Improving Subsurface Stress Characterization for Carbon Dioxide Storage Projects by Incorporating Machine Learning Techniques
Project Number (DE-FE0031684)

Robert Will

New Mexico Tech - PRRC

U.S. Department of Energy

National Energy Technology Laboratory

Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting

August 26-30, 2019

Project Team

- New Mexico Tech – PRRC
- Los Alamos National Lab
- Sandia National Lab
- Geotechnical consultants
  - Tom Bratton
  - Jim Rutledge
  - Don Lee

Presentation Outline

- Project Overview
- Technical Status
- Accomplishments to Date
- Lessons Learned
- Synergy Opportunities
- Project Summary

Project Overview

The primary objective of this 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**.

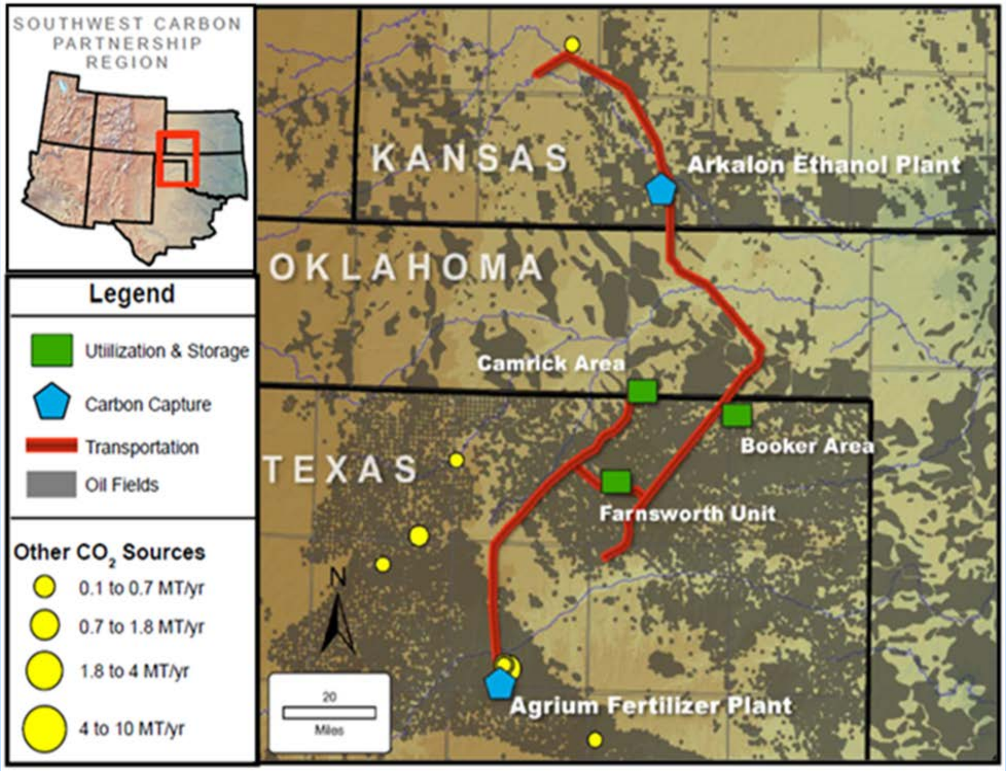
The proposed integration methodology is an adaptation of industry accepted practices for calibration of flow simulation models to coupled geomechanical models for improved stress prediction. Computational challenges will be overcome through application of Machine learning.

We will use 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.

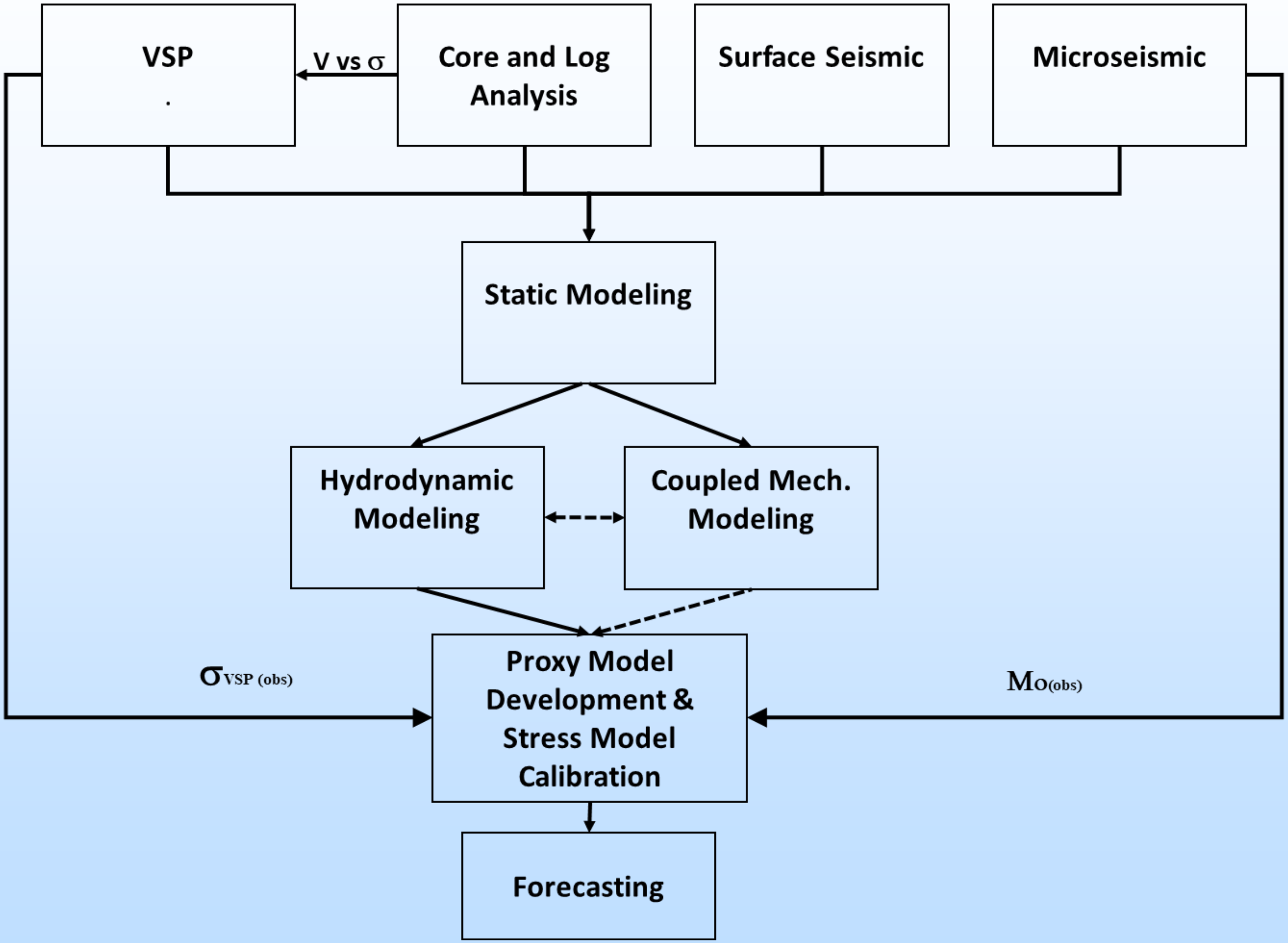
Field Site

Farnsworth CO2 WAG EOR Project, Texas

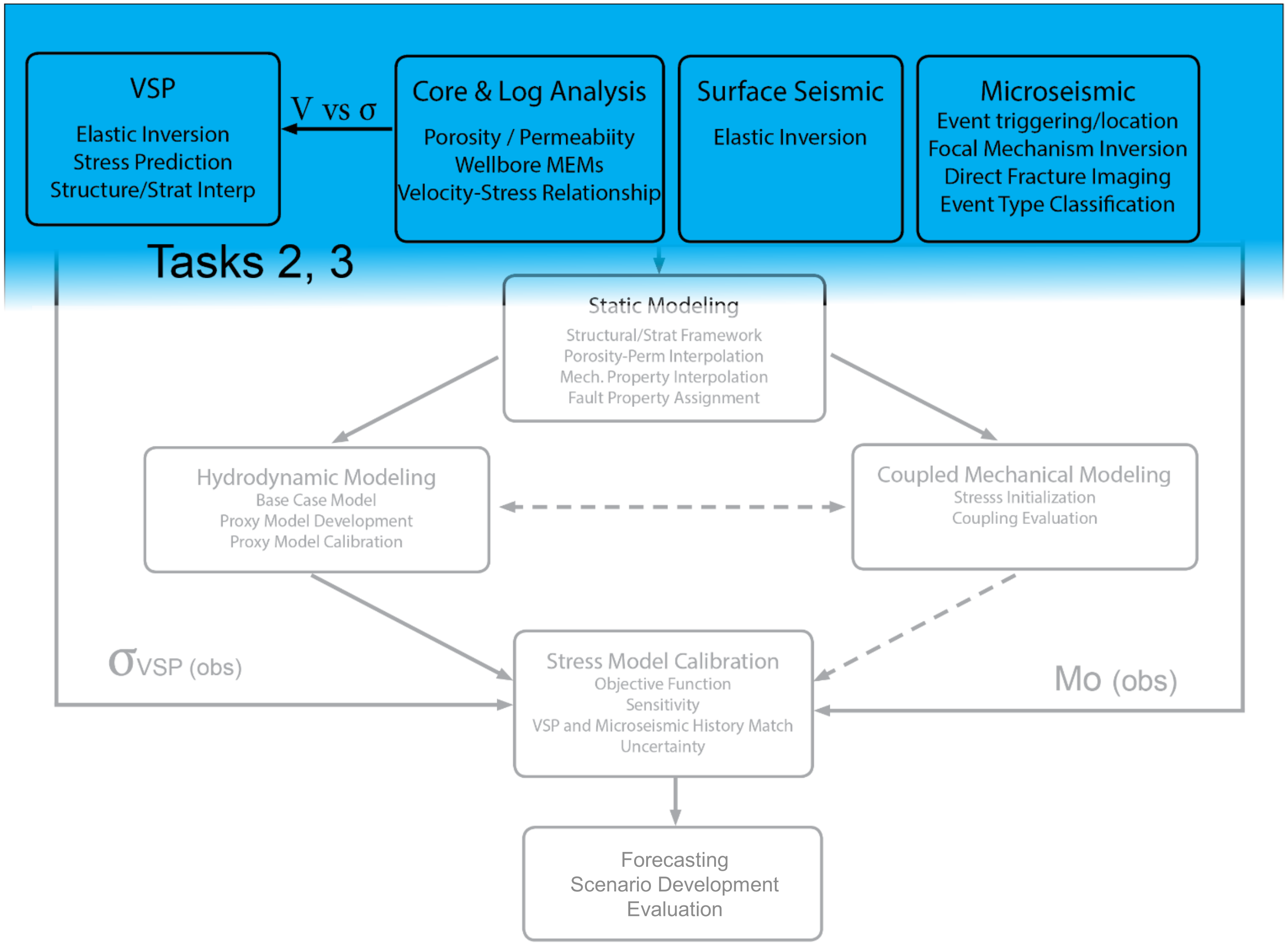
- Discovered 1956
- Primary depletion until~ 1965
- Waterflood until ~2010
- CO2 WAG EOR Starting 2010
- 2 anthropogenic CO2 sources
- As of June 2019;
  - 1,359,520 metric tonnes of CO_2 purchased
  - 1,281,224 of purchased CO_2 stored within Morrow B sand
  - ~ 94% of purchased CO_2 stored
- Extensively characterized by the SWP partnership



