Advancing Characterization of Faults Through Deployment of Novel Geophysical, Geochemical and Geomechanical Technologies at the San Juan Basin (SJB) CarbonSAFE Site

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Management Project Review Meeting
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Project Participants

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- Graduate Students

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- **Mr. Thomas Coleman**
- Dr. Carlos Maldaner
- Dr. David Podrasky

- **LANL**
- **Dr. Lianjie Huang**

Contractors

- Dr. Tom Bratton

- **AHS**
- **Dr. Michael P. Smith**
- Dr. Christopher Smith
- Mr. Patrick Gordon

Project Overview

- Funding Profile
- Project Performance Dates:

07/01/2021– 03/30/2025

	BP1 07/01/21 - 03/31/23		BP2 04/01/23 - 03/30/24		BP3 04/01/24 - 03/31/25		Total	
	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share	DOE Funds	Cost Share
NMIMT	332,640	32,389	169,139	43,195	156,146	28,481	657,924	104,064
University of Utah	54,419	13,608	26,449	6,612	14,132	3,530	95,000	23,750
Silixa LLC	246,970	140,315	-	23,800	-	23,800	246,970	187,915
LANL	79,996	-	80,008	-	39,996	-	200,000	-
Total ($)	714,025	186,312	275,596	73,607	210,274	55,811	1,199,894	315,729
Total Cost Share %		20.7%		21.1%		21.0%		20.8%

Project Overview: Objectives

- The project will carry out field deployment of an integrated suite of cost-effective and novel geophysical, geochemical, and geomechanical technologies for detection and characterization of faults and fractures.

- The project will deploy these technologies at the San Juan Basin (SJB) CarbonSAFE Phase III site

- To permanently deploy an integrated behind casing fiber optic sensing system, including Distributed Strain Sensing (DSS), Distributed Temperature Sensing (DTS), and a high sensitivity Distributed Acoustic Sensing (DAS) system.

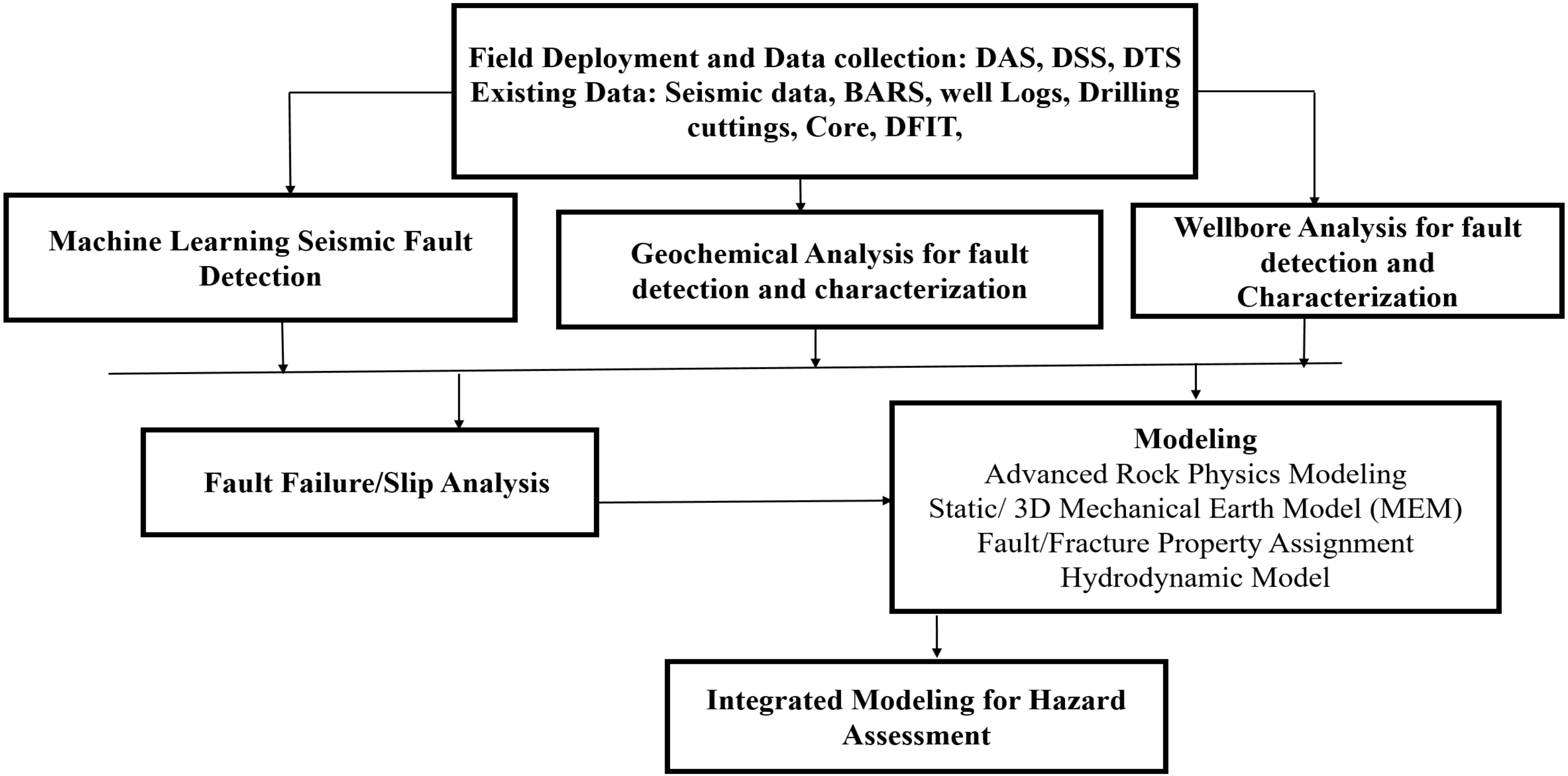
- To employ Rock Volatile Stratigraphy (RVStrat), a novel geochemical technology that uses drill cuttings and core, to locate faults (including aseismic faults) and estimate their sizes and orientations.

Project Overview: Objectives

- To detect faults near and more distant from the well bore, including faults in the crystalline basement rock, using a novel multi-scale U-Net machine learning method to evaluate 3D surface seismic and 3D VSP images.

- To integrate proposed technologies to develop advanced rock physics and coupled thermo-hydrodynamic-mechanical models in combination with the Monte Carlo method, to determine state of stress on each mapped fault and estimate long-term slip potential and/or maximum fault slip potential resulting from large-scale CO_2 injection.

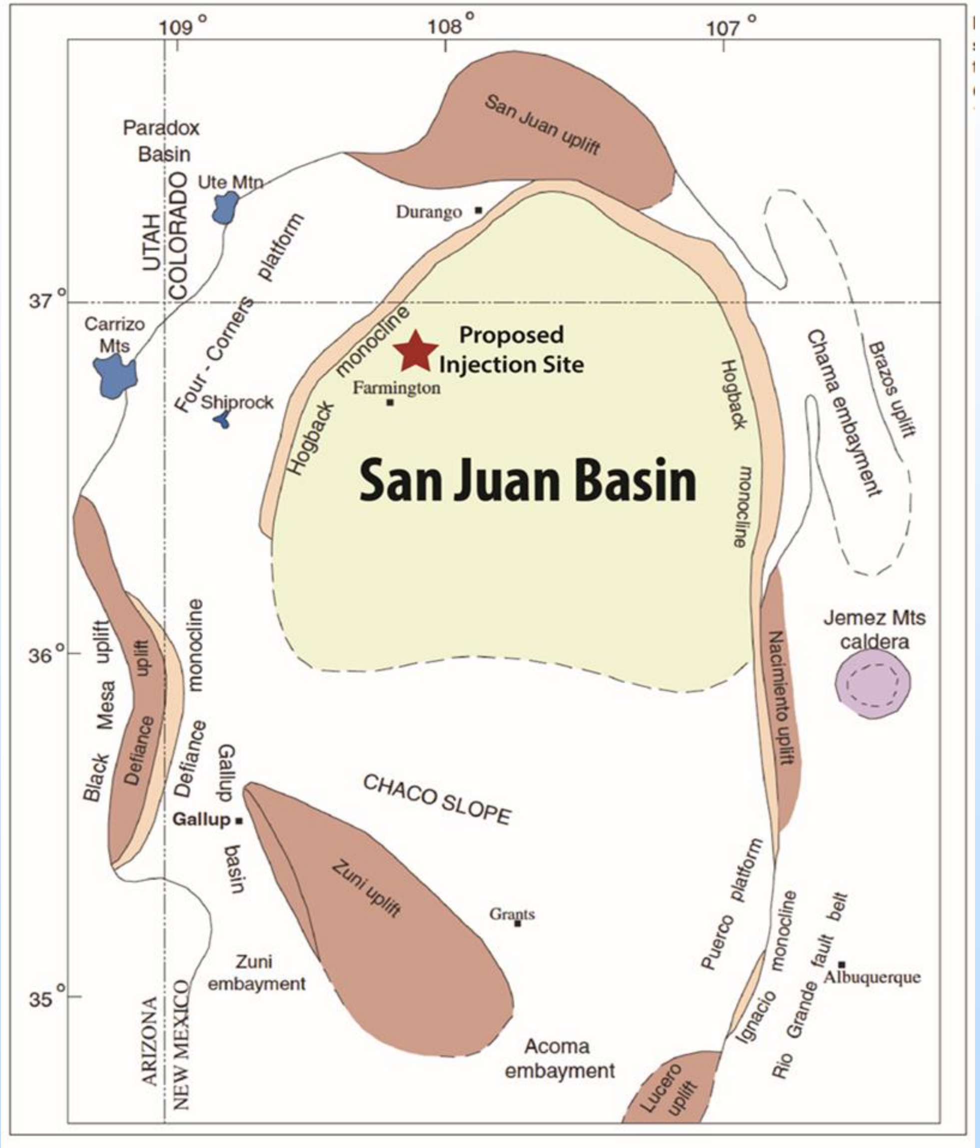
Project Approach

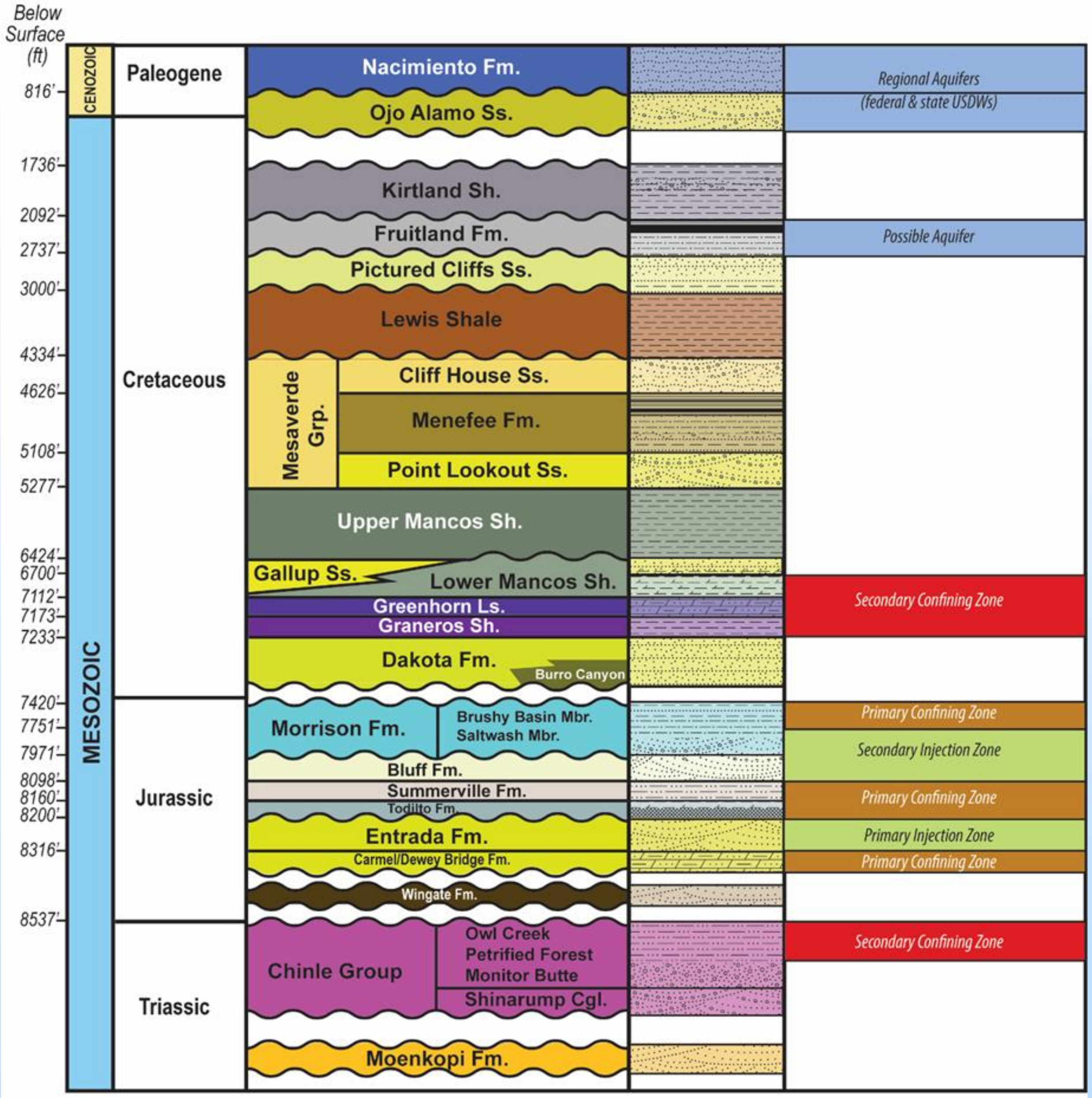


Milestones

Task/ Subtask	Milestone Title & Description	Planned Completion Date	Status
1.0	Project Kick-off meeting		Attend Meeting
2.2	Deployment of DAS/DSS/DTS behind casing in the SJB CarbonSAFE stratigraphic well	02/02/2023	Completed
2.4	Drilling cuttings, core and legacy core cuttings assembled	02/02/2023	Completed
3	Seismic analysis detecting aseismic and basement faults	08/31/2023	Completed
4	RVstrat approach detecting and characterizing faults	03/31/2024	Ongoing
5.1/5.2	Wellbore analysis detecting and characterizing geological features such as faults	10/31/2023	Ongoing
5.3	Determination of principal stress, pore pressure within storage complex	03/31/2024	Partially completed. Calibration with Step rate test
6.1/6.2	Compilation of fault information and baseline seismicity within storage complex and basement	03/31/2025	Completed
6.3	Fault slip analysis	09/30/2024	Ongoing
7.1	Completion of static model for numerical simulation	10/30/2023	Completed
7.3	Numerical modeling for hazard assessment	02/28/2025	Ongoing

Storage Complex @ San Juan Basin





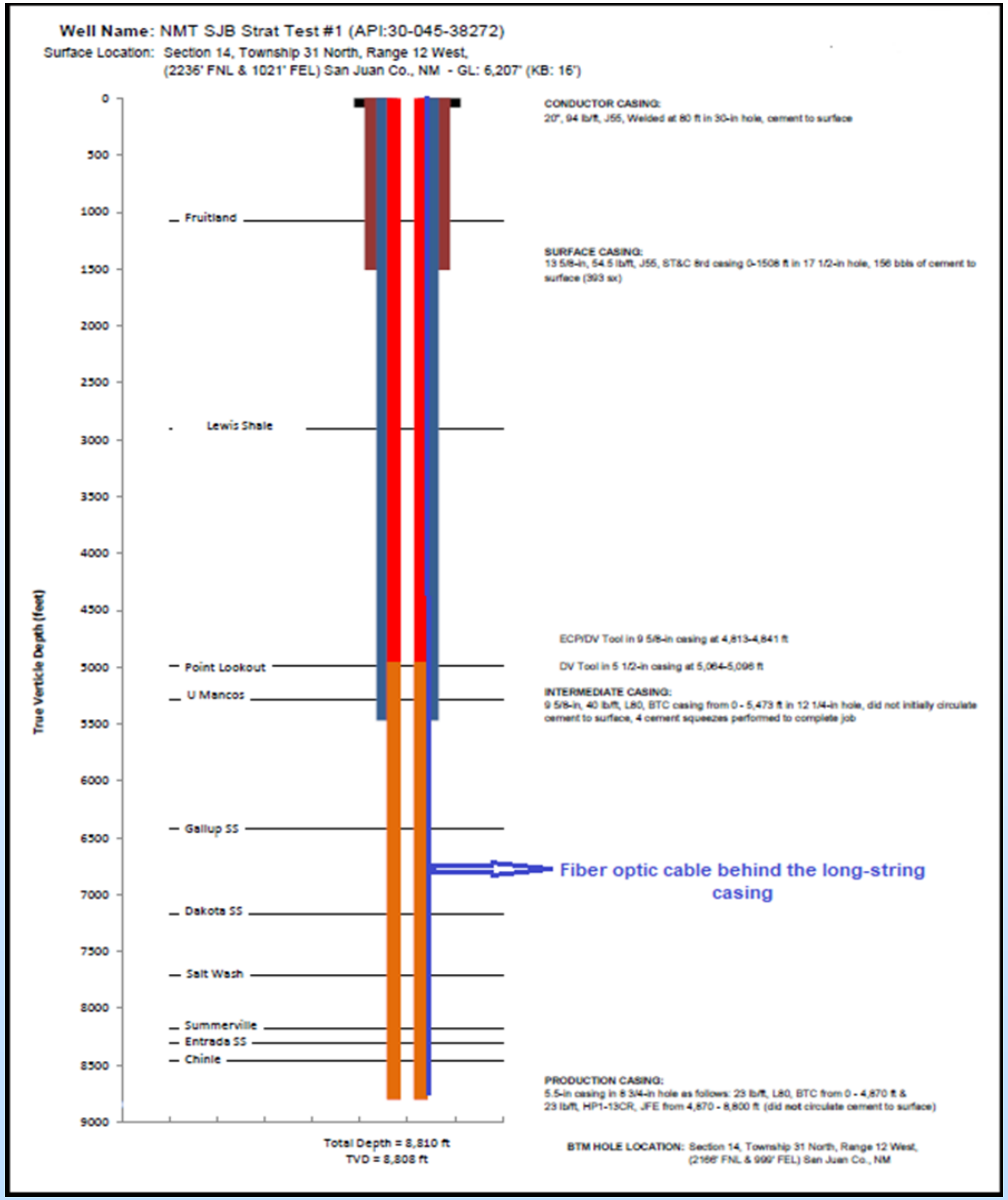
SJB CarbonSAFE Project Facts

Key Project Facts

- Perform Site Characterization of storage complex within San Juan Basin
- Source CO2 from Escalante H2 plant, located in Prewitt, NM, USA.
- Initial UIC Class VI permit submitted in 2023
- Community and stakeholder outreach on CCS technology and its benefits

Characterization Plan

- Drilled characterization well, perform injectivity tests
- Recovered ~ 450 ft of Core, sampled drilling cuttings, advanced log suites measurements
- Perform suites of laboratory experiments and numerical models
- Purchased 100 sq.miles 3D seismic, acquire 3D VSP,
- Installed DAS/DTS/DSS Optical fiber behind casing

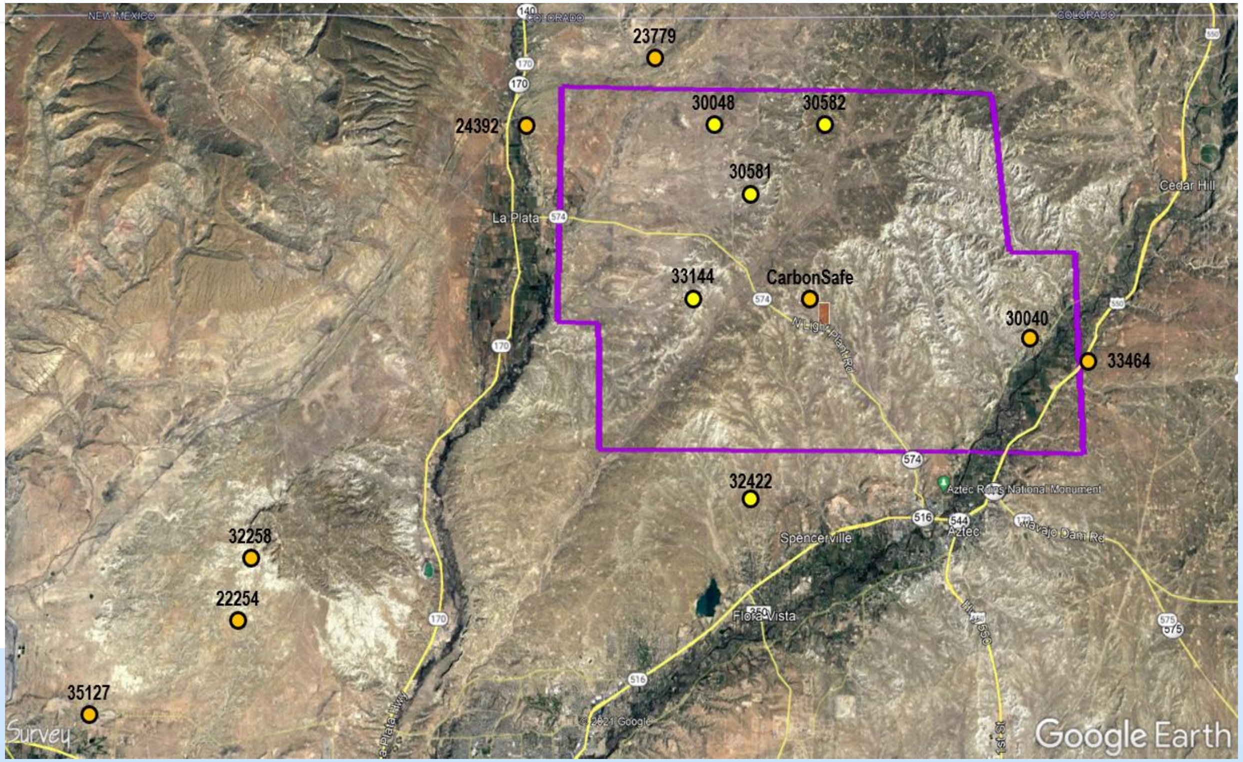


Stratigraphic Well Design

Our Approach to Earth Modeling

	Seismic, Wellbore images	Triple-combo, Sonic, Core	Wellbore images, Sonic, Core	Petrophysics, Sonic, Core
Intrinsic properties	**Framework** Structure Faults Horizons	**Petrophysics** Lithology, Vcl Porosity, Sw Matrix Perm Elastic Moduli	**Mechanical** Strat Column Facies Support Fracture Attributes	**Rock Strength** Compressive & Tensile Strength Friction Angle
Extrinsic properties	**Vertical Stress** Overburden	**Pore Pressure** Pore Pressure	**Stress Direction** Maximum Horizontal Stress Direction	**Stress Magnitude** Minimum & Maximum Horizontal Stress
	Density log, Petrophysics	Formation testing, Petrophysics, Mud logs	Wellbore images, Sonic, 4-Arm calipers	In-situ stress tests, Sonic

Brie and Bratton, 1994



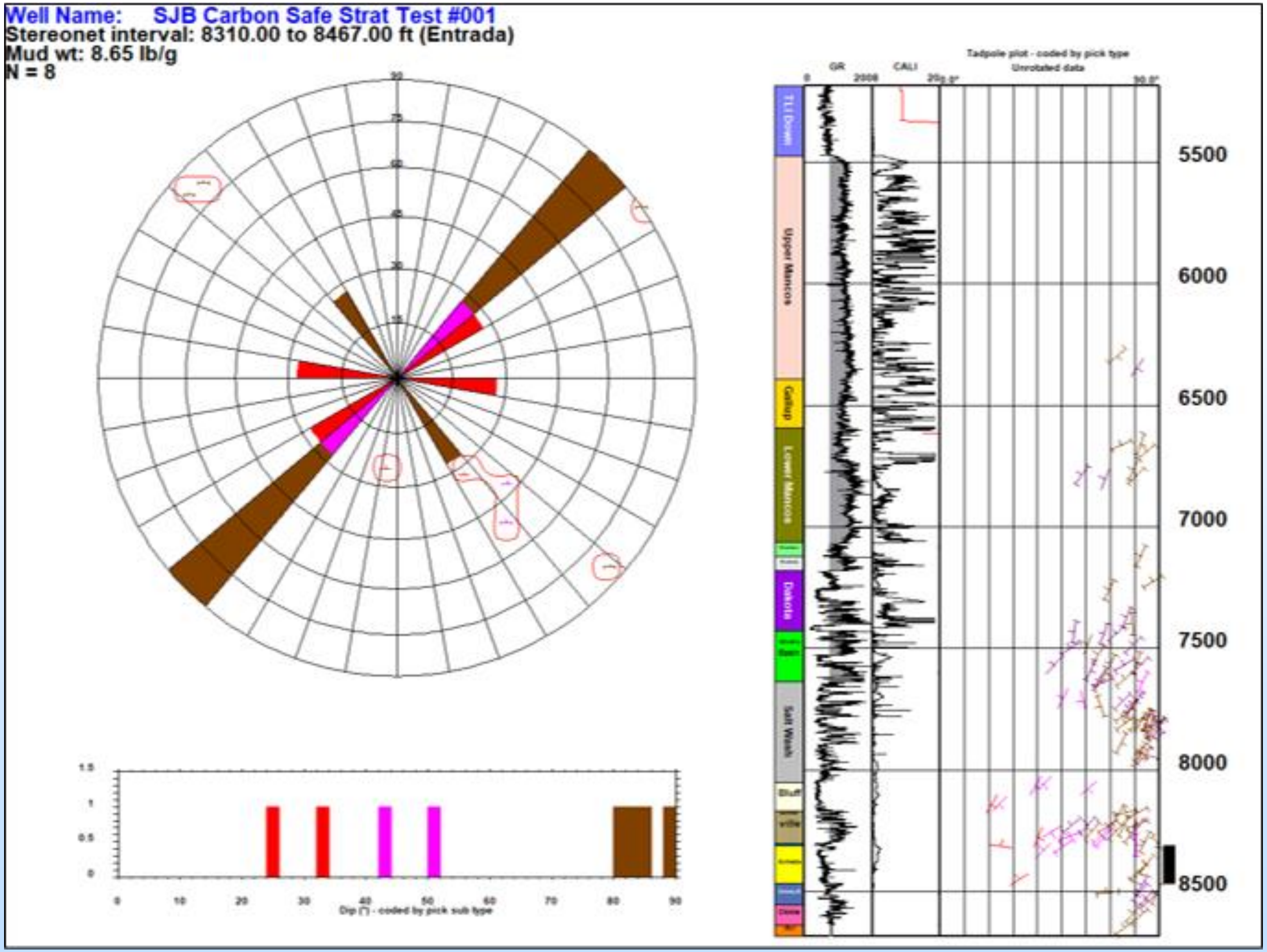
A petrophysical analysis has been completed on 14 wells and a geomechanical analysis has been completed on a single well.

Wells used for Petrophysical analysis

Entrada Fractures mapped from Borehole Images

The 8 fractures mapped from the Entrada consist of 4 high-angle open fractures and 4 low-angle cemented and closed fractures.

FractureStudies LLC looked at 121.6’ of Entrada core, identifying 5 fractures.

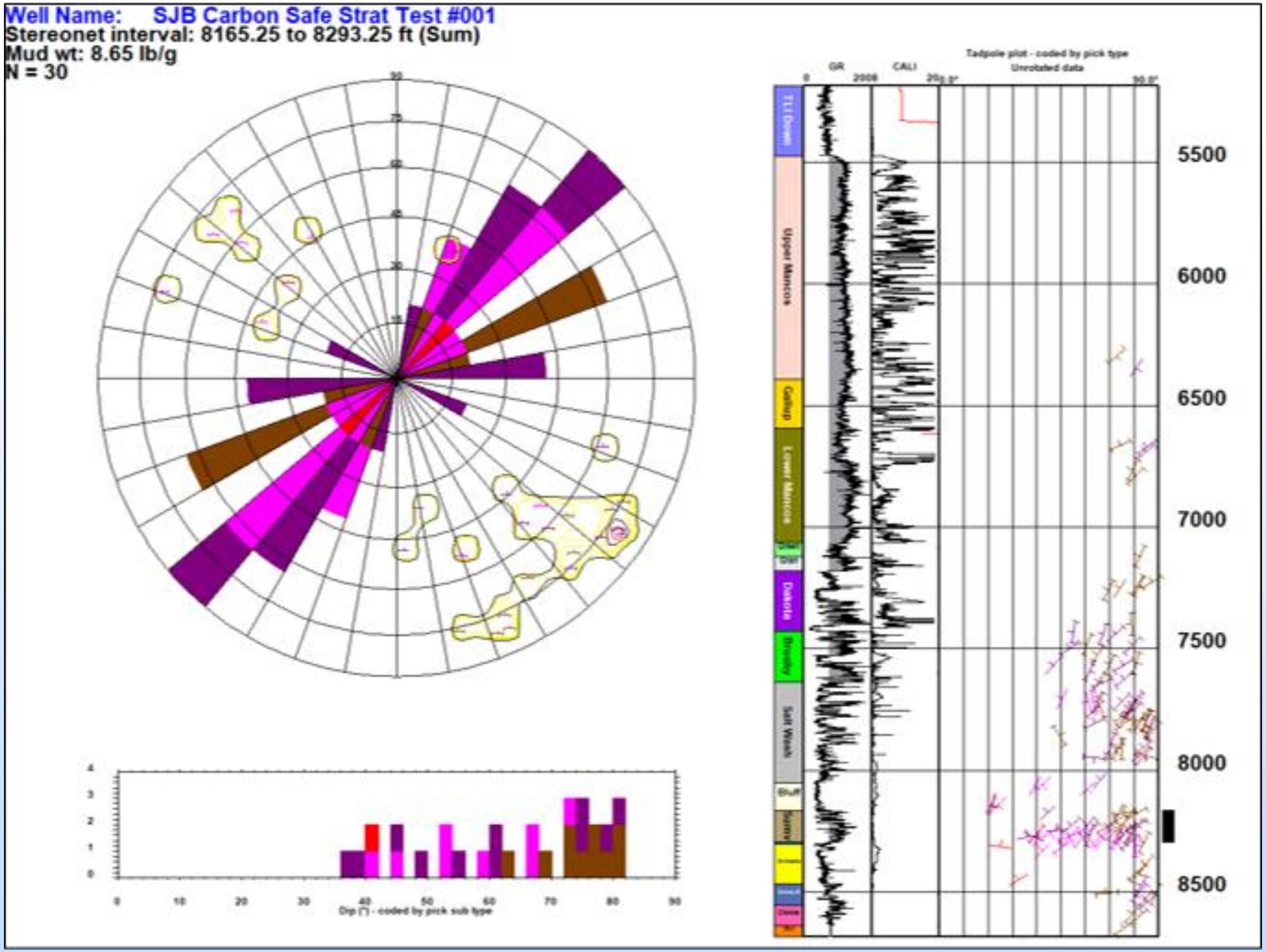


Summerville Fractures

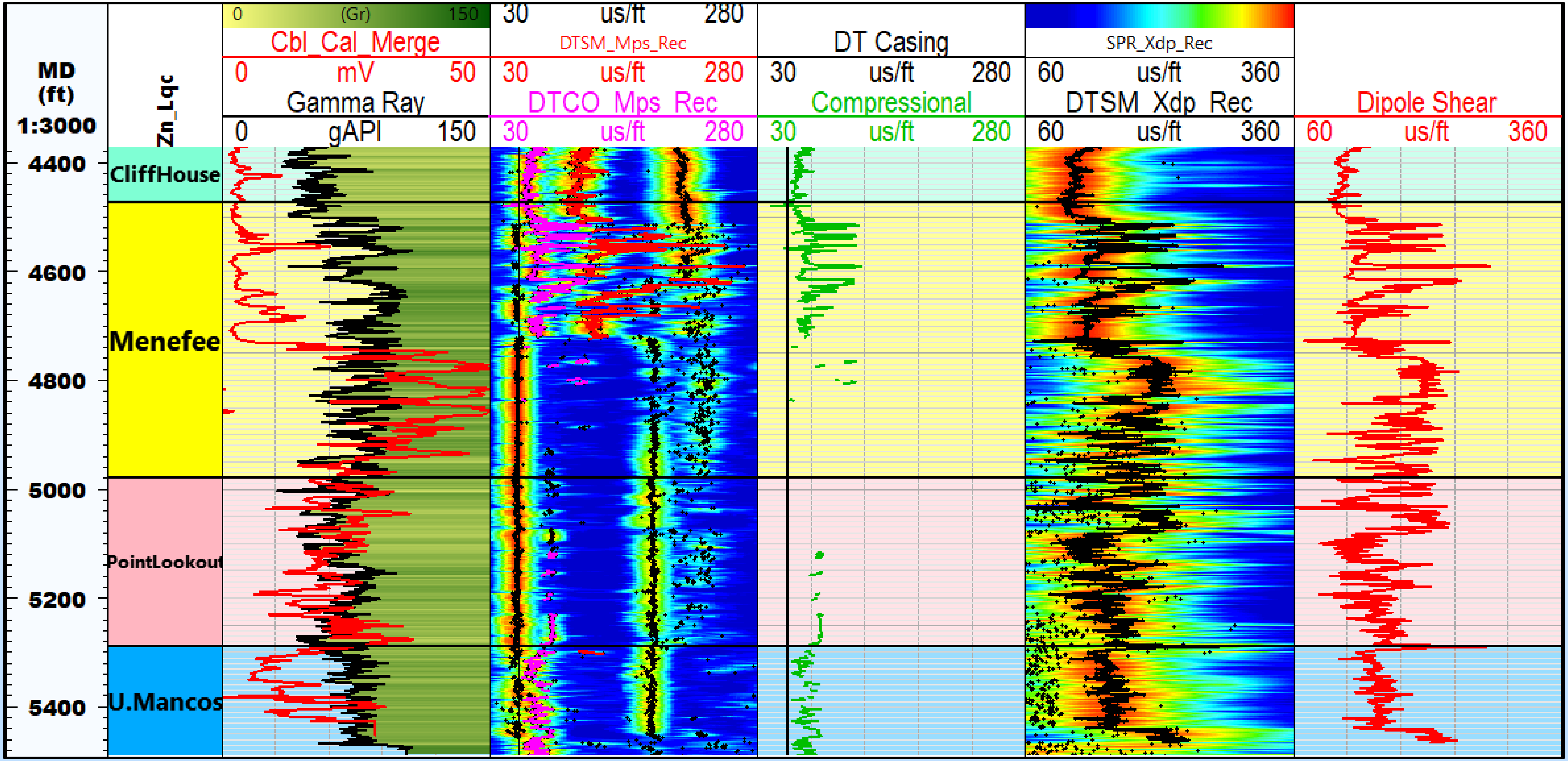
The Summerville yielded 30 fractures, comprised of open, partially-open, cemented, and closed types. Summerville fractures display a NE-SW strike trend.

From the 124.95' of Summerville core, FractureStudies LLC identified 51 fractures. More than half (27) of these fractures were classified as shear fractures from compaction; another 7 fractures were from syn-sedimentary dewatering.

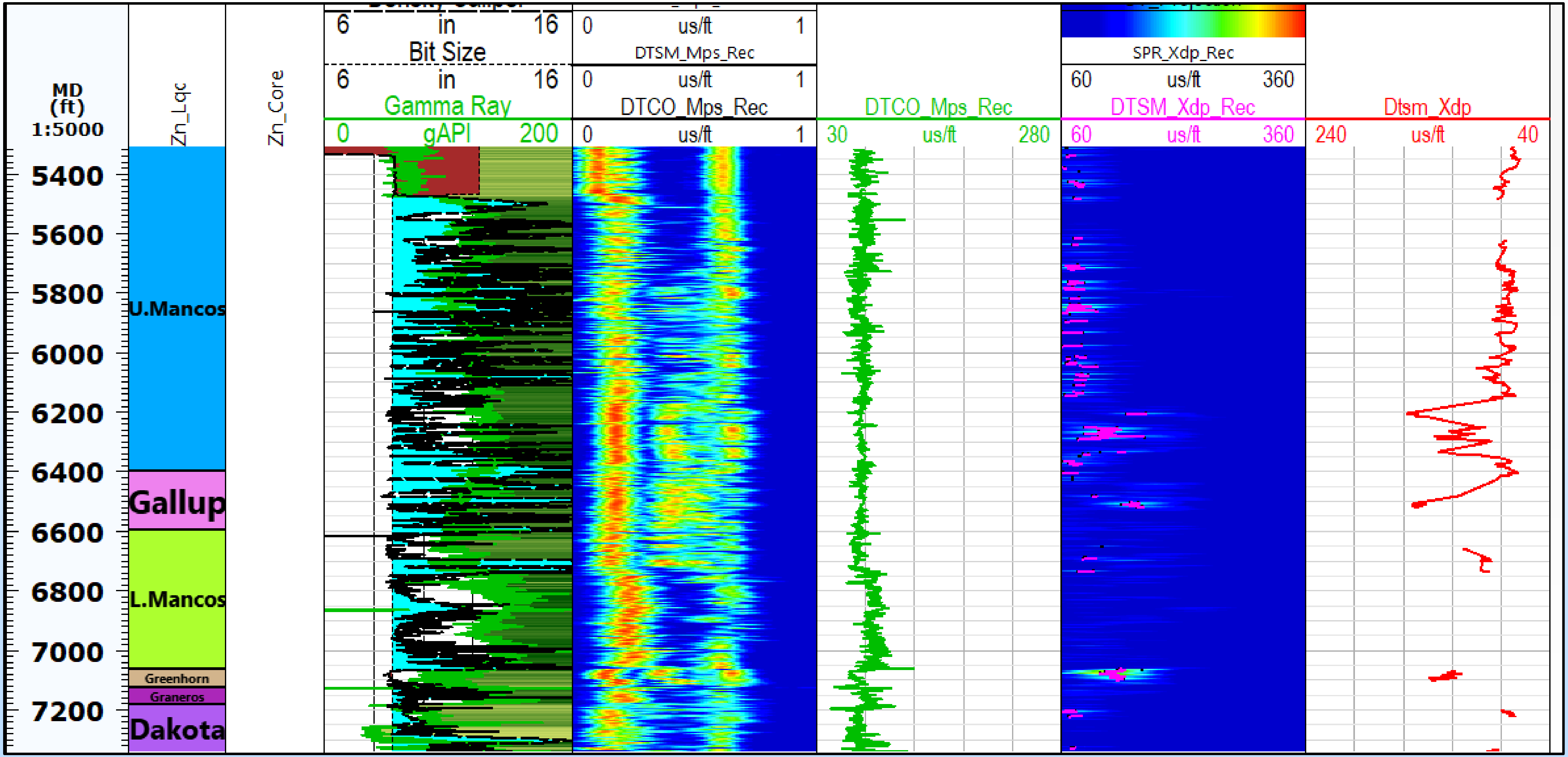
These types of fractures are difficult to resolve using image data.



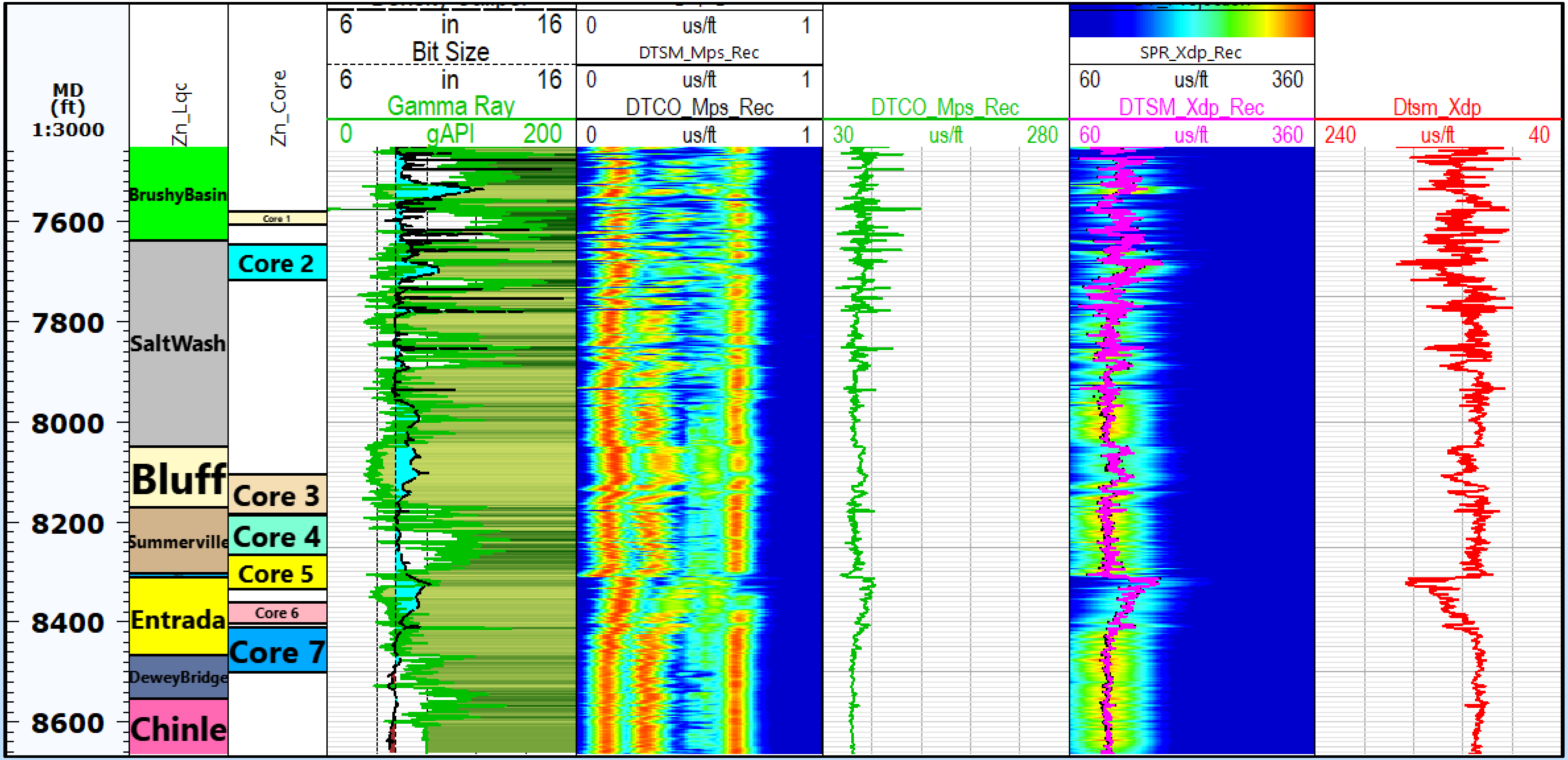
No compressional due to poor cement, but good shear



No shear due to the small sonic tool, but good compressional



Good compressional and shear in the cored interval



Greenberg-Castagna

TABLE 1. Representative regression coefficients for shear-wave velocity (β_C[km/s]) versus compressional-wave velocity (α_C, [km/s]) in pure porous lithologies: $\beta_C = a_{i2}\alpha_C^2 + a_{i1}\alpha_C + a_{i0}$ (Castagna *et al.* 1992).

Lithology	a_{i2}	a_{i1}	a_{i0}
Sandstone	0	0.80416	−0.85588
Limestone	−0.05508	1.01677	−1.03049
Dolomite	0	0.58321	−0.07775
Shale	0	0.76969	−0.86735

$$\beta_C = 0.5\left(\left\{\sum_{i=0}^{L} X_i \sum_{j=0}^{N_i} a_{ij}\alpha_C^j\right\} + \left\{\sum_{i=0}^{L} X_i\left[\sum_{j=0}^{N_i} a_{ij}\alpha_C^j\right]^{-1}\right\}^{-1}\right), \qquad 1 = \sum_{i=0}^{L} X_i, \qquad (1)$$

Limits: Complex mineralogy, shale vs. clay, texture, and stress

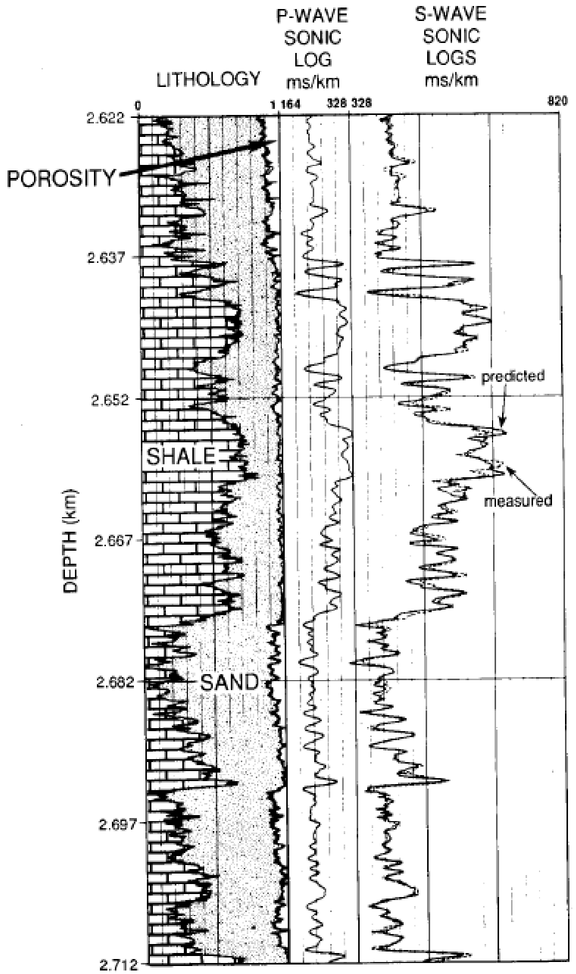
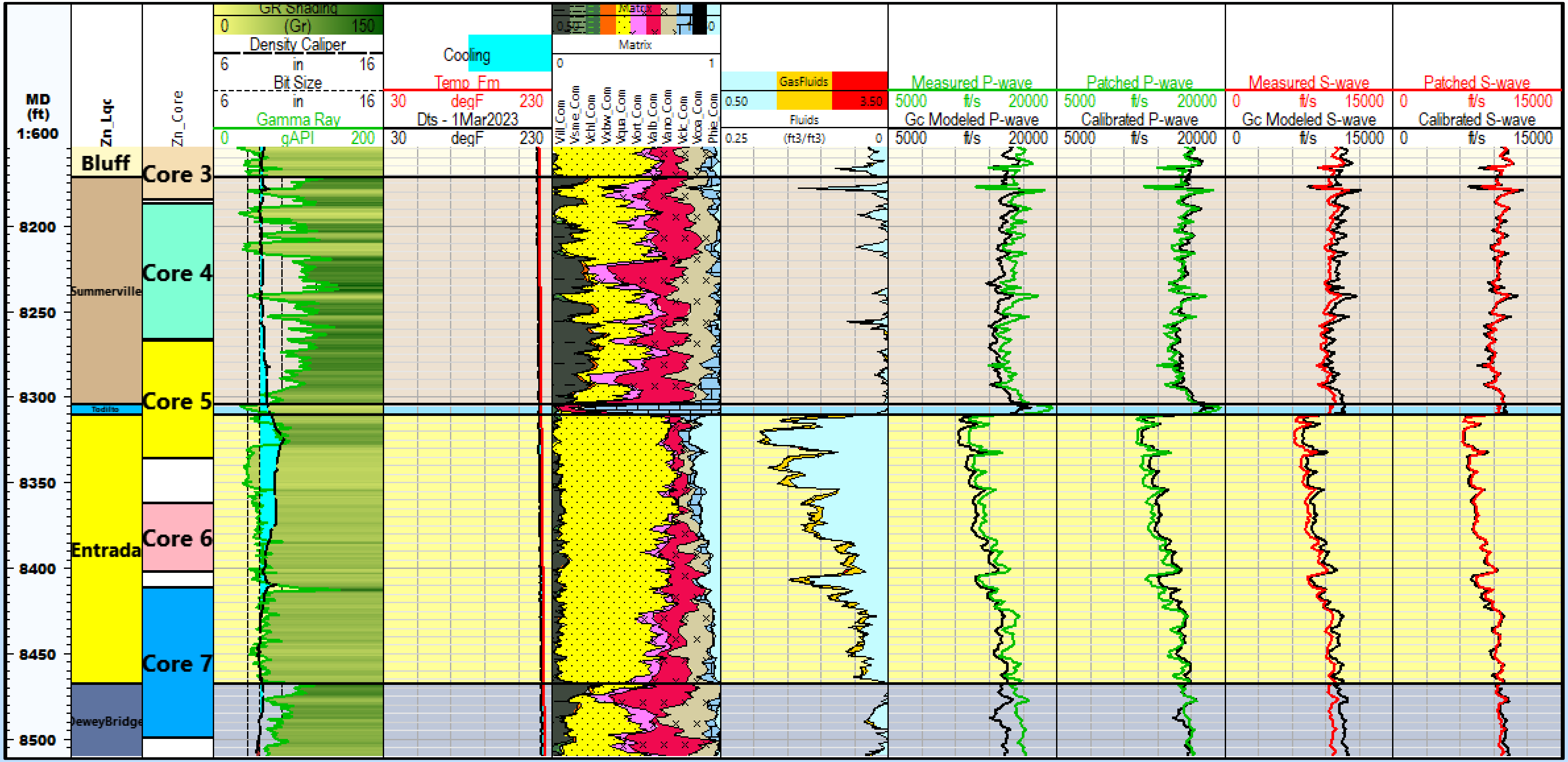


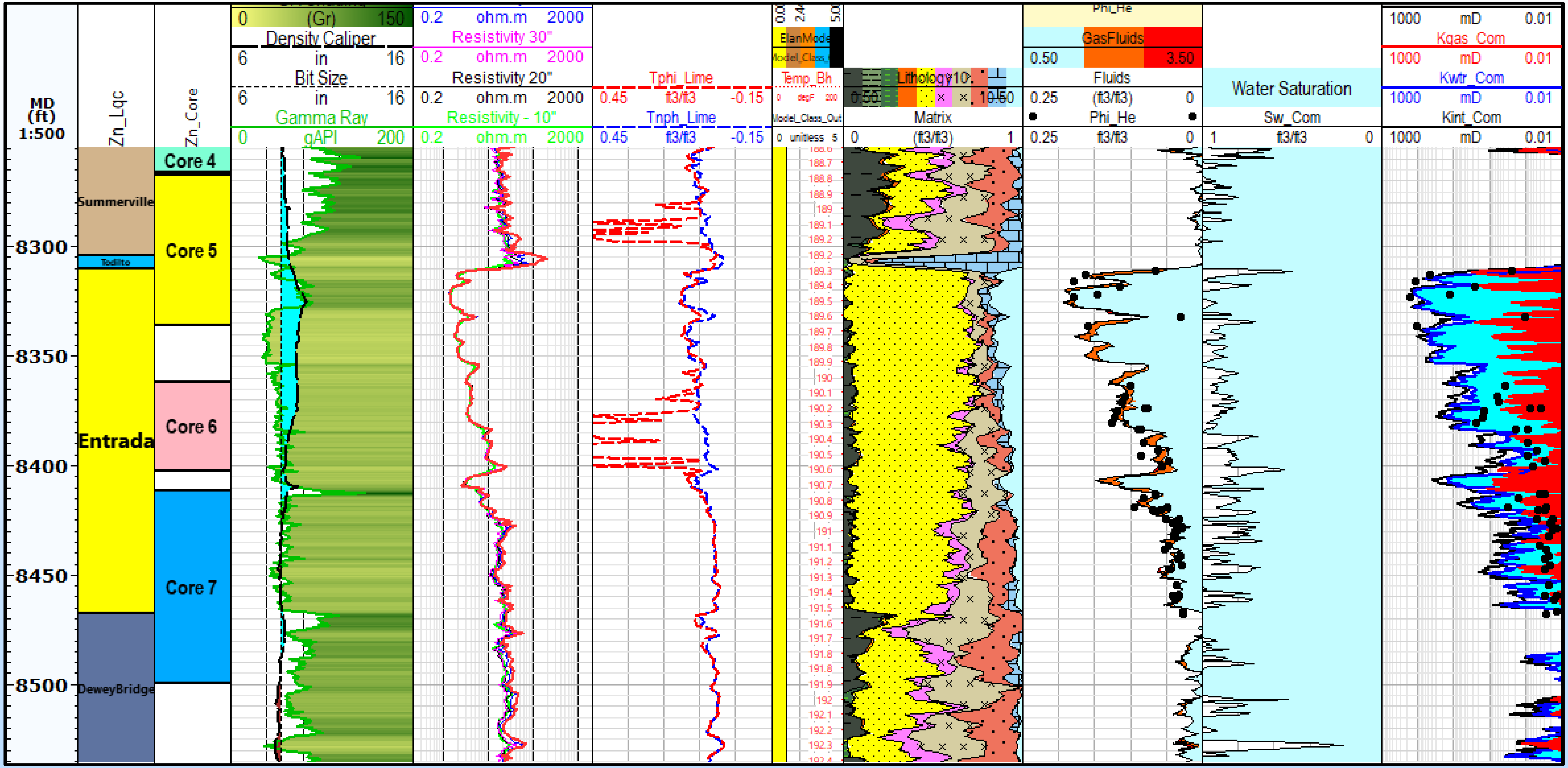
FIG. 4. South Texas clastics example. Lithology analysis and transit-time log measurements. Estimated shear-wave transit-time overlain on waveform-derived measured shear-wave transit time.

Greenberg, M., and Castagna, J., Geophysical Prospecting, Vol 40., p195-209 (1992)

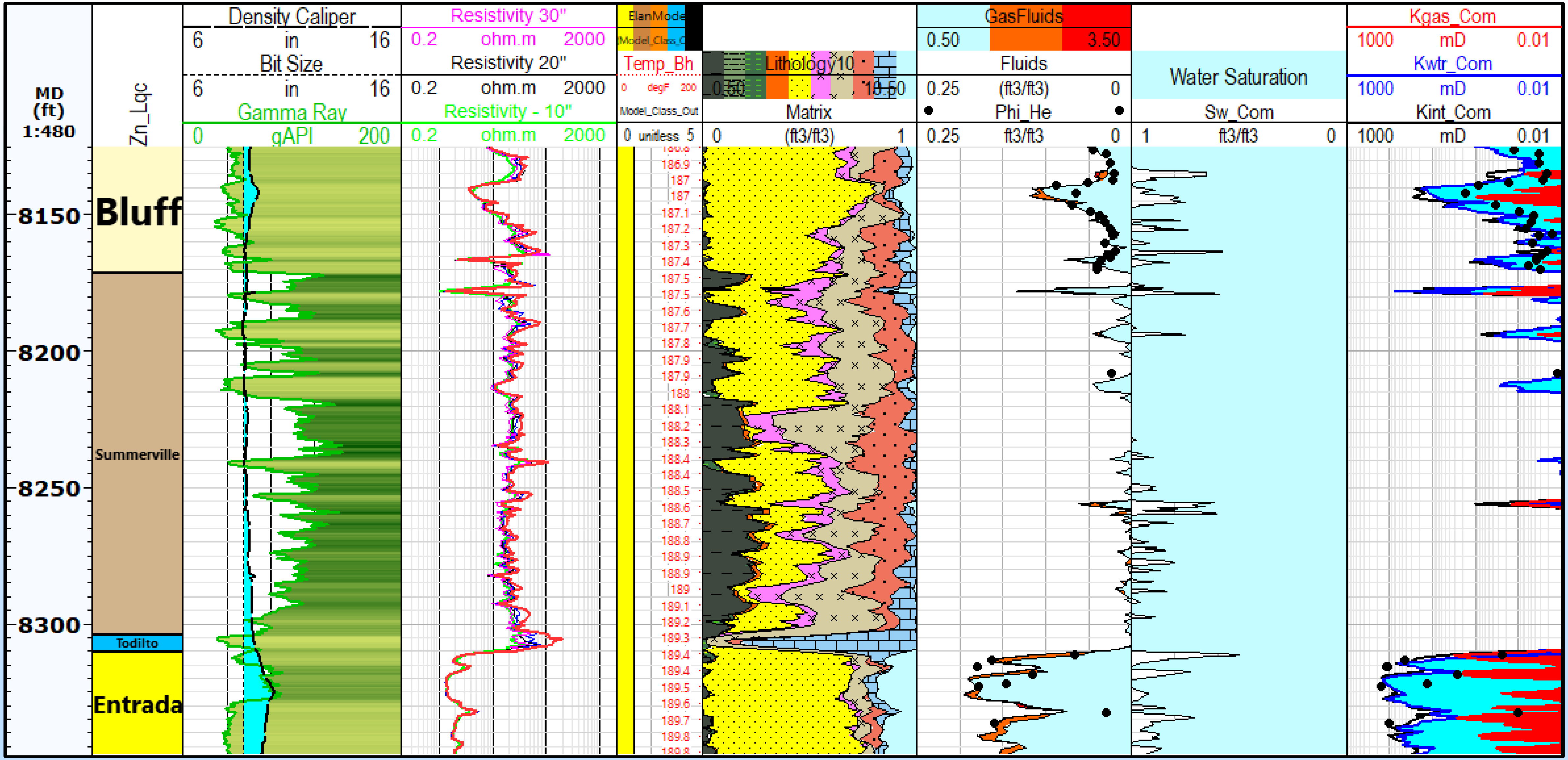
Patching of sonic velocities



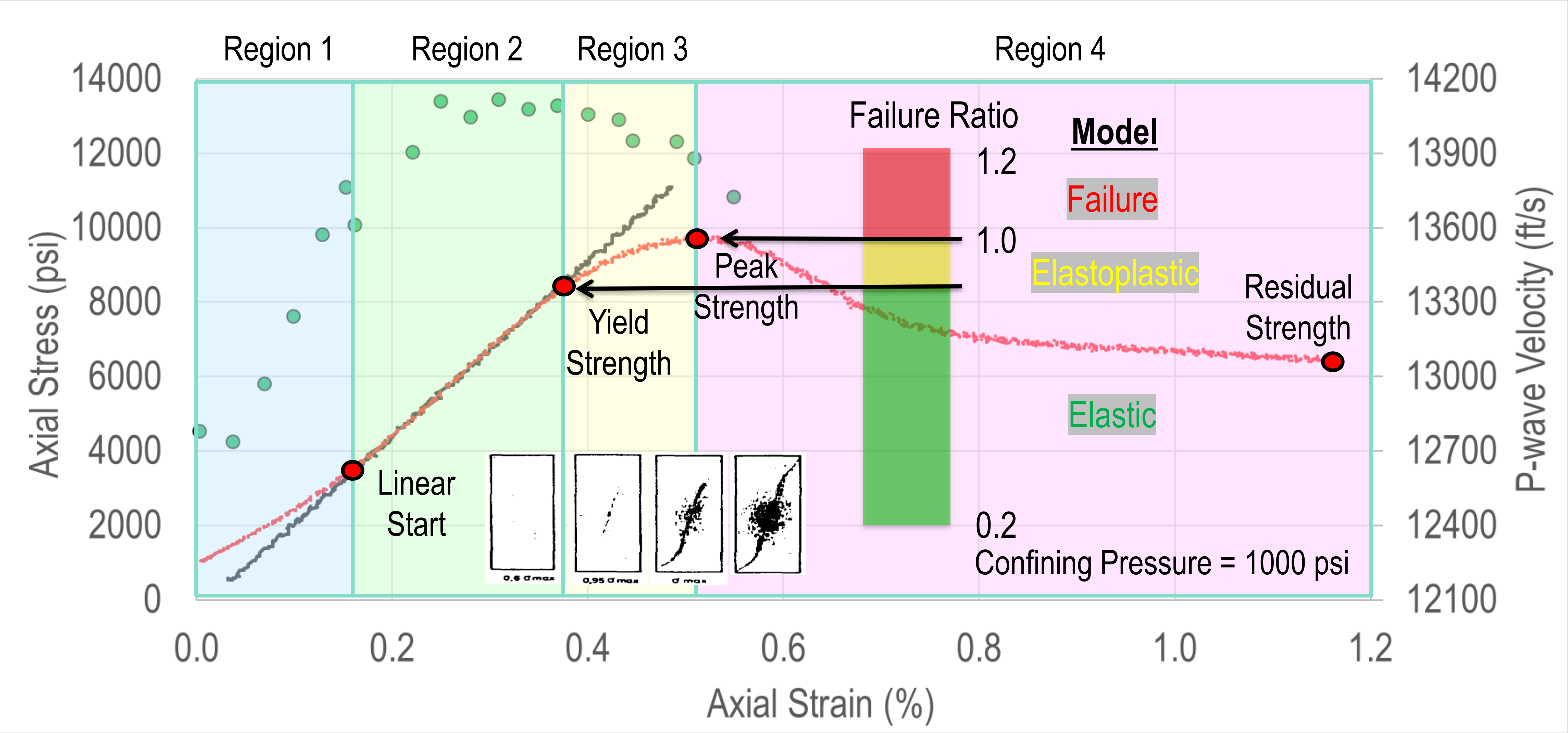
Entrada petrophysics



Summerville petrophysics

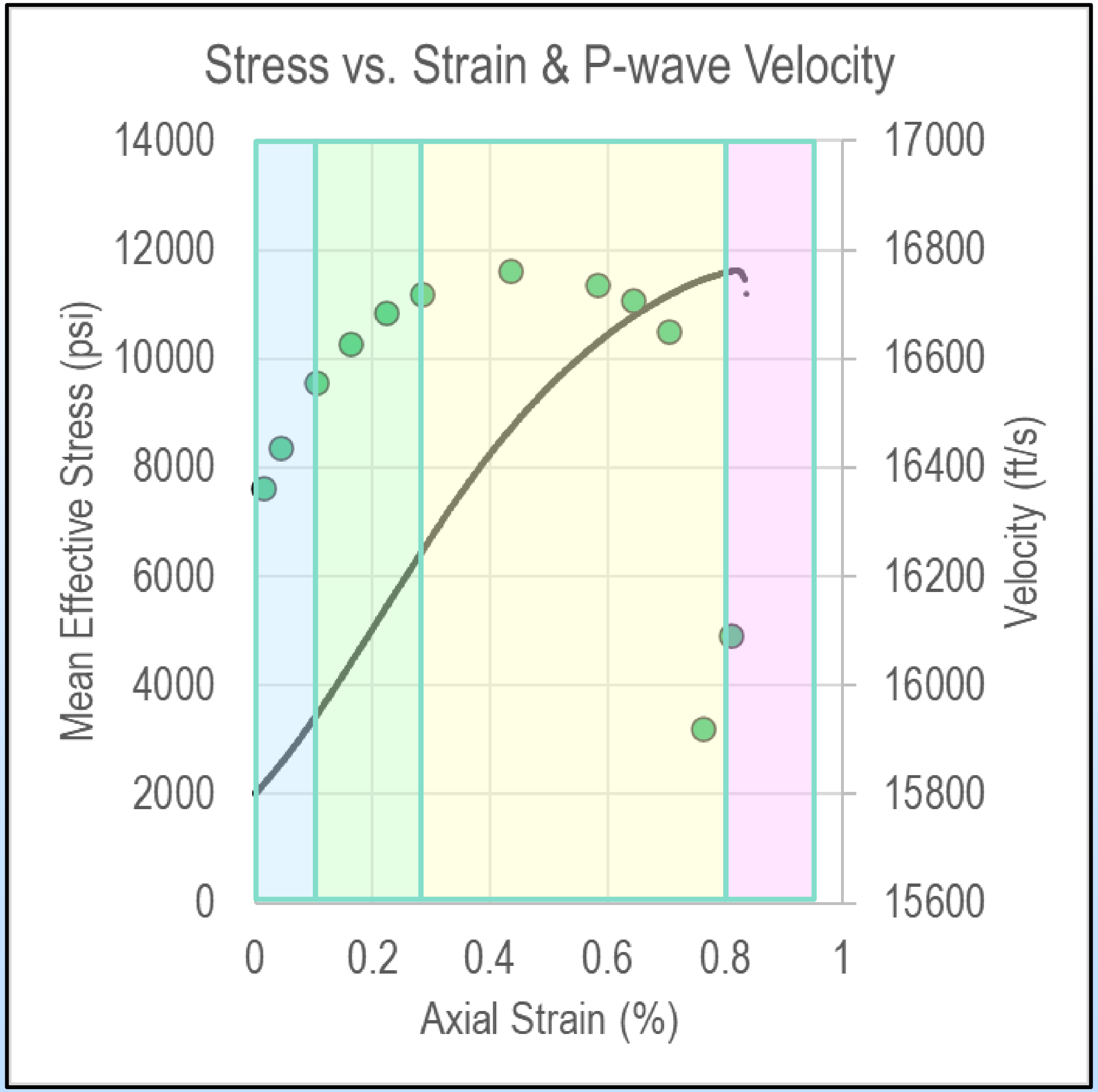


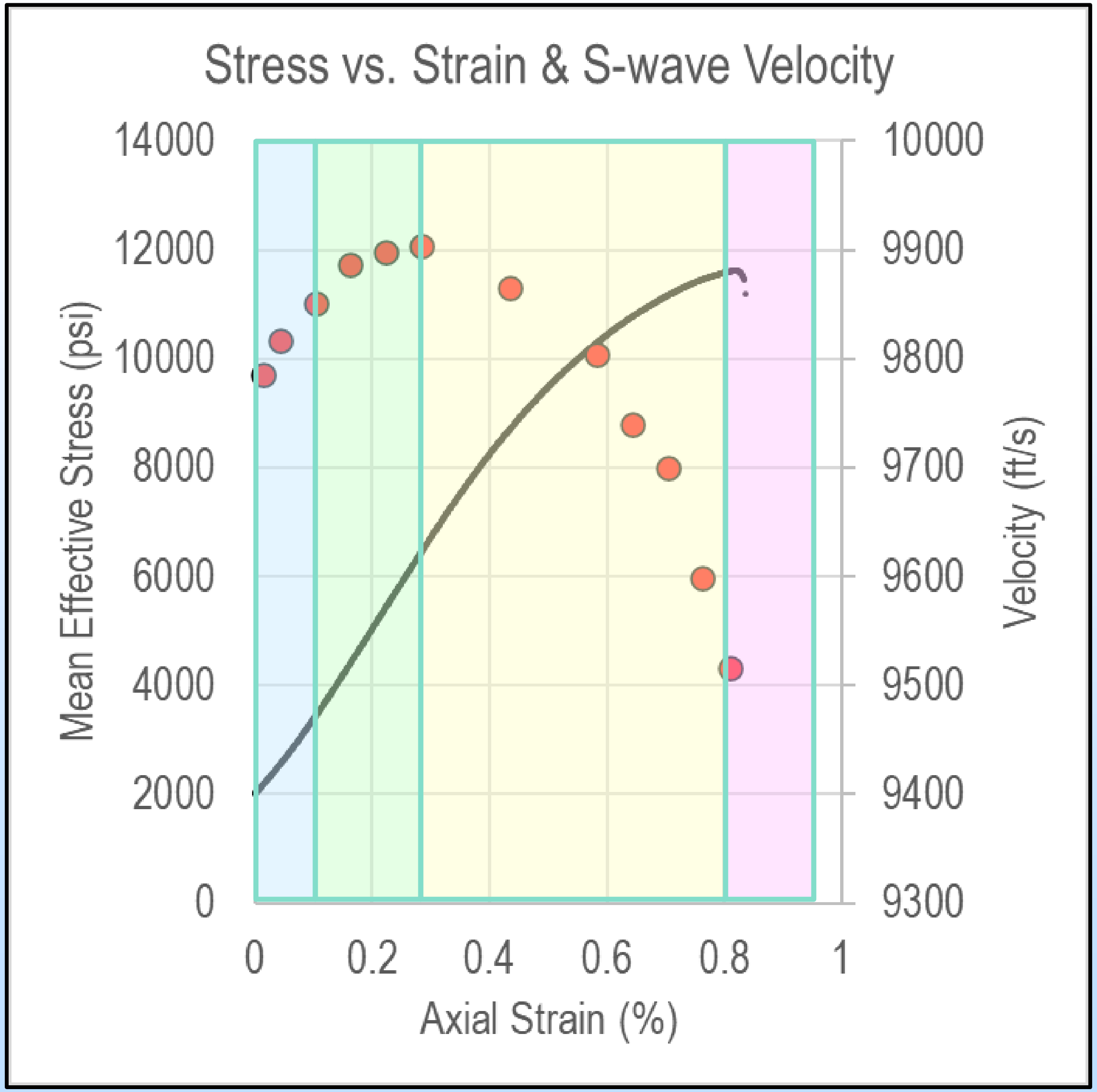
Rock behavior – Mechanical (typical stress vs. strain curve)



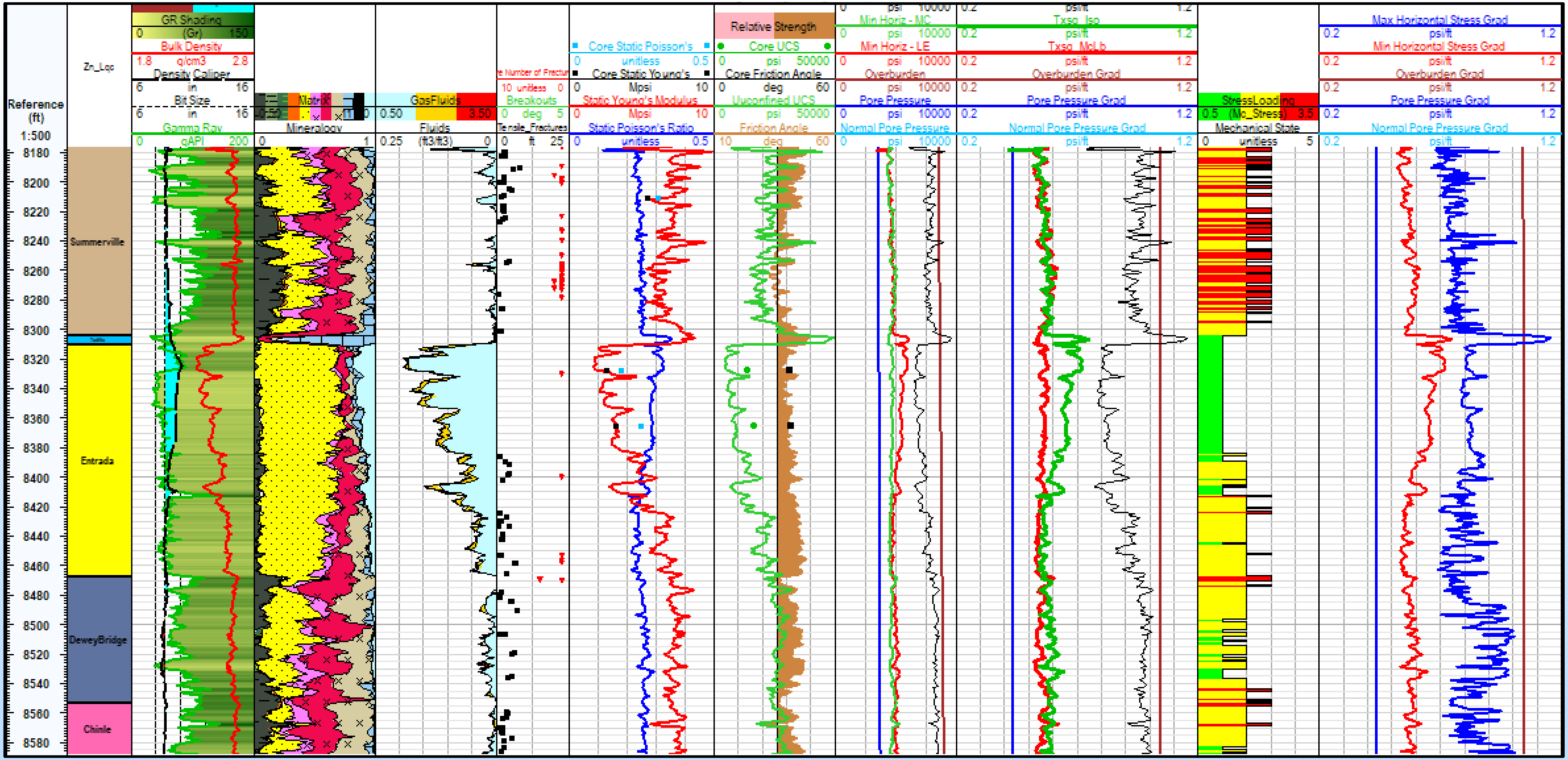
Hallbauer, D., et al., ISRM (1973)

Triaxial test 3-36-2 (Summerville – Tan cluster) Pc=3000 psi



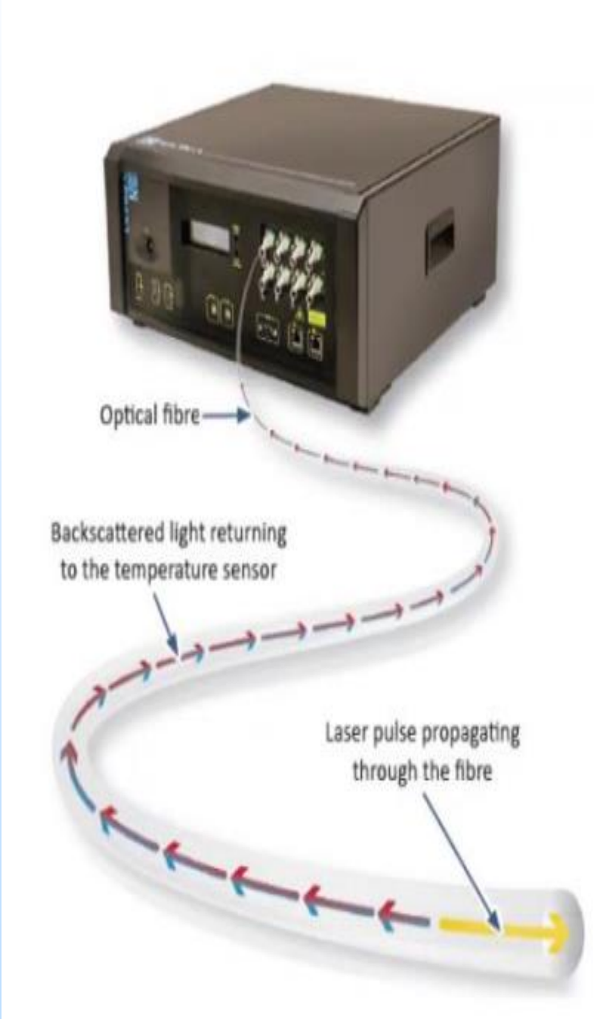


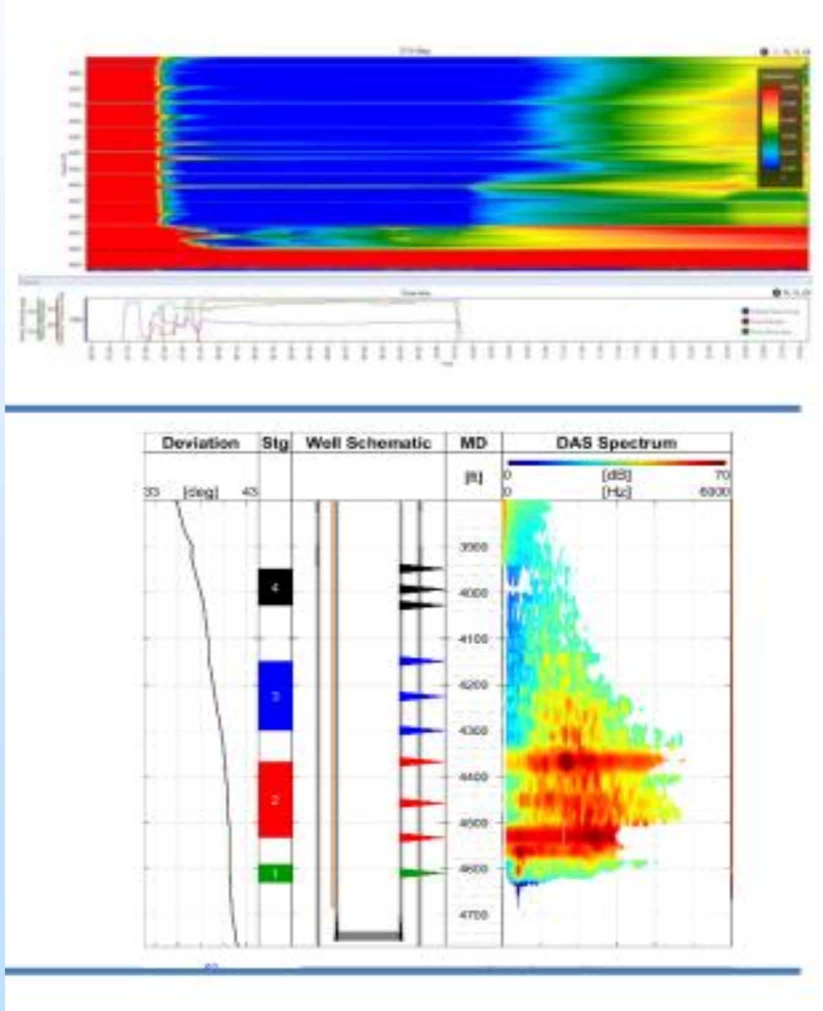
Mechanical model – Injection and confining



Silixa Distributed Optical Fiber Technology

Fiber Optics Installation ➔ **Monitoring Solutions** ➔ **Data Interpretation** ➔ **Assess Risks**





- Faults/Fractures Detection and Characterization
- Matrix/Fractures/ Faults Geomechanical Properties Evaluation
- Micro-seismicity Monitoring

Data Acquisition- Fiber Optic

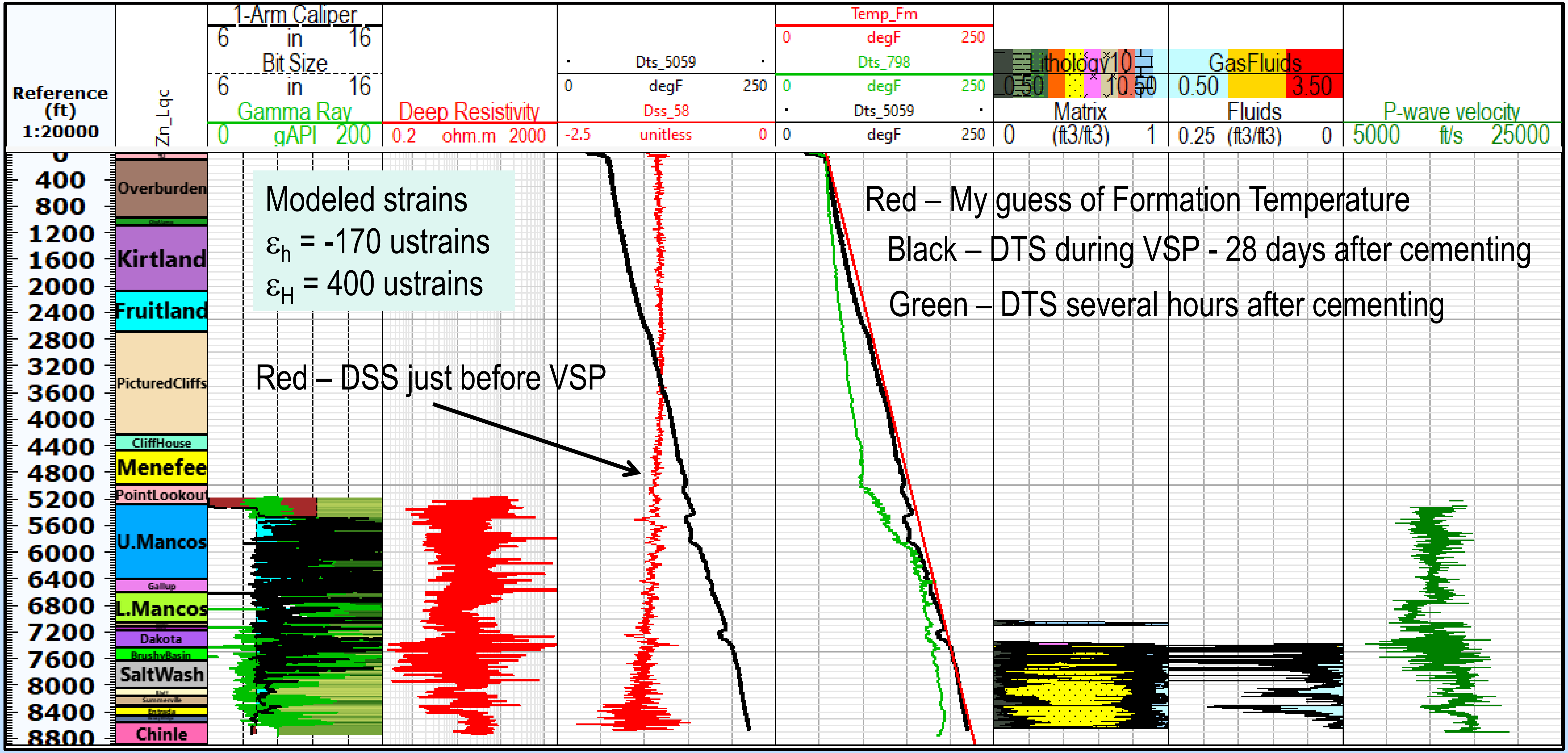
The DTS, DSS, and DAS data acquisition plan includes:

- **Mobilization 1** – Fiber optic cable deployment
  - Measurements during fiber optic cable deployment
  - DSS and DTS surveys after the cable reaches total depth
  - DSS and DTS surveys during and after the cementation process

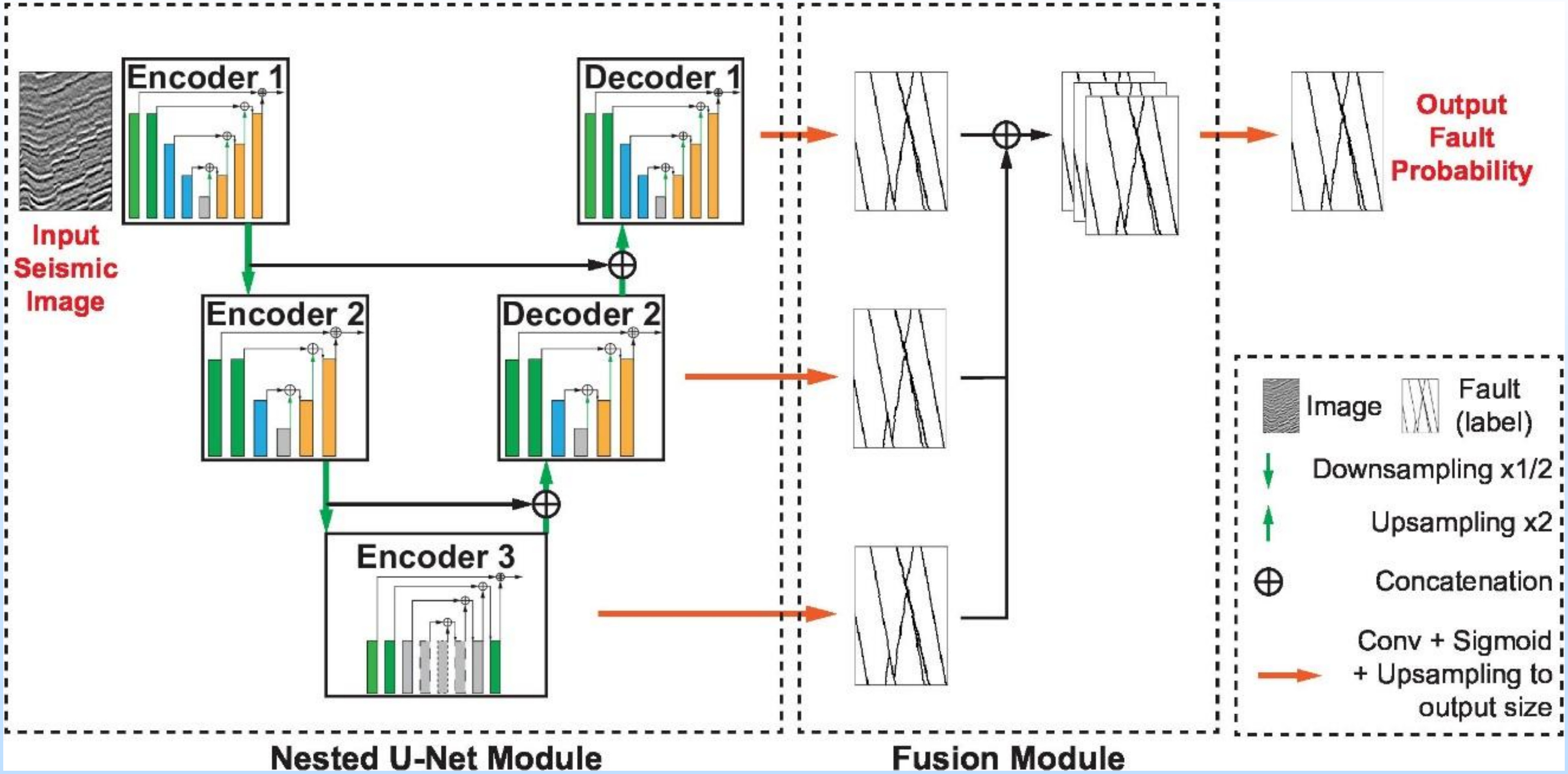
- **Mobilization 2** – Baseline
  - Strain (DSS) baseline
  - Temperature (DTS) baseline
  - Acoustic (DAS) baseline (ambient noise log)
  - Zero-offset and Walk-away VSP
  - Seismicity baseline

- **Mobilization 3** – Injection Test
  - Continuous monitoring during DFIT using DTS, DSS, DAS

Fiber optic temperature and strain



Nested-Residual U-Net (NRU) Fault Detection



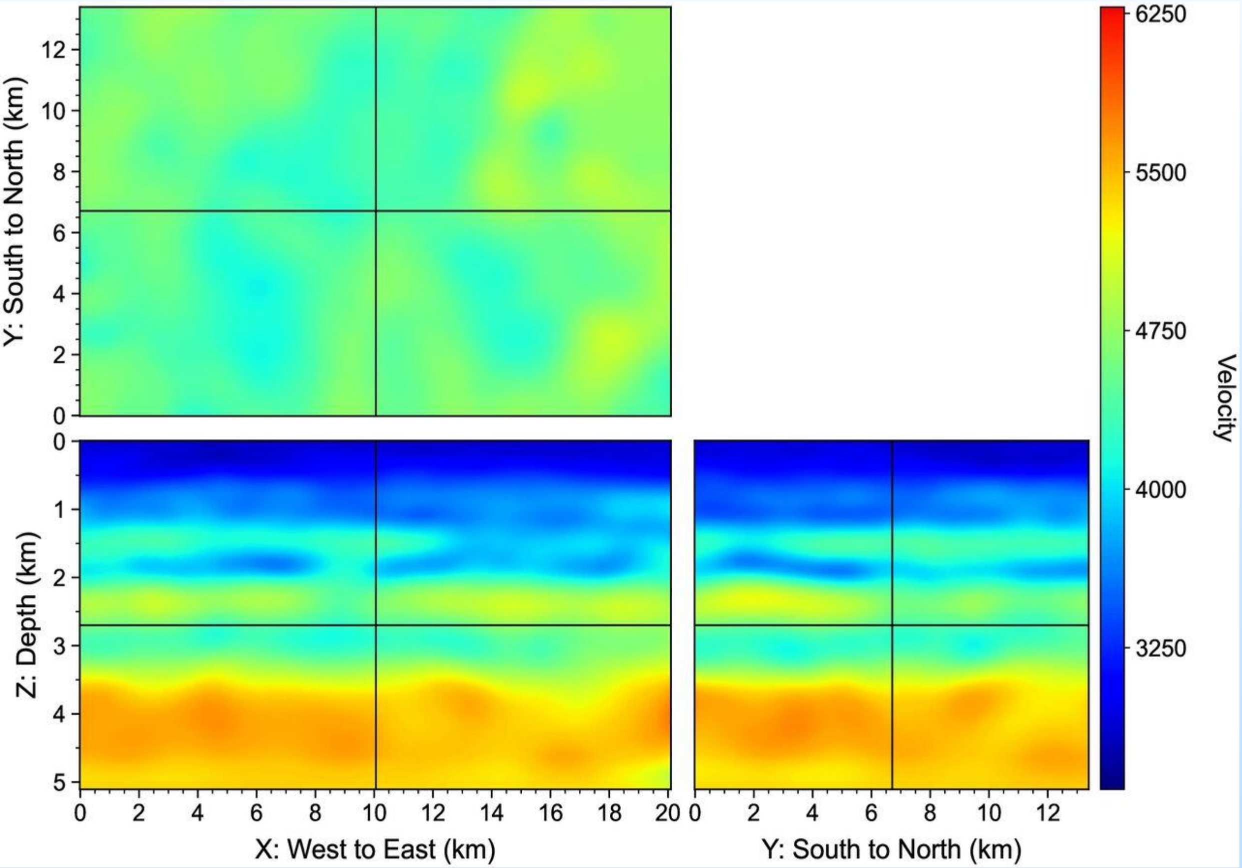
(Gao, Huang, Zheng, 2022)

LANL's ML Workflow

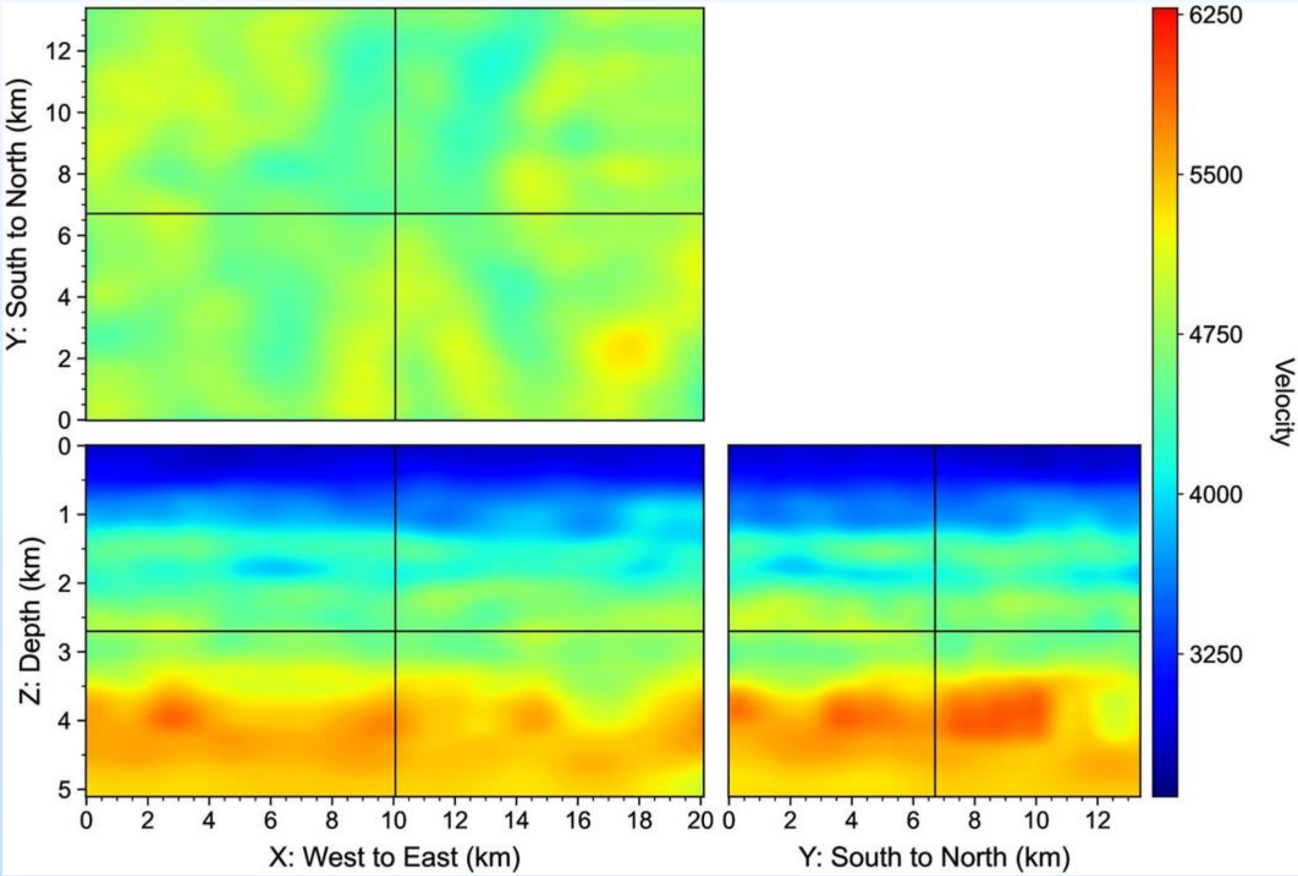
- The project procured a legacy 3D surface seismic dataset acquired at the San Juan CarbonSAFE storage site in 1998.
- We update the 3D velocity model using prestack depth migration velocity analysis (MVA) with the Paradigm™ 22 Software Package.
- We perform 3D prestack depth migration to obtain a 3D subsurface structural image.
- We use anisotropic diffusing filtering to reduce image noise and improve the reliability of fault detection.
- We delineate faults on the 3D migration image using LANL's recently developed machine-learning algorithm (Gao, Huang, Zheng, 2022).

Velocity Modeling

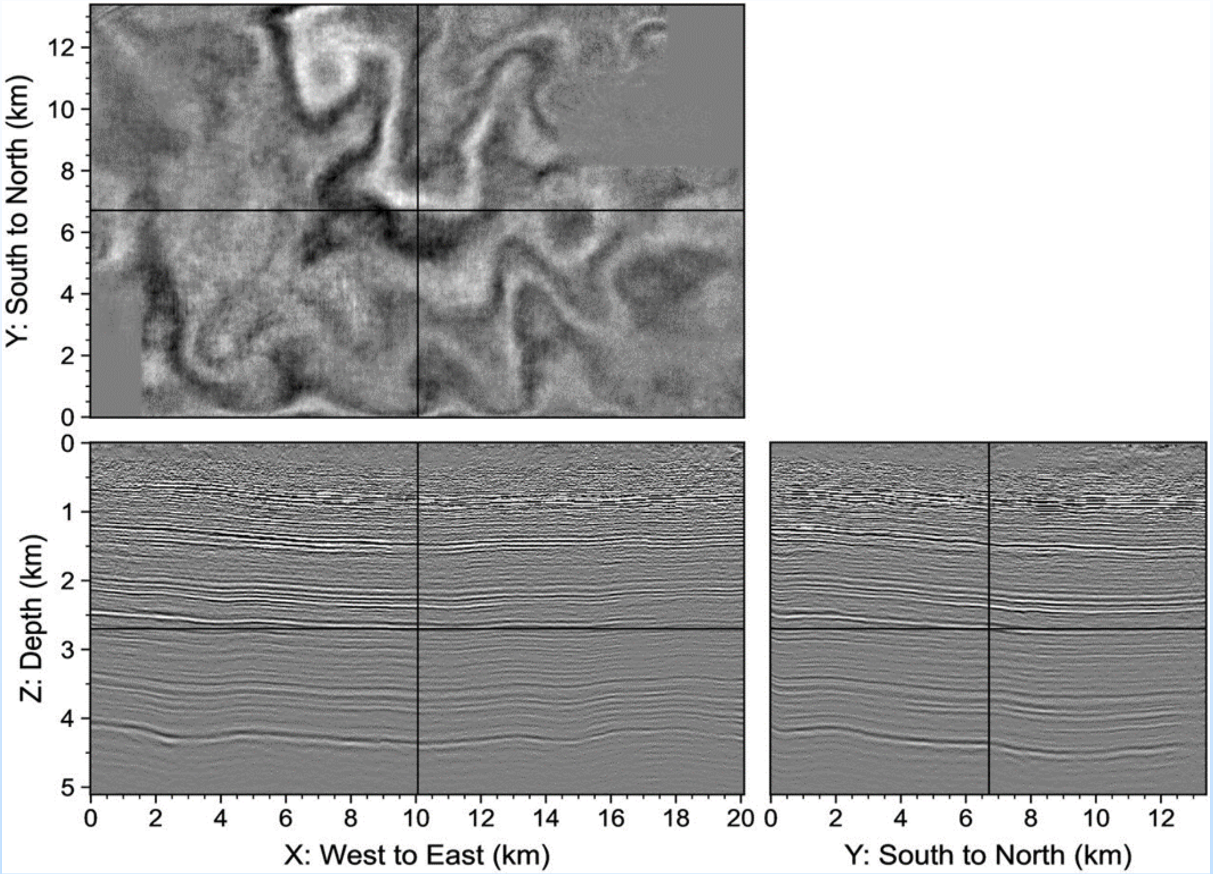
Initial 3D Velocity Model



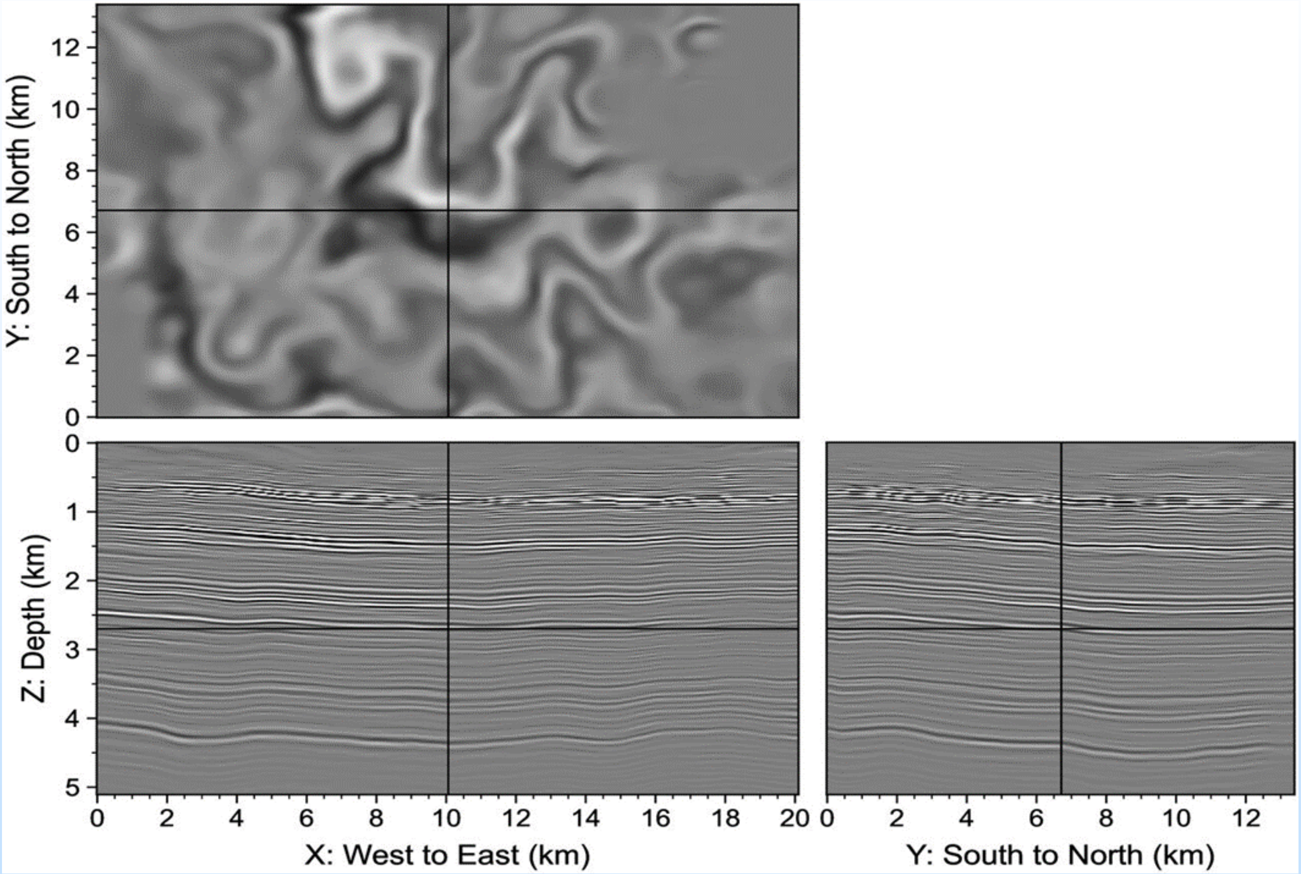
MVA-Updated 3D Velocity Model



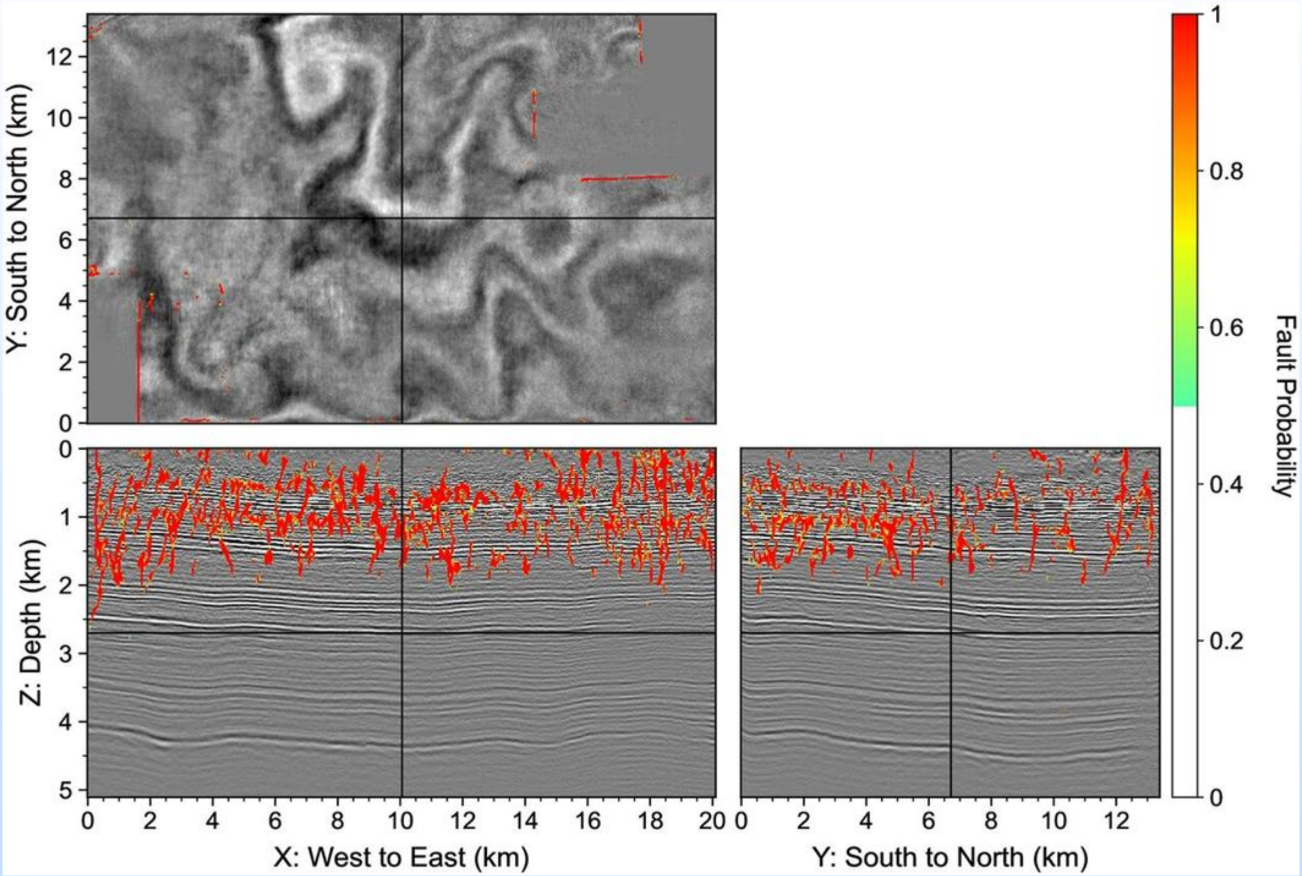
Original 3D Migration Image



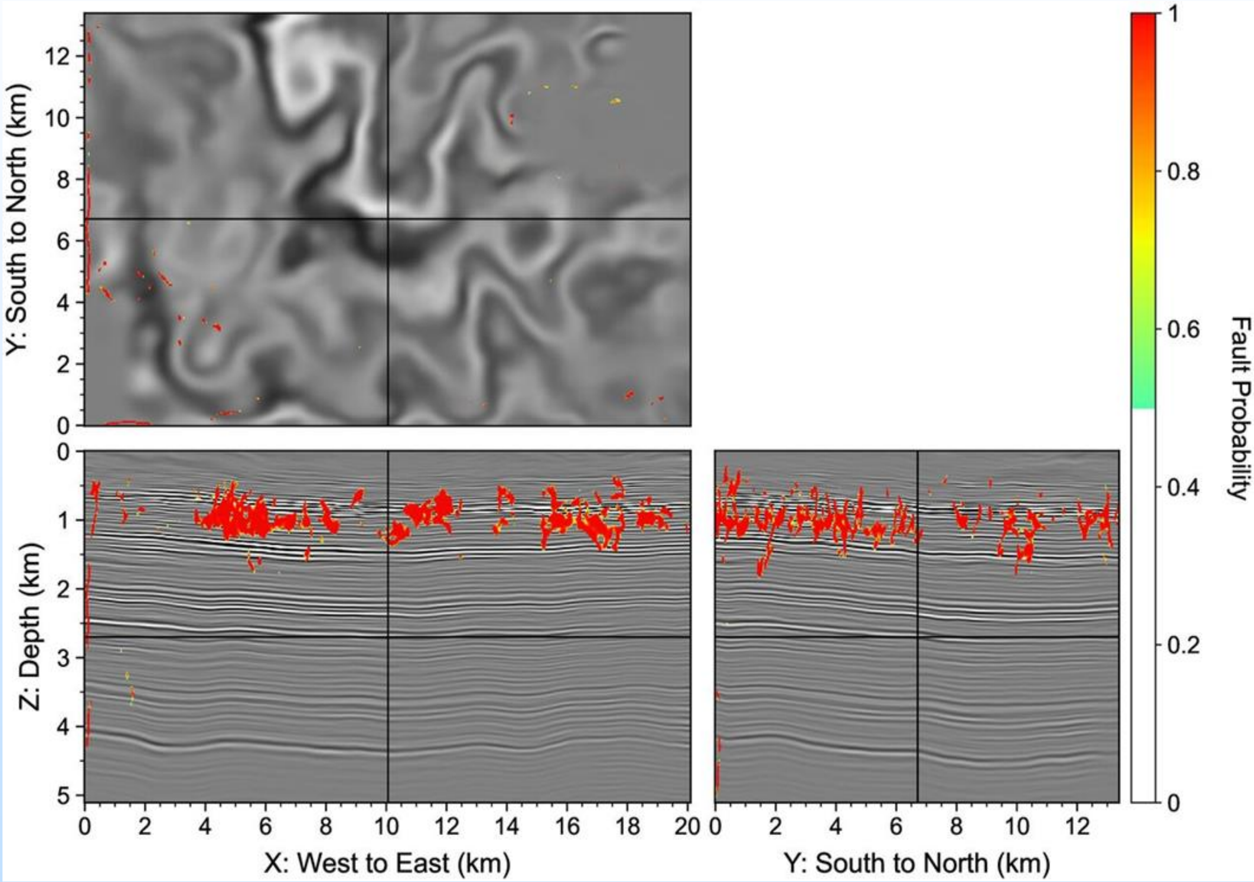
Denoised 3D Migration Image



ML Fault Detection on Original 3D Migration Image

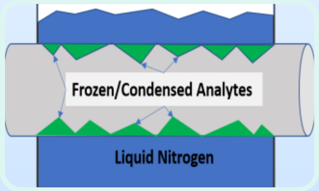


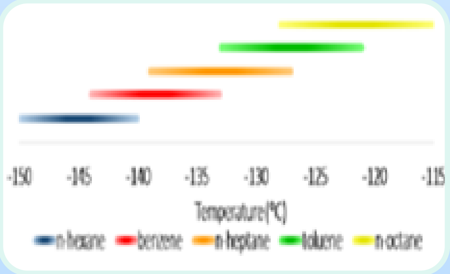
ML Fault Detection on Denoised 3D Migration Image

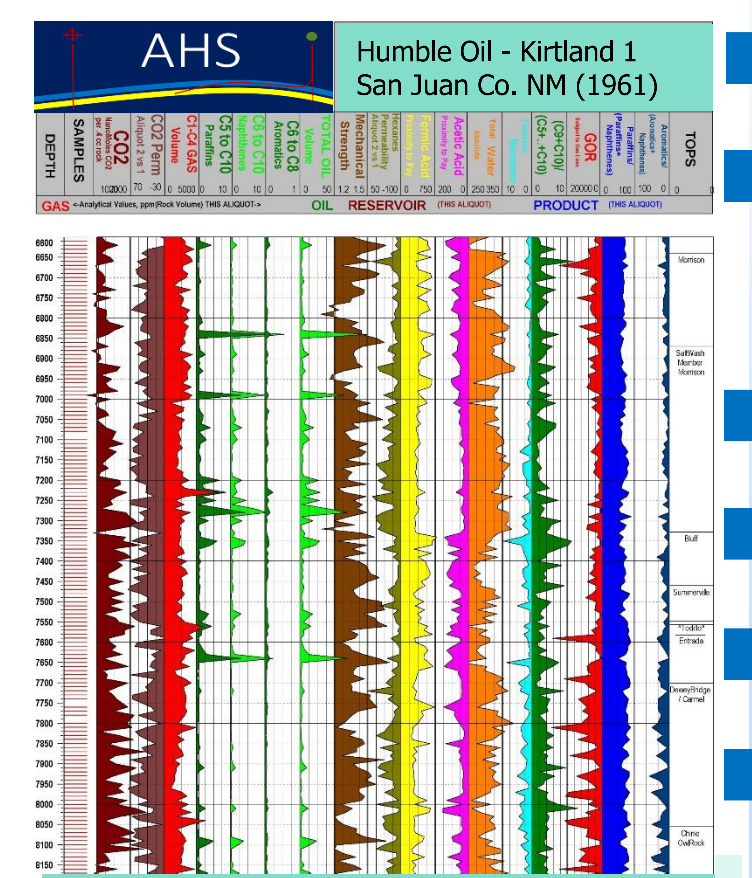


AHS Rock Volatiles CCS Well Site Evaluation

Analyze Rock Volatiles ➡ Analyze Nearby Well ➡ Assess Risks





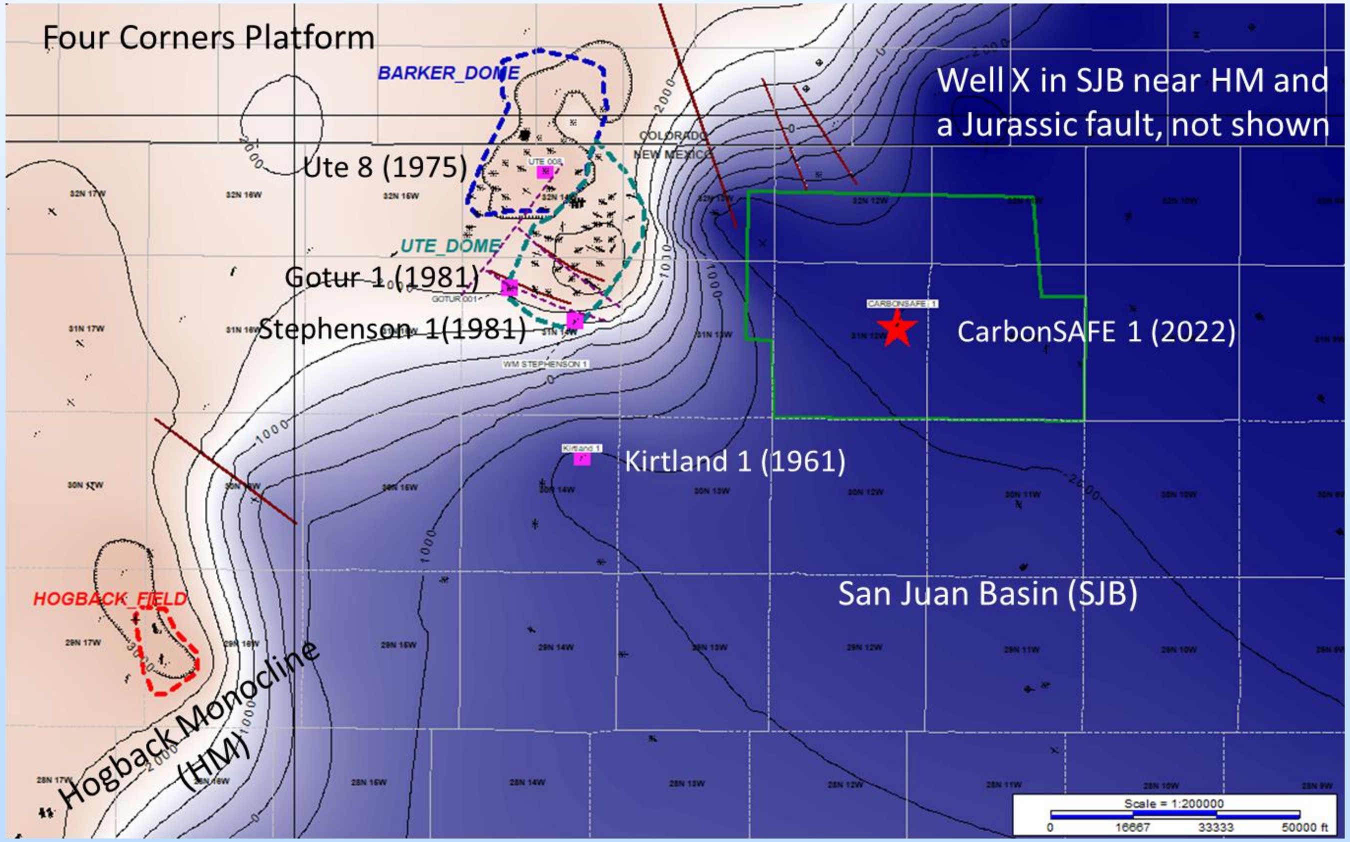


Kirtland 1; 14 miles SSW of CarbonSAFE1 Site

- Faults/Fractures
- Fault Activating
- Fluid Conduits
- CO_2 Seals
- CO_2 Permeability
- Past CO_2 Loss
- Future CO_2 Loss

Current Status – Analytical Work

- RVS was run on legacy cuttings from five wells with Jurassic coverage to understand what subsurface features may be encountered in CarbonSAFE 1 well prior to drilling
- Sealed and unsealed cuttings and core samples collected on CarbonSAFE 1; Sealed cuttings were analyzed in 2023
- Unsealed cuttings have been analyzed twice previously and failed due to QC issues; current “Run 3” test of 22 samples (235 in previous runs) produced usable data and is set to proceed with additional cuttings – coordinated with NMT



Site Evaluation

- Based on the needs and goals of the SJB CarbonSAFE project and the learning from the RVS analysis of the legacy cuttings from the SJB and platform five features of interest were identified that could be addressed with RVS data from the CarbonSAFE 1 cuttings.

Feature of Interest	Status in CarbonSAFE 1 Well
Petroleum System - Lateral Migration	?
Petroleum System - Vertical Migration	?
Carbon Dioxide Regional Baseline	?
Nature of Carbon Dioxide Release	?
Vertical Seals	?

Site Evaluation

- While the question of lateral migration of HCs needs to be evaluated, features of interest based on the evaluation of legacy cuttings samples were identified and the results in relation to the SJB storage site are overall encouraging, especially in relation to a lack of a history of CO2 migration/loss and evidence of strong vertical seals

Feature of Interest	Status in CarbonSAFE 1 Well
Petroleum System - Lateral Migration	Needs Evaluation
Petroleum System - Vertical Migration	Encouraging
Carbon Dioxide Regional Baseline	Encouraging
Nature of Carbon Dioxide Release	?
Vertical Seals	Positive

Comparing CO2 Values supporting Vertical Seals

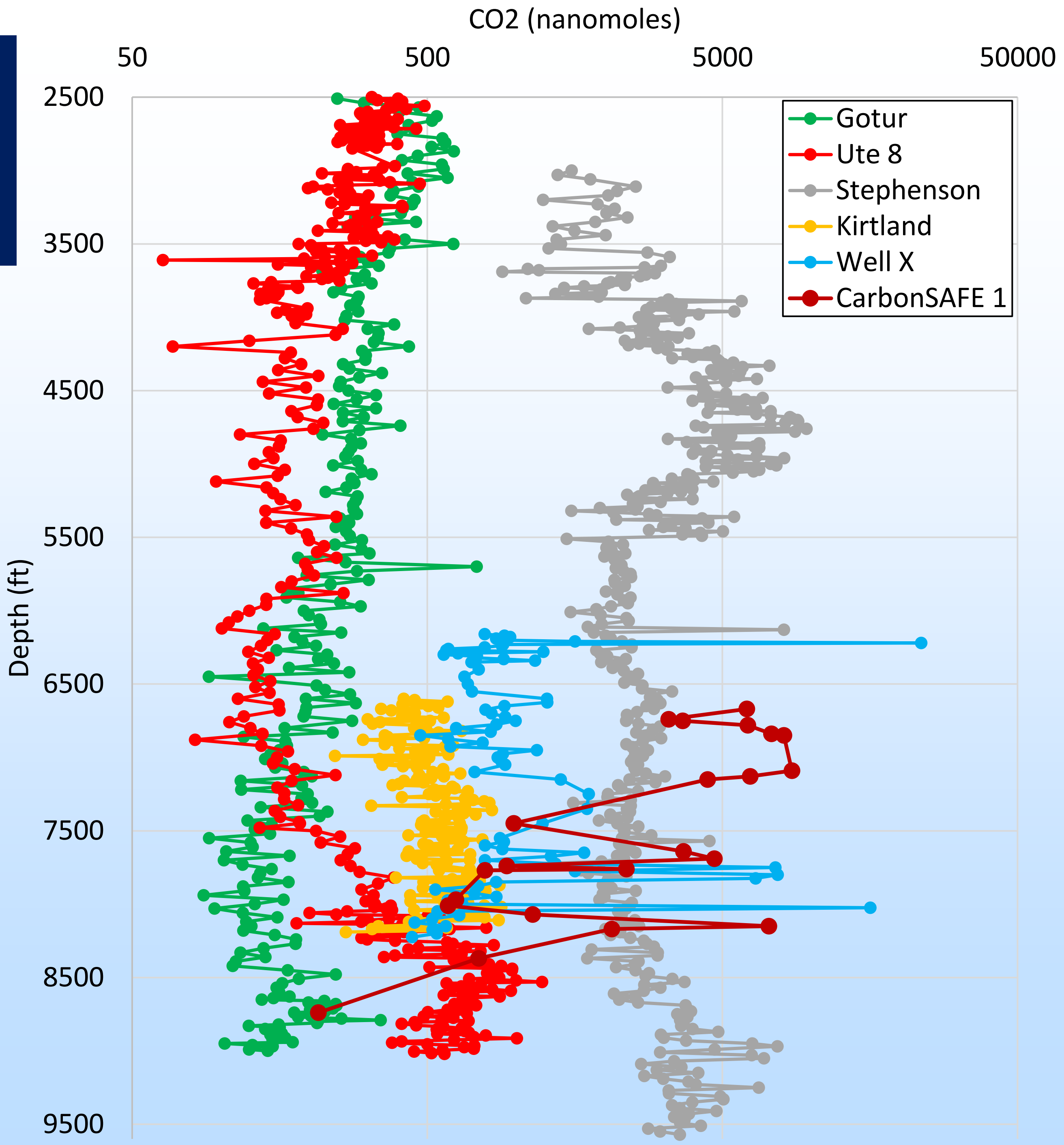
In general, the values for the SJB are higher than those of the Four Corners Platform.

In the case of Kirtland 1 and Well X the median values for CO2 from the Brushy Basin through the Dewey Bridge/Carmel are 520 and 860 nanomoles, respectively.

State Strat appears to have the higher value due to the presence of likely biological activity reflected in notable and discrete distributions of organic acids which correlate with zones that contained enhanced CO2 content – this can be reconciled with State Strat well being present in a portion of the basin which has undergone past subsurface activities as understood.

The median values of CO2 in the section of interest in Run 2 and Run 3 are 3770 vs 1060 nanomoles respectively

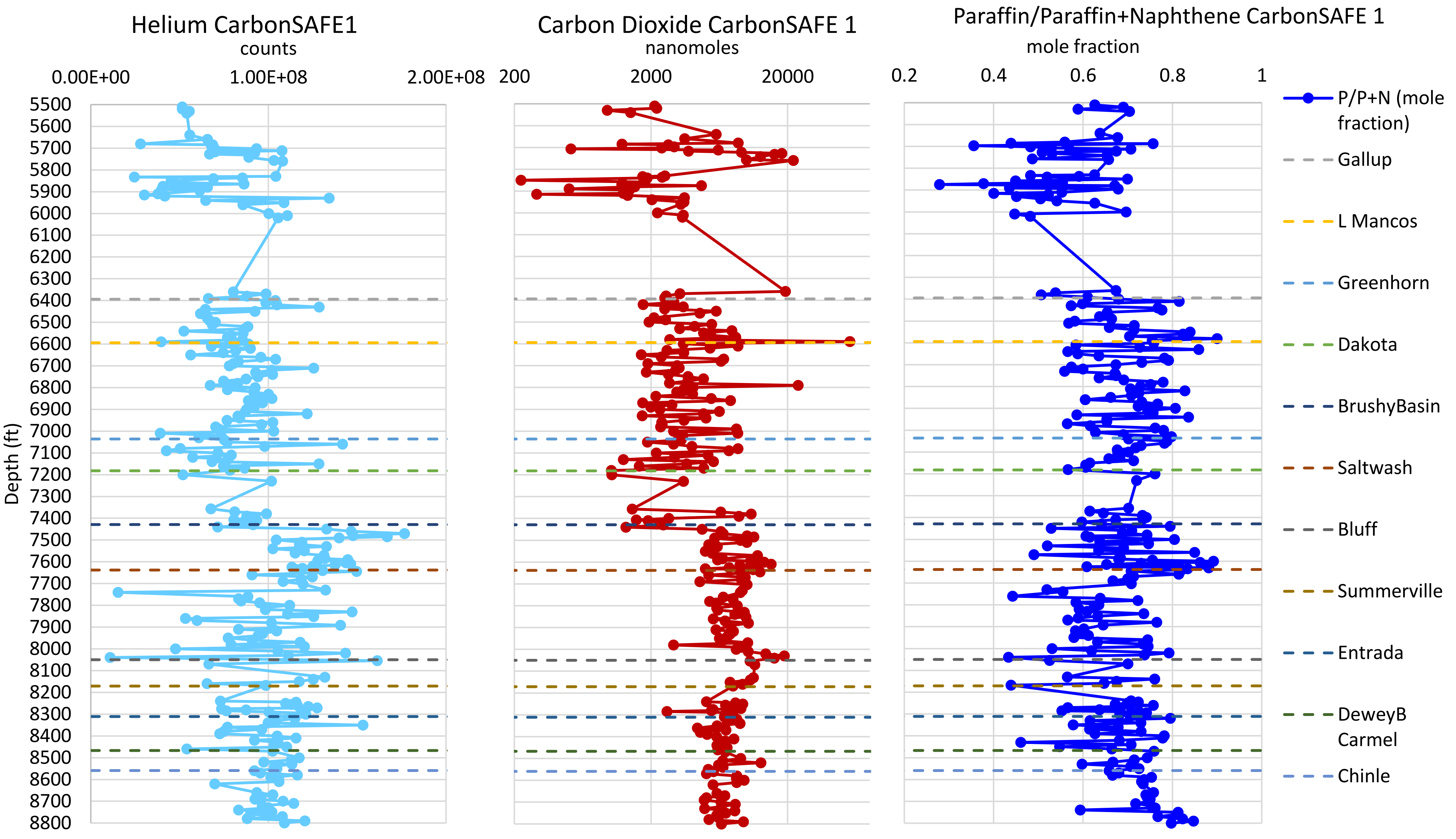
While a small sample size, **at present the CO2 values from Run 3 in the target zone is within the range that could be expected in the SJB**



Vertical Seals

- Geochemical evidence of several significant seals in the primary and secondary seals
- CO_2 and helium show a stepwise change in the top of the Brushy Basin indicating an excellent seal
- HC composition indicates a potential seal in the U. Mancos and Chinle
- Other seals are possible

Very positive evidence for the existence of good quality seals at CarbonSAFE 1

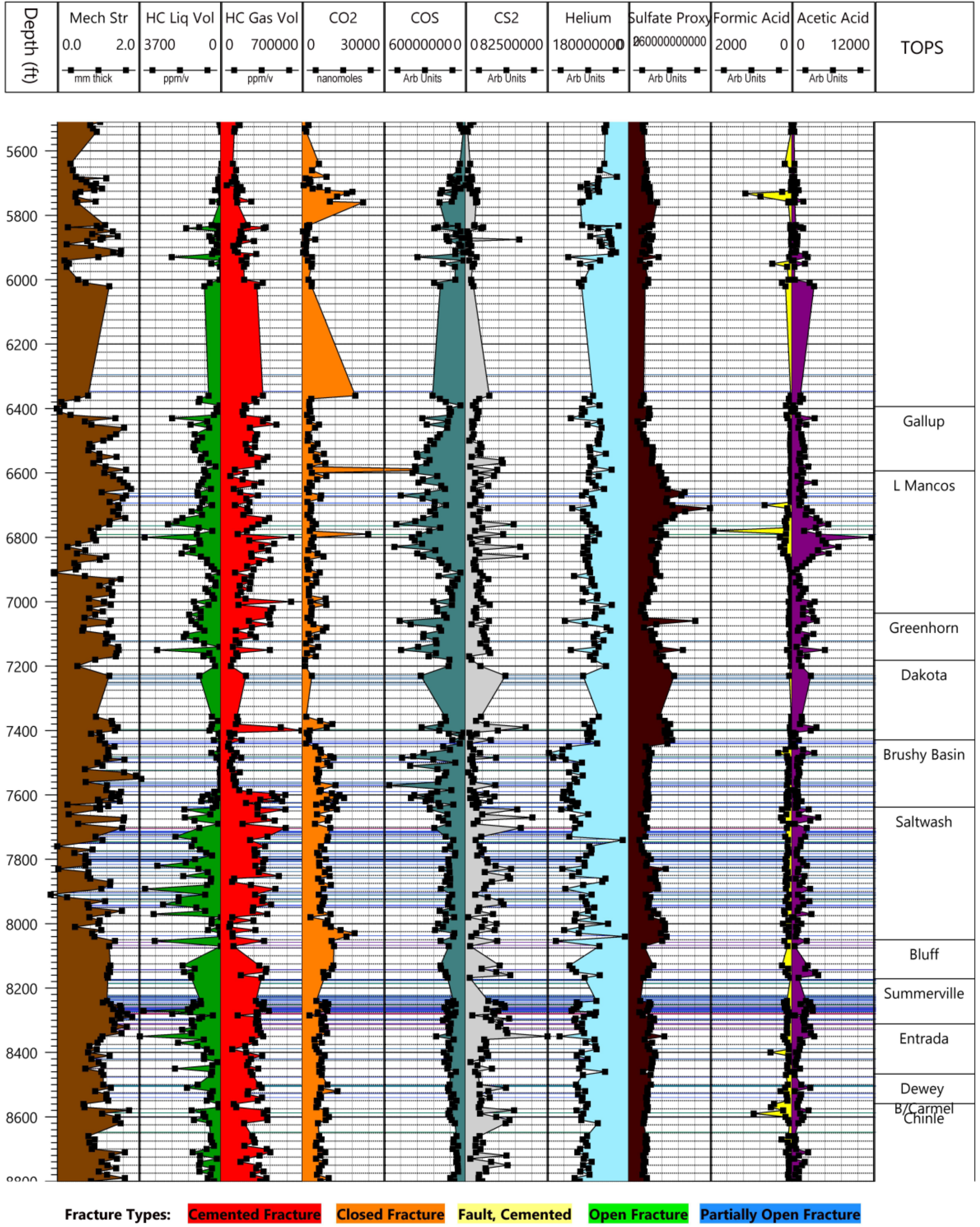


Fractures

A
H
S

Role of fracture in lateral and potentially vertical migration given core description are important – hoping to pursue a HC typing strategy similar to Kirtland

Initial integration of fracture data from image log with sealed data are encouraging – though historically this has been done with unsealed rock samples



Coupled Hazard Modeling Workflow

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Fiber Optic Measurements
1. **At the end of drilling**
2. **Step rate test**

- DTS (Temperature measurement)
- DSS (Strain measurement)

Thermal-Hydrodynamic-Mechanical-Chemical integrated model

Static Modeling
3D Geological model
3D Mechanical properties
Faults modelling

Historical injection/production data:
- Injection/production rate
- Bottom hole pressure

Hydrodynamic modelling

We are here

Trapping mechanisms:
- Structural trap
- Soluble trap
- Residual trap

Geochemical reactions:
- Brine components
- Solid components
- Injection fluid components

Thermal effect:
- Low temperature of injection fluid
- Contraction effect

Calibrate:
Stress and strain

Pressure, Temperature, Saturation exported for Geomechanics modelling:
- Stress in 3 directions
- Strain in 3 directions

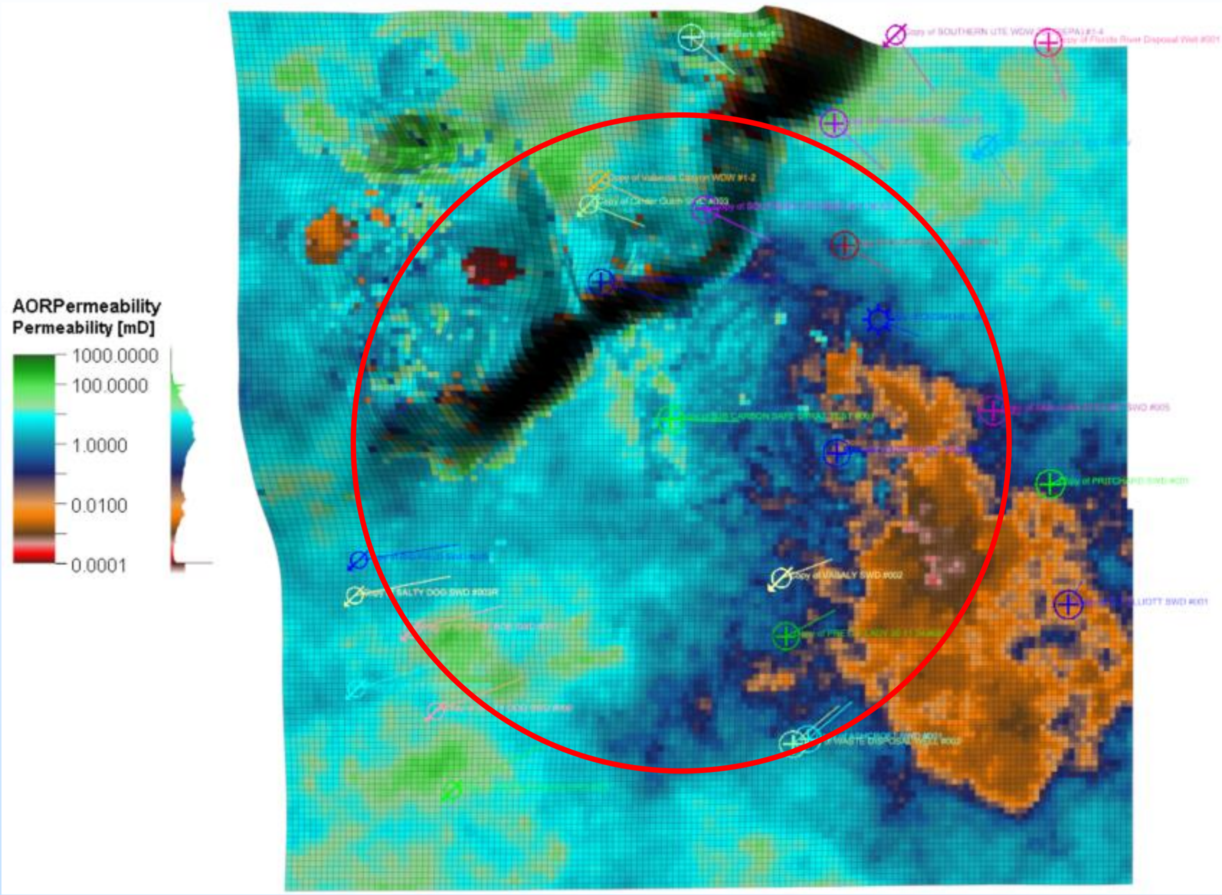
- Calibrated model

- Forecasting model

➢ Note: (in CMG) from We are here:
- Including thermal effect costs about 3-5 days to complete a run
- Including geomechanics takes even longer
- Need to work on a crop model rather than the whole basin model

Preliminary results

1. Hydrodynamic model: History matching of injection rate and BHP data of SWD wells near SJB Strat well.
2. Integrated trapping mechanisms including structural, soluble, residual, and geochemical trapping.
3. Observe temperature change due to CO2 injection (optional).
4. Initialization of geomechanical model on a smaller area to speed up computational time (working-on).



CO_2 injection - Different trapping mechanisms

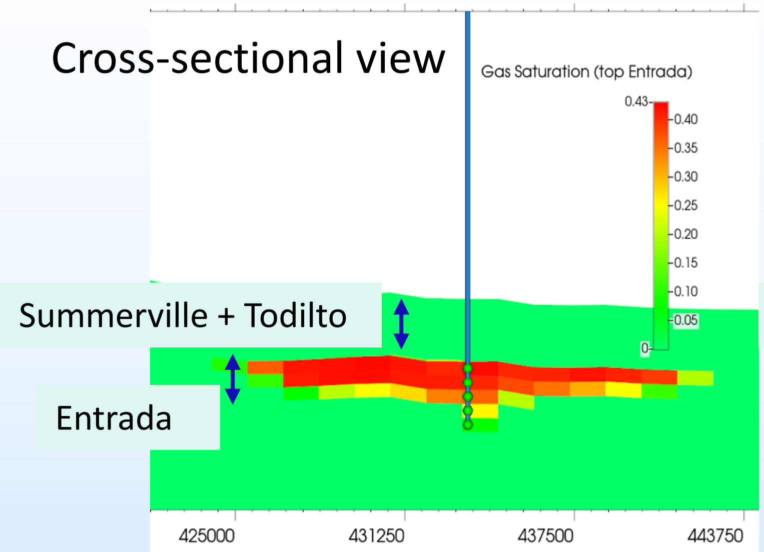
Reservoir properties Entrada formation	
Porosity	As shown in geologic model
Permeability	As shown in geologic model
Pore pressure gradient	**0.42** psi/ft (estimated by 1D MEM analysis)
Formation fracture gradient	**0.62** psi/ft
Formation temperature	**0.0194** F/ ft
Water salinity	34,000 ppm
Initial water saturation	100% (assumption made for conservative CO_2 plume)
Injection well setup	
Bottom hole pressure	**90%** of formation fracture pressure
Wellhead temperature	60 F
Injection fluid	**100% CO_2**
Injection rate	20 MMSCFD over 30 years (2025 – 2055)

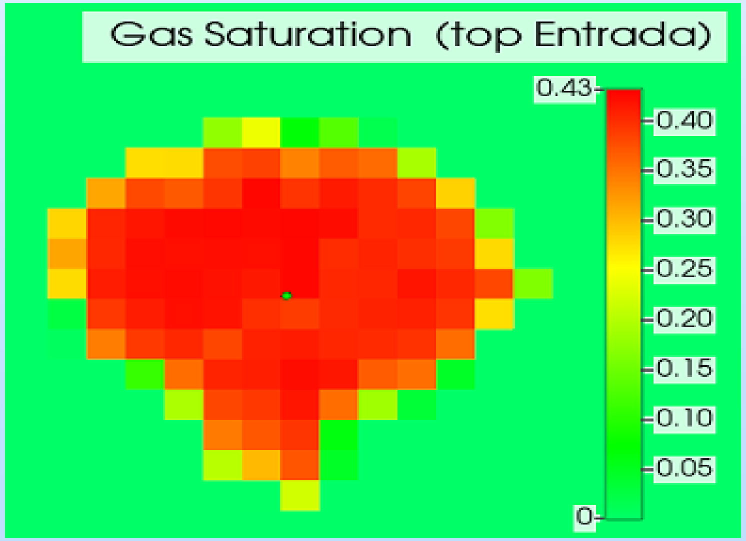
CO2 injection - Different trapping mechanisms

- SJB Strat well test:
  - Injection rate: 20 MMSCFD
  - BHP: 4630 psi

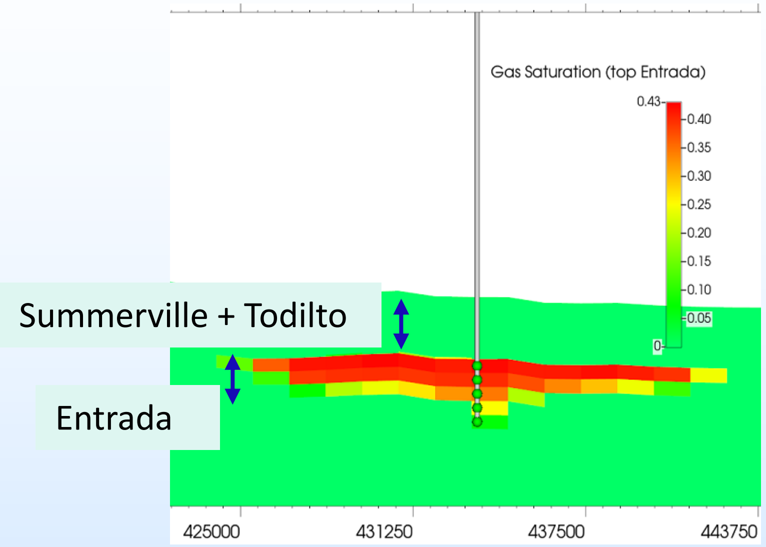
- CO2 plume diameter: 3 miles
- Supercritical CO2 is trapped in Entrada formation, no migration to Todilto and Summerville.

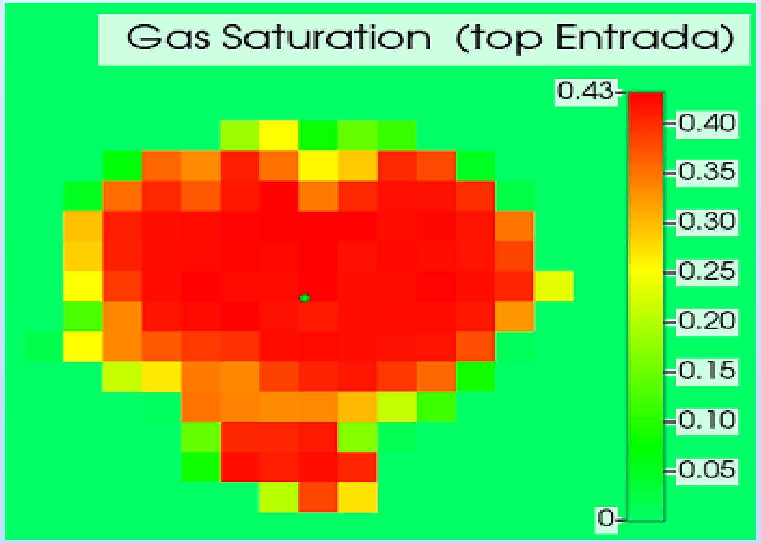
End of injection





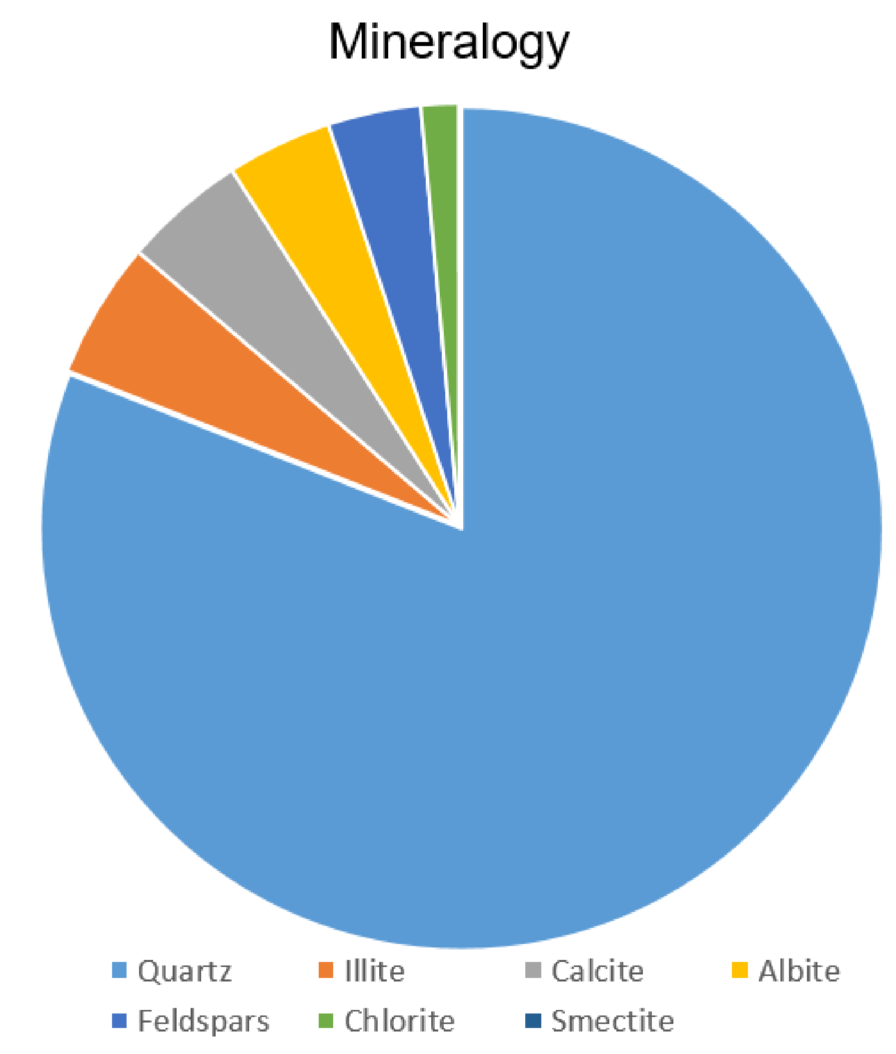
100 years after shut-in





Geochemical Reactions

Ions	Concentration (ppm)
Na+	6245
Ca2+	24
Mg2+	13
Cl-	7633
HCO3-	336
CO32-	450
pH	8.37



Mineral	Fraction
Quartz	0.733914
Illite	0.047642
Calcite	0.042657
Albite	0.036645
Anorthit	0.0181
K-Feldspars	0.032322
Chlorite	0.013051
Smectite	0.000184

Geochemical Reactions

Typical Reactions

Aqueous Chemical Equilibrium Reactions

$CO_{2(aq)} + H_2O = (HCO_3^-) + (H^+)$

$H_2O = (OH^-) + (H^+)$

$(HCO_3^-) = (CO_3^{2-}) + (H^+)$

Mineral Dissolution & Precipitation Reactions

Quartz $(SiO_2) + H_2O = H_4SiO_4$

Calcite $+ H^+ = Ca^{2+} + CO_3{}^{2-}$

Illite$+ 8H^+ = 2.3Al^{3+} + 5H_2O + 0.6K^+ + 0.25Mg^{2+} + 3.5SiO_{2(aq)}$

Albite $+ 4H^+ = Al^{3+} + 2H_2O + Na^+ + 3SiO_2$

Anorthit $+ 8 H_2O = (Ca^{2+}) + (Al(OH)^{4-}) + H_4SiO_4$

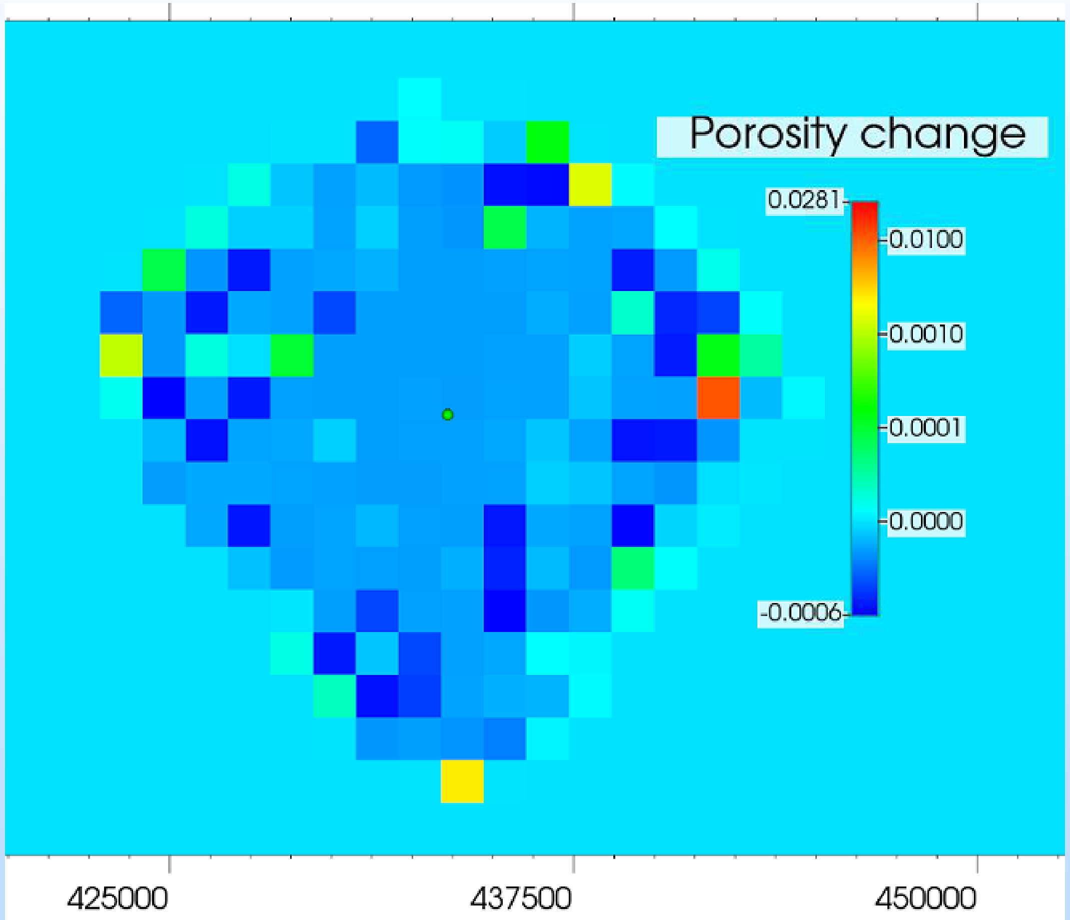
K-Feldspars $+ 8 H_2O = (K^+) + (Al(OH)^{4-}) + H_4SiO_4$

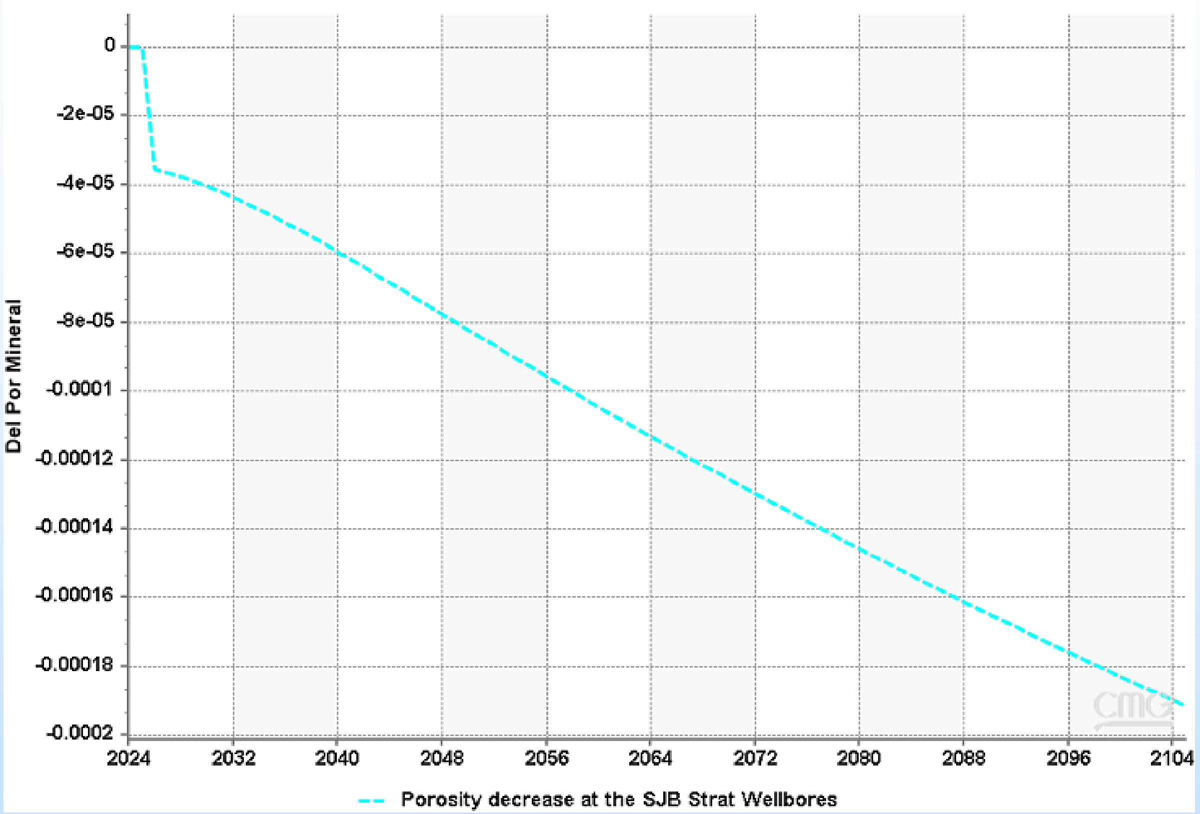
Chlorite $+ 16 (H^+) = (Mg^{2+}) + (Al^{3+}) + H_4SiO_4 + H_2O$

Smectite $+ 7 (H^+) = (Al^{3+}) + (Ca^{2+}) + (Fe^{2+}) + (Fe^{3+}) + H_2O + (K^+) + (Mg^{2+}) + (Na^+) + SiO_2$

Porosity change

- Calcite precipitation and formation of Quartz caused reduction in porosity





- Porosity reduction due to Calcite and Quartz precipitation
- This change is not signification because of low concentration of Ca++. It will be considerable in formations where Ca++ is dominant.

Summary Slide

- We have performed 3D migration velocity analysis and prestack depth migration of the 3D surface seismic data acquired at the San Juan Basin CarbonSAFE project site.
- We have performed machine-learning fault detection on the denoised 3D migration image.
- We found that there are no major faults around the primary CO2 injection zone, the Entrada formation at ~ 2.5 km depth, and that there are no major basement faults either.
- Established a baseline for DAS/DTS/DSS responses post-drilling operations.
- Utilized AHS drilling cuttings analysis to establish lateral and vertical storage integrity within the storage complex

Next Steps

a. Complete analysis of unsealed cuttings and core and incorporate into sealing and migration assessment of the San Juan Basin

b. Continue the integrated hazard modeling

c. Acquire a time-lapse fiber data during the injection test at the SJB CarbonSAFE site and include information into integrated hazard modeling

Acknowledgements

The project would like to thank DOE for the award opportunity through DE-FE0032064 and our partners. We would like to acknowledge additional support from San Juan Basin CarbonSAFE project.