Improving Subsurface Stress Characterization for Carbon Dioxide Storage Projects by Incorporating Machine Learning Techniques

(DE-FE0031684)

William Ampomah, PhD

New Mexico Tech - PRRC

U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2020 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

September 10, 2020

Presentation Outline

- Project overview
- Project objectives
- Technical Approach
- Accomplishments
- Synergy Opportunities
- Summary

Program Overview

– Funding Profile

– Project Performance Dates:

10/01/2018 – 09/30/2021

	Budget		Budget		Budget	
	Project Year 1		Project Year 2		Project Year 3	
	DOE	Cost share	DOE	Cost share	DOE	Cost share
New Mexico Tech (Recipient) - Cash	$ 308,034.80	$ 64,856.06	$ 340,729.27	$ 64,639.40	$ 303,499.19	$ 63,595.20
Schlumberger Technology - InKind	$ -	$ 66,666.67	$ -	$ 66,666.67	$ -	$ 66,666.67
Non-FFRDC Subtotal:	$ 308,034.80	$ 131,522.73	$ 340,729.27	$ 131,306.07	$ 303,499.19	$ 130,261.87
Sandia National Lab	$ 50,000.00	$ -	$ 50,000.00	$ -	$ 50,000.00	$ -
Los Alamos National Lab	$ 150,000.00	$ -	$ 150,000.00	$ -	$ 100,000.00	$ -
FFRDC Subtotal:	$ 200,000.00	$ -	$ 200,000.00	$ -	$ 150,000.00	$ -

Project Team

New Mexico Tech

Dr. William Ampomah (PI)
Dr. Robert Will
Dr. Robert Balch
Dr. Qian Sun
Dr. Gary Axen
Mr. George El-Kasseh
Ms. Martha Cather

LANL

Dr. Lianjie Huang

SNL

Dr. Timothy Draelos

Consultants

Mr. James Rutledge
Dr. Thomas Bratton

Mr. Donald Lee

Students

Ms. Marcia McMillan
Mr. Noah Hobbs

Program Overview

Goals and Objectives

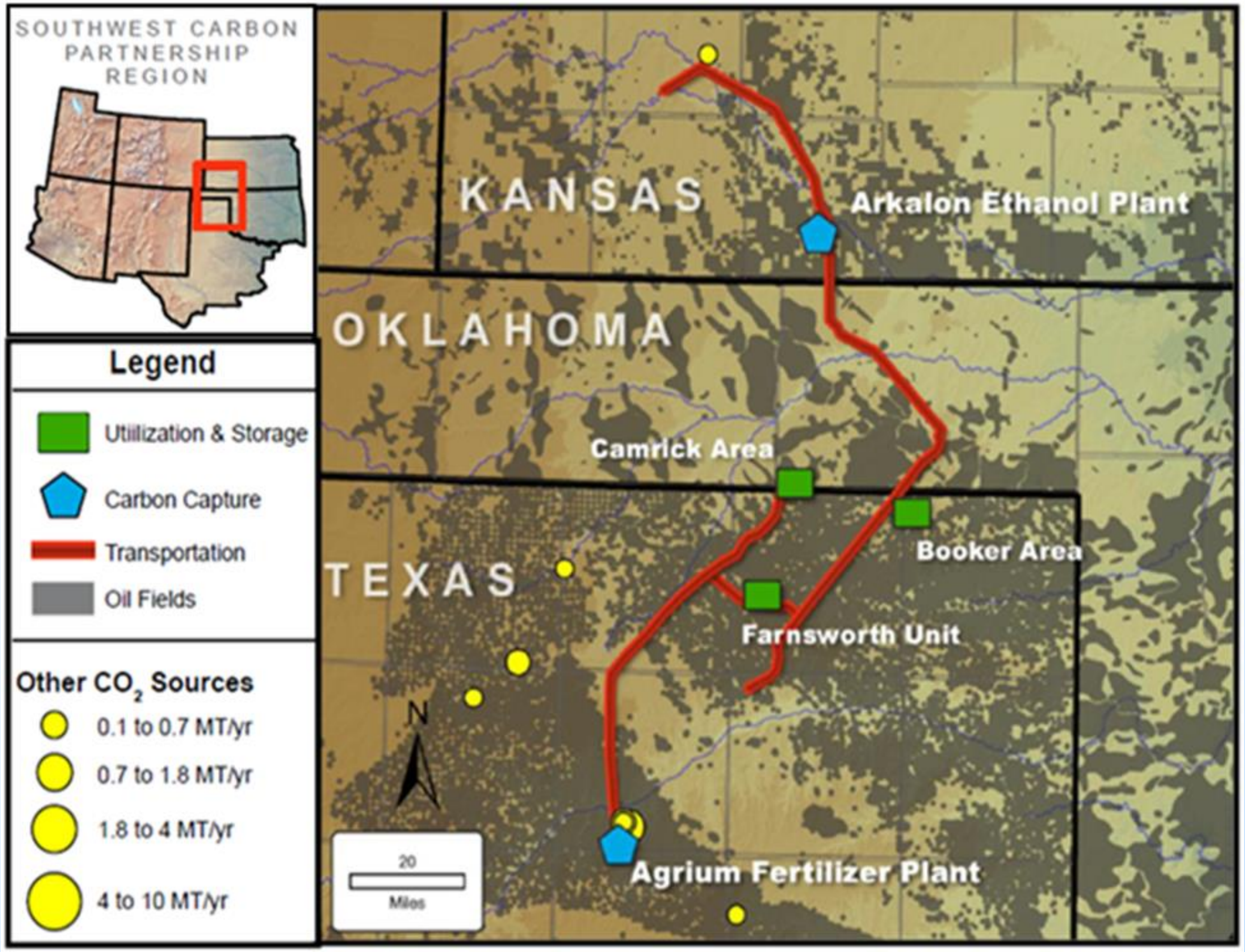
- The primary objective of our project is to develop a framework to boost the reliability of characterization and prediction of the state of stress in the overburden and underburden (including the basement) in CO_2 storage reservoirs using novel machine learning and integrated geomechanics and geophysical methods.

- We are using field data and models developed by the Southwest Regional Partnership on Carbon Sequestration (SWP) for the Farnsworth Unit (FWU), a CO_2 enhanced oil recovery (EOR) project being conducted by Perdure in Ochiltree County, Texas, to verify the improved capabilities of our methods.

- The integration methodology is an adaptation of industry accepted practices for calibration of flow simulation models to coupled geomechanical models for improved stress prediction. Computational challenges will be overcome through application of Machine learning.

Technology/Site Selection

- Demonstrated at the Farnsworth Unit ongoing CO2 EOR development:
  - Discovered 1956
  - Primary depletion until~ 1965
  - Waterflood until ~2010
  - CO2 WAG EOR Started 2010
- 2 anthropogenic CO2 sources
- Extensive characterization dataset previously was acquired, and modeling performed by the SWP partnership