Methodology: Workflow

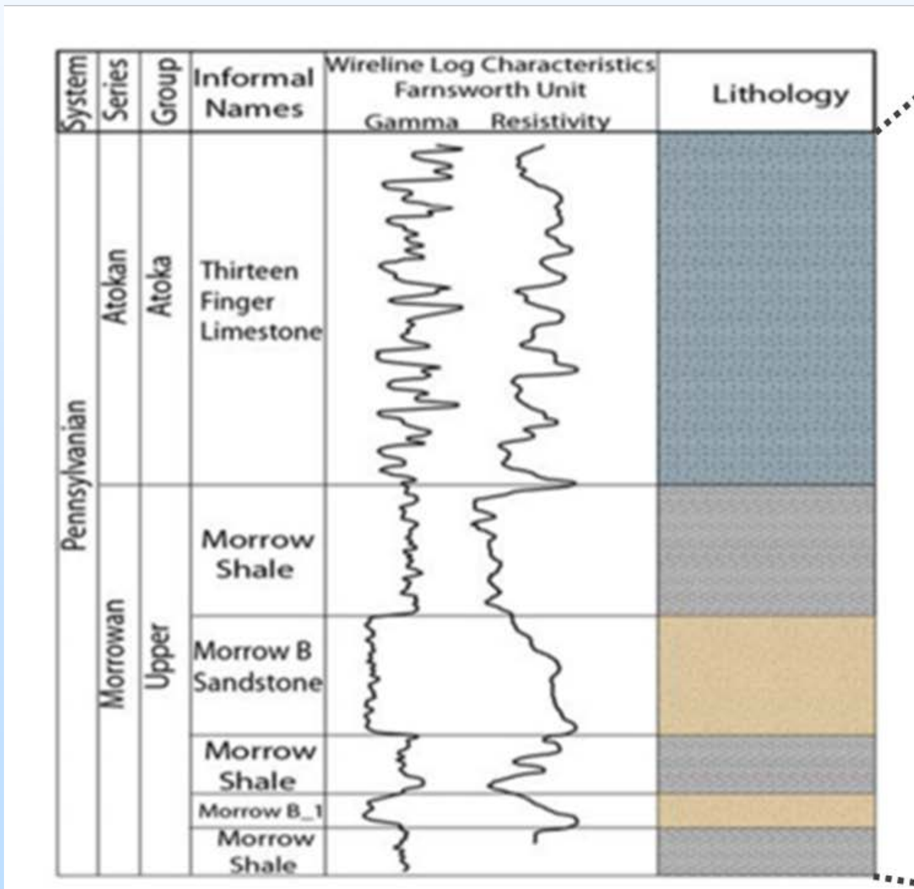


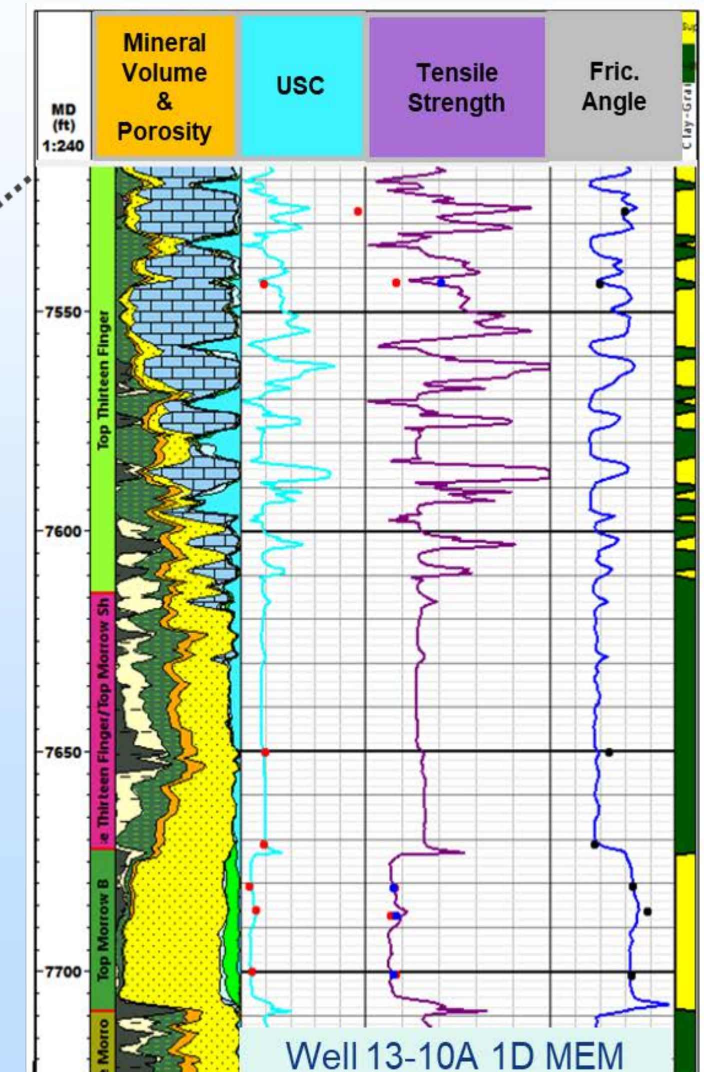
Methodology: Geotechnical Analysis



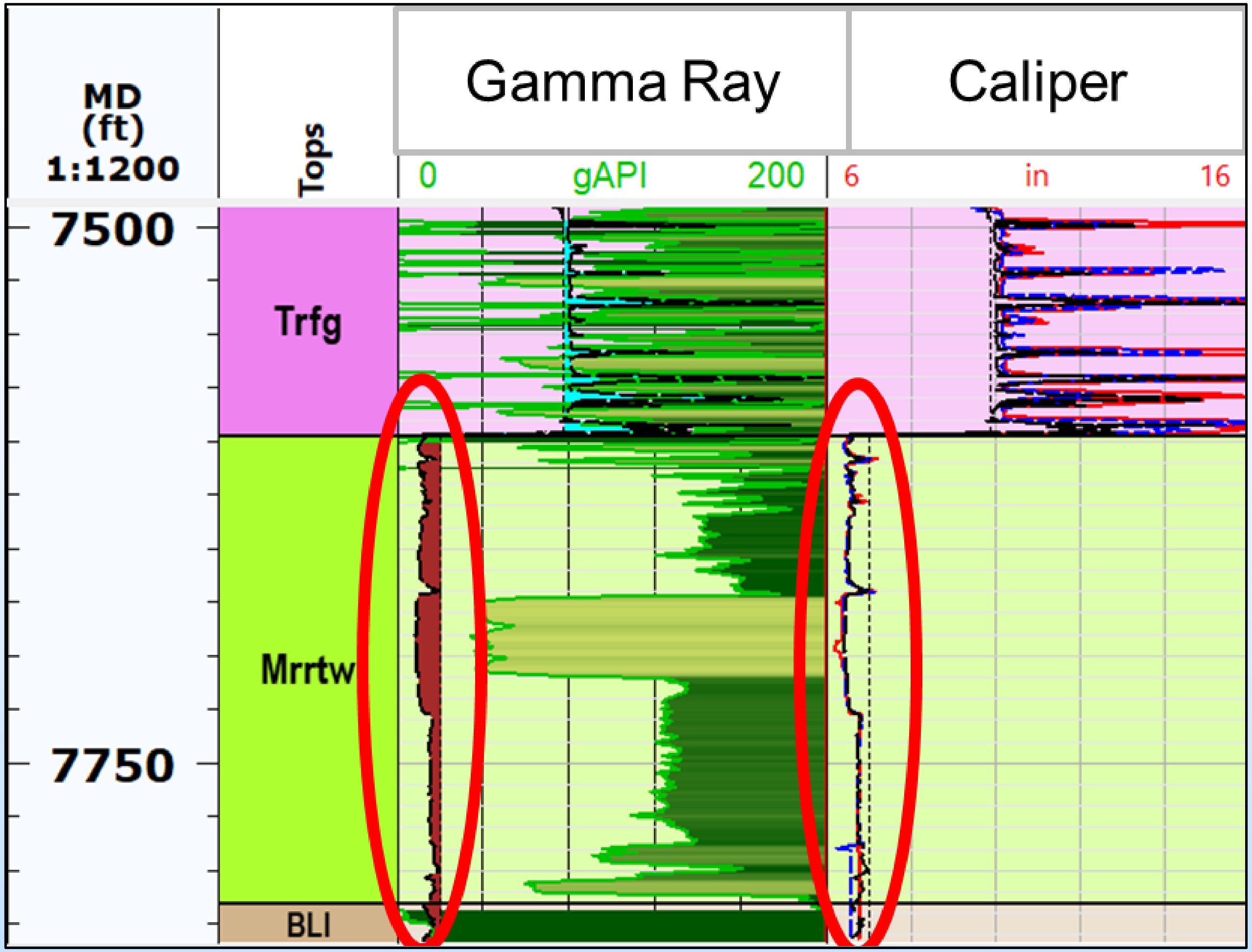
1D MEM Mechanical Properties

The well MEM integrates geophysical logs (sonic scanner, density, etc) and is calibrated to geomechanical Core tests.





