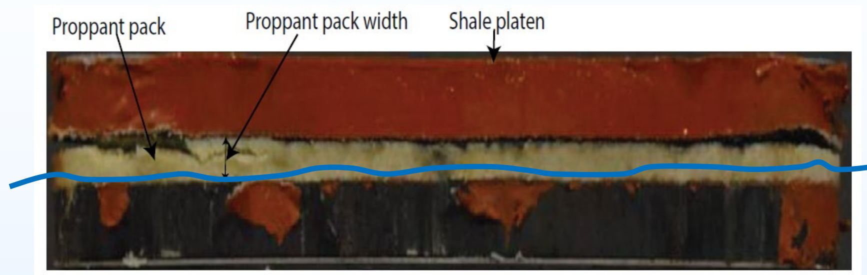
- ➢ **Preparation of Illite-Smectite clay coated capillary tubes as a function of base fluid salinity and characterization of the coated surfaces.**
- ➢ **Wettability experiments in Illite-Smectite clay coated microfluidic channels.**
- ➢ **Measurement of contact angle data of Caney shale rocks and fluids**
- ➢ **Measurement of conductivity, pH, and TDS of Caney Produced water, and TAN and TBN of the Crude oil.**

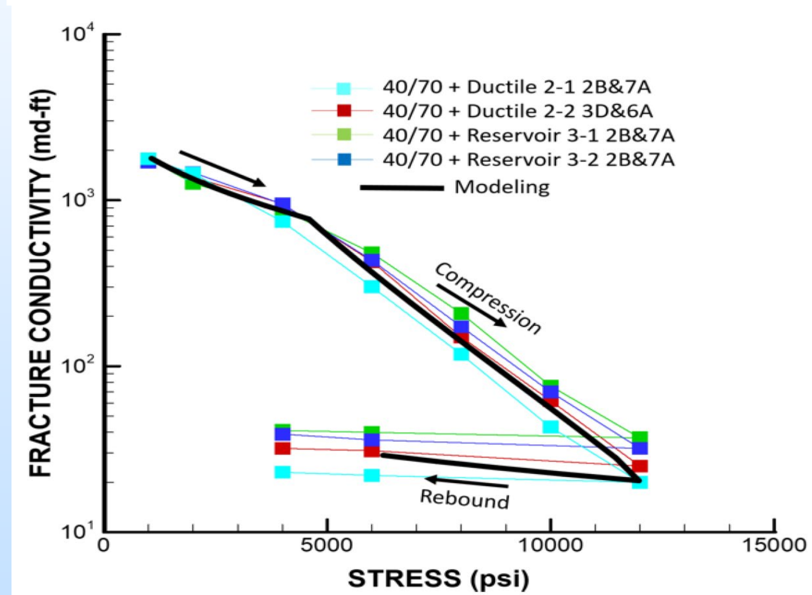
Progress, Data Integration & Collaboration

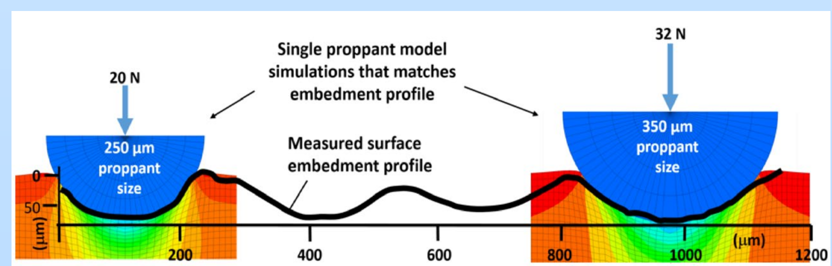
Task 13: Coupled Processes Modeling- Jonny Rutqvist

Subtask 13.2: Model Calibration for Phase II

- ✓ Completed modeling of propped fracture conductivity experiment (multilayer)
  - **Sand compaction and grain crushing cause irreversible conductivity reduction**
  - **A modified cam-clay model for sand compaction and rebound modeling**
- ➢ Ongoing modeling of OSU flow through experiments of monolayer propped fractures
  - **Proppant embedment has significant impact on fracture conductivity**
- ✓ Updated proppant creep embedment modeling using UPITT new creep properties



