Improving Production in the Emerging Paradox Oil Play

DE-FE0031775

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U.S. Department of Energy

National Energy Technology Laboratory

Resource Sustainability Annual Project Review Meeting

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Acknowledgements

NATIONAL ENERGY TECHNOLOGY LABORATORY

U.S. DEPARTMENT OF ENERGY

ZEPHYR ENERGY

Key Organization Aspects

- Funding (DOE and Cost Share)
  - $8M Federal, $3M+ Cost-Share, $11M+ Total
- Overall Project Performance Dates
  - January, 2020 – March, 2024

Project Team:

Statistical Petrophysics LLC

Presentation Outline

- Improving Production in the Emerging Paradox Oil Play
  – Background & Objectives
  – Accomplishments to Date
    - Core analyses
    - Fracture Analysis
    - Petrophysics & Machine Learning
    - Model development
    - Uncertainty Quantification
  – Lessons Learned
  – Synergy Opportunities
  – Summary

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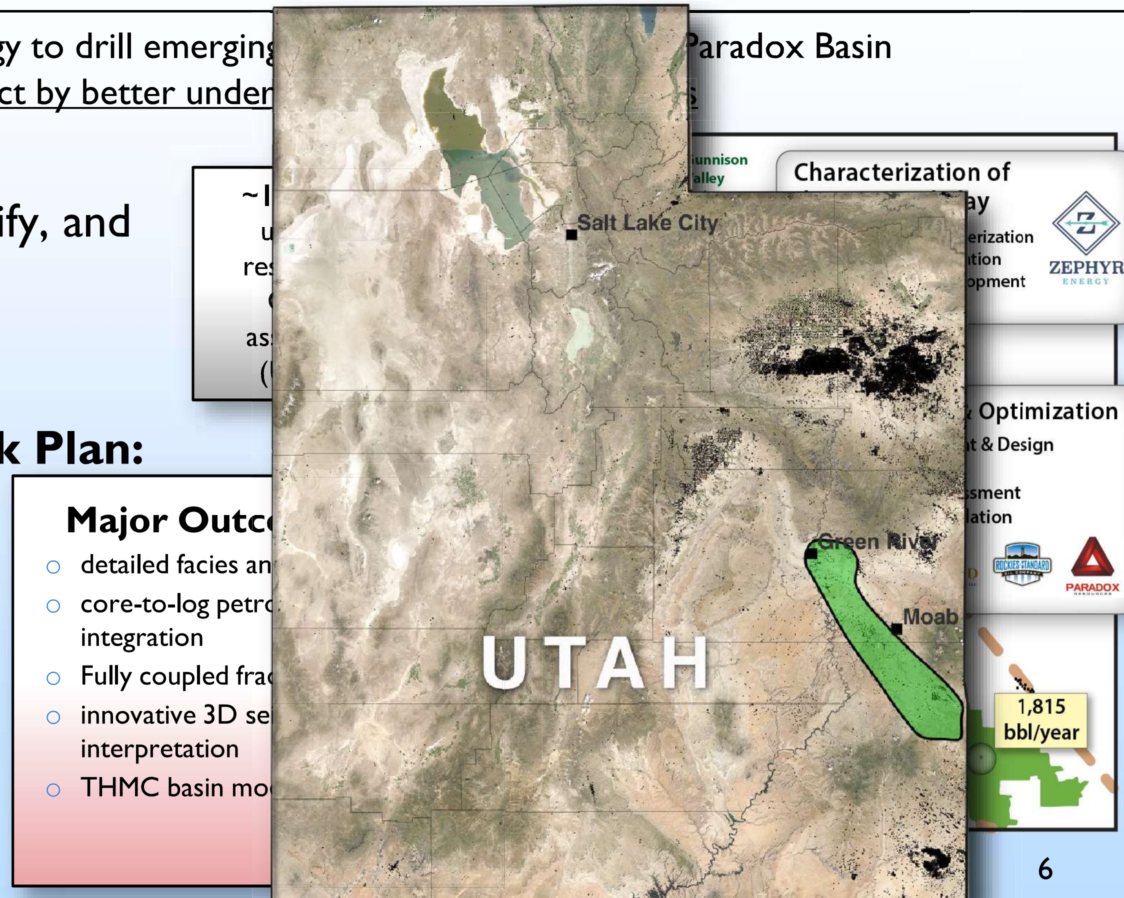
Background & Objectives

- **Objective**: determine / test best strategy to drill emergin… Paradox Basin Play - <u>maximize production, minimize impact by better under</u>…

- **Key Tasks**: characterize, quantify, and interpret <u>natural fractures</u> in the Paradox Play



Experimental Design and Work Plan:

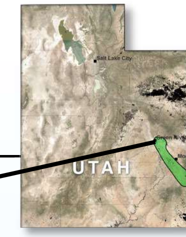
- Fundamental THMC characterization
- Forecast location, extent and mechanisms of <u>natural fractures</u>
- Develop drilling strategy to maximize intersection with natural fractures
- develop a tactical stimulation strategy
- Test the best approach

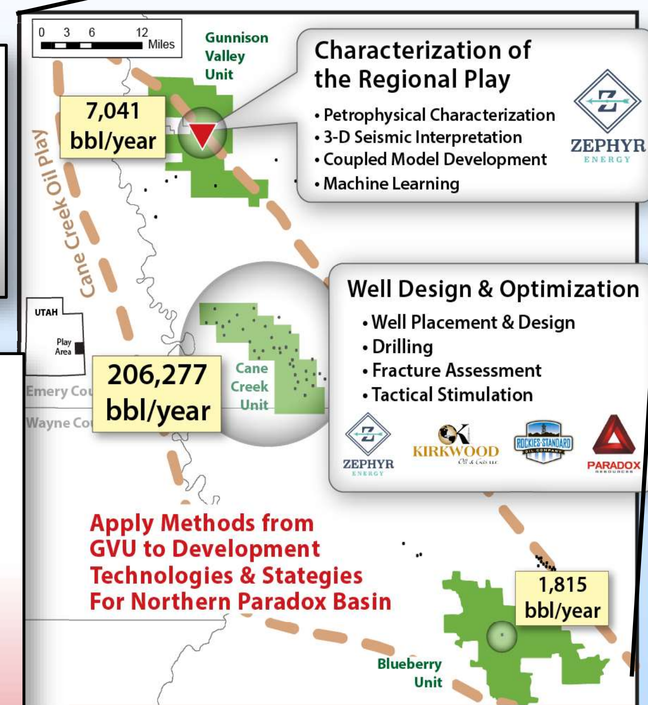
Background & Objectives

- **Objective**: determine / test best strategy to drill emerging unconventional northern Paradox Basin Play - <u>maximize production, minimize impact by better understanding of natural fractures</u>

- **Key Tasks**: characterize, quantify, and interpret <u>natural fractures</u> in the Paradox Play

~1.2 billion BOE undiscovered resources in the Cane Creek assessment unit (USGS, 2012)





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- Fundamental THMC characterization
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- Develop drilling strategy to maximize intersection with natural fractures
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- Test the best approach

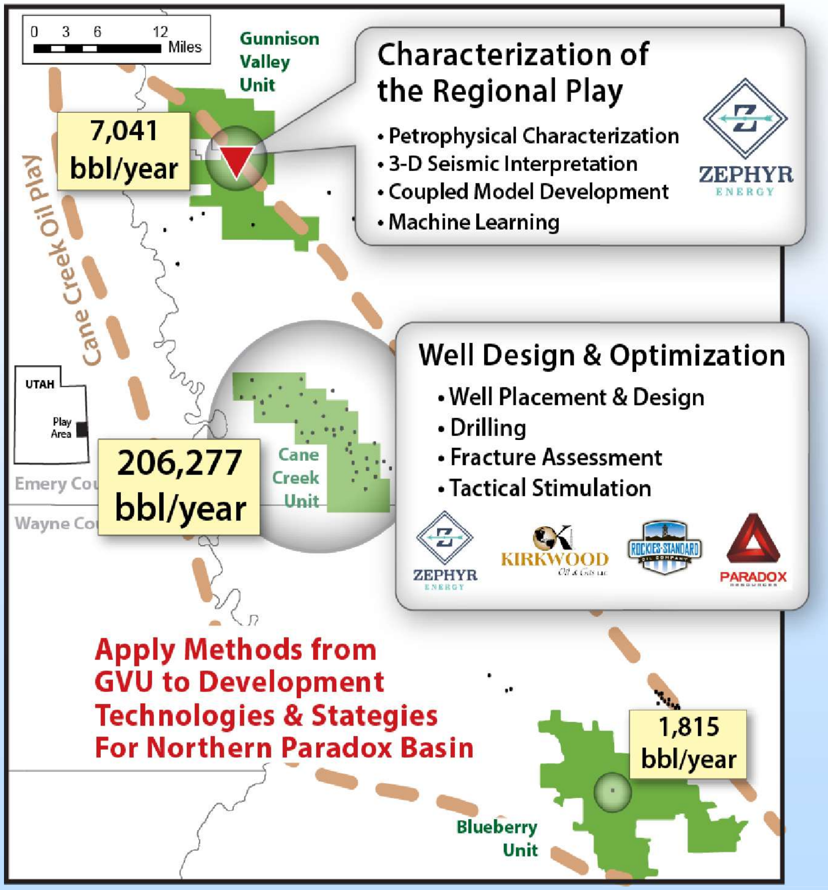
Major Outcomes:

- detailed facies analysis of core
- core-to-log petrophysical integration
- Fully coupled fracture model
- innovative 3D seismic interpretation
- THMC basin model for forecasting

Background & Objectives

Experimental Design and Work Plan

1. Characterize fundamental geology, hydrology, and geomechanics
2. Forecast location, extent and mechanisms of natural fractures throughout the play (all years);
3. Develop drilling strategy to maximize intersection with (dominant) natural fractures (this year and next)
4. Use high-resolution characterization data to develop a tactical stimulation strategy (this year and next)
5. Test the best approach
   (with the operator, determine whether (3) new drilling design or (4) the new tactical stimulation design will be more effective, and test in the field in new well(s) with strategic drilling and tactical stimulation (years 3 and 4).



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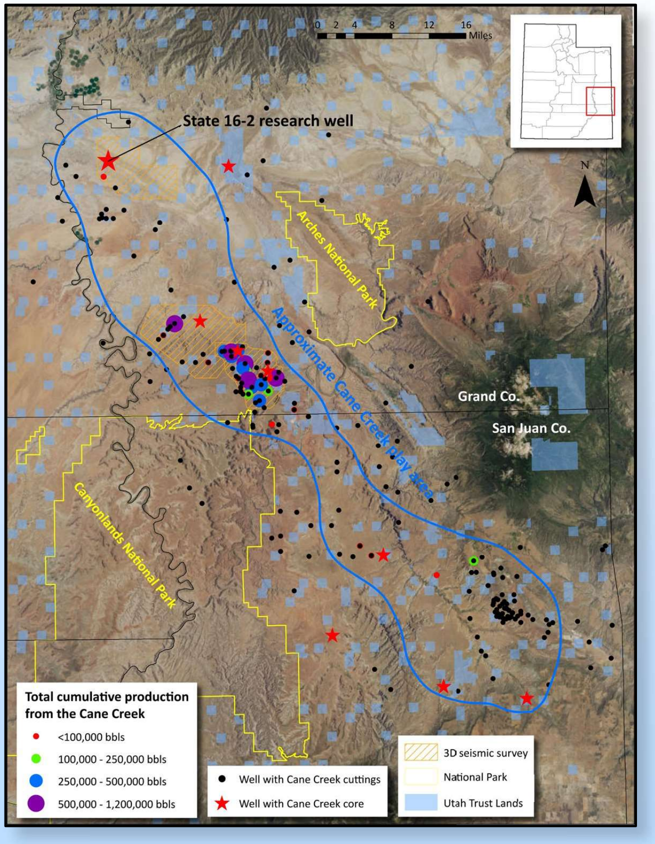
The Field Laboratory