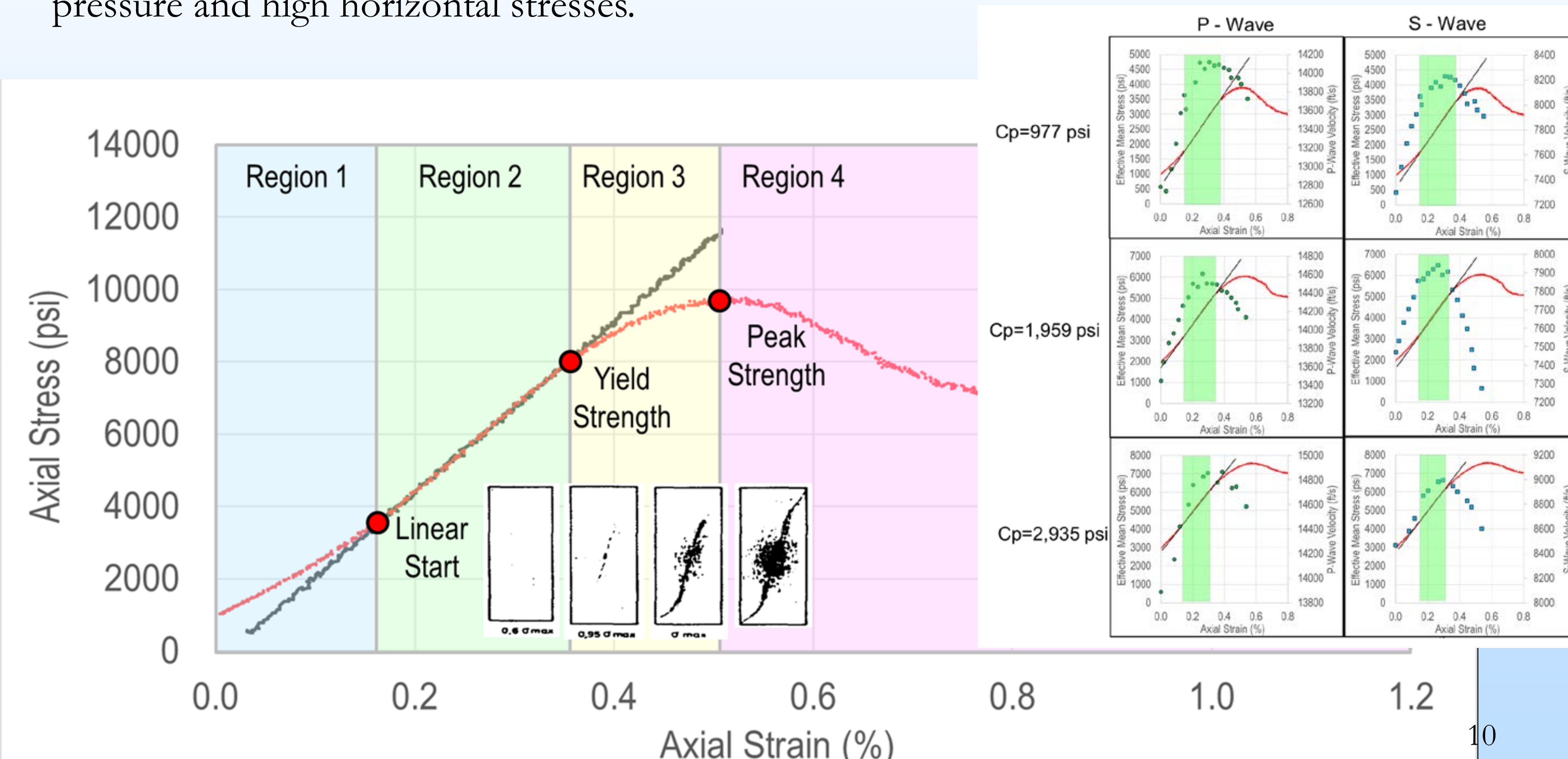
Observed Borehole Deformation



- Borehole caliper observations indicate significant symmetrical reduction in borehole diameter throughout the Morrow formation suggesting plastic deformation under high horizontal stress.
- Borehole failure in shallower sections indicate high anisotropic horizontal stresses.

Stress Sensitive Velocity in Core

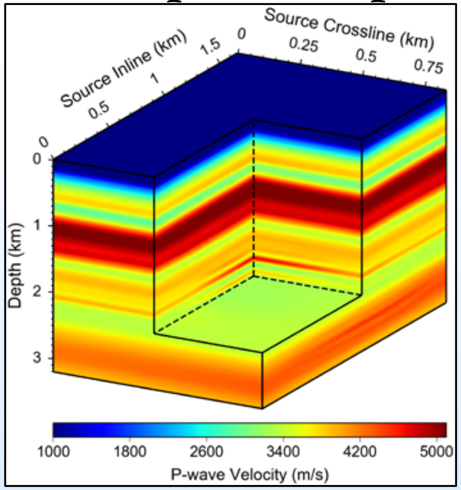
- Analysis of core test data shows significant variation in linear elastic region and yield strength.
- Velocity versus stress behavior is consistent with microcracks suggesting possible prior plastic deformation incurred as a result of very low pre-development hydrostatic pressure and high horizontal stresses.



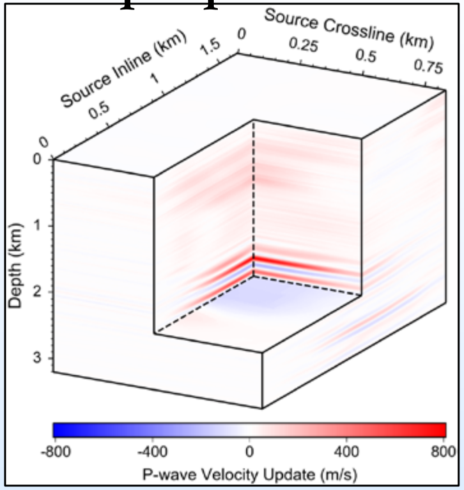
Joint Time Lapse VSP Inversion

- Regularization of time lapse inversion is improved through joint inversion.
- 4 available 3D/3C VSP Surveys:
  - Baseline: February 2014
  - Monitor 1: January 2015
  - Monitor 2: November 2016
  - Monitor 3: December 2017
- Baseline velocity model was constructed by combining surface seismic and VSP velocity models.

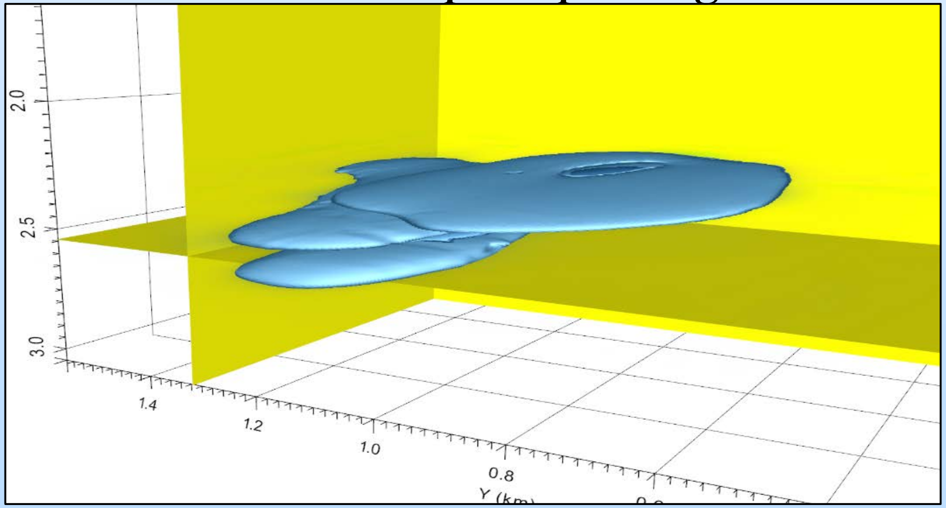
Updated Vp



Vp Updates



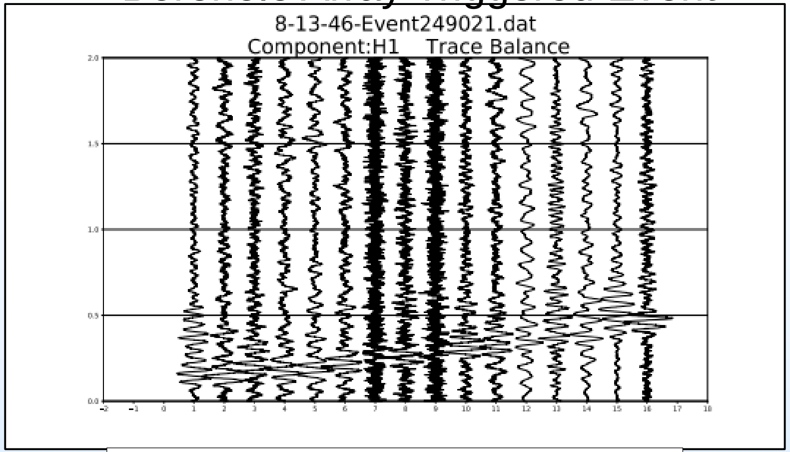
M2 Time-lapse Vp changes

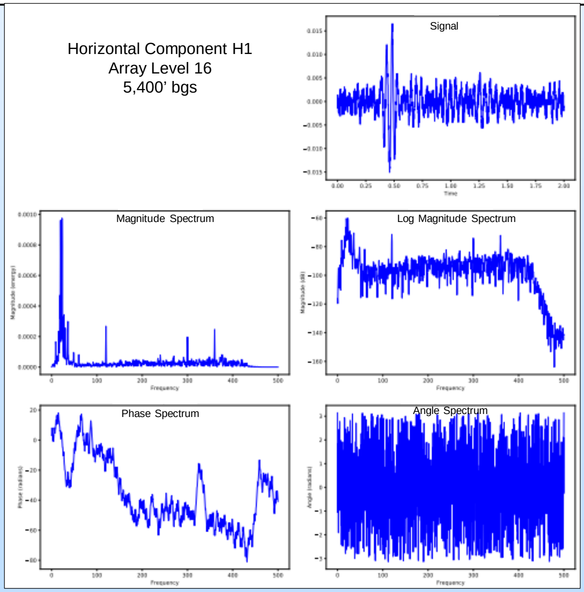


Microseismics

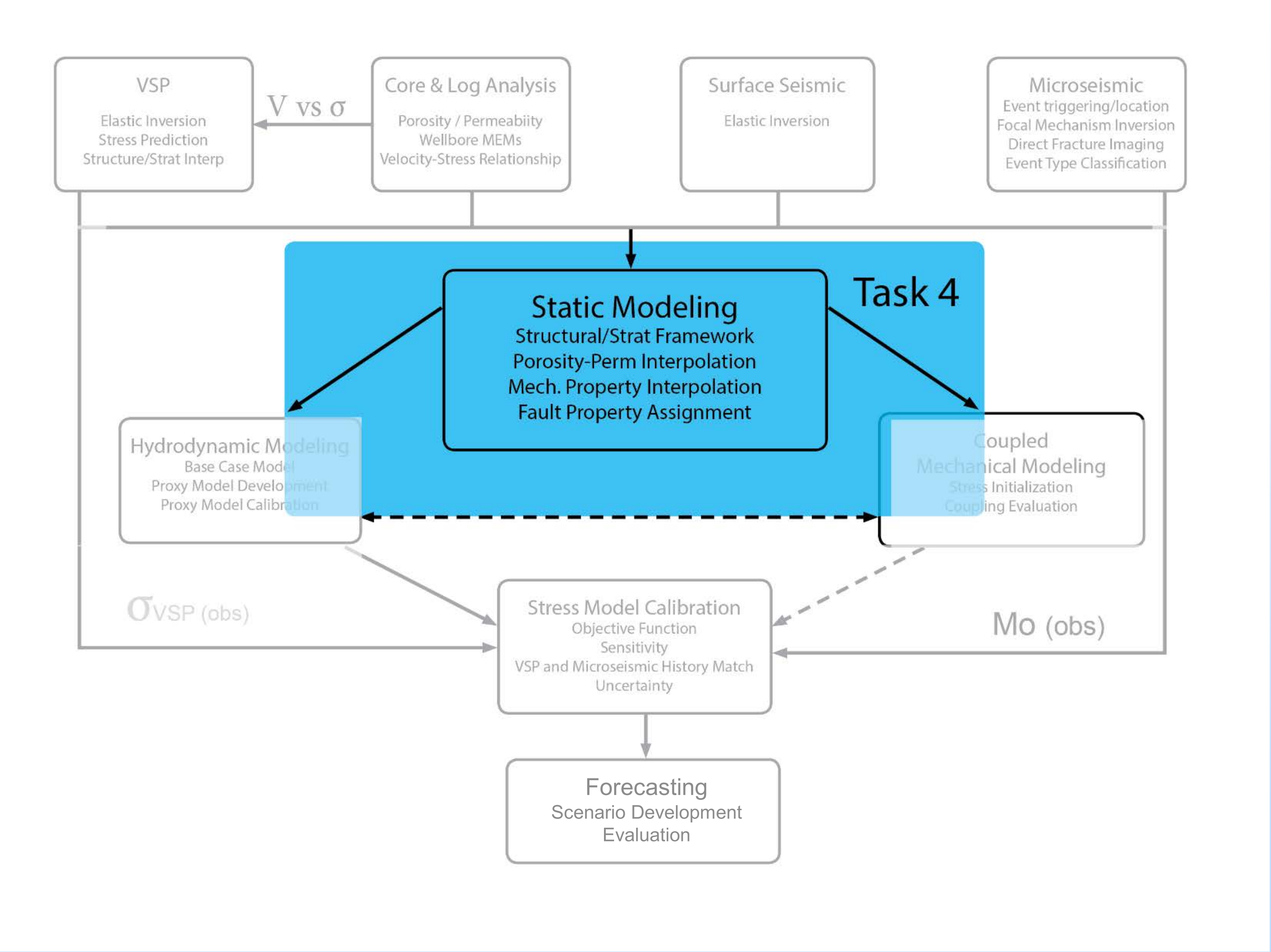
- A vertical 16 level 3 component OYO-Geospace digital microseismic monitoring array has been deployed in a well approximately 500' from the study pattern injector. Data is being recorded continuously at 1 ms sampling intervals in 1 minute duration SEG-Y format records.
- The vertical array is supplemented by 20 surface recording stations configured with CMG 3T broadband sensors recording on RefTek RT 130 data loggers and solar power.
- The surface array locations were selected using ray tracing modeling with the vertical array to optimize the composite array for event location and characterization.

