Recent Advancements in Mechanical Earth Modeling at Farnsworth Unit, Texas, USA*

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Abstract

The Southwest Partnership on Carbon Sequestration (SWP) administers a CO_2 carbon capture utilization and storage (CCUS) project sponsored by the U.S. Department of Energy. The SWP project is located in a mature waterflood undergoing conversion to CO_2 enhanced oil recovery (EOR) at Farnsworth, Texas, USA, operated by Perdure Petroleum LLC. Utilized CO_2 is anthropogenic, and the field has 15 active injection patterns established between October of 2010 and December of 2016. Major project goals are optimizing the storage/production balance, ensuring storage permanence, and developing best practices for CCUS. A key component of this effort is generating detailed geologic and flow models.

This presentation provides a review of work performed toward the development of a 3D coupled Mechanical Earth Model (MEM) for use in assessment of caprock integrity, fault reactivation potential, and evaluation of stress dependent permeability in reservoir forecasting. Mechanical property estimates computed from geophysical logs at selected wellbores were integrated with 3D seismic elastic inversion products to create a 3D “static” mechanical property model sharing the same geological framework as existing reservoir simulation models and includes three major faults. Stresses in the MEM were initialized from wellbore stress estimates and reservoir simulation pore pressures. One way and two way coupled simulations were performed using Schlumberger’s Eclipse 300 and Visage compositional flow and geomechanical solvers through the PETREL GM workflow environment.

Coupled simulations were performed on history matched primary, secondary (waterflood), and tertiary (CO2 WAG) recovery periods, as well as an optimized WAG prediction period. These simulations suggest that the field has been operating at conditions which are not conducive to either caprock failure or fault reactivation. Two way coupled simulations were performed in which permeability was periodically updated as a function of volumetric strain using the Kozeny-Carmen porosity-permeability relationship. These simulations illustrate the importance of frequent permeability updating when recovery scenarios result in large pressure changes such as in field re-pressurization through waterflood after a long primary depletion recovery period. Conversely, production forecasting results are less sensitive to permeability update frequency when pressure cycles are short and shallow as in WAG cycles.

The ongoing mechanical modeling effort continues to provide valuable insights into reservoir hydraulic and mechanical behavior at FWU and will be used as the starting point for new research into reservoir stress and seismic risk under another DOE funded project.

Funding for this project is provided by the U.S. Department of Energy under Award No. DE-FC26-05NT42591. Additional support has been provided by site operator Perdure Petroleum LLC.

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RECENT ADVANCEMENTS IN MECHANICAL EARTH MODELING AT FARNSWORTH UNIT, TEXAS, USA

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Presentation Outline

- SWP Overview
- Coupled Hydrodynamic/Geomechanical Modeling Workflow Overview
- Petrophysical-Mechanical Modeling
- FWU Life-of-Field Coupled Modeling
- Integrated Stress Model Calibration Workflow
- Stress-Strain-Velocity Evidence in Log and Core

Presenter's notes:

1 -We'll start with a very brief overview of the SWP project
2 - We'll then review the workflow used for our coupled geomechanical modeling
3 - We'll review key petrophysical and mechanical data used to create our models and see how these were brought together to create our 3D coupled mechanical earth model
4 - We'll see this model applied to the Farnsworth field through coupled simulations extending approximately 50 years of field development from primary depletion, through waterflood, and recent, early stages of CO_2 WAG EOR
5 – We'll look at how this work fits into our overall strategy for the stress modeling project with machine learning
6 – We'll review evidence of stress in borehole data which we intend to incorporate into calibration of our stress estimation model

Southwest Regional Partnership - Farnsworth

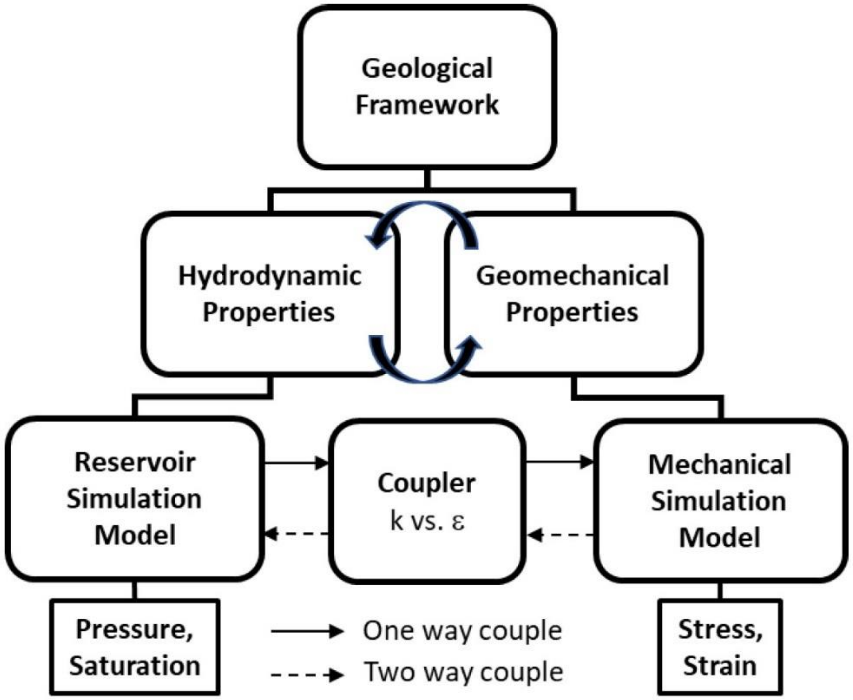
- Farnsworth Unit was discovered in 1955. Over 100 wells were completed by the year 1960.
  - Water injection for secondary recovery started in 1964.
  - CO_2 first injected in 2010.

- Anthropogenic Supply: 500-600,000 Metric tons CO_2/year supply

Presenter's notes:

Farnsworth unit is a Carbon Capture, Utilization and Storage project. CO2 is sourced from two anthropogenic sources, the Arkalon Ethanol Plant in Liberal Kansas, and the Agrium Fertilizer plant in Borger Texas shown as the blue pentagons. Over 100 miles of pipeline (in red) connect the two sources to 3 currently active projects and can be extended to several more fields in the area. Grey shaded portions of the map show oil fields in the vicinity of these two point sources of CO2. The operator built or partnered in compression and dehydration facilities at each site. Carbon cost is low, between $20 and $30 per tonne, which is important since no natural CO2 available.

Coupled Geomechanical Modeling Workflow



- Geologic model captures structure and stratigraphy and also integrates well logs and 3D seismic
- 13-10A 1D MEM elastic properties is correlated with the 3D seismic to populate geomechanical properties of the 3D MEM.
- Existing compositional hydrodynamic simulation is coupled with geomechanical computations.
- Volumetric strain reflects porosity changes and impacts permeability
  - → One Way
  - → Two Way

Presenter's notes:

This is a Block diagram of Mechanical Earth Model workflow applied at FWU. On the top we see the geological (structural and stratigraphic) framework that has been developed through combined efforts of many researchers over many years.

Next this common geologic framework is populated with hydrodynamic and geomechanical properties required for flow simulation and mechanical modeling. A combination of machine learning, Bayesian methods, and stochastic methods are used to create these models. The arrows between these two (boxes) reflect the potential correlations between geological and mechanical properties as well (*Presenter's notes continued on next slide*)

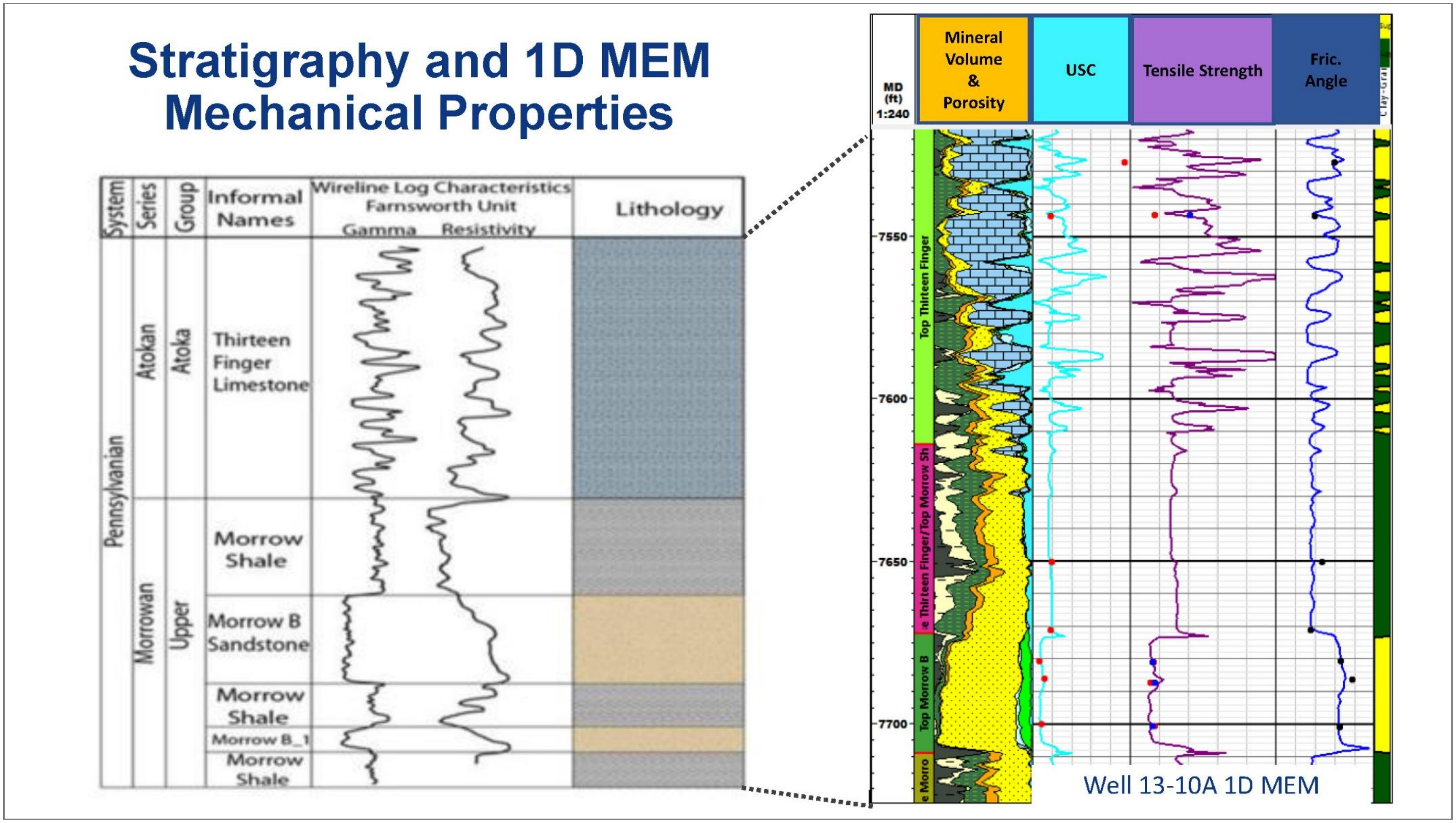
(*Presenter's notes continued from previous slide*)

as the extensive use of seismic inversion products and geophysical logs for developing all property distributions. Next, we do numerical simulations of both compositional flow and mechanical deformation. Pore pressures from flow simulations are periodically passed to the mechanical for accurate estimation of effective stresses. These simulations may, and have been, coupled in 2 ways:

1-way – No stress dependent permeability effect. Permeability changes resulting from stress induced porosity changes are NOT fed back to the simulator. Computationally, the impact of 1 way coupling is that a set of pre-existing pressure arrays at pre-selected steps can be fed sequentially to the geomechanical solver upon demand.

2-way – Porosity is modified as a function of effective stress and permeability is periodically updated using an empirical or analytical poro-perm relation. The computational impact of 2 way coupling is that the flow simulator runs in stepwise tandem with the geometrical simulator, receiving periodic modifications to the permeability distribution computed by the coupler.

In either case, the selection of pressure update times can be critical depending on the pore pressure history and stress sensitivity.



Presenter's notes:

One the left is a simplified stratigraphic section encompassing our storage unit (reservoir plus primary [morrow shale] and secondary [trfg]) seals.

On the right are mineralogy and mechanical properties (well or 1D MEM) for well -13-10A. The MEM integrates geophysical logs (sonic scanner, density, and others) and is calibrated to Geomechanical Core tests.

(*Presenter's notes continued on next slide*)

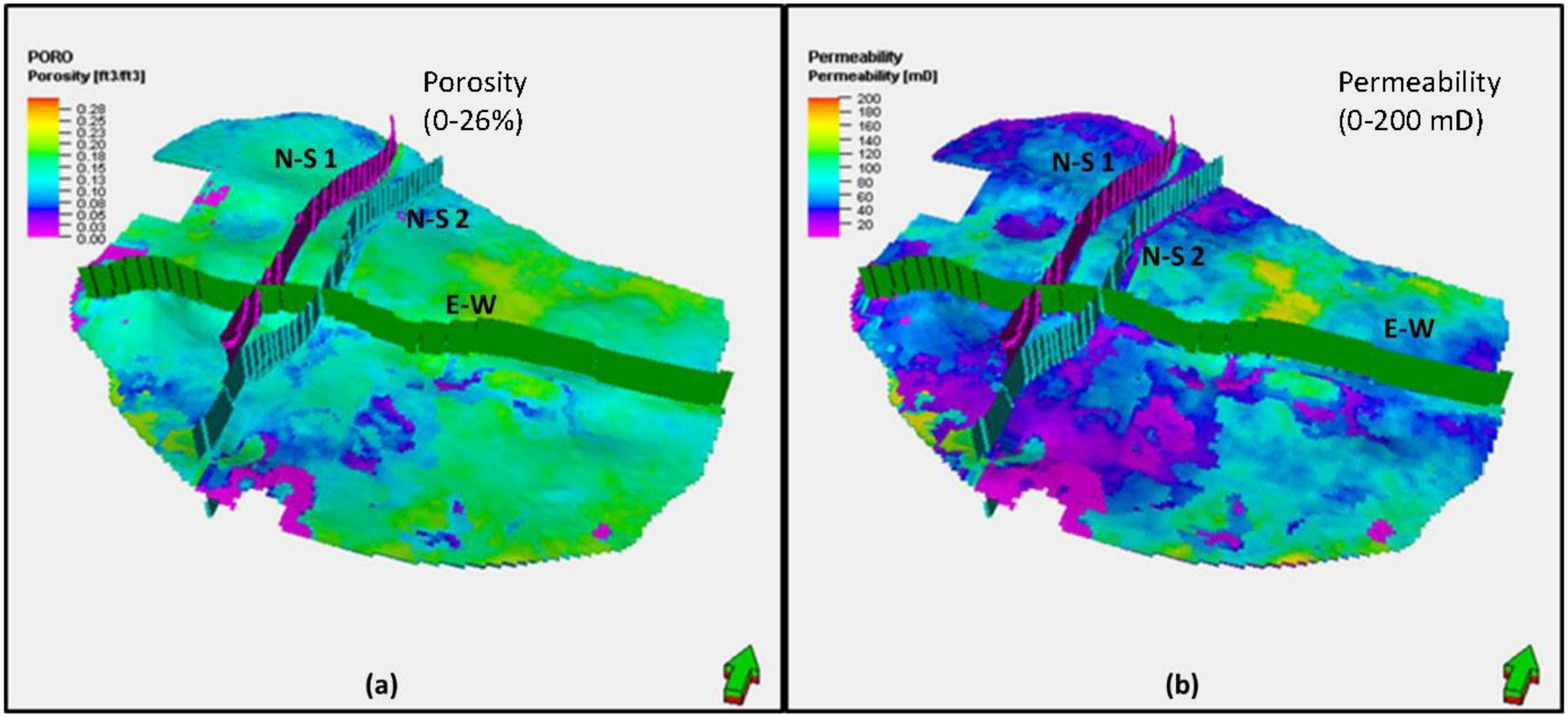
(*Presenter's notes continued from previous slide*)

The geomechanical test suite included:

- Single-Stage Triaxial (TXC) tests
- Multi-stress Compression (MSC) tests
- Unconfined Compression (UCS) tests
- Indirect Tensile Strength Tests – Brazilian method
- Ultrasonic Velocity

The dots plotted on the tracks are core data used for calibration and fitting of empirical relationships.

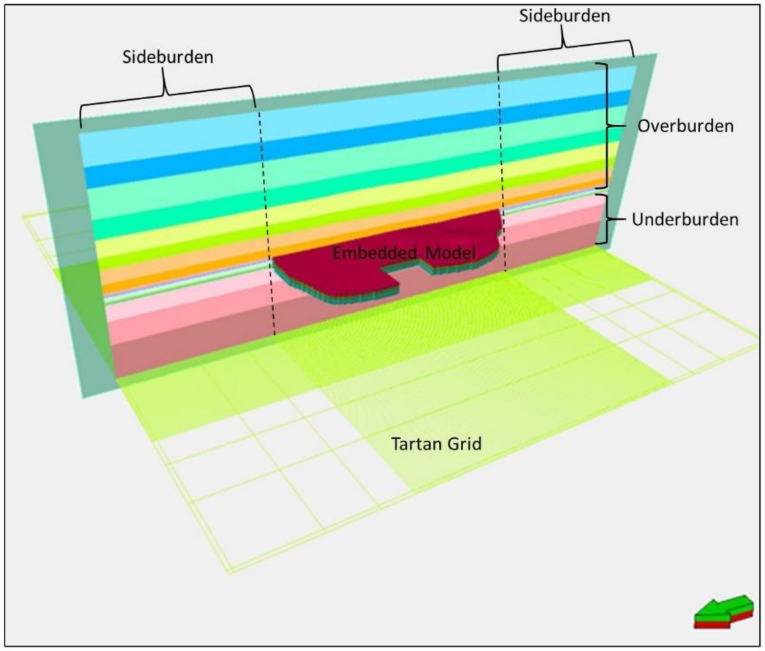
Reservoir Simulation Model Poro-Perm and Faults



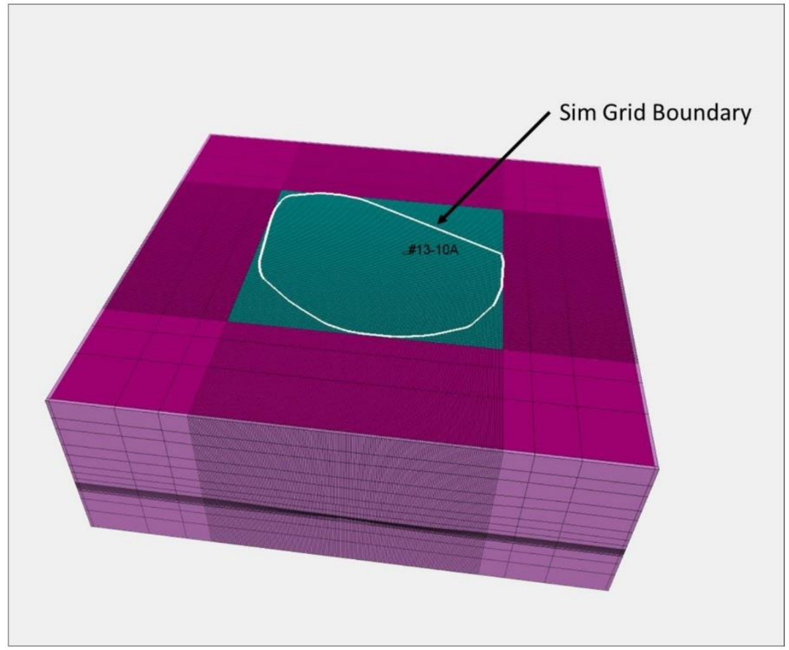
Presenter's notes:

Here we have the porosity and permeability distributions used for the existing reservoir simulation model. Also shown are model faults interpreted from 3D seismic data. The faults were present in both fluid flow and geomechanical simulations.

Sim Model Embedding for Mechanical Boundaries



Vertical slice showing grid Z-Y skeleton, layering, and over/under/side burden



3D MEM Grid

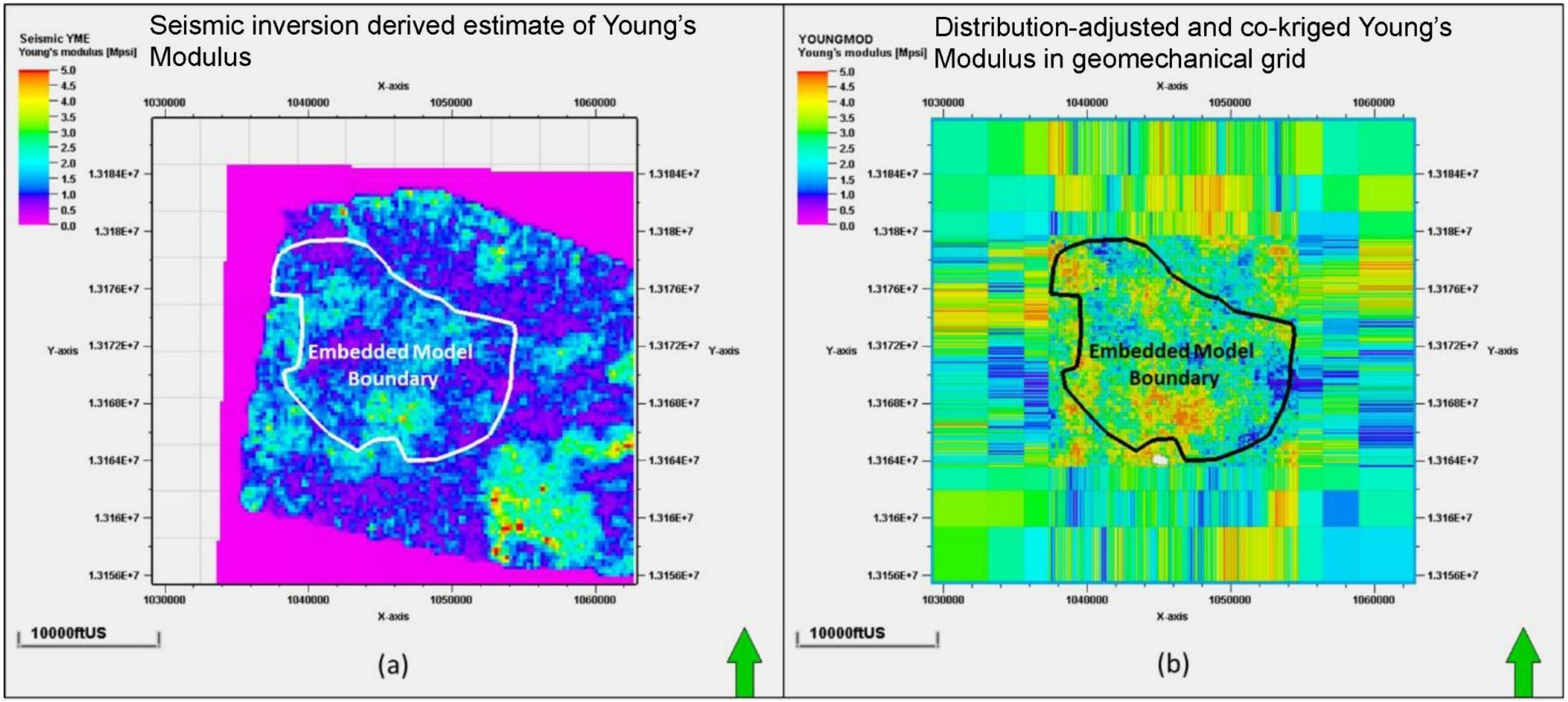
Presenter's notes:

For geomechanical modeling this flow simulation grid is embedded in a larger grid in order to apply important estimated stress/strain boundary conditions.

The left figure shows Overburden, underburden and sideburden sections. The "tartan" grid structure refined in X,Y, and Z in and proximal to the reservoir simulation grid and coarsens outward for computational efficiency.

The right figure shows the final grid with the trace of the embedded grid projected to the top of the model shown in white.

Mechanical Property Interpolation with Elastic Inversion



Presenter's notes:

Next, mechanical moduli and other properties were interpolated into the mechanical grid through geostatistical integration of geophysical log derived mechanical properties and seismic inversion products. Seismic inversion products were used to compute mechanical moduli and were co-simulated with mechanical property logs.

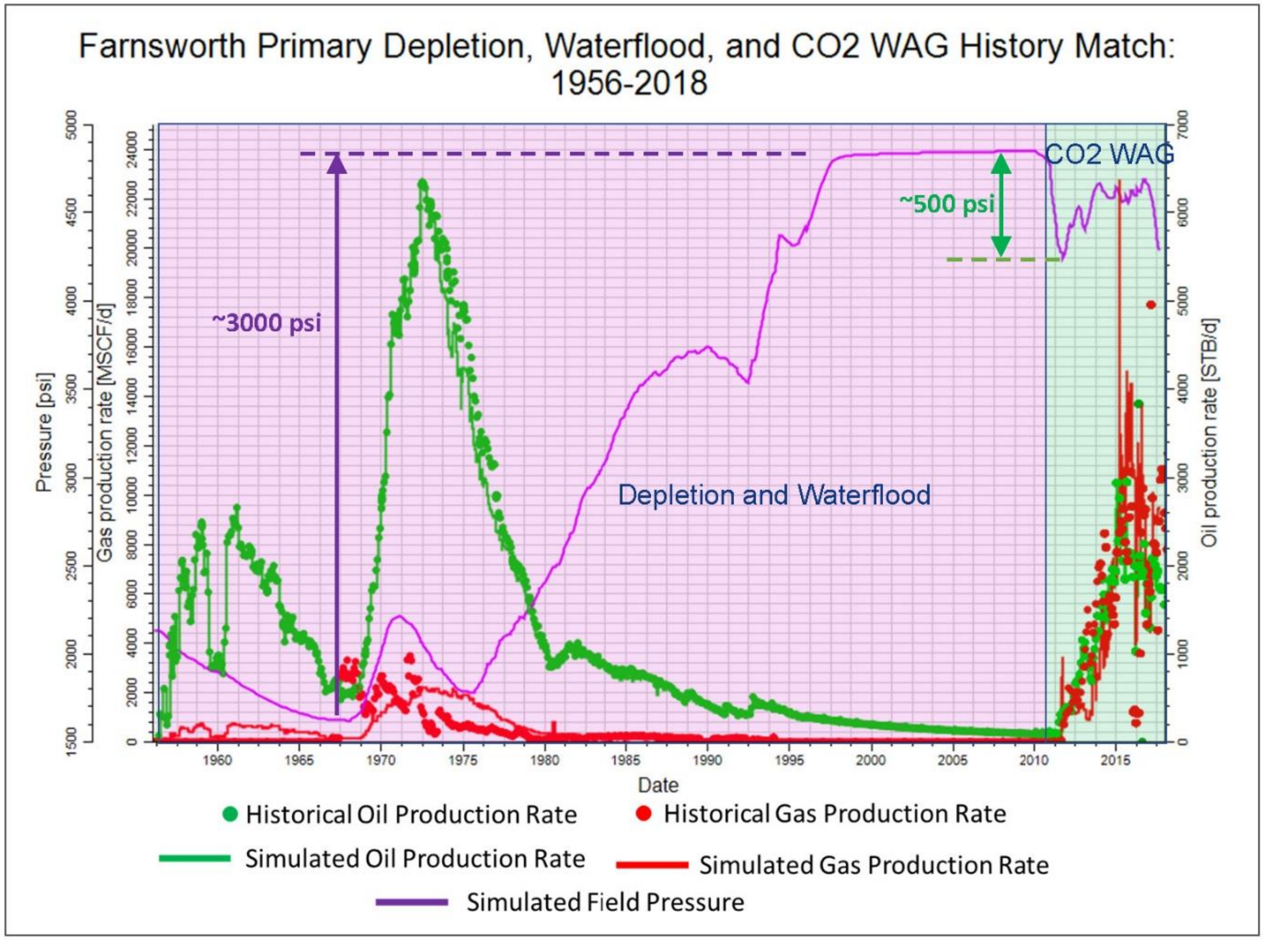
The left figure shows the seismic-derived young modulus coverage in the model area. Due to incomplete coverage seismic coverage and the limitation of insufficient mechanical log data to formulate log variograms for interpolation, variograms from seismic data were used as proxies for geostatistical extrapolation of mechanical properties through co-simulation with well log data. (*Presenter's notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

The figure on the right shows the resulting young modulus distribution in the mechanical grid. Where sufficient data exists the seismic derived properties and calibrated well log derived properties showed good correlation with magnitude differences due to measurement scale.

The change on magnitude from left figure to the right figure reflects the magnitude adjustment resulting from the geostatistical integration process. Spatial trends in the interpolated data reflect the trends in the seismic data, while univariate statistics are consistent with calibrated log data.

Oil/Gas Production History Match and Pressure History



Presenter's notes:

Now let's look at some applications of the model on the Farnsworth field.

This figure shows the simulated (solid lines) and observed (dots) oil (green) and gas (red) production from our history matched model along with simulated field pressure (magenta). (*Presenter's notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

- Starting with discovery and primary depletion recovery (~1956-!~1967) characterized by a roughly 500 psi reduction of reservoir pressure and ultimately declining production
- followed by a long period of secondary (waterflood) recovery characterized by initial increase and then decline in oil recovery and significant increase in field pressure. Reservoir pressure increased by nearly 3000 psi during the waterflood phase.
- Most recently the field has been under CO2 WAG EOR characterized by increased oil production and relatively minor pressure fluxuations within a 500 psi range.

Remember these pressure fluxuations because pore pressure has a direct impact on effective stress and resulting volumetric strain changes which could significantly impact permeability in stress sensitive reservoirs.

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.

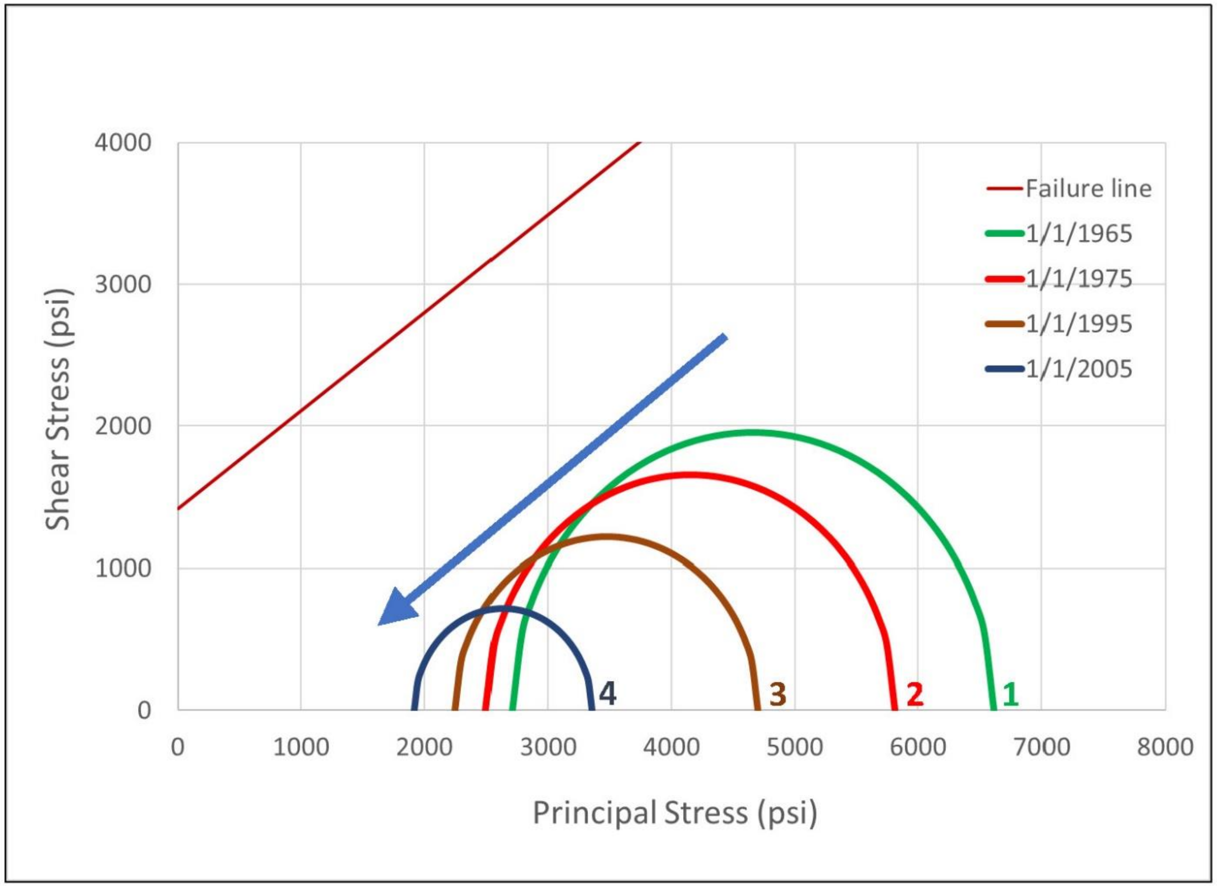
Presenter's notes:

The SWP has been using our coupled model to study various geomechanical aspects of the FWU field including caprock integrity and fault stability. What I'll present here are some of the results of our studies of the impact of stress sensitive permeabilities on coupled model results and calibration.

We did this through 2-way coupled simulations of the primary-secondary and WAG production periods which have dramatically different net pressure changes.

For our preliminary sensitivity studies we used Kozeny-Carman as our porosity-permeability functional relationship while stress dependent porosity and permeability measurements are being conducted in our lab at NMT.

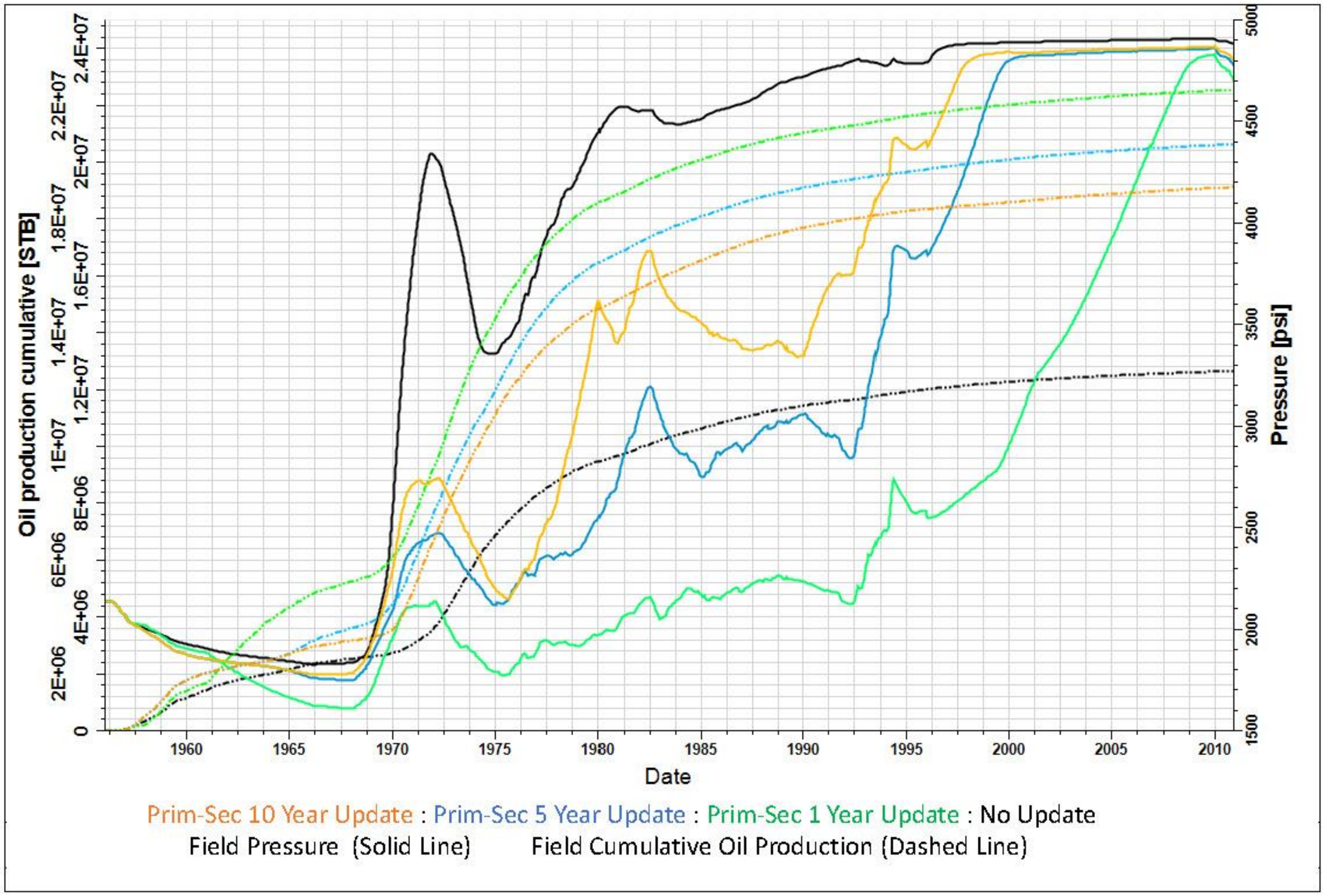
Primary and Secondary (Waterflood) Mohr Circle Analysis



Presenter's notes:

This figure shows a sequence of Mohr circles representing stress in the Morrow B during the waterflood period. The more or less monotonic 3000 psi increase in reservoir pressure observed in the field history plot results in a montonic decrease in effective stress which is reflected in the progressive reduction average total principal stress and in Min and Max principal stress differentials. This large net stress change translates into net volumetric stress change.

Impact of Permeability Updating: Primary-Waterflood Period



Presenter's notes:

Now lets look at how this effects reservoir simulation and forecasting results.

This figure shows simulated field pressure (solid lines) and cumulative oil production (dashed lines) for the primary and secondary recovery period with no permeability updating (black), 1 year updating (green) 5 year updating (blue) and 10 year updating (orange). All simulations were performed with similar well rate and bottom hole pressure controls.

(*Presenter's notes continued on next slide*)

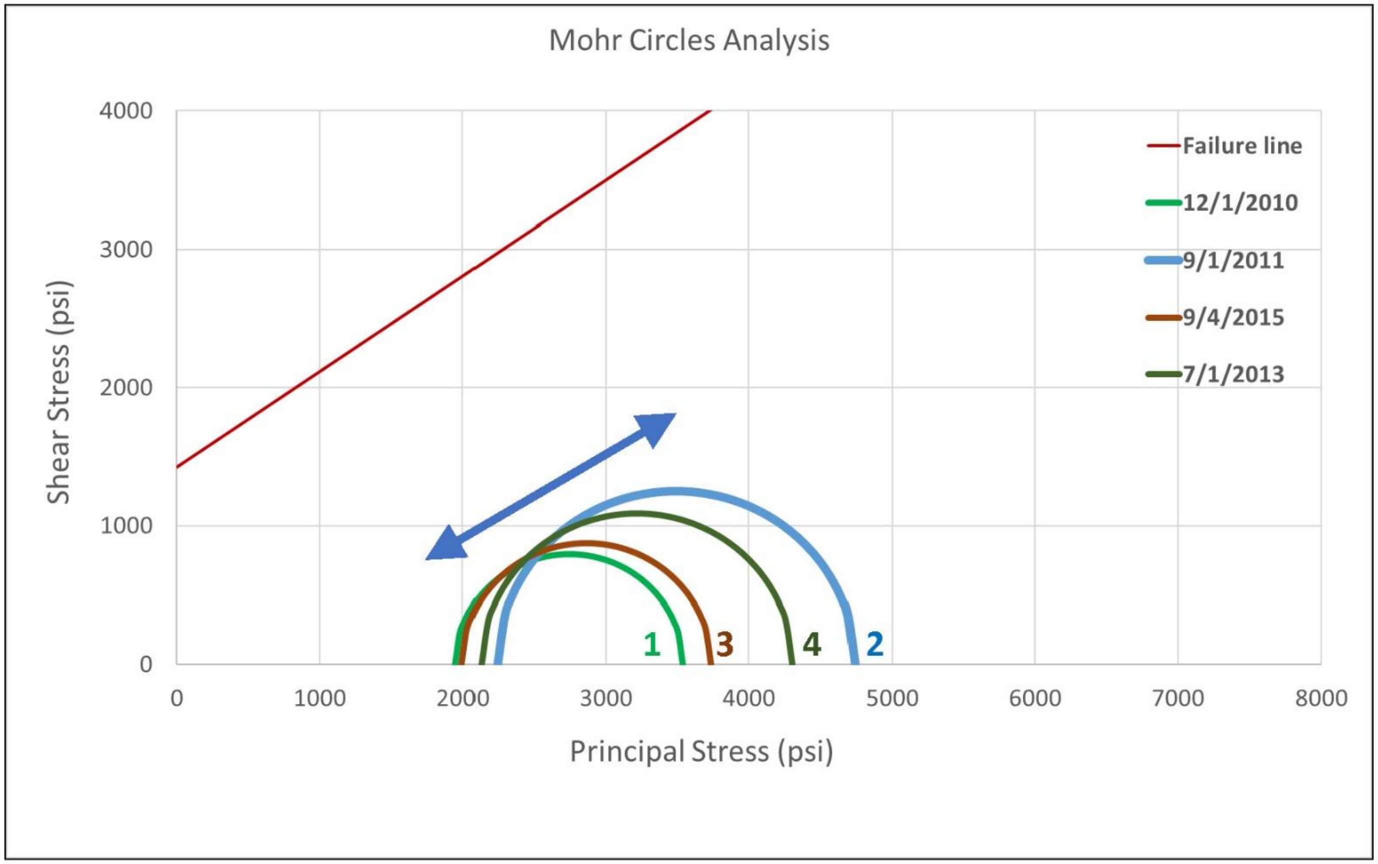
(*Presenter's notes continued from previous slide*)

Some trends can be seen …

- As update frequency increases the simulated results diverge from the base (no update) case.
- Cumulative production: As update frequency increases, production increases over the no-update case. This is because of stress-strain effects increasing porosity and permeability. Less frequent updates mean that permeability improvement lags. As the time between pressure and perm updates get longer the result approaches the no-update case.
- Pressure: More frequent updates … resulting in improved production … means more voidage and lower field pressure as compared to the no-update case. Again, as updates get less frequent the result approaches the no-update case.

We feel that this case is pretty straight forward and indicate that permeability updating is needed, the more frequent the better. The ideal case for this coupling scheme would be geomechanical solution and permeability updates at EVERY flow simulator solution step, which is computationally impractical.

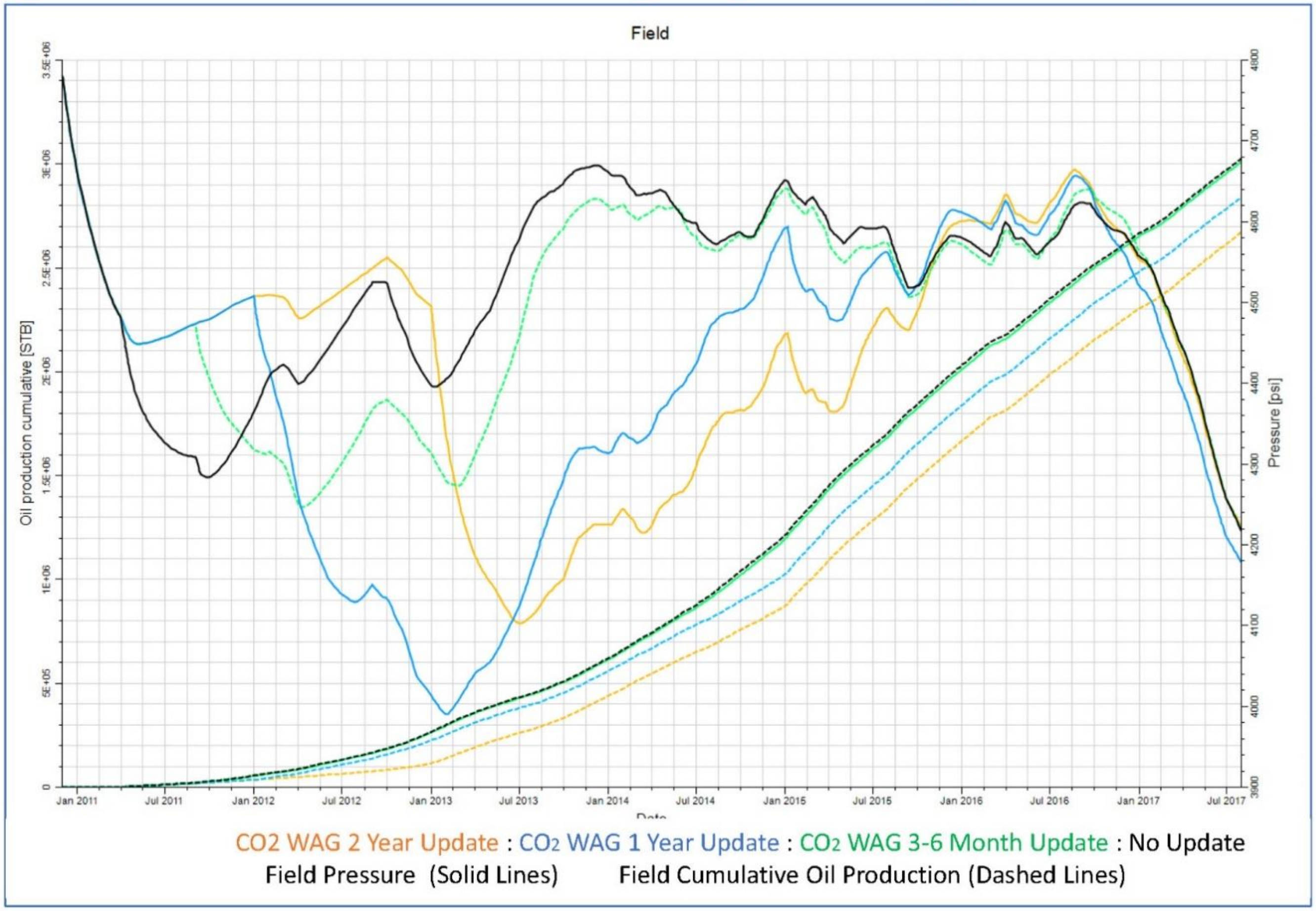
Farnsworth CO_2-WAG Mohr Circle Analysis



Presenter's notes:

This figure shows a sequence of Mohr circles representing stress in the Morrow B during the CO2 WAG. Recall the field pressure history for this period with high pore pressures which varied only 500 psi and was almost cyclic in behavior. The higher pore pressure is reflected here in lower average total principal stresses and variations through the WAG period are cyclic and within a limited range. Resulting total volumetric strain changes are similarly limited.

Impact of Permeability Updating: WAG Period



Presenter's notes:

This figure shows simulated field pressure (solid lines) and cumulative oil production (dashed lines) for the CO2 WAG recovery period with no permeability updating (black), and 3 month updating (green), 1 year updating (blue). Again, all simulations were performed with similar well rate and bottom hole pressure controls.

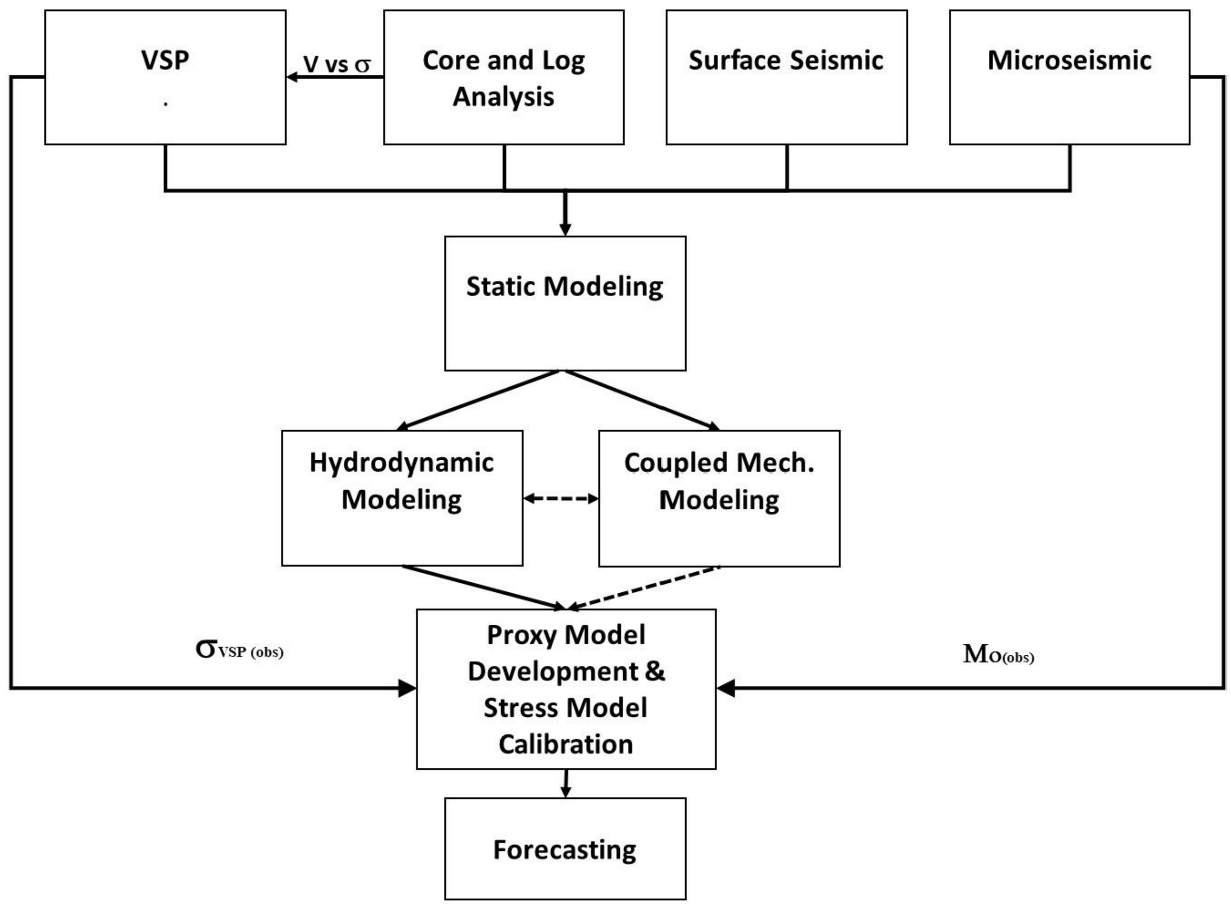
Here we see a reversal in the trends observed in the waterflood case. Here, as update frequency increases, the result approaches the no update case. We believe that this is because, instead of monotonically increasing or decreasing, the pressures, effective stresses, and strains, are cycling with little (*Presenter's notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

overall net change. Infrequent updates lag reality and can in this case potentially be "less correct" than no-update at all.

What do we take away from these two slides? We can't attribute these trends and variations in simulation results entirely to volumetrics and permeability enhancements alone. Other analysis (not shown) indicate that stress dependent poro-perm effects are small (<1p.u. and <2 Md) even for the dramatic variations in pressure and stress observed in the waterflood period. It is more likely that these differences are in part the result if interaction between reservoir properties and simulator fluid rate controls and pressure targets. This hi-lights the complexities of model calibration and accurate production forecasting with coupled models in stress sensitive reservoirs. More work is planned for this challenging problem as part of the stress modeling project.

Coupled Stress Model Calibration Workflow



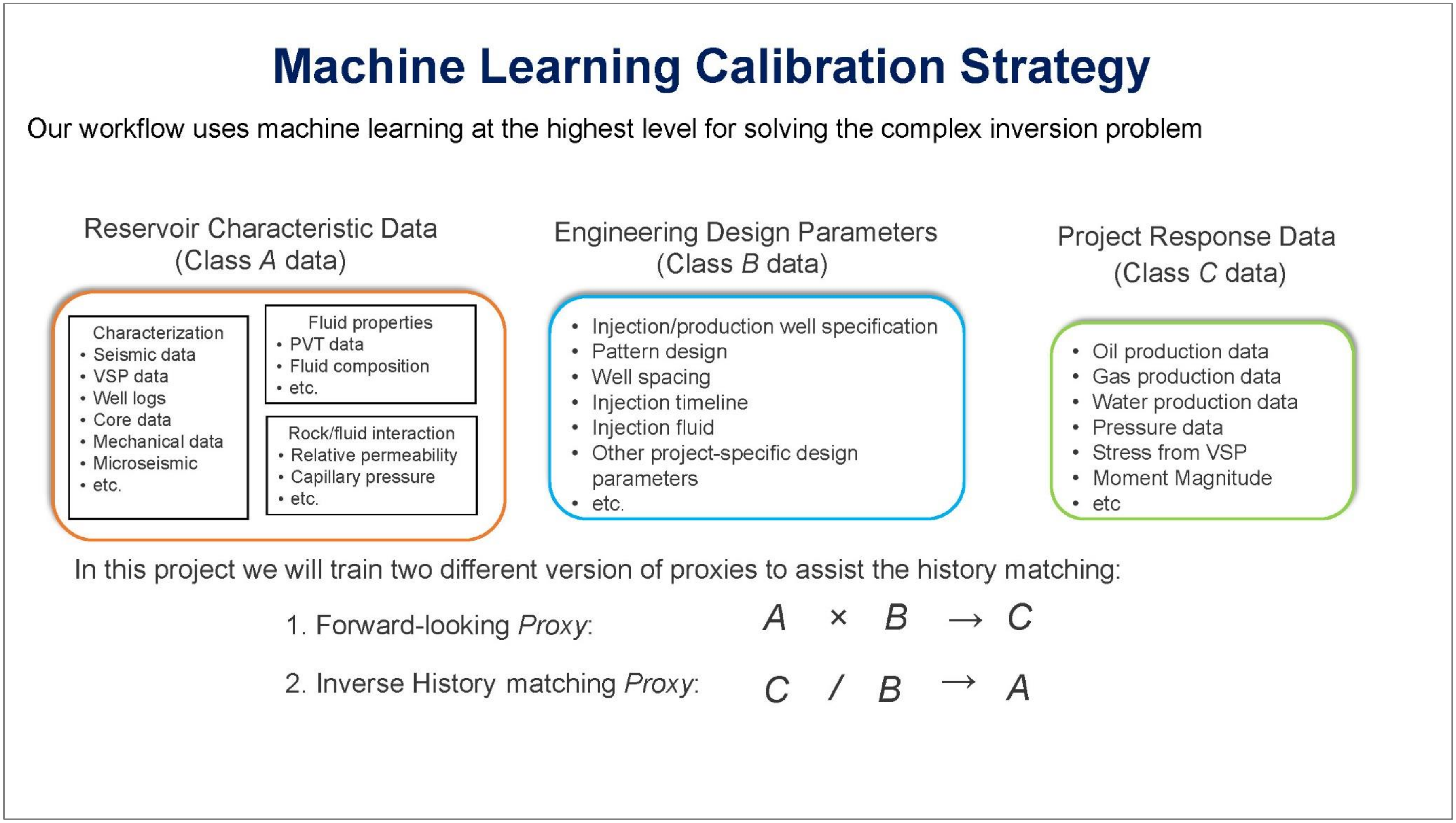
Presenter’s notes:

That’s a brief look at some of our work to create good coupled forward modeling capabilities for the Farnsworth field as part of the SWP project. A more detailed study is under way with separate funding. The objective of the stress project is to incorporate indirect time variant observations of stress, such as time-lapse VSP and microseismicity, for <u>calibration</u> of a stress predictive model. An accurate and efficient forward modeling scheme is fundamental to this process and, computationally, the difference between the requirement for 2-way coupling versus one-way coupling is HUGE. Hence, our motivation for the studies shown previously. (*Presenter’s notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

We will use a forward model to compute a "simulated versus observed" data penalty function, which will be minimized through model parameter adjustment by means of one of many available optimization schemes. The difference is that, in addition to engineering data (pressures rates etc), our observed dataset (and penalty function) will include time-lapse elastic response and microseismicity. Our forward model will be our coupled hydro-mechanical model with elastic and seismological post processing calculations.

With a caveat … this is a poorly conditioned and computationally intensive problem. How to we plan to do this?



Presenter's notes:

Model based machine learning using reduced order (proxy) models.…

- In reservoir engineering applications, machine learning models needs to process three categories of data: the reservoir characteristic data, project design data and the field responses data.

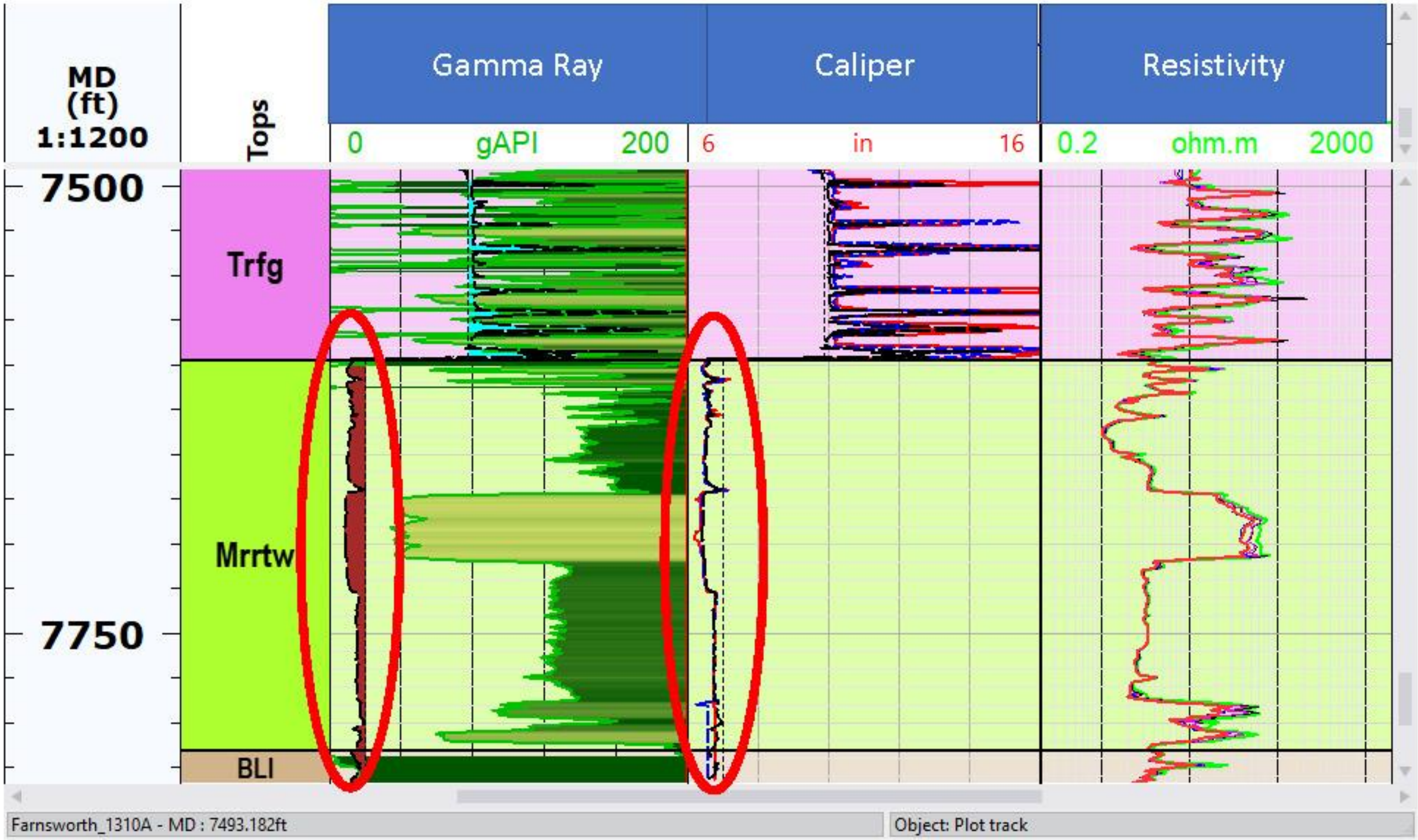
A forward-looking model (our coupled hydro-mechanical model) utilizes reservoir properties and engineering design parameters as input to predict the production performance (response function). This type of ML models are typically (*Presenter's notes continued on next slide*)

(*Presenter’s notes continued from previous slide*)

employed as production forecasting tools.

- An inverse history matching model utilizes production performance, such as production history and pressure measurements (and time-lapse VSP elastic response and microseismicity) as input, to predict the suitable model to tune a numerical model and obtain a satisfactory history matching result.
- In reality, the inverse history matching process exhibits strong nonunique nature of the solution. It means that there are many combination of reservoir properties that could obtain satisfactory matching quality. Therefore, a robust and practical history matching workflow may comprehensively use the forward and inverse-looking proxies and the high-fidelity numerical to address this issue.

Stress Indicators: Borehole Deformation



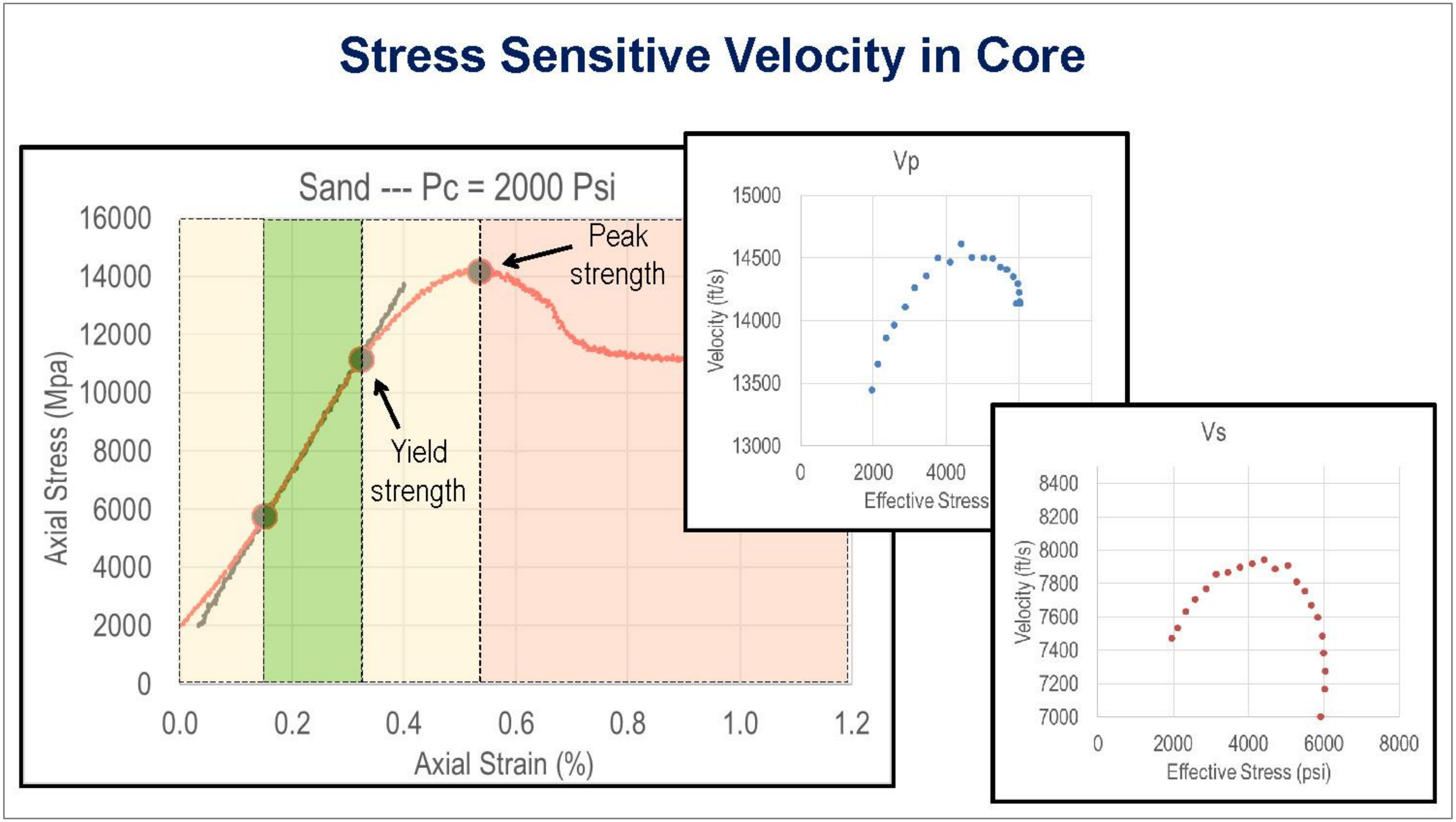
Presenter's notes:

Although the stress project is at an early stage, through our analysis of logs and core We see various indirect indicators of stress in the subsurface at FWU… (*Presenter's notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

Analysis of available logs and core indicate that the subsurface is highly stressed, and at core scale shows clear stress-velocity sensitivity.

In this slide calibrated sonic caliper logs (center track) show significant reduction in borehole diameter (red outline) which is assumed to have developed through plastic deformation during the several hours elapsed between drilling and logging. This deformation is seen in the Morrow B sand as well as overlying and underlying shales. The brown curve (left track) indicated diameter reduction on the order of ~0.5 inches below bitsize. It is noted that the hole is circular and there are no break-outs in this section. Shallower sections exhibit significant break-outs.



Presenter's notes:

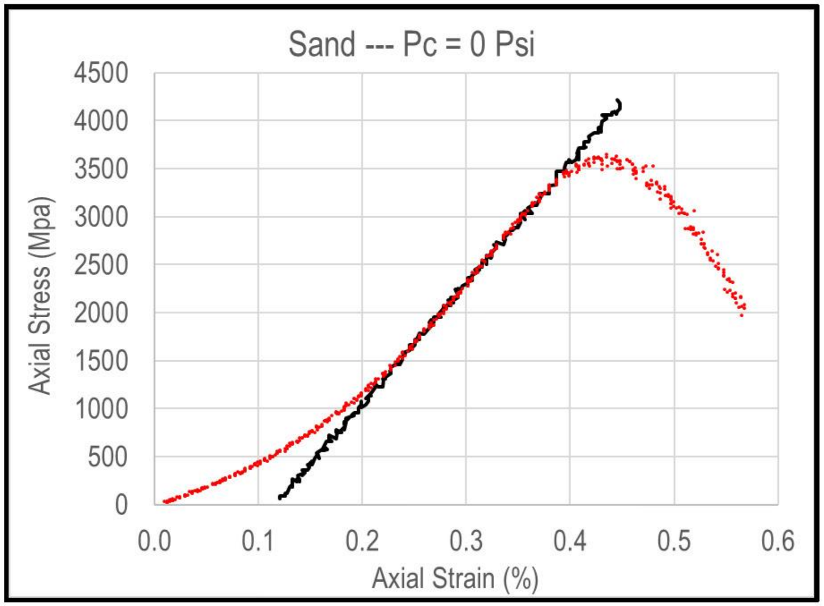
This slide shows stress-strain plot (left) from mechanical testing of a morrow b core sample at confining stress of 2000 psi. Note the non-linear behavior below approximately 2000 psi applied stress.

Vp and Vs versus stress analysis (right) exhibit clear stress-velocity dependence with velocity increasing at lower stresses.

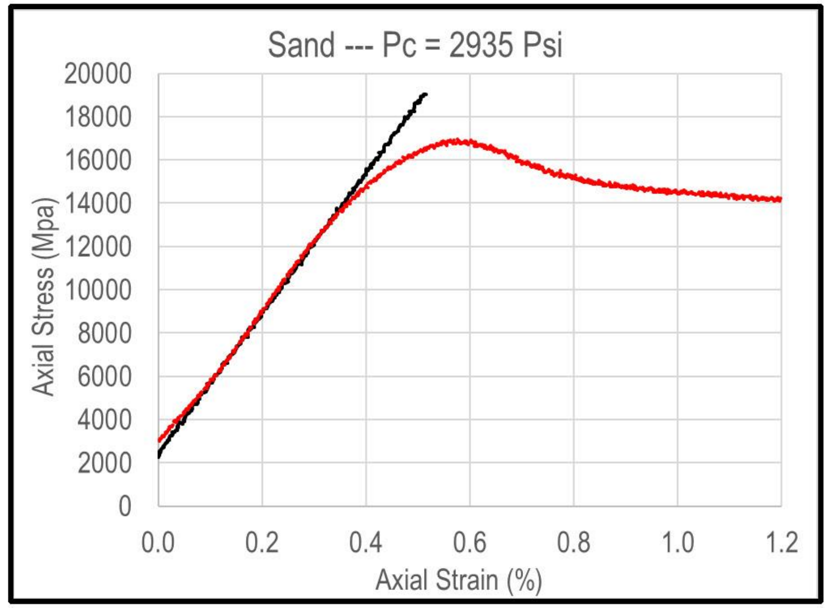
It is believed that both behaviors (stress-strain and stress-velocity) are related and are due to compliant microcracks closing at low applied stress and new microcracks forming after yield has been exceeded causing both non-linear stress strain behavior and stress-velocity trend reversals.

Stress Evidence of Microcracks in Core Analysis

Unconfined



Confined



Presenter's notes:

As further evidence of microcracks, this slide shows stress-strain behavior of a morrow B core sample at unconfined (left), ~3000 psi confining pressure (right). The unconfined sample has a significant amount of concave upwards behavior; it last until about 0.23 strain.

The confined sample shows less of this behavior because the microcracks are closed by the confining pressure.

These observations will be key in developing our stress-velocity relationships which will be needed for post processing of results from the coupled simulator to create the simulated terms of our history matching penalty function.

Summary

Ongoing geomechanical studies at PRRC enjoy the benefits of:

- An excellent field dataset for "life-of-field" reservoir engineering studies
- Highly developed geological and calibrated compositional reservoir simulation models
- A rich core, log, and geophysical dataset for geomechanical characterization

PRRC has leveraged these to receive award of a challenging Stress Modeling project which is funding:

- Studies into characterization of induced microseismicity
- Development of machine learning methods for model optimization
- Advanced geophysical and log analysis for geomechanical characterization
- Collaboration with national laboratories on advanced seismic analyses

Acknowledgement

- Funding for this project is provided by the U.S. Department of Energy's (DOE) National Energy Technology Laboratory (NETL) DOE Award No. DE-FE31684 and through the Southwest Regional Partnership on Carbon Sequestration (SWP) under and under DOE Award No. DE- FC26-05NT42591.
- The presenter thanks Bob Will, Tom Bratton, William Ampomah, Don Lee, and Marcia McMillan for their contributions to the work presented here.
- Additional support has been provided by the site operator and Schlumberger.

Questions