- **Zephyr State 16-2 and State 16-2-LN-CC, White Sands Unit, Utah**
  - **Vertical: December 2020 to January 2021**
  - **Horizontal: July 2021**



Data Collection from Field Lab

- **Data Collected - State 16-2 well**
  - Core – 110 ft
    - 9638’ to 9728’ – Cane Creek
    - 9728’ to 9748’ – Salt 22, Clastic 23 (~8 ft), Salt 23
  - Cuttings
    - Surface to 6465’ – 50 ft sample spacing
    - 6465’ to TD – 10 ft sample spacing in clastic zones
  - Sidewall cores
    - 31 sidewall cores in 11 upper clastic zones
    - Clastic 1, 2, 3, 4, 5, 7, 8, 9, 11, 17, 18/19
  - Geophysical logs
    - Vertical: Triple combo, sonic, lithoscanner†
    - Horizontal: Triple combo, sonic, FMI

† No Cane Creek logs (stuck core barrel)

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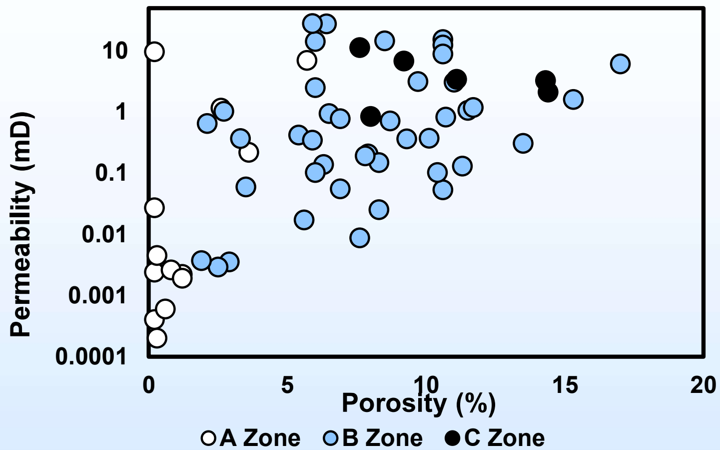
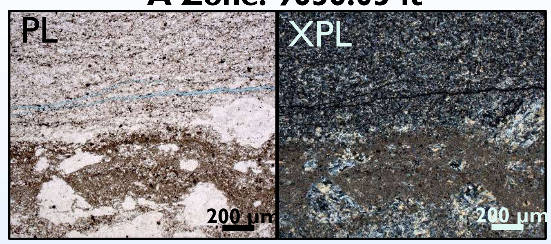
Reservoir Quality & Characterization

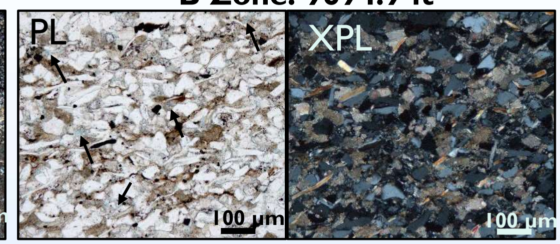


A Zone: 9656.05 ft

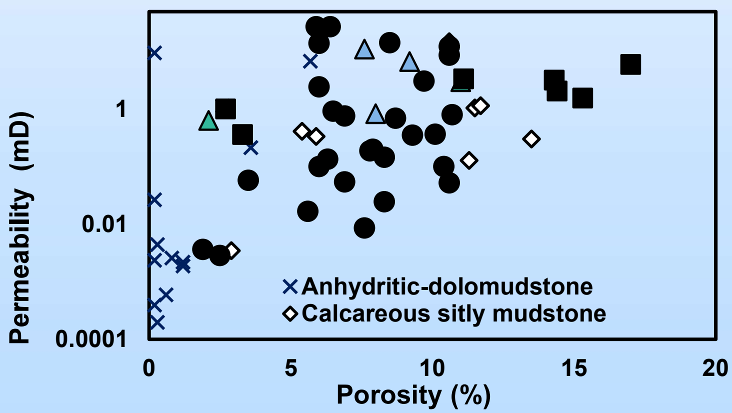


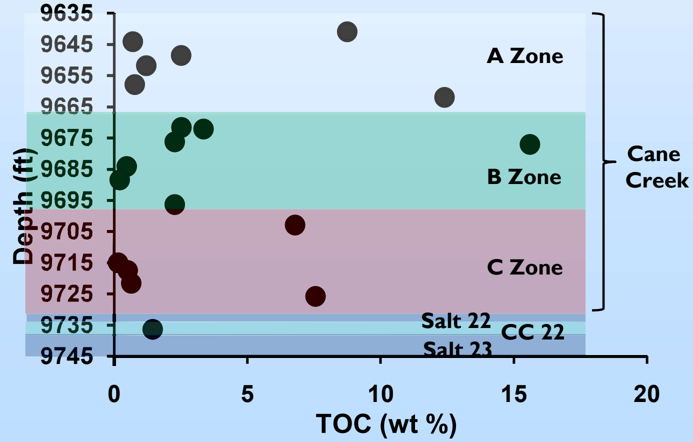
Nodular anhydritic-dolomudstone with 0.217 mD and 3.6 porosity; fracture porosity.

B Zone: 9694.9 ft

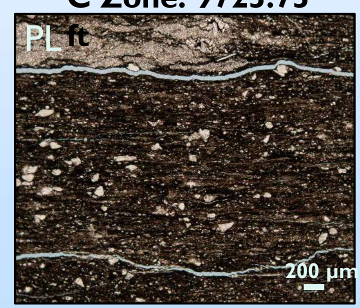


Sandstone/siltstone with 0.359 mD and 9.3 porosity; intergranular and micro porosity observed (arrows); calcite cement





C Zone: 9725.75

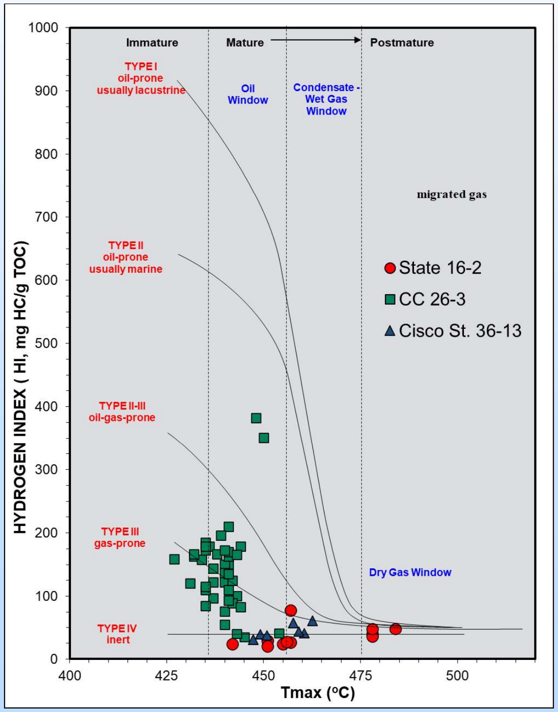


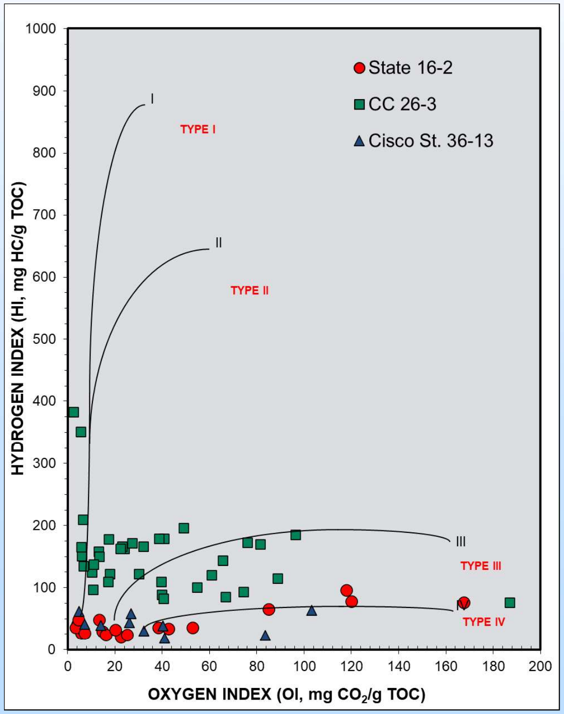
Algal laminated calcareous silty organic-rich mudstone; parting fractures (blue) with 3.26 mD and 14.3 fracture porosity and TOC of 7.56 wt %

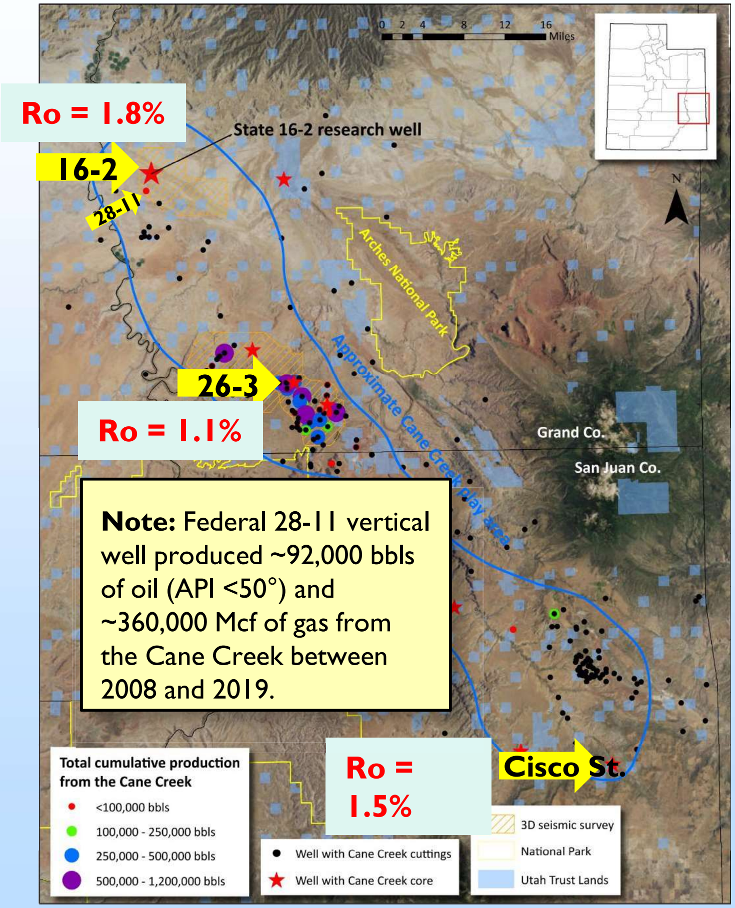
Source Rock Analysis

SRA for State 16-2 Cane Creek:

- TOC up to 15% (average in shales = ~4%)
- HI is low (average of 35), plots within Type IV/oxidized inert [hydrogen index]
- S2 is low (average = 1.3) [kerogen yield]
- Ro from VR = 1.8%
- Tmax averages 465 (ranges from 451-484)