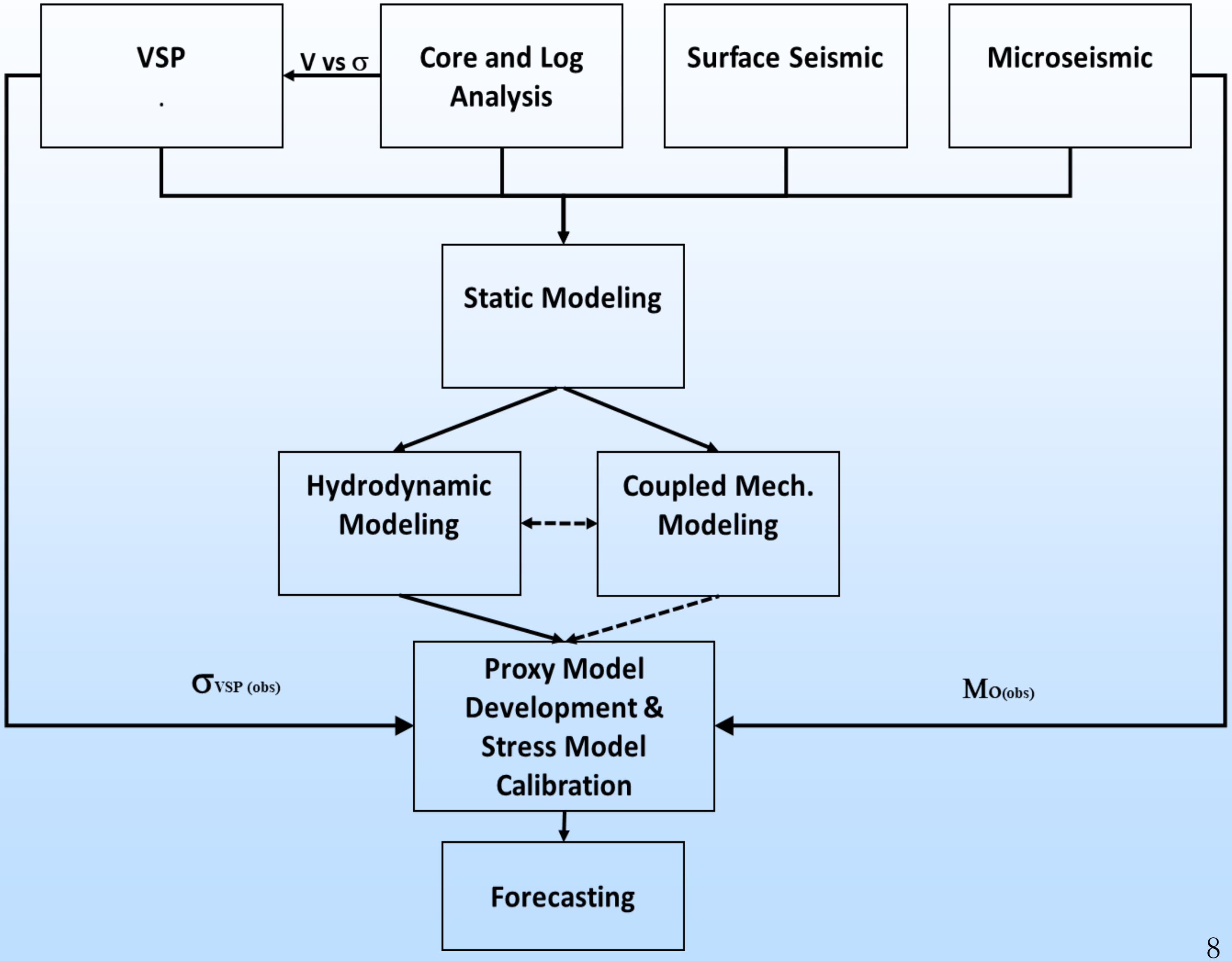


Technology/Site Selection

- Extensive available site characterization dataset includes:
  - 3D surface seismic
  - Repeat 3D VSP, repeat cross-well seismic
  - Extensive borehole geophysical logging and coring
  - Passive seismic monitoring array
- Prior data analysis and modeling:
  - 3D seismic depth imaging
  - Time-Lapse VSP processing
  - Core petrophysical and geomechanical testing
  - Integrated 3D geological modeling
  - History matched full field compositional reservoir simulation

Technical Approach/Project Scope

- The final outcome of this work will be a methodology for integration of multi-disciplinary data to reduce uncertainty in estimation of stress changes in the storage complex and underburden.
- Significant project risks include stress-sensitivity of rock behavior under anticipated effective stress changes, and microseismic data characteristics.
- The robust characterization dataset which includes extensive geological, geophysical, and geomechanical, and seismological data provide opportunities for technical risk mitigation through alternative integration strategies.



Technical Approach/Project Scope

Task/ Subtask	Milestone Title	Planned Completion
2.2	1D MEM Model	2/28/19
2.4	VSP Elastic Inversion	10/31/19
2.6	VSP Stress Estimation	2/28/19
3.0	Microseismic Analysis	11/31/2020
4.0	3D MEM Model	9/30/2019
5.0	Hydrodynamic History Matching	3/31/2020
6.0	Evaluation of one-way and two-way coupling process	8/30/2020
7.1	Stress Objective function formulation	7/30/2020
7.4/7.5	Completion of VSP - microseismic history matching	5/31/2021
8.0	Forecasting pressure and stress	8/30/2021

Technical Approach/Project Scope
(Project Success Criteria)

- Develop a structural and stratigraphic framework honoring basin development and fault kinematic principles.

- Produce elastic-waveform inversion results on already acquired 3D surface seismic data and time-lapse 3D VSP data.

- Utilize machine learning techniques to identify spectro-temporal features in the microseismic data which will allow for event location and event classification.

- Generate a high resolution mechanical Earth model (MEM) integrating all available geological, geophysical, and mechanical characterization data.

- Develop a history matching framework which involves a proxy model using machine learning algorithm and optimization techniques to calibrate simulation model as well as coupled hydrodynamic-geomechanical model to observed data.

Project risks and mitigation strategies

Perceived Risk	Risk Rating			Mitigation / Response Strategy
	Likeli-hood	Impact	Overall	
Cost/Schedule Risks:				
Meeting deliverables on schedule	M	H	M	• Some adjustment will be necessary to achieve project ultimate objectives
Budget allocations	M	M	H	• Reallocate funds if possible

Progress and Current Status of Project

Achievements to Date

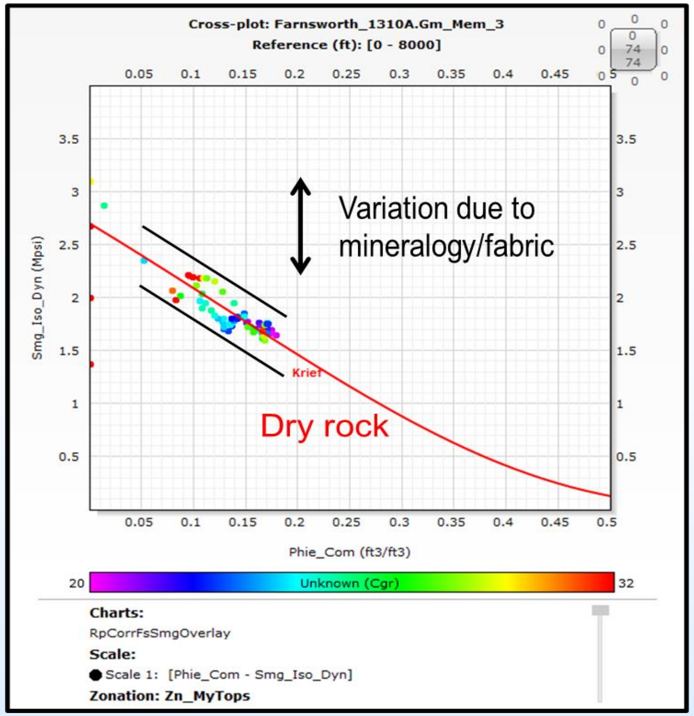
- We have rebuilt new initial anisotropic models by upscaling well logs using the Schoenberg-Muir method within layers divided according to P-wave impedance, and have determined the HTI positions and parameters besides VTI parameters in most areas.
- Have detected and located hundreds of microseismic events.
- The located events show two distribution peaks in the histogram of distribution of microseismic events along depth.
- The upper peak coincides with a geologic formation containing strong horizontal transverse isotropic properties revealed from well-log analysis, while the lower peak lies within a different geologic formation.
- Completed final geological and geomechanical static models for hydrodynamic flow and coupled simulations
- Completed final history matching modeling utilizing machine learning based workflow
- Completed evaluation of 1-way and 2-way coupling options for stress calibration process
- At the later stages of objective function development to aid calibration of coupled modeling efforts

Wellbore Geophysical and Mechanical Data Analysis

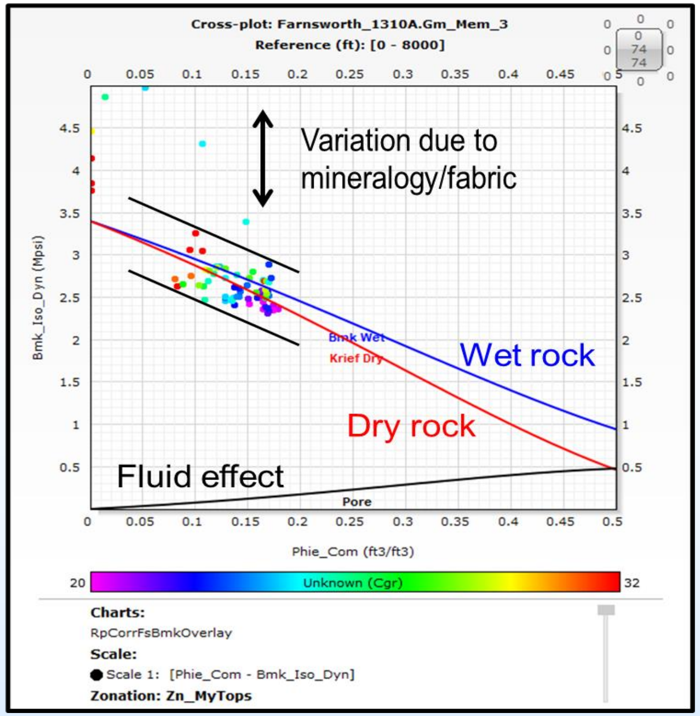
The project enjoys the benefit of a rich mechanical characterization dataset facilitating:

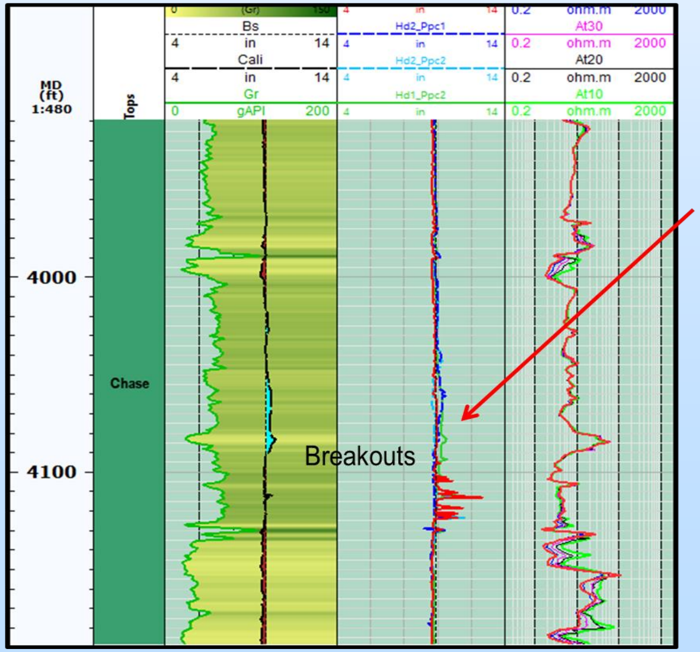
- Analysis of geophysical logs supported development of a site specific rock physics model for required fluid substitution computations.
- Analysis of extensive borehole geophysical and drilling data providing insights into stress anisotropy characteristics in the reservoir and overburden.
- Analysis of core mechanical test results providing calibration of geophysical log derived mechanical properties and stress sensitivity of velocities.

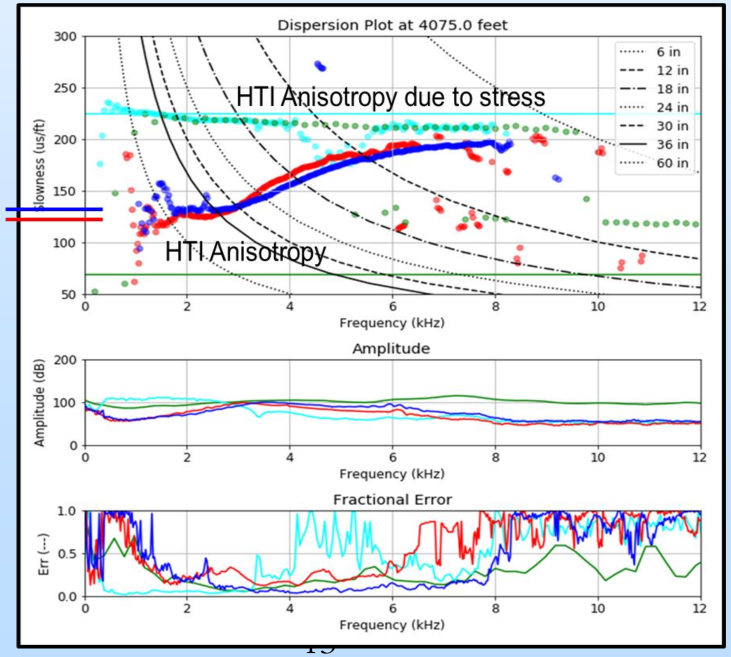
Shear Modulus vs. Porosity



Bulk Modulus vs. Porosity

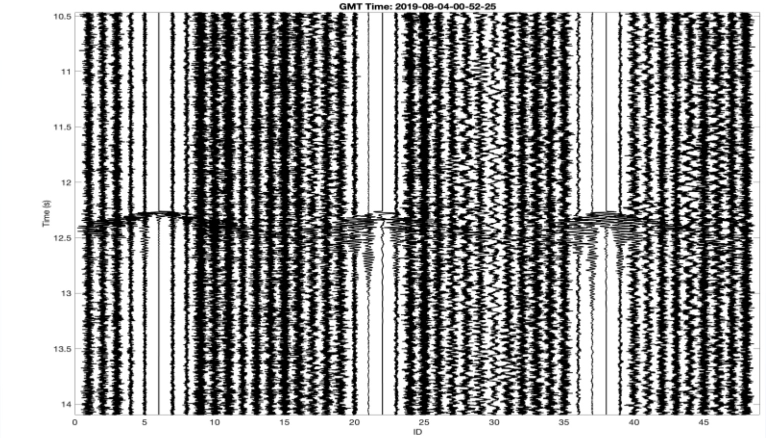


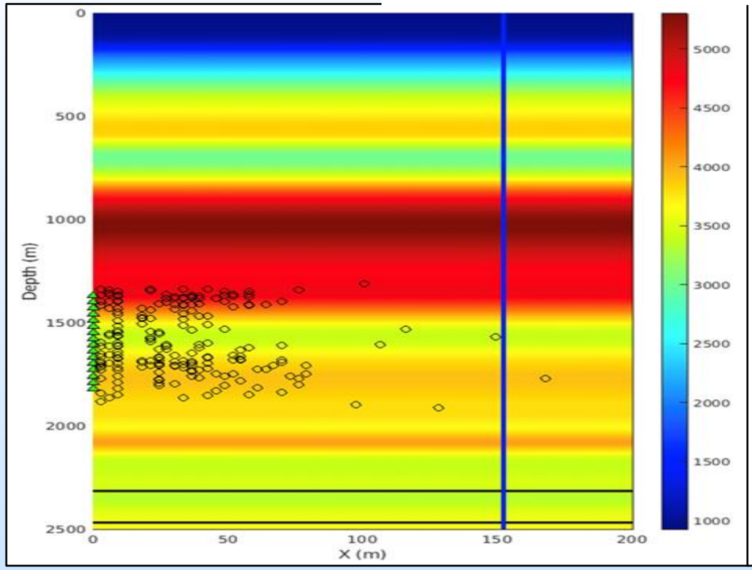


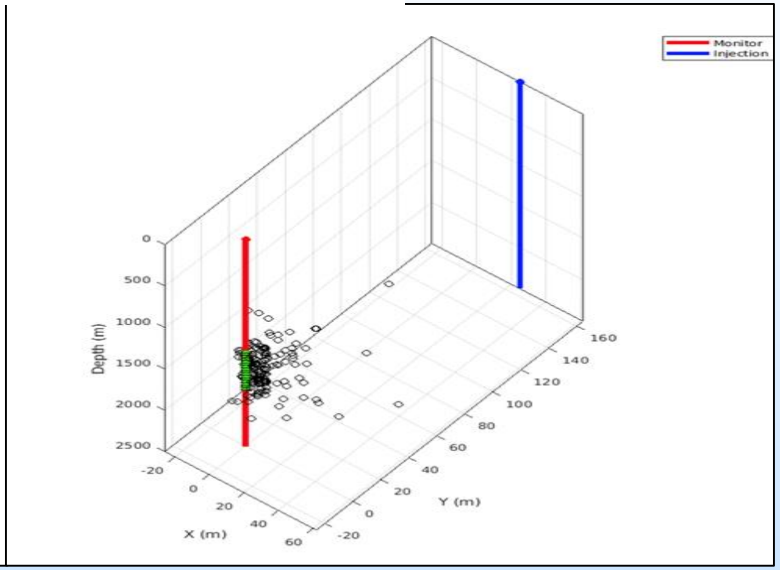


Microseismic Monitoring

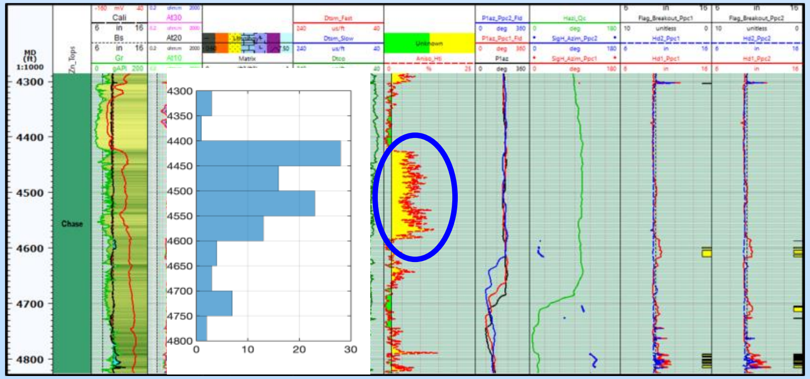
- Microseismic monitoring network comprises 16 level digital 3C borehole mounted geophone array and 20 surface 3C seismometer stations.
- Detected and located hundreds of microseismic events.
- All detected events are located in the overburden, no events detected from injection formation.
- The upper event distribution peak coincides with a geologic formation containing strong horizontal transverse isotropic properties revealed from well log.
- Convolutional autoencoder machine learning method is being developed for signal discrimination from high amplitude tube waves





