SCHOOL OF ENERGY RESOURCES

# At the Forefront of Energy Innovation, Discovery & Collaboration

UNIVERSITY OF WYOMING

# Optimizing accuracy of determinations of $CO_2$ storage capacity and permanence, and designing more efficient $CO_2$ storage operations: An example from the Rock Springs Uplift, Wyoming

*DOE Project DE-FE0009202*


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**University of Wyoming Carbon Management Institute**



U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS
August, 2015


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# Presentation Outline

- Benefits of this program to DOE's CCUS goals
- Objectives and goals of the study
- Technical overview: integrated approach to characterizing and assessing uncertainty relative to geologic heterogeneity
- Conclusions

# Benefit to the Program

**Creation and refinement of tools and methodologies to reduce storage site uncertainties**

- Development of a new seismic workflow analysis
- Large-scale tectonic processes characterization and their impacts on the confining potential of sealing strata; seal bypass systems
- Identification of the impact of well completion techniques and in-situ testing on formation brine chemistries: introduced anthropogenic uncertainty
- Reservoir brine analysis methodologies for fluid containment, evolution, and reactions

**Identification of essential steps for reducing uncertainty and maximizing storage and containment**

- Identify primary lithologic character of best seals; diagenetic enhancement of seals
- Perform in-situ well testing for reservoir conditions, fracture gradient, etc.
- Utilization of stacked reservoir analysis for reducing sealing uncertainties, and defining best injection targets
- Application of sensitivity analysis for highest uncertainties, periods of high risk
- Development of well design scenarios that minimize scaling risks
- Identified critical research gaps

# Benefit to the Program *(continued)*

**Testing and validation of tools and steps on RSU site**

- Identified primary and secondary seals
- Implementation of new calculations for $CO_2$-water-rock systems, high-pressure mercury injection, interfacial tension, and wettability data that are realistic for the study site
- Development of new, conservative $CO_2$ column height (plume) estimates for structural traps/dipping strata-lowest risk volume
- Refined storage estimates of Wyoming's Paleozoic reservoirs based on new conclusions
- Extrapolate geologic heterogeneity to other potential storage sites

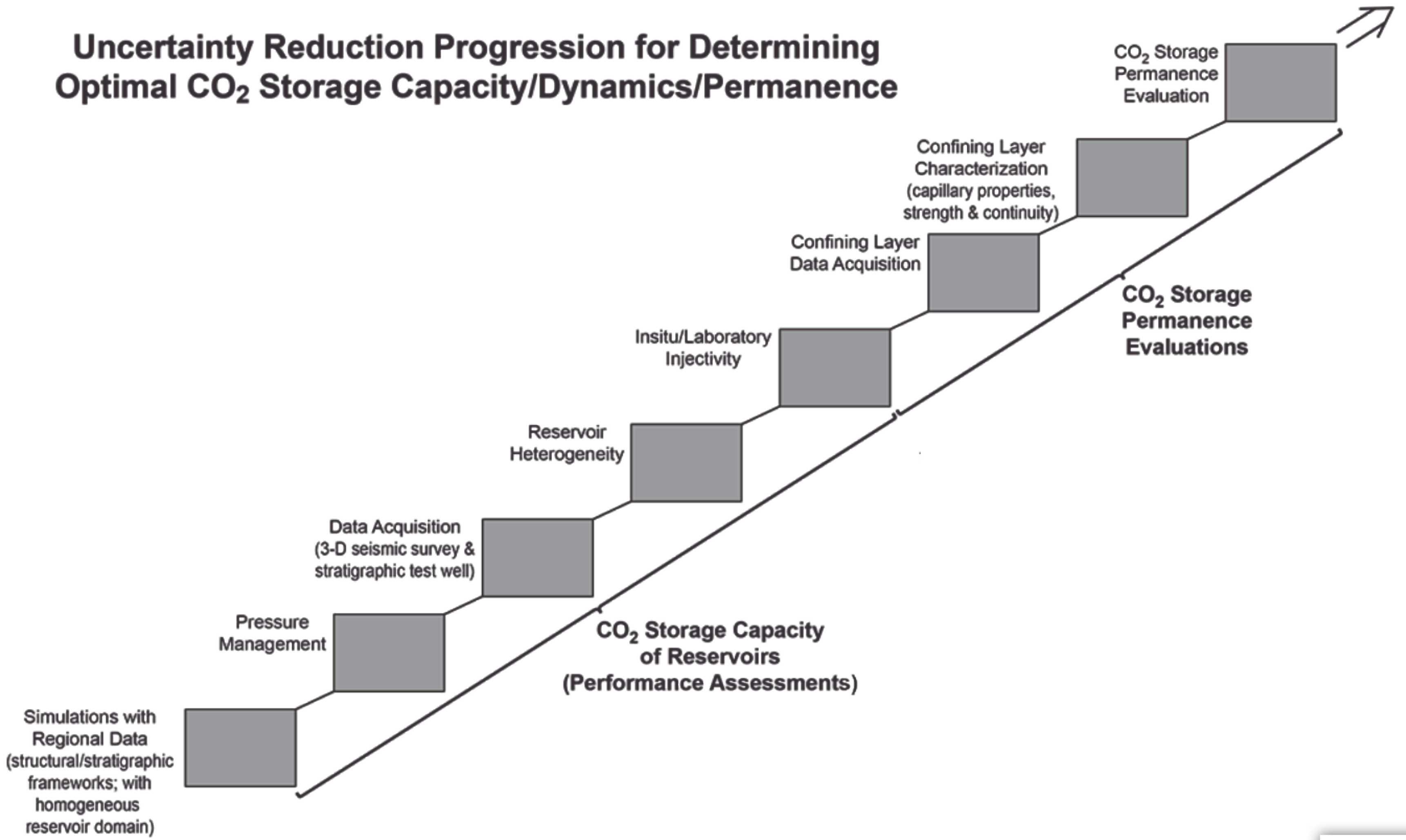
# Project Overview:
## Goals and Objectives

**The objectives for the project are as follows:**

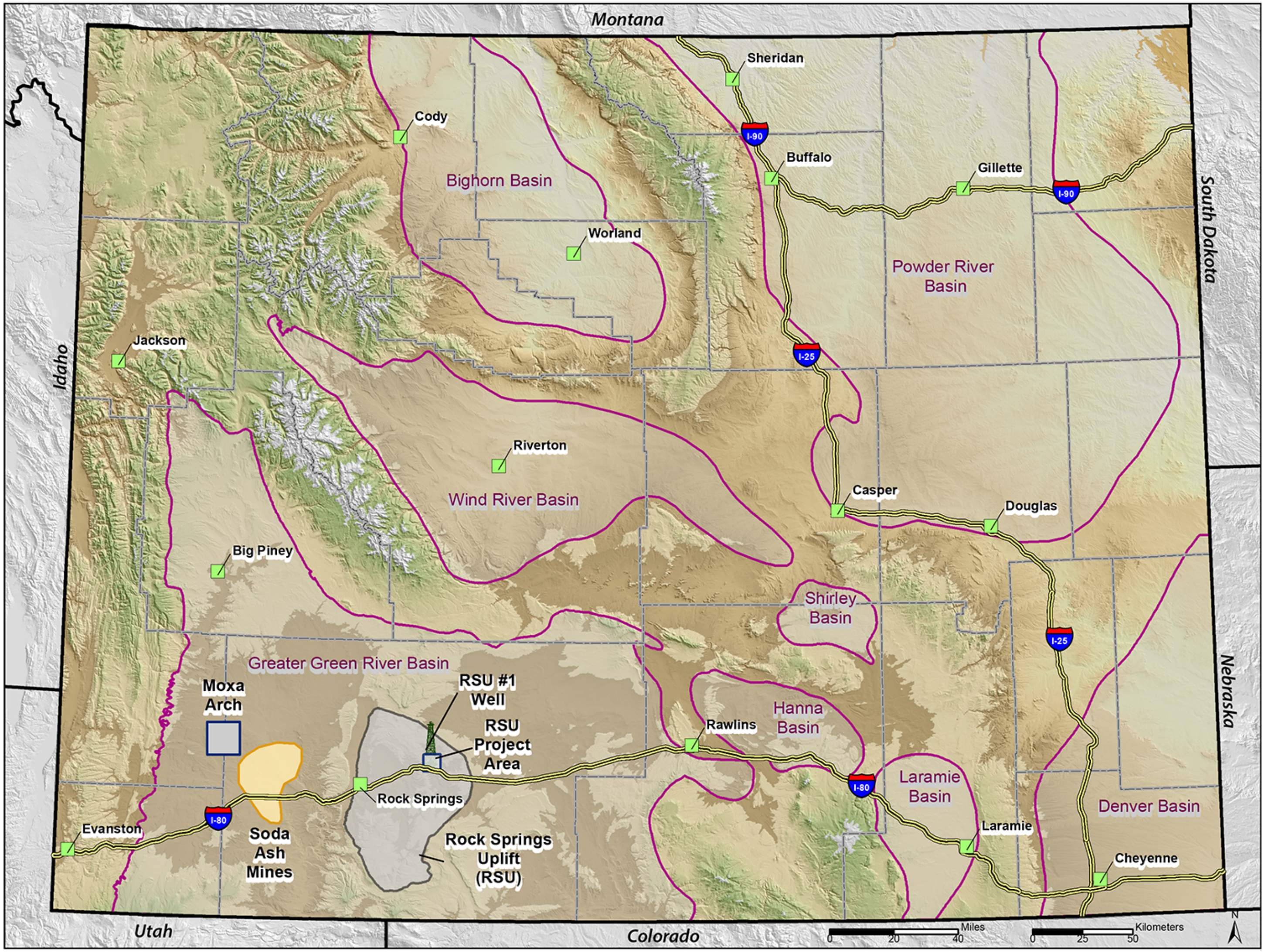
1) Reduce uncertainty in estimates of $CO_2$ storage capacity at the Rock Springs Uplift;
2) Evaluate and ensure $CO_2$ storage permanence at the study site by defining sealing potential and character, specifically with regards to geological heterogeneity; and
3) Improve the efficiency of potential storage operations by designing an optimal $CO_2$ injection/brine production strategy.

**Working towards overall goal of reducing uncertainty to the lowest possible levels.**

# Integrated Work Flow



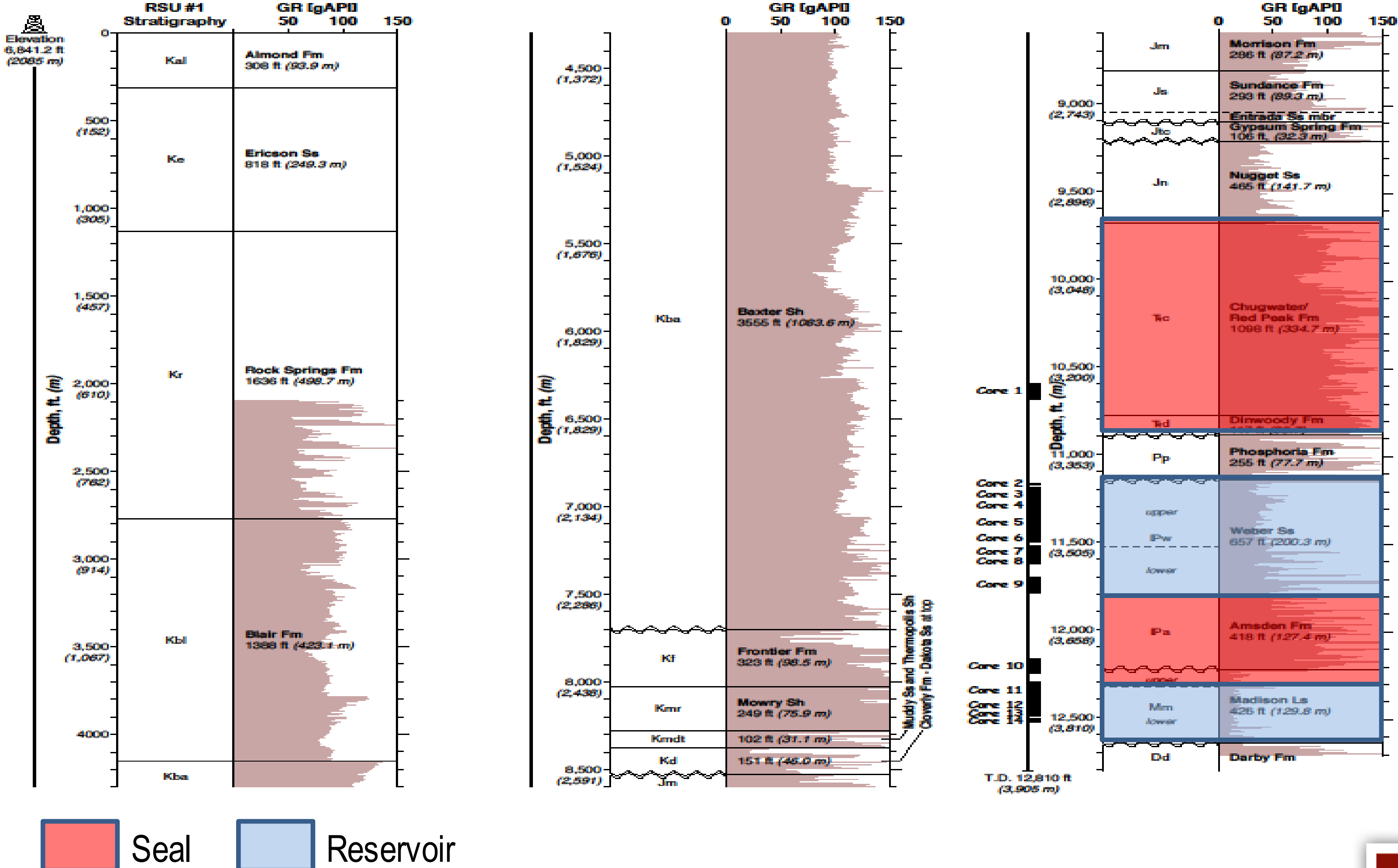
# Study Area

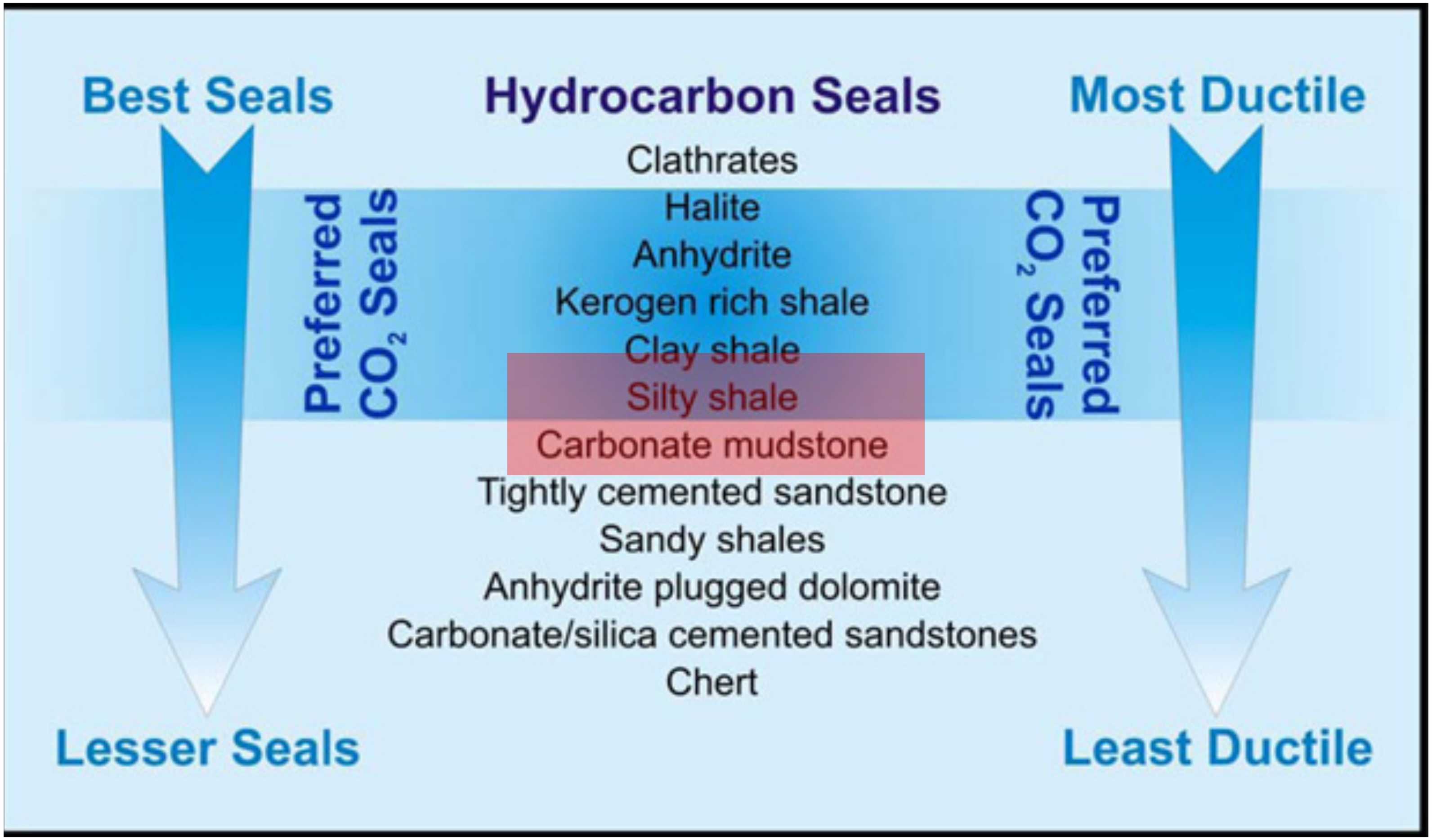


Montana
Idaho
South Dakota
Nebraska
Utah
Colorado
Sheridan
Cody
Buffalo
Gillette
Bighorn Basin
Worland
Powder River Basin
Jackson
Riverton
Wind River Basin
Casper
Douglas
Big Piney
Shirley Basin
Greater Green River Basin
Moxa Arch
RSU #1 Well
RSU Project Area
Hanna Basin
Rawlins
Laramie Basin
Rock Springs
Evanston
Soda Ash Mines
Rock Springs Uplift (RSU)
Laramie
Denver Basin
Cheyenne
I-90
I-25
I-80
Miles
0 20 40
Kilometers
0 25 50
N

# Technical Overview

## Stratigraphic Section of the Well



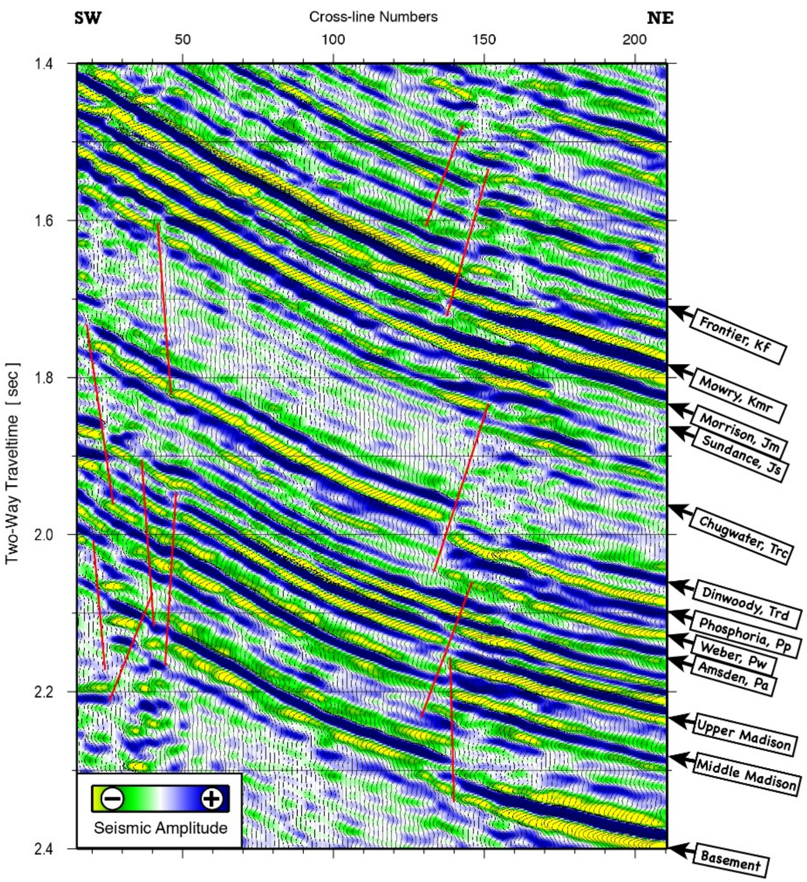


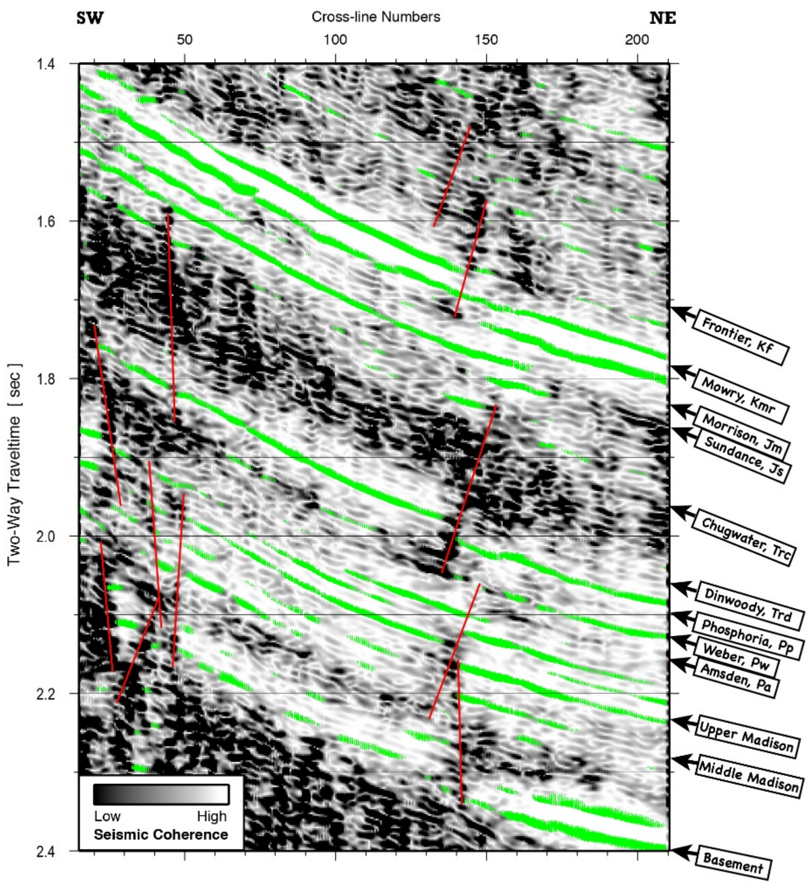

Idealized lithologic seal chart, sealing lithology from this study are highlighted in red

Figure modified from IEAGHG, March 2009

# Seal Bypass Systems

Method: Reflection continuity analysis of seismic data correlated with regional geologic history: Curvature, Coherency, Amplitude, Gradients, Spectrogram Analysis

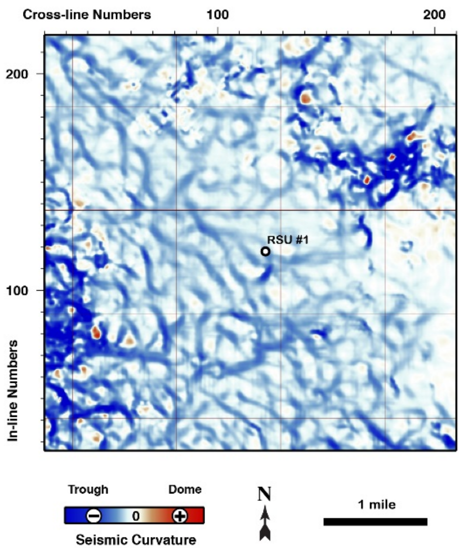


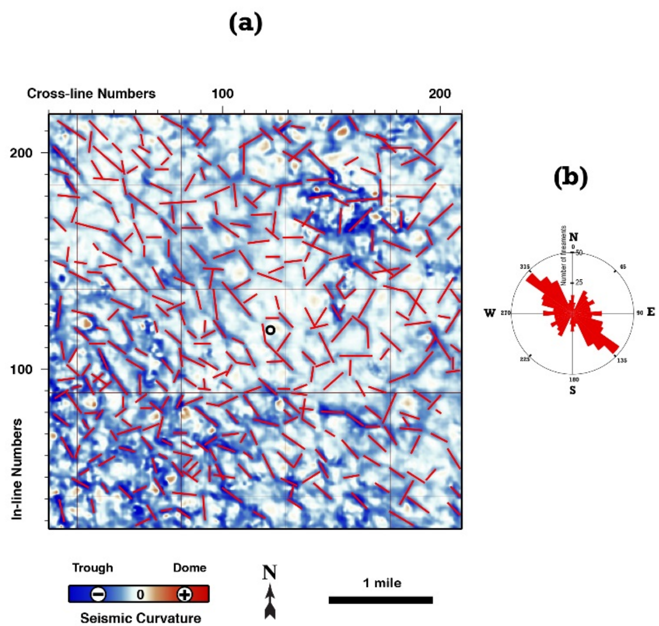
# Seal Bypass Systems

Curvature Analysis: Interpreting Fold, Joint, and Fracture Systems in Horizon Slices

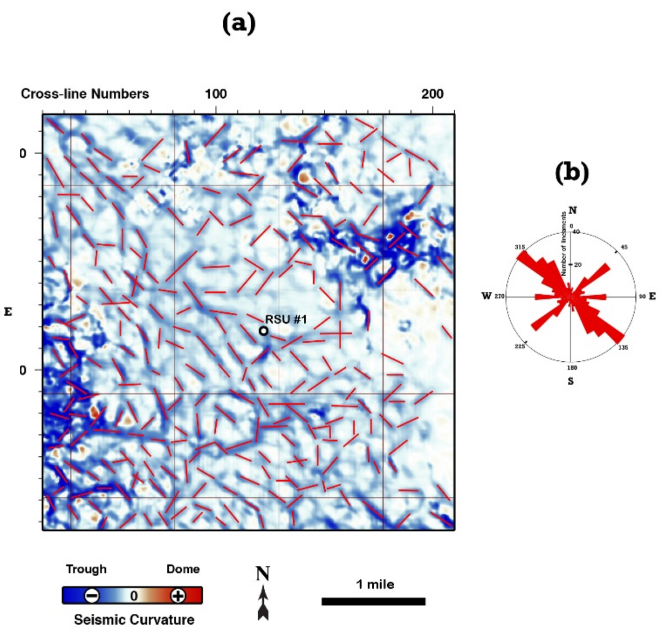
## Preliminary Analysis




## Interpreted Slices



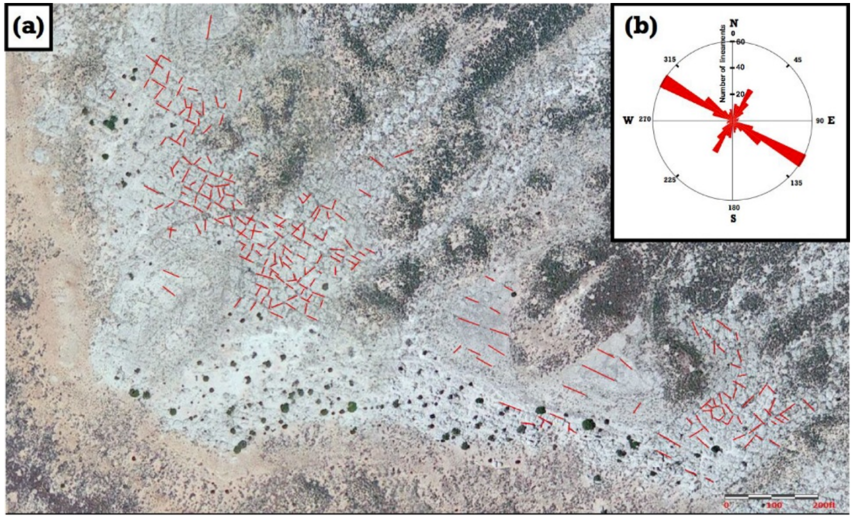

1. Triassic seal




2. Madison reservoir

# Seal Bypass Systems

Outcrop Study of Joint and Fracture Systems in Cretaceous Sandstones: Study Site

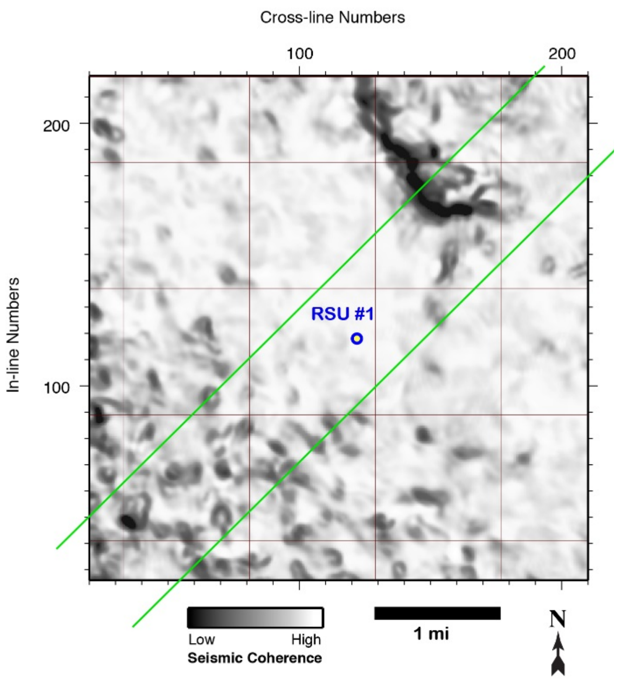



Dominant joint/fracture systems formed during the Laramide – related to flexure of sediments on the flank of the RSU

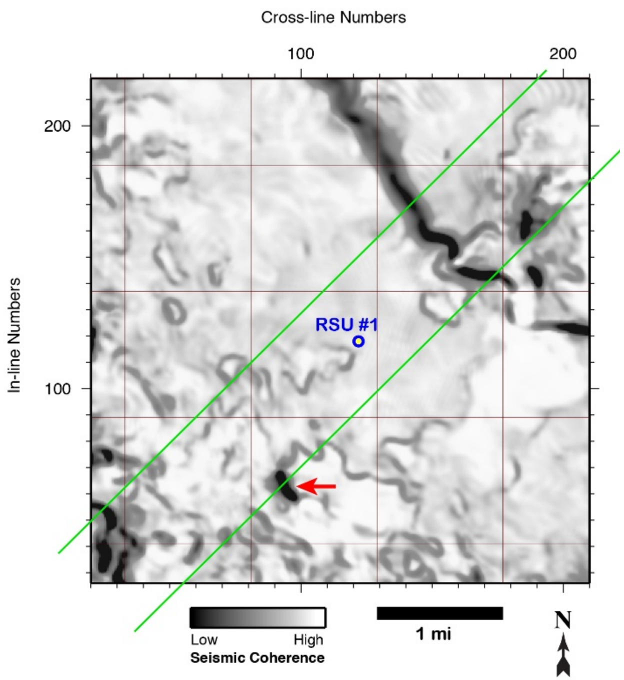
# Seal Bypass Systems

Coherency Analysis: Interpreting Anomalous (non-lateral) Features in Horizon Slices

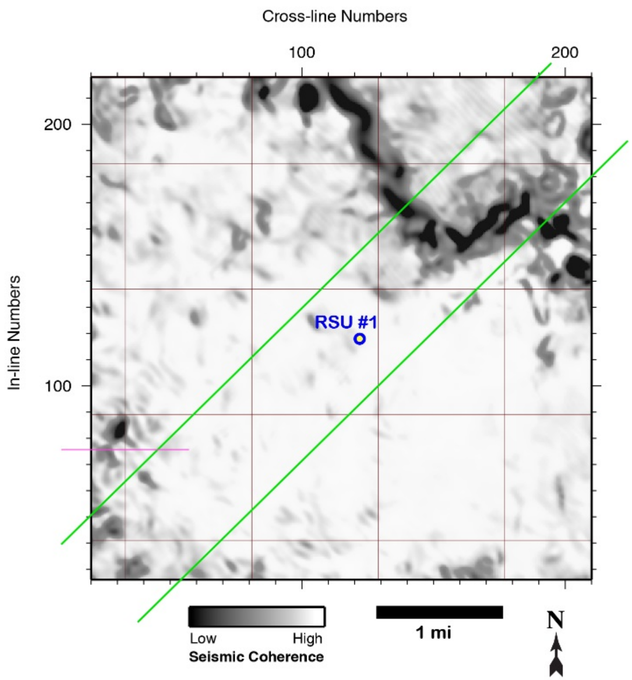
## Triassic Seal




## Permian Seal

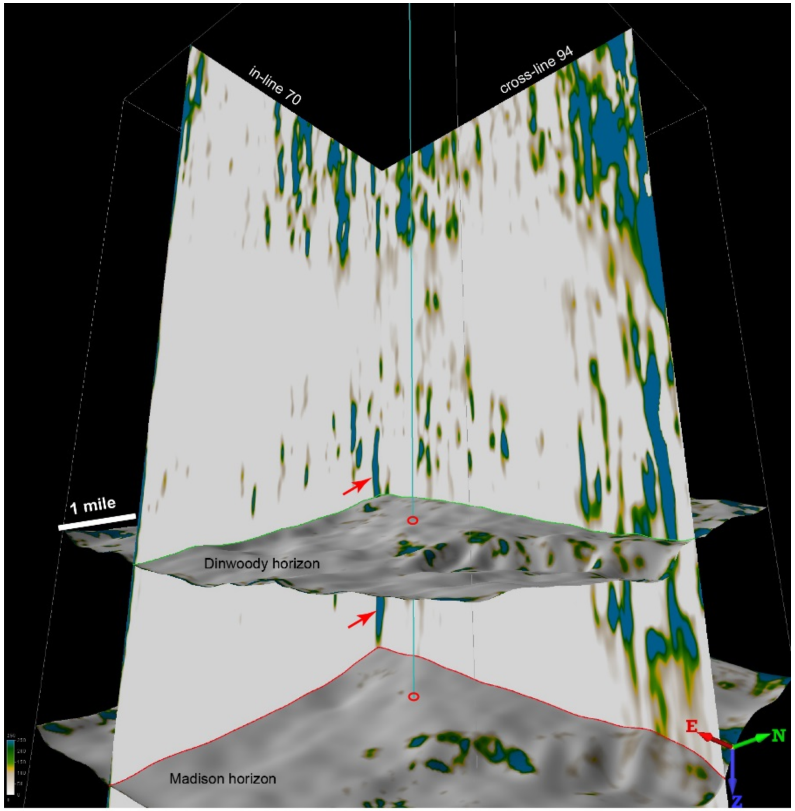


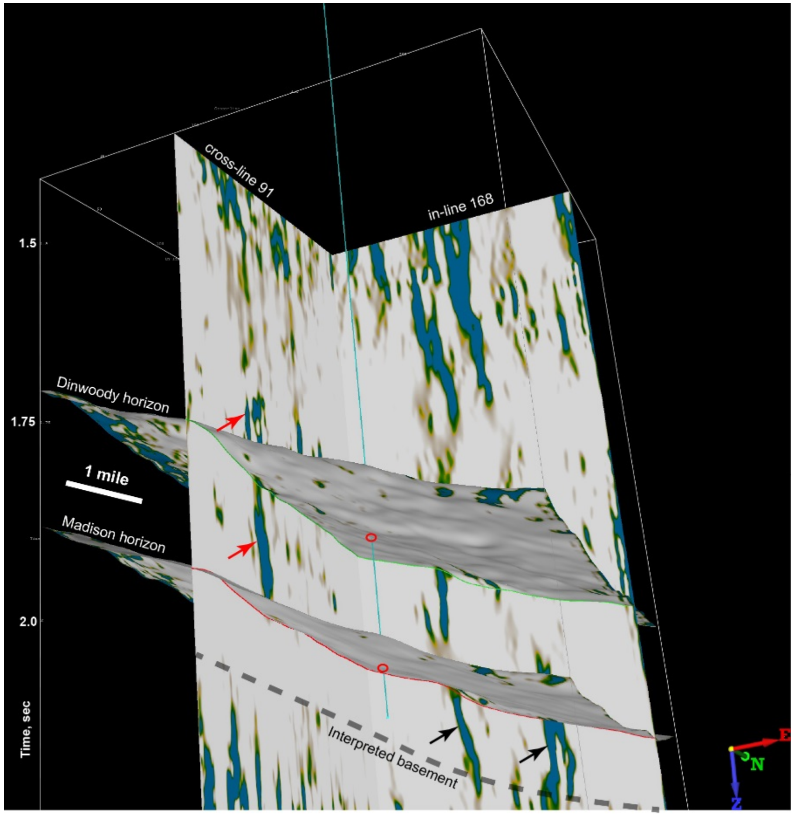

## Mississippian Reservoir



# Seal Bypass System: Karstification

Coherency Analysis: Interpreting Anomalous (non-lateral) Features in Vertical Sections




Rock Integrity
High Low
Attribute

RSU #1 well projection

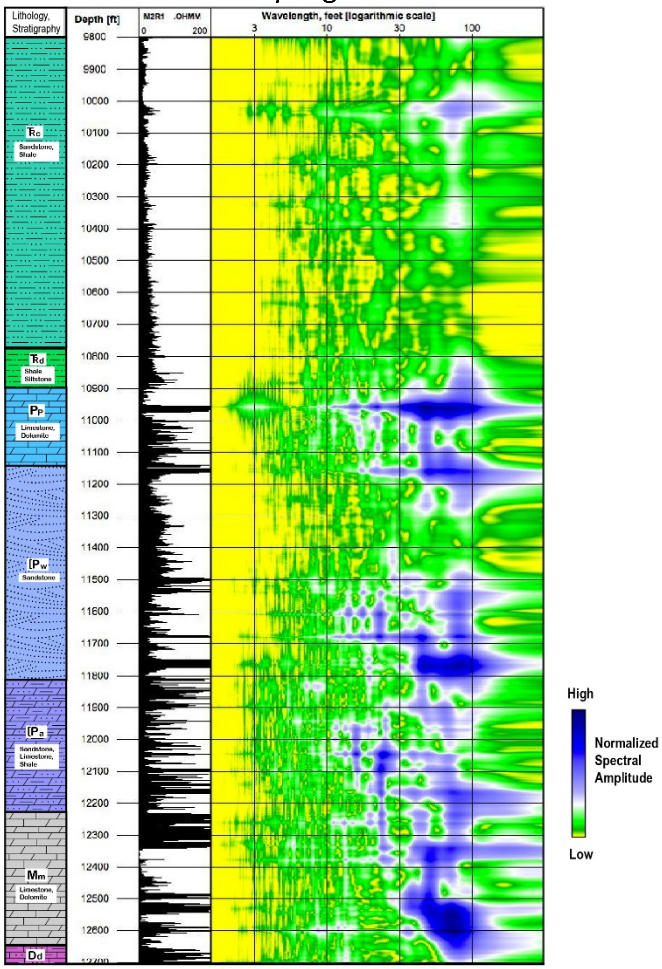
Rock Integrity
High Low
Attribute

RSU #1 well projection

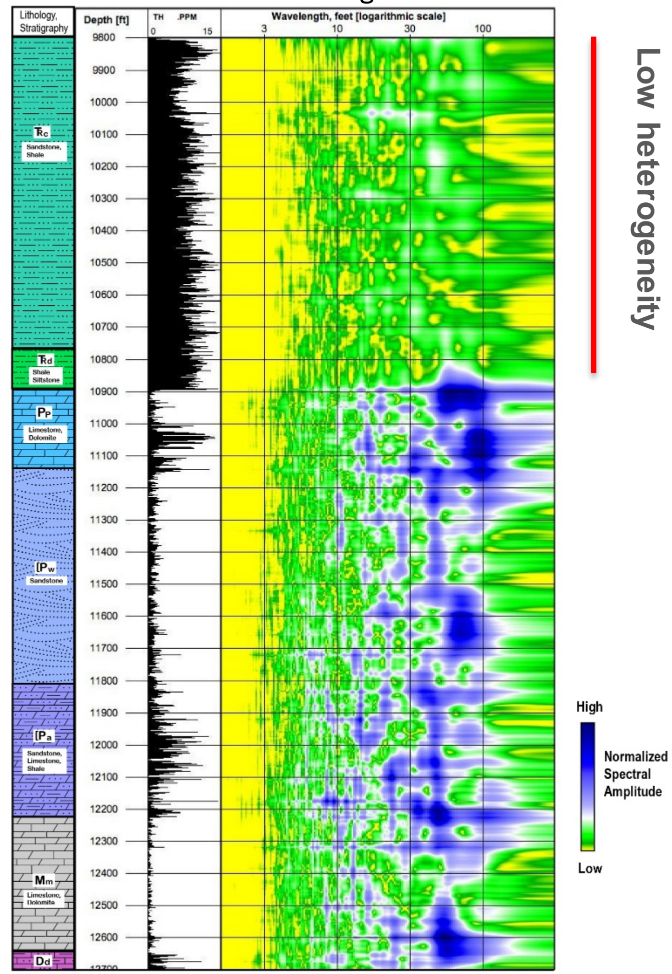
# Seal Bypass System: Heterogeneity Analysis

Spectrogram Analysis: 1-D to 2-D Transformation for Lithological Heterogeneity

Density Log



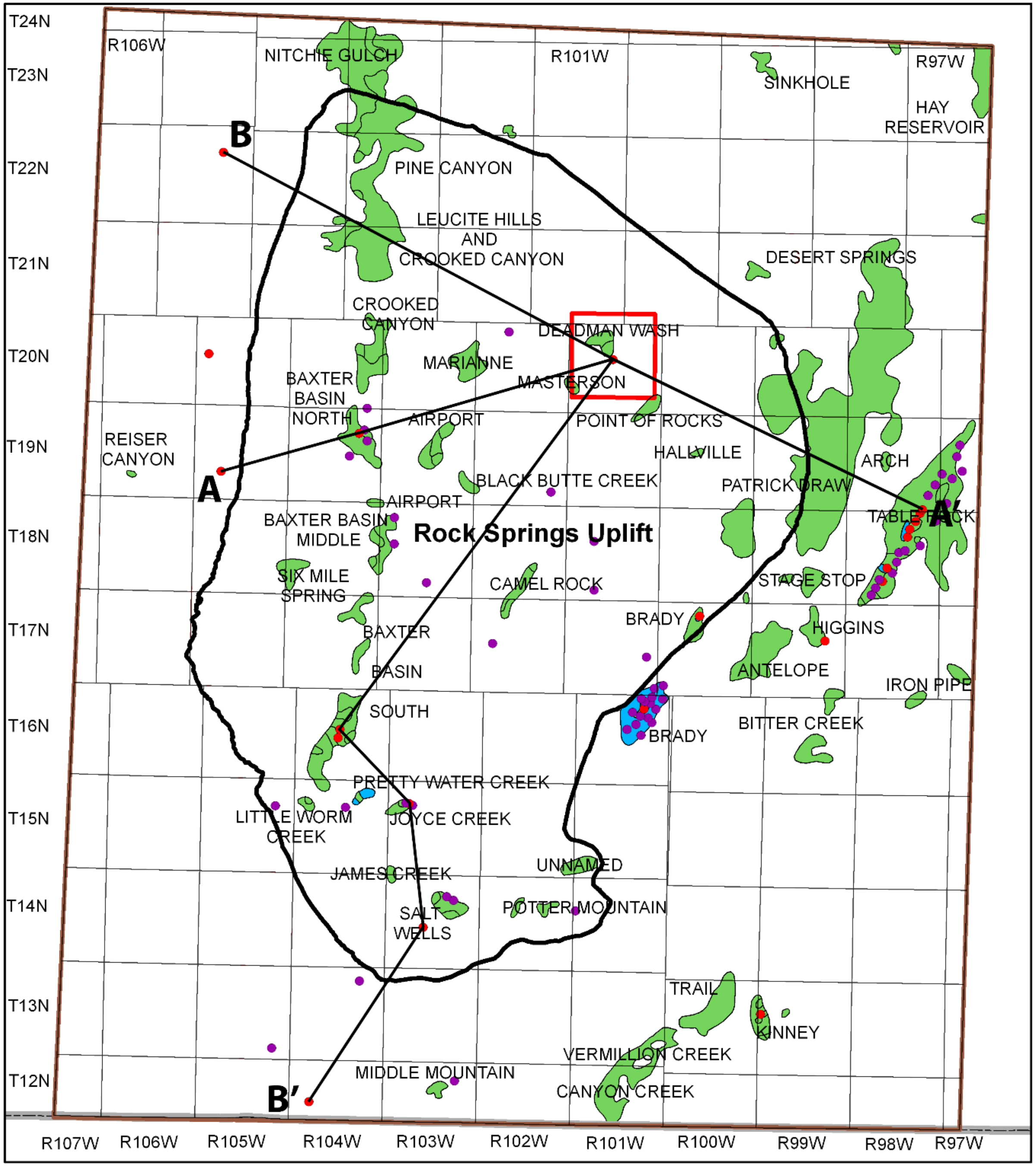

Thorium Log



# Theory of Spectrogram Analysis

- A SPECTROGRAM of a well log is a visual representation of the spectrum of spatial wavenumbers (wavelengths) as they vary with depth. The algorithmic instrument used for spectrogram calculation is direct Fourier transform. Computationally, the Fourier transforms are done continuously at every depth sample with a set of log data in parametrically defined windows. The transformed results obtained for different size of spatial windows are stacked together and normalized. This technique allows to bypass the Heisenberg's uncertainty principle, and to provide the balanced resolution (both in depth and wavenumber). Depending on the geological task, the balancing factor can be set to improve either depth or wavelength resolution.

# Oil and Gas Fields in the Rock Springs Uplift Area




**Legend**

Oil and Gas Field Ages

- Mesozoic
- Paleozoic

Oil and Gas Tests

- Weber Penetrations (55)
- Madison Penetrations (20)

Other Map Features

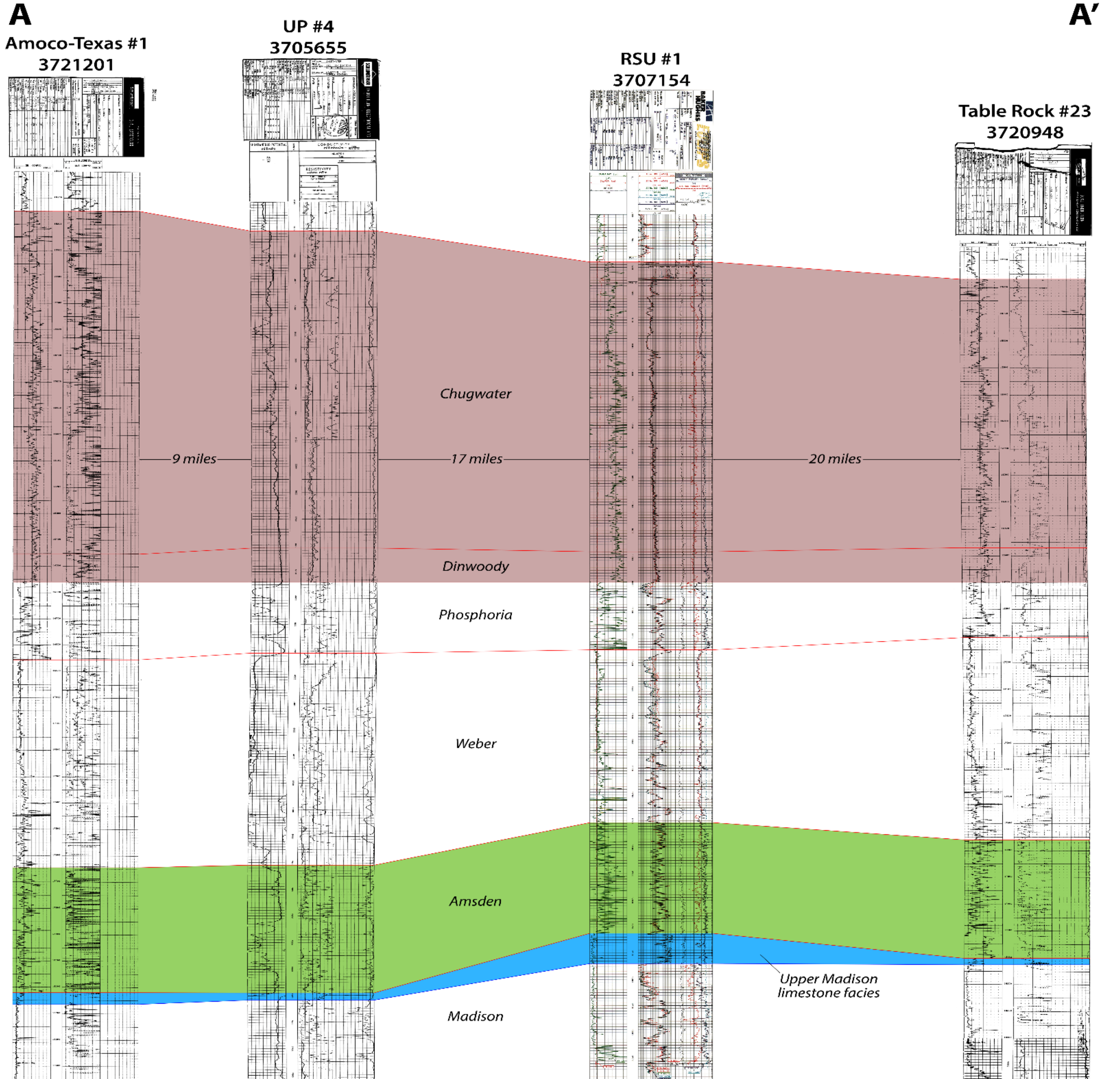
- Rock Springs Uplift Boundary
- RSU #1 Seismic Footprint
- Township-Range Lines
- State Border

N

**Scale**

0 2 4 8 12 16 Miles

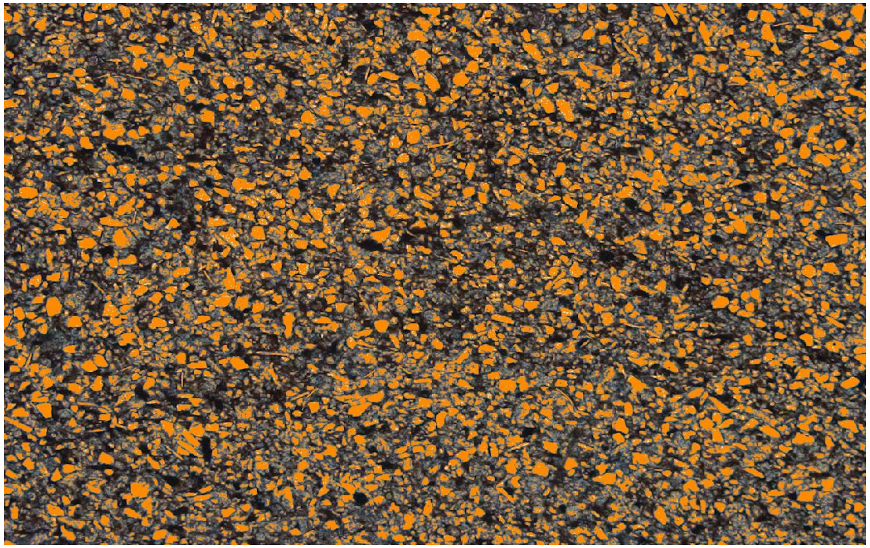
# Regional petrophysical evaluation of targeted seals



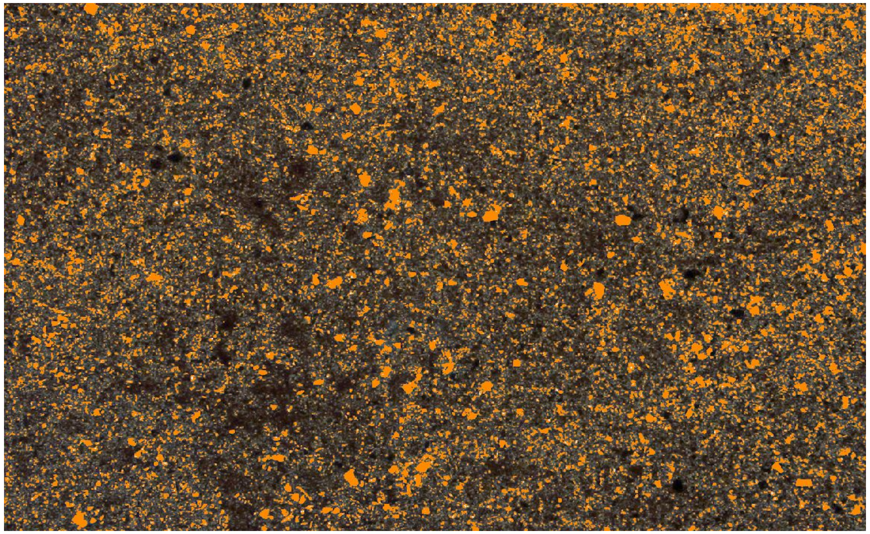

S C H O O

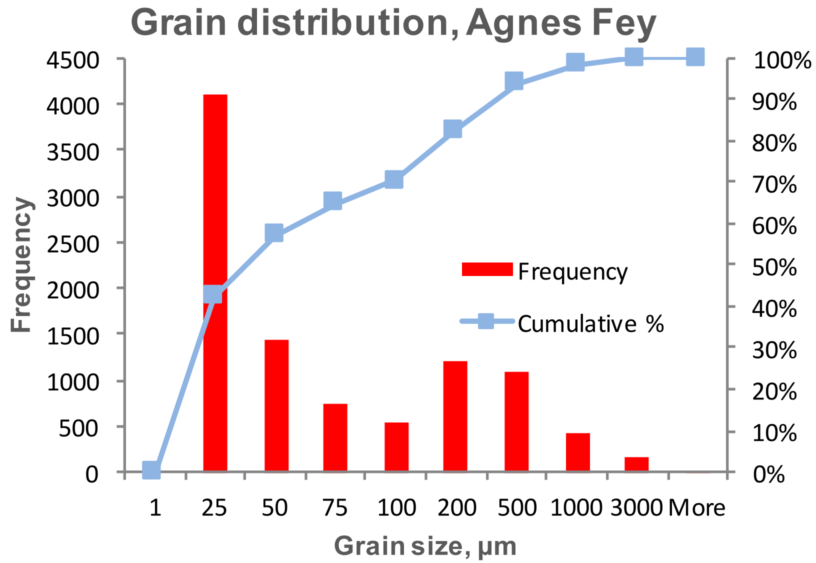
# Petrographic correlations

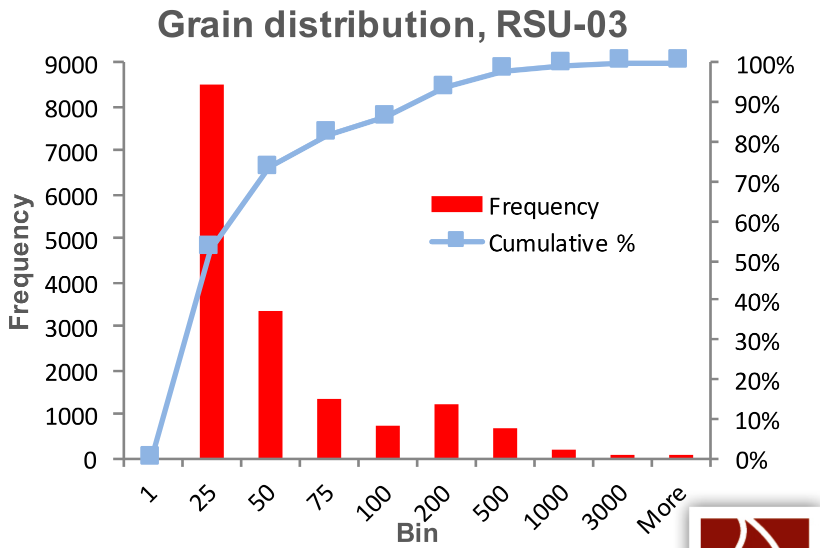
Regional core

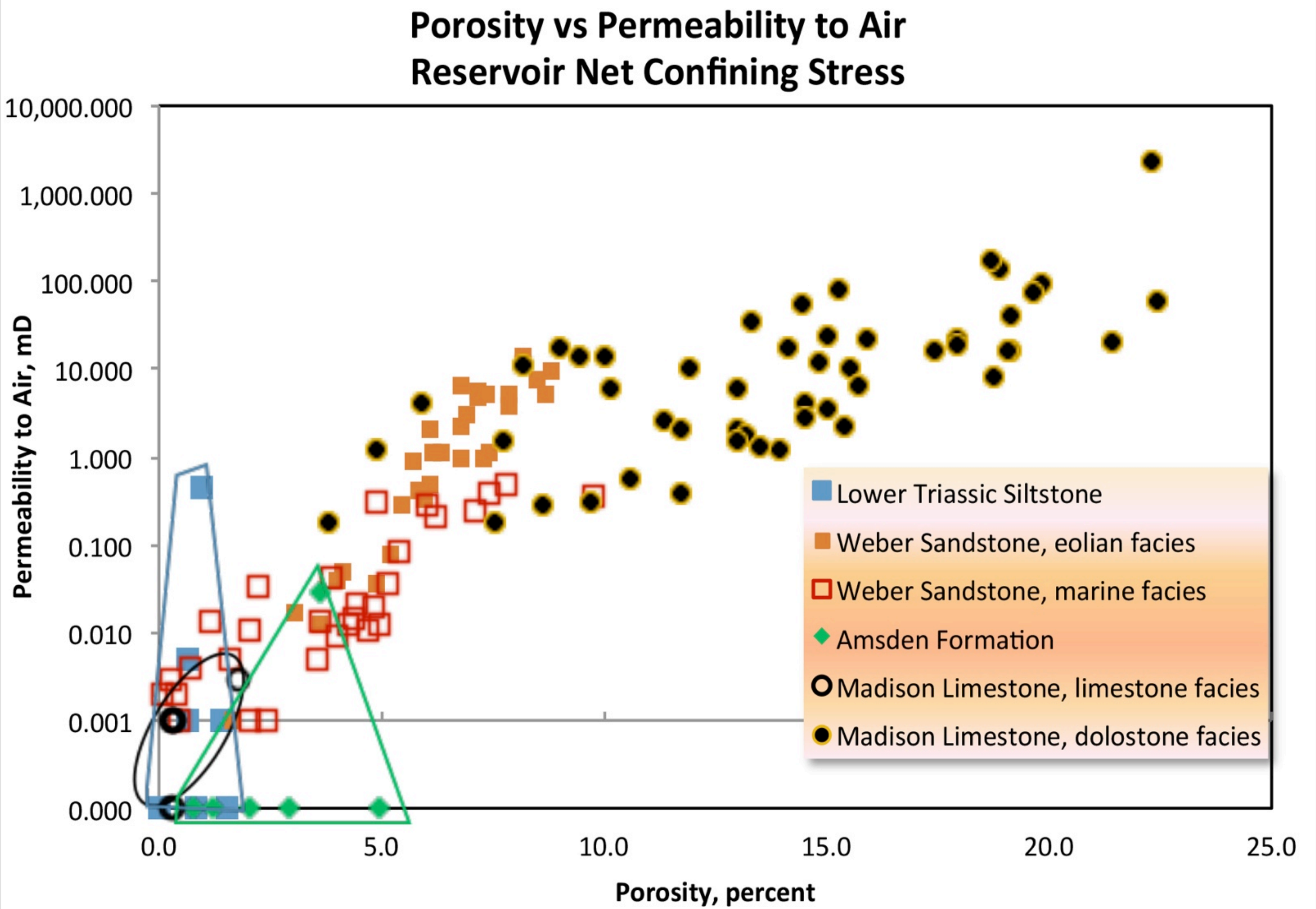


Study site

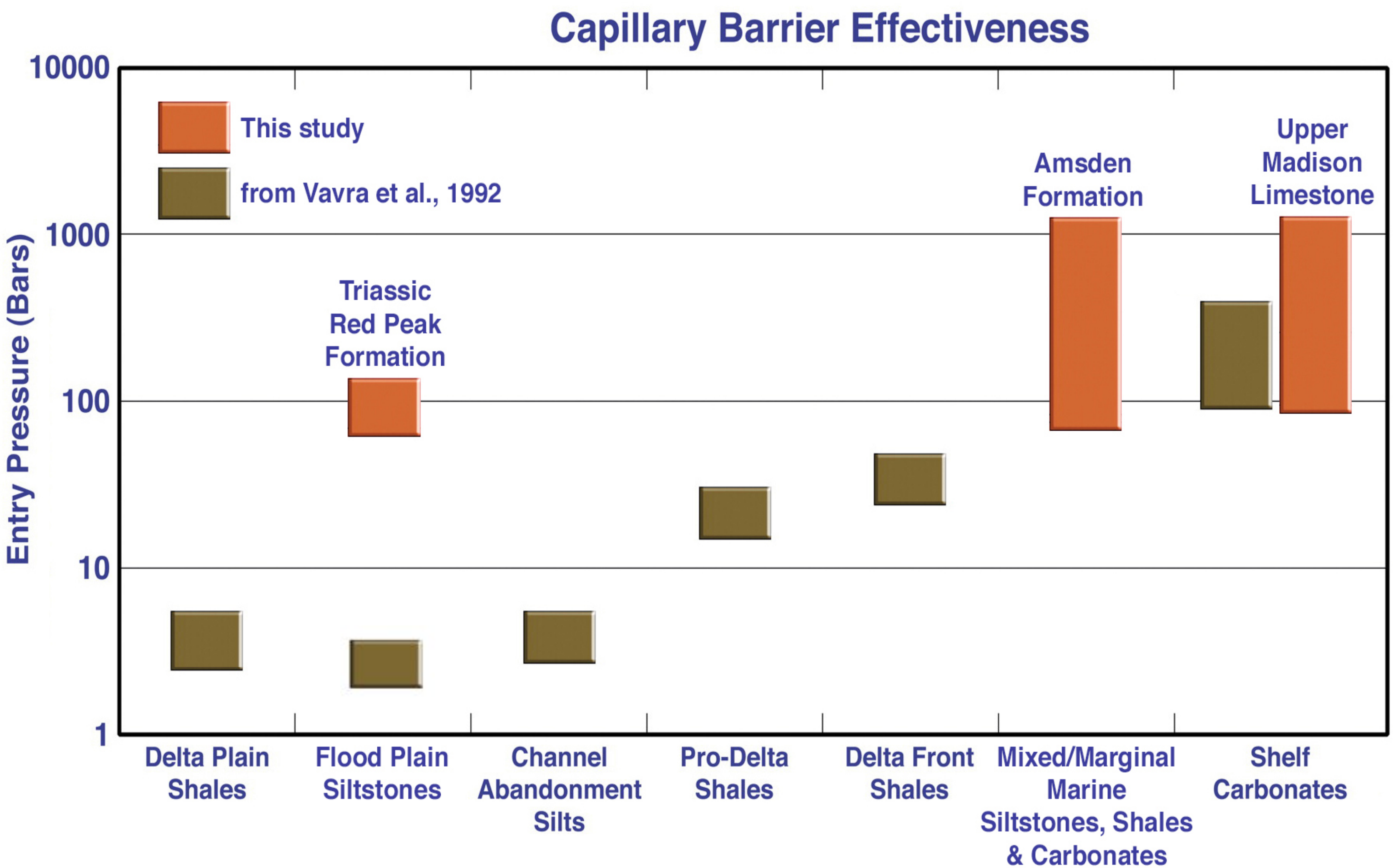




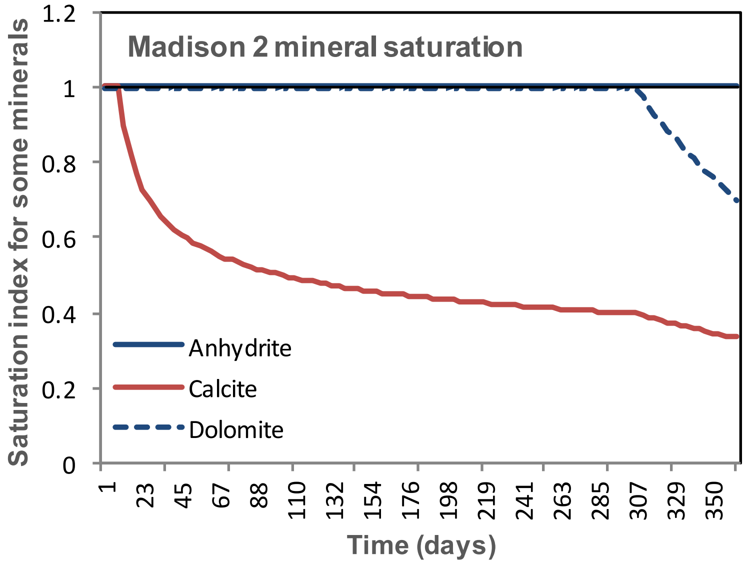



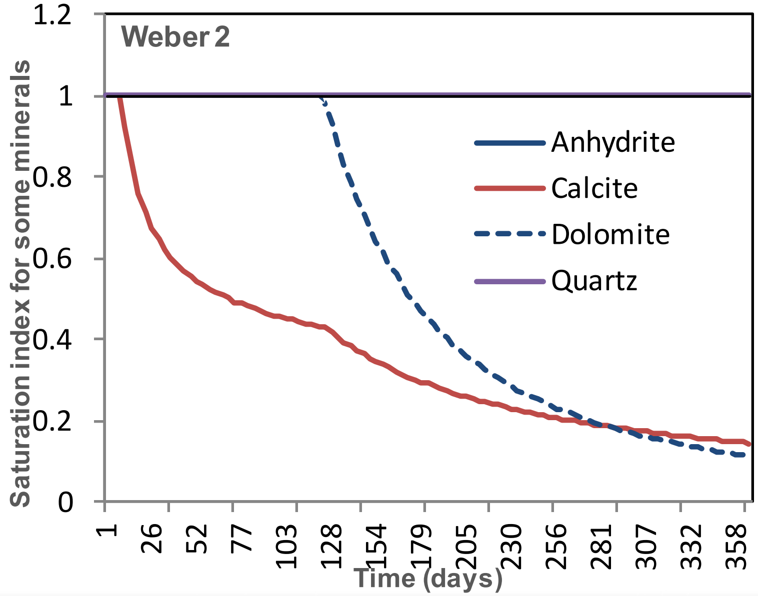

Porosity vs Permeability to Air
Reservoir Net Confining Stress
Permeability to Air, mD
10,000.000
1,000.000
100.000
10.000
1.000
0.100
0.010
0.001
0.000
0.0
5.0
10.0
15.0
20.0
25.0
Porosity, percent
Lower Triassic Siltstone
Weber Sandstone, eolian facies
Weber Sandstone, marine facies
Amsden Formation
Madison Limestone, limestone facies
Madison Limestone, dolostone facies

# Depositional and diagenetic history has increased sealing potential



# $CO_2$ injection models

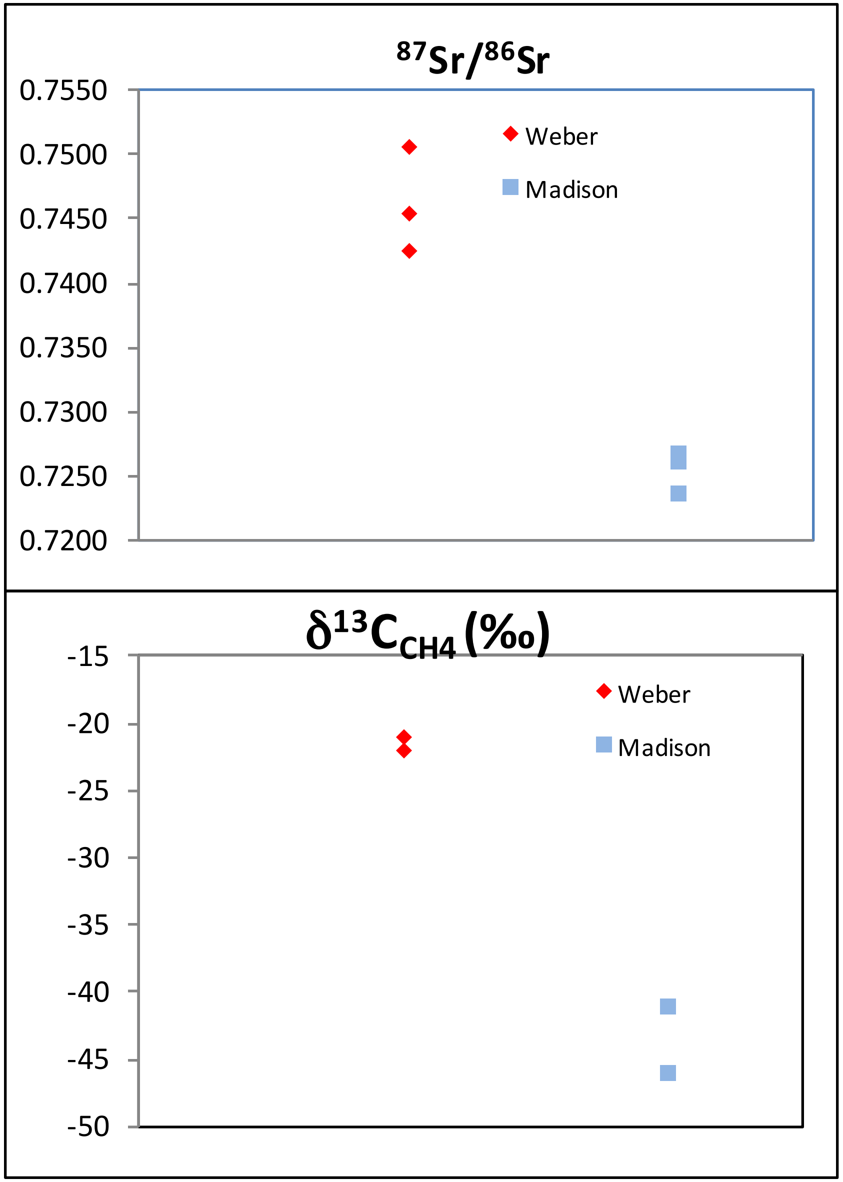



Mineral saturation indices for reactive minerals: calcite, dolomite and anhydrite

- Calcite dissolves in both reservoirs
- Continued injection leads to dolomite dissolution
- Anhydrite precipitates in both reservoirs as a response to excess calcium from calcite dissolution

Overall, predicted porosity increase, though scaling response in produced fluids




# Evaluation of fluid confinement

Reservoir fluids are isotopically distinguishable

- Weber Sandstone has radiogenic $^{87}Sr/^{67}Sr$ values (0.7505 to 0.7424) indicative of interaction with older detrital grains
- The $d^{13}C_{CH4}$ of the Weber Sandstone are relatively light (-22.0 and -21.0 ‰) relative to Madison samples (-46.0 and -41.0‰)
- Both isotopic compositions are indicative of thermogenic methane.

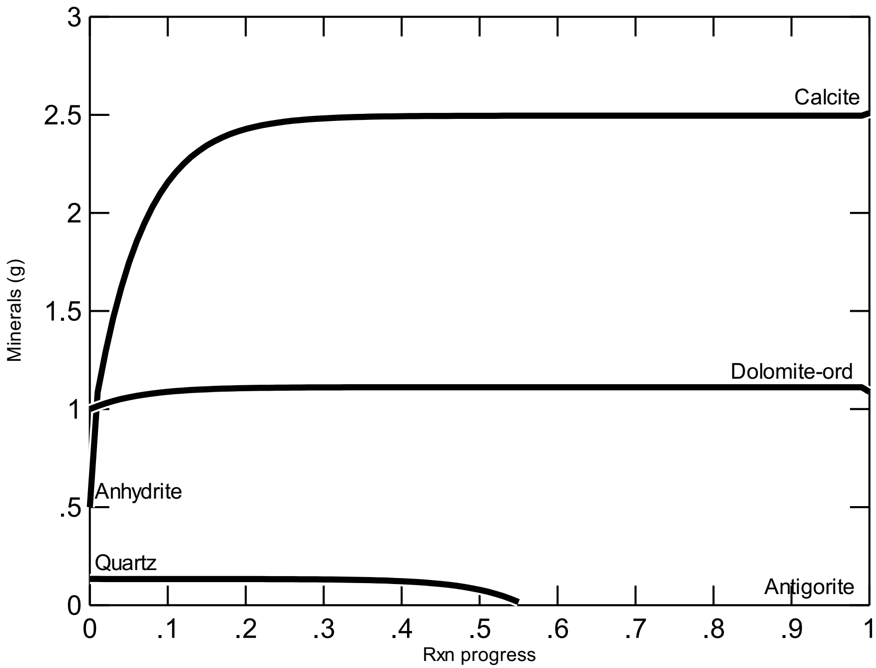
## Evaluation of seal failure

Two main mechanical failures are recognized to occur during $CO_2$ injection, tensile fracturing and shear slip of pre-existing fracturing (Rohmer and Seyedi, 2010). Geochemical conceptual models have been developed to represent these failures scenarios.

In the result of seal failure it is estimated that:

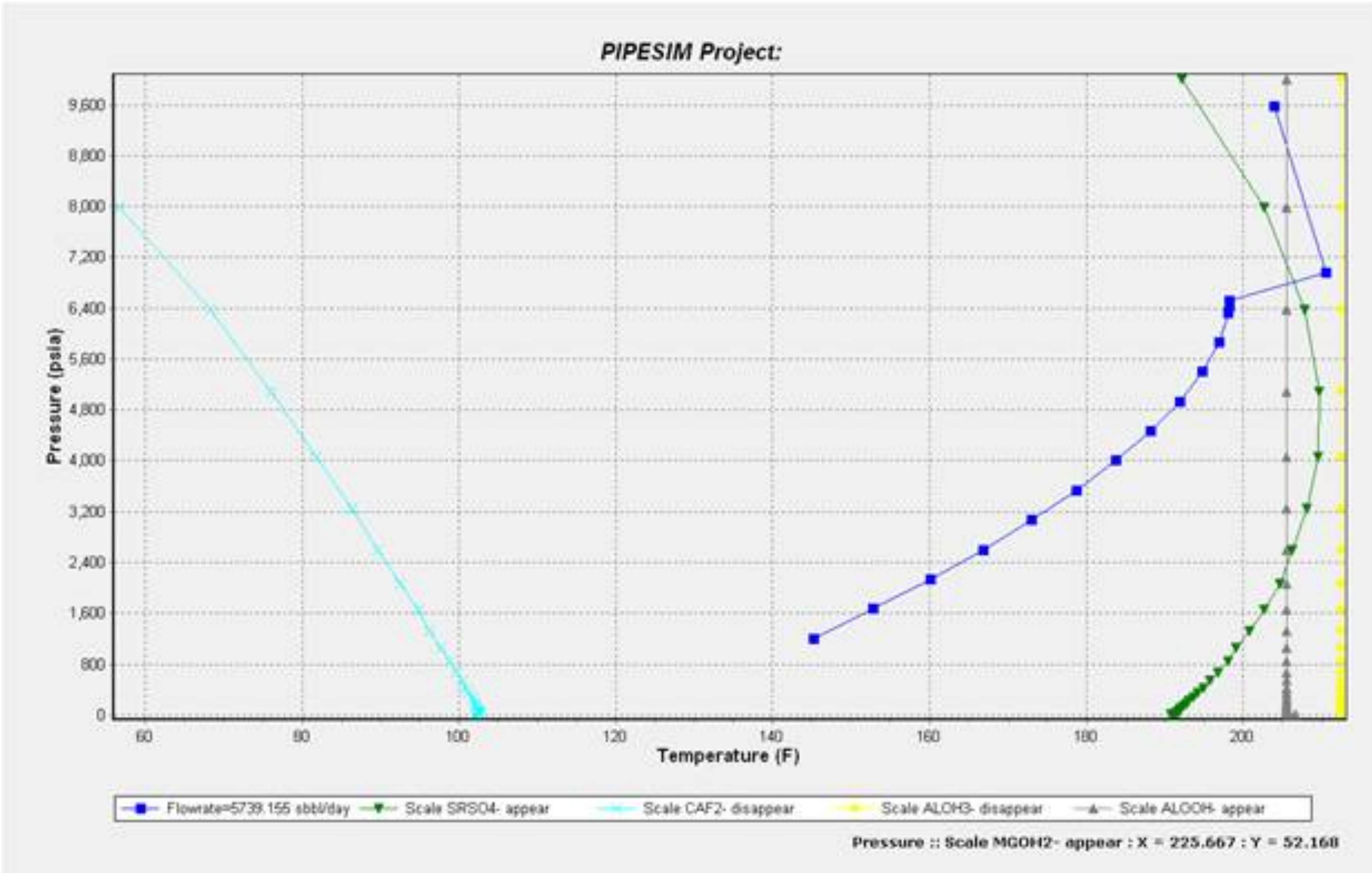
- pH increases from 4.5 to >7
- Calcite, and some dolomite will precipitate
- Calcite precipitation may increase the original calcite volume in the fracture by 200%, suggesting that fractures would fill relatively quickly

These estimations are consistent with observations made on the RSU core; calcite filled fractures in the core suggest high $pCO_2$ fluids have moved through the system and calcite has dropped out.



# Optimized water production engineering

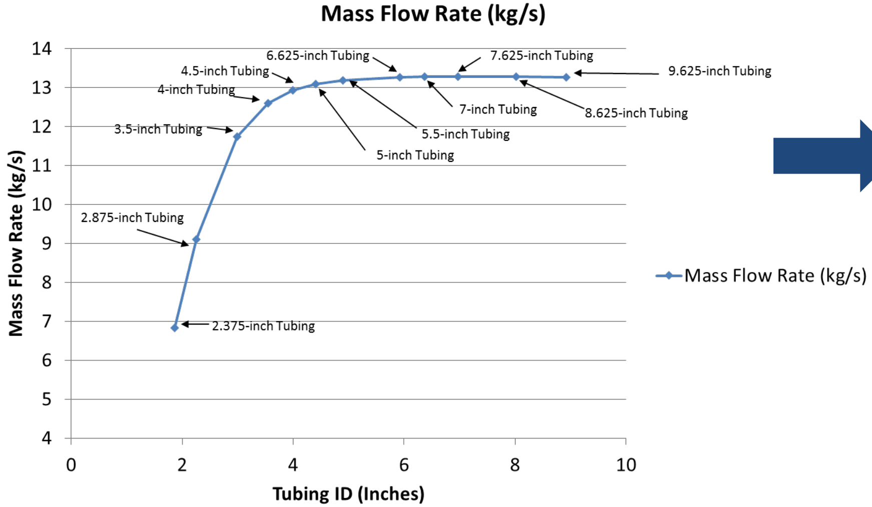
Potential for scaling at all depths



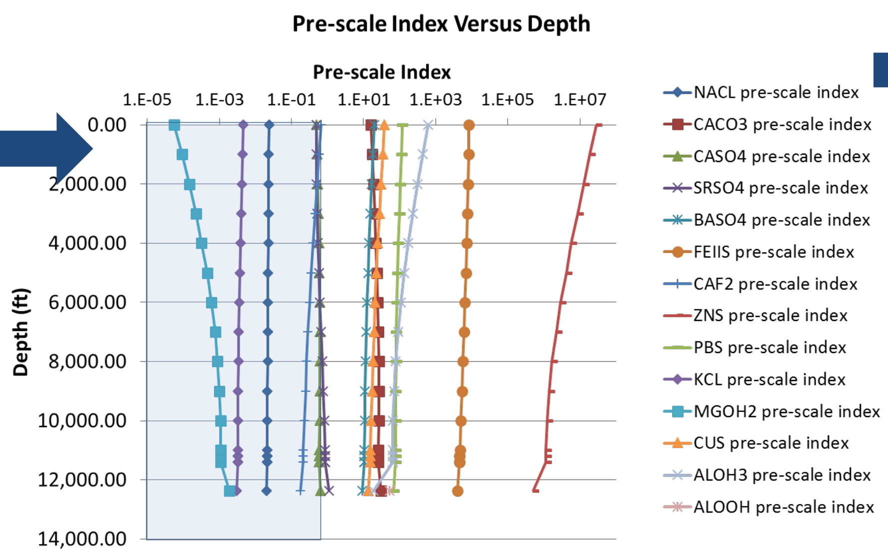
# Well sizing, scale modeling and corrosion analysis

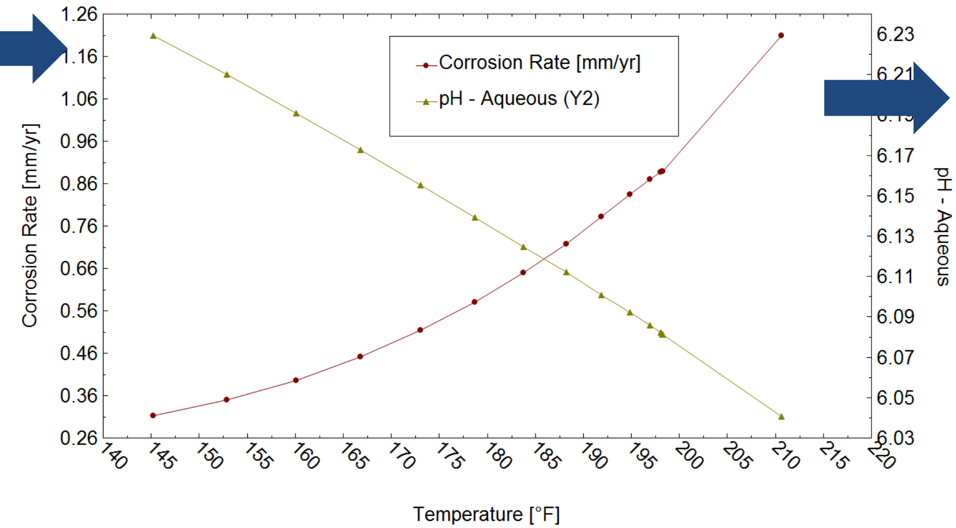
## Well Inputs

- Wellhead data
- Bottom-hole data
- Mass production rate

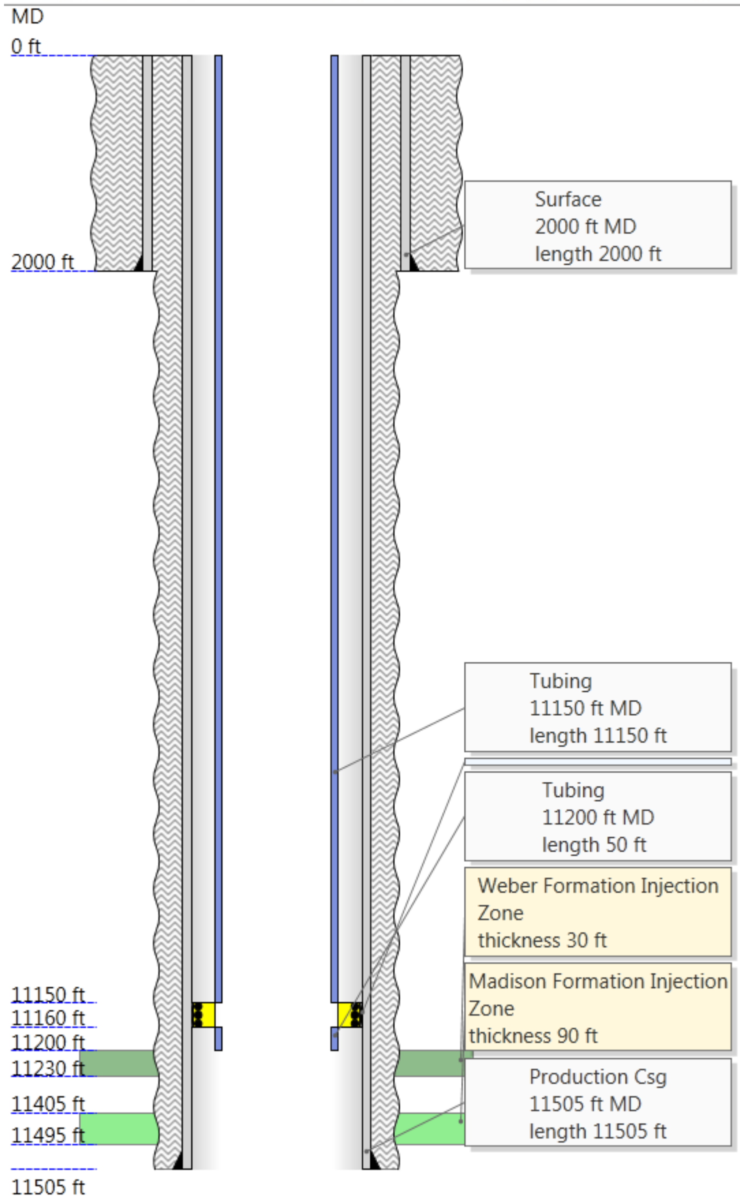



| Cations | mg/L |
|---|---|
| Na+1 | 31083.67 |
| K+1 | 3762.32 |
| Ca+2 | 1279.11 |
| Mg+2 | 193.61 |
| Sr+2 | 50.75 |
| Ba+2 | 0.11 |
| Fe+2 | 0.03 |
| Pb+2 | 0.00 |
| Cu+2 | 0.01 |
| Al+3 | 0.02 |
| **Anions and Neutrals** | **mg/L** |
| Cl-1 | 51992.08 |
| SO4-2 | 1854.35 |
| HCO3-1 | 2595.76 |
| F-1 | 2.20 |
| NH3 | 38.94 |
| HS-1 | 63.77 |



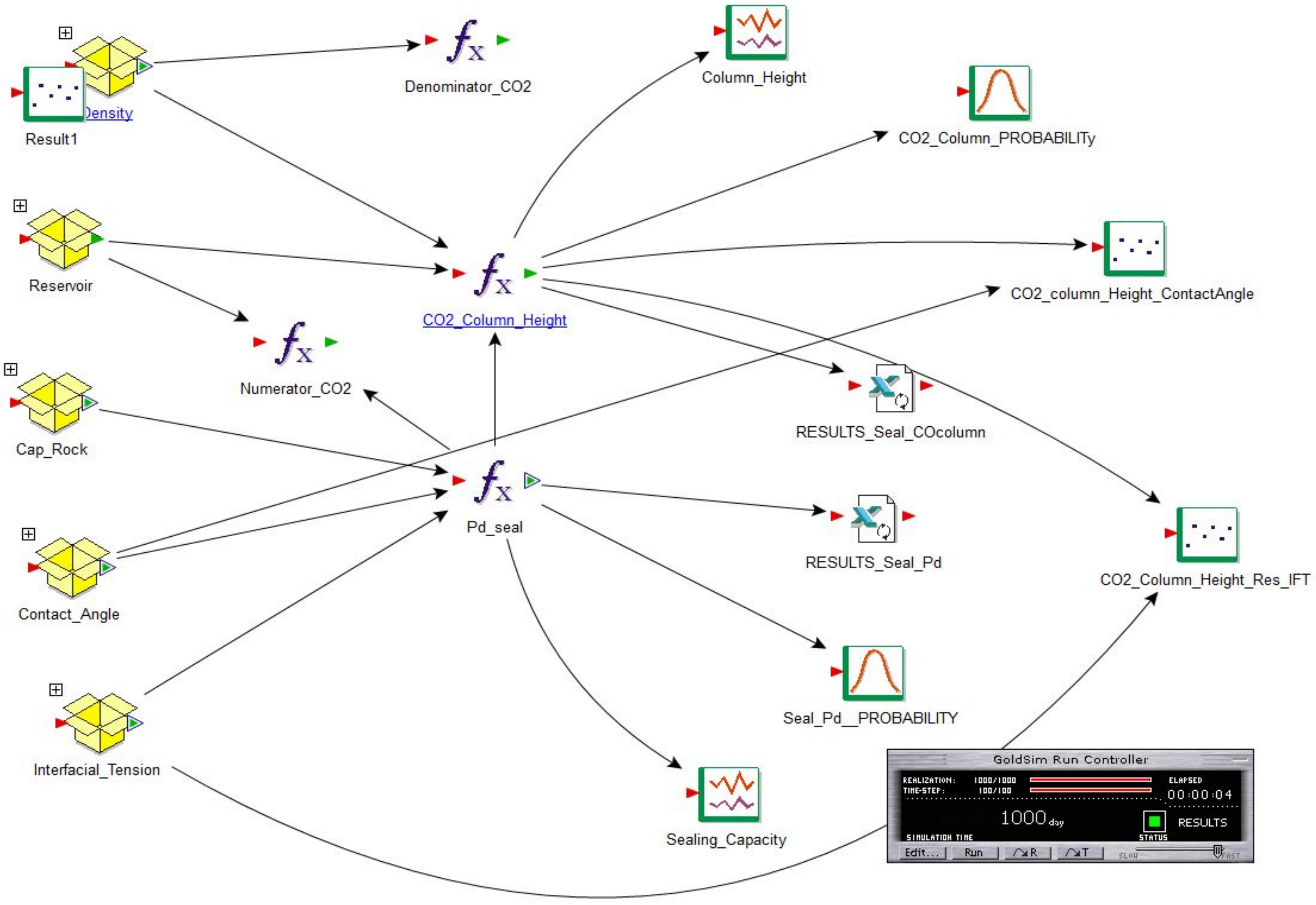



# Design: scale and corrosion

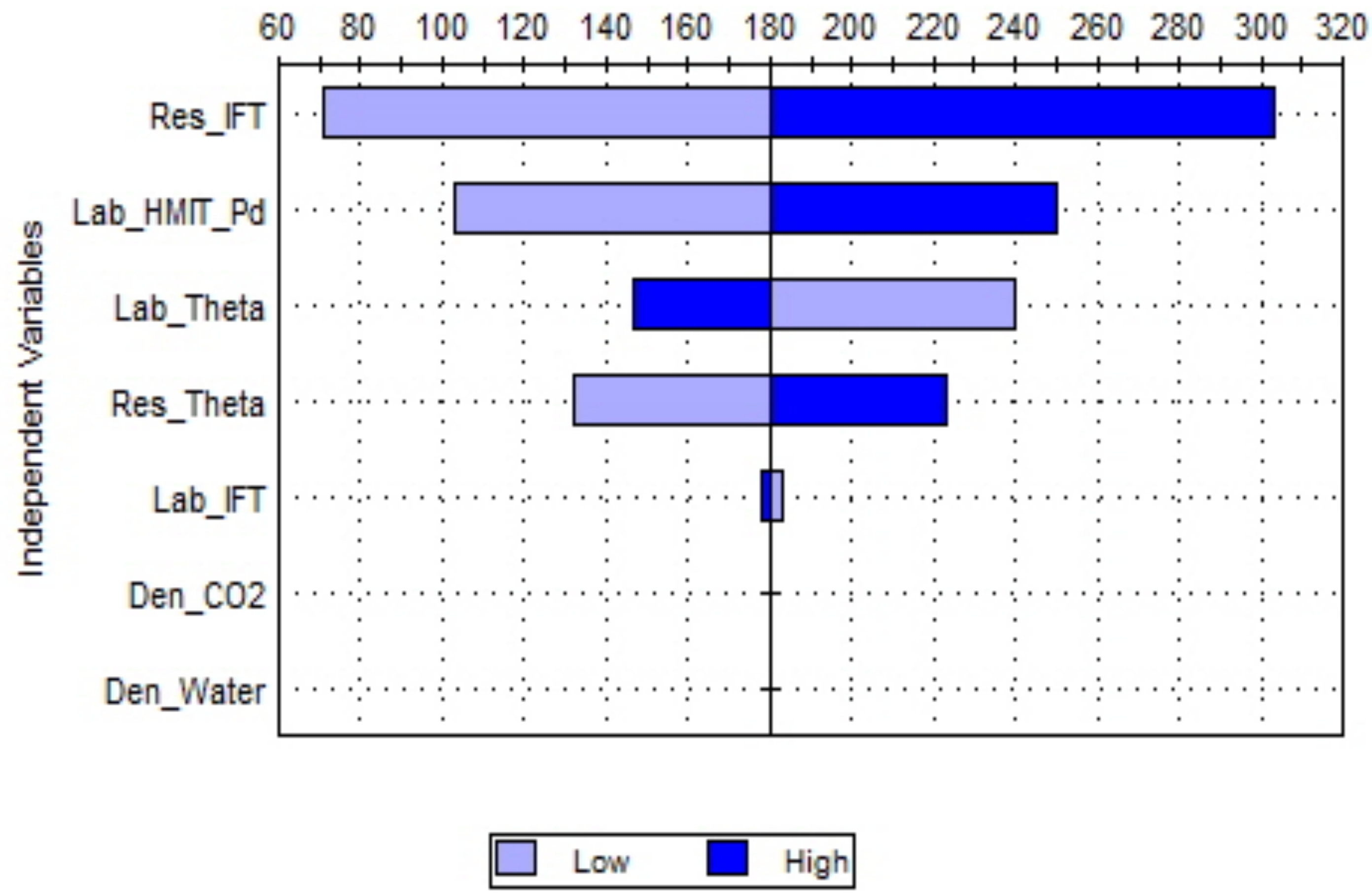



| String | Size | Top (ft) | Bottom (ft) |
|---|---|---|---|
| Surface | 10.75 in | 0 | 2,000 |
| Production Casing | 7.625 in | 0 | 11,505 |
| Production Tubing | 5 in 15lb/ft | 0 | 11,200 |

# Sensitivity analysis

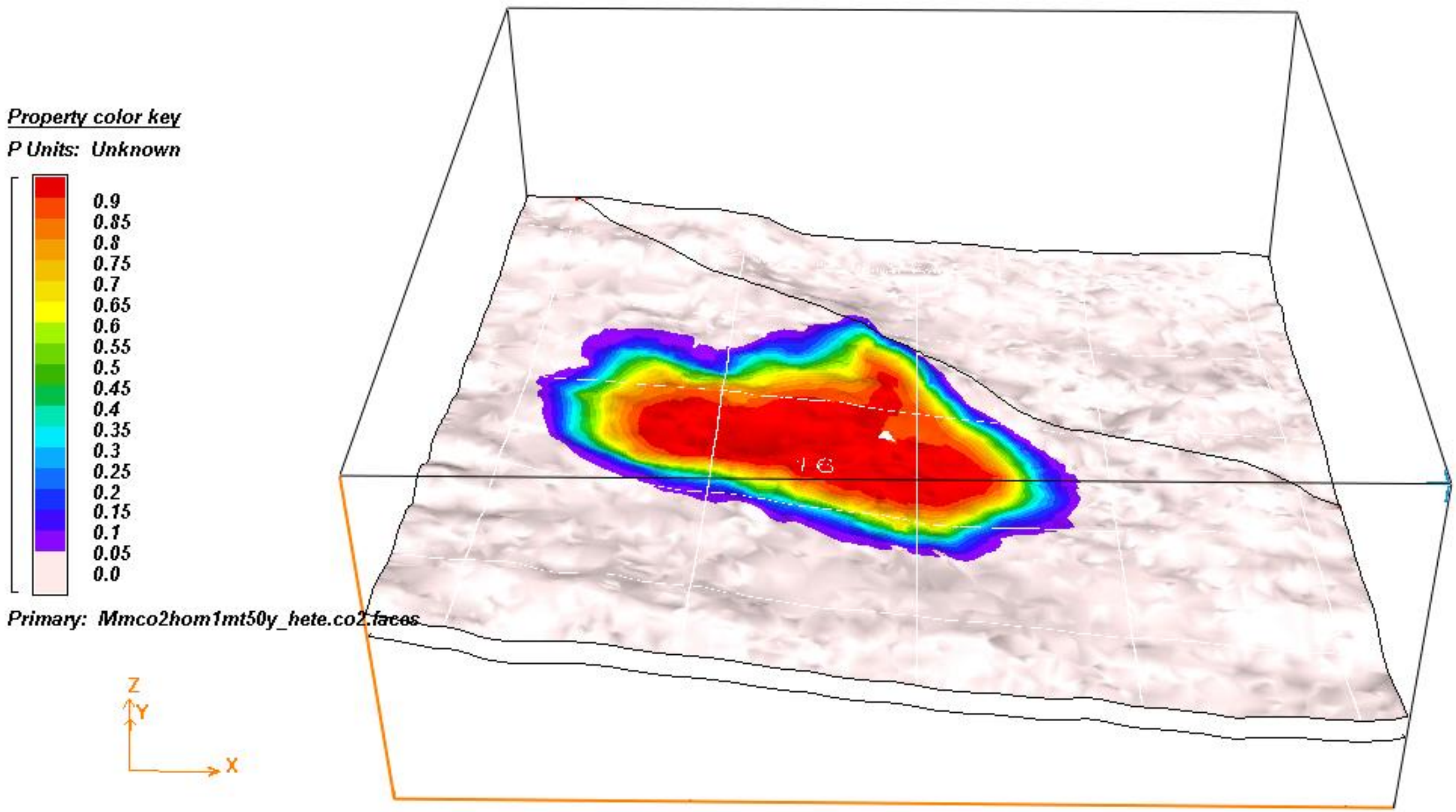


# Sensitivity analysis



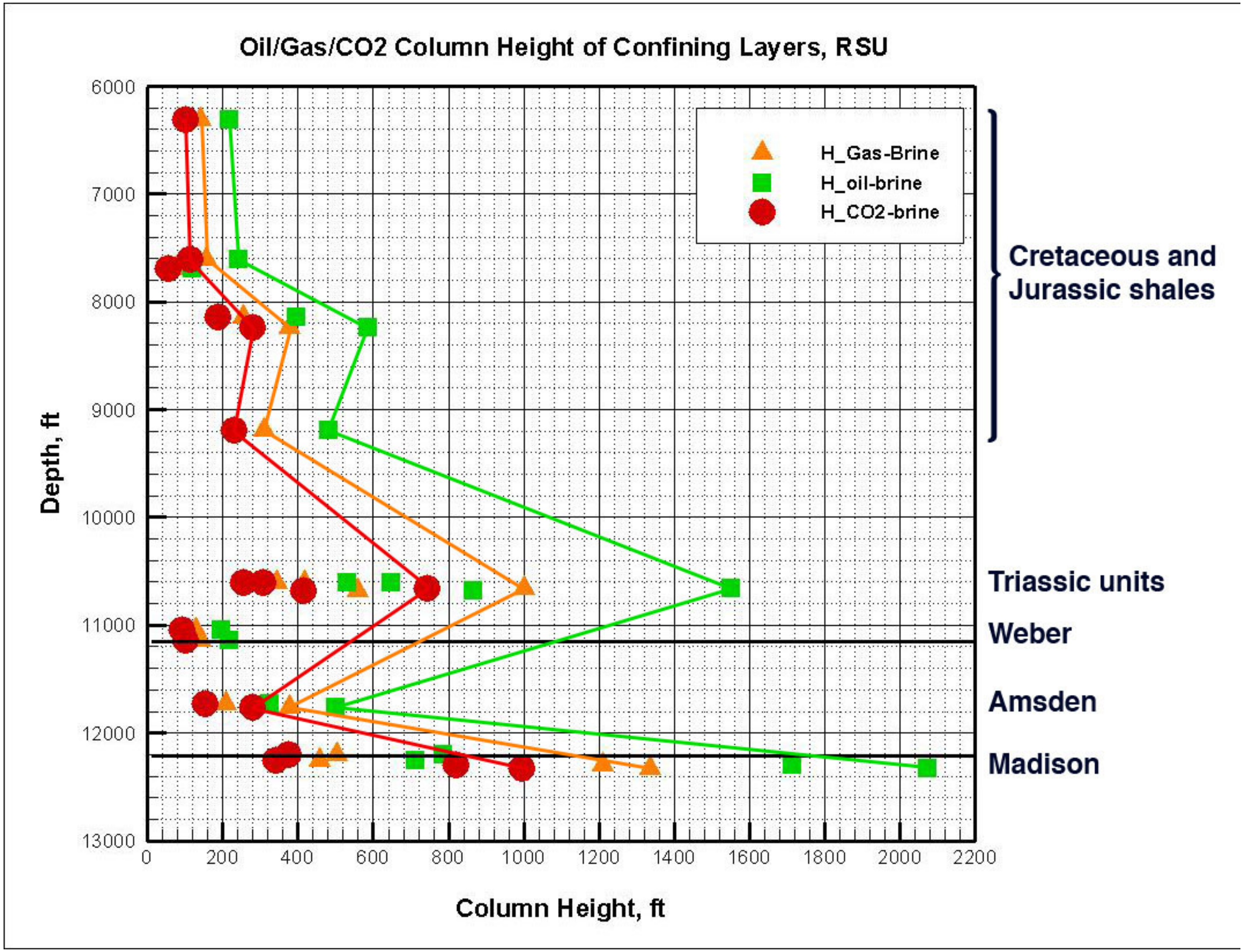

IFT of seals in a multi-phase fluid regime introduces the most uncertainty relative to containment

# Updated dynamic plume model



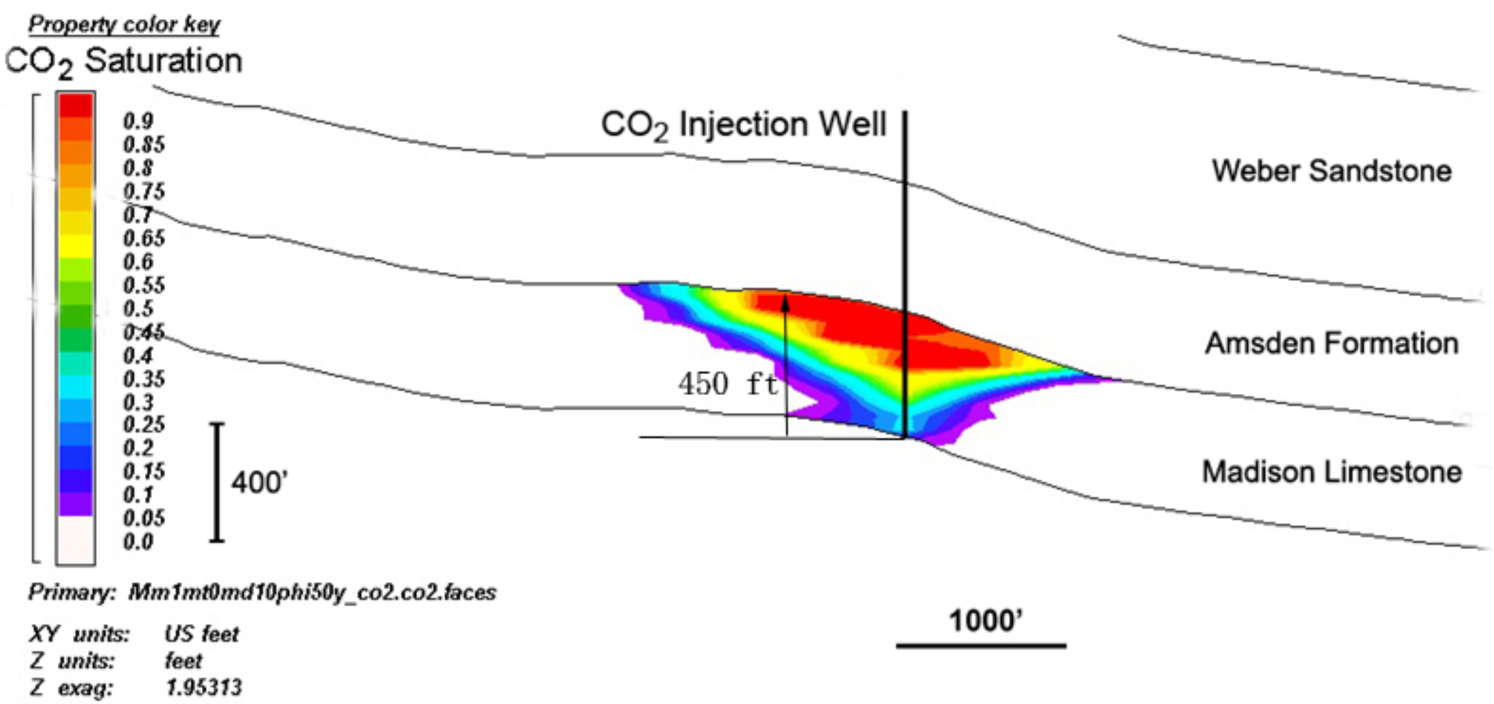

Irregular shape of the $CO_2$ plume because of the reservoir heterogeneity/local structure. Quaternary fault interferes with the plume.

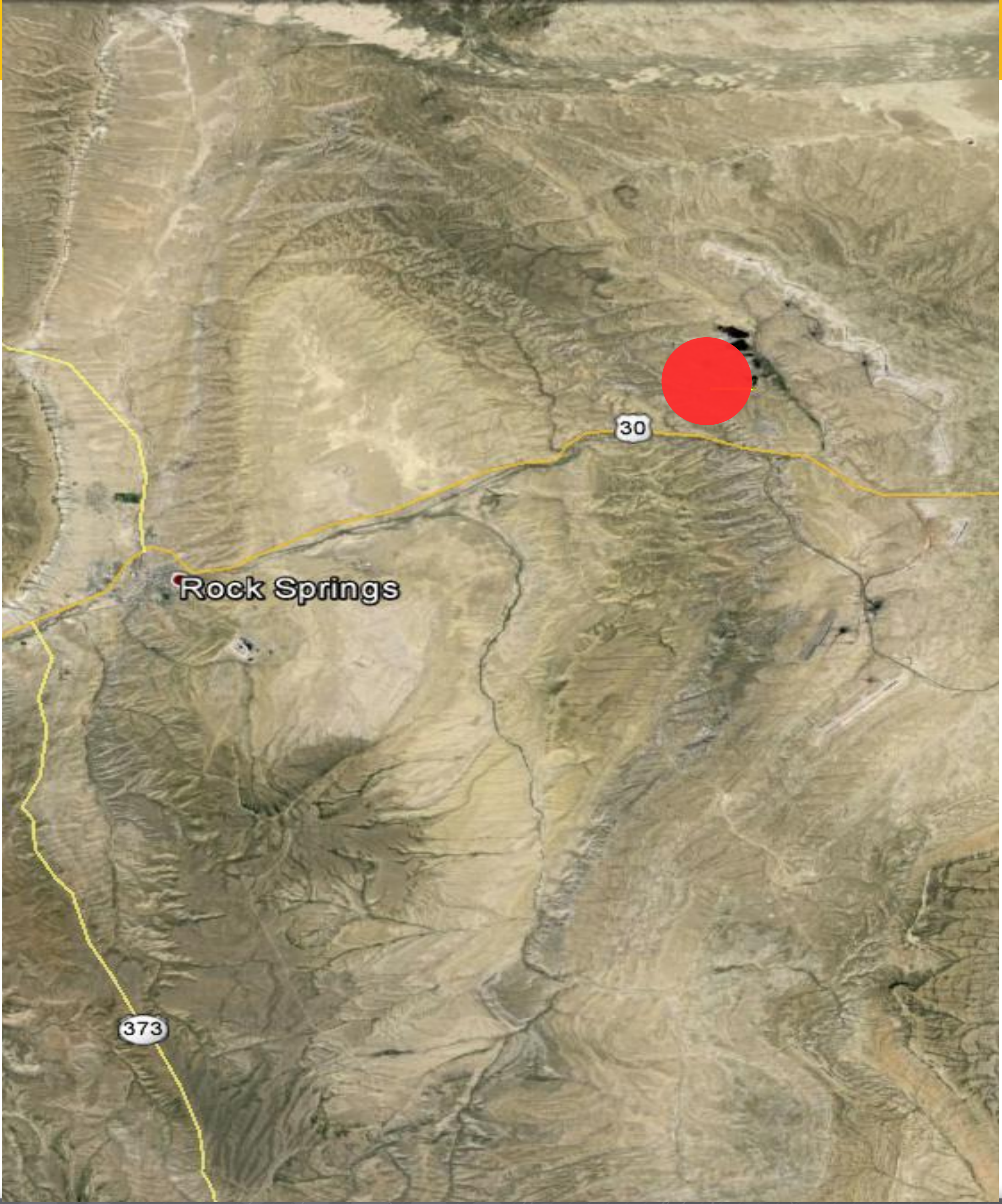
# Column height calculations; reassessing the $CO_2$-$H_2O$-Brine system



## Verification of the integrity of the confining layers - injected $CO_2$ is trapped below the upper most portion of the Madison Limestone and the Amsden Formation.

FEHM Simulation Results for the Madison Limestone, RSU
Homogeneous Porosity/Permeability Rock/Fluid Volume
Porosity 10%, Permeability 10 md, 50 Mt/50 years






## New $CO_2$ plume estimates

1.6 mile plume radius at the study site before plume risks approaching column height max (450'). Identified as red circle.

An estimated total of 25MT of $CO_2$ could be conservatively stored at the study site.

Additional storage on the RSU could be implemented, with careful consideration of overlap to decrease the risk of seal failure.

# Accomplishments to Date

- Identification of analysis crucial to determining seal assessments relative to $CO_2$ injection capacities; identified the seal variables with the highest uncertainties and primary and secondary seals
- Development of new, conservative $CO_2$ column height estimates for dipping Paleozoic strata in southwest Wyoming; relevant to all structural traps
- Development of methodologies for utilizing limited subsurface data and stacked reservoirs for reducing regional sealing uncertainties
- Development of well design scenarios that minimizes scaling risks at the site
- Refined storage estimates of Wyoming's Paleozoic reservoirs relative to new findings

# Research gaps

- Realistic column height calculations: lack of IFT data on sealing lithologies
- Lack of comprehensive, pressurized-deep brine geochemical/isotopic lab
- Unified pressure mitigation techniques for pressure control

# Conclusions

- The study site in southwest Wyoming can retain injection volumes with 99% certainty relative to sealing strata data
  - Multiple primary and sealing strata with minimal permeability and characterized lithologies (i.e. diagenetic effects, mechanical properties, etc.)
  - Non-communicable reservoir fluid systems (isotopes, geochemistry, fluid migration histories, in-situ pressure tests)
  - Geologically old seal bypass systems up-dip, less risk
- Refined injection and storage model estimates for the study site relative to the lowest possible uncertainties and risk suggest a holding capacity of 25MT
- Development of integrated production/injection strategies has optimized storage capabilities at the study site
- Highest risk introduced during injection phase: robust reservoir pressure management plan significantly reduces the risk of seal failure

# Summary

## Ensuring storage permanence; transferrable conclusions for reducing the uncertainties of sealing systems

- Stacked reservoir systems ideal for sites with limited data
- Characterization of geologic heterogeneity, geochemistry, and paragenetic history is necessary for lateral seal evaluations
- Seismic derivation of seal bypass systems coupled with geologic interpretation will identify primary structural risks
- Reservoir fluid analysis will identify interconnectivity of stacked reservoirs
- Accurate IFT analysis is critical for true holding capacity estimates
- Storage in dipping strata will impact column height estimates
- Geologic heterogeneity assessments are critical for accurate storage estimates and injected fluid responses
- Highest/uncertainty risk introduced during injection phase
  - A robust reservoir pressure management plan will greatly reduce the risk of leakage

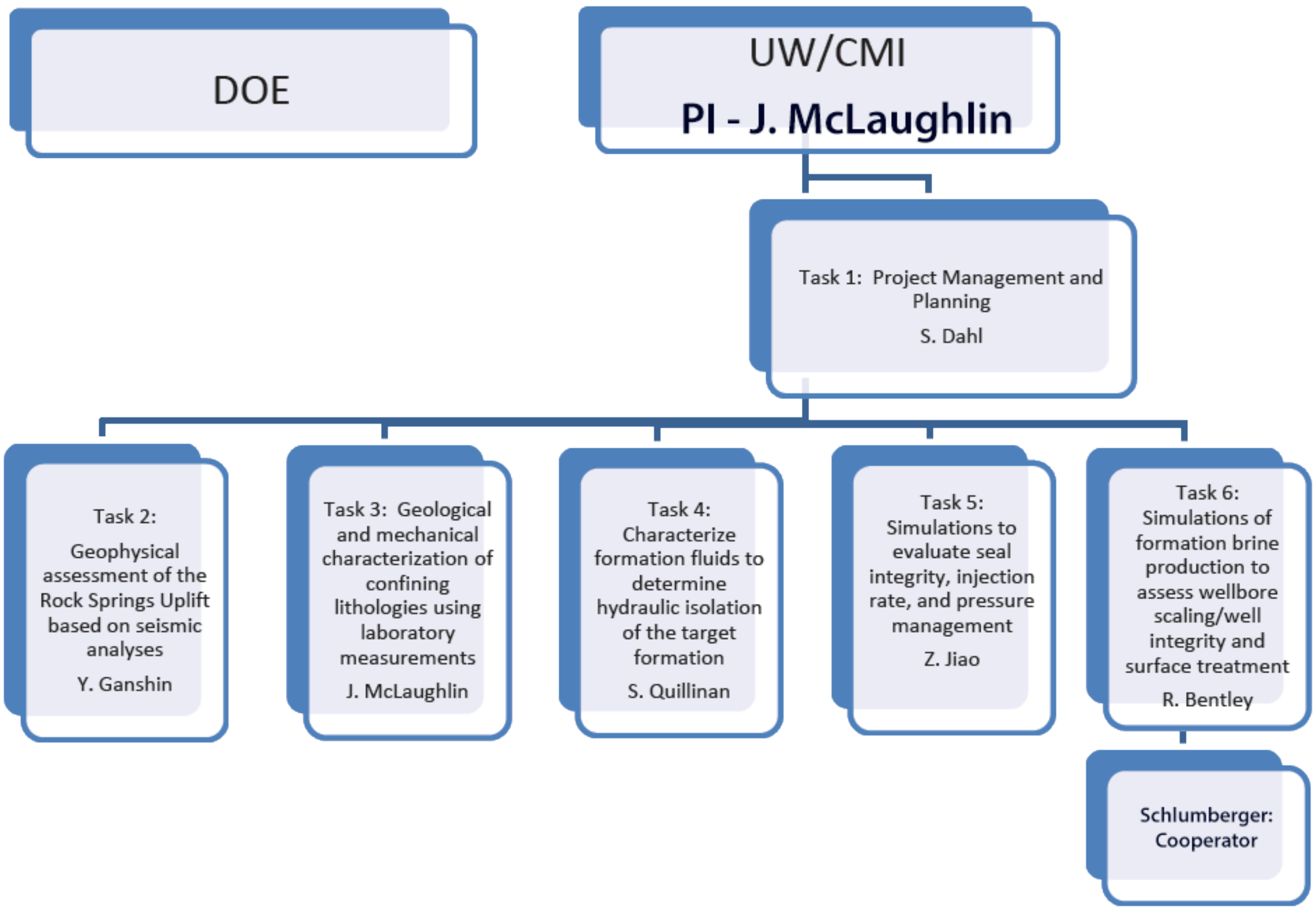
# Acknowledgements

This project is funded in part by the U.S. Department of Energy's National Energy Technology Laboratory (Project DE-FE0009202), and the authors would like to thank Project Manager Karen Kluger for her guidance and support.

# Appendix

– Organization chart
– Gantt chart
– Bibliography

# Organization Chart



Task Collaboration | BP1 (2012: O N D; 2013: J F M A M J J A S) | BP2 (O N D; 2014: J F M A M J J A S) | BP3 (O N D; 2015: J f M A M J J A S)

| | Gantt Chart | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| 1 | Project Management & Planning - $360,718 | | | | | | |
| 1.1 | Project Management Plan | | | | | | |
| * | Revised project management plan - COMPLETED | | | | | | |
| 1.2 | Collaboration Meetings | | | | | | |
| * | Kick Off Meeting - COMPLETED | | | | | | |
| * | Yearly Meeting - COMPLETED EARLY | | | | | | |
| * | Yearly Meeting | | | | | | |
| * | Yearly Meeting | | | | | | |
| 1.3 | Reporting | | | | | | |
| * | Final report | | | | | | |
| 1.4 | Project Management | | | | | | |
| 2 | Geophysical assessment of the Rock Springs Uplift based on seismic attributes - $88,943 | | | | | | |
| 2.1 | Determine target formation tops - COMPLETED | | x | | x | | x |
| 2.2 | Track the identified seismic horizons - COMPLETED | | x | | x | | x |
| 2.3 | Prepare volumetric seismic attributes for 3-D survey - BEGAN EARLY - COMPLETED | | x | | x | | x |
| * | Complete volumetric seismic attributes for Jim Bridger 3-D survey - COMPLETED | | | | | | x |
| 2.4 | Investigate and identify seismic attributes for seal characterization - COMPLETED | | x | | x | | x |
| 2.5 | Prepare horizon maps | | x | | x | | x |
| * | Complete horizon maps showing seismic attribute variations along confining layers and quick look report | | | | | | x |
| 3 | Geological and mechanical characterization of confining lithologies using laboratory measurements - $157,074 | | | | | | |
| 3.1 | Perform shear strength tests - COMPLETED | | | | | | x |
| 3.2 | Perform capillary pressure tests for displacement pressure and sealing capacity) - COMPLETED | | | | | | x |
| * | Complete geochemical, mineralogical and isotopic laboratory tests and quick look report - COMPLETED | | | | | | x |
| 3.3 | Measure porosity and permeability - BEGAN EARLY | | | | | | x |
| 3.4 | Analyze and define petrographic geochemical and mineralogical properties - COMPLETED | | | | | | x |
| 3.5 | Locate and evaluate other available core samples - COMPLETED | | | | | | x |
| * | Locate and analyze additional core data available for target area | | | | | | x |
| 3.6 | Perform petrophysical analysis of well logs - BEGAN EARLY | x | | x | x | x | x |
| * | Integrate rock property data into tasks 2, 4, 5, 6 - BEGAN EARLY | | x | x | x | x | x |
| * | Complete report detailing character and rock properties of targeted confining lithologies | | | | | | x |
| 3.7 | Prioritize rock evaluation criteria for Best Practices Manual | | | | | | x |
| 4 | Characterize formation fluids to determine hydraulic isolation of target formation - $116,392 | | | | | | |
| 4.1 | Perform isotopic analysis - COMPLETED | | | | | | x |
| 4.2 | Perform geochemical analysis - COMPLETED | | | | | | x |
| * | Complete interpretation of formation fluid laboratory results and quick look report - COMPLETED | | | | | | x |
| 4.3 | Define the hydraulic isolation of the target reservoir | | | x | | | x |
| 4.4 | Perform reaction path modeling - COMPLETED | x | x | | x | x | x |
| * | Creation of reaction path model - COMPLETED | | | | | | x |
| * | Describe water quality parameters needed for water-treatment facilities of the produced water - COMPLETED | | | | | | x |
| 4.5 | Evaluate geochemical reactions associated with seal failure | | x | | x | x | x |
| * | Evaulation of water/rock interactions for various seal failure scenarios | | | | | | x |
| * | Isotopic analyses of the formation fluid and quick look report | | | | | | |
| 4.6 | Evaluate techniques for use in Best Practices Manual | x | x | | x | x | x |
| 5 | Simulations to evaluate seal integrity, injection rate, and pressure management - $139,970 | | | | | | |
| 5.1 | Detailed 3-D geological property models for targeted reservoir and confining formations | x | x | x | x | x | x |
| * | Complete construction of detailed 3-D geological property models and quick look report - COMPLETED | | | | | | x |
| 5.2 | Performance assessments of diverse injection scenarios | x | x | x | x | x | x |
| * | Create performance assessments of diverse injection scenarios | | | | | | x |
| 5.3 | Evaluate the importance and effects of numerical simulation parameters - BEGAN EARLY | x | x | x | x | x | x |
| * | Prioritize importance and effects of parameters for numerical simulation | | | | | | x |
| 5.4 | Best Practices Manual for numerical simulations of CO2 storage | x | x | x | x | x | x |
| 6 | Simulations of formation brine production to assess wellbore scaling/well integrity and surface treatment - $142,872 | | | | | | |
| 6.1 | Simulate and evaluate wellbore scaling issues | | x | x | x | | x |
| 6.2 | Evalute the effects of brine chemistry on well construction and casing integrity | | x | x | x | | x |
| * | Complete geochemical model of formation fluids under various constraints | | | | | | x |
| 6.3 | Evaluate the effects of brine chemistry on machinery associated with produced water treatment | | x | x | x | | x |
| * | Define and design best possible wellbore and water treatment facility and quick look report | | | | | | x |
| 6.4 | Integrate and prioritize modeling results and design data from subtasks 6.1 - 6.3 into the Best Practices Manual | | x | x | x | | x |
| 7 | Rock Springs Uplift integrated geological and geophysical CO2 storage assessment | | | | | | |
| * | List of formations for evaluation - COMPLETED | | | | | | |
| * | Complete comprehensive strategy for the storage of CO2 in Wyoming's Paleozoic Stratigraphic Section | x | x | x | x | x | x |

* Denotes milestone
Red bar denotes completed tasks/subtasks
Yellow bar denotes continuing progress through December 31, 2013
Green bar denotes tasks/subtasks began earlier than scheduled and continuing progress of those tasks.

# Bibliography


**<u>21st Annual Geological Society of America – Denver, CO – October 2013</u>**

Abstracts presented:

- *An Integrative Strategy to Increase the Economic Feasibility of CO2 sequestration: Mining Brines from Saline Storage Reservoirs*
- *Geochemical evolution of deep saline brines from Paleozoic reservoirs in southwest Wyoming; implications for potential CO2 sequestration*

**<u>Thirteenth Annual Carbon Capture, Utilization and Storage Conference – Pittsburgh, PA – April 2014</u>**

Abstracts presented:

- *Geologic Controls on Sealing Capacity; Defining Heterogeneity Relative to Long-Term $CO_2$ Storage Potential in Wyoming*
- *The Geochemical Characterization of Reservoir Fluids: Defining the Fluid and Rock System and Identifying Changes to Baseline Conditions Due to Well Completion*
- *Geologic and Stratigraphic Characteristics of Multiple Stacked Sealing Formations at the Rock Springs Uplift, Wyoming*