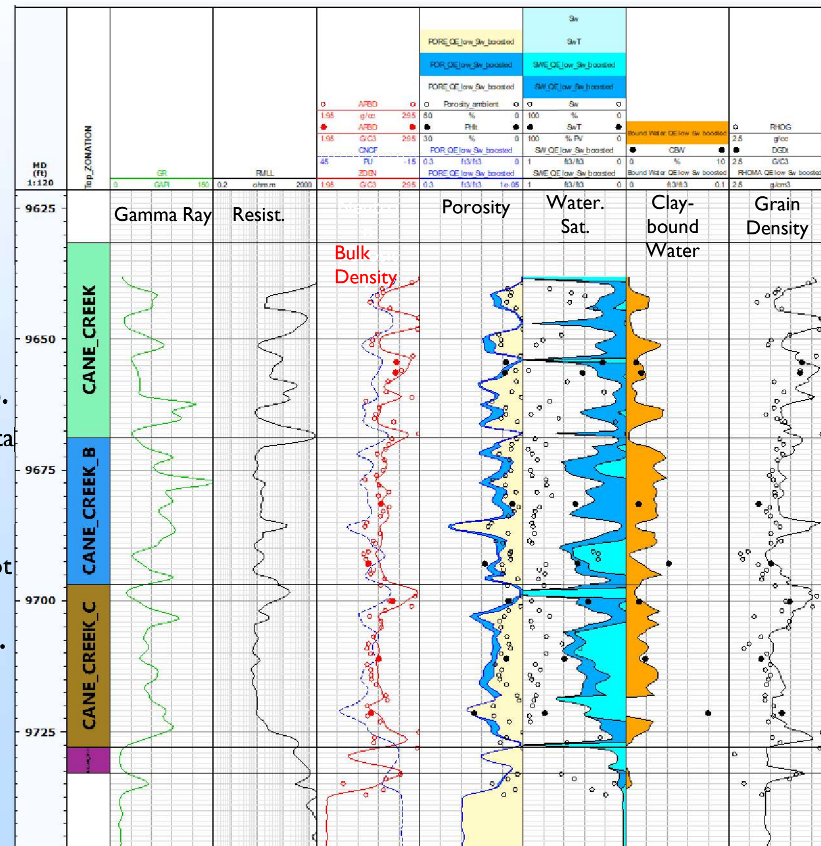




Water Saturations

Water Saturations inconsistent from core-scale to log-scale to field-scale

- **Water saturation values from original core analyses were anomalously high.**
  - Could not be matched by petrophysical model without mismatching porosity and using unreasonable model parameters in saturation model.
  - Cannot be justified by well production.
- Re-tested using different lab and different analytical technique
  - Tested 3 wax-preserved samples and 4 unpreserved samples (~1.5 yrs old) from Cane Creek whole core.
  - Original data came from "routine" core analysis on whole plugs; re-tested using both GRI/Retort analysis + "Routine" analysis on splits of crushed material.
- **Results show GRI/retort data much more in-line with expectations (solid points).**
- "Routine" split samples (not plotted) in-line with GRI/retort data, not original "Routine" data
  - Suggests original lab data are unreliable – esp. S_w significantly higher than expected.
  - New data provide useable calibration data for petrophysical model.
  - Preserved and unpreserved samples show general agreement, suggesting the core has not appreciable desiccated since collection.
- **Currently running Thermovravimatric Analyses (TGA) on splits of new samples.**
  - Similar measurement to GRI/retort.
  - Runs on much smaller samples (10s of mg instead of 10s of g).
  - Potential to run TGA on cuttings from upcoming well(s).



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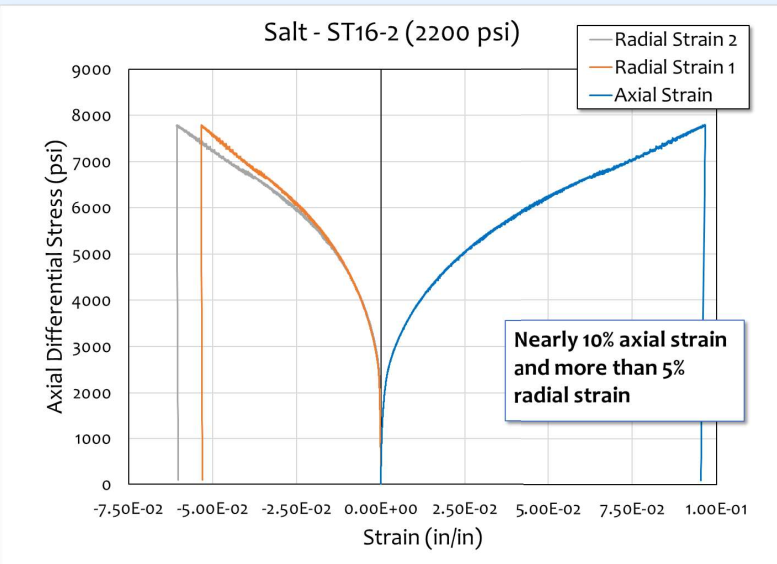
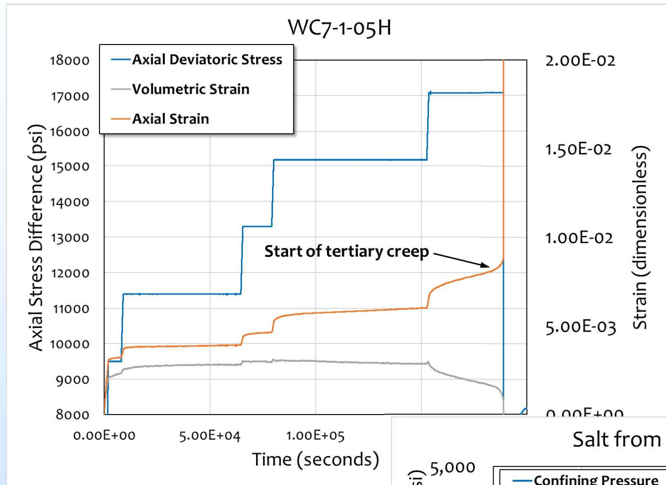
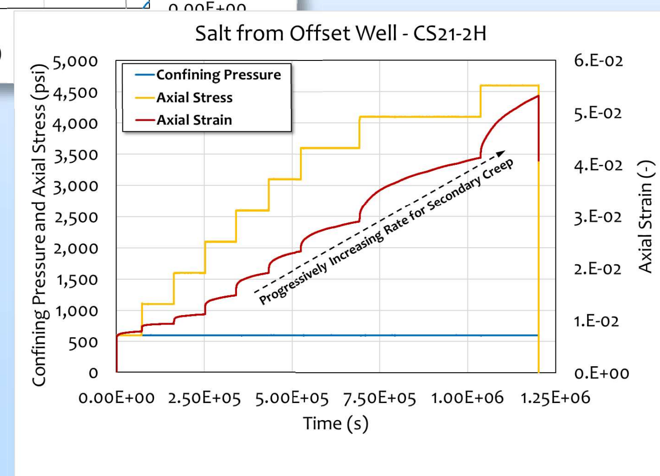
Rock Mechanics

Triaxial Mechanical Properties of Clastics and Salts

- Comprehensive suite of mechanical properties
- Data for all ten preserved core sections (clastics) and for salt
- Triaxial compression, Brazilian tensile strength, fracture toughness, creep







Rock Mechanics

Triaxial Mechanical Properties of Clastics (plug size)

Figure 2. Triaxial test results for Cane Creek clastics.

1st row: 1.5" diameter samples.

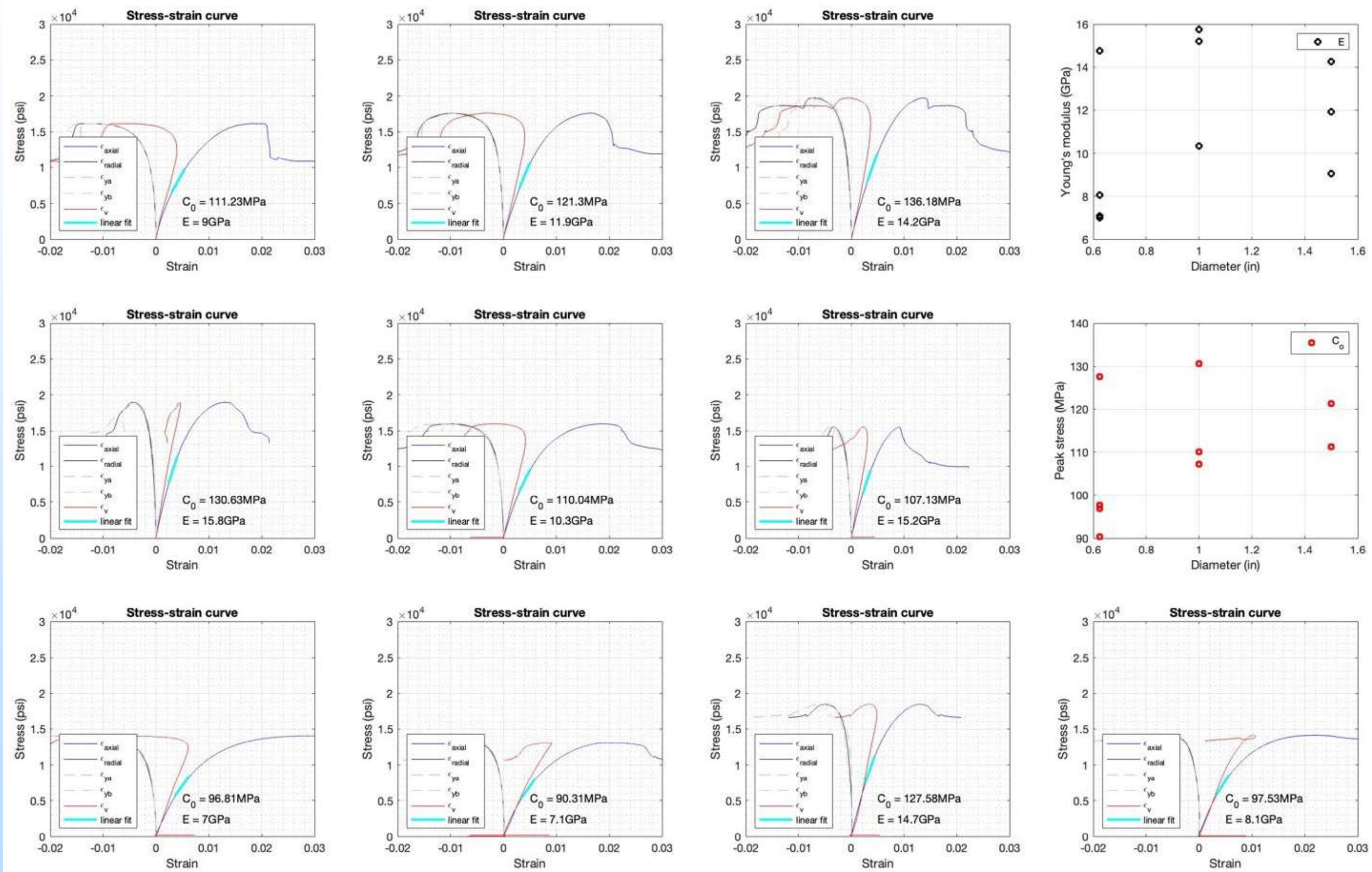
2nd row: 1" diameter samples.

3rd row: 0.625" diameter samples.

1.5" diam.

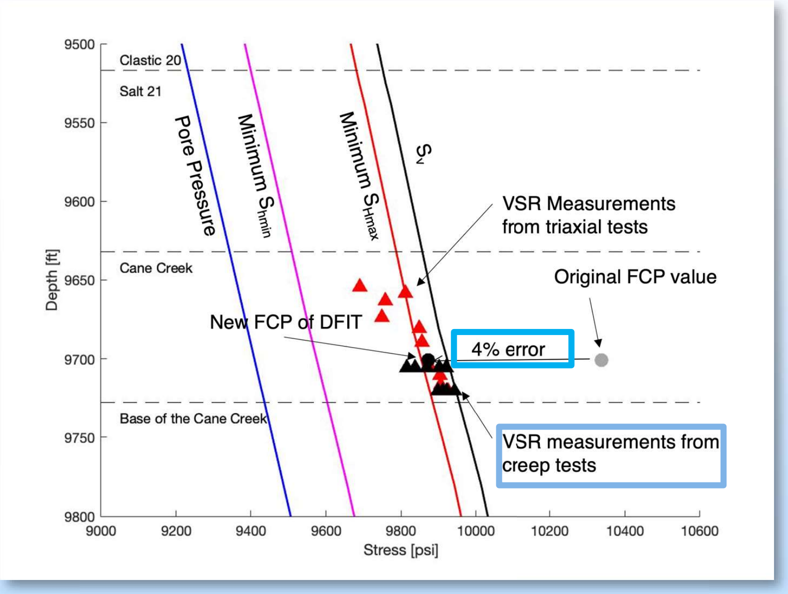
1.0" diam.

0.625" diam.



