Integrated characterization of CO_2 storage reservoirs on the Rock Springs Uplift: combining geomechanics, geochemistry, and flow modeling

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DE-FOA0001037 Kickoff Meeting

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Presentation Outline

- Benefits and overview
- Methodology
- Outcomes
- Organization and communication
- Tasks
- Deliverables
- Risks
- Schedule

Benefit to the Program

- **Program goals addressed**
  - Develop and validate technologies to ensure 99% storage permanence
  - Develop Best Practice Manuals (BPMs) for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation.

Project Benefits Statement

The project will conduct research under Area of Interest 1, Geomechanical Research, *by developing a new protocol and workflow to predict the post-injection evolution of porosity, permeability and rock mechanics, relevant to estimate rock failure events, uplift and subsidence, and saturation distributions, and how these changes might affect geomechanical parameters, and consequently reservoir responses*. The ability to predict geomechanical behavior in response to CO_2 injection could increase the accuracy of subsurface models that predict the integrity of the storage reservoir. The technology developed in this project contributes to two Carbon Storage Program goals: *developing and validating technologies to ensure 99 percent storage permanence; and develop Best Practice Manuals (BPMs) for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization; public outreach; well management activities; and risk analysis and simulation*.

Project Overview: Goals and Objectives

Overall Objective

Create and evaluate an integrated workflow that incorporates elements of geology, geochemistry, petrophysics, reservoir simulation, and geomechanics using current data from the Rock Springs Uplift in Wyoming and experimental results from petrophysical, geochemical, geomechanical, and multiphase flow experiments on rock and fluids characteristics of the RSU to predict quantitatively lithologic and geomechanical reservoir conditions of stress and fluids distributions.

Project Overview:
Goals and Objectives

Specific Objectives

1) Test new facies and mechanical stratigraphy classification techniques on the existing RSU dataset

2) Determine lithologic and geochemical changes resulting from interaction among CO_2, formation waters, and reservoir rocks in laboratory experiments

3) Determine the effect(s) of CO_2-water-reservoir rock interaction on rock strength properties; this will be accomplished by performing triaxial strength tests on reservoir rock reacted in Objective #2 and comparing results to preexisting triaxial data available for reservoir rocks

Project Overview:
Goals and Objectives

Specific Objectives (continued)

4) Identify changes in rock properties pre- and post-CO_2 injection

5) Identify the parameters with the greatest variation that would have the most effect on a reservoir model

6) Make connections between elastic, petro-elastic, and geomechanical properties

7) Develop ways to build a reservoir model based on post-CO_2-injection rock properties

8) Build a workflow that can be applied to other sequestration characterization sites, to allow for faster, less expensive, and more accurate site characterization and plume modeling.

Project Overview:
Goals and Objectives

Relationship to DOE program goals

Our approach can be adapted to other sites to guide site characterization and design of surveillance and monitoring techniques to meet the goal of 99% safe storage, reach ±30% model accuracy, contribute to the BPM, and reduce time and cost of site characterization.

Methodology

- We will develop and test a new set of tools and methodology for assessing current reservoir conditions and predicting geomechanical dynamics and the mechanical integrity of a reservoir after injection of CO_2.

- Our research will use the comprehensive dataset that was recently developed for the Rock Springs Uplift (RSU) in southwestern Wyoming.

Methodology

- This research will improve our understanding of the geomechanical effect of CO_2 injection on two types of reservoir rocks: sandstone and carbonate.
- This research will develop a new technique and workflow to predict post-injection evolution of rock strength, and the manner in which these changes might affect geomechanical parameters and reservoir modeling.
- This process will take place through geochemical and geomechanical laboratory experiments on core from the RSU stratigraphic test well, geomechanical analysis, statistical rock physics analysis, and reservoir modeling. The proposed work will build on the strong foundation of studies already completed for the RSU, including field work and subsurface characterization of lithology, structure, mechanical stratigraphy, fracture systems, and in-situ stress.

Rock Springs Uplift, SW Wyoming, USA