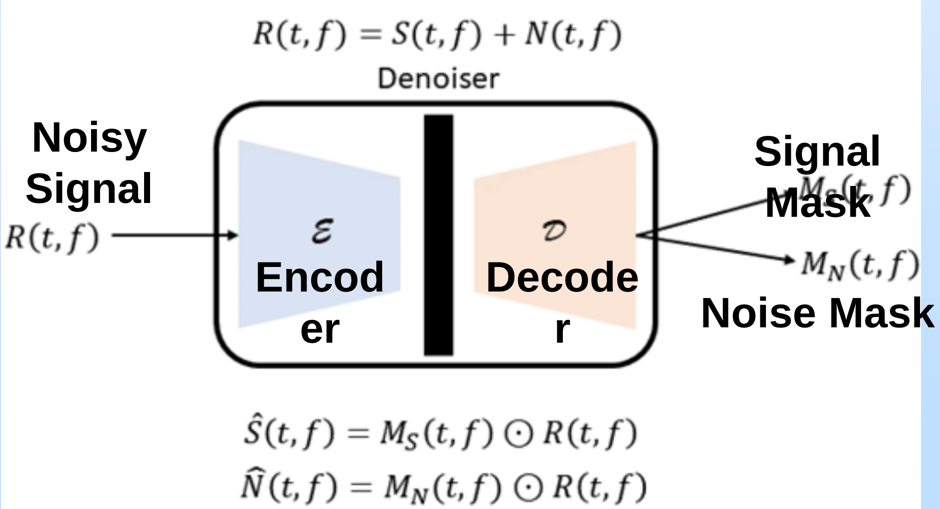


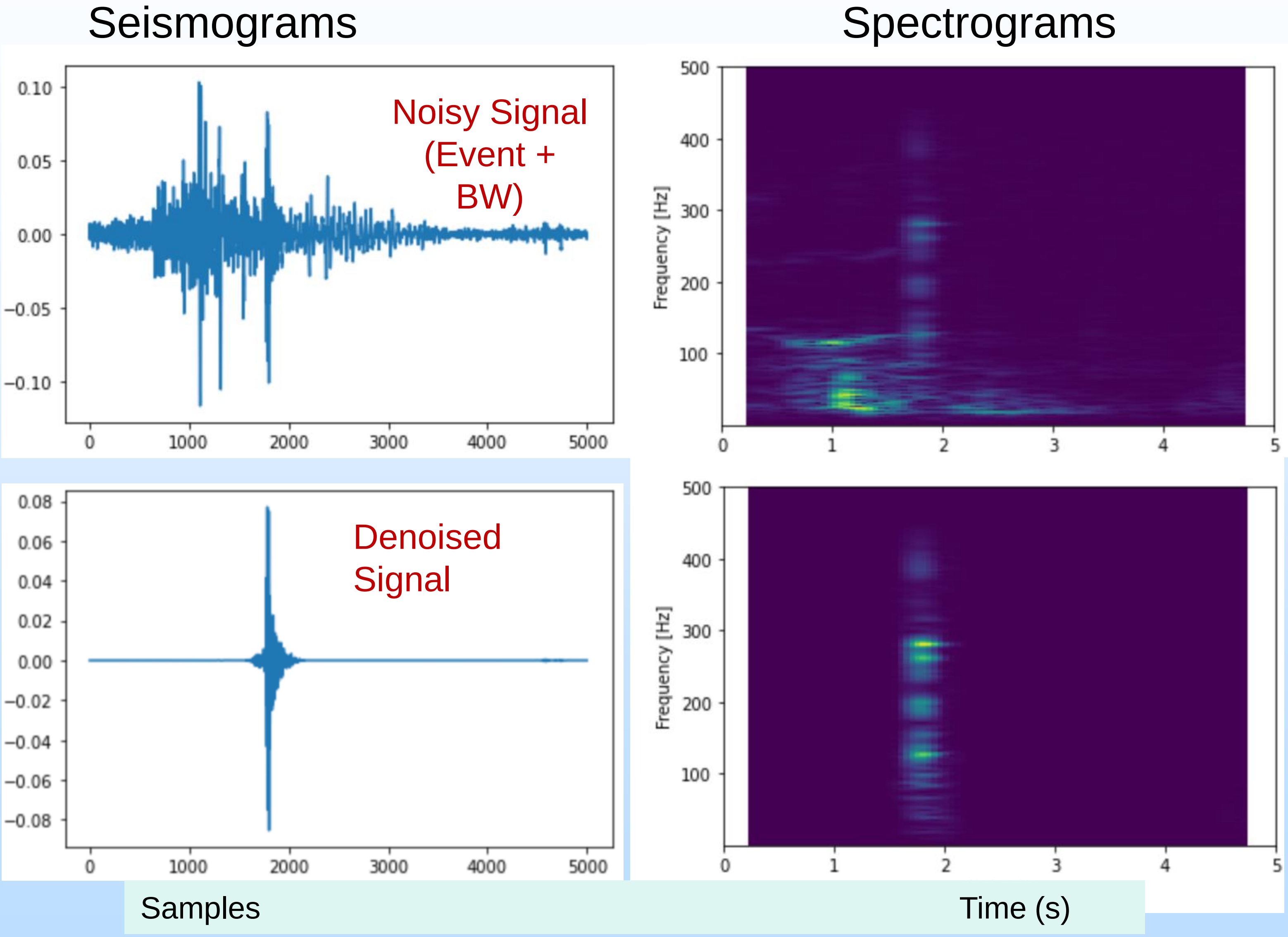
Histogram of microseismic events vs logs



SNL Microseismic Denoiser to Remove Borehole Waves from Microseismic Waveforms

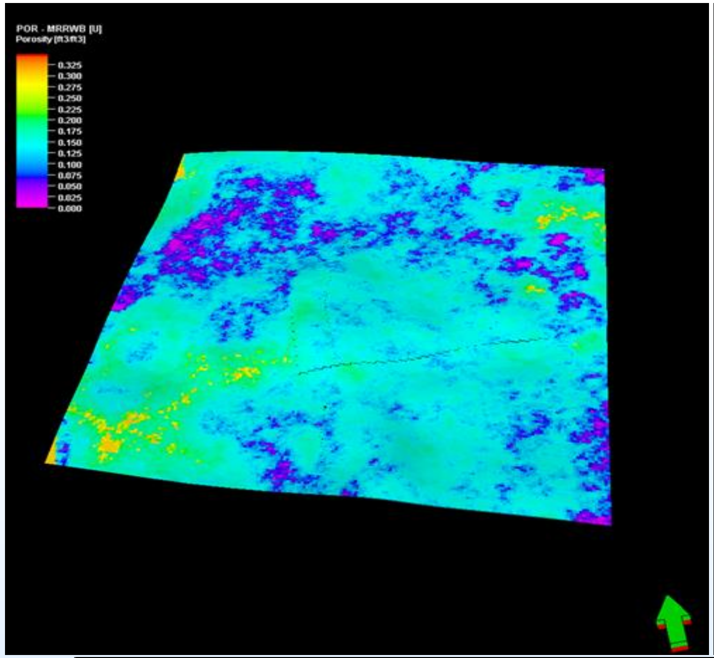
- Deep Denoising Autoencoder
  - Trained on Noisy Signal inputs artificially created from isolated ground truth