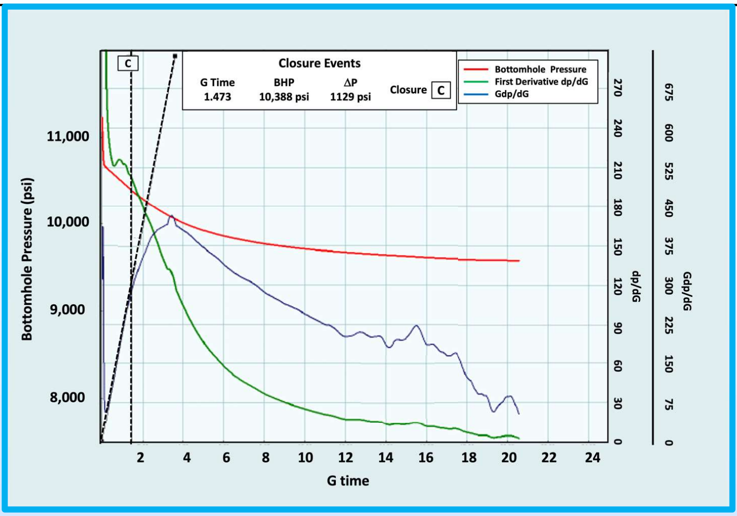
State of Stress (LHPS)

- Geomechanical tests inform the state of stress using viscoelastic stress relaxation theory

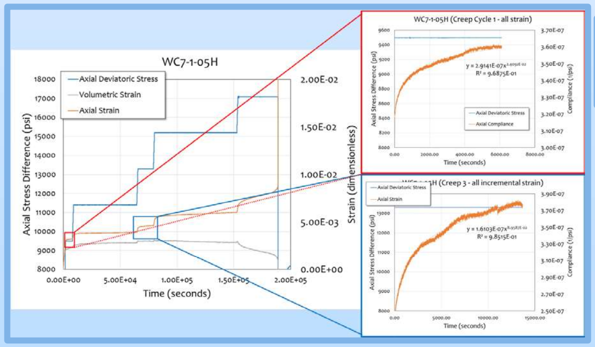


Two types of geomechanical tests are used:

1. Triaxial measurements for Young's modulus
2. Creep tests of *B* and *n*



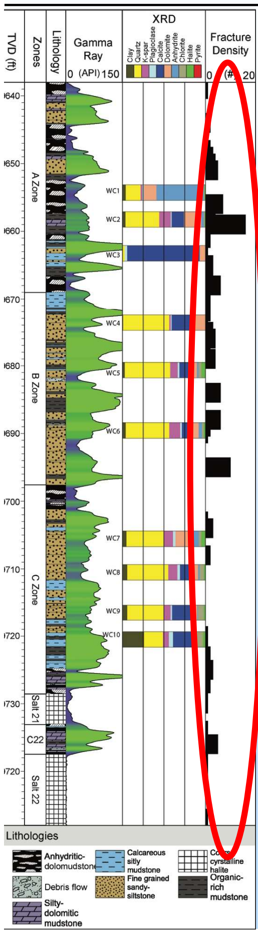
There may be an error in the Fracture Closure Pressure from the DFIT



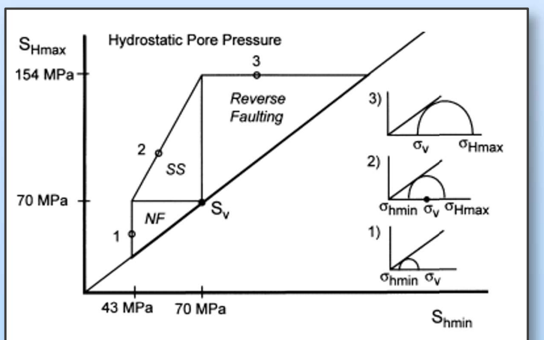
Creep results are dependent on axial stress

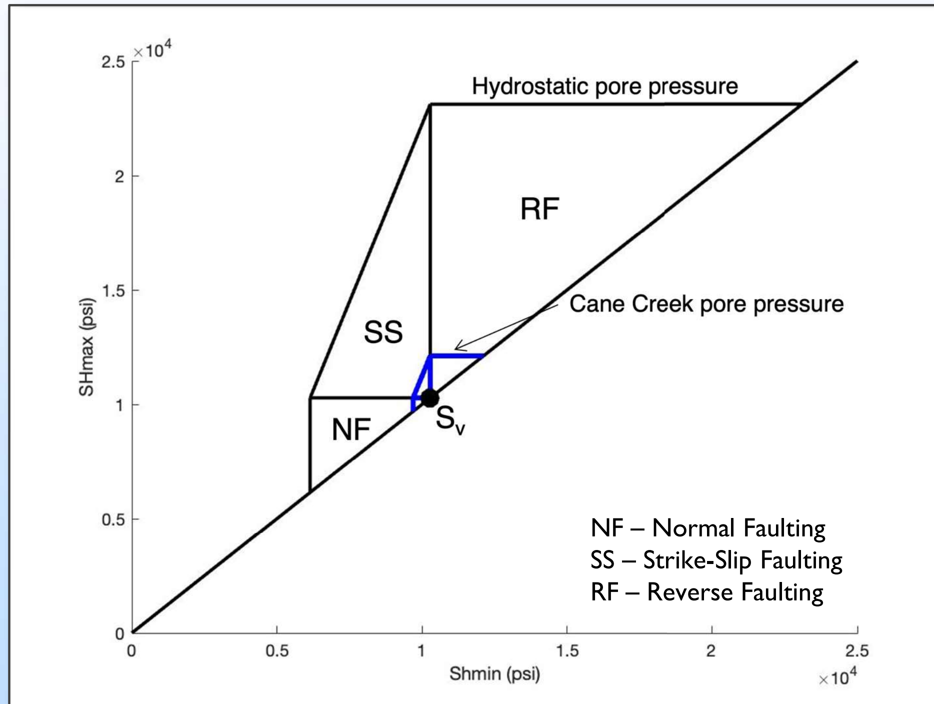
McCormack et al. (2023)

State of Stress



- Results indicate that the state of stress is nearly isotropic and lithostatic
  - Least horizontal principal stress is lower in the A and B zones where there are more fractures
  - The elevated pore pressure reduces the possible stress states, leading toward isotropy
  - The interbedded halite may also contribute to a more relaxed stress state

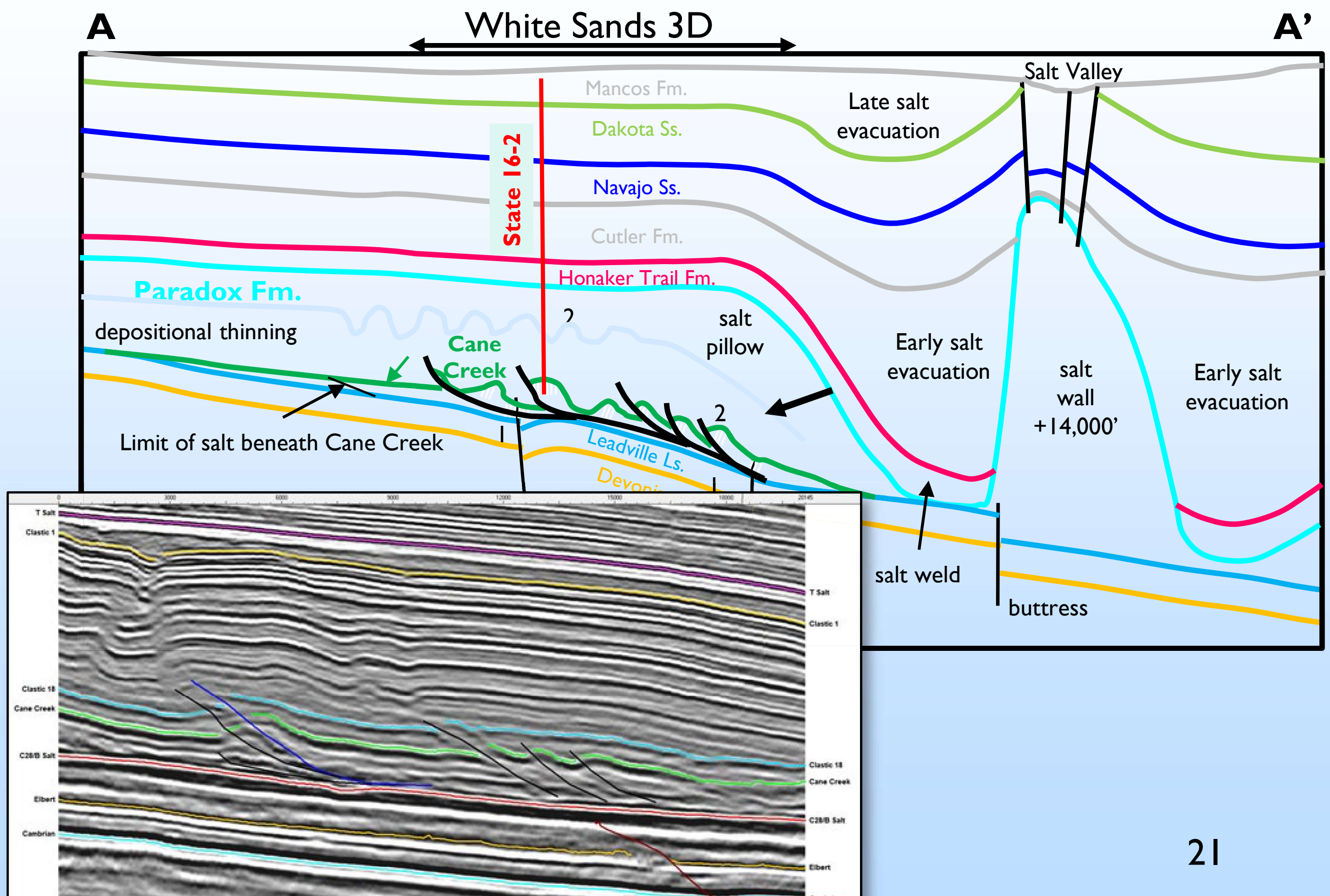




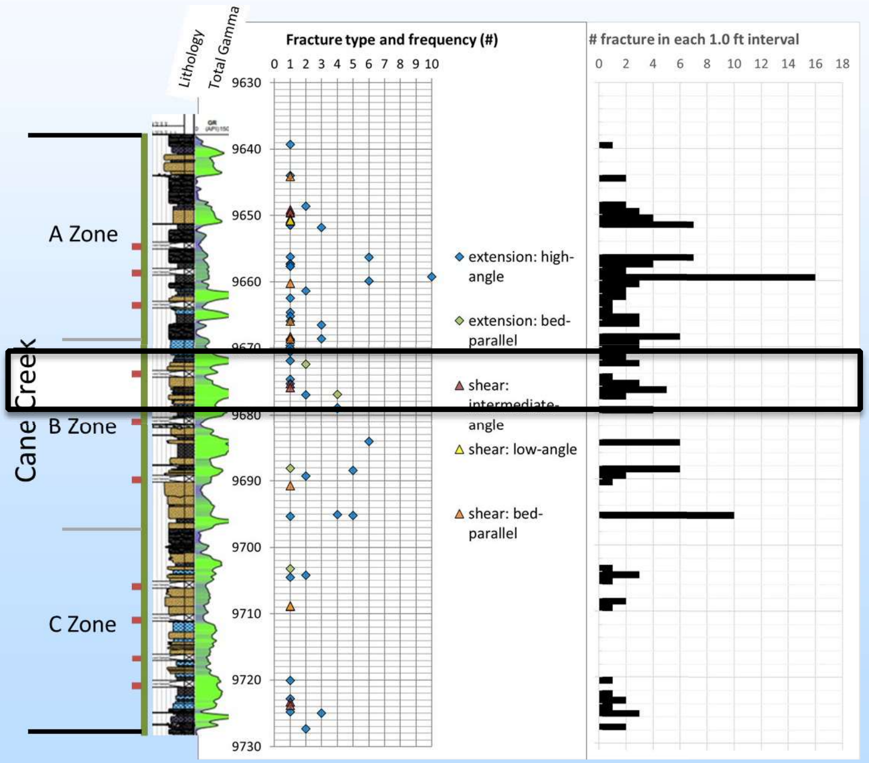
Natural Fractures

Natural fractures

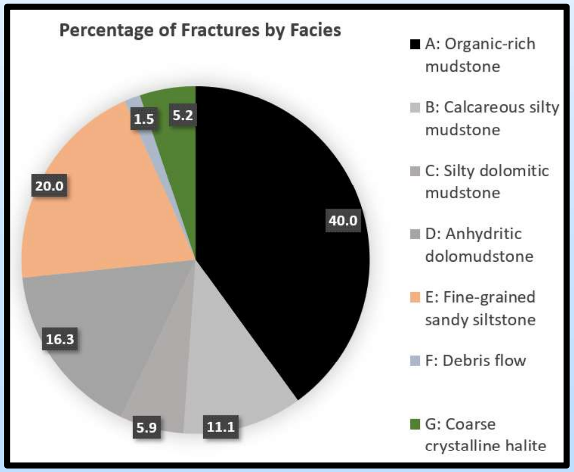
- Structural cross section showing the main structural elements and prospective areas for commercial hydrocarbon accumulations.
- Open natural fractures in the Paradox clastics are a primary target.
- The best wells are associated with open fractures found along
  1. **reactivated basement faults**
  2. **Curvature associated with salt tectonics**
- Loading of the basin resulted in the mobilization and shortening of thick salt beds and diapiric anticlines
- Folding and faulting of the clastics is caused by late salt deformation