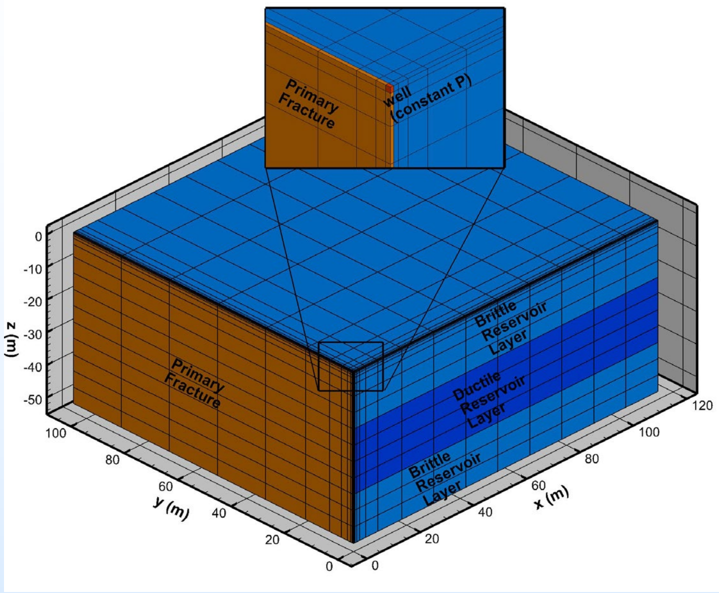


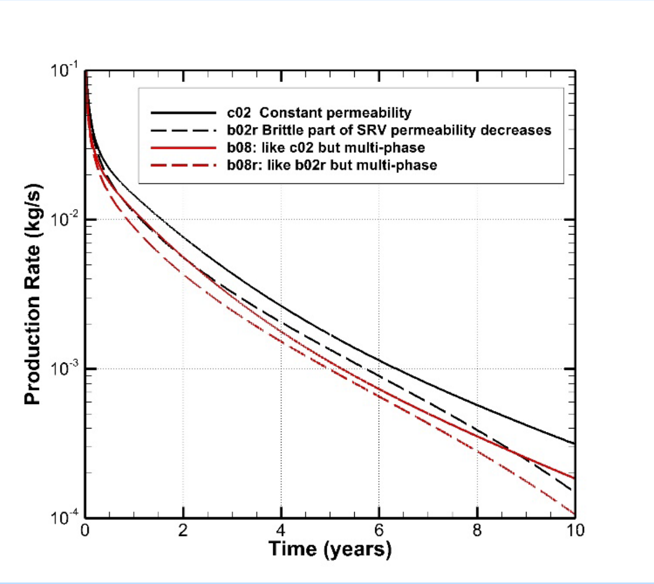


Task 13: Coupled Processes Modeling

Subtask 13.1: Modeling Simulation and Production

- Previous production modeling is extended from single-phase gas flow (pure CH_4) to two-phase flow (gaseous CH_4 and aqueous-phase brine)
- Initial simulations with generic relative permeability and capillary pressure curves show brine production is small, but noticeably decreases gas production
- Next round of simulations will constrain relative permeability and capillary pressure curves using results from OSU laboratory studies on microfluidic channels
  - Surface tension and contact angle measurements determine capillary pressure strength
  - Contact angle informs wettability, which affects the shape of relative permeability curves





Task 13 Key Findings & Future work

Task 13: Coupled Processes Modeling Summary

- ✓ Proppant embedment significant for monolayer propped fractures especially in ductile units
- ✓ Proppant compactions and crushing significant for propped fracture conductivity
- ✓ Long-term production decline is caused by permeability decrease in brittle or ductile layers

Task 13: Coupled Processes Modeling Future work

- ➢ Complete modeling of OSU flow-through experiments
- ➢ Update fracture stress-permeability models for the production model
- ➢ Constrain relative permeability and capillary pressure models using OSU laboratory data
- ➢ Update coupled process modeling of production

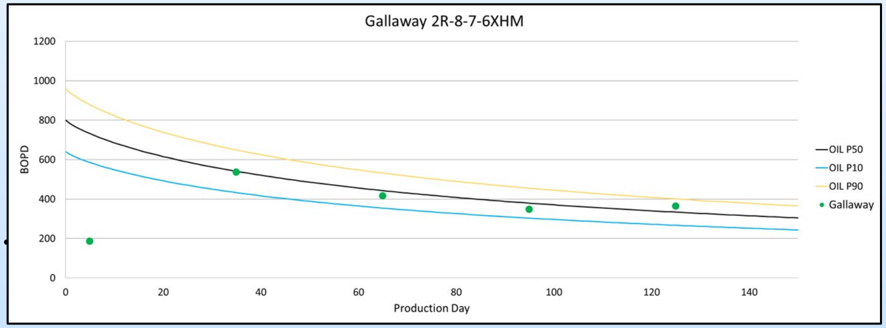
Task 14 Drilling, Stimulation and Production Economical and Technical Analysis

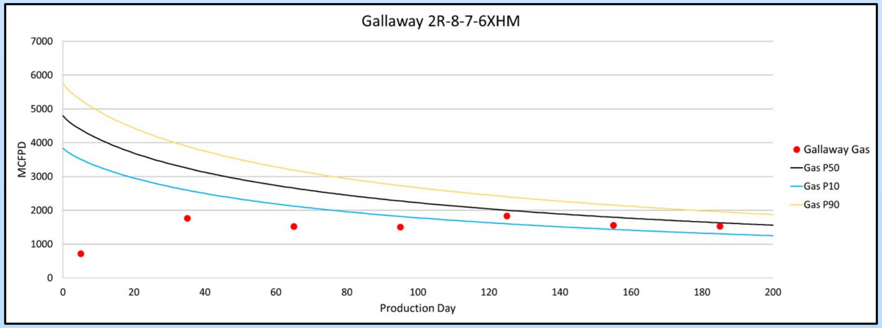
Subtask 14.1 Post analysis of drilling and completion of the horizontal well.

- Drilling of Gallaway resulted in actual 358.8 hrs on-bottom rotating (to 22,708 ft) vs pre-simulated 393 hrs planned (to 24,453 ft) – difference in total depth makes up time difference
- Some formation tops were at different depths than planned and less sand was drilled on Gallaway as compared to Garrett

Simulated Gallaway Results					Actual Gallaway Results				
Hole Size (in)	Depth In (ft)	Depth Out (ft)	Avg. ROP (ft/hr)	Total Hours (hrs)	Hole Size (in)	Depth In (ft)	Depth Out (ft)	Avg. ROP (ft/hr)	Total Hours (hrs)
17.5	335	1,520	167.1	7.0	17.5	208	1,528	335.5	3.9
12.25	1,520	13,600	53.4	226.5	12.25	1,528	13,660	59.1	205.2
8.75	13,600	24,453	67.8	159.5	8.75-8.50	13,660	22,708	60.3	149.7
Average well ROP			61.4		Average well ROP			62.7	
Total rotating time				393.0	Total rotating time				358.8

- The Gallaway completion design was simulated in GOHFER using Tomanay core and log data and decline data analysis from 24 nearby Springer wells.
- GOR of 6.0 from Reservoir 3 seen on Garrett was used. First month GOR was around 3.0 and is climbing towards Reservoir 3 characteristics
- We will continue to monitor production going forward



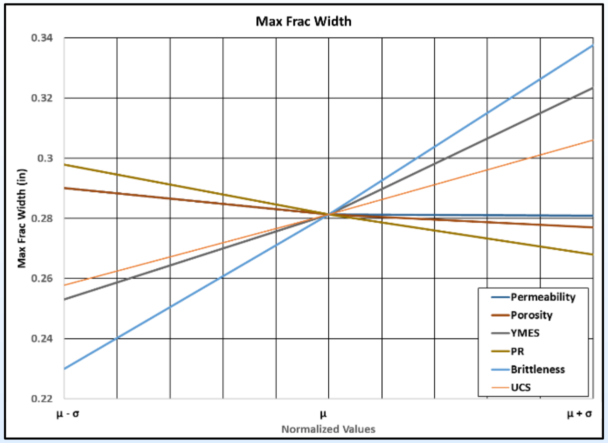


Task 14 Drilling, Stimulation and Production Economical and Technical Analysis

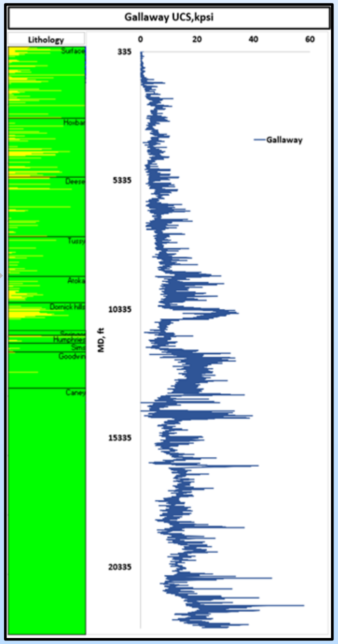
Subtask 14.2 Design drilling and completion for individual areas

- Rock geomechanical correlations were developed for Reservoir 3 based on Tomanay core testing data (U. Pitt and OSU)
- A geomechanical comparison has been done between the Garrett and Gallaway reservoir properties.