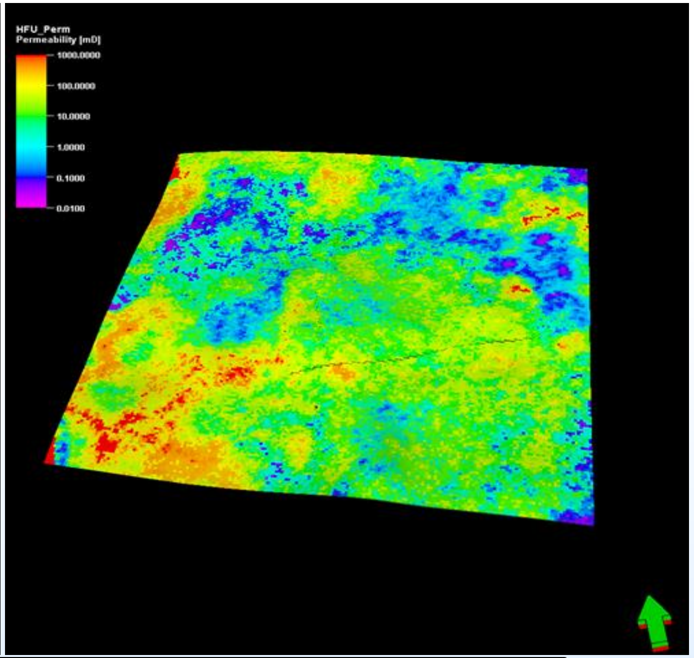


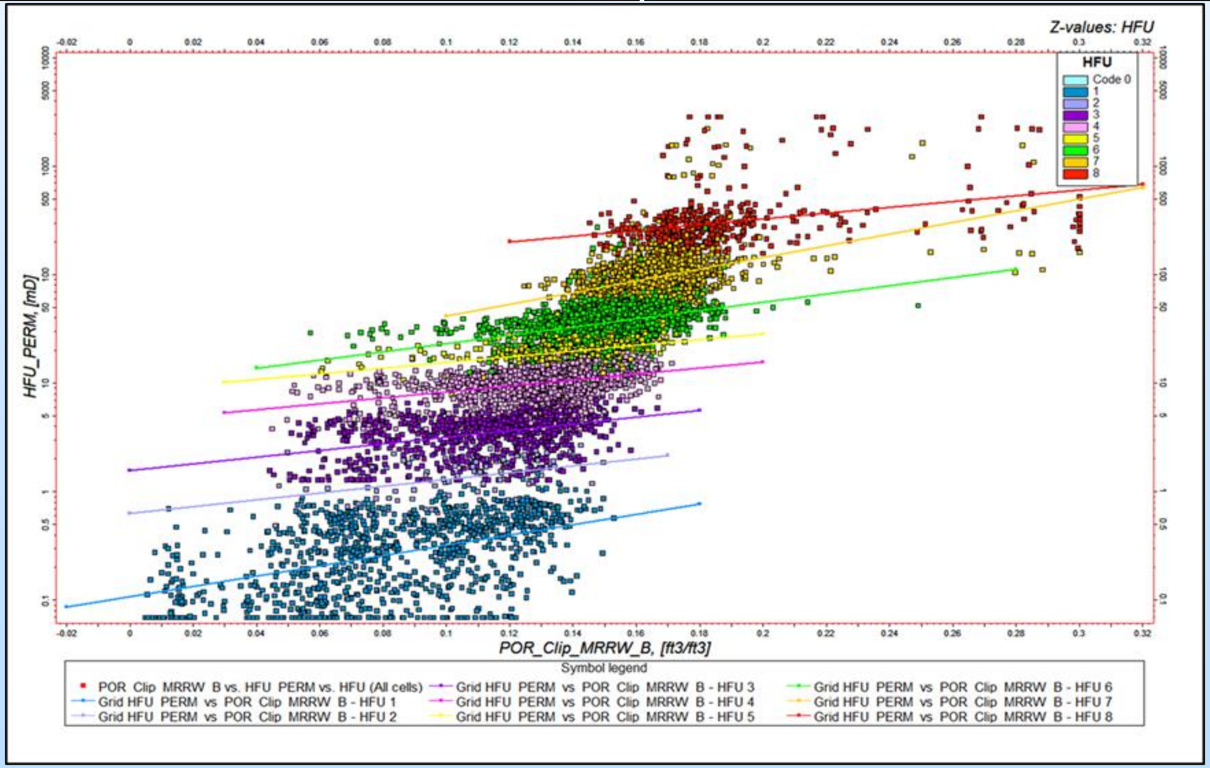


Geological and Geomechanical Static Modeling

- The geological model developed by SWP has been updated with structural and stratigraphic reinterpretation of newly depth imaged seismic data.
- The updated model extends from ground surface to below the injection zone (Morrow B reservoir).
- Petrophysical properties of the reservoir and caprock have been updated through integration of geophysical logs, core, and seismic elastic inversion products.
- Elastic properties of the reservoir, underburden, and overburden have been updated through integration of well data based 1-D Mechanical Earth Models (MEM) derived from geophysical logs and core analysis.