Natural Fractures



- ***Organic-rich mudstone has the most fractures***
- ***Variety of open vs cemented***
- ***Halite, anhydrite, and calcite cement fill and lining***
- ***Apertures range from 0 to 1 mm***
- ***Effective fracture volume ranges from 0 to 7,000 mm^3***
- ***Micro-macro scale faulting***
- ***Local scale fracture network will accompany regional scale fracture analysis and modeling; generally trend NW-SE***



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Petrophysics + Machine Learning

The team is developing a Machine Learning model enabling spatial propagation of high-tier logs (e.g., Lithoscanner) **across the basin**, **by training lower-tier logs** (e.g., triple combo only) to high-tier logs from the State 16-2 and CC 7-1 wells

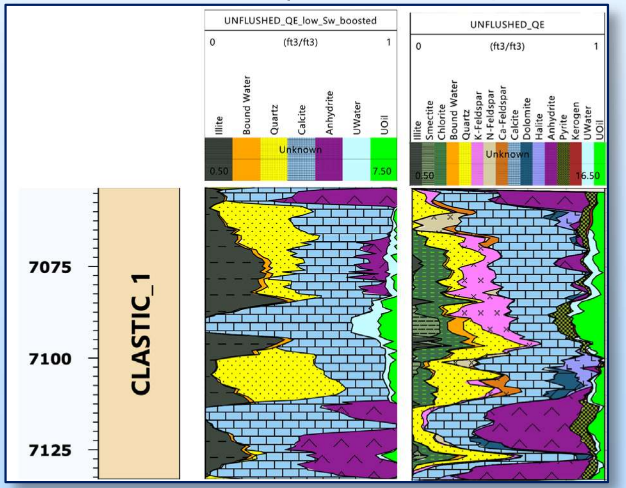
- Supplement legacy logs with pseudo lithoscanner data based on ML model
- Increase well control of sonic data using pseudo sonic data from ML models

Goal:

- Improve petrophysical model – increased number of inputs greatly improves petrophysical inversion
- Better estimates of porosity and saturations
- Improve electrofacies models
- Provides properties/facies for basin model
- Provide additional data for geomechanical model (increased well control)

Petrophysical Model - TCOM only inputs

Petrophysical Model - TCOM + Lithoscanner inputs



Petrophysics

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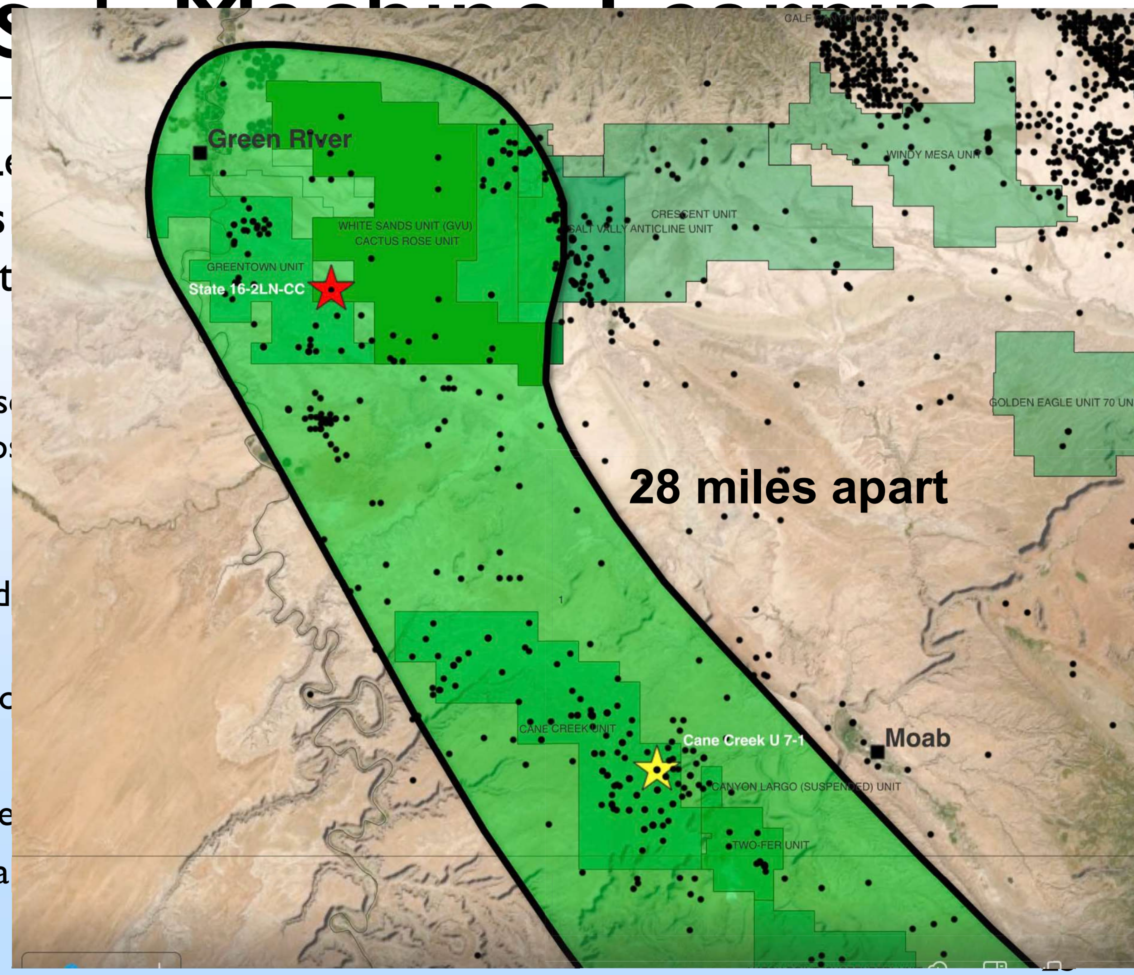

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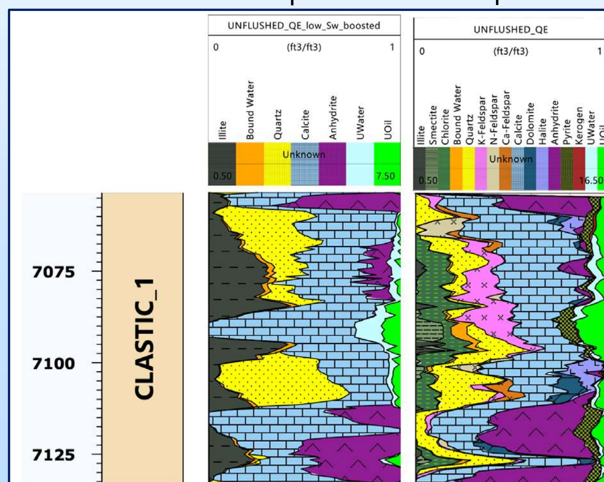


Petrophysics + Machine Learning

Machine Learning (ML) model…

…for propagating sonics

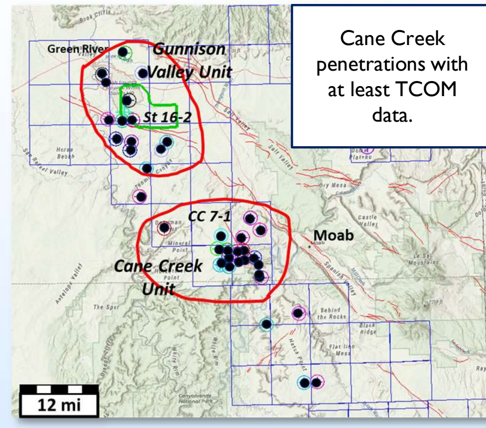
- Trained in State 16-2 clastics, validated in shifted State 16-42 Cane Creek section
- <u>Input</u>: Triple combo + Platform Express data. <u>Output</u>: P-, S-wave sonic travel times

…for propagating elemental abundances

- Trained across State 16-2 and Cane Creek 7-1 high-tier data
- Validated in randomized held-out sections of State 16-2, Cane Creek 7-1
- Provide element-by element performance of ML model

Assessment of ML-informed petrophysical model

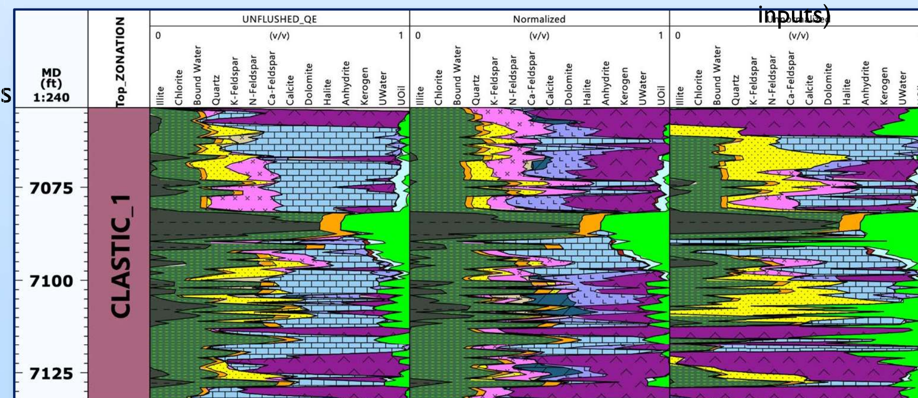
- Created pseudo-Lithoscanner logs from Triple combo logs in State 16-2 well to validate against recorded logs.
- Ran identical petrophysical model on recorded logs (Triple combo+Lithoscanner) and pseudo-logs (recorded Triple combo+pseudo-Listhoscanner) for comparison.
- Quantifying uncertainty of petrophysical model given uncertainty of inputs



Recorded logs

ML model (normalized inputs)

ML model (unnormalized inputs)



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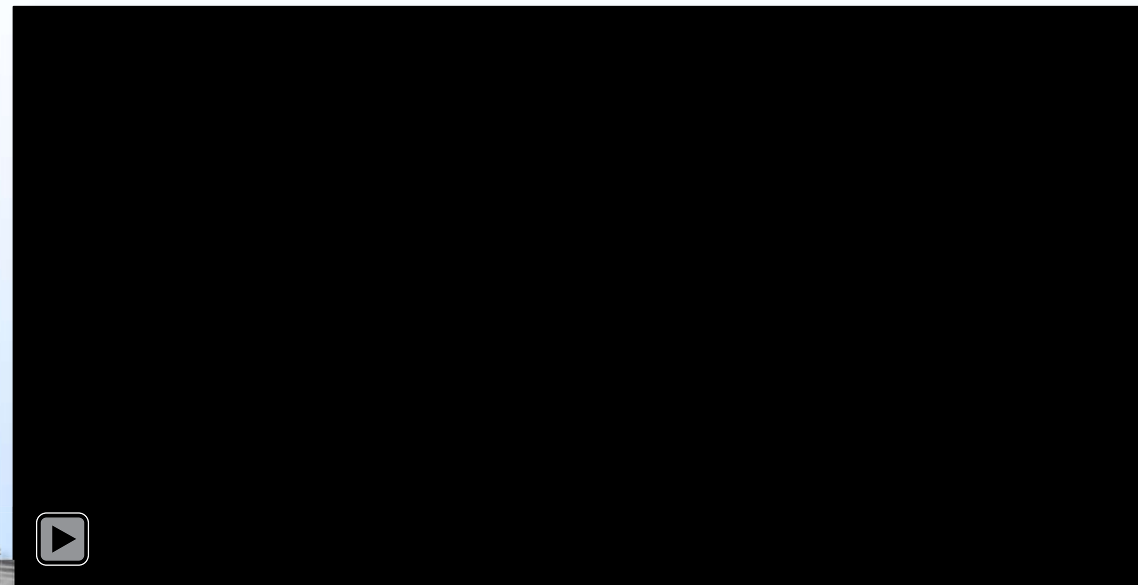
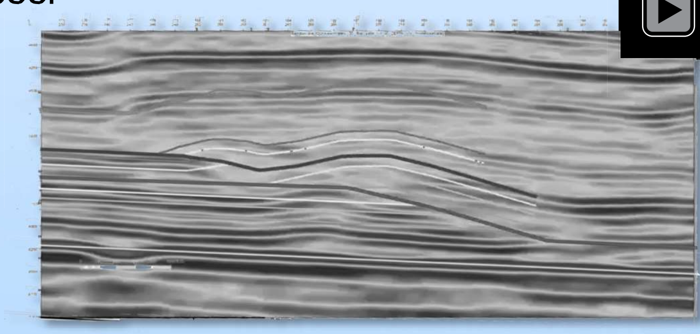
Seismic Interpretation

3D Seismic Survey Interpretation

- Delineated seismic surfaces for the White Sands Unit (WSU)
- Identified sections of structural restoration lines that characterize the lower Paradox Formation deformation
- Forward modeled Cane Creek and all indexed horizons to provide a realistic, kinematically viable interpretation of fault geometries, especially where seismic image quality is poor





Images Reversed

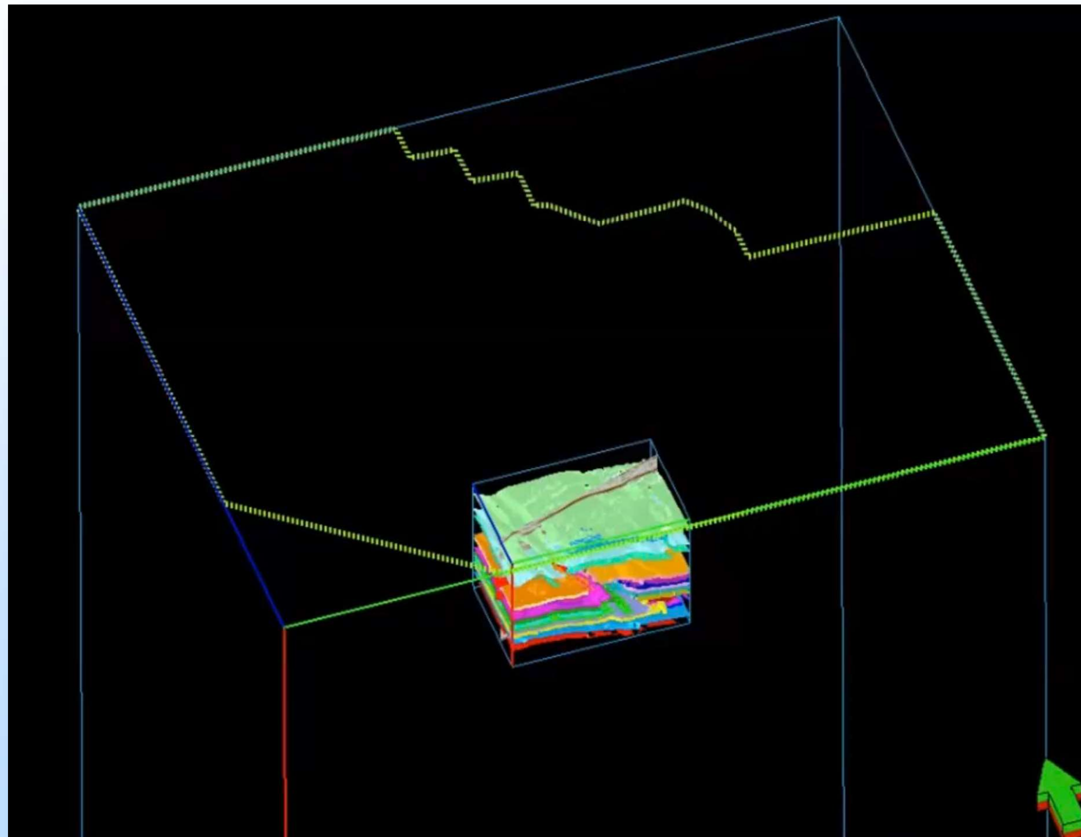
Seismic Interpretation

3D Seismic Survey Interpretation

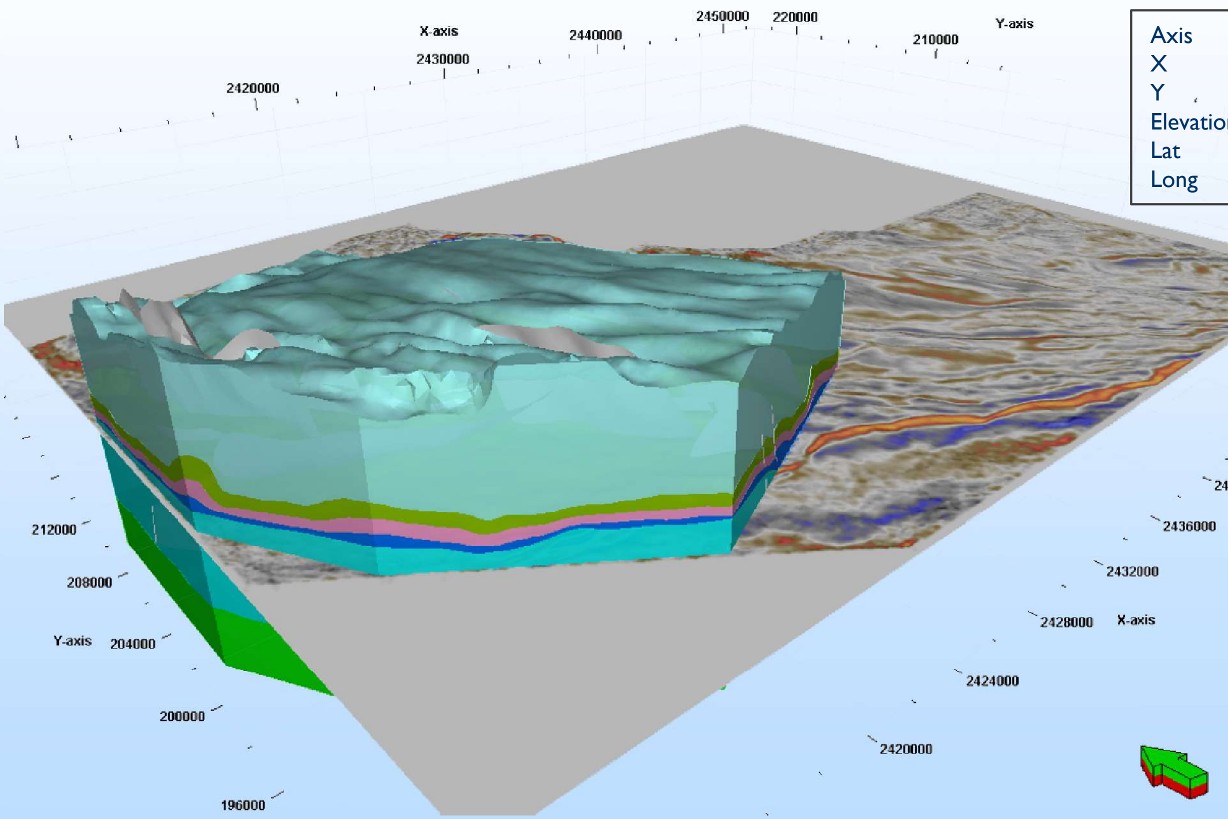
• Team modeled lower Paradox faulting vs upper Paradox folding and the mechanisms that constraint the different deformations style.
• Deformation is primarily controlled by the thickness of the mechanically weak salt:

- **The thinner salt interbeds in the lower Paradox fault**

- **The thicker salt beds in the upper Paradox fold.**



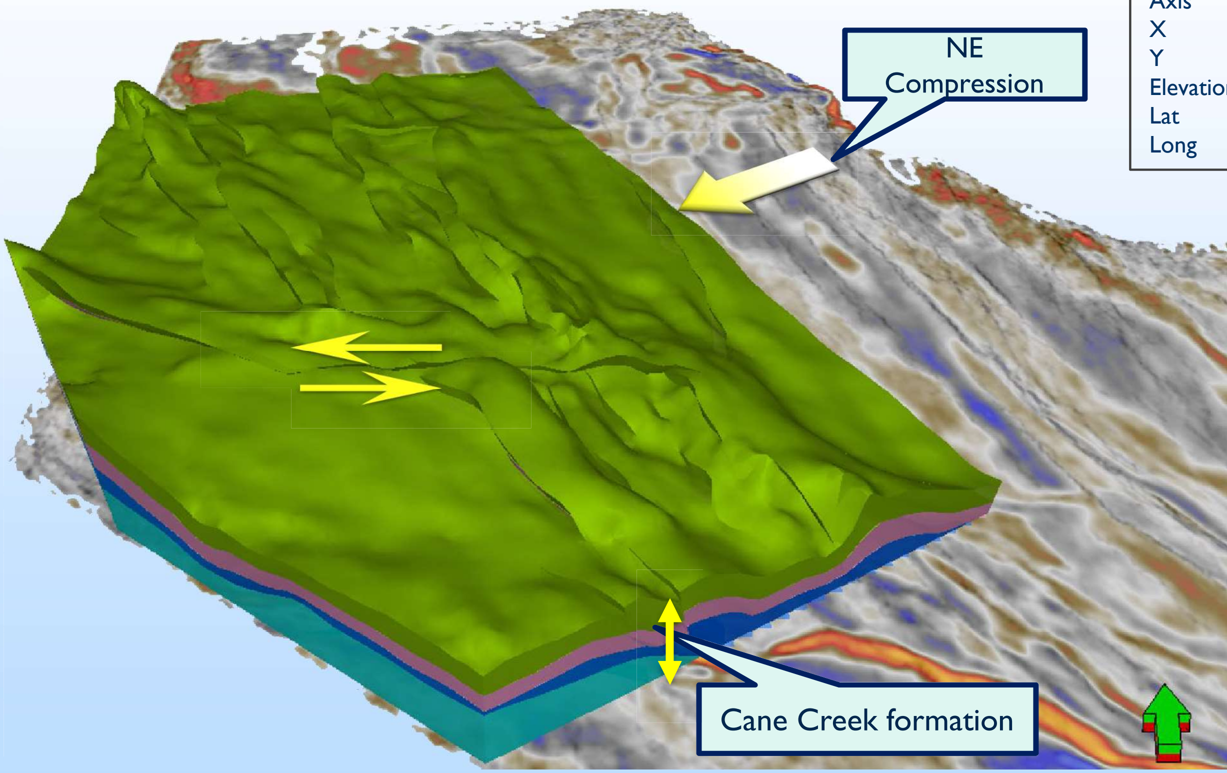
3D Structural Framework Development



Axis	Min	Max	Delta
X	2407800.00	2429000.00	21200.00
Y	191400.00	215000.00	23600.00
Elevation depth [ft]	-7916.47	-2850.41	5066.06
Lat	~38.84889433	~38.91463764	~0.06574331
Long	~-110.06819094	~-109.99237373	~0.07581721

Grid cells (nI x nJ x nK)	106 x 118 x 472
Grid nodes (nI x nJ x nK)	107 x 119 x 473
Total number of grid cells:	5903776
Total number of grid nodes:	6022709
Total number of Simbox cells:	3744368
Number of geological horizons:	305
Number of geological layers:	304
Total number of 2D cells:	12508
Total number of 2D nodes:	12733
Total \defined 2D nodes:	7941
Average Xinc:	200.00000000
Average Yinc:	200.00000000
Average Zinc (along pillar)	13.90196877
Rotation angle:	0.00000000

3D Structural Framework Development



Axis	Min	Max	Delta
X	2407800.00	2429000.00	21200.00
Y	191400.00	215000.00	23600.00
Elevation depth [ft]	-7916.47	-2850.41	5066.06
Lat	~38.84889433	~38.91463764	~0.06574331
Long	~-110.06819094	~-109.99237373	~0.07581721

Grid cells (nI x nJ x nK)	106 x 118 x 472
Grid nodes (nI x nJ x nK)	107 x 119 x 473
Total number of grid cells:	5903776
Total number of grid nodes:	6022709
Total number of Simbox cells:	3744368
Number of geological horizons:	305
Number of geological layers:	304
Total number of 2D cells:	12508
Total number of 2D nodes:	12733
Total \defined 2D nodes:	7941
Average Xinc:	200.00000000
Average Yinc:	200.00000000
Average Zinc (along pillar)	13.90196877
Rotation angle:	0.00000000

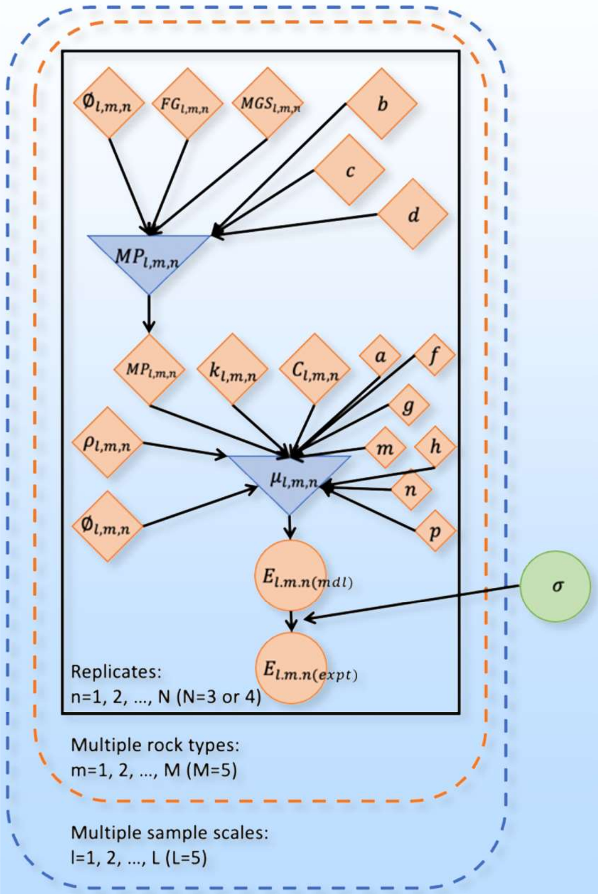
Presentation Outline

- Improving Production in the Emerging Paradox Oil Play
  - Background & Objectives
  - Accomplishments to Date
    - Core analyses
    - Fracture Analysis
    - Petrophysics & Machine Learning
    - Model development
    - Uncertainty Quantification
  - Lessons Learned
  - Synergy Opportunities
  - Summary

Uncertainty Quantification

Uncertainty Quantification - develop a Bayesian learning approach to quantify (1) DATA UNCERTAINTY and (2) MODEL UNCERTAINTY

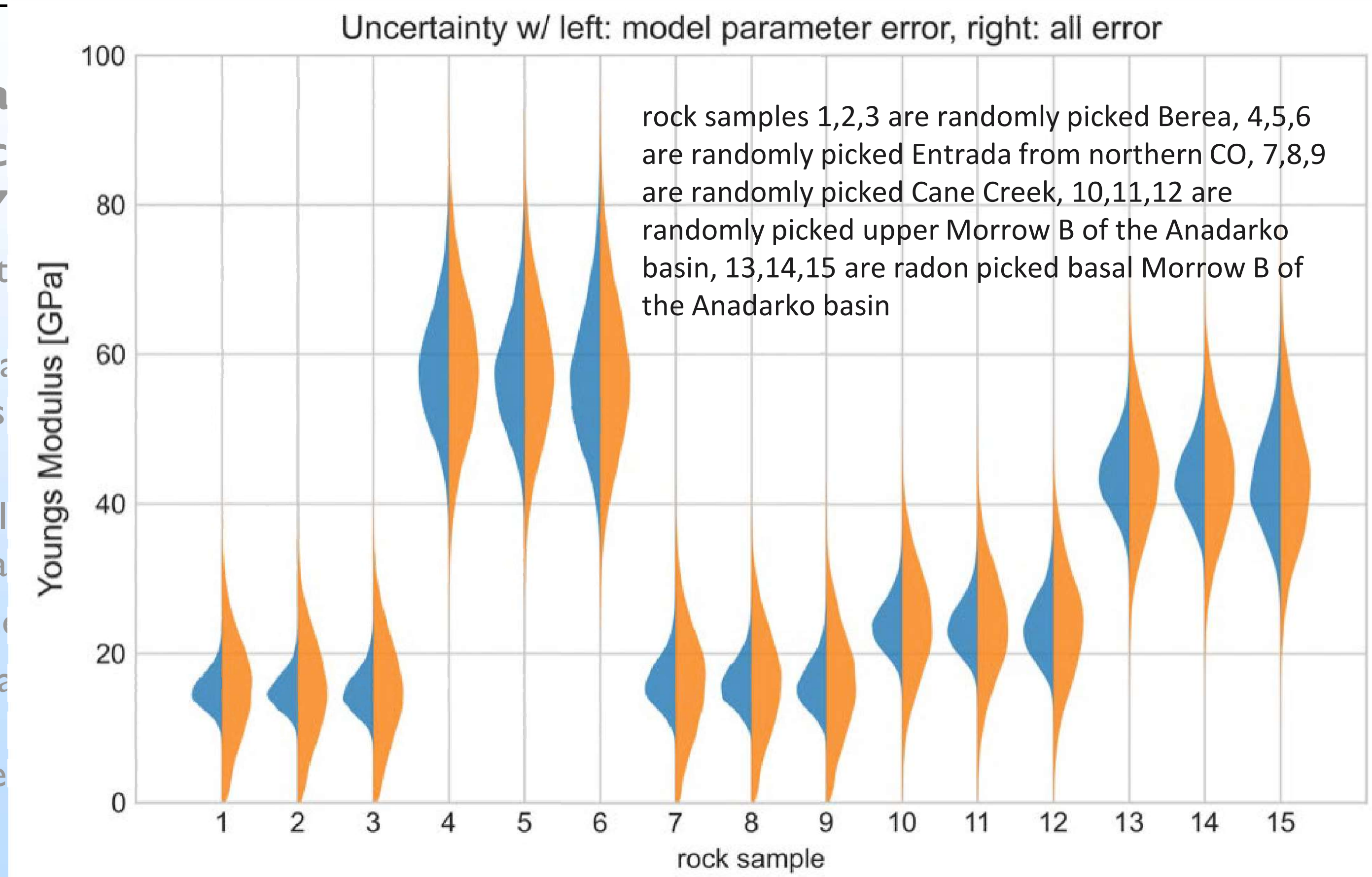
- Addresses variability in the petrophysical data:
  - Legacy Data
  - Environmental Corrections
  - Data processing by logging companies or operators
- Outputs:
  - Petrophysical data normalization
  - Quantified variation for P10, P50, P90 estimations
- Geomechanics uncertainty quantified initially
  - Controlling factors: sample diameter, porosity, bulk density, clay content, permeability, Mean Grain Size, Gramework Grains/Cement Content



Uncertainty Quantification

Uncertainty Qua
learning approac
UNCERTAINTY

- Addresses variabilit
  - Legacy Data
  - Environmenta
  - Data process
- Outputs:
  - Petrophysical
  - Quantified va
- Geomechanics unce
  - Controlling fa
    clay content,
    Grains/Ceme



Presentation Outline

- Improving Production in the Emerging Paradox Oil Play
  - Background & Objectives
  - Accomplishments to Date (SUMMARY)
    - Core analyses
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Accomplishments to Date

- **Geologic Characterization of Cane Creek and Development of Facies Model**
  - Porosity, Permeability, fluid saturations, source rock work on the Cane Creek core and associated clastic zones
  - Source rock analysis
  - Specialty core analyses (water saturation, MICP, wettability, relative perm) and geomechanics complete
  - Fracture Analysis
- **Petrophysical log analyses/correlations, Models**
  - Machine Learning applications to correlate State 16-42 Paradox Fm logs to those in State 16-2
- **Delineating seismic surfaces for Reservoir Model**
  - A test volume of the preliminary structural interpretation was prepared as a "water-tight" framework model; work continues to incorporate the structural interpretations into the large model domain.

Future Testing, Development and Commercialization

- Hypothetical horizontal well scale-up plan for area covered with 3D seismic
- Opportunities for expansion to other areas within the Paradox Basin & with other operators/partners
- Opportunity for numerous horizontal wells in one small area targeting the natural fracture play, with countless opportunities beyond 3D area
- Utilization of advanced stimulation monitoring technologies including Distributed Acoustic Sensors (DAS) in horizontal well
- Further targets if commercial results can be achieved by hydraulic stimulation
- Multiple stacked pay opportunities beyond the primary Cane Creek reservoir

Presentation Outline

- Improving Production in the Emerging Paradox Oil Play
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Synergy Opportunities

- Oil & Gas Program
  - Seismic monitoring using fiber optics
  - Machine Learning – Full-waveform inversion in seismic imaging
  - LANL – pressure control & fracture management
- Other NETL-funded Partner Initiatives
  - CarbonSAFE San Juan Basin – investigations into induced seismicity using mechanical Earth Models
  - CUSP and SWP – knowledge base & detailed analyses on geomechanics in the region
  - DE-FOA-0002401 - detection and characterization of faults and quantification of fluid migration through the caprock layer
  - Hydrogen storage initiatives – utilization of findings on state of stress, geomechanics, and interplay of clastic and salt layers

Presentation Outline

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Project Summary

- **Project**:
  - \$11,000,000 project over 4 years (\$8M Federal, \$3M cost-share by local operators)
  - Project drilled and characterized data from a 9,748 ft stratigraphic well (110 ft of core, cuttings, sidewall core, geophysical logs)
  - Multiple operators in/around Paradox Basin to benefit from optimized drilling strategies and reduced environmental impacts
  - Coordination with educational institutions and company-led training to transfer tech skills for development of play

THE UNIVERSITY OF UTAH

ZEPHYR ENERGY

UTAH DNR UTAH GEOLOGICAL SURVEY

THE UNIVERSITY OF ARIZONA

KIRKWOOD Oil & Gas LLC

Statistical Petrophysics LLC

NATIONAL ENERGY TECHNOLOGY LABORATORY

BYU

U.S. DEPARTMENT OF ENERGY

Drilling of project stratigraphic well – Jan 2021,

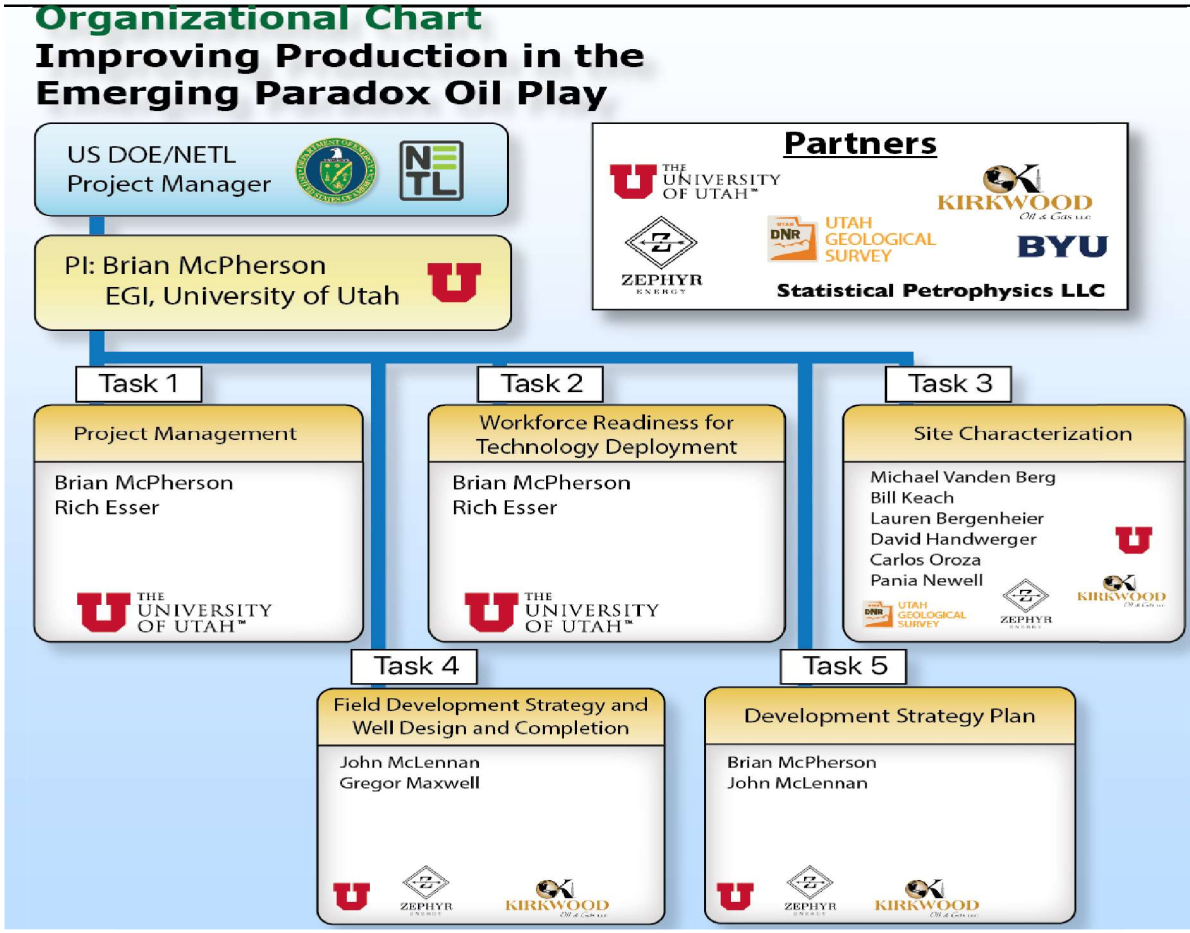
Benefit to the Program

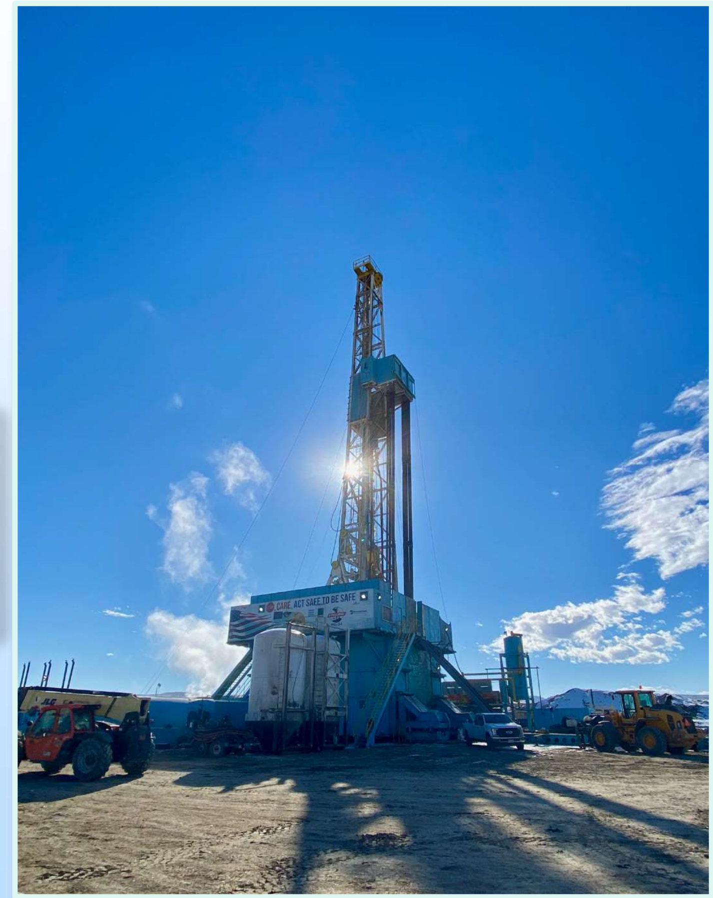
- The primary project objective is to characterize the emerging Cane Creek play and develop technologies and strategies that can accelerate the development the play, including the evaluation of:
  - Economic viability
  - Optimal well completion design
  - Fracture treatment design
  - Field development choices that can lead to maximum ultimate recovery
- Cane Creek Play
  - Natural fractures = key to maximizing production and minimizing environmental impact
  - It will also be evaluated as a resource play (not just a fracture play)
  - Well stimulation will be considered (How do you stimulate wells without fracking into salt?)
  - The project has access to a quality 3D seismic critical to fracture density and orientation and follow up data from the recently drilled State 16-2LN CC lateral well

Project Overview - Goals and Objectives

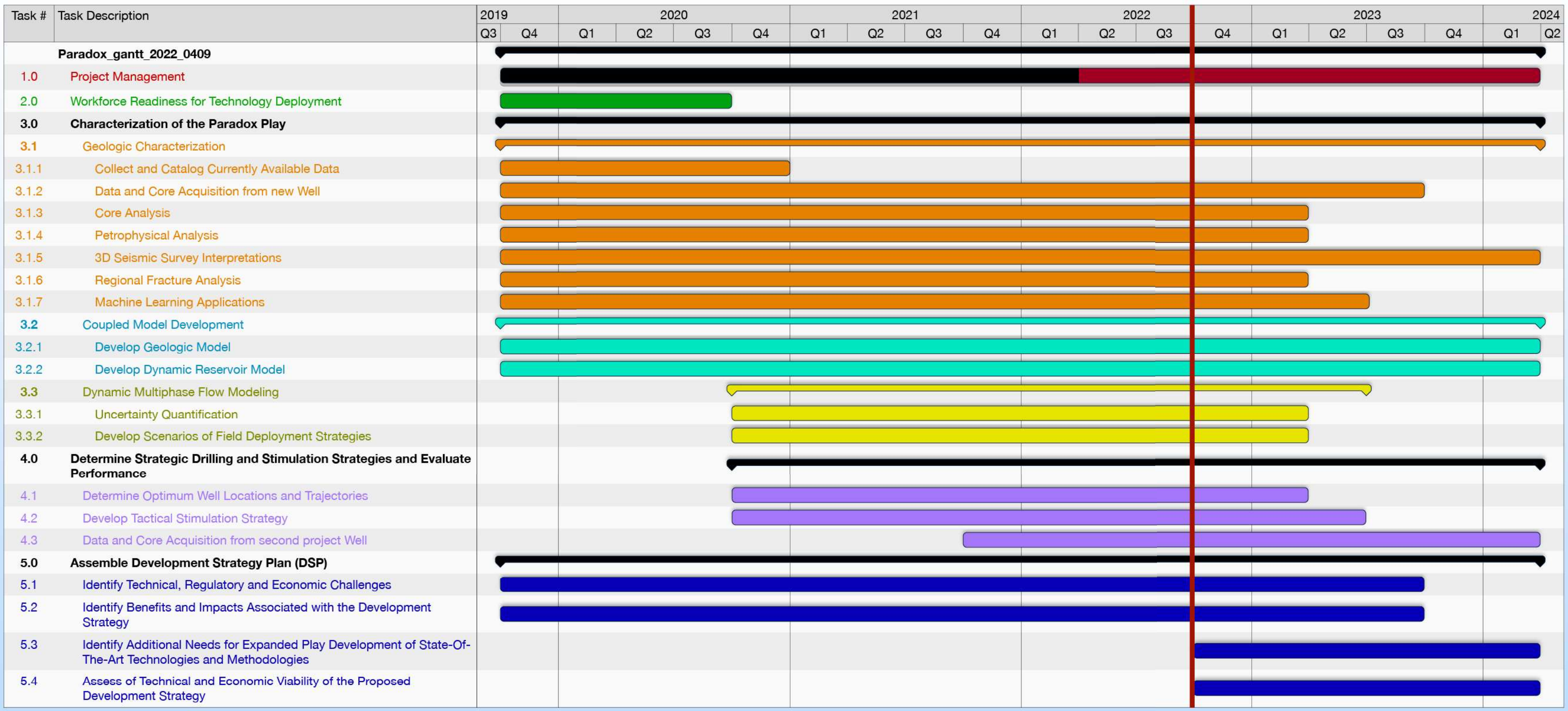
Task/Subtask	Description	Date	Success Criteria
2.0	Workforce Readiness Plan	First continuation application	A detailed plan ready after reviewing the required skill sets and training/certifications (if any), and identifying the appropriate source or personnel for the workforce.
3.1	Geologic Characterization	Q4 2022	A geologically characterized basin model integrating 3D seismic data, well logs, core data, and production histories using machine learning algorithms.
3.2	Coupled Model Development	Q2 2023	A multi-continuum dynamic reservoir model, that combines the geological and discrete fracture network models, ready for simulating multiphase flow in the play.
4.3	Well Drilling	Q1 2023	Cased and cemented horizontal well that yield at least 50 feet of horizontal core to study the fracture network and its changes throughout the basin.
4.3	Well Characterization	Q2 2023	Fracture characterization and assessment of productive potential, reservoir properties, and stimulation treatment effectiveness.
5	Development Strategy Plan	Q1 2024	Develop a plan to effectively assess the technical and economic viability of further development of emerging UOG plays in the area and others across the US.

Organization Chart





Gantt Chart



Task #
Task Description
2019
2020
2021
2022
2023
2024
Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2
Paradox_gantt_2022_0409
1.0 Project Management
2.0 Workforce Readiness for Technology Deployment
3.0 Characterization of the Paradox Play
3.1 Geologic Characterization
3.1.1 Collect and Catalog Currently Available Data
3.1.2 Data and Core Acquisition from new Well
3.1.3 Core Analysis
3.1.4 Petrophysical Analysis
3.1.5 3D Seismic Survey Interpretations
3.1.6 Regional Fracture Analysis
3.1.7 Machine Learning Applications
3.2 Coupled Model Development
3.2.1 Develop Geologic Model
3.2.2 Develop Dynamic Reservoir Model
3.3 Dynamic Multiphase Flow Modeling
3.3.1 Uncertainty Quantification
3.3.2 Develop Scenarios of Field Deployment Strategies
4.0 Determine Strategic Drilling and Stimulation Strategies and Evaluate Performance
4.1 Determine Optimum Well Locations and Trajectories
4.2 Develop Tactical Stimulation Strategy
4.3 Data and Core Acquisition from second project Well
5.0 Assemble Development Strategy Plan (DSP)
5.1 Identify Technical, Regulatory and Economic Challenges
5.2 Identify Benefits and Impacts Associated with the Development Strategy
5.3 Identify Additional Needs for Expanded Play Development of State-Of-The-Art Technologies and Methodologies
5.4 Assess of Technical and Economic Viability of the Proposed Development Strategy