Parameters	Garrett	Gallaway	Difference %
UCS Ave. (ksi) Range (Stand. Dev.)	7.07 1.95 – 12.6 (1.73)	9.18 2.76 – 38.5 (3.79)	23%
Porosity Ave. (%) Range (Stand. Dev.)	3.56% 2.4% - 7.8% (0.66)	3.18% 1.1% – 6.3% (0.82)	12.8%
Permeability Ave. (nD) Range (Stand. Dev.)	177.23 92.5 – 605.8 (55.5)	148.55 30.0 – 426.0 (62.2)	19.3%
Young's Mod. Ave. (Mpsi) Range (Stand. Dev.)	4.56 1.3 – 8.1 (1.11)	5.99 1.8 – 25.1 (2.48)	23.9%
Poisson's Ratio Ave. (-) Range (Stand. Dev.)	0.181 0.117 – 0.332 (0.031)	0.158 0.045 – 0.29 (.042)	14.8%



- Preliminary parametric studies have been performed on maximum fracture width in GOHFER to identify potential criteria for selective stimulation in the Caney



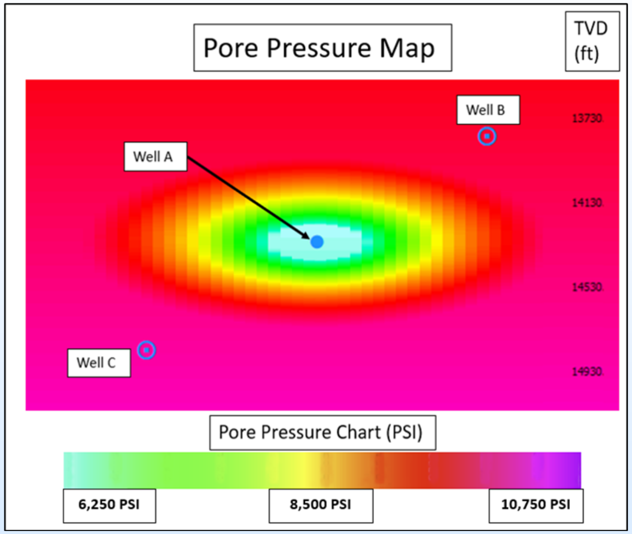
Gallaway - Strength Log

- The Gallaway strength log with some minor adjustments will be used to simulate and optimize drilling on planned wells for field development.
- Well design, operating parameters and equipment will be simulated for lowest cost/ft.
- The optimized drilling CAPEX will be used in the economical field development analysis

Task 14 Drilling, Stimulation and Production Economical and Technical Analysis

Subtask 14.3 Economical analysis.

- Current investigations on well spacing is ongoing
- A new offset well at 880’ spacing had its stimulation in GOHFER to measure the effects of the offset well with a wellbore pressure reduced by 3500 PSI
- The preliminary study indicates that this reduction impacted production but is still economic and maintains an 880’ spacing is adequate.
- Additional tests will be conducted to evaluate reasonable depletion pressure from 1500-2000 PSI impacts on child wells.
- This information will be fed into GOHFER to optimize well spacing which will help optimize the assets net value in future sections.
- The project economic development tool has added two new features, multi-well with timeline integration and NGL liquids extracted from the natural gas stream.



Well "A" Not Depleted (Virgin Reservoir Pressure)								
			CUMS		Rates		CUMS	
Well	IP Oil	IP Gas	1 YR oil	1 YR gas	1 YR oil	1 YR gas	5 YR Oil	5 YR Gas
Well "B"	799	2797	82,880	290,081	147	515	201,966	706,881
Well "C"	788	2759	83,305	291,568	148	520	197,001	689,505
Well "A" Depleted by 3500 PSI								
			CUMS		Rates		CUMS	
Well	IP Oil	IP Gas	1 YR oil	1 YR gas	1 YR oil	1 YR gas	5 YR Oil	5 YR Gas
Well "B"	616	2156	64,316	225,105	114	399	154,252	539,884
Well "C"	588	2058	63,540	222,390	112	394	142,646	499,263

Comparative 1 YR and 5 YR Cumulative Production and Production Rates Comparing Wells That Are Both High and Low in the Formation Relative to the Depleted Well and The Resulting Production Values When the Offset well was Depleted by 3500 PSI

Task 14 Key Findings & Future work

Summary points BP 3:

- ✓ Analysis and quality control on all drilling and stimulation data from the Gallaway well.
- ✓ Drilling and production post analysis indicate good match with pre-simulated drilling rotating hours and production of the Gallaway well.
- ✓ Geological, geomechanical and petrophysical property analysis from drilling data from the Gallaway compared to the Garrett.
- ✓ Initiated stimulation parametric analysis to determine benefits of selective stimulation and effects on reservoir drawdown on well spacing.
- ✓ Completed field economics program development with added multiwell timeline capabilities and NGL cost benefit calculator.
- ✓ Kolmer, H.P., Cunningham, C. M., Al-Dushaishi, M.F, 2022, ROP Optimization of Lateral Wells In SW Oklahoma: Artificial Neural Network Approach, Paper OPTC2022-91464, published in Proceedings of ASME, OPTC2022, Houston, Texas, USA 20-21, September 2022. **Full conference paper.**

Planned for BP4:

- ➢ **Finalize optimized Caney well drilling and equipment plan and evaluation of selective stimulation benefits**
- ➢ **Prepare a field development plan for Caney Shale that is safe, economically and technically sound.**
- ➢ **Prepare final report and publications/presentations.**

Additional Information

Published Journal Papers

Task 12.A Radonjic:

1. Awejori, G.A., Doughty, C., Xiong, F., Spycher, N. Paronish, T., Radonjic*, M., *Integrated Experimental and Modeling Study of Geochemical Reactions of Simple Fracturing Fluids with Caney Shale*, Energy & Fuels, 36, 17, 10064–10081, August 22, 2022, https://doi.org/10.1021/acs.energyfuels.2c01739.
2. Xiong, F., Rother, G., Radonjic*, M., *Insights into controls of mineralogy and pore structure on the density of adsorption phase in shales under supercritical conditions*, Energy & Fuels, 36, 17, 10110–10122, August 22, 2022 https://doi.org/10.1021/acs.energyfuels.2c01847.
3. Katende, A., Rutqvist, J., Benge, M., Seyedolali, A., Bunger, A., Puckette, J.O., and Radonjic*, M., *Convergence of micro-geochemistry and micro-geomechanics towards understanding proppant shale rock interaction: A Caney shale case study in southern Oklahoma, USA*. Journal of Natural Gas Science and Engineering 96, 104296. December 2021. *https://doi.org/10.1016/j.jngse.2021.104296*.
4. Katende, A, Connell, . L. O', Rich, A. , Rutqvist, J. and Radonjic*, M., *A comprehensive review of proppant embedment in shale reservoirs: Experimentation, modeling and future prospects*. Journal of Natural Gas Science and Engineering, 95, 104143. November 2021. *https://doi.org/10.1016/j.jngse.2021.104143*.

Published Full Conference Papers

Task 12.A Radonjic: Rock-fluid Interactions

1. Awejori, G.A., Whitworth, L., Paronish, T., Xiong, F., Katende, A., Radonjic*, M., *Fluid Induced Elemental and Mineralogy Alterations of Caney Shale,* Presented at American Rock Mechanics Association Conference (ARMA), 2022. June 29-July 1, in Santa Fe, NM (2022).

2. Katende, A., Allen, C., Rutqvist, J., Nakagawa, S., Massion, C., Awejori, A.G., Xiong, F., and Radonjic*, M., *Experiments and Modeling of Proppant Embedment and Fracture Conductivity for the Caney Shale, Oklahoma, USA*. Presented at American Rock Mechanics Association Conference (ARMA), Santa Fe, NM, June 29-July 1, 2022.

Presentations & Abstracts

Task 12.A Radonjic: Rock-fluid Interactions:

1. Awejori, G.A., Spycher, N.F., Paronish, T.J., Radonjic, M., *Geochemical Compositional Changes due to Fracturing Fluid Interaction with Caney Shale, South Central Oklahoma, USA*. Presented at Goldschmidt Conference, Honolulu, HI, July 10-15, 2022.
2. Allen, C., Katende, A., Xiong, F., Massion, C., Krumm, R., **Radonjic*, M.** *Subsurface Engineering of Conductive Fractures in Caney Shale, Southern Oklahoma: A Step Towards Energy Transition,* Presented virtually at Goldschmidt Conference, Honolulu HI, July 10-15, 2022.
3. Katende, A., Allen, C., Rutqvist, J., Nakagawa, S., Massion, C., Awejori, A.G., Xiong, F., and Radonjic*, M., *Experiments and Modeling of Proppant Embedment and Fracture Conductivity for the Caney Shale, Oklahoma, USA*. Presented at American Rock Mechanics Association Conference (ARMA), Santa Fe, NM, June 29-July 1, 2022.
4. Awejori, G.A., Whitworth, L., Paronish, T., Xiong, F., Katende, A., Radonjic*, M., *Fluid Induced Elemental and Mineralogy Alterations of Caney Shale,* Presented at American Rock Mechanics Association Conference (ARMA), Santa Fe, NM, June 29-July 1, 2022.

Publications and Presentations

Task 12.A Radonjic: Rock-fluid Interactions Presentations and Abstracts:

5. Katende, A., Allen, C., Rutqvist, J., Nakagawa, S., Massion, C., Awejori, A.G., Xiong, F., and Radonjic*, M., *Experiments and Modeling of Proppant Embedment and Fracture Conductivity for the Caney Shale, Oklahoma, USA*, Presented virtually at the July 2022 proppant consortium meeting hosted by Core Labs Inc at Colorado School of Mines.

6. Allen, C., Krumm, R., Katende, A., Massion, C., Xiong, F., Radonjic*, M., *Subsurface Engineering of Conductive Fractures in Caney Shale, Southern Oklahoma: A Step Towards Energy Transition*, poster presented at Undergraduate Research Symposium, Stillwater OK, April 19, 2022.

7. Roubik, A., Dean, B., Radonjic*, M., *Impact of Fluid & Proppant Volumes on Oil & Natural Gas Returns in the Caney Shale of Oklahoma*, poster presented at Undergraduate Research Symposium, Stillwater OK, April 19, 2022.

8 Awejori, G.A., Katende, A., Xiong, F., Radonjic*, M. *Geochemical and Geo-mechanical Responses of Caney Shale to Fracturing Fluid Compositions and Reservoir Conditions*. presented virtually at Geological Society of America (GSA) Connects. Portland OR, October 10-13, 2021.

Presentations and Abstracts:

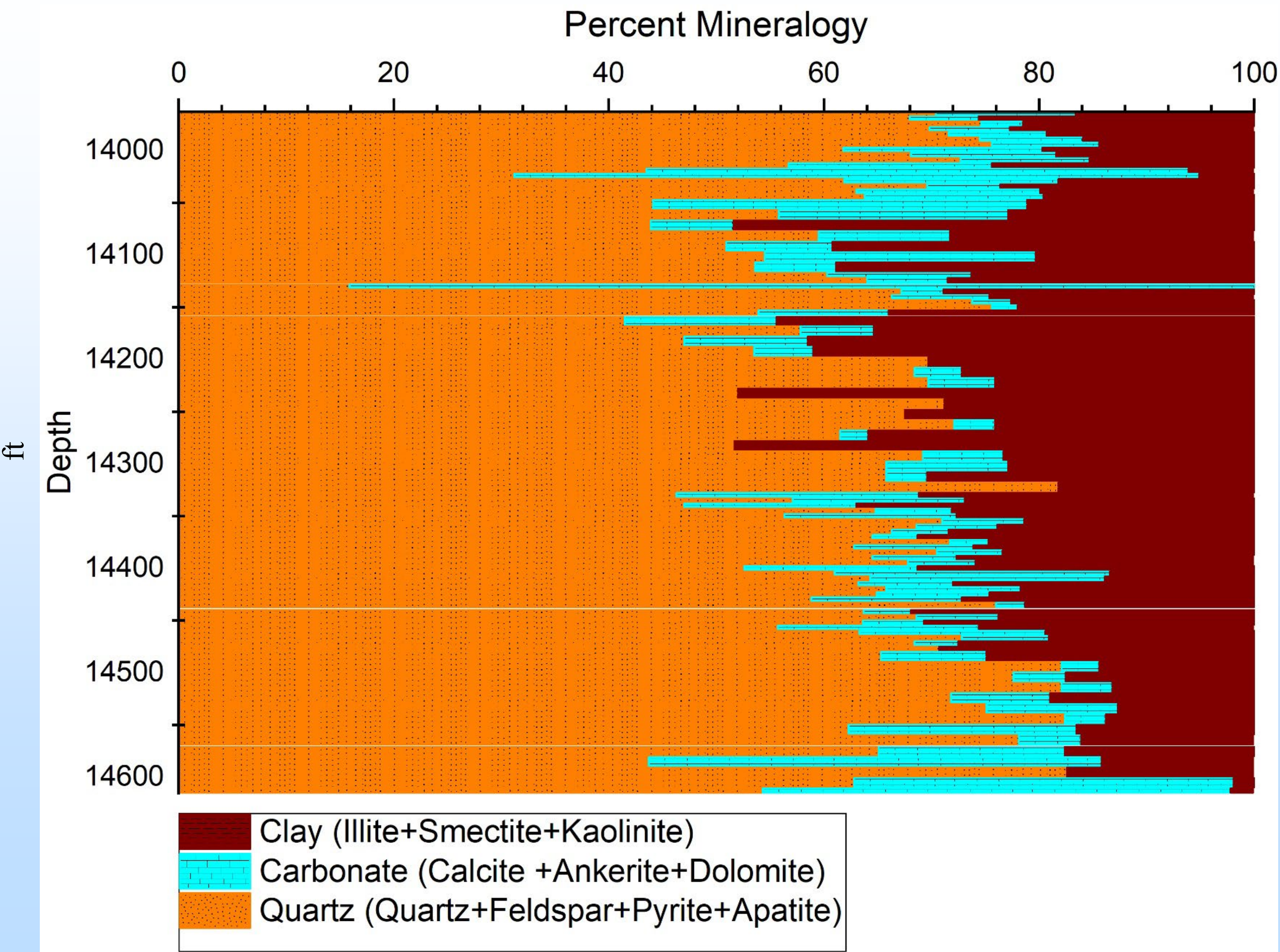
Task 12.A: Radonjic: Rock-fluid Interactions:

9. Awejori G.A., and Radonjic*, M. *Chemical Reactivity of Caney Shale to KCl-Brines at Elevated Temperature and Pressure*. Presented at American Institute of Chemical Engineers (AIChE) Conference, Boston, MA, November 15-19, 2021.

10. Katende, A., Rutqvist, J., Benge, M., Seyedolali, A., Bunger, A., Puckette, J.O., and Radonjic*, M., *Micro-geochemistry and Micro-geomechanics towards understanding proppant shale rock interaction: A Caney Shale case study, USA*. Presented virtually at the American Geophysical Union, New Orleans, LA, December 13-17, 2022. https://agu.confex.com/agu/fm21/meetingapp.cgi/Paper/990408.

11. Xiong, F., Allen, C., Katende, A., Awejori, G.A., Kilian, K., Massion, C., Radonjic, M., *Integrated Geochemistry-Geomechanics Approach to Optimization of Hydraulic Fractures Permeability in Caney Shale, SW Oklahoma*. Accepted to be presented at American Institute of Chemical Engineers (AIChE) Annual Meeting, Phoenix, AZ, November 13-18, 2022.

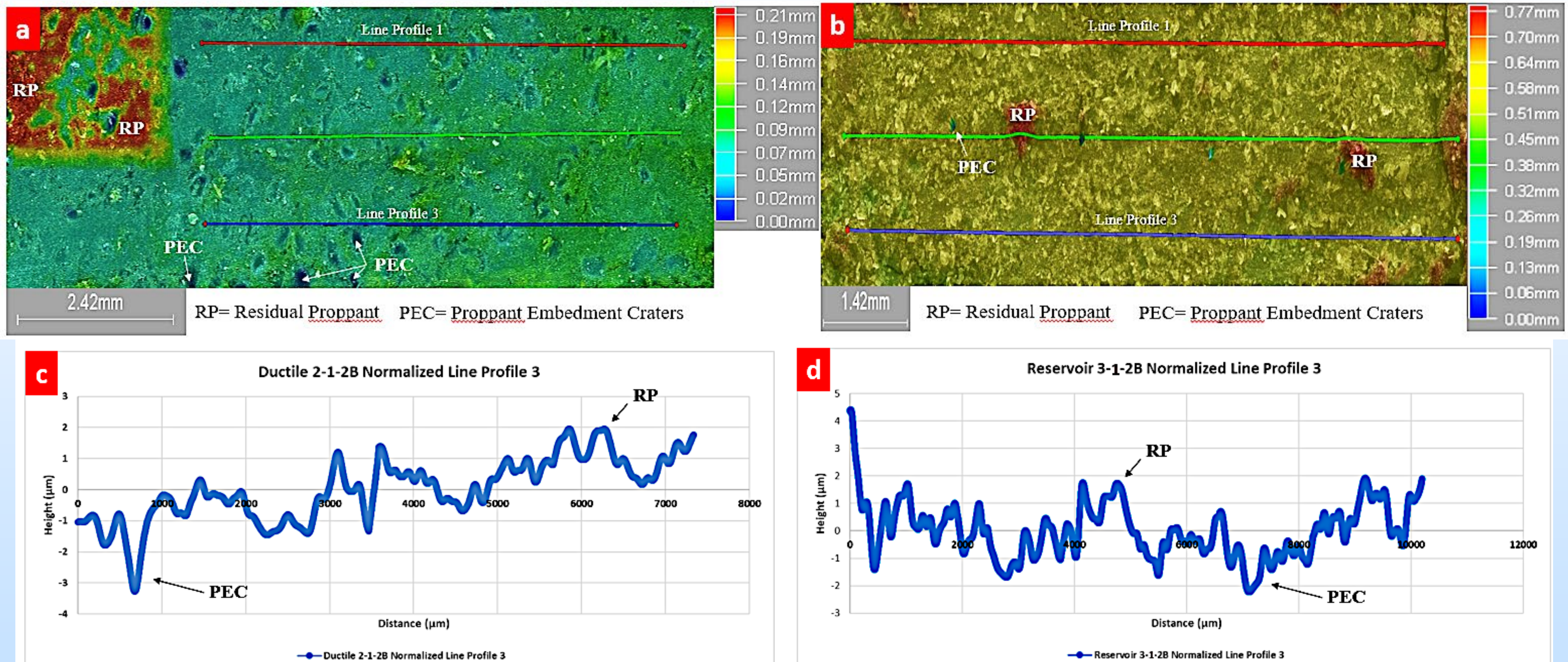
Task 12A.1 Geochemistry & Rock-Fluid Interactions



Task 12A.2 Proppant Embedment & Fracture K

Quantitative Characterization of Proppant Embedment

post API 19D Fracture Conductivity Test



Optical microscopy showing effect of proppant embedment on fracture wall surface roughness (a,b)

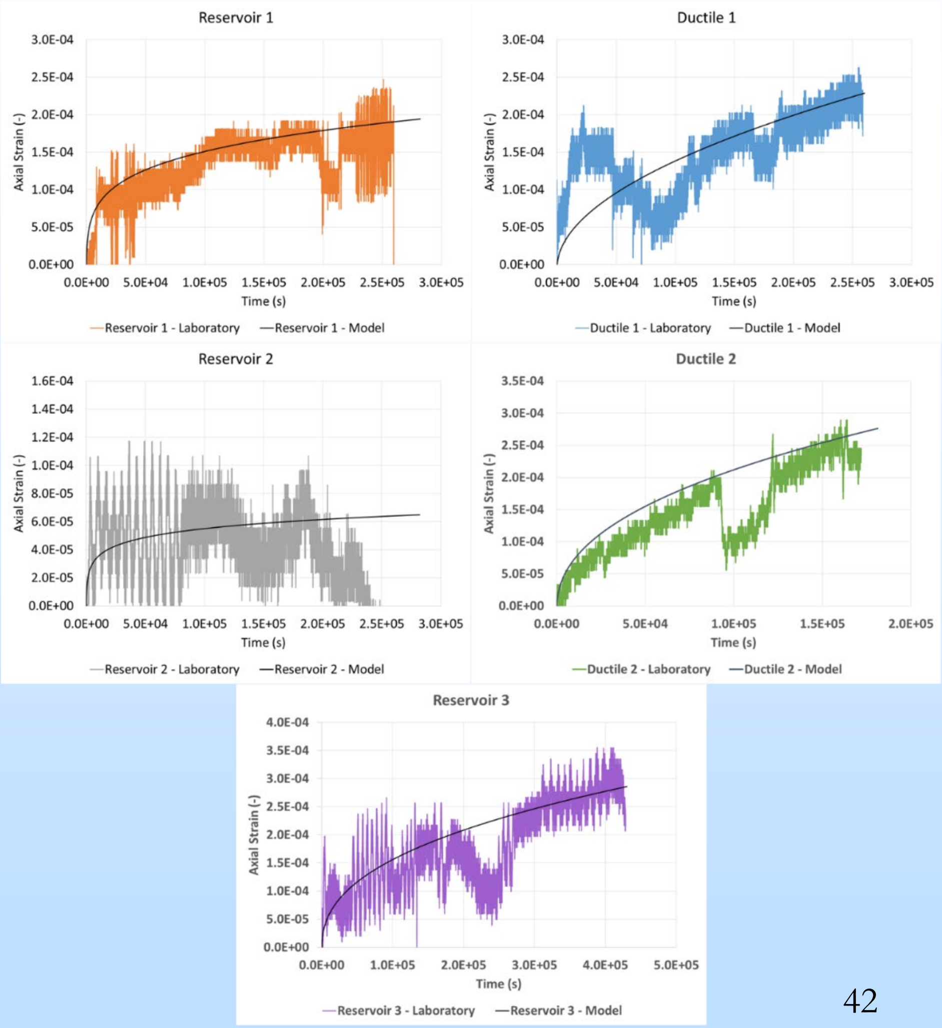
Proppant embedment depth along the third cross-sectional line (c,d)

Katende, A., Rutqvist, J., Benge, M., Seyedolali, A., Bunger, A., Puckette, J.O., and Radonjic*, M., *Convergence of micro-geochemistry and micro-geomechanics towards understanding proppant shale rock interaction: A Caney shale case study in southern Oklahoma, USA*. Journal of Natural Gas Science and Engineering 96, 104296. December 2021. *https://doi.org/10.1016/j.jngse.2021.104296*.

Appendix

University of Pittsburgh: In-situ stress model progress

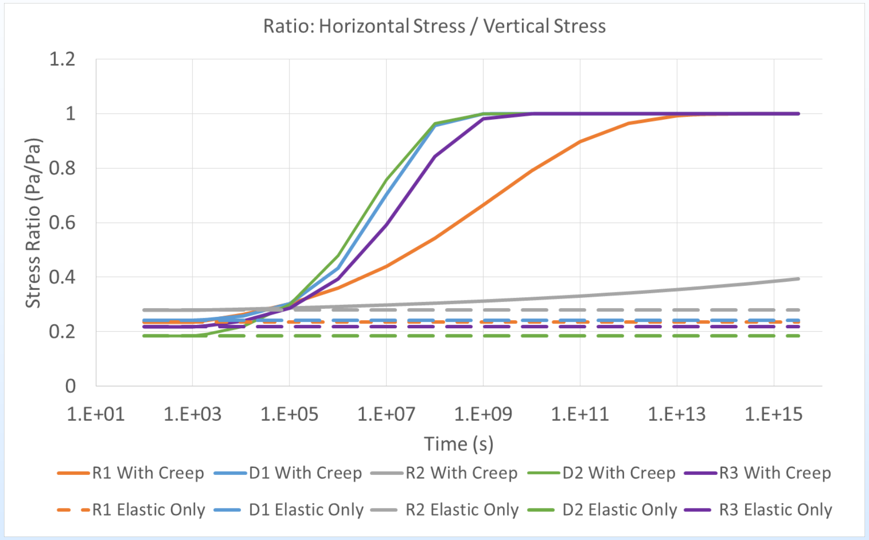
- Initial benchmarking of axial strain to lab-scale model
- Able to match measured axial strain during creep test
- Lab-scale model verified and used to extend model into 3D

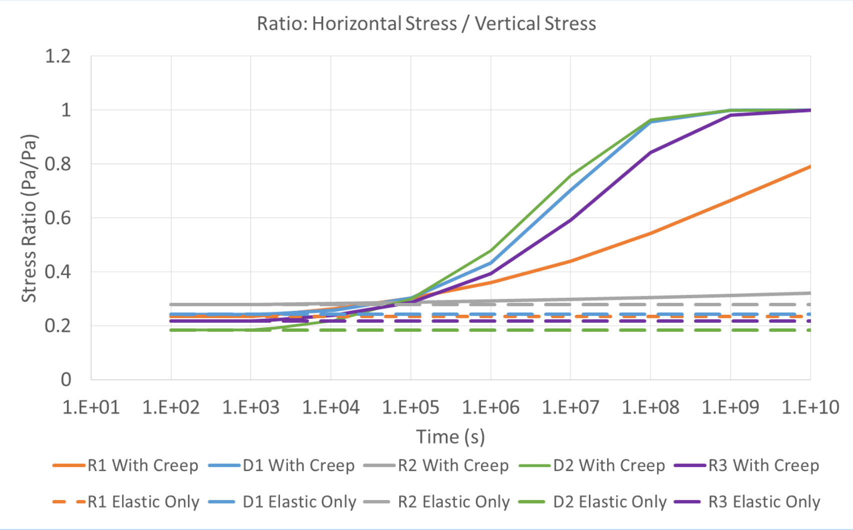


Appendix

University of Pittsburgh: In-situ stress model progress

- Ongoing development of 3D in-situ stress model
    - Have verified creep properties against lab-scale testing for vertical samples
    - Will verify lab-scale model against horizontal and 45° samples
- Initial results show tendency to reach hydrostatic stress state
    - Ratio of horizontal to vertical stress tends towards one
    - Rate dependent on creep properties





TASK 12C: Microfluidics Experiments & Fluids Evaluation

Density and Viscosity data
at 20 °C and 18 °C, 1 atm, respectively

Fluid	Viscosity (cP)	Density (g/cm³)
DI Water	1.04	0.994
5,000 ppm brine	1.12	1.001
10,000 ppm brine	1.23	1.004
30,000 ppm brine	1.26	1.018
n-Decane	0.92	0.732
Crude Oil	2.25	0.790
Produced Water	1.15	1.020

Interfacial tension data at 20 °C and 1 atm.

Non-Aqueous Phase	Aqueous Phase	IFT (mN/m)
n-Decane	DI Water	51.18
	5,000 ppm brine	47.51
	10,000 ppm brine	46.27
	30,000 ppm brine	43.81
Crude Oil	Produced Water	4.9

Wettability of Illite-clay coated microfluidic surface upon exposure to aqueous and organic liquids

Experiment	Fluid contacting the microfluidic chip first	Wettability			
		Advancing Contact Angle (°)		Receding Contact Angle (°)	
		Before Aging	After Aging	Before Aging	After Aging
DI Water, n-Decane	n-Decane first	Oil Wet	Oil Wet	Oil Wet	Oil Wet
	DI Water first	Water Wet	Oil Wet	Water Wet	Oil Wet
5k ppm brine, n-Decane	n-Decane first	Oil Wet	Water Wet	Oil Wet	Water Wet
	5k ppm brine first	Water Wet	Water Wet	Water Wet	Water Wet
10k ppm brine, n-Decane	n-Decane first	Oil Wet	Oil Wet	Oil Wet	Oil Wet
	10k ppm brine first	Water Wet	Water Wet	Water Wet	Water Wet
30k ppm brine, n-Decane	n-Decane first	Oil Wet	Oil Wet	Oil Wet	Oil Wet
	30k ppm brine first	Oil Wet	Oil Wet	Oil Wet	Oil Wet
Produced water,	Crude oil first	Oil Wet	Oil Wet	Oil Wet	Oil Wet
	Produced water	Water Wet	Water Wet	Water Wet	Water Wet

Benefit to the Program

✓Swelling potential, fines migration, and wettability alteration of clay minerals are critical aspects for drilling and production operations in shales.

✓Through literature search, we identified Illite and Smectite are the dominating clay minerals of Caney shale.

✓We developed experimental protocols for preparing Illite and Illite-Smectite clay coated microfluidic surfaces.

✓We performed visual/microfluidics studies of Illite and Illite-Smectite (30:70 %by wt.) clays swelling, and Illite clay wettability alteration and fines migration phenomena.

✓The measured fluid properties (density, viscosity, and interfacial tension) are of great importance for production strategies and forecasting of Caney shale.

Project Scope and Objectives

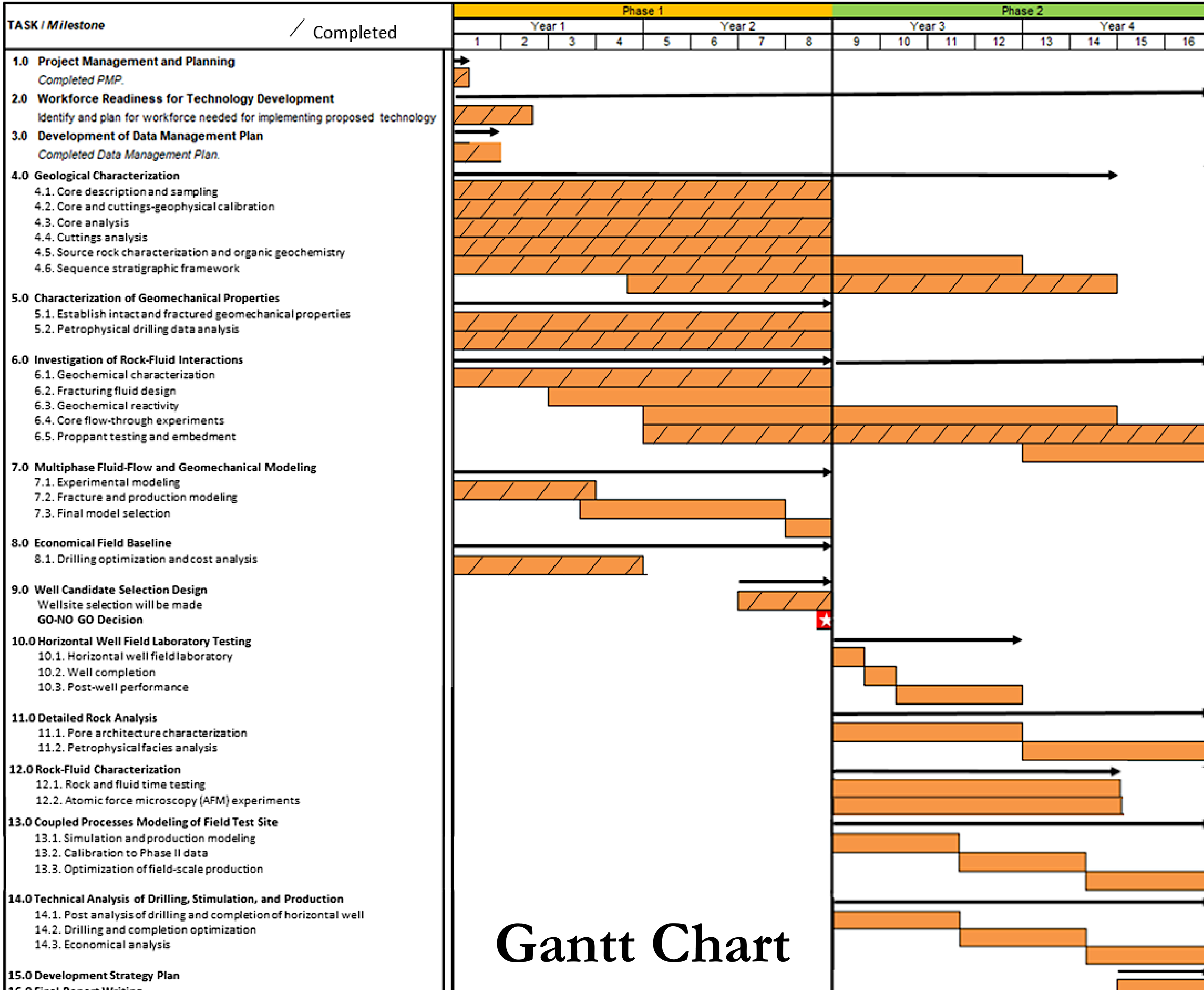
Key objectives for Phase I are completed as planned:

- ✓ Sound project management and planning.
- ✓ Effective data management.
- ✓ Coring and logging of the Caney Shale interval.
- ✓ Geological and petrophysical reservoir characterization, as well as geochemical and microstructural characterization of existing outcrop and core data as well as newly drilled cores from Caney shale.
- ✓ Establishing geomechanical properties from geophysical well logs, cores and drilling data.
- ✓ Simulate hydraulic fractures and flow to optimize stimulation design.
- ✓ Investigate and optimize applicable fracturing options including fracturing fluids, and fluid/rock interactions, relevant to water usage, proppant embedment and wellbore integrity.

Key objectives planned for Phase II are:

- Drilling, logging and stimulating a horizontal well at the Caney Shale Field Laboratory.
- Geological, geomechanical, petrophysical, and geochemical analysis of well cuttings and produced fluids to further understand reservoir architecture and variability of production streams among hydro-fracture stages and how it might impact fracture conductivity over time.
- Apply hydraulic fracture-flow simulators for optimizing stimulation of multistage-fractured horizontal wells and verification against laboratory and field data.
- Prepare a field development plan for Caney Shale that is safe, economically and technically sound.

Gantt Chart


TASK / Milestone
Completed
Phase 1
Phase 2
Year 1
Year 2
Year 3
Year 4
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
1.0 Project Management and Planning
Completed PMP.
2.0 Workforce Readiness for Technology Development
Identify and plan for workforce needed for implementing proposed technology
3.0 Development of Data Management Plan
Completed Data Management Plan.
4.0 Geological Characterization
4.1. Core description and sampling
4.2. Core and cuttings-geophysical calibration
4.3. Core analysis
4.4. Cuttings analysis
4.5. Source rock characterization and organic geochemistry
4.6. Sequence stratigraphic framework
5.0 Characterization of Geomechanical Properties
5.1. Establish intact and fractured geomechanical properties
5.2. Petrophysical drilling data analysis
6.0 Investigation of Rock-Fluid Interactions
6.1. Geochemical characterization
6.2. Fracturing fluid design
6.3. Geochemical reactivity
6.4. Core flow-through experiments
6.5. Proppant testing and embedment
7.0 Multiphase Fluid-Flow and Geomechanical Modeling
7.1. Experimental modeling
7.2. Fracture and production modeling
7.3. Final model selection
8.0 Economical Field Baseline
8.1. Drilling optimization and cost analysis
9.0 Well Candidate Selection Design
Wellsite selection will be made
GO-NO GO Decision
10.0 Horizontal Well Field Laboratory Testing
10.1. Horizontal well field laboratory
10.2. Well completion
10.3. Post-well performance
11.0 Detailed Rock Analysis
11.1. Pore architecture characterization
11.2. Petrophysical facies analysis
12.0 Rock-Fluid Characterization
12.1. Rock and fluid time testing
12.2. Atomic force microscopy (AFM) experiments
13.0 Coupled Processes Modeling of Field Test Site
13.1. Simulation and production modeling
13.2. Calibration to Phase II data
13.3. Optimization of field-scale production
14.0 Technical Analysis of Drilling, Stimulation, and Production
14.1. Post analysis of drilling and completion of horizontal well
14.2. Drilling and completion optimization
14.3. Economical analysis
15.0 Development Strategy Plan
16.0 Final Report Writing