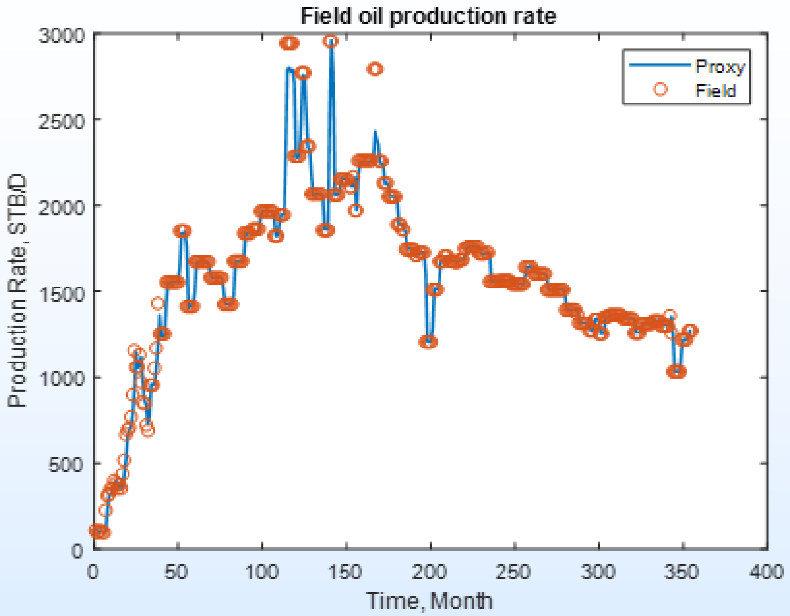


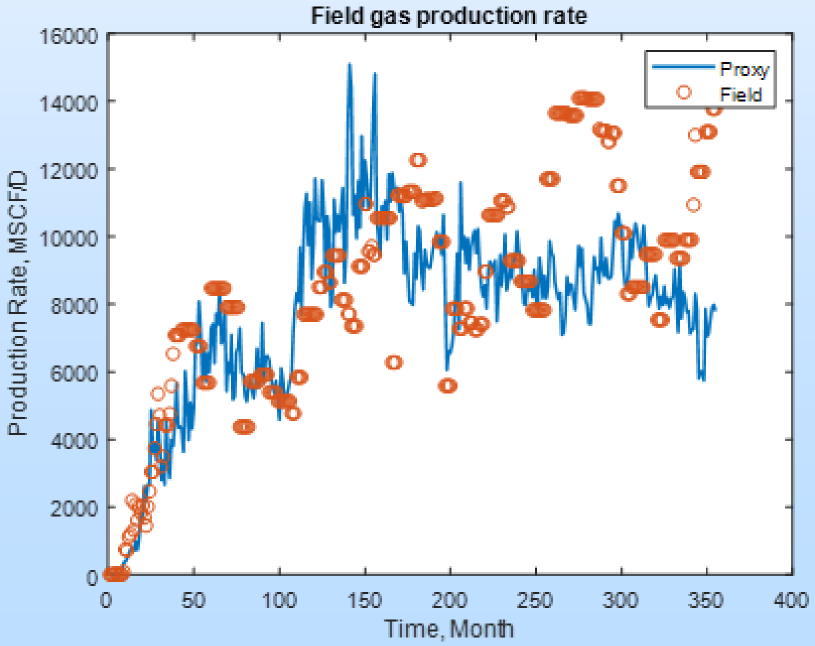




Hydrodynamic Flow Calibration

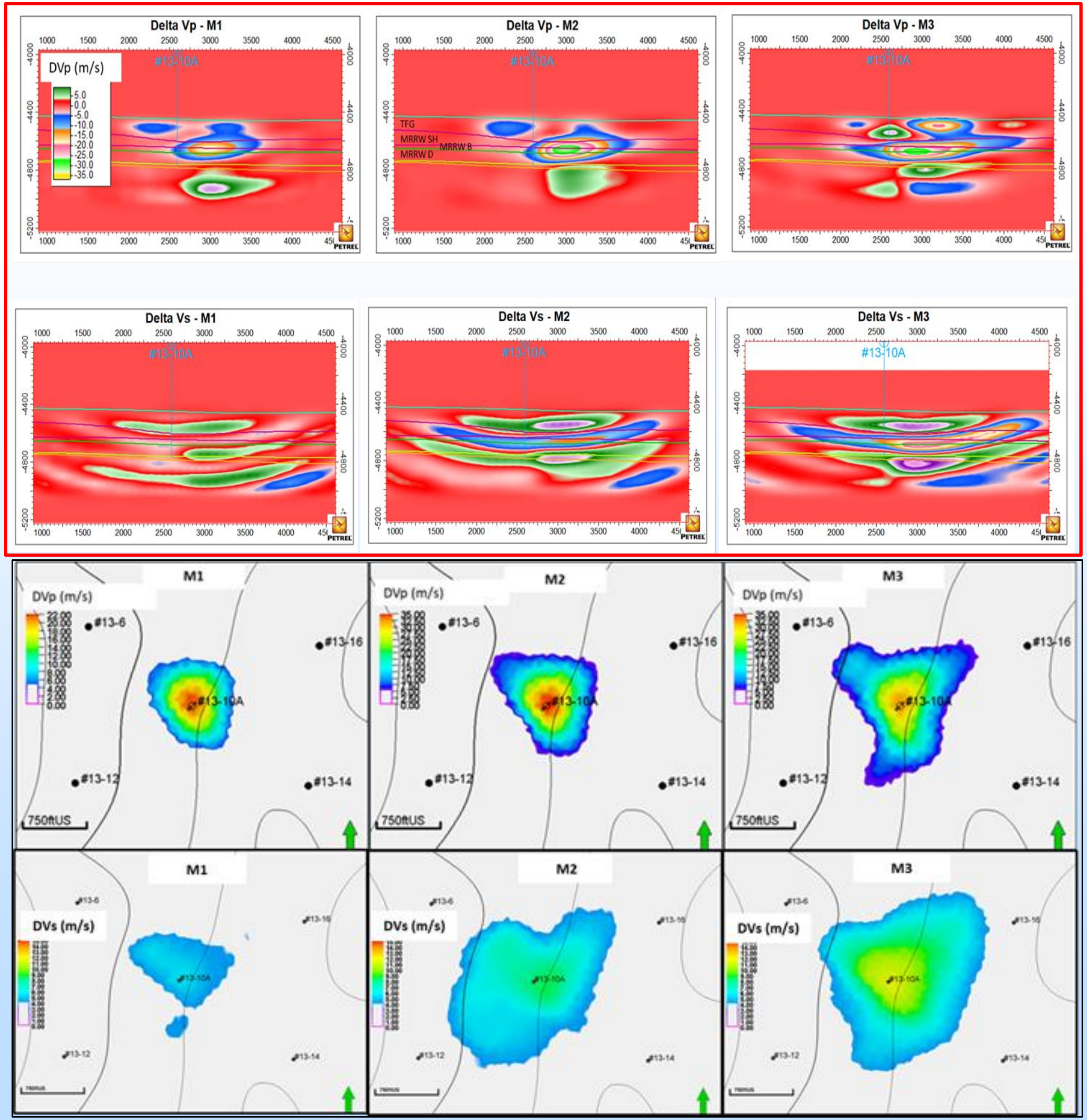
- Primary/Secondary (pressure depletion/waterflood) and tertiary (CO2 WAG) periods were history matched using proxy modeling and machine learning optimization.
- Separate proxy models were developed for primary/secondary and CO2 WAG development periods each using 100 full physics runs to train and verify proxy models.
- Particle swarm optimization was employed and coupled with the proxy models to minimize the history matching error
- Optimized reservoir parameters were verified in full physics simulations.





Time-Lapse VSP Processing and Analysis

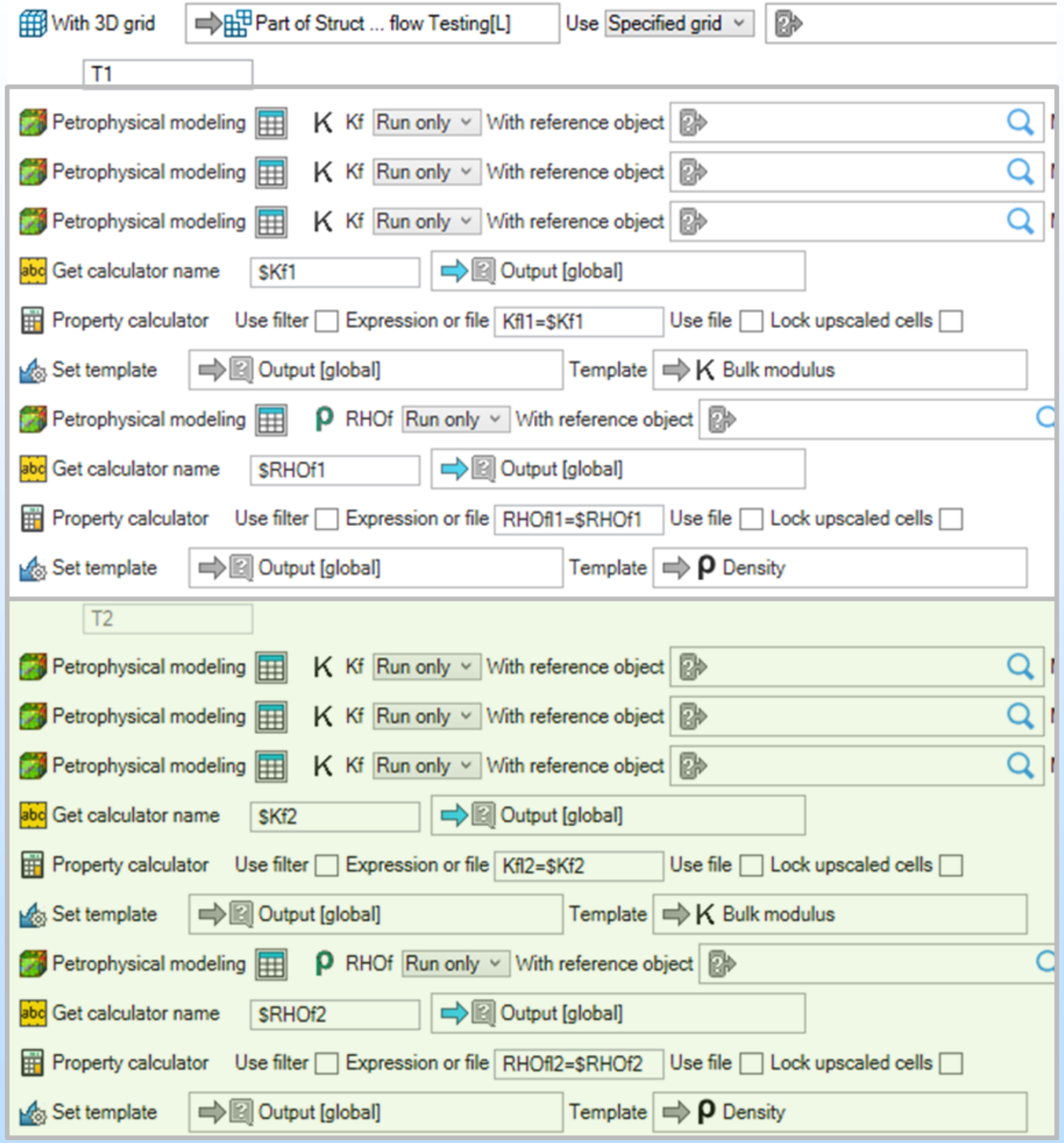
- 3D traveltime tomography and 3D hybrid time-frequency multi-scale elastic-waveform inversion were used to refine the baseline velocity models with all survey source points.
- The same 3D traveltime tomography and 3D elastic-waveform inversion were applied to three repeat VSP survey datasets.
- Resulting P and S wave velocity anomalies show temporal and spatial evolution with expectations from 5-spot CO2 WAG production pattern
- Persistent S wave anomaly is evidence of stress sensitivity in Morrow B formation



Fluid EOS Modeling Using NIST SuperTrapp in PETREL Process Manager

For Each VSP Survey Time:

- Read Eclipse fluid component fraction property grids.
- Read Eclipse pressure and water saturation property grids.
- Invoke external SUPERTRAP FORTRAN executable for EOS calculations.
- Compute fluid modulus and density property grids for use in fluid substitution calculations.