Borehole Array Triggered Event



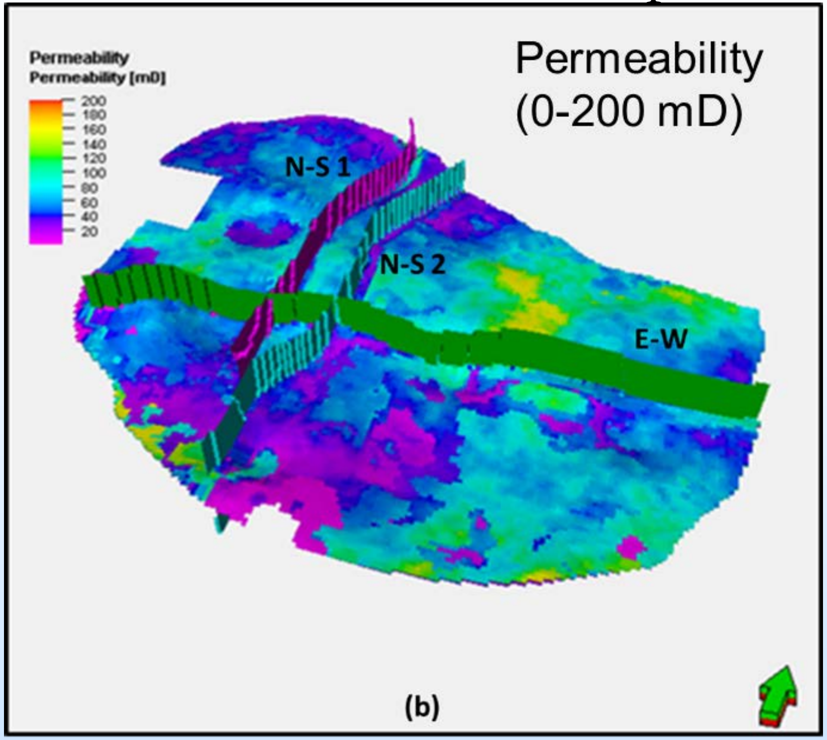


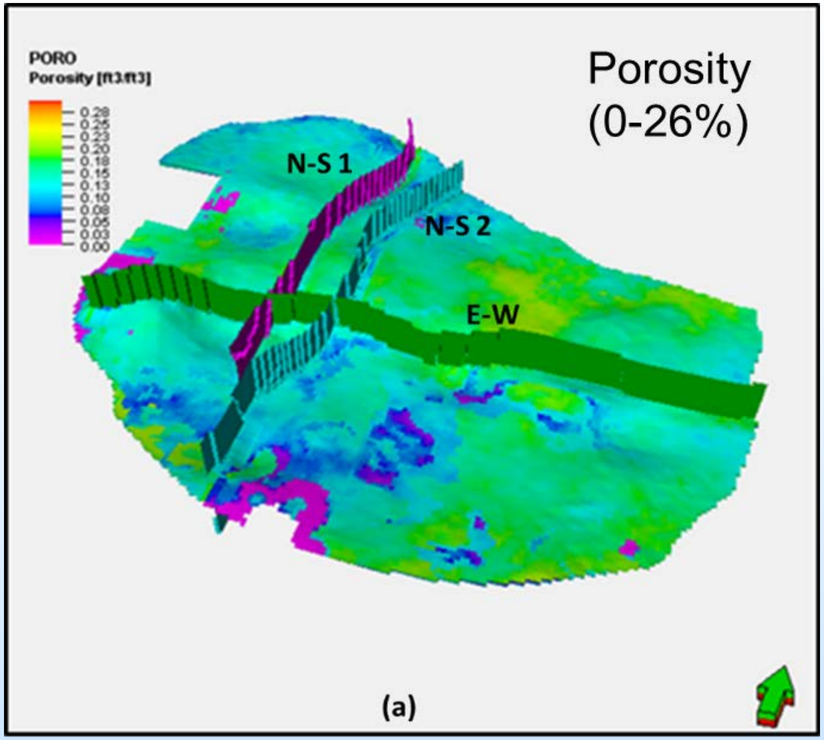
Methodology: Static Modeling



Geologic Model

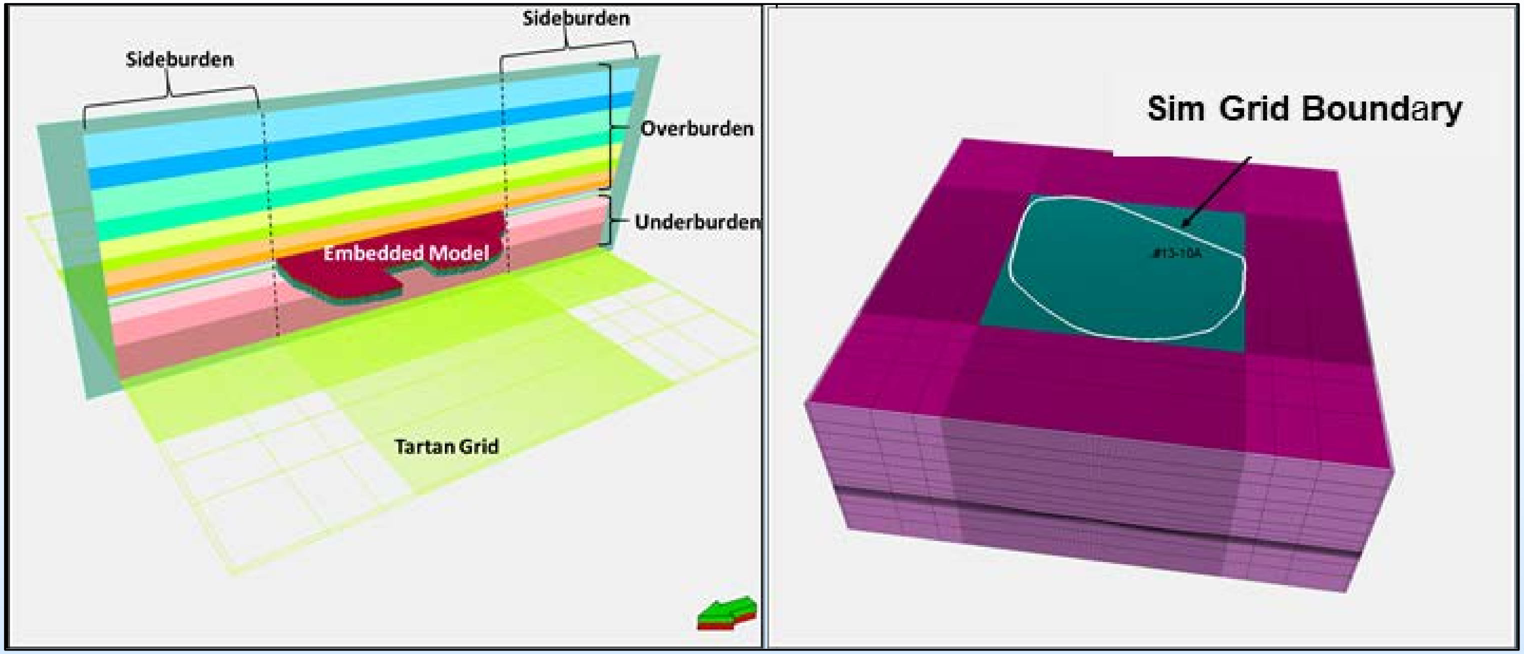
Upscaled Model





- Reservoir hydrodynamic properties were interpolated on a fine scale stratigraphic/structural framework utilizing a hydraulic flow unit (HFU) methodology based on the *Winland R35* method was used.
- The fine scale model was upscaled for area of interest, for a total of 229,504 cells that are 100 ft on a side.
- Reservoir porosity ranges from 9.2% to 24% with a mean of 14.6%. Permeability ranges from 0.01 mD to 181 mD with an average value of 58 mD.

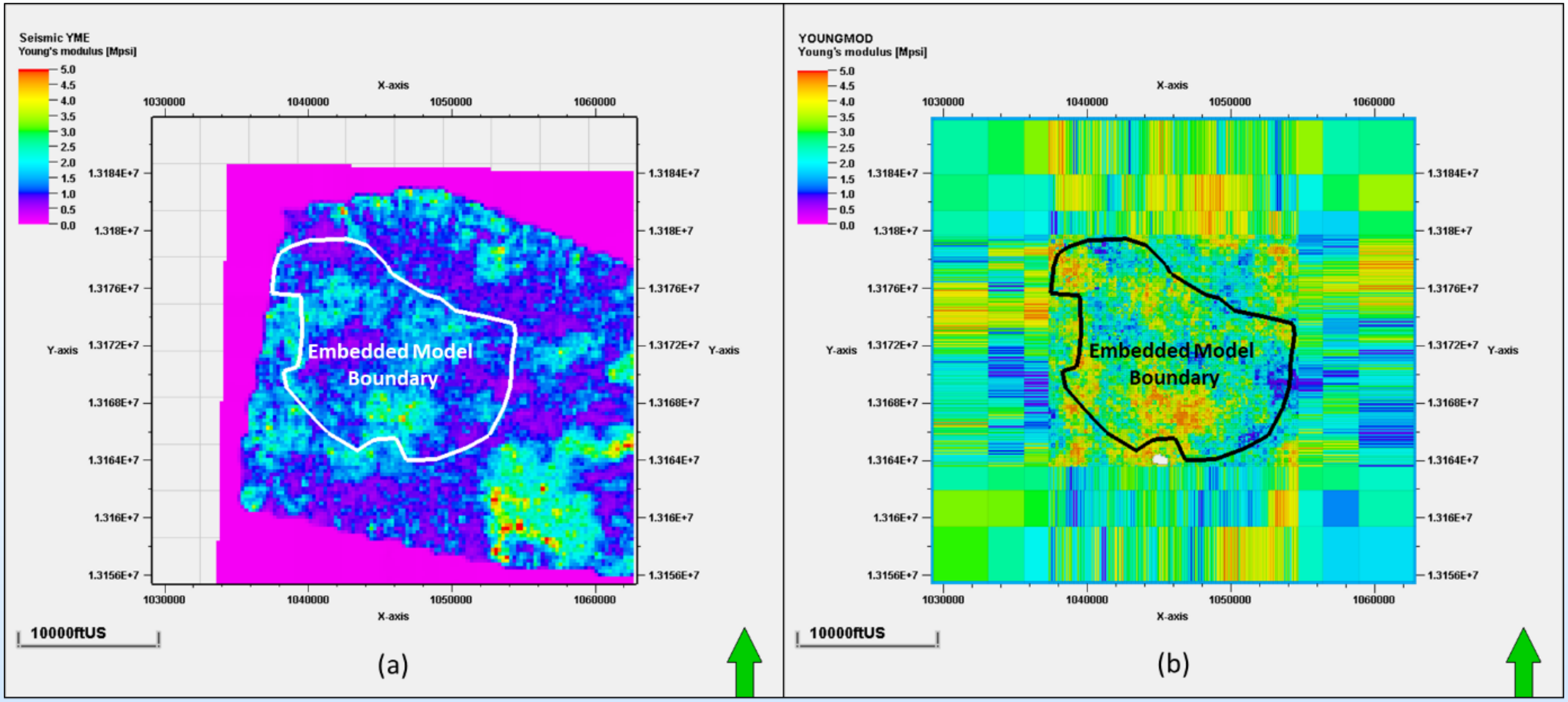
Static Mechanical Earth Model



- For coupled modeling the mechanical grid is constructed around the simulation in order to apply important estimated stress/strain boundary conditions. The simulation grid is “embedded” within the mechanical grid.

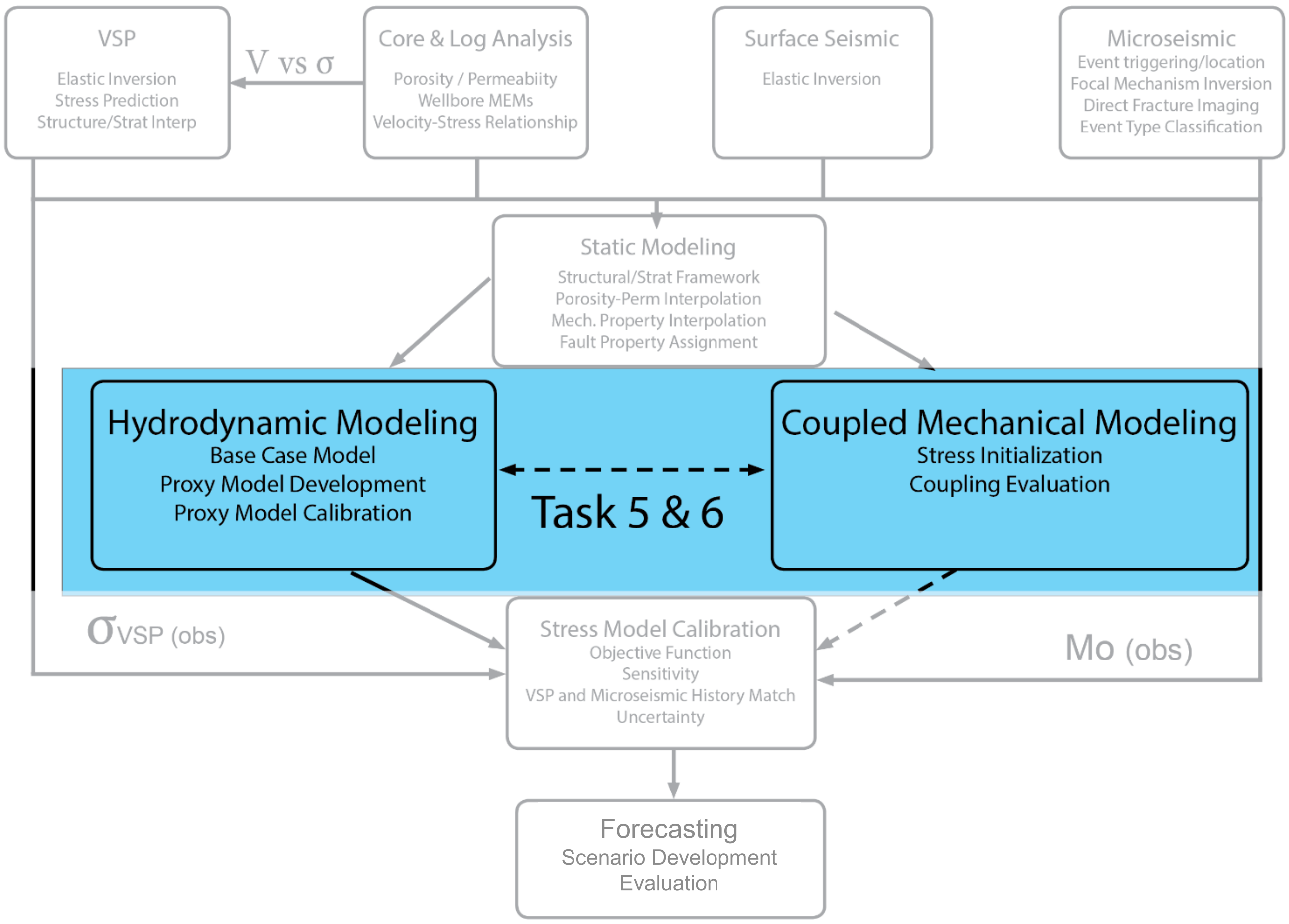
- The “tartan” grid structure is consistent with the simulation grid and refined in X,Y, and Z and coarsens outside the embedded area for computational efficiency.

Static Mechanical Earth Model



- Mechanical moduli and other properties were interpolated into the mechanical grid through geostatistical integration of geophysical log derived mechanical properties and seismic inversion products.
- Due to incomplete coverage seismic coverage and the limited mechanical log data, variograms from seismic data were used as a proxies for geostatistical extrapolation of mechanical properties through co-simulation with well log data.

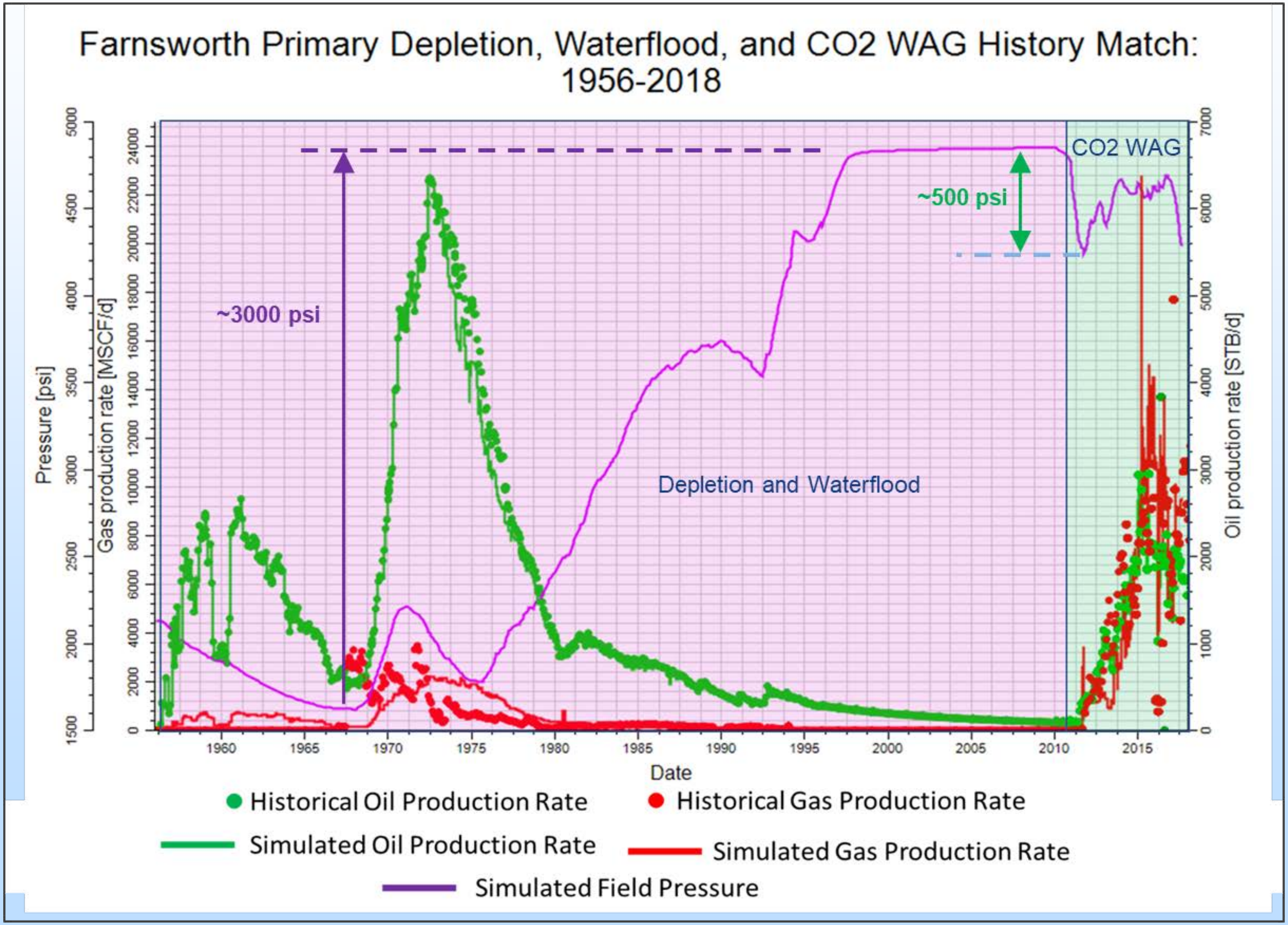
Methodology: Dynamic Modeling



Coupled Simulations

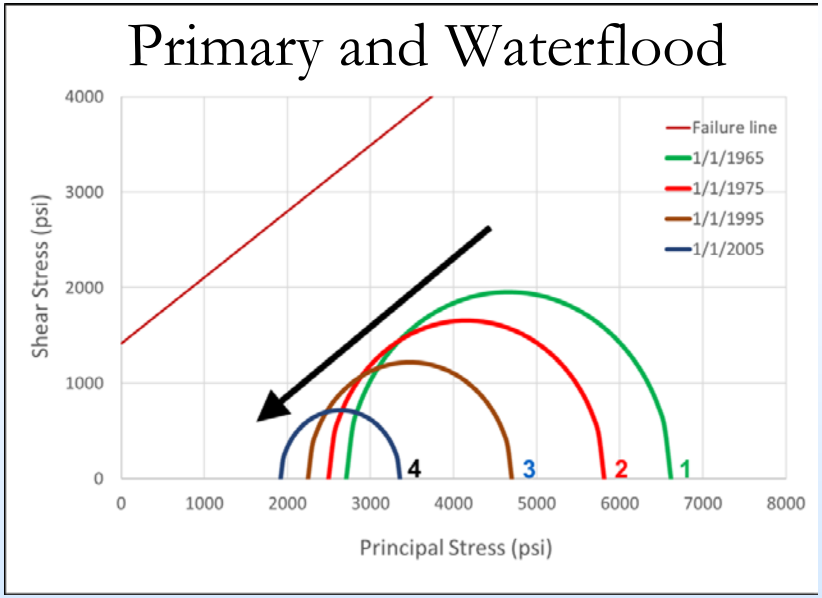
- Coupled simulations were run for depletion-waterflood and CO_2 WAG periods to investigate importance of stress dependent permeability on reservoir performance and geomechanical state.
- Permeability is updated at selected pressure steps using Kozeny-Carman relationship where porosity change is a function of total volumetric strain from initial condition.
- Stress dependent permeability measurements on core are under way at NMT.

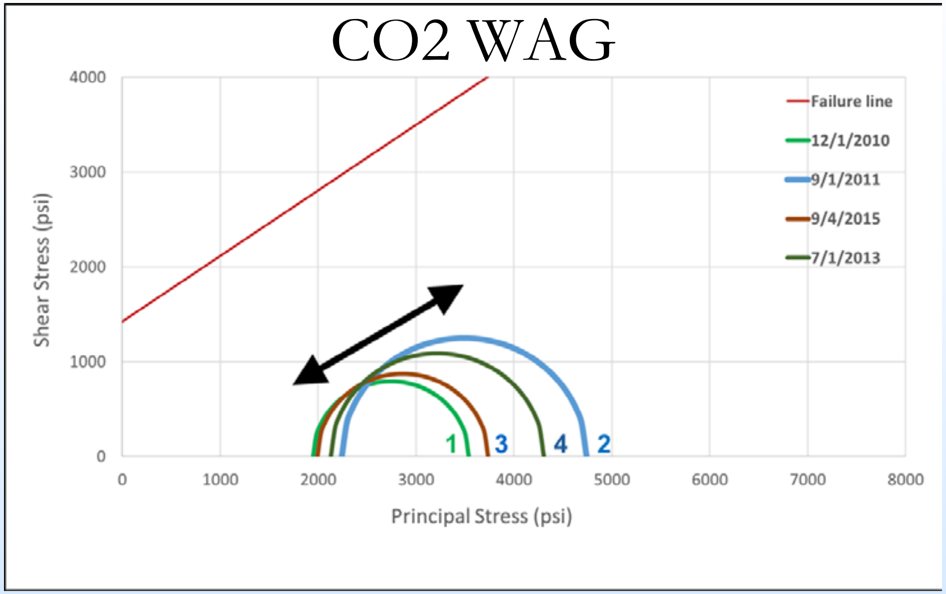
Flow Simulation Model History Match



Coupled Mechanical Modeling

Effective Stress Behavior

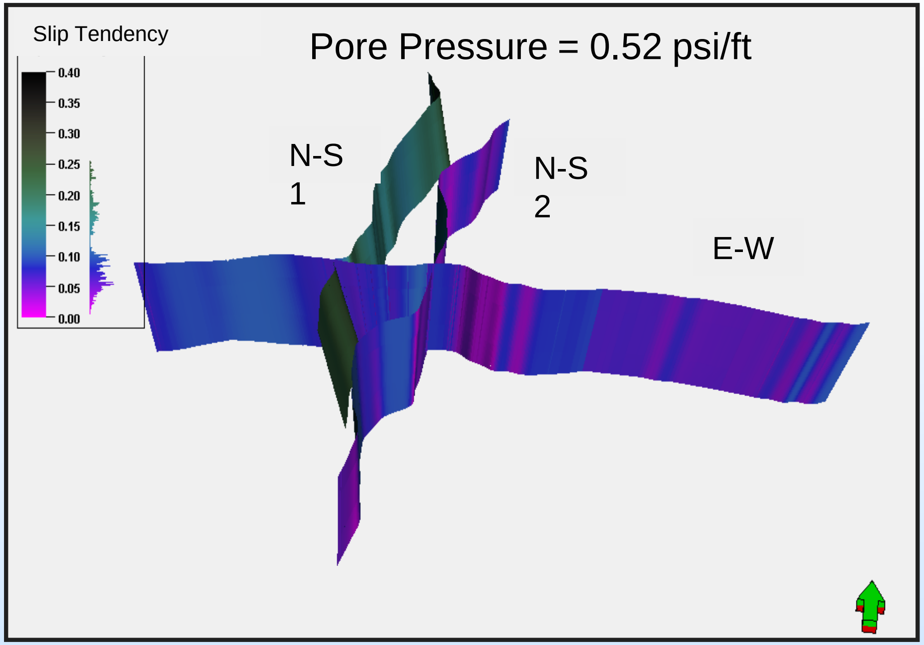


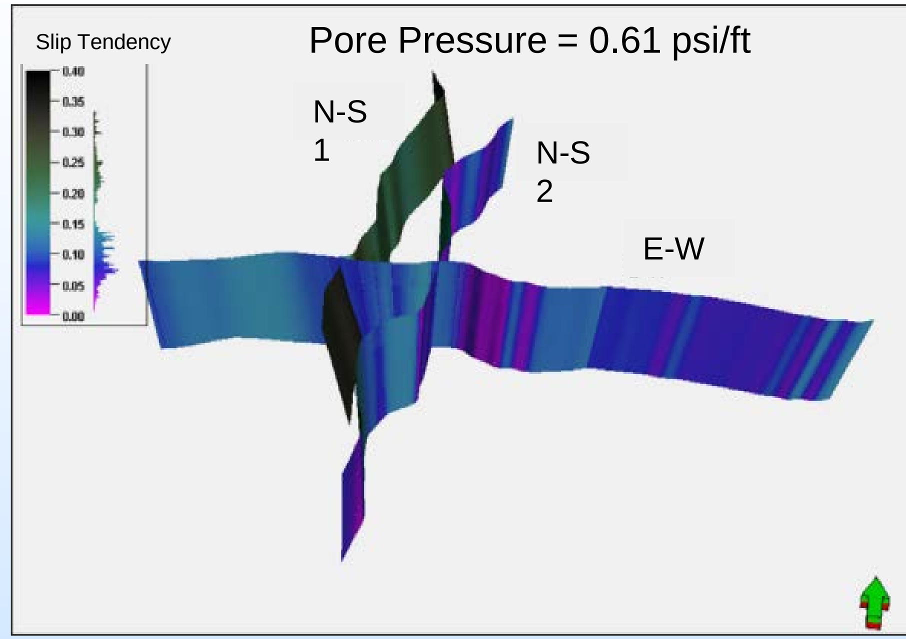


- During the waterflood period the reservoir experienced a monotonic 3000+ psi increase in reservoir pressure and corresponding decrease in a net incease in effective stress. This net effective stress change translates into net volumetric stress change.
- During the CO2 WAG period the reservoir experienced ~500 psi cyclic pore pressure cycles resulting in negligible net change in effective stress.
- During coupled simulations porosity is updated as a function of effective stress.
- During 2 way coupled simulations reservoir permeability is updated as a function of porosity.

Coupled Mechanical Modeling

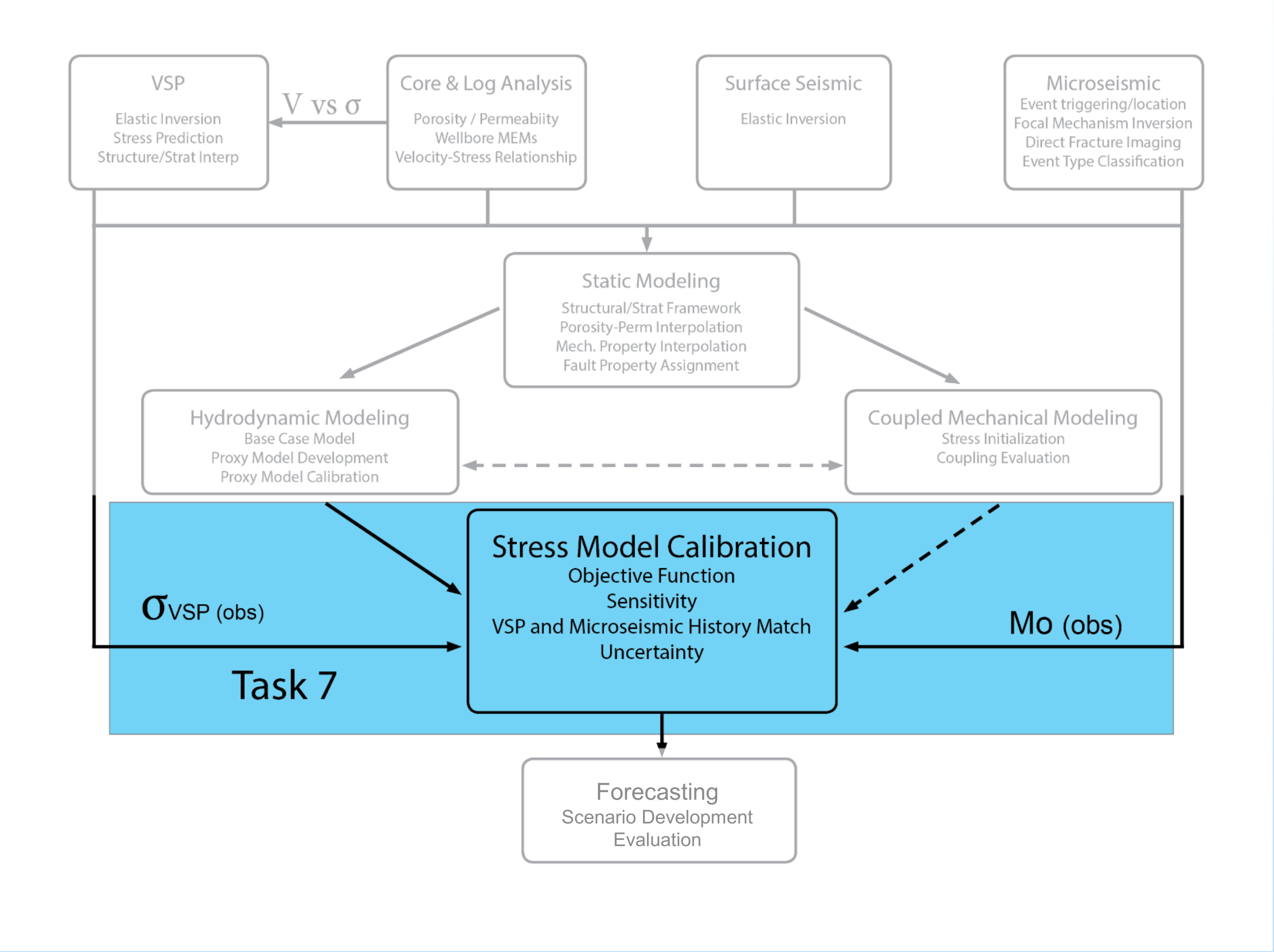
Fault Stability vs Pore Pressure





- Slip tendency is the ratio of shear to normal stress
- Cohesionless fault: $\mu = T_s = \frac{\tau}{\sigma_n'} = \frac{\tau}{\sigma_n - P_p}$
  - μ: coefficient of friction, T_s: Slip Tendency, τ: Shear stress, σ_n: normal stress,
  - σ'_n: effective normal stress, P_p: pore pressure
- Faults are stable within range of uncertainty in estimated pore pressure.

Methodology: Model Calibration



Machine Learning: Proxy Modeling and Inversion

Reservoir Characteristic Data
(Class ***A*** data)

Characterization
- Seismic data
- VSP data
- Well logs
- Core data
- Mechanical data
- Microseismic
- etc.

Fluid properties
- PVT data
- Fluid composition
- etc.

Rock/fluid interaction
- Relative permeability
- Capillary pressure
- etc.

Engineering Design Parameters
(Class ***B*** data)

- Injection/production well specification
- Pattern design
- Well spacing
- Injection timeline
- Injection fluid
- Other project-specific design parameters
- etc.

Project Response Data
(Class ***C*** data)

- Oil production data
- Gas production data
- Water production data
- Pressure data
- Stress from VSP
- Moment Magnitude
- etc

In this project we will train two different version of proxies to assist the history matching:

1 - Forward-looking *Proxy*: $A \times B \rightarrow C$

2 - Inverse History matching *Proxy*: $C \ / \ B \rightarrow A$

Machine Learning: Proxy Modeling and Inversion

Reservoir Characteristics (Class *A* Data)

Engineering Design (Class *B* Data)

Project Response (Class *C* Data)

Characterization
- Seismic data
- VSP data
- Well logs
- Core data
- Mechanical data
- Microseismic
- etc.

Fluid properties
- PVT data
- Fluid composition
- etc.

Rock/fluid interaction
- Relative permeability
- Capillary pressure
- etc.

- Injection/production well specification
- Pattern design
- Well spacing
- Injection timeline
- Injection fluid
- Other project-specific design parameters
- etc.

- Oil production data
- Gas production data
- Water production data
- Pressure data
- Stress from VSP
- Moment Magnitude
- etc

We will train two different version of proxies to assist the history matching:

1. Forward-looking *Proxy*: *A* × *B* → *C*
2. Inverse History matching *Proxy*: *C* / *B* → *A*

Machine Learning Applications

- Clustering and classification in data integration for static (geol, geoph, geomech)
- Automated seismic structural (fault/fracture) interpretation
- Proxy modeling and optimization for flow/geomechanical simulation calibration and forecasting
- Deep Learning for Microseismic event triggering (Dynamic Detector Tuning)
- Clustering/Classification of MS events based on event attributes and waveforms
- MS event phase Identification (First-P vs. not-First-P phase).

Accomplishments to Date

- Well mechanical earth models
  - Calibrated mechanical properties
  - Minimum stress characterization
- Core and log velocity stress analysis
- Joint Time-lapse VSP Inversion
- Seismic elastic inversion and geomodel update in progress
- Preliminary coupled modeling
  - Fault stability analysis
  - 1-way vs 2-way coupling with permeability updating
- Various conference presentations and publications (SPE, EAGE, AGU, CMTC, GSA)

Lessons Learned/Unanticipated Results

- **Maximum Horizontal Stress**: Lack of suitable data (DFIT, Minifrac, etc) for calibration of maximum stress will necessitate estimation by finite element modeling of borehole deformation and breakouts. This may have to be done anyway because of the requirement for more than a single depth point calibration at the reservoir interval.
- **Mapping of Basement Structure:** Due to depth to basement and overlying formation density the basement cannot be mapped with the available gravity data. However, deep seismic reflectors will be correlated from other parts of the basin mapped in the basin study.
- **Structure/Stratigraphic Reinterpretation:** Seismic reprocessing and reinterpretation of some previously mapped faults to depositional features adds valuable insight to interpretation of basin stress history.

Lessons Learned/Unanticipated Results

- **Reservoir Under-pressure:** The under-pressured state of the Morrow B formation at discovery has been known and comprehended in all reservoir simulation work performed to date. However, understanding the in-situ stress-strain conditions the in the under-pressured state will be pivotal for modeling current rock stress-velocity behavior.
- **Antrhopogenic Seismic Noise:** The Seismic monitoring array is detecting various forms of anthropogenic noise from as-yet unidentified sources. Some naturally occurring or "induced" events are visible. Potential noise sources are road traffic, submersible and surface pumps, agricultural irrigation mechanisms, and generators.

Lessons Learned/Unanticipated Results

- **Shallow "induced" Microseismicity:** Analysis of data from the analog array suggests an event source approximately 500' from the monitoring array, located in depth approximately at the top of the Kansas City formation and coincident with significant mechanical property anomalies and borehole failure. The frequency of these events appears to be correlated with injection activity at the nearest injector with an approximate ~7 day lag.
- **Poor Analog Microseismic Waveforms:** It has been determined that, although providing unique insights into possible correlation between event activity and geomechanical subsurface state, due to excessive noise, the legacy SWP microseismic data will not support analysis requiring stable event waveforms.
- **Digital Borehole and Surface Arrays:** The stress model calibration will rely on new data from the digital borehole and surface stations (and VSP).

Synergy Opportunities (1)

- The technologies presented during this session are mainly focused on laboratory and field direct and non-direct measurements of stress.
- While direct measurements of stress are possible in the laboratory and some borehole scenarios, methods for estimating in the inter-well space suffer from ambiguity resulting in non-unique interpretation.
- Data ambiguity may be phenomenological, spatial, or temporal.
- Our work recognizes this problem and is focused on developing the framework for treating such ambiguities through 3D joint multi-physics inversion incorporating time-lapse observations.
- Computational challenges are treated through a combination of machine learning techniques for forward modeling and model inversion.
- Each new measurement technology and/or constitutive model derived from measurements, whether direct or indirect, may be incorporated as an observation or constraint within this framework.
- Each (unique) observation incrementally reduces ambiguity, improving stress estimation.

Project Summary

Key Findings

Geomechanical Data Analysis:

- Analysis of mechanical logs and core tests have established key rock properties in two characterization wells. Variable borehole deformation throughout the vertical section provides insights to vertical stress profile. Core analysis indicated stress sensitive velocities with confining pressure.
- Basin development studies provide possible mechanism for under-pressure in reservoir at discovery presenting a potential change in the interpretation of stress-strain and stress-velocity dependence under current conditions.

Seismic Analysis:

- Depth imaging and reinterpretation of 3D surface seismic data within the context of the basin development study has resulted in reinterpretation of some previously mapped faults to depositional features (karst collapses, differential compaction boundaries).
- Initial joint time-lapse VSP inversion results in stable yet low amplitude time-lapse differences generally consistent with prior rock physics modeling studies.

Project Summary

Key Findings

Static Modeling

- Based on the geomechanical data analysis and specific project objectives the new geological model grid has been developed with larger lateral and vertical extents, rotated orthogonal to estimated horizontal principle stress directions.
- Existing SWP model has been used to support preliminary coupled model investigations.

Coupled Modeling

- Preliminary coupled modeling results indicate that faults are stable (slip tendancy <~0.25) and reservoir is not near failure.
- 1-way versus 2-way coupling tests suggests that for coupling requirements may vary between primary/waterflood and WAG simulations. Model initialization may require 2-way coupling while short term WAG simulations might not.

Project Summary

Next Steps

- FE modeling of borehole deformation/failure for stress initialization.
- Detailed analysis of under-pressured reservoir stress and rock failure condition.
- Complete new static geological and mechanical earth models.
- Calibrate new reservoir simulation model with machine learning proxy model technique.
- Commence development of coupled simulation proxy model.
- Begin evaluation of microseismic data for event location, characterization, and machine learning applications.

Thank You …

Questions?

Appendix

Project 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.

Program Goals Addressed

- ✓ To "develop capabilities to predict the **pressure migration and the geomechanical impacts** of this pressure in the storage complex."
- ✓ To "**integrate geomechanical impacts into models to assess and mitigate risk**, including studies of faults, fractures, and seismicity from pressure changes related to injection, ..."
- ✓ "… to be **demonstrated in a relevant field environment** or applied to relevant field data for validation."
- ✓ **Predict, and compare with field observations**, the temporal and spatial stress and pressure changes in the underburden (particularly in the basement) which result from injection
- ✓ **Reduce the uncertainty in detection** of faults and fractures and the prediction of their movements.

Benefit Statement

The proposed project will benefit the detection and assessment of stored CO_2 within injection formation through development of:

- A method for integration of a collection of production and monitoring data with multiple physics, spatial, and temporal sampling characteristics, to reduce reservoir model uncertainty.
- A generalized methodological framework which may be extended to arbitrary collections of oilfield production and monitoring data.
- A probabilistic methodology which facilitates reservoir model forecasting with realistic uncertainty.
- A complementary probabilistic economic analysis based on joint inversion outcomes.

Expected Project Outcome

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.

Intermediate outcomes include;

- Products from several state-of-the-art geotechnical data analyses.
- Geological and geomechanical models developed from the outputs of geotechnical analyses using geostatistical and machine learning methods.
- A high fidelity compositional flow simulation model calibrated using machine learning (proxy modeling and optimization) techniques.
- A coupled flow-geomechanical simulation model which includes structural features derived from geotechnical data analyses and calibrated to stress observations.

Project Overview (1):

SOPO Goals, Objectives, Success Criteria

Goal: Development of a structural and stratigraphic framework model that is consistent with basin history and fault kinematic principles.

Success Criteria: Structural components will be consistent with plausible stress history and rock mechanical interpretation. Mechanical model will achieve a stable initial condition.

Project Overview (2):
SOPO Goals, Objectives, Success Criteria

Goal: Use of machine learning for extraction of structural and stratigraphic features from multiple seismic volume attributes including edge detection and azimuthal anisotropy.

Success Criteria: Explicit and implicit structural fractures (faults and fractures).

Project Overview (3):

SOPO Goals, Objectives, Success Criteria

Goal: Use of a novel elastic-waveform inversion technique on time lapse VSP data to estimate high-resolution spatial and temporal changes in stress/pressure.

Success Criteria: Statistically reliable and mechanically consistent estimation of velocity-stress relationship.

Project Overview (4):

SOPO Goals, Objectives, Success Criteria

Goal: Joint inversion of clustered microseismic data for focal mechanisms of microseismic events, and use of least-squares reverse-time migration of microseismic waveform data to image fracture/fault zones directly.

Success Criteria: Delineation of fault and fracture geometry and determination of principal stress direction.

