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Integrated Reflection Seismic Monitoring and Reservoir Modeling for Geologic CO_2 Sequestration

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John Rogers, co-PI
Mark Sparlin
Jeff Meyer

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Presentation Outline

- **Project Goals and Objectives**
  - Background
  - Geophysical and Reservoir aspects - POC
  - Software
- **Feasibility Study**
  - Data processing & interpretation
  - Geophysical analysis
  - Fluid Replacement & Seismic detectability:

    Brine replaced with CO2
- **Conclusions & Summary**

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Goals & Objectives

Motivation:

- CO_2 monitoring using time lapse seismic (4D)
  - **Proven in oil industry EOR, Sleipner, etc.**
  - **4D seismic acquisition is expensive**
  - **Integration of reservoir & seismic challenging**

- This Project:
  - **Proof of Concept:**
    - ☞**Spatially sparse, temporally dense 4D seismic**
    - ☞**Reservoir modeling coupled with seismic simulation**
  - **4D seismic integrated with reservoir modeling (software platform)**

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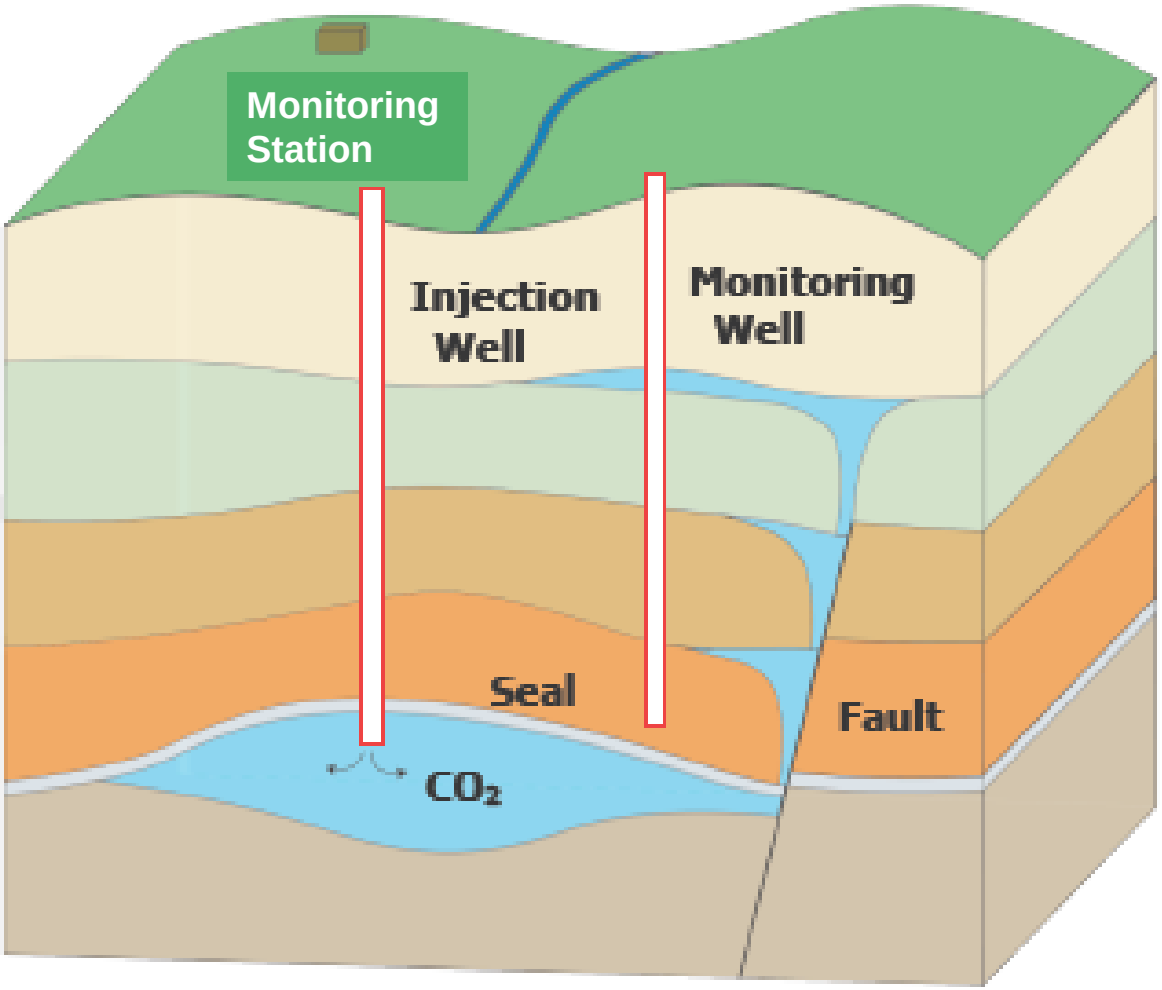
CO_2 MVA



From Harris et al., 2007 Global Climate & Energy Project Report

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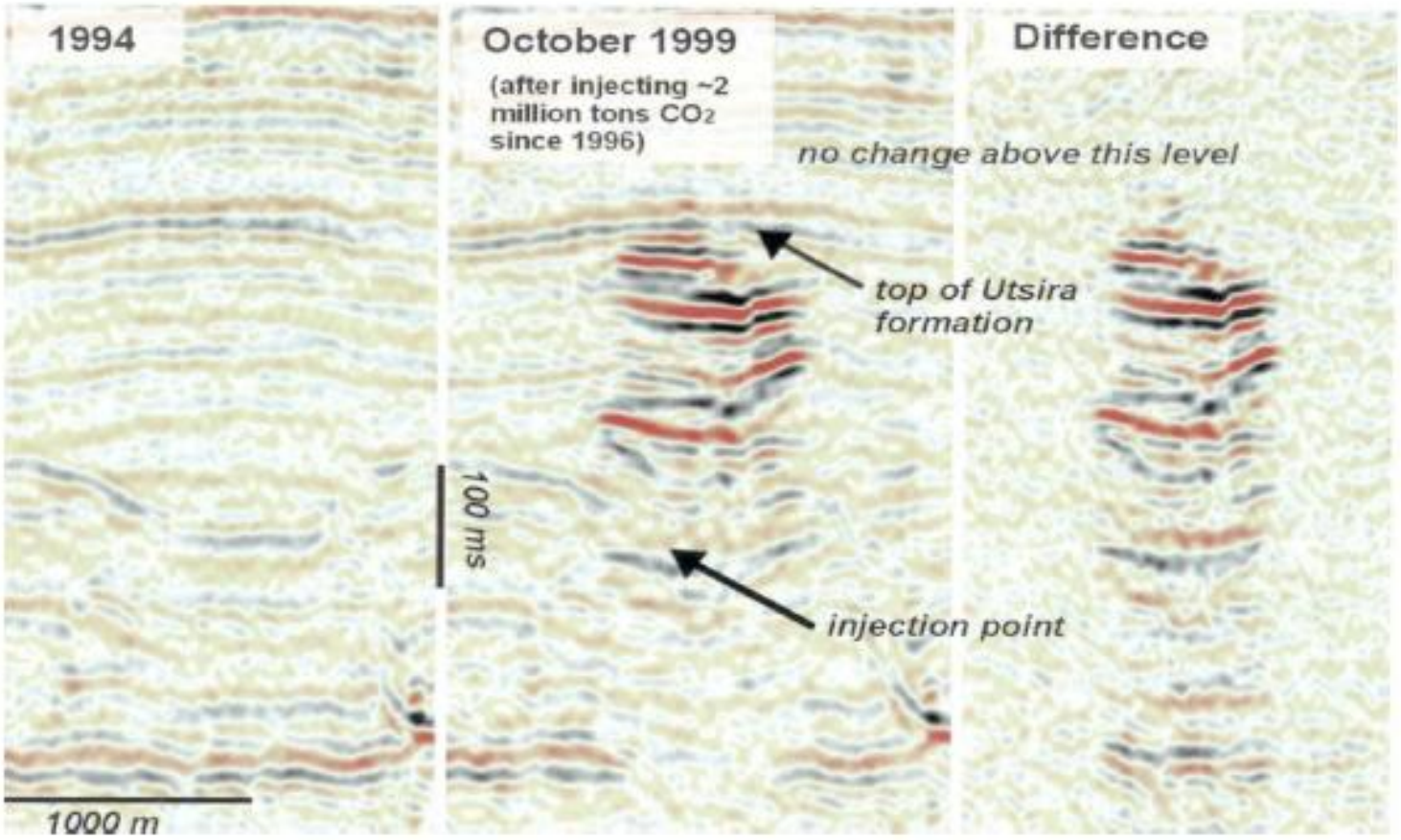
4D Seismic for CO_2



Saline aquifer CO2 injection at Sleipner, Norwegian North Sea. High spatial resolution, low temporal resolution

From Harris et al., 2007 Global Climate & Energy Project Report

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Monitoring CO_2 with seismic

- **Several Case histories in sequestration**
  - Enhanced oil recovery experience
- **4D seismic is expensive**
- **Lower cost by using sparse seismic:**
  - *Spatially sparse surface seismic arrays integrated with a dense baseline array, allow increased temporal resolution*

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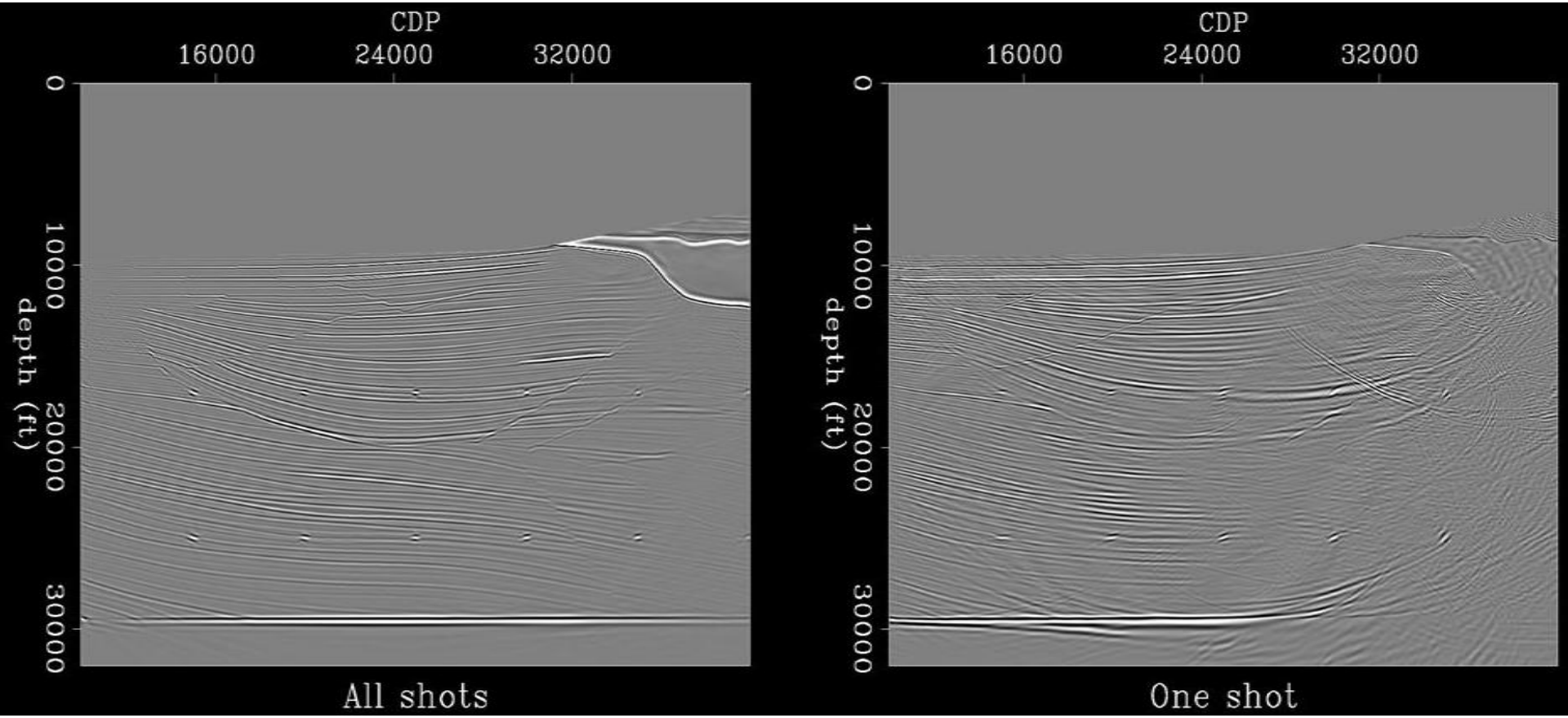
Sparse Seismic



The image on the left is generated with RTM depth imaging algorithm using all 500 of the available shots, while the image on the right is generated using only one shot. One shot provides a relatively high quality result, showing that sparse surface coverage is adequate for monitoring surveys.

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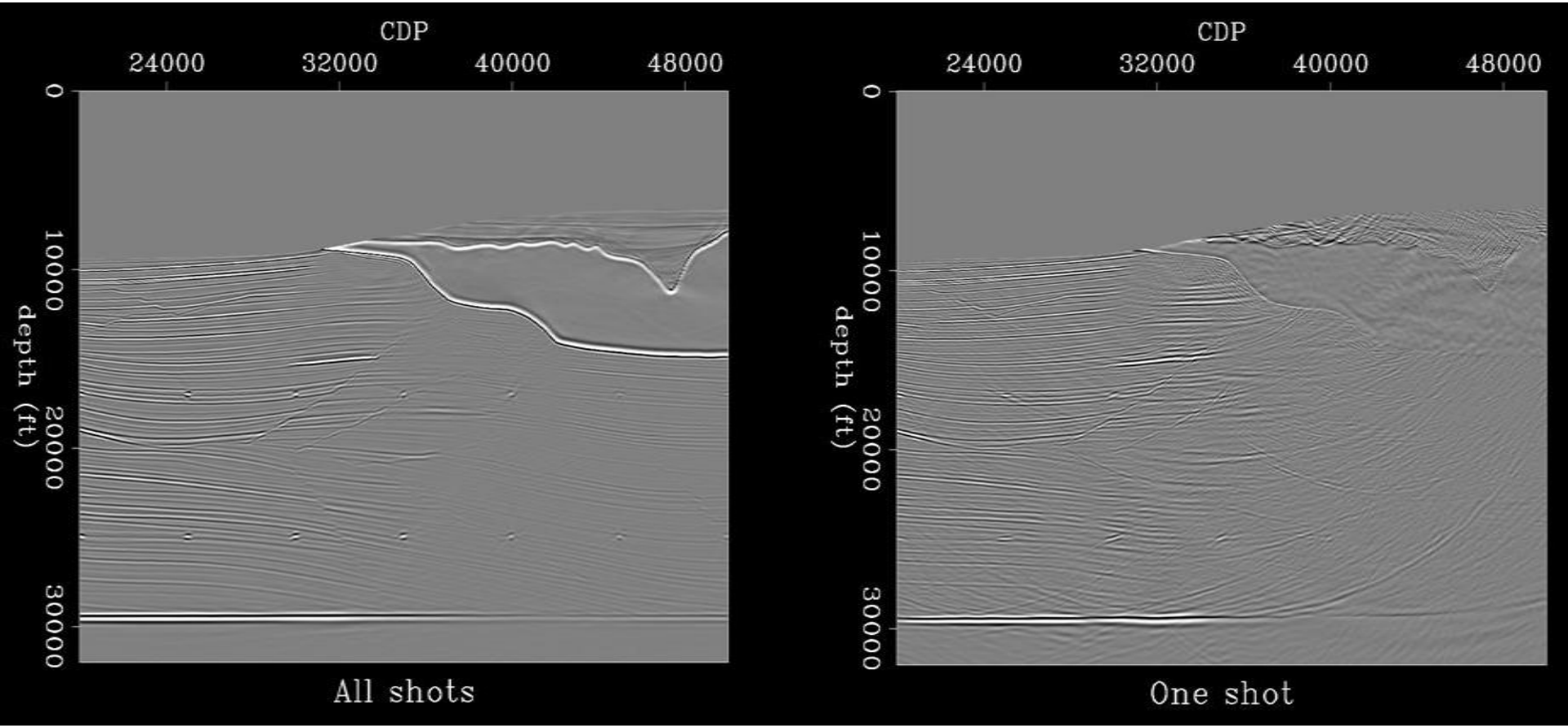
Sparse Seismic



The image on the left is generated with RTM depth imaging algorithm using all 500 of the available shots, while the image on the right is generated using only one shot. One shot provides a relatively high quality result, showing that sparse surface coverage is adequate for monitoring surveys.

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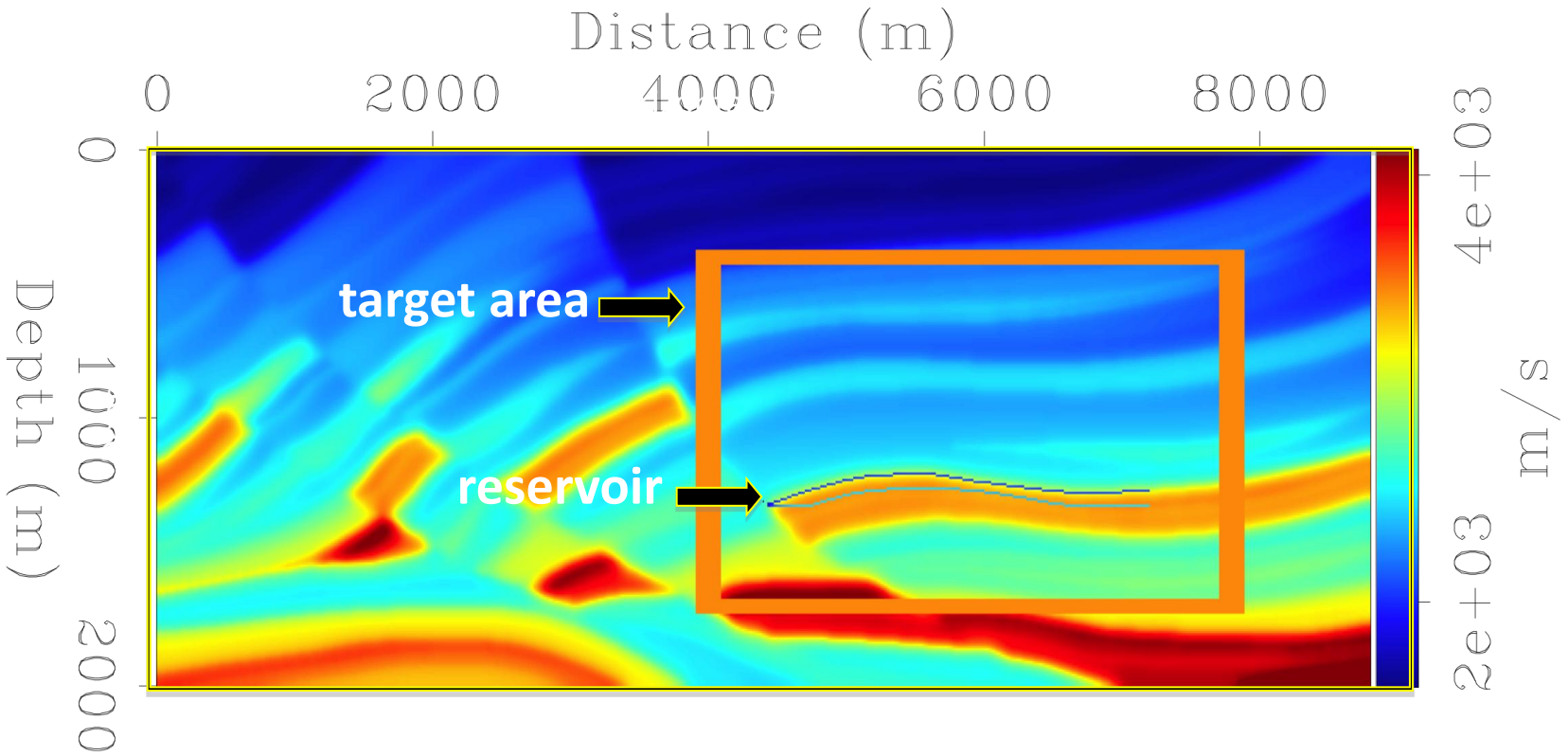
Synthetic 4D time-lapse example
Reservoir Model



From Gboyega Ayeni, 2009, Stanford University

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Time-lapse images: Complete data (Migration)

From Gboyega Ayeni, 2009, Stanford University

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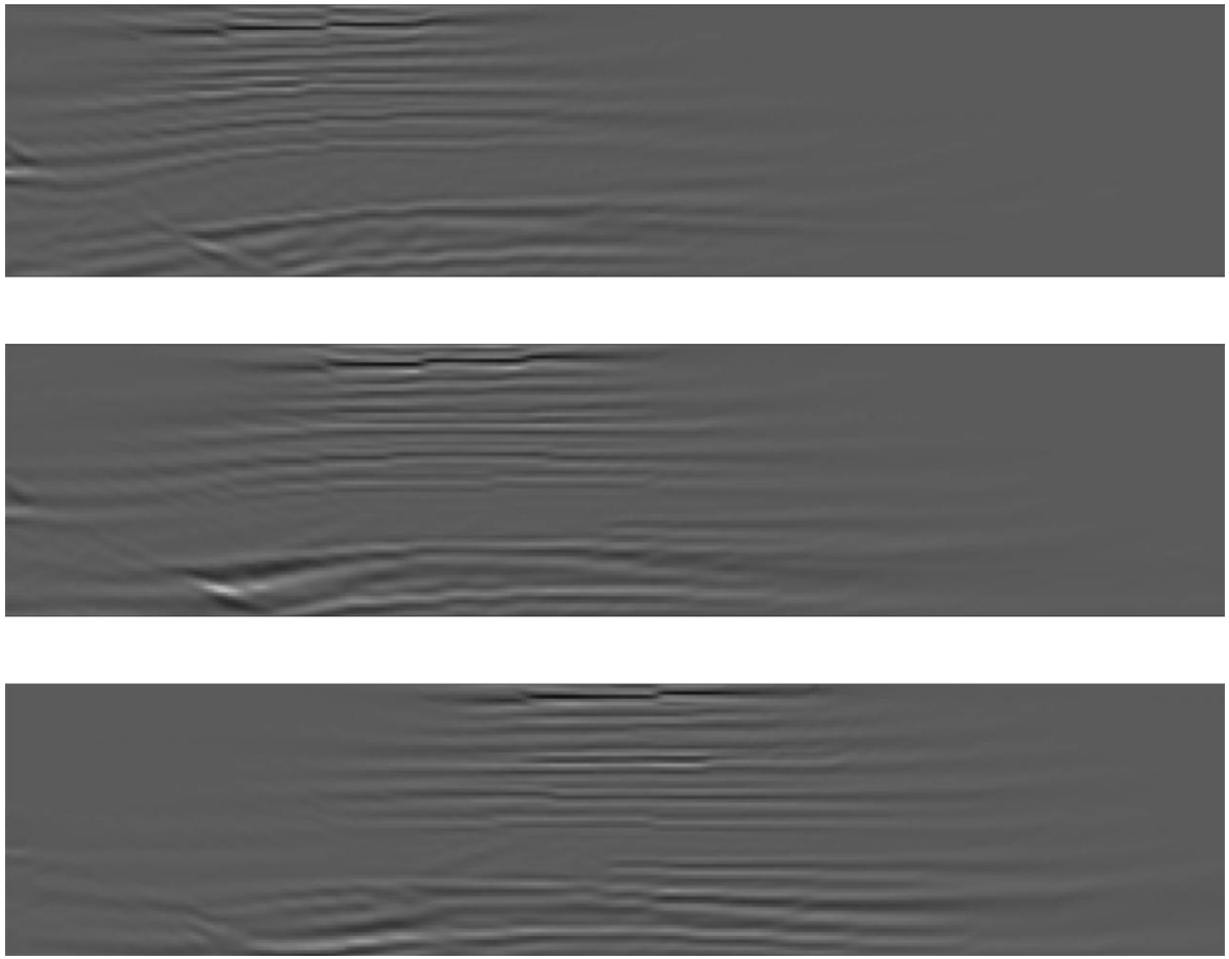
Time-lapse images: Incomplete data (Migration)



From Gboyega Ayeni, 2009, Stanford University

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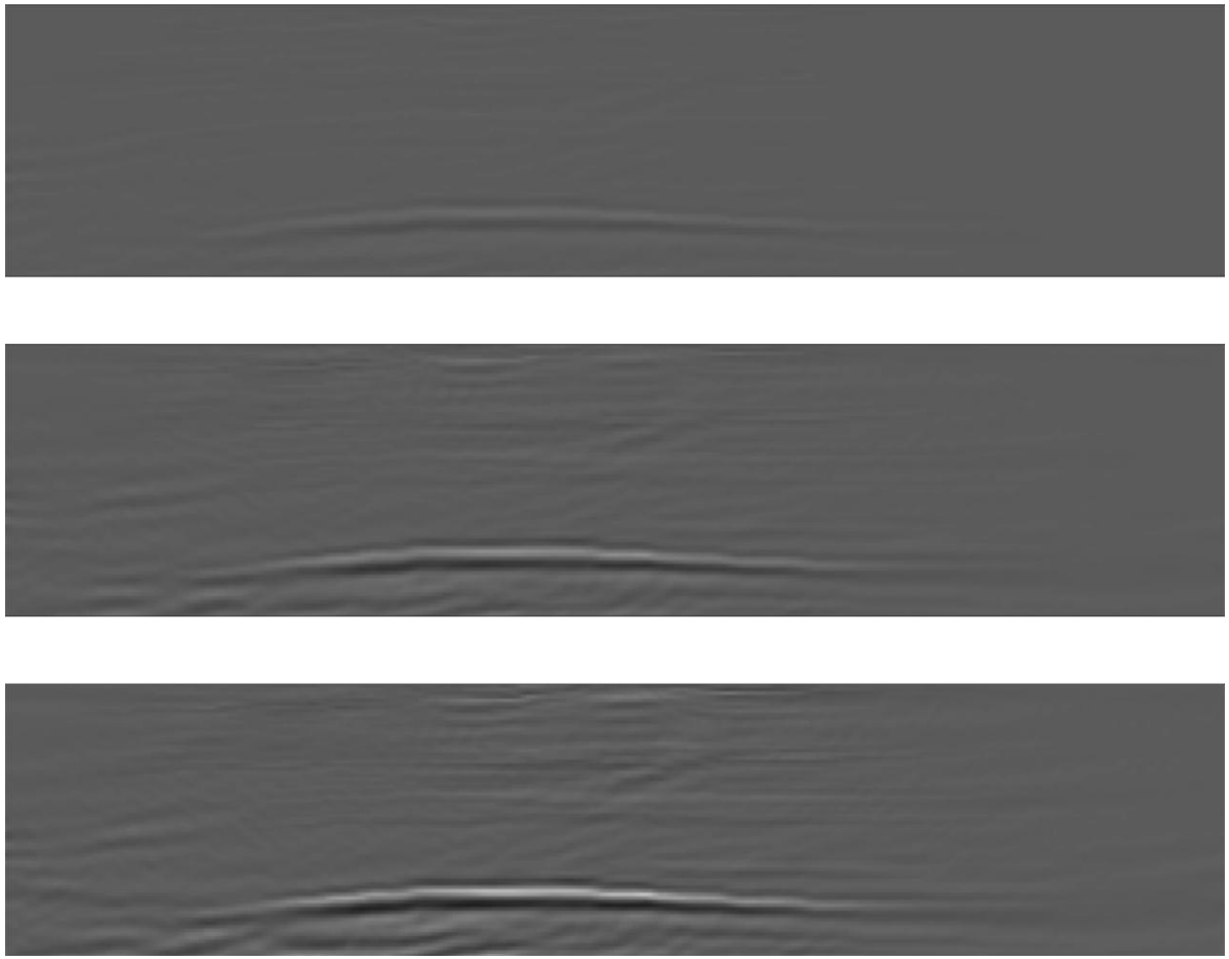
Time-lapse images: Incomplete data (Migration inversion)



From Gboyega Ayeni, 2009, Stanford University

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Time-lapse images: Complete data (Migration)

From Gboyega Ayeni, 2009, Stanford University

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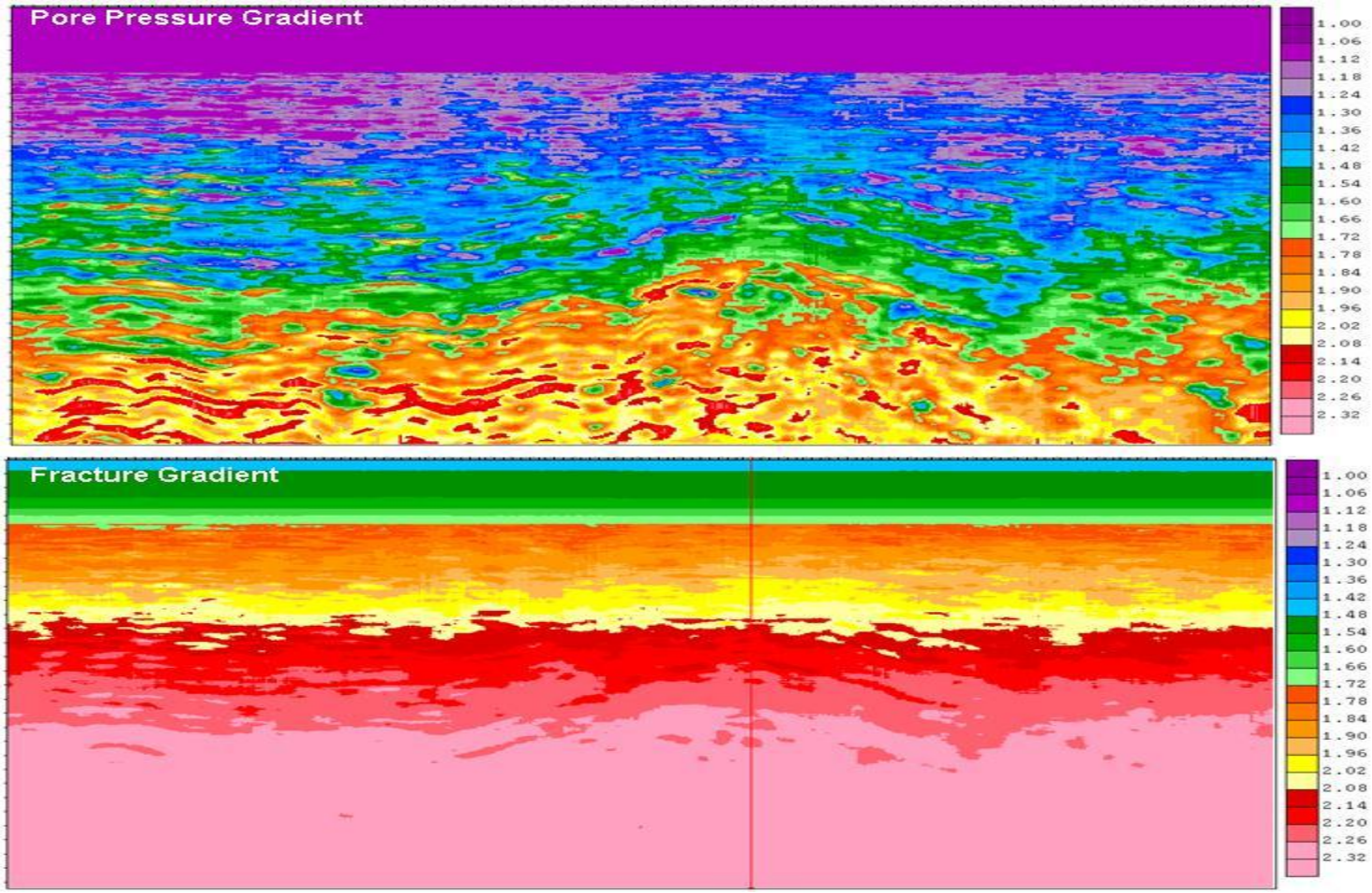
4D Attributes



Sections of pore pressure gradient and fracture gradient from a 3-D volume showing pressure variations in the subsurface in an offshore gas field in Mexico. Pore pressure is critical for assessment of seal integrity and for mapping fracture distribution. Both are critical to assure CO2 sequestration and to monitor and detect reservoir leakage.

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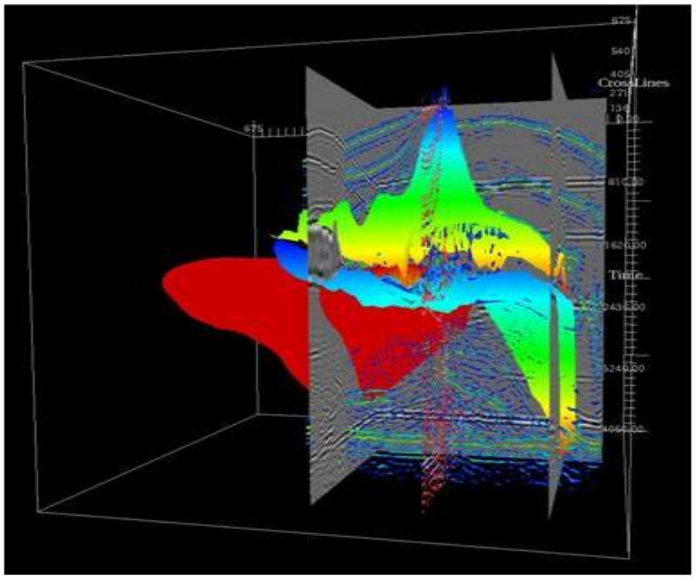
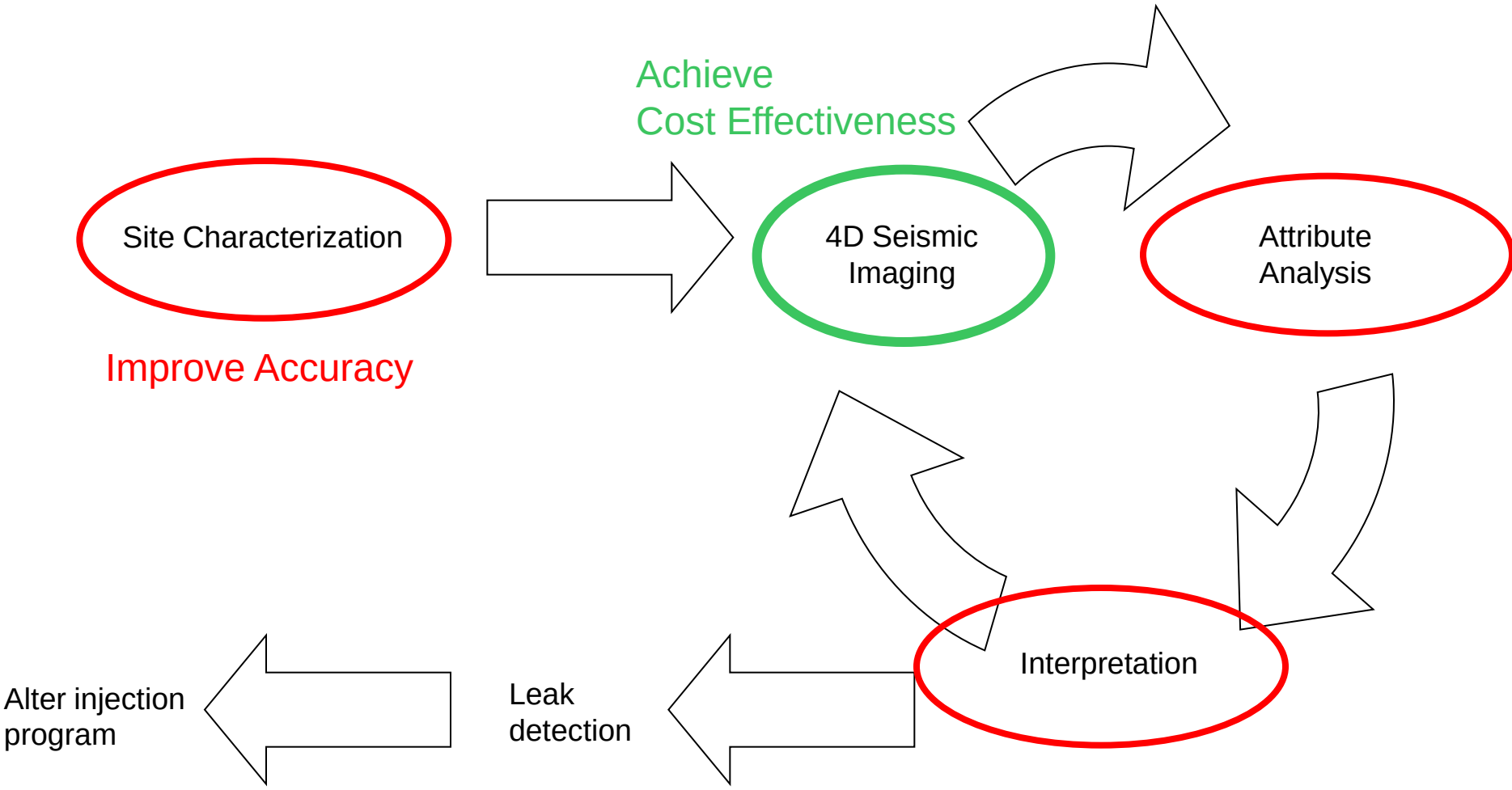
Software Infrastructure

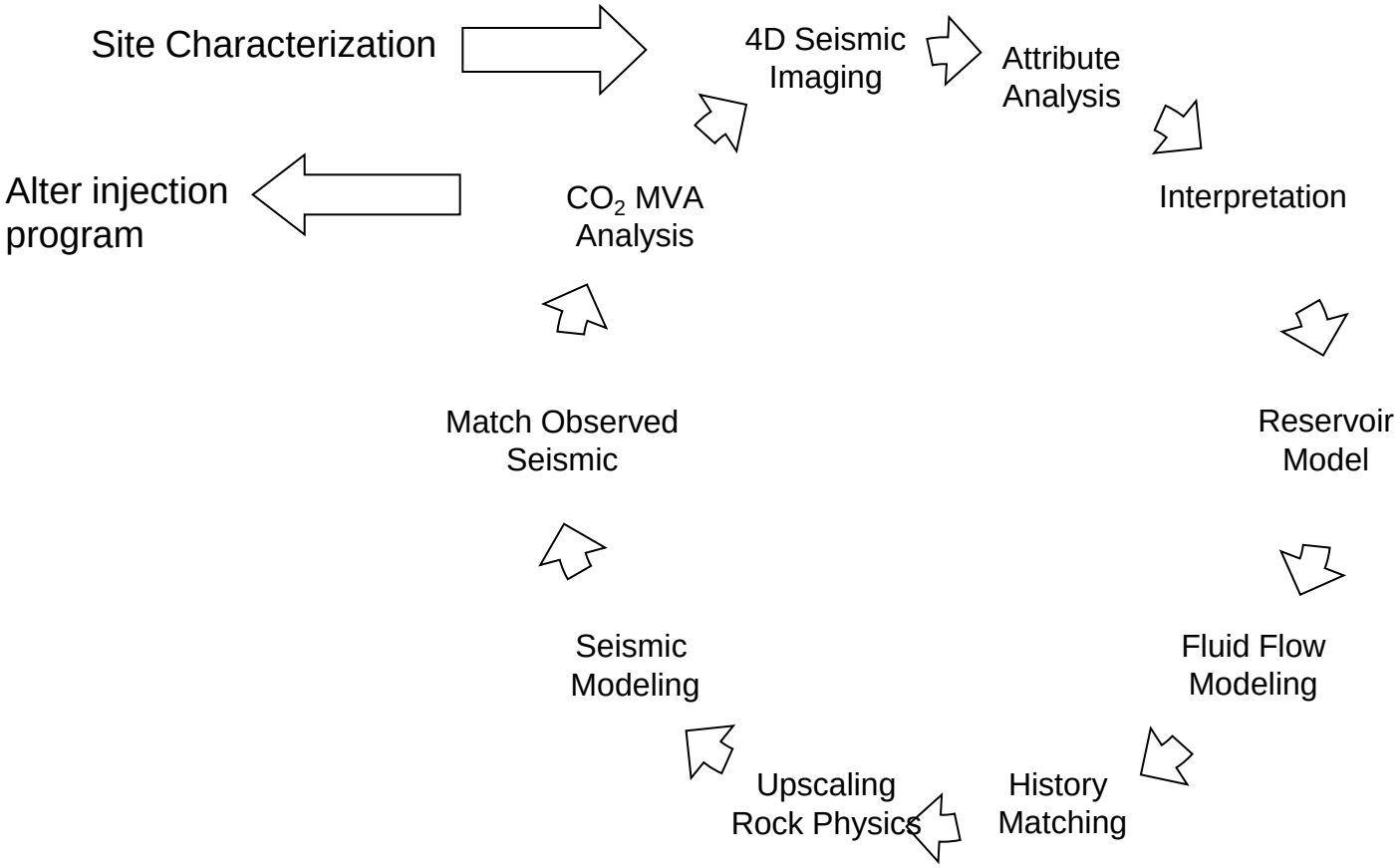
- **Software infrastructure for CO2 MVA:**
  - Integrated seismic, well, geologic, reservoir
  - Integrated database
  - Optimized for HPC
  - Visualization
  - Collaboration

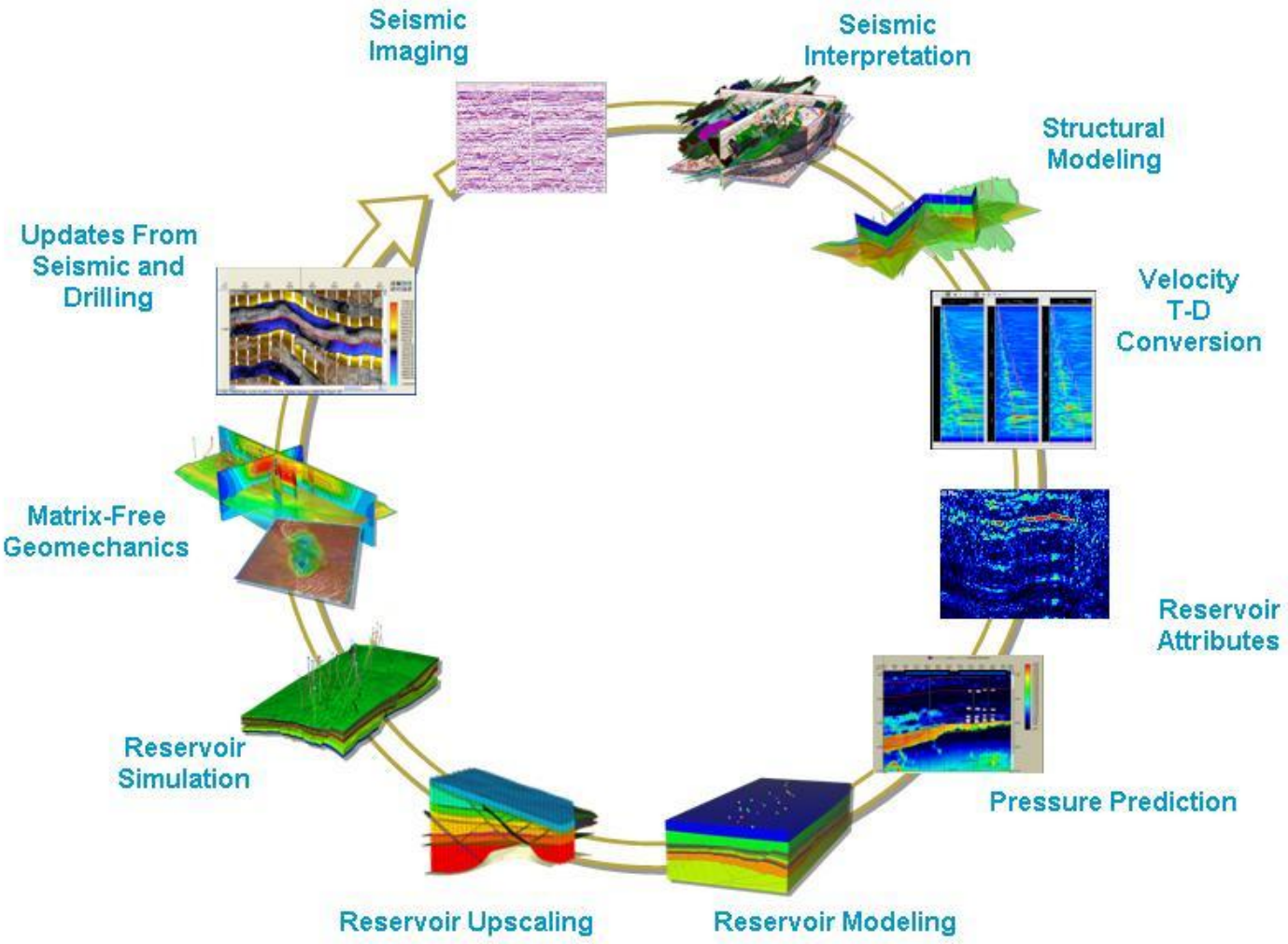


CO_2 Sequestration Monitoring Cycle



CO_2 Sequestration Monitoring Cycle





The software tools and infrastructure proposed herein will seamlesly allow the multidisciplinary integration of the full suite of technologies necessary for CO2 MVA within Fusion's GeoPRO™, and JOA's JewelSuite™. This figure illustrates how data will flow from one application to the next within an integrated framework. It will be possible to skip steps, add steps and modules, and to enter the workflow at any point on the "circle."

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Feasibility Study

Preliminary Seismic Interpretation and Geophysical Analysis of the Crow Mountain Saline Aquifer: RMOTC, Teapot Dome 3D Seismic Data Set

- **Complete processing of 3D seismic data**
  - **Through time & depth migration**
  - **Reservoir geophysics**
    - Complete attribute analysis, geopressure
    - Integrating geologic and well information
  - **This gives us:**
    - Site Characterization
    - Baseline for sparse 4D monitoring
    - Basis to build reservoir model to simulate sparse 4D

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Preliminary Seismic Interpretation and Geophysical Analysis of the Crow Mountain Saline Aquifer: RMOTC, Teapot Dome 3D Seismic Data Set

- **Geologic Column**

- **Well ties and Seismic Characterization of Crow Mountain**
  - –Spectral Decomposition Character of Crow Mountain
  - –Spectral Inversion of Crow Mountain

- **Fluid Replacement Modeling (FRM) of Brine With CO_2 in Crow Mountain**
  - –Synthetic Offset Gather Modeling of FRM Models

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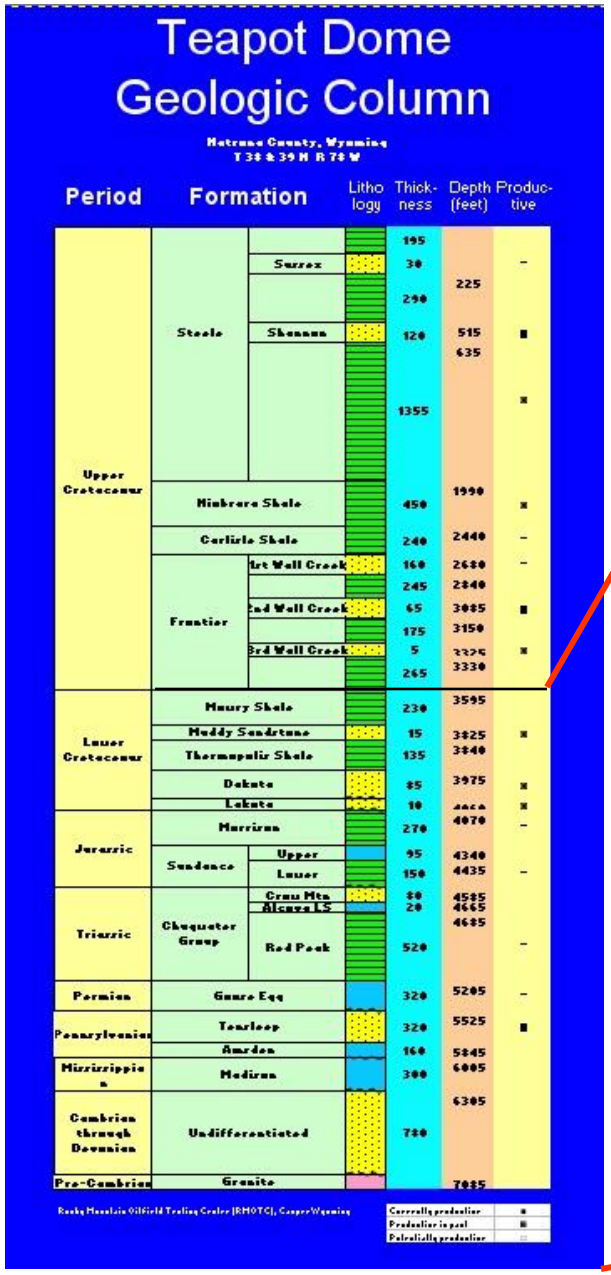
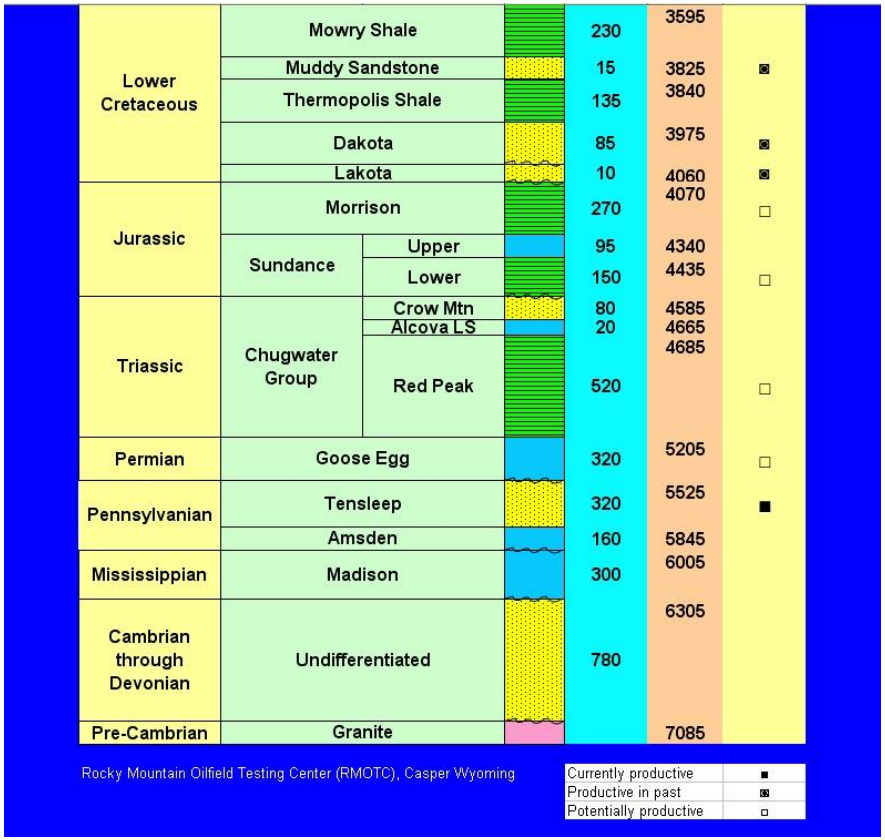
Geologic Section, Natrona County, Wyoming





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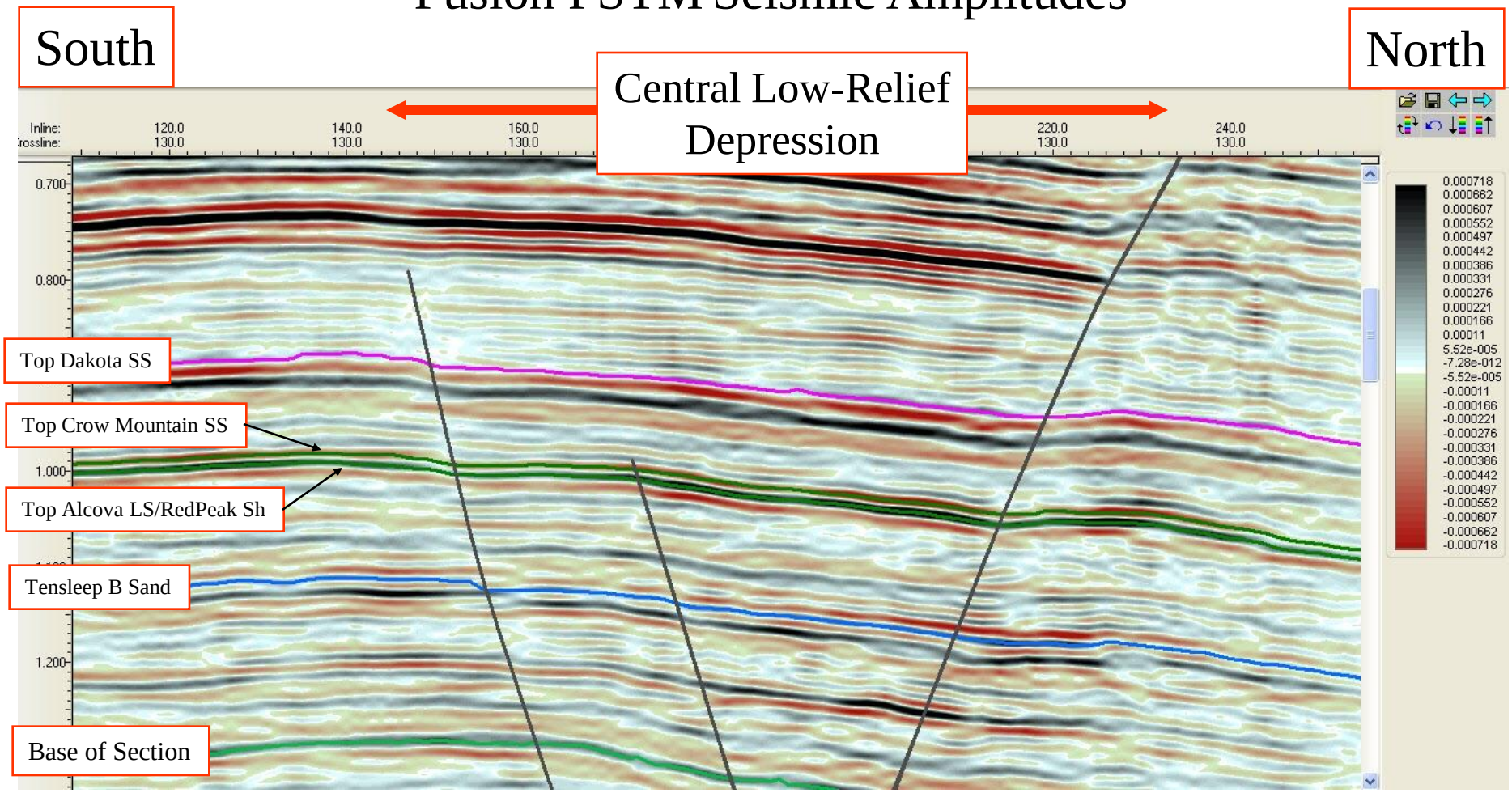
Cross Line 130 Across Central, Low-Relief, Depression/Graben Structure

Fusion PSTM Seismic Amplitudes



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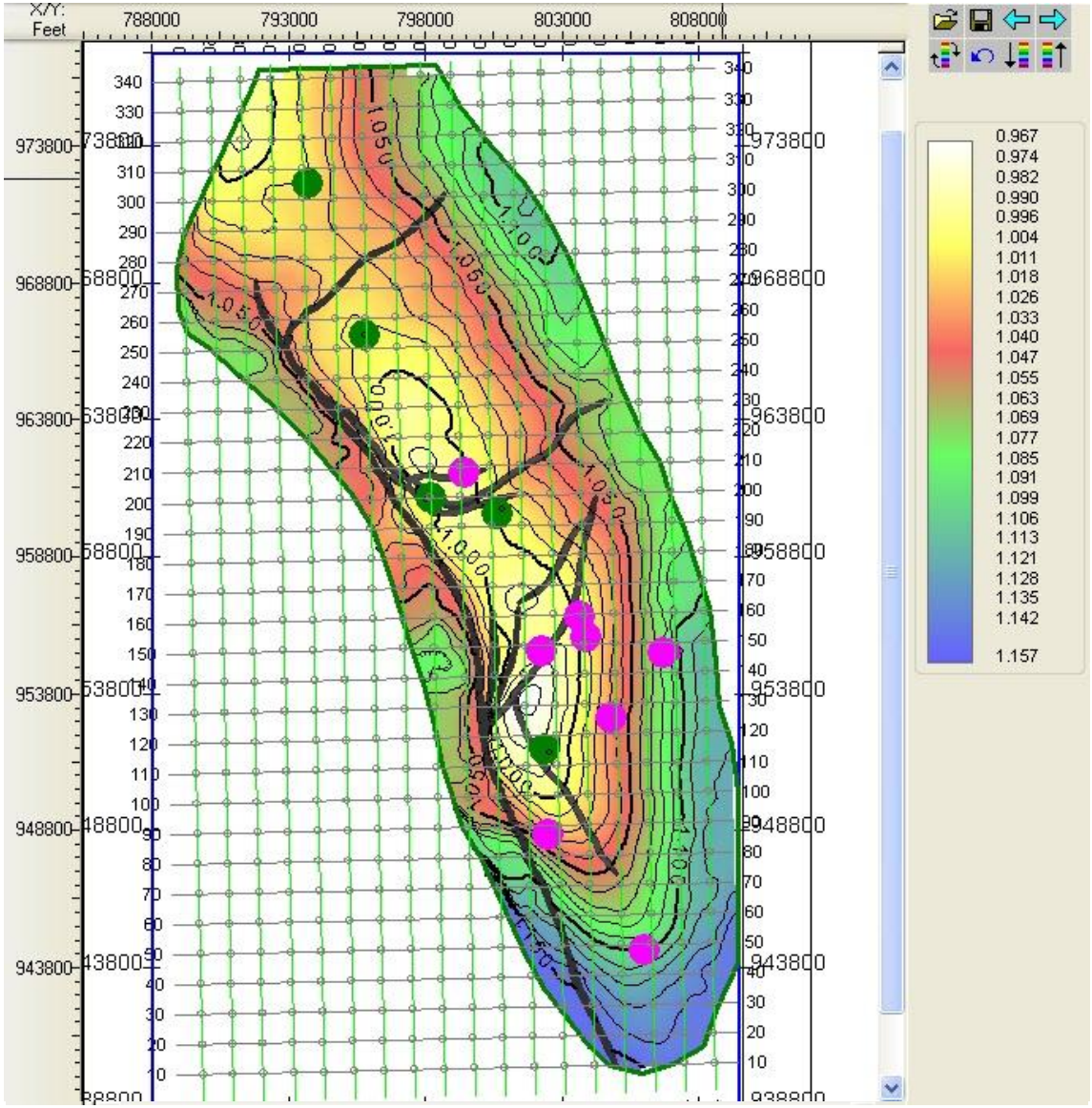
Preliminary Time Map of Crow Mountain Saline Aquifer

Map Showing Thirteen Wells Used For Correlation; Having Greater Than 3000 Feet of Sonic and Density Logs Recorded



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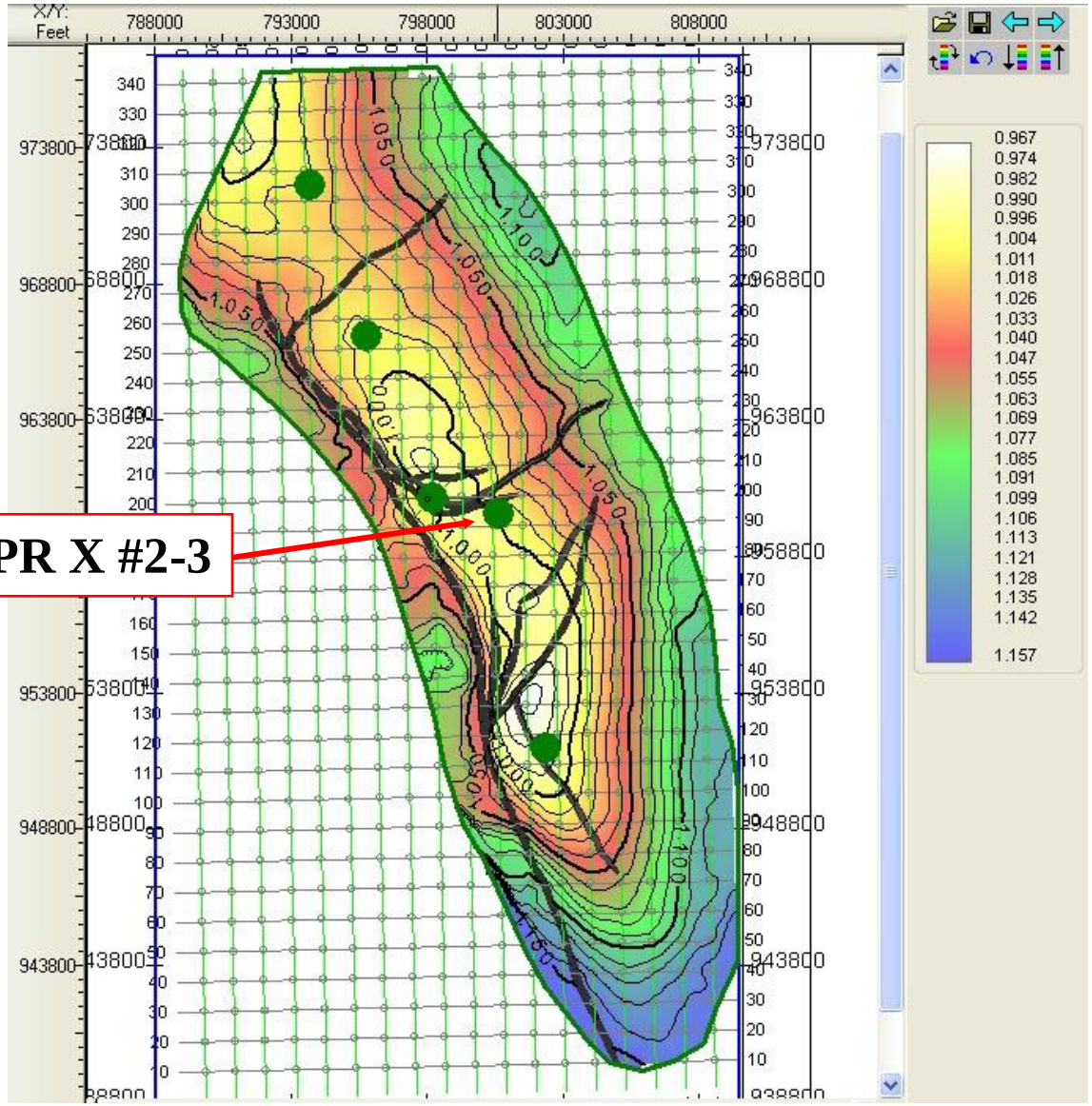
Preliminary Time Map of Crow Mountain Saline Aquifer

Map Showing Five Wells With Crow Mountain Tops and Greater Than 3000 Feet of Sonic and Density Logs Recorded and Used For Synthetic Tie Evaluation



Department NPR X #2-3

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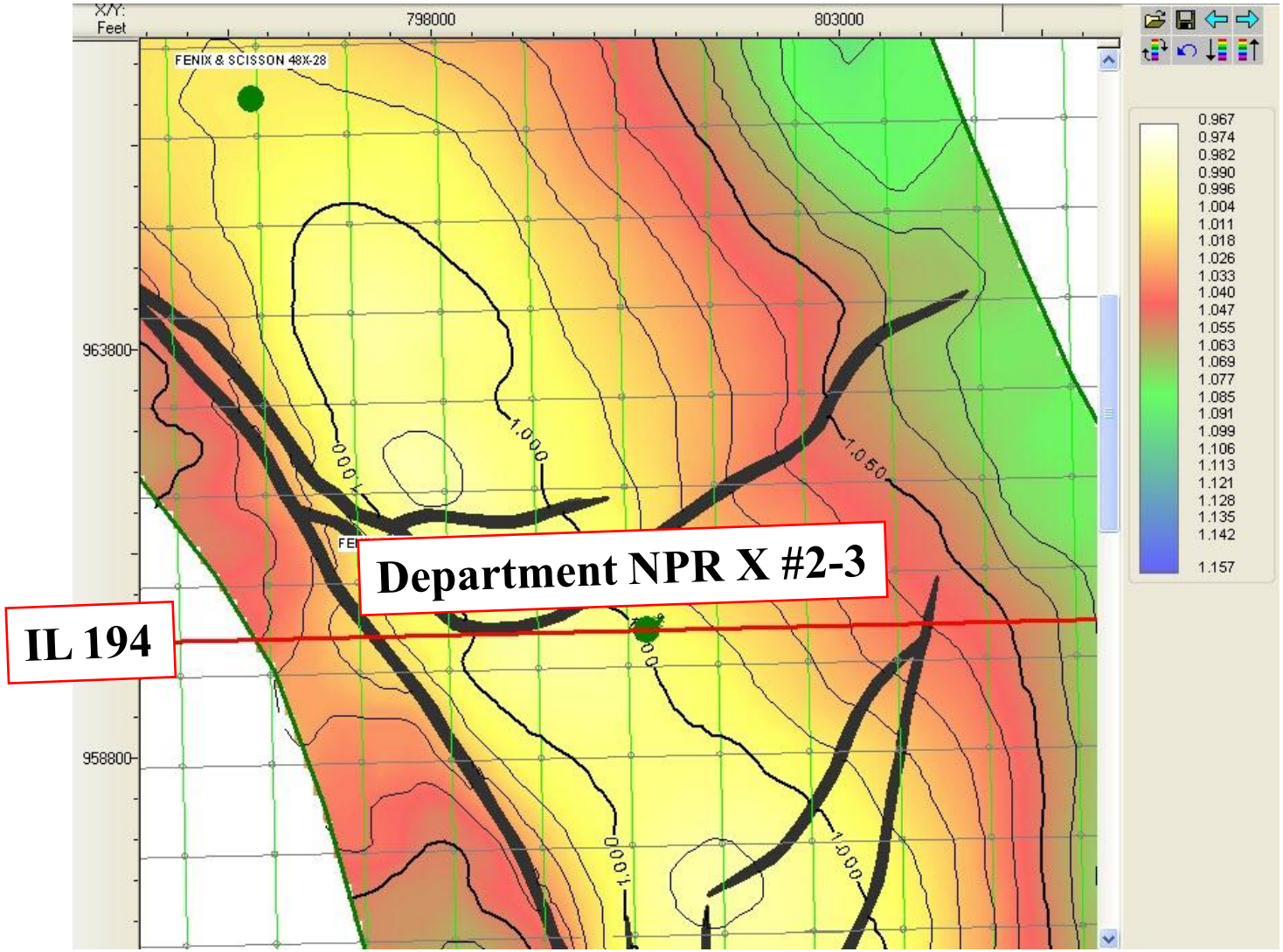
Preliminary Time Map of Crow Mountain Saline Aquifer

Middle Section of Survey: With Department NPR X #2-3 Well on Inline 194



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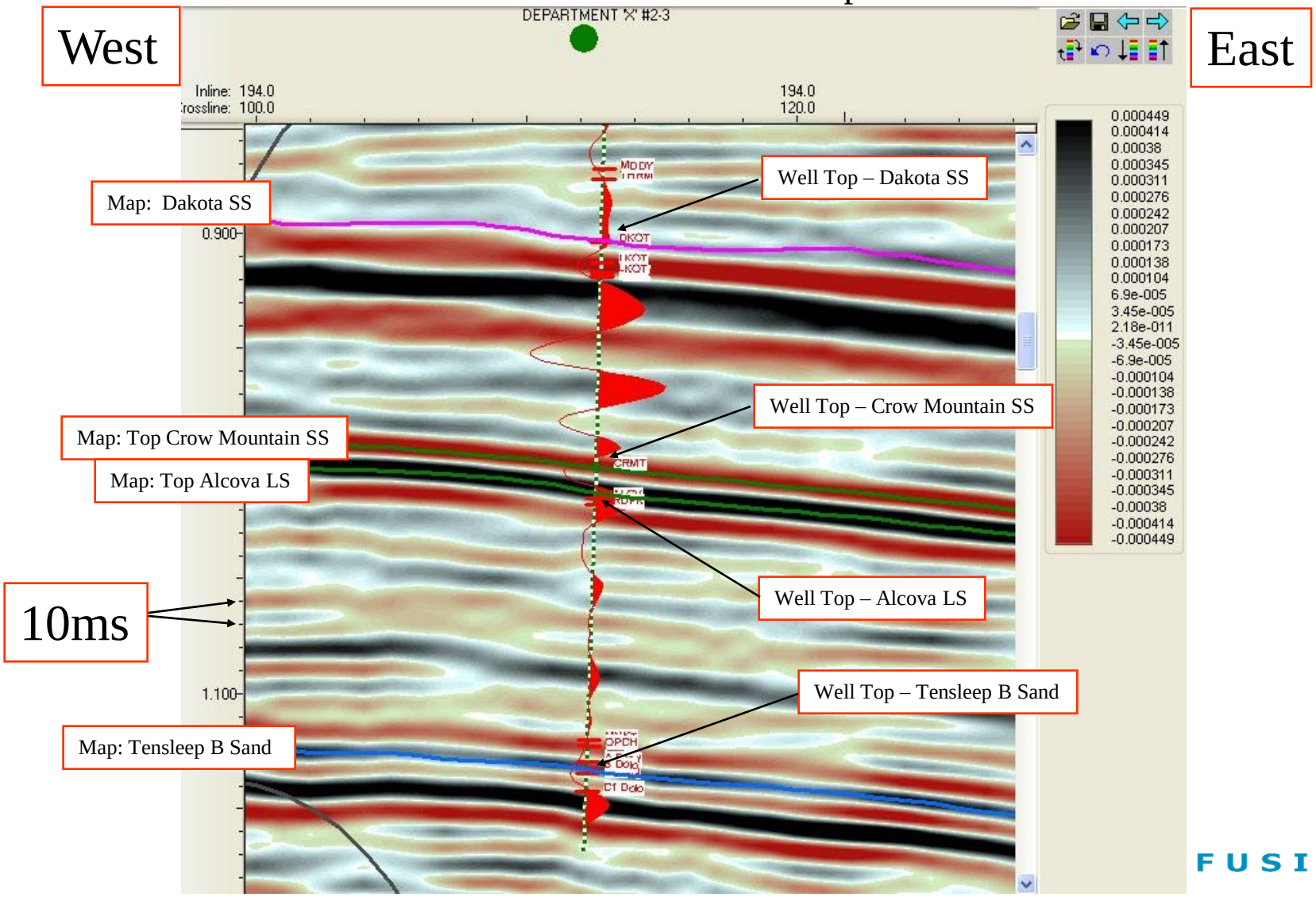
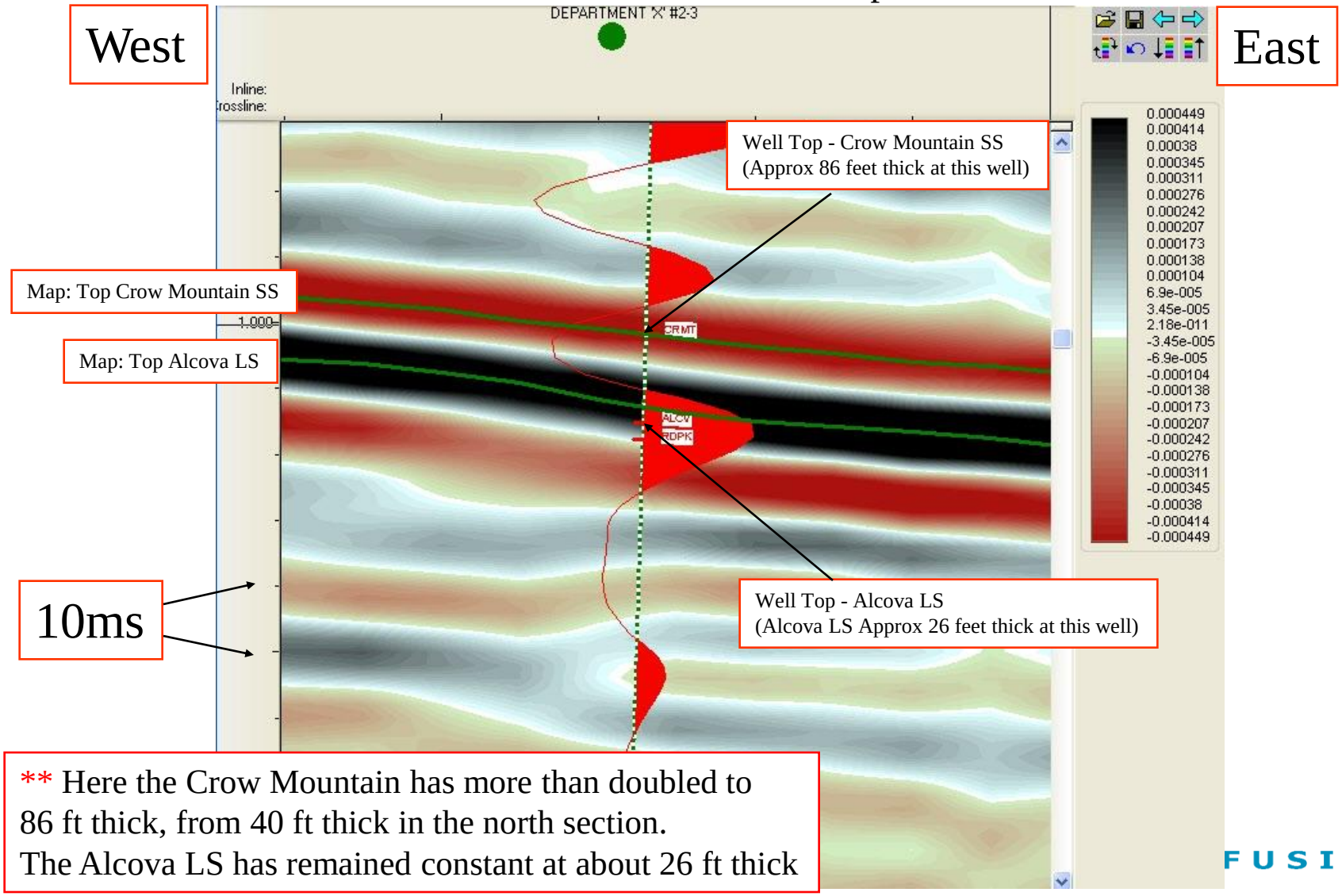
Inline 194 Across Department NPR X #2-3 Well
Middle Section of Survey

Fusion PSTM Seismic Amplitudes



Inline 194 Across Department NPR X #2-3 Well
Middle Section of Survey

Fusion PSTM Seismic Amplitudes



** Here the Crow Mountain has more than doubled to 86 ft thick, from 40 ft thick in the north section.
The Alcova LS has remained constant at about 26 ft thick

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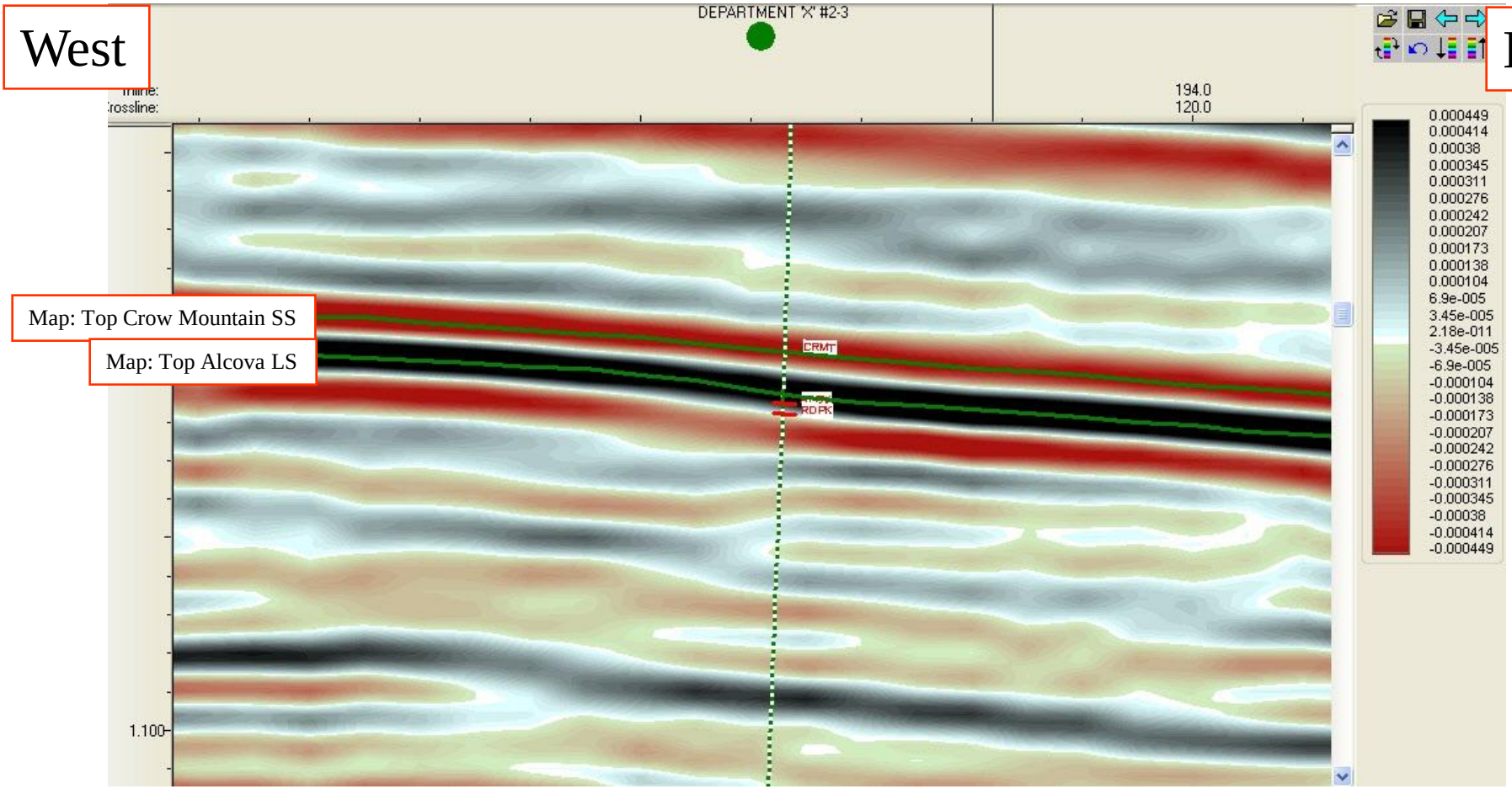
Inline 194 Across Department NPR X #2-3 Well
Central Section of Survey

Fusion PSTM Seismic Amplitudes

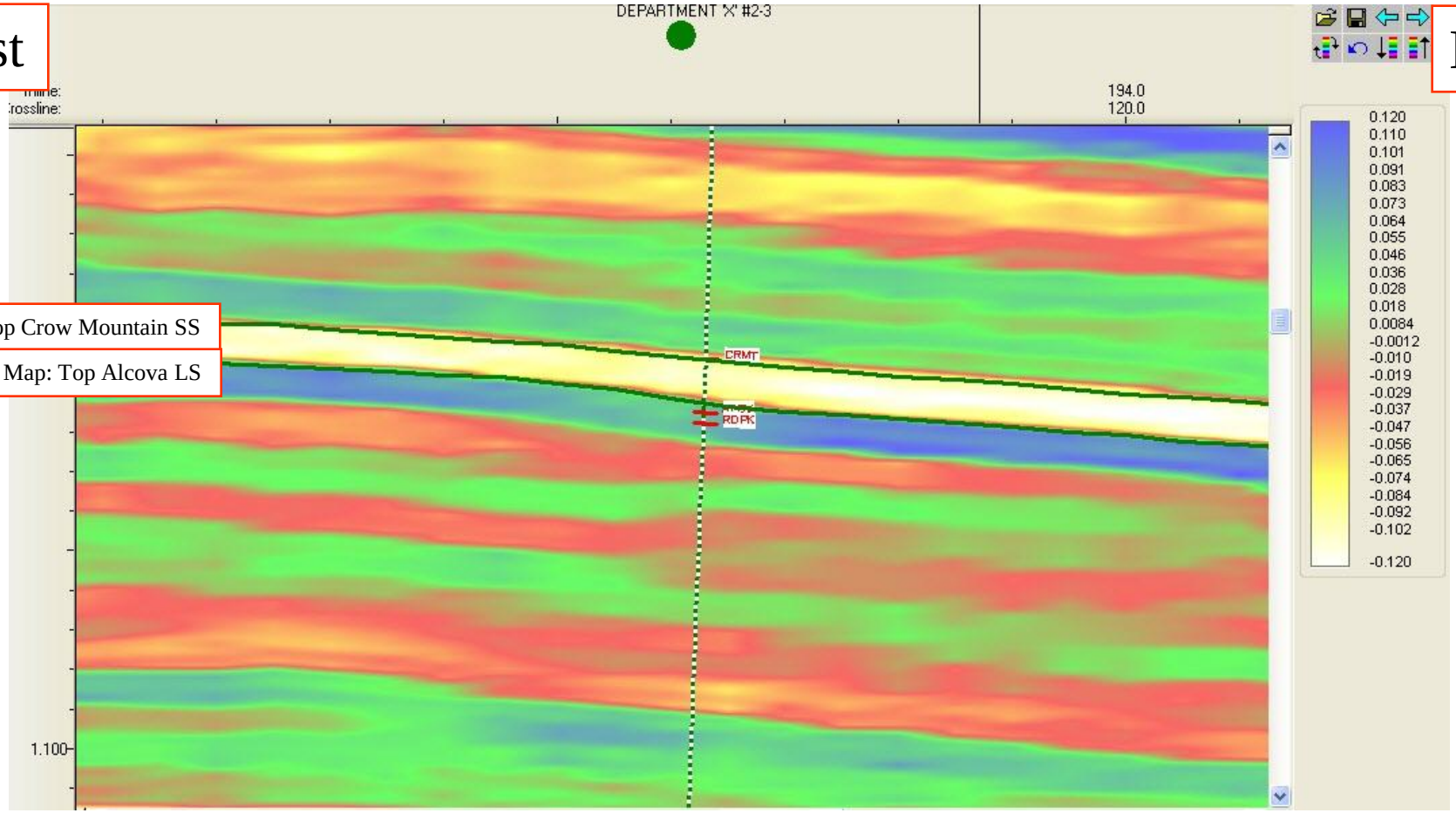


Inline 194 Across Department NPR X #2-3 Well
Central Section of Survey

Fusion ThinMAN Relative Acoustic Impedance Section

West

East



Map: Top Crow Mountain SS

Map: Top Alcova LS

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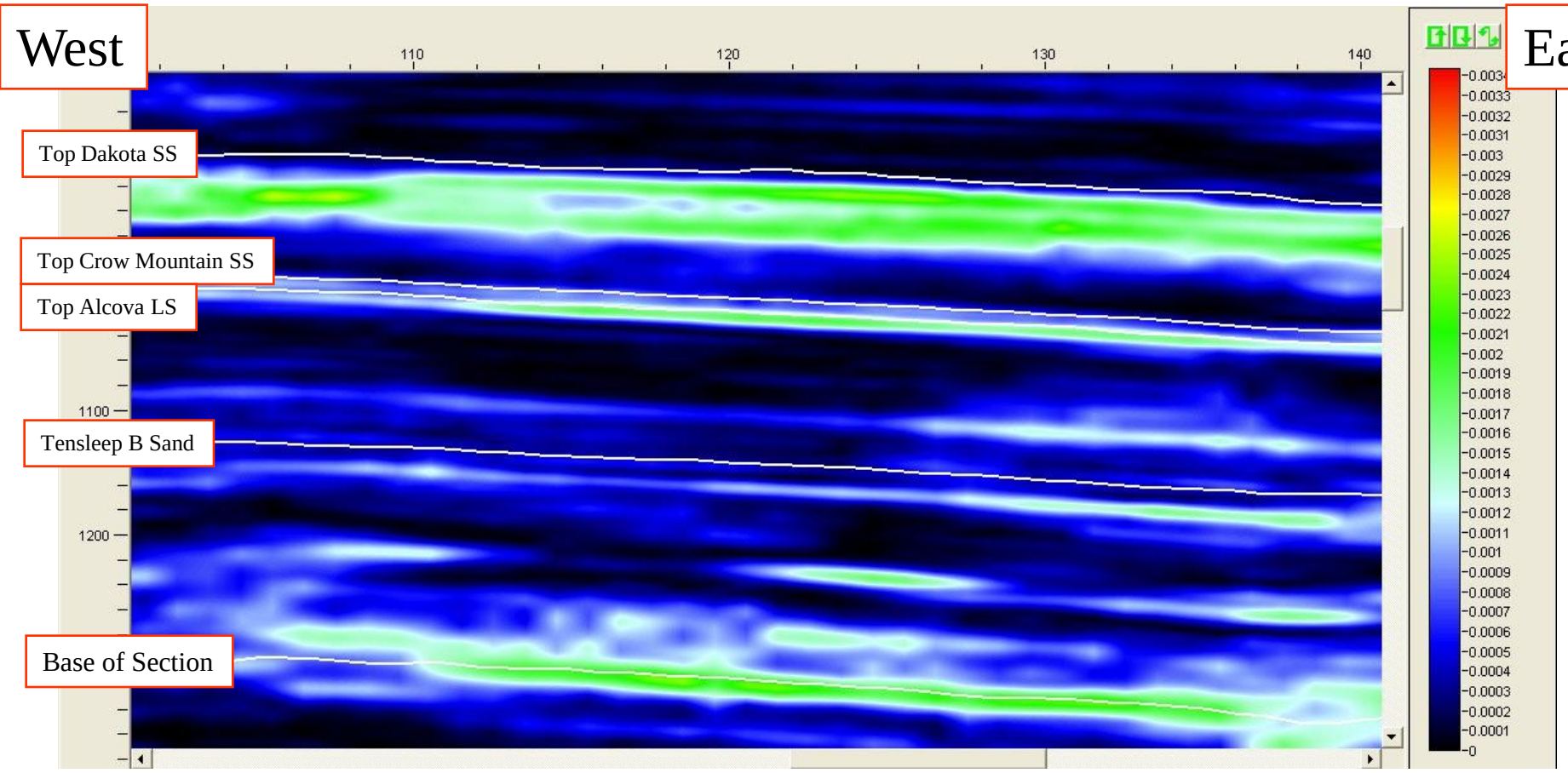
Zoom of Spectral Decomposition: Inline 194 Across Central Section

Continuous Wavelet Transform: Section Amplitudes at 20 Hz



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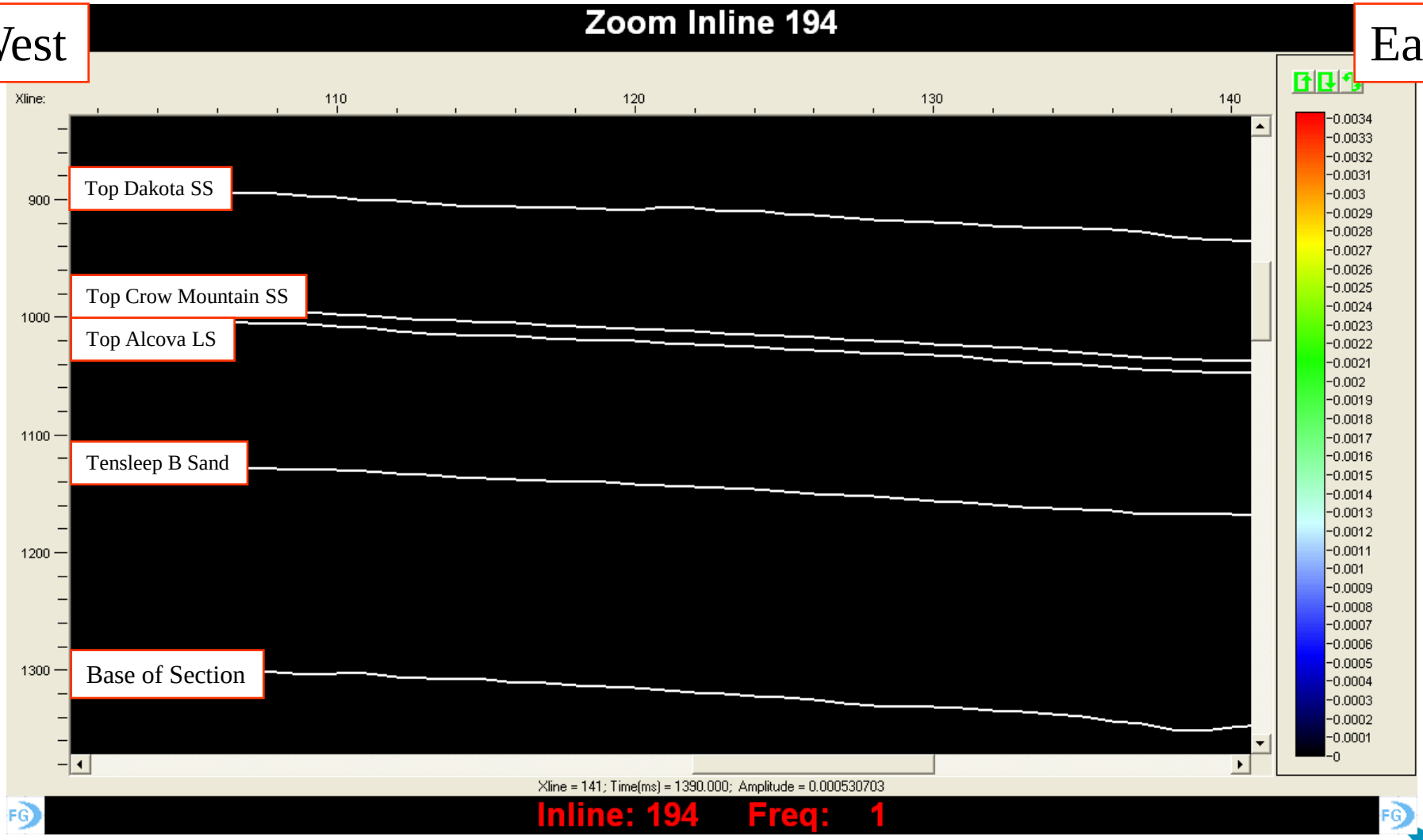
Zoom of Spectral Decomposition: Inline 194 Across Central Section

Continuous Wavelet Transform Amplitudes AVI 1 to 100 Hz

West

East



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Preliminary Seismic Interpretation and Geophysical Analysis of the Crow Mountain Saline Aquifer: RMOTC, Teapot Dome 3D Seismic Data Set

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  - Synthetic Offset Gather Modeling of FRM Models

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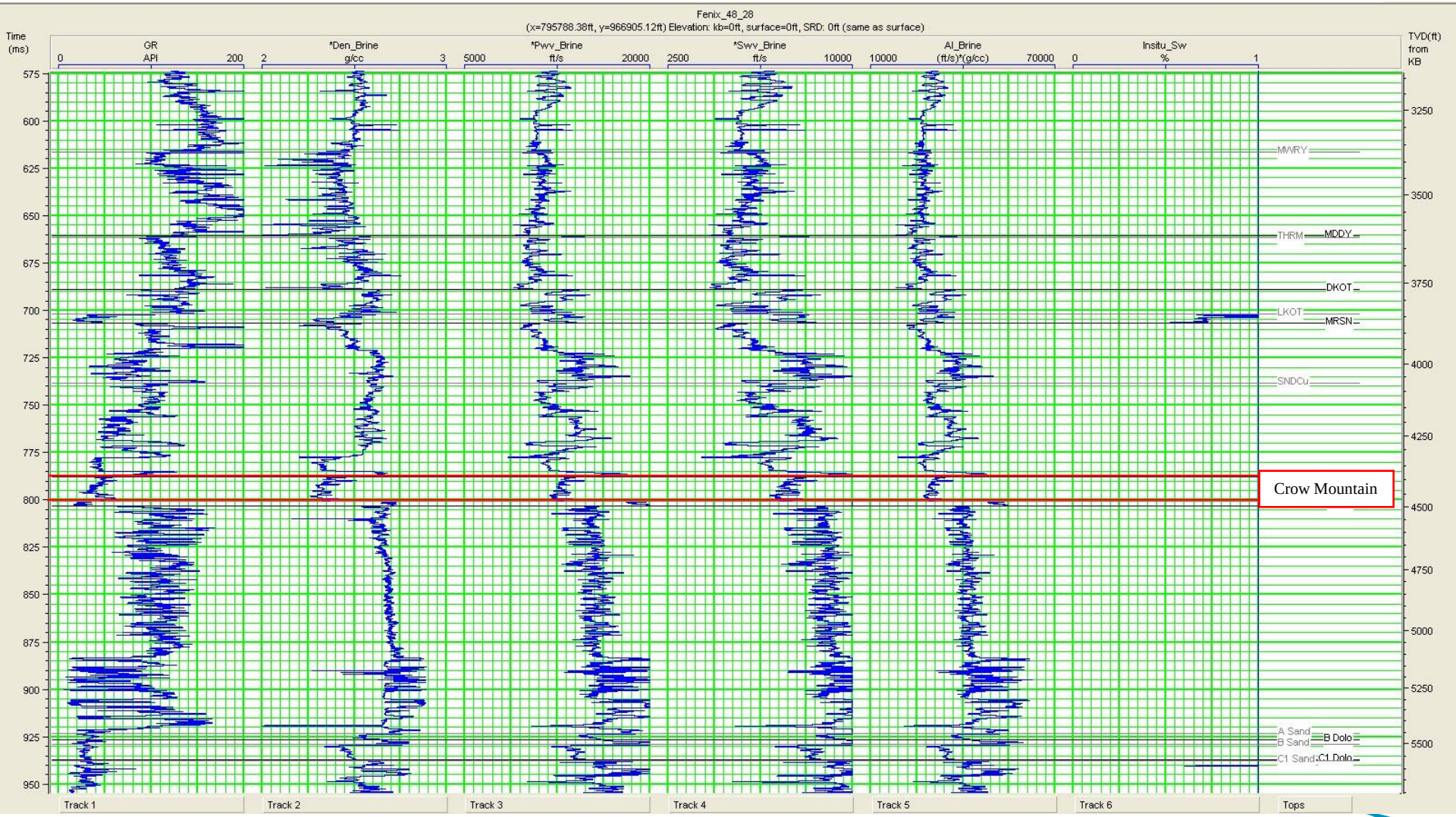
Fenix &Scisson 48X-28 Well

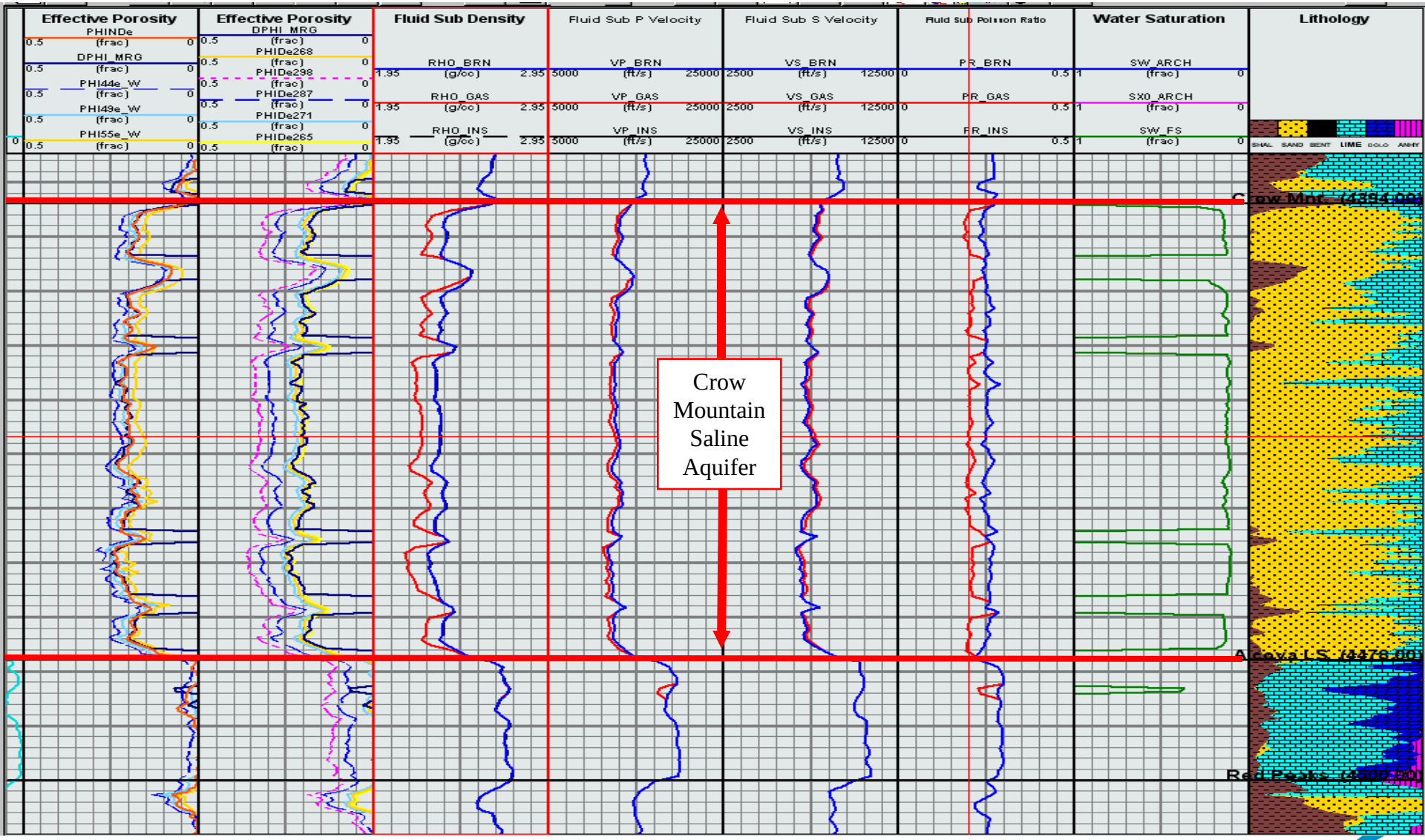
In-situ Edited Well Logs



Fenix &Scisson 48X-28 Well

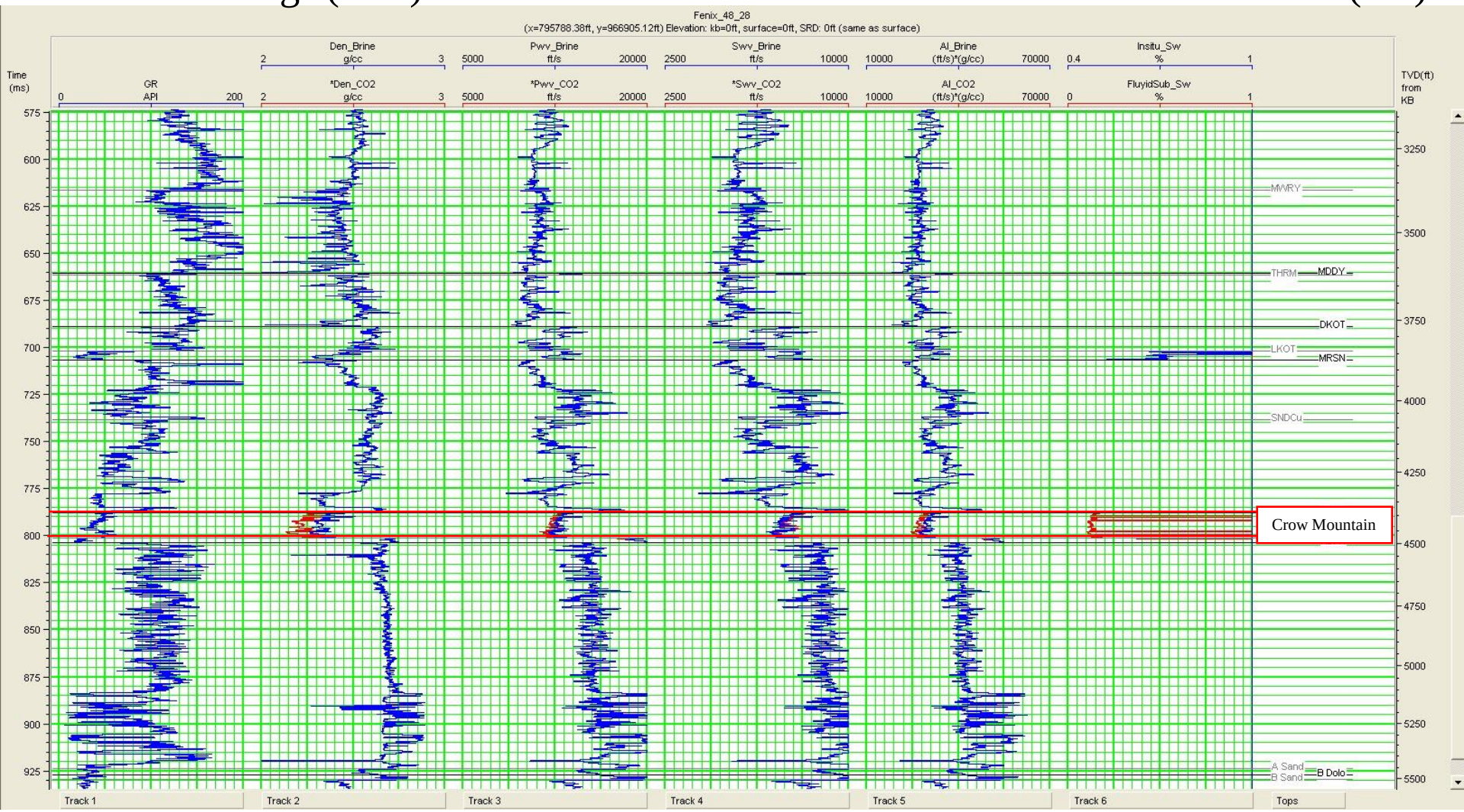
Full Petrophysical Analysis with Fluid Substitutions

Including Six Component Multi-Mineral Lithologic Analysis



Fenix &Scisson 48X-28 Well

In-situ Wet Logs (blue) and FRM of Crow Mountain With 88% CO2 Saturation (red)



Zoom Fenix &Scisson 48X-28 Well

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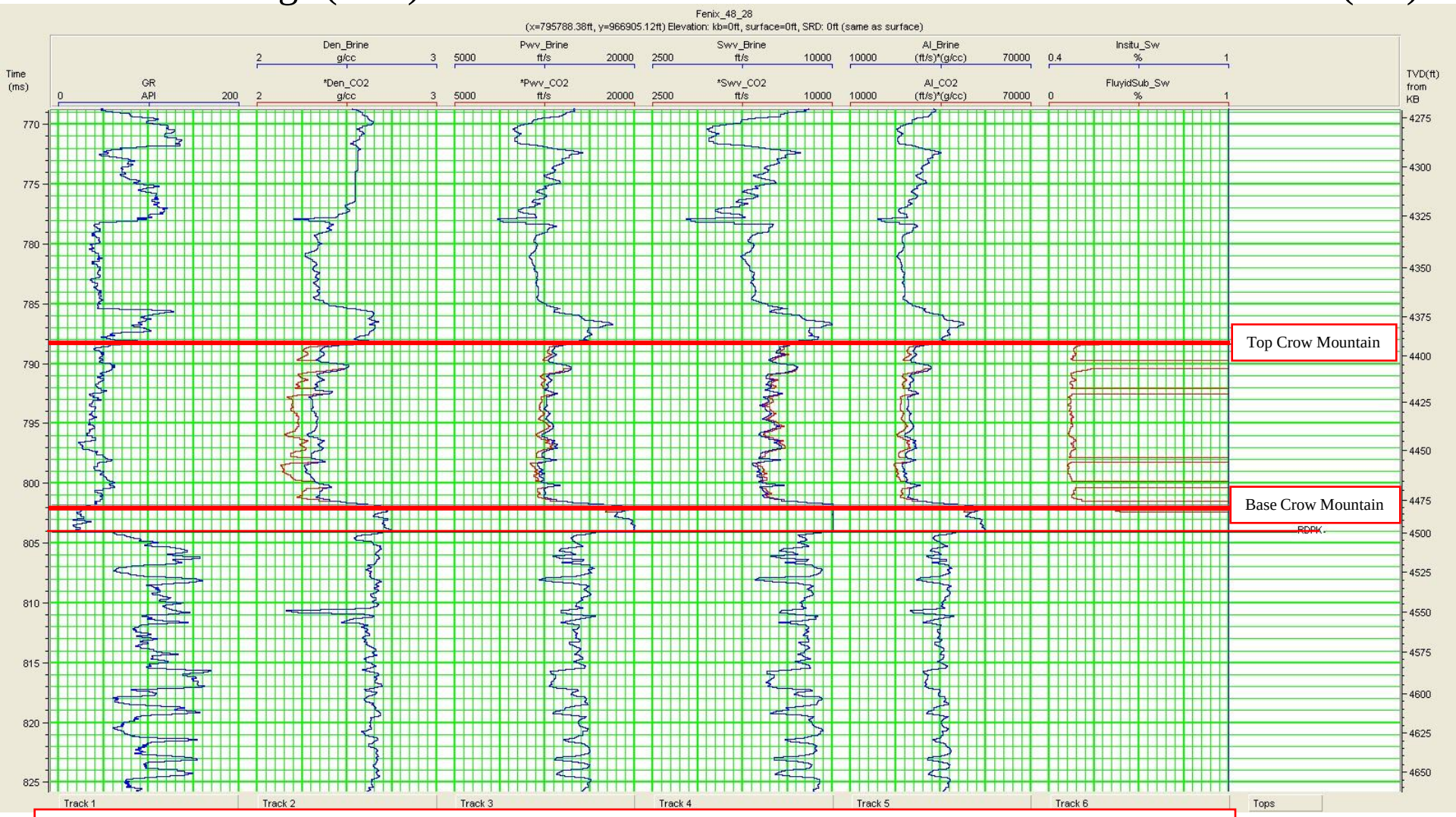

** The significant change with the FRM is 0.1 gm/cc (4%) decrease in bulk density of the formation by replacing brine with CO2 in the effective porosity of the Crow Mountain

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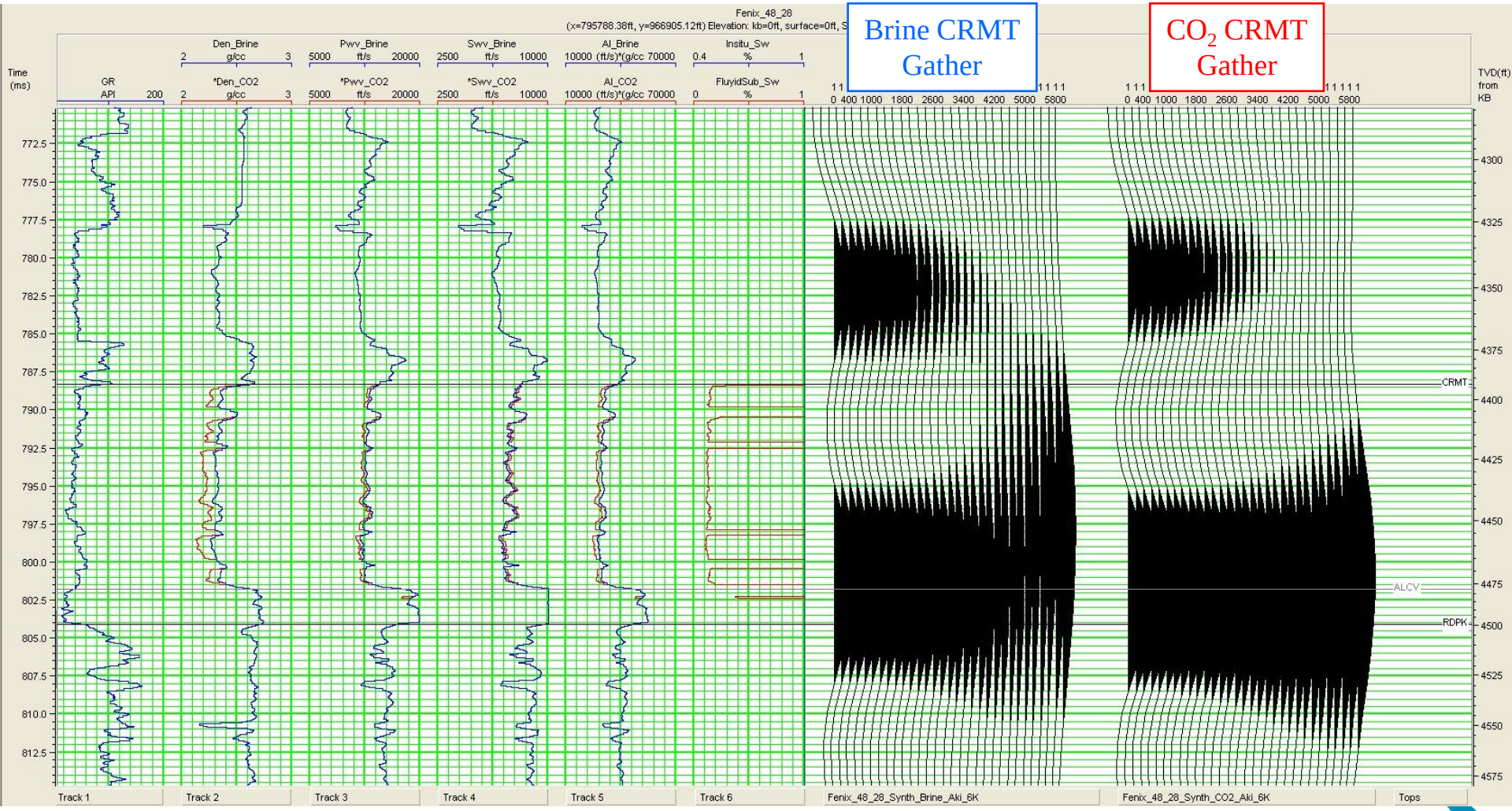
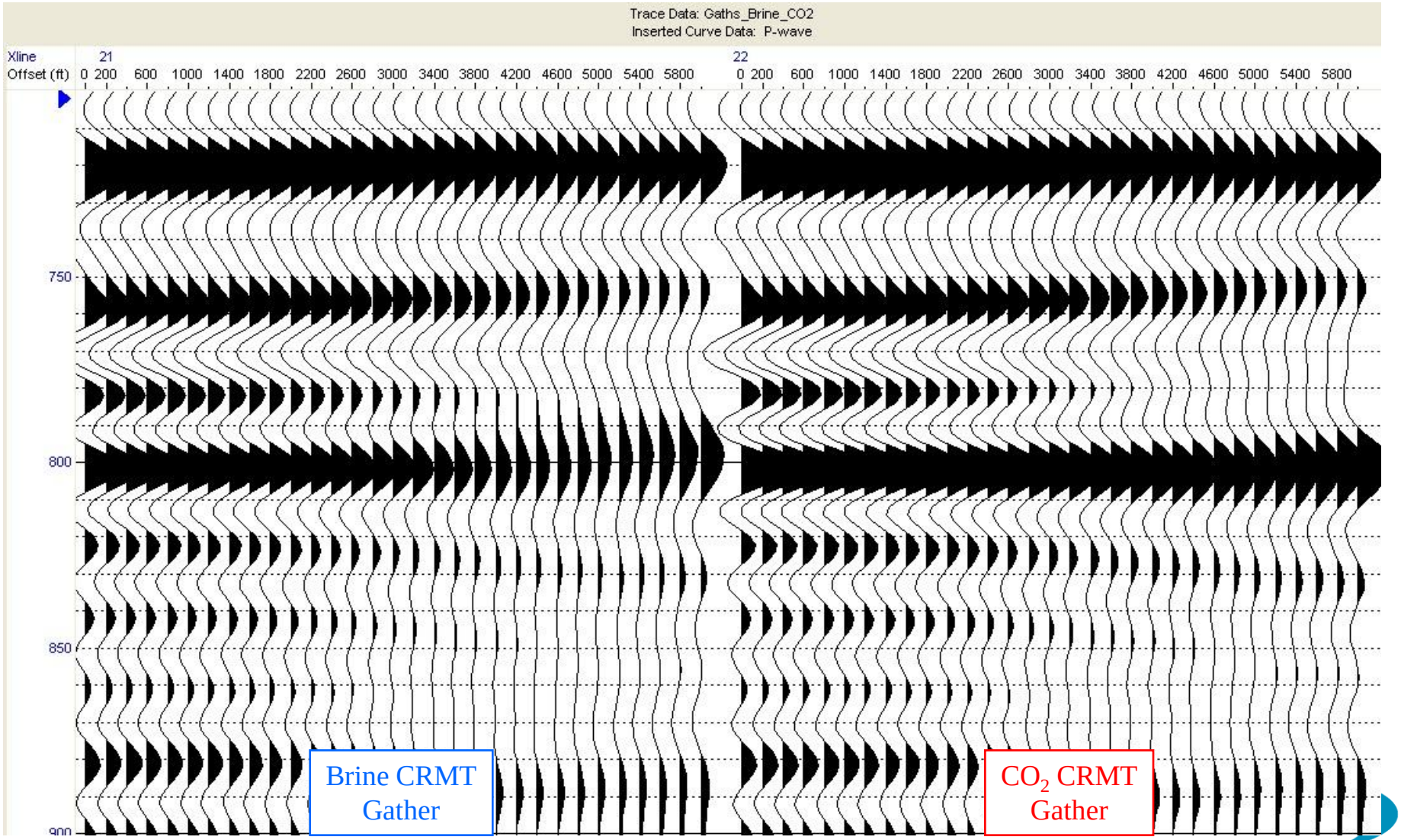
Zoom Fenix &Scisson 48X-28 Well

Synthetic Offset Gathers Computed to 6000 ft for the In-situ Wet logs and the FRM CO2 Saturated Logs of the Crow Mountain



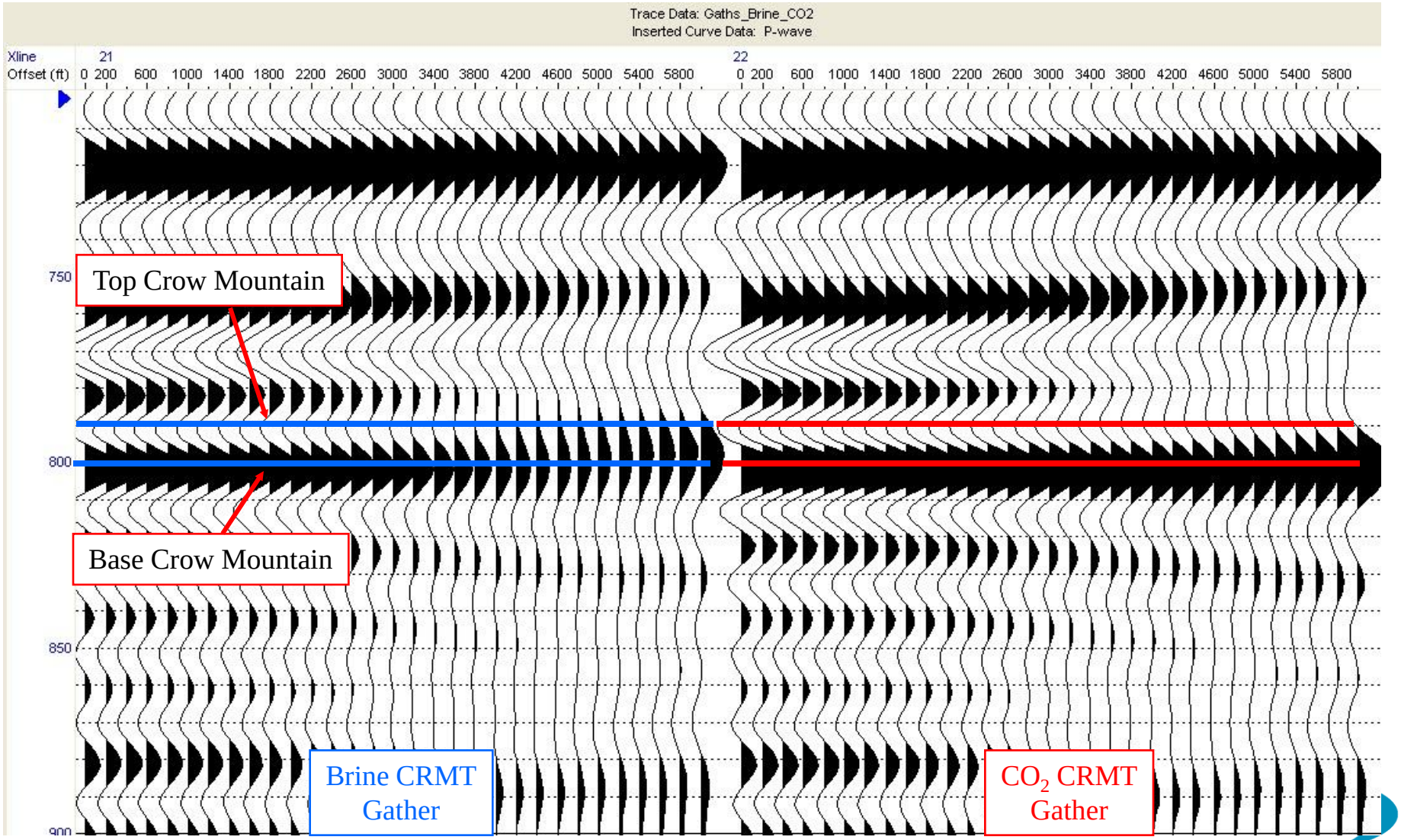
Zoom Fenix &Scisson 48X-28 Well

Synthetic Seismic Line Created From Offset Gathers Computed For In-situ Wet logs and the FRM CO2 Saturated Logs of the Crow Mountain



Zoom Fenix &Scisson 48X-28 Well

XL 21 and 22 of Synthetic Seismic Line Created From Offset Gathers Computed For In-situ Wet logs and the FRM CO2 Saturated Logs of the Crow Mountain



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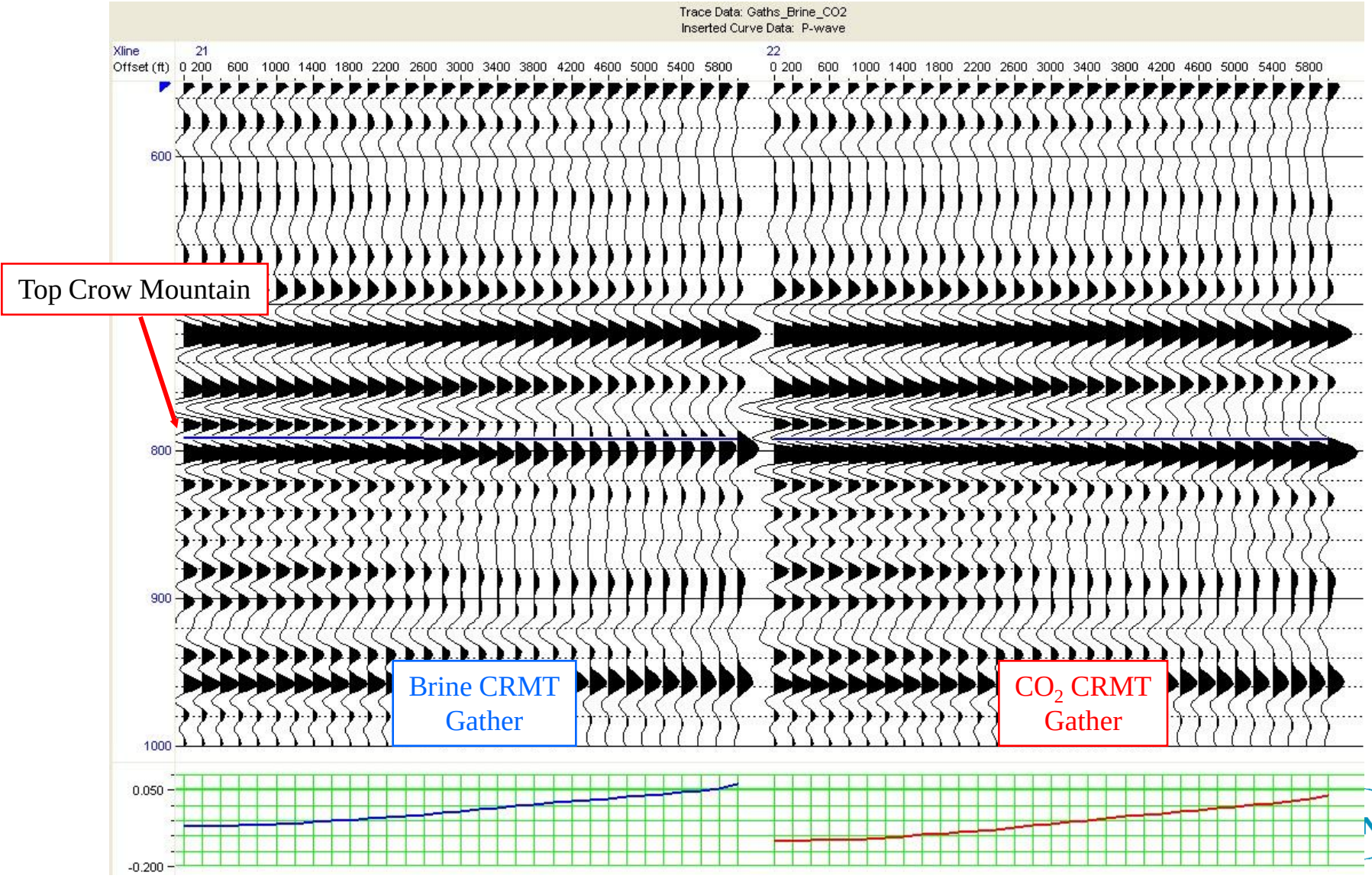

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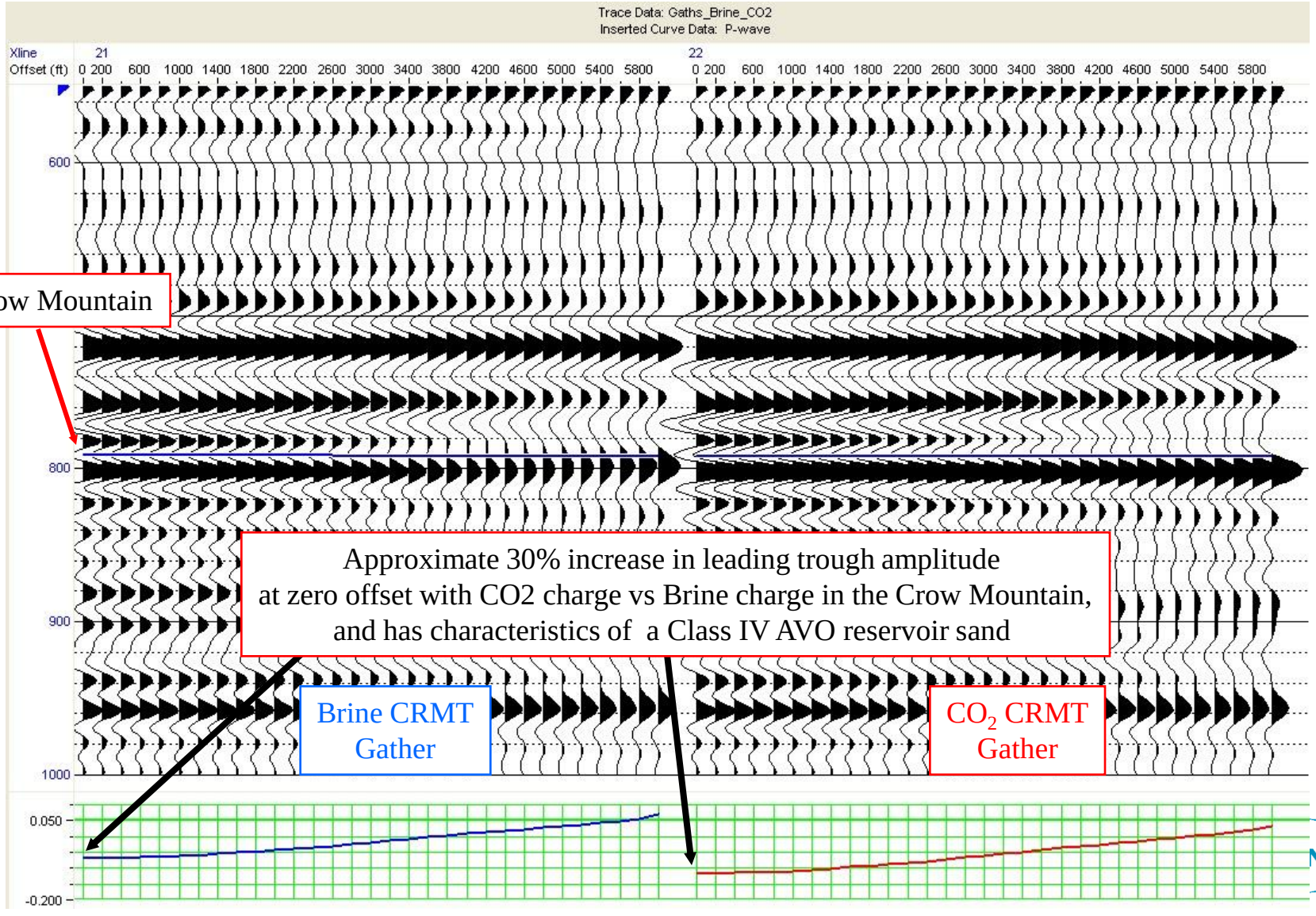
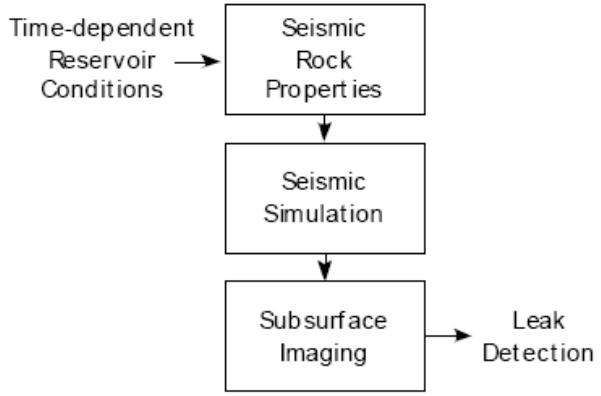


Feasibility Study

Next Steps:



- **Build reservoir model**
- **Simulate fluid flow – CO2 injection**
  - Upscale, rock physics -> velocity & density
- **Simulate seismic surveys**
  - Baseline
  - Time-lapse
- **Imaging of simulated seismic data**
- **Sparsity analysis**
  - Illumination compensation, migration inversion…
- **POC – CO2 MVA recommendations**

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Conclusions & Status

- Target saline aquifer characterized
  - **Building reservoir model**
  - **Spectral and Reflectivity inversion results suggest enhanced detectability**
- Fluid substitution & simple synthetics
  - **CO2 charge results in:**
  - **Diminished leading peak**
  - **Stronger Trough at top of Crow Mountain**
  - **Stronger Peak at base of Crow Mountain**
- Next Steps of POC:
  - **Reservoir simulation**
  - **Seismic simulation**
  - **Sparsity analysis**

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