T1

T2

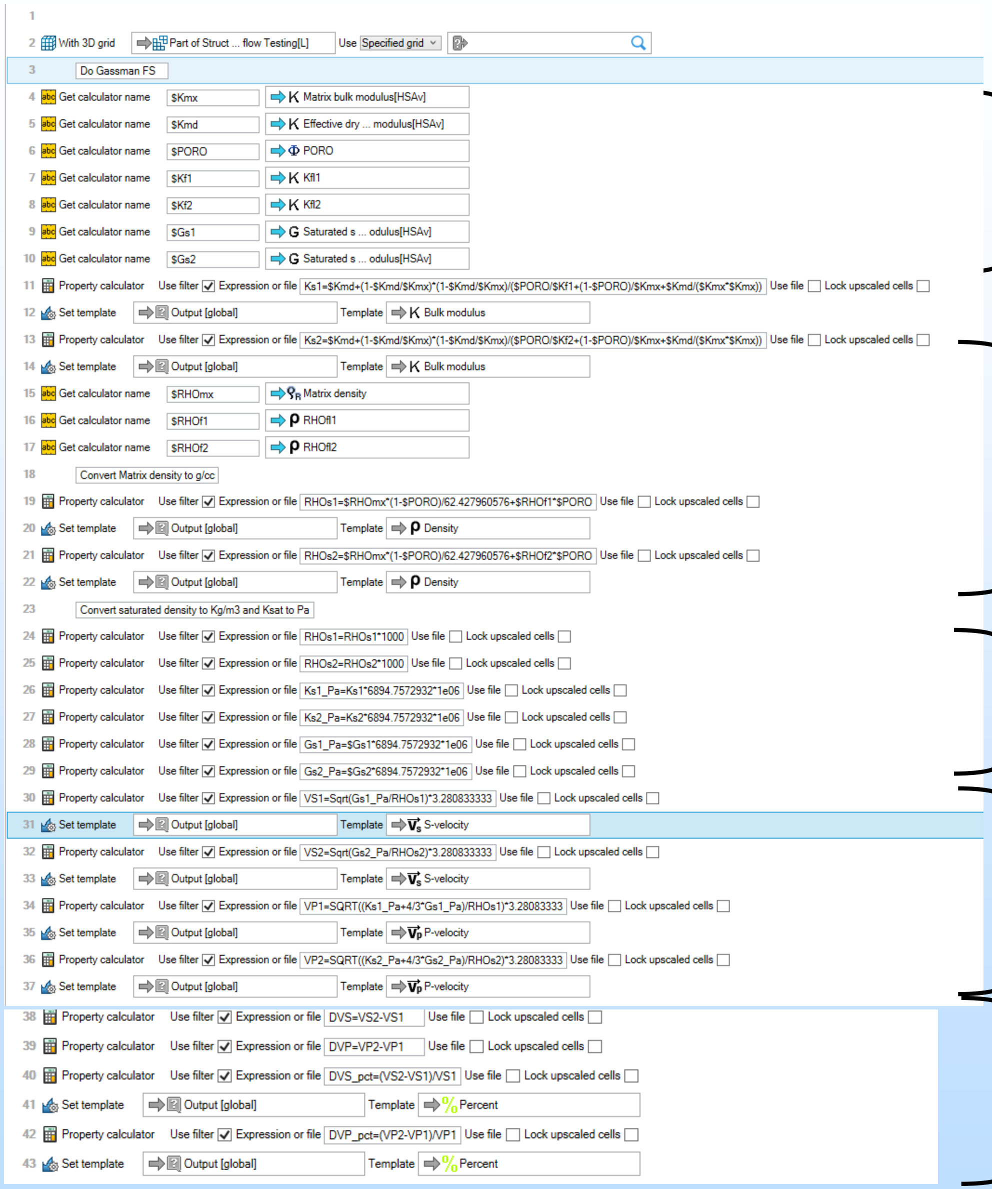
Implementation of FWU Rock Physics Model in PETREL Process Manager

For Each VSP Survey Time:

- Interpolate K_s, G_s, K_{dry}, G_{dry},
- Read Porosity property grid and .
- Read fluid SUPERTRAPP modulus and density.
- Compute Gassmann K_{sat} and ρ_{sat} property grids.
- Compute V_p and V_s property grids.

For Each Baseline-Monitor Set:

- Compute ΔVp and ΔVs property grids.



Read fluid and matrix properties

Compute Time 1 and Time 2 Ksat and RHOsat

Unit conversions

Calculate Time 1 and Time 2 velocities

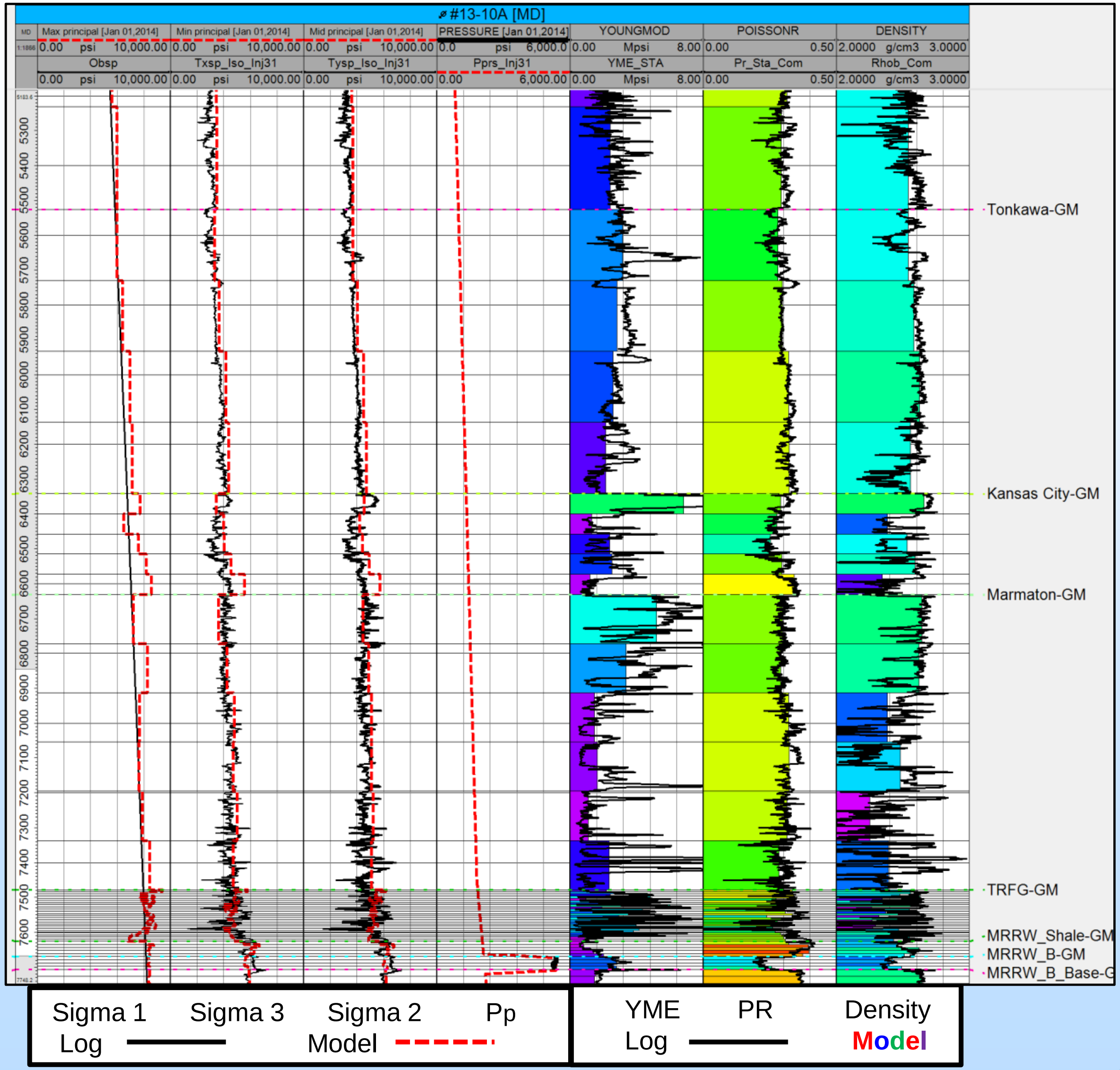
Calculate Time 1 and Time 2 velocity differences

Coupled Modeling – MEM Initialization

- The initial 3D MEM stress state is established by imposition of horizontal stresses at lateral model boundaries (sides), and vertical stress computed from overburden loading.
- Initial estimates of principal vertical and horizontal stresses at model boundaries are computed from integrated Well log and core 1D Well MEM's.
- Horizontal 3D MEM stress boundary conditions are iteratively adjusted to achieve agreement of principal stresses between the 3D MEM and Well MEM stresses.

Stress Initialization

Well MEM and 3D Model Predictions Overlaid at Well 13-10A



Gaps/Challenges/Hurdles

- Our major challenge is the characteristics of our observed microseismicity, which is emanating from the overburden rather than the reservoir, and which lacks the linear spatial organization indicative of faults and other failure mechanisms.
- Such spatial clustering/organization is the basis for two of our proposed geophysical imaging and inversion techniques (joint reverse time migration for fault/fracture imaging and joint focal mechanism inversion). These two products are fundamental to our strategy for integration of microseimicity for stress model calibration.
- However, our borehole and core geomechanical data analyses has yielded very interesting insights into high levels of stress anisotropy in the overburden zones from which microseismicity is emanating.
- Additionally, the elastic inversion of VSP data has yielded 3D volumes of rock elastic anisotropy attributes (Thompson parameters).
- Our proposed process modification involves integration of borehole geomechanics and seismic anisotropy volumes to develop a 3D mechanical model describing the anisotropic stress conditions in the overburden.
- The mechanical model will be used to investigate potential source mechanisms for the observed microseismicity through forward modeling.
- In the new strategy observed microseismicity would be used as an independent observation for validation of hypothetical source mechanisms.

Synergy opportunities

- The team continuous to collaborate with researchers within Southwest Regional Partnership to compliments each projects efforts.

- Continue to share results with scientific community and field operator to improve operations

Summary Slide

Key Findings/ Lessons Learned

- The far-field stresses are aggressive enough to cause significant mechanical deformation (breakouts, inward radial strain) and variations in acoustical velocities at three different scales (core – log – seismic).
- The differential horizontal stresses are large enough to cause mechanical breakouts and dipole acoustical anisotropy.
- The stress changes due to fluid injection/removal are large enough to cause observable changes in acoustical velocities.
- Acoustical variations due to changes in fluid properties is likely a small effect compared to changes in stress loading.
- The quality of initial anisotropic parameters plays an important role in conversion rates and reliability of anistropic inversion.

Summary Slide

Future Plans

- Continue to quantify the relationship between mechanical deformation and stress
- Continue to quantify the relationship between acoustical velocity changes and stress.
- Calibrate coupled model with time-lapse VSP inversion velocities.
- Refine the microseismic 3D location results and estimate focal mechanism characteristics.
- Utilize anisotropic tomography and elastic-waveform inversion to invert for anisotropic parameters of full-size models so support characterization of stress anisotropy in the overburden.
- Use the coupled model and focal mechanism modeling to evaluate potential causality for observed overburden microseismicity.

Acknowledgements

The project would like to thank DOE for the award opportunity through DE-FE0031684 and our partners.

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Organization Chart

New Mexico Tech - Prime Contract

PRRC - Project Management, (Tasks 1-8)
Ampomah - PI
Balch - Project Manager, Co-PI
Czoski, Will, El-Kaseeh, RAs
EES - Axen - Fault kinematics (Tasks 4-8)

Los Alamos National Laboratory

Huang (Co-PI) - Seismic imaging, inversion (Tasks 1-3, 8)

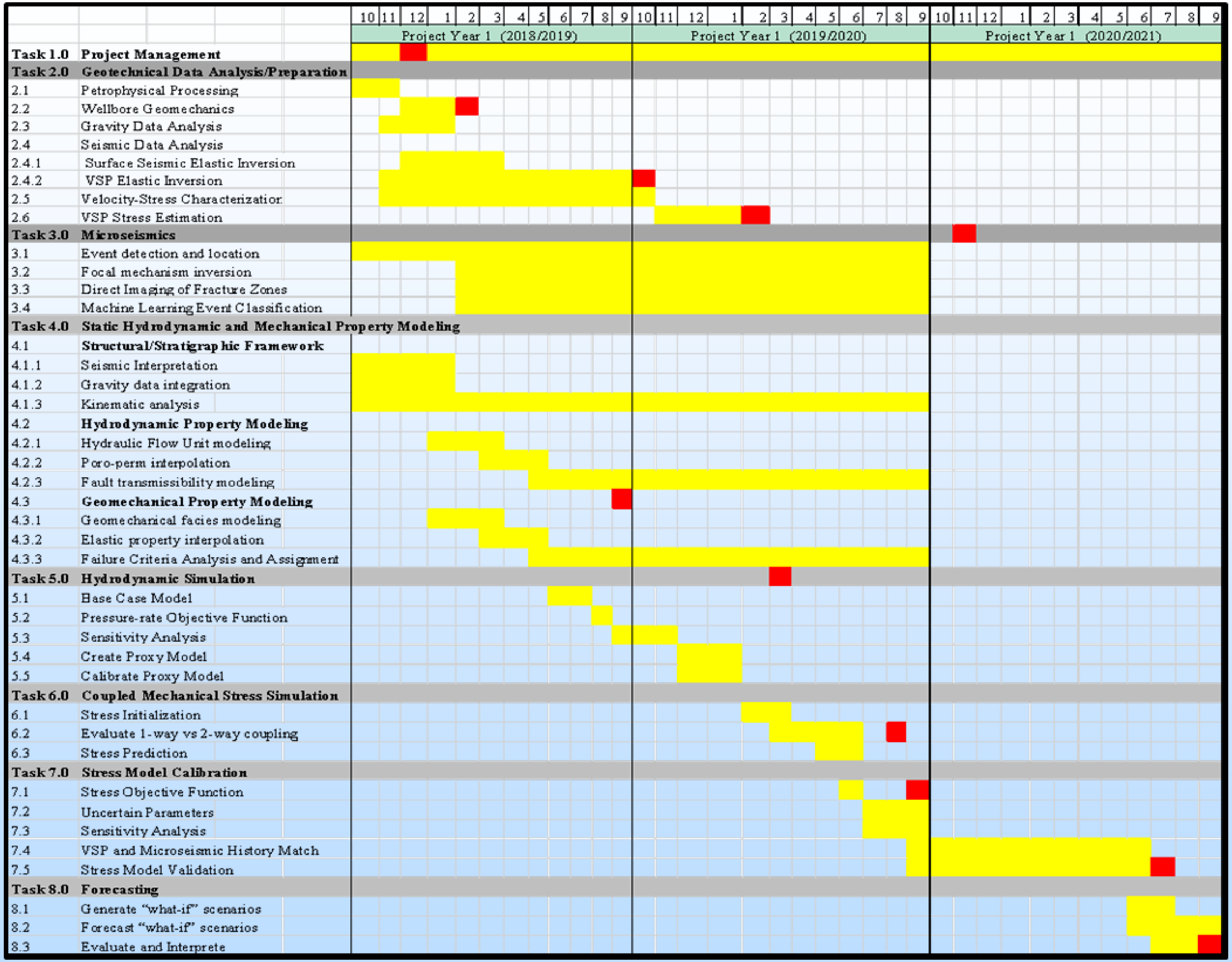
Sandia National Laboratory

Draelos - Machine Learning (Tasks 3, 5, 8)

Consultants

Rutledge - Geophysical methods, passive seismic monitoring (Tasks 2, 8)
Lee - Development of models (Tasks 4, 6, 7, 8)
Bratton - Geophysical methods, passive seismic monitoring (Tasks 2, 4, 6,7)

Gantt Chart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Project Year 1 (2018/2019)
Project Year 1 (2019/2020)
Project Year 1 (2020/2021)
Task 1.0 Project Management
Task 2.0 Geotechnical Data Analysis/Preparation
2.1 Petrophysical Processing
2.2 Wellbore Geomechanics
2.3 Gravity Data Analysis
2.4 Seismic Data Analysis
2.4.1 Surface Seismic Elastic Inversion
2.4.2 VSP Elastic Inversion
2.5 Velocity-Stress Characterization
2.6 VSP Stress Estimation
Task 3.0 Microseismics
3.1 Event detection and location
3.2 Focal mechanism inversion
3.3 Direct Imaging of Fracture Zones
3.4 Machine Learning Event Classification
Task 4.0 Static Hydrodynamic and Mechanical Property Modeling
4.1 Structural/Stratigraphic Framework
4.1.1 Seismic Interpretation
4.1.2 Gravity data integration
4.1.3 Kinematic analysis
4.2 Hydrodynamic Property Modeling
4.2.1 Hydraulic Flow Unit modeling
4.2.2 Poro-perm interpolation
4.2.3 Fault transmissibility modeling
4.3 Geomechanical Property Modeling
4.3.1 Geomechanical facies modeling
4.3.2 Elastic property interpolation
4.3.3 Failure Criteria Analysis and Assignment
Task 5.0 Hydrodynamic Simulation
5.1 Base Case Model
5.2 Pressure-rate Objective Function
5.3 Sensitivity Analysis
5.4 Create Proxy Model
5.5 Calibrate Proxy Model
Task 6.0 Coupled Mechanical Stress Simulation
6.1 Stress Initialization
6.2 Evaluate 1-way vs 2-way coupling
6.3 Stress Prediction
Task 7.0 Stress Model Calibration
7.1 Stress Objective Function
7.2 Uncertain Parameters
7.3 Sensitivity Analysis
7.4 VSP and Microseismic History Match
7.5 Stress Model Validation
Task 8.0 Forecasting
8.1 Generate "what-if" scenarios
8.2 Forecast "what-if" scenarios
8.3 Evaluate and Interprete