Fluid Substitution Modeling to Determine Sensitivity of Time-Lapse 3-D Vertical Seismic Profile Data to Injected CO_2*

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Abstract

For commercial scale carbon capture and storage projects it is essential for site operators and regulators to understand the fate of injected CO_2. The Southwest Regional Partnership on Carbon Sequestration is testing monitoring technologies at Farnsworth field, TX, and of particular interest is the use of 4D vertical seismic profiles centered on CO_2 injection wells to cost effectively monitor plume growth and distribution. The reservoir interval is a Morrowan age fluvial sandstone deposited in an incised valley at about 2800 m depth, with porous sands between 10 to 25 m thick. Farnsworth Field was first developed in 1958, and was converted to a water flood in the late 1960's. Chaparral Energy took the field over in 2011 and instituted a CO_2 flood using 100% anthropogenic CO_2 generated at an ethanol plant and a fertilizer plant. Ultimately, the majority of injected CO_2 will be sequestered. In order to detect and quantify the CO_2 plume in time-lapse VSP data it is important to understand the seismic sensitivity of the interval to the replacement of fluids with CO_2. Through 2015, three wells have had baseline 3D VSP data acquired, and one injection well had a repeat survey after seven months of CO_2 injection. 3D VSP surveys offer a higher level of detail at reservoir intervals since active source energy from surface shot points only needs to travel through near surface layers in the downward direction to receivers in the well-bore, reducing the effect of attenuation in near-surface formations. 3D VSP surveys at Farnsworth can image as much as 1.5 km away from the center well, which allows examination of full injection patterns. To optimize timing of repeat VSP acquisition, the sensitivity of the 3D VSP surveys to CO_2 injection was analyzed to determine at what injection volumes a seismic response to the injected CO_2 is observable. Static geologic models were generated for pre-CO_2 and post-CO_2 reservoir states by interpreting, and populating fine scale geologic models using baseline 3D VSP data, and then by history matching pre and post CO_2 models. These generated static states of the model, where CO_2 replaces oil and brine in pore spaces, allow for the generation of impedance volumes which when convolved with a representative wavelet, are used to generate synthetic seismic volumes used to contrast synthetic and actual time lapse 3D VSP datasets.

Acknowledgement

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Southwest Regional Partnership on Carbon Sequestration

Presenter's notes: Welcome to my talk about Fluid Substitution Modeling to Determine Sensitivity of Time Lapse 3D VSP to injected CO2.

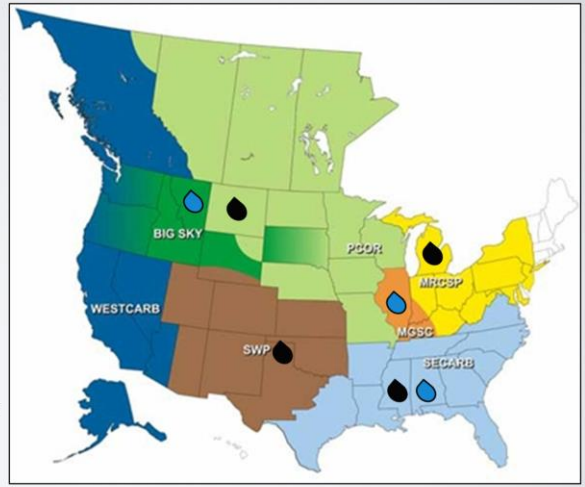
Outline

- The Southwest Regional Partnership on CO_2 Sequestration (SWP) and CCUS
- Monitoring at CO_2 storage sites
- Time-Lapse seismic monitoring
- Timing of repeat surveys
- Modeling Workflow
  - Static Model (Geologic)
  - Reservoir Simulation
  - Rock Physics
  - Seismic Modeling
- Conclusions

Presenter's notes: To begin, I will introduce the Southwest Partnership on CO2 sequestration, I will give a brief introduction to monitoring technologies used at storage sites, and will talk about the potential of time-lapse seismic for imaging reservoir changes due to CO2 injection, and how to predict when repeat surveys should be performed.
I will discuss a modeling workflow to determine viability and timing of repeat surveys which incorporates detailed geologic models, reservoir simulation to determine fluid states at different times, the use of rock physics to compute seismic properties for different fluid states, and differencing of synthetics based off of these models for the purpose for determining feasibility of the technology for thin, deep, horizons.
I hope to show that this modeling process is a valuable tool for predicting the response of a reservoir to CO2 injection.

USA Case Studies for CCS

- US Department of Energy Regional Carbon Sequestration Partnerships
  - Seven regional partnerships
- Each demonstrating injection of at least 1,000,000 metric tons of CO_2
- Four of these projects are demonstrating storage in conjunction with EOR
- Developing "best practices" for utilizing captured CO_2

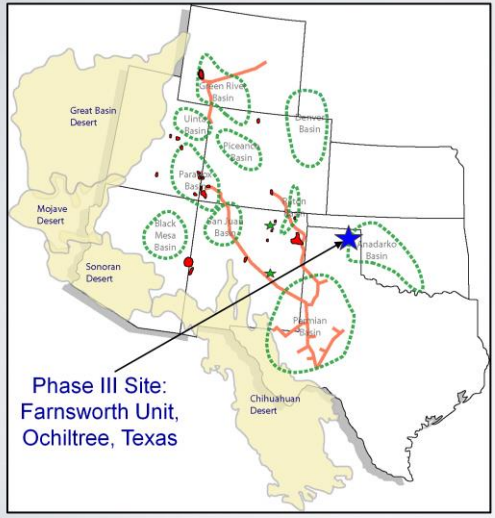


SPE 180408

NETL S W P Southwest Regional Partnership on Carbon Sequestration

Presenter's notes: This shows you the regional distribution of carbon capture and storage projects in the U.S..
Black drops show the approximate location of large scale CO2 EOR / sequestration demonstration projects in the United States.
The Southwest regional partnership on carbon sequestration, signified by SWP on this map is a consortium of three universities, three national laboratories, service companies, and operating partners including Chaparral Energy who operates eight CO2 EOR projects utilizing man-made CO2. Farnsworth Unit is the location of the SWP's large scale demonstration project.

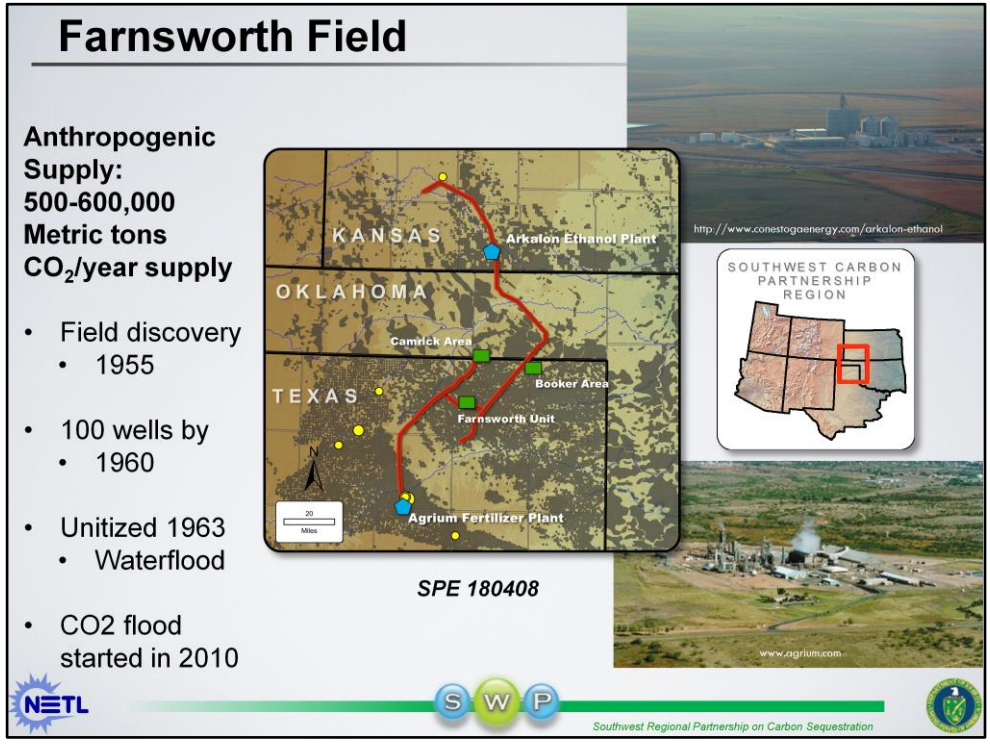
Southwest Partnership Goals



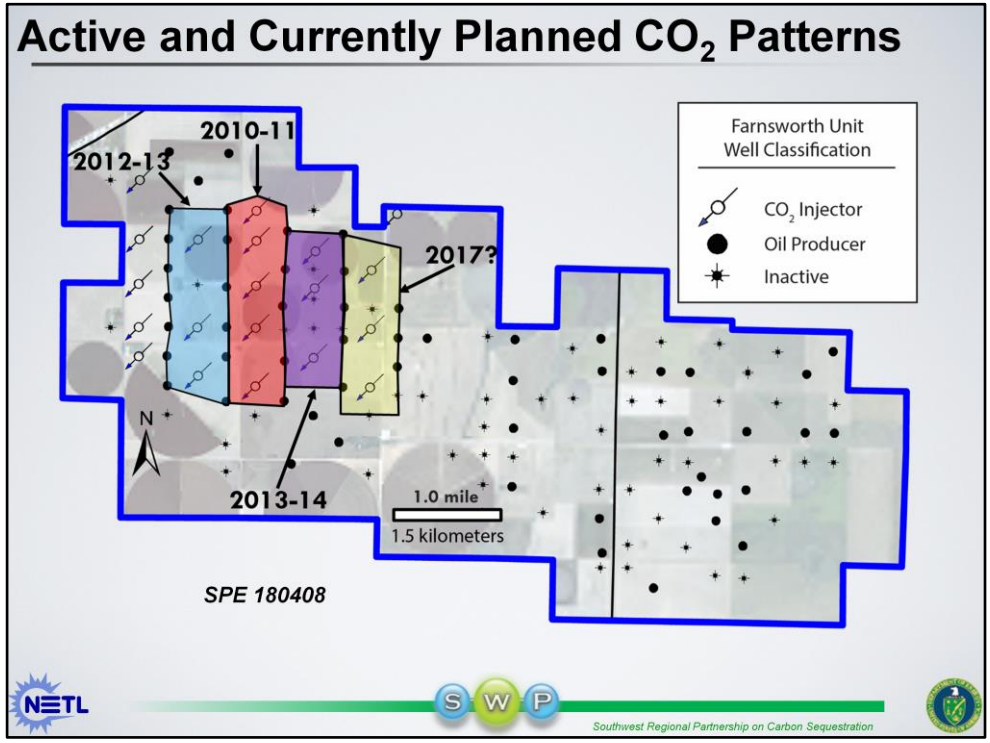
The SWP's Phase III project is a large-scale EOR-CCUS test

- **General Goals:**
- One million metric tons CO_2 injection
- Optimization of storage engineering
- Optimization of monitoring design
- Optimization of risk assessment
- Blueprint for CCUS in southwestern U.S.

Presenter's notes: The SWP has the intention to inject 1million metric tonnes of CO2 by 2018.
The purpose being that we want to optomize storage engineering, monitoring design and risk assessment.
Our efforts are considered a blueprint for CCUS in the southwestern US.



Presenter's notes: Farnsworth unit is a Carbon Capture, Utilization and Storage project.
We are injecting into the Morrow B interval at well head 13-10A currently CO2 is sourced from two anthropogenic sources, the Arkalon Ethanol Plant in Liberal Kansas, and the Agrium Fertilizer plant in Borger Texas.
Over 100 miles of pipeline 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.
Chaparral can vary delivery to fields to maintain operational flexibility.
Chaparral built or partnered in compression and dehydration facilities at each site.
Carbon cost is low, ~$0.60 per mcf, less than paying for natural CO2, even if it were regionally available.



Presenter's notes: This slide shows active and planned patterns where CO2 injection is being observed by the SWP.
Farnsworth unit is located in actively farmed land, at present only the western half is being developed for CO2 EOR, though eventually as funds allow, the eastern side will also be developed.
The red shaded region shows the injection pattern for the years 2010 and 2011, the blue shaded region corresponds to 12/13,
purple occurred during 13/14 and future injection will occur to the east.

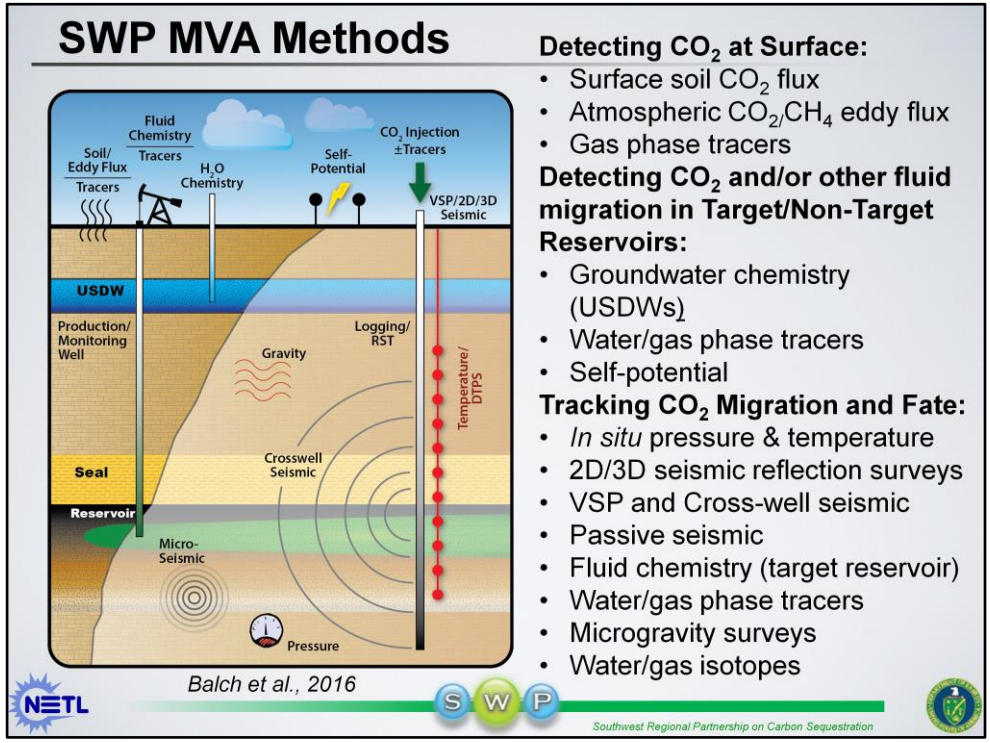
SWP Monitoring, Verification, and Accounting

SWP MVA Objectives at the Farnsworth Unit

- Collect and analyze data needed to characterize injected CO_2 volumes
- Study CO_2 migration (temporal and spatial)
- Understand trapping mechanisms
- Monitor pathways for potential leakage (USDW and atmosphere)
- Facilitate storage security predictions using simulation

Monitoring is accomplished with direct and indirect methods

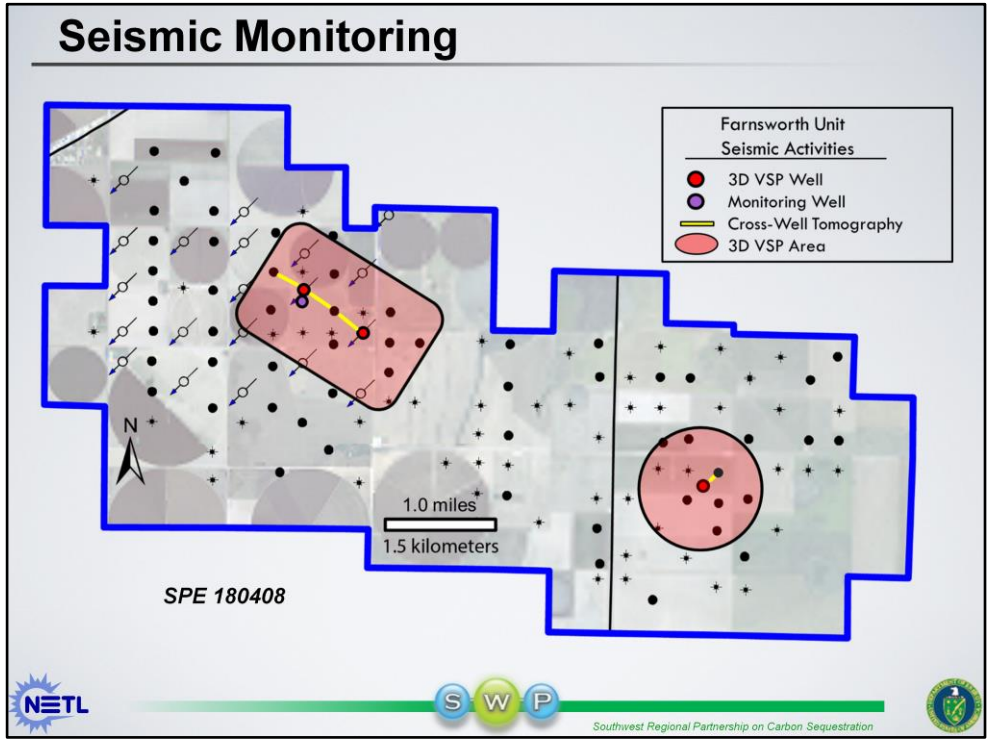
Presenter's notes: The SWP is invested in studying CO2 volume, its temporal and spatial migration within a reservoir, fault seal and trappings: stratigraphic, solubility and residual trappings and predict long-term storage security.



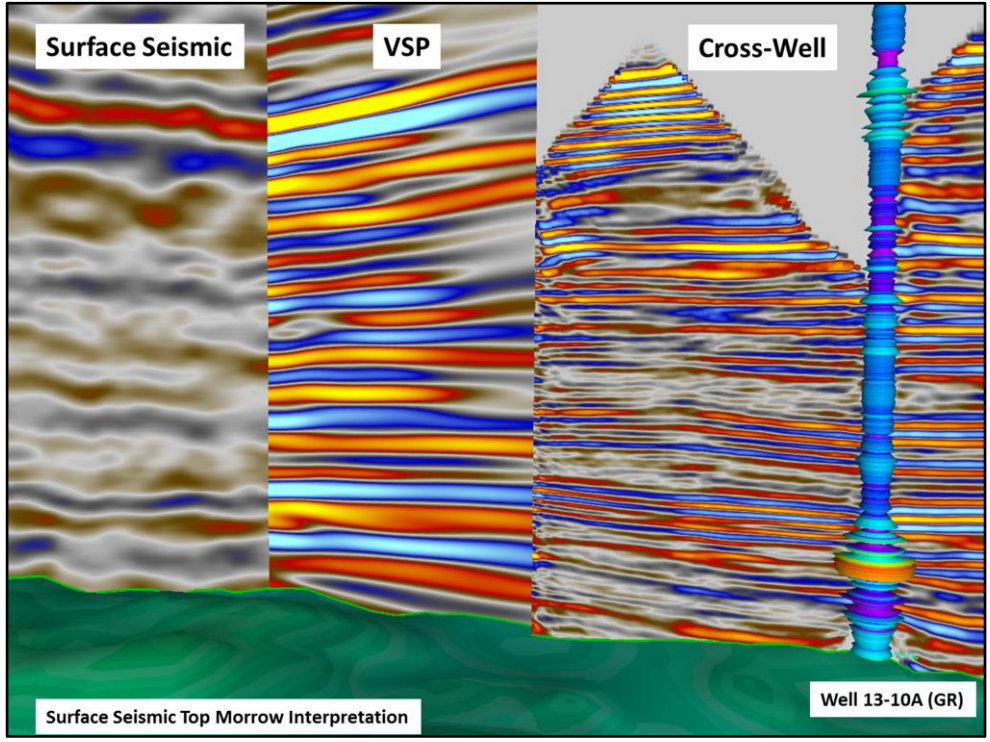
Presenter's notes: This is a cross section of all of the monitoring, verification and accounting methods that occur in the field.
We have

Soil and Eddy Flux Tracers
atmospheric flux tracers
groundwater and formation water chemistry monitoring
tracer injection
and seismic monitoring

All of these include base line and repeated measurements for accurate and long-term comparison concerning the evolution of the injected CO2.



Presenter's notes: Seismic data has been an integral part of the characterization program and includes a baseline 42 mi^2 3D survey over the entire field, this extends far beyond the image presented above.
Three baseline 3d VSPS centered on injection wells : See pink shaded region.
Four baseline cross-well tomography segments between injector/producer pairs : See yellow lines.
In addition, a dedicated monitoring well has a 16 level 3 component passive seismic monitoring array installed within it : the purple dot.

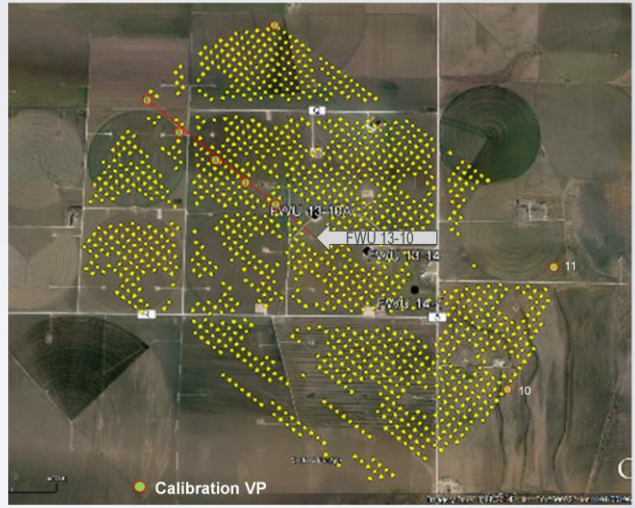


Presenter's notes: Multiple scales of seismic data allow for leveraging of information.
Core and log-scale data at the well-bore can be interpreted out to increasingly lower resolution data sources.
From right to left, Gamma Ray log in the 13-10A injection well, cross-well tomography, 3D VSP, and surface seismic data.
Surface Seismic: Low resolution at depth, but can have a large 2D and 3D extent.
VSP: Has a high resolution at depth, but is limited a small region around the borehole.
Crosswell: extremely high vertical resolution but is narrowly limited to 2D sections between wells.

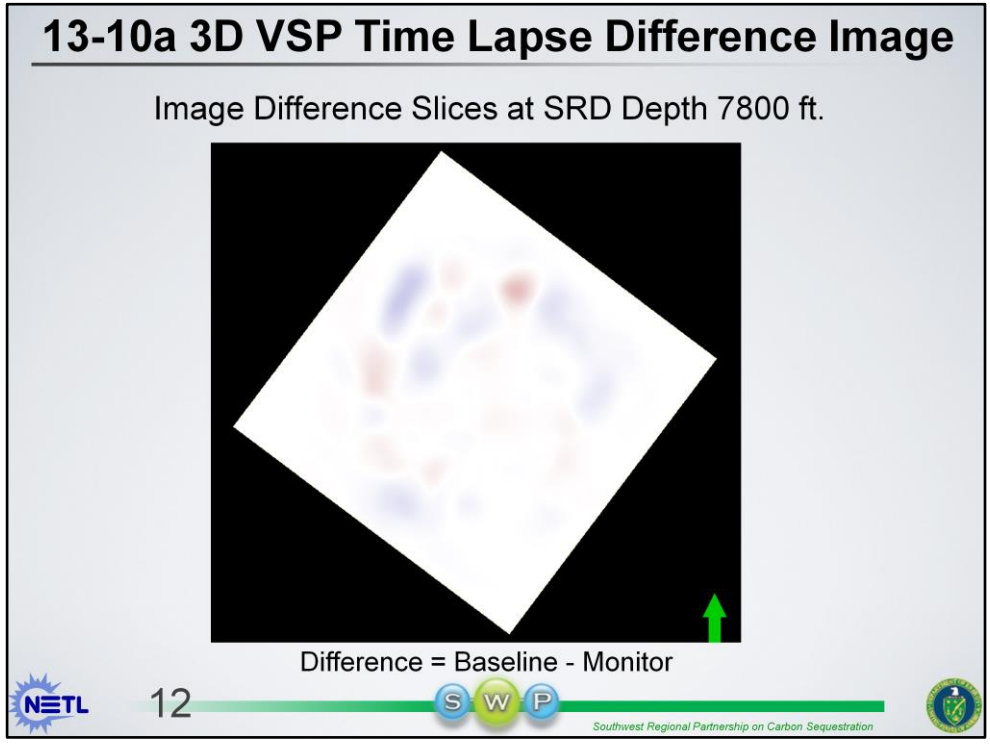
Time-Lapse 3D VSP Surveys

Data Acquired February 2014, January 2015

- Processed by WesternGeco
- Processing 1st and second 13-10a VSPs with ~28,000 Metric tonnes CO^2 injected
- Excellent repeatability
- Cursory differencing inconclusive



Presenter's notes: This slide shows surface shot points for a repeat 3D VSP survey centered on the 13-10a injection well.
This survey is used as the base for all seismic monitoring efforts subsequently.

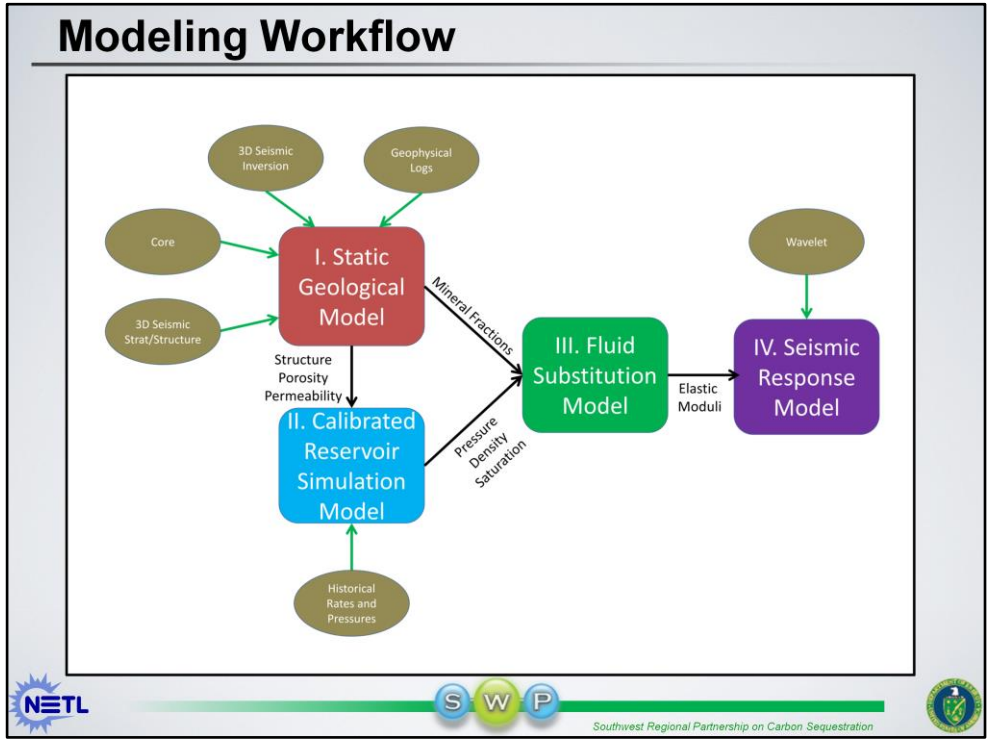


Presenter's notes: Differencing the 2014 and 2015 surveys was inconclusive as demonstrated by this image difference slice at 7800 ft. the unit of injection at farnsworth Field.

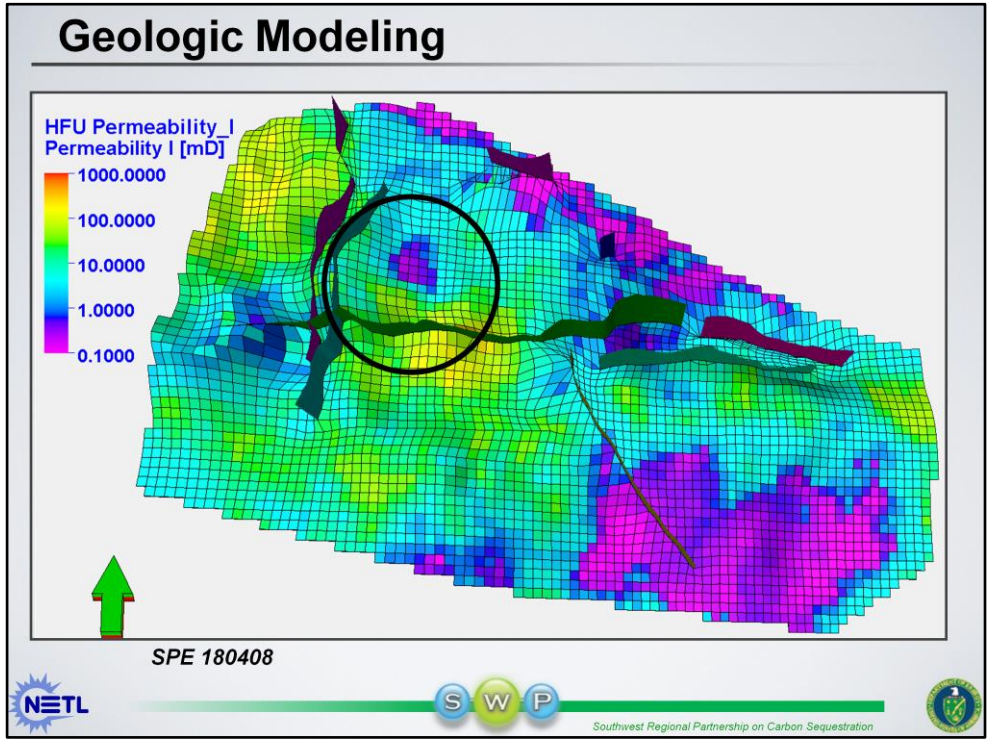
Fluid Substitution Modeling

- **Model can be populated with fluids for multiple cases**
  - **Post waterflood**
  - Post 30,000 tonnes injection, etc.
- **Fluid filled models can have synthetic seismic generated from them**
  - Can difference to find expected response at varying CO2 injection levels
  - Useful for determining detection thresholds
  - Help determine timing of future VSP repeats

Presenter's notes: We preformed fluid substitution modeling on the reservoir using oil and water for post waterflood and post CO2 injection. From here we are able to generate synthetic seismic that can then be differenced to show the response of the CO2 at various injection levels, to determine threshold detection levels and help constrain the timing of future VSP repeats



Presenter's notes: Modeling begins by development of a static geologic model using all available data such as logs, core, inversion, and seismic stratigraphy and structure. The fine scale geologic model is history matched, and then used to predict the fluid state of the reservoir at various times corresponding to different CO2 injection volumes. The fluid substitutions can change the elastic properties of the rock, which can then impact the seismic response of the models.



Presenter's notes: This slide shows average permeability at the Morrow B interval with interpreted faults. Faults have offsets in the reservoir and can impact fluid flow, and storage security. Typical models have millions of grid blocks and are usually up-scaled when simulating the Morrow B and its immediate caprock.

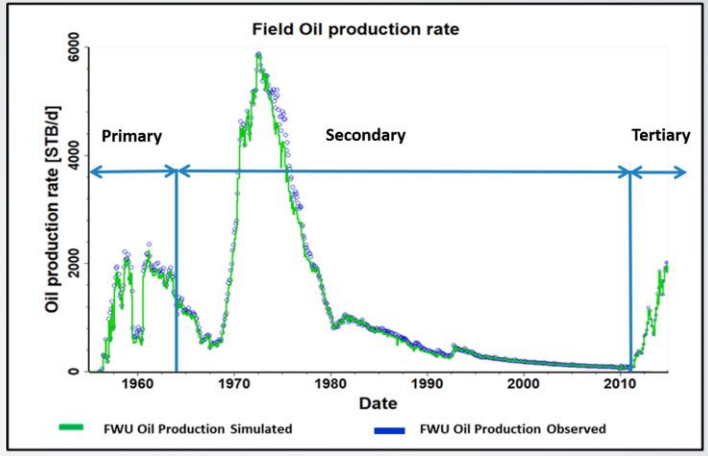
For this model structure and stratigraphy are supported by 3D seismic volume and well picks. Stochastic porosity interpolation supported by core and log data from 51 wells.

Porosity is related to permeability by Hydraulic Flow Units determined by pore throat size using the Winland equation. There are 8 HFUs in the Morrow B and this image shows just the topmost layer.

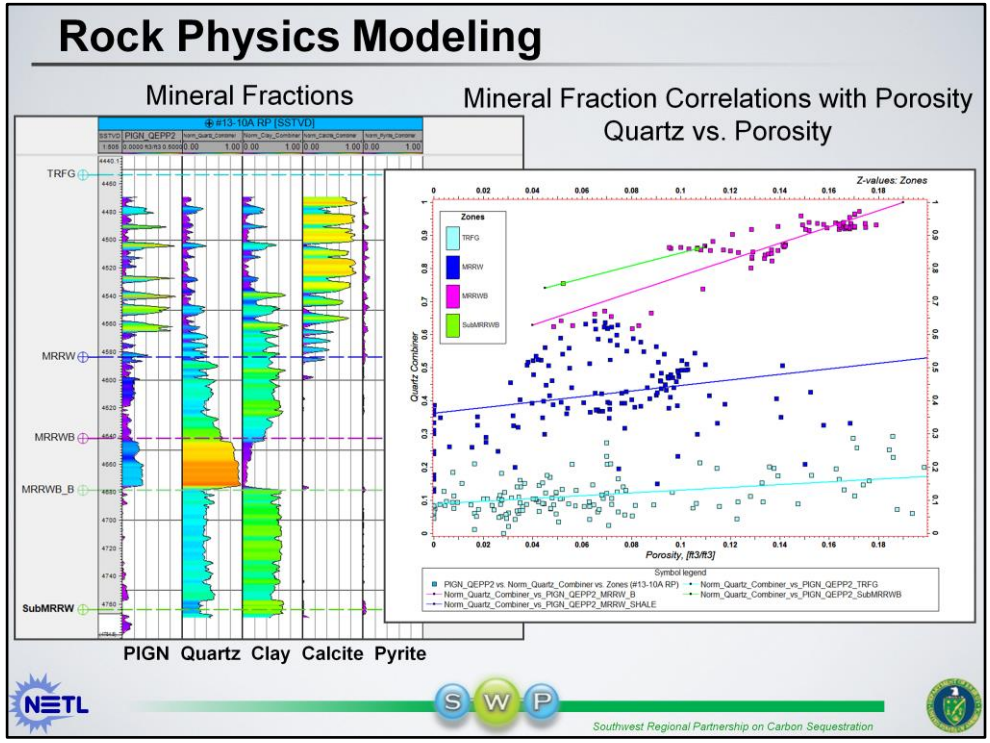
This circle shows the approximate area of the 3D VSP used in this study.

Reservoir Simulation

- Primary:
  - 1956 – 1964
    - 9.3% of OOIP
- Secondary:
  - 1964 – 2010
    - 21.3% of OOIP
- Tertiary CO_2:
  - 2010-20??
    - ?



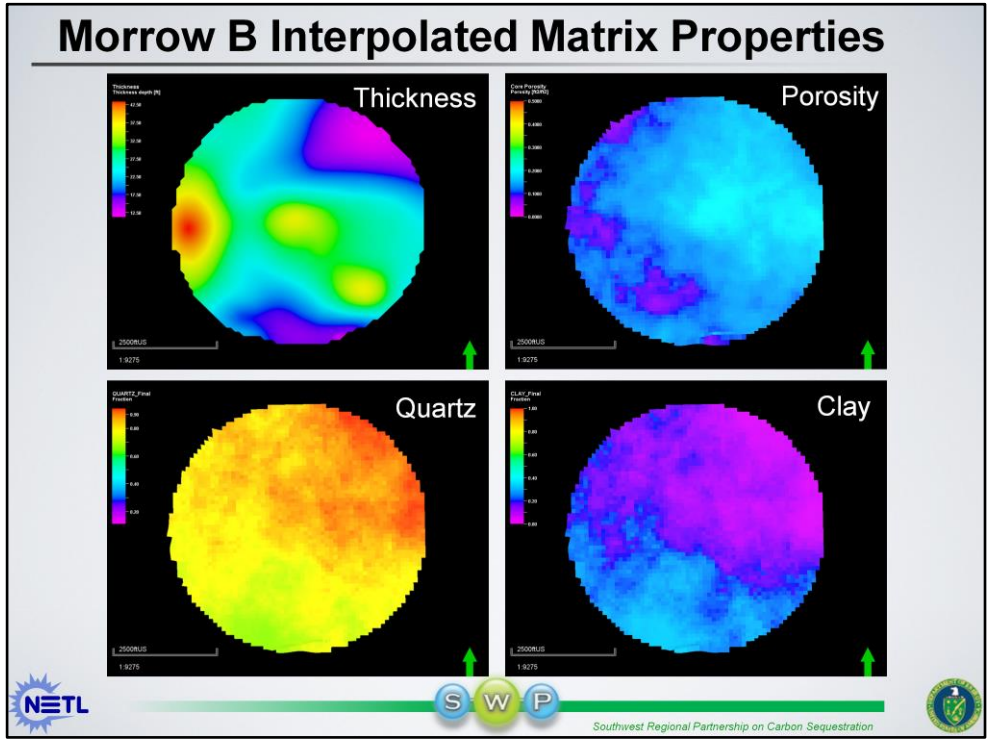
Presenter's notes: History match for the simulation model used to determine fluid substitutions for the rock physics modeling of the 3D VSP volume centered on the 13-10a injection well.



Presenter's notes: Mineral fraction logs from ELAN logs were used to understand the relationships between matrix properties and fluid properties such as saturations, densities, and pressure.

Here we can see the location of the Morrow B

This graph demonstrates the relationship between quartz and calcite that was important for justifying the rock physics modeling

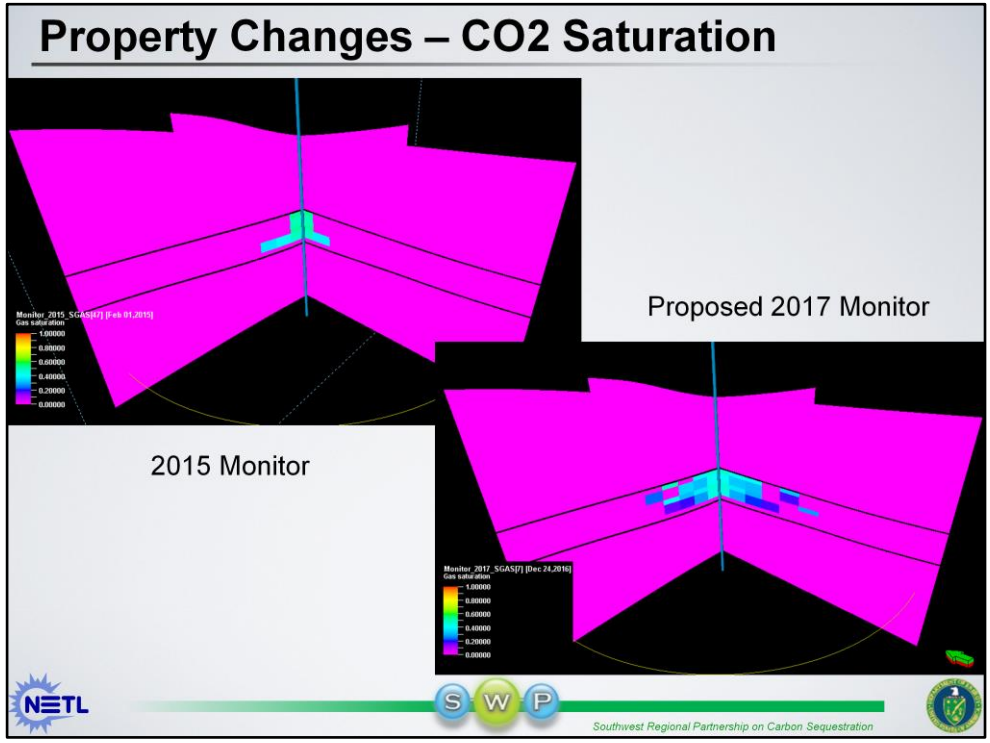


Presenter's notes: As an example, relationships were observed between quartz and Clay with Porosity.

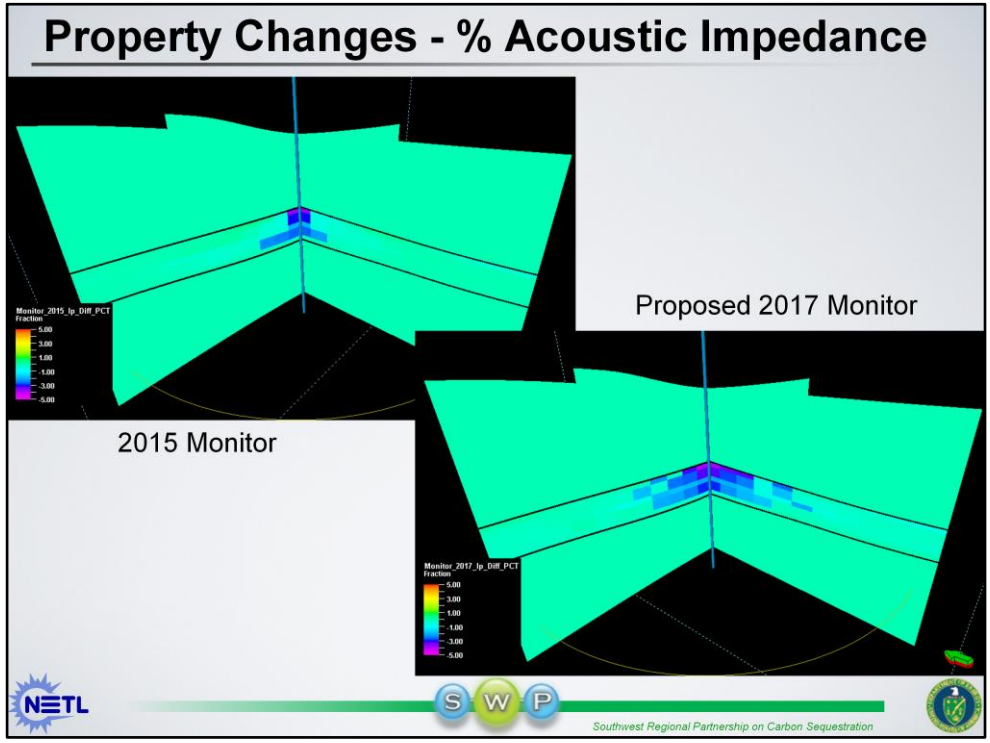
Elastic Modeling Summary

- Key Inputs
  - State: Saturation and Density of Water, Oil, Gas
  - Rock Physics: Matrix of Quartz, Clay, Calcite
    Average Hashin-Shtrikman Bounds for elastic moduli
- Outputs
  - Compressional and Shear Velocity
  - Compressional and Shear Impedance
  - Bulk Density
  - Fluid Bulk Modulus
- Evaluation
  - Differences in elastic properties and seismic response for modeled reservoir conditions at times of anticipated monitor surveys.

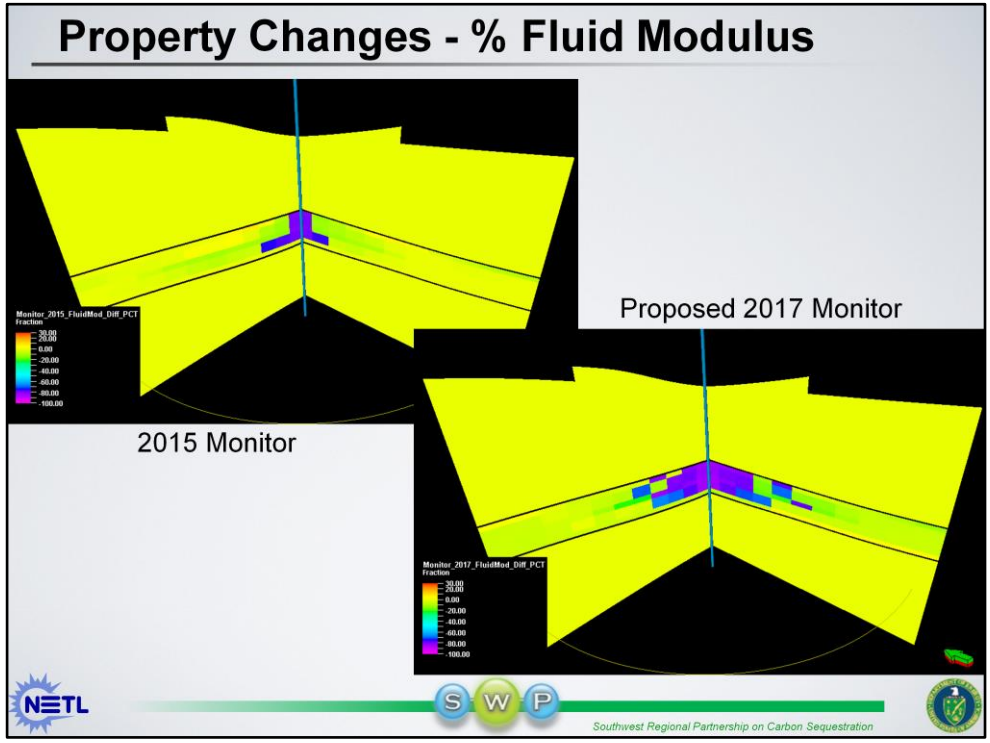
Presenter's notes: When building an elastic model of the rock the key inputs are the saturation and density of water, oil and gas
Using average Hashin-Shtrikman bounds, and literature derived density values of quartz, clay and calcite we were able to compute the compressional and shear velocity and compressional and shear impedance, the bulk density and bulk fluid modulus
We have logged values of quartz, clay and calcite densities, which in the future as the model becomes more refined, we will input our own values



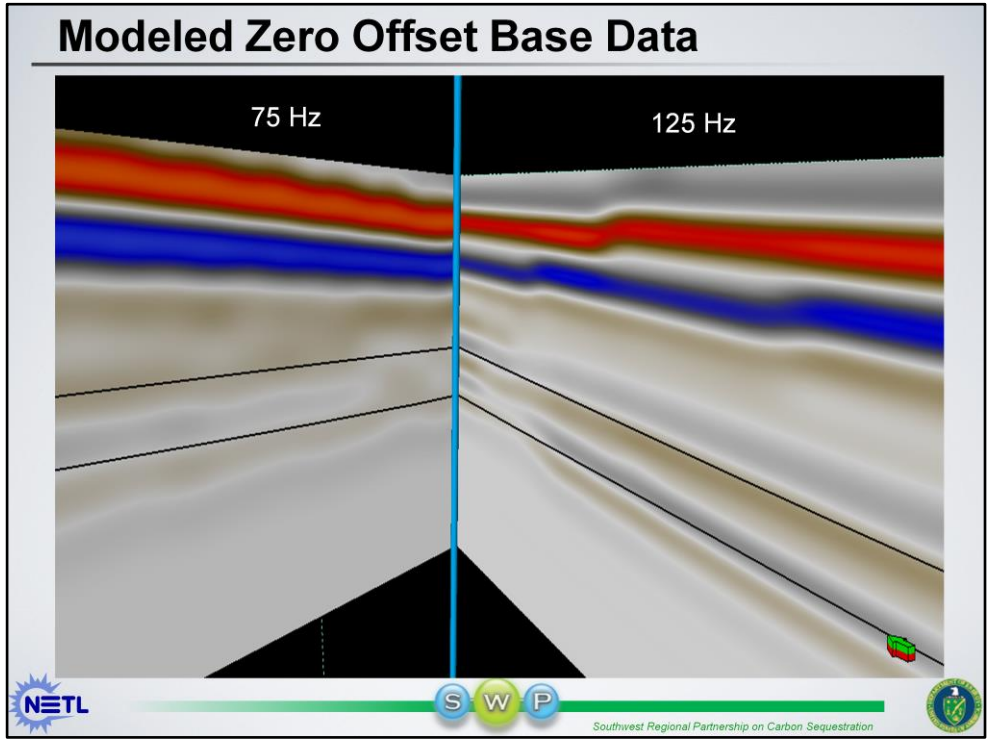
Presenter's notes: These images show the simulated percent change of the CO2 saturation in the reservoir after 2 and 4 years of injection.



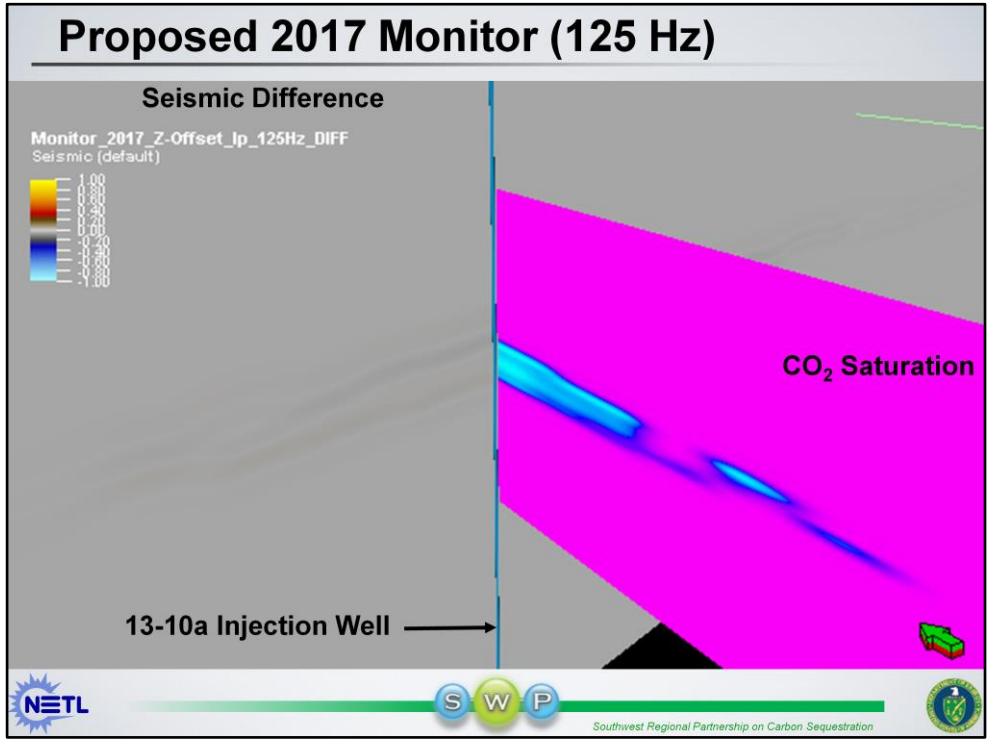
Presenter's notes: These images show the simulated percent change of the Acoustic Impedance after 2 and 4 years. The salient point to grasp in this image is that the percent acoustic impedance change is detecting the miscible front between the CO2 flood and the WAG flood.



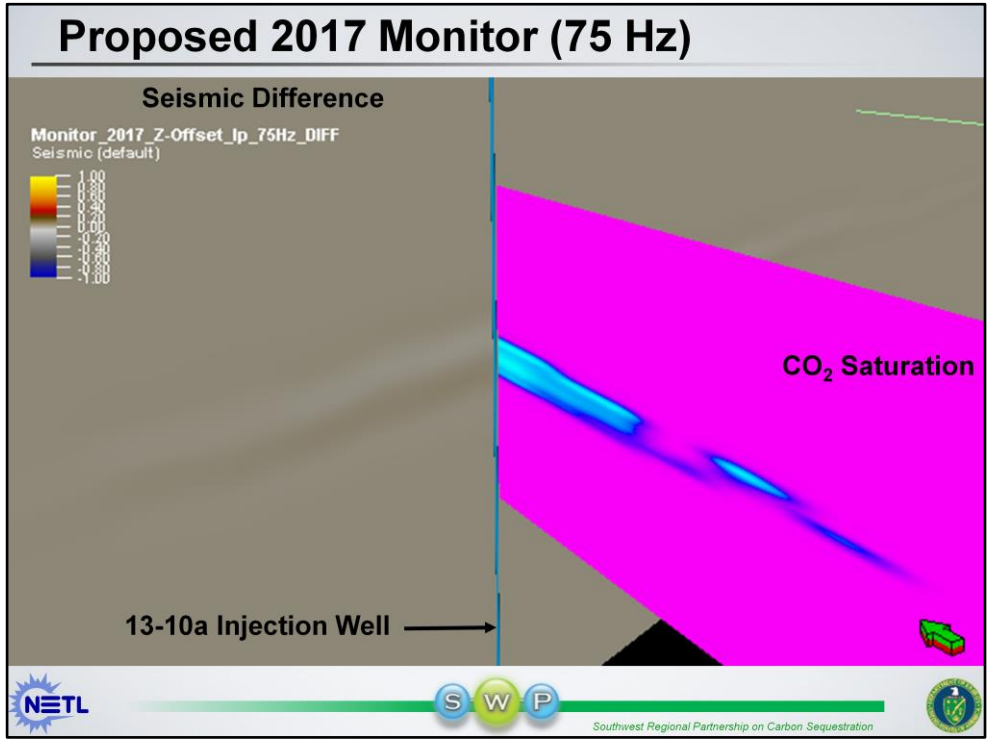
Presenter's notes: Here you can see the simulated percent change of the fluid modulus 2 and 4 years after the base.



Presenter's notes: Synthetic seismic data was generated from the rock physics model using a 75hz Ricker wavelet and a 125hz Ricker wavelet juxtaposed together around the 13-10A injection well.



Presenter's notes: Seismic difference for a 125 Hz Ricker wavelet is in the background and is contrasted with CO2 saturation simulated after 4 years of injection at the injection well shown in the image.
Although it is hard to see, there is a 4% difference visible using a 125hz Ricker wavelet.



Presenter's notes: This is the simulated seismic difference for a 75 Hz Ricker wavelet is in the background and is contrasted with CO2 saturation simulated after 4 years of injection at the injection well shown in the image.

Conclusions

- The miscible flood and WAG EOR field development scenario presents complex fluid properties and distributions
- Elastic property changes are driven by effective fluid modulus changes which include both the pure phase CO2 “plume” and portions of the miscible front
- Seismic modeling of zero offset P-wave seismic data suggests very subtle time lapse response extending laterally beyond the extent of pure phase CO2, corresponding to changes in fluid modulus
- Time-lapse response improves with higher data acquisition frequencies
- Since seismic monitoring cannot be viewed in terms of just the “CO2 plume”, qualitative interpretation of time-lapse effects is impossible
- Fluid substitution based interpretation is required to understand the sensitivity of these systems

Acknowledgements

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