Adaptive Joint Moment Tensor Inversion

Joint inversion: events in a cluster are inverted using the same focal mechanism
(strike, dip, rake, ISO and CLVD) but different source durations and moments

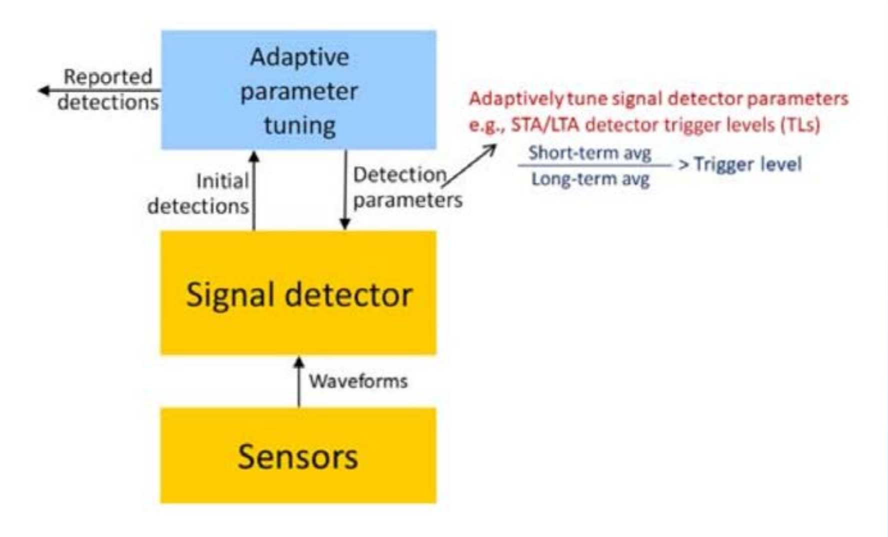
Adaptive inversion: each event is further inverted based on the joint inversion
result with a search range of $\pm 10°$ for strike, dip and rake, ± 0.05 for ISO and
CLVD

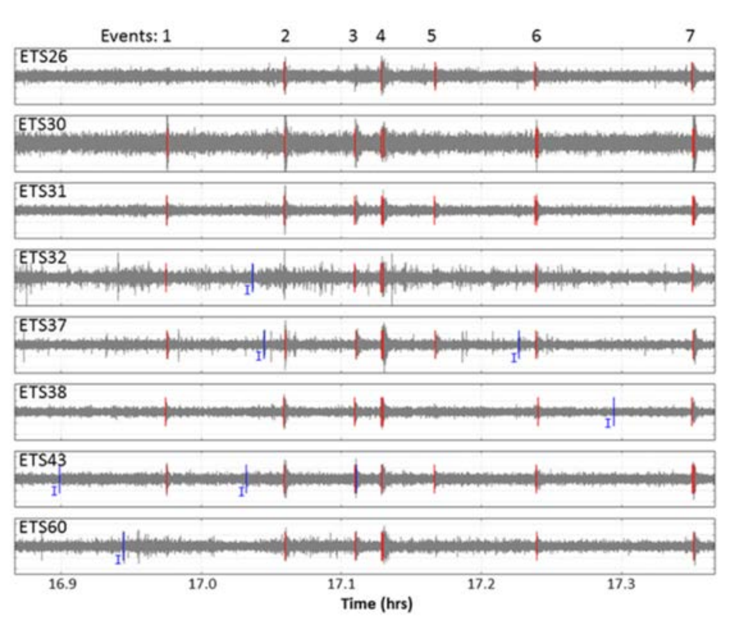
Project Overview (5):
SOPO Goals, Objectives, Success Criteria

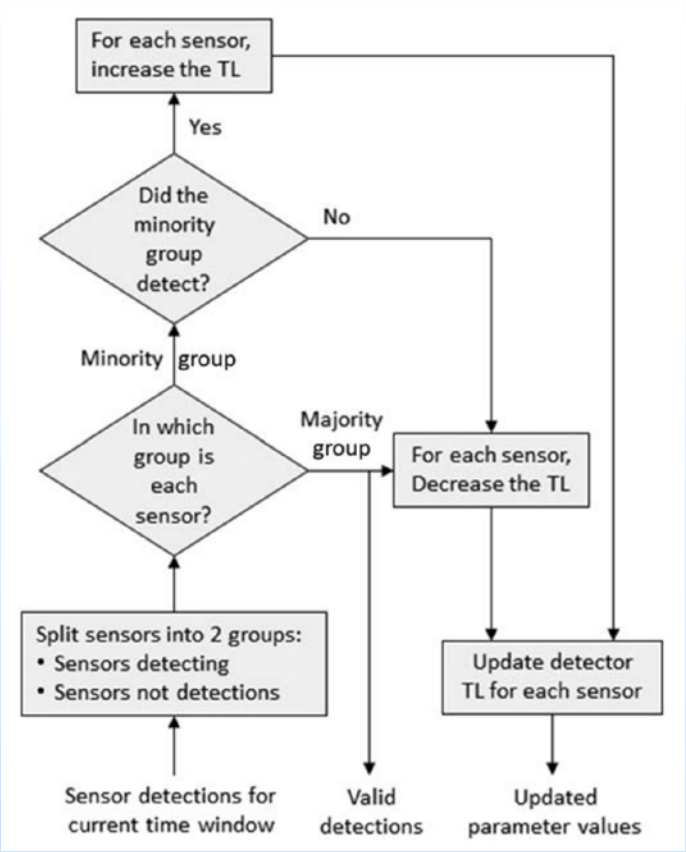
Goal: Use of deep neural network machine learning with convolutional and recurrent layers for classification of microseismic events.

Success Criteria: Demonstration of superior performance of the classification of microseismic events against a state-of-the-art approach on a held-out test set.

Dynamic Detector Tuning







Timothy J. Draelos, Matthew G. Peterson, Hunter A. Knox, Benjamin J. Lawry, Kristin E. Phillips-Alonge, Abra E. Ziegler, Eric P. Chael, Christopher J. Young, and Aleksandra Faust; Dynamic Tuning of Seismic Signal Detector Trigger Levels for Local Networks, Bulletin of the Seismological Society of America,

Project Overview (6):
SOPO Goals, Objectives, Success Criteria

Goal: Integration of available geological, geophysical, and mechanical characterization data and analyses to develop a high resolution MEM.

Success Criteria: Consistency with wellbore mechanical model and achievement of equilibration/initialization.

Project Overview (7): SOPO Goals, Objectives, Success Criteria

Goal: Development of a history-matching framework using a proxy model with machine learning and optimization techniques.

Success Criteria: Achieving acceptable minimization of objective function.

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)

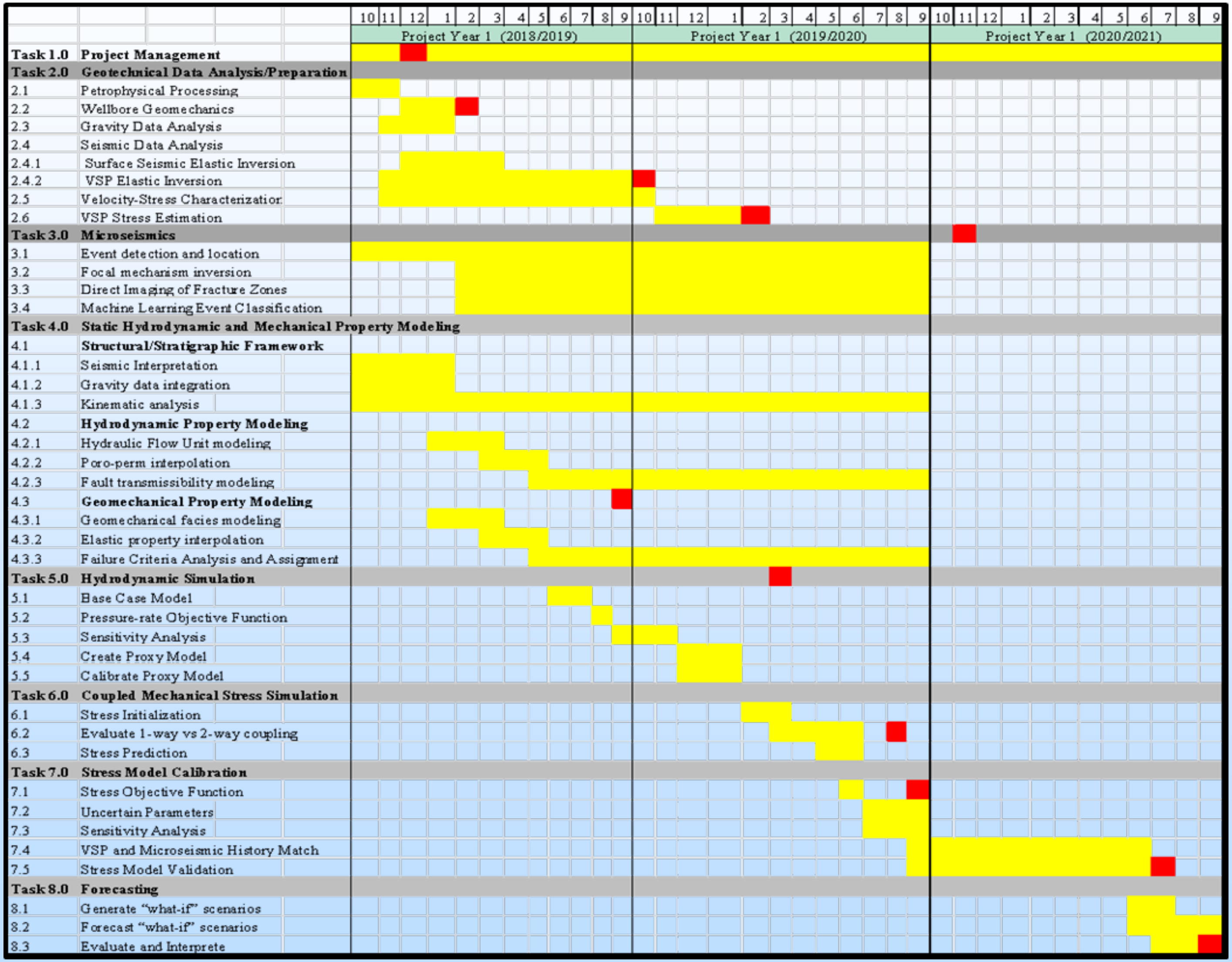
Consultants

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


10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9
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

Bibliography

– List peer reviewed publications generated from the project per the format of the examples below.

- Journal, one author:
  - Gaus, I., 2010, Role and impact of CO_2-rock interactions during CO_2 storage in sedimentary rocks: International Journal of Greenhouse Gas Control, v. 4, p. 73-89, available at: XXXXXXX.com.
- Journal, multiple authors:
  - MacQuarrie, K., and Mayer, K.U., 2005, Reactive transport modeling in fractured rock: A state-of-the-science review. Earth Science Reviews, v. 72, p. 189-227, available at: XXXXXXX.com.
- Publication:
  - Bethke, C.M., 1996, Geochemical reaction modeling, concepts and applications: New York, Oxford University Press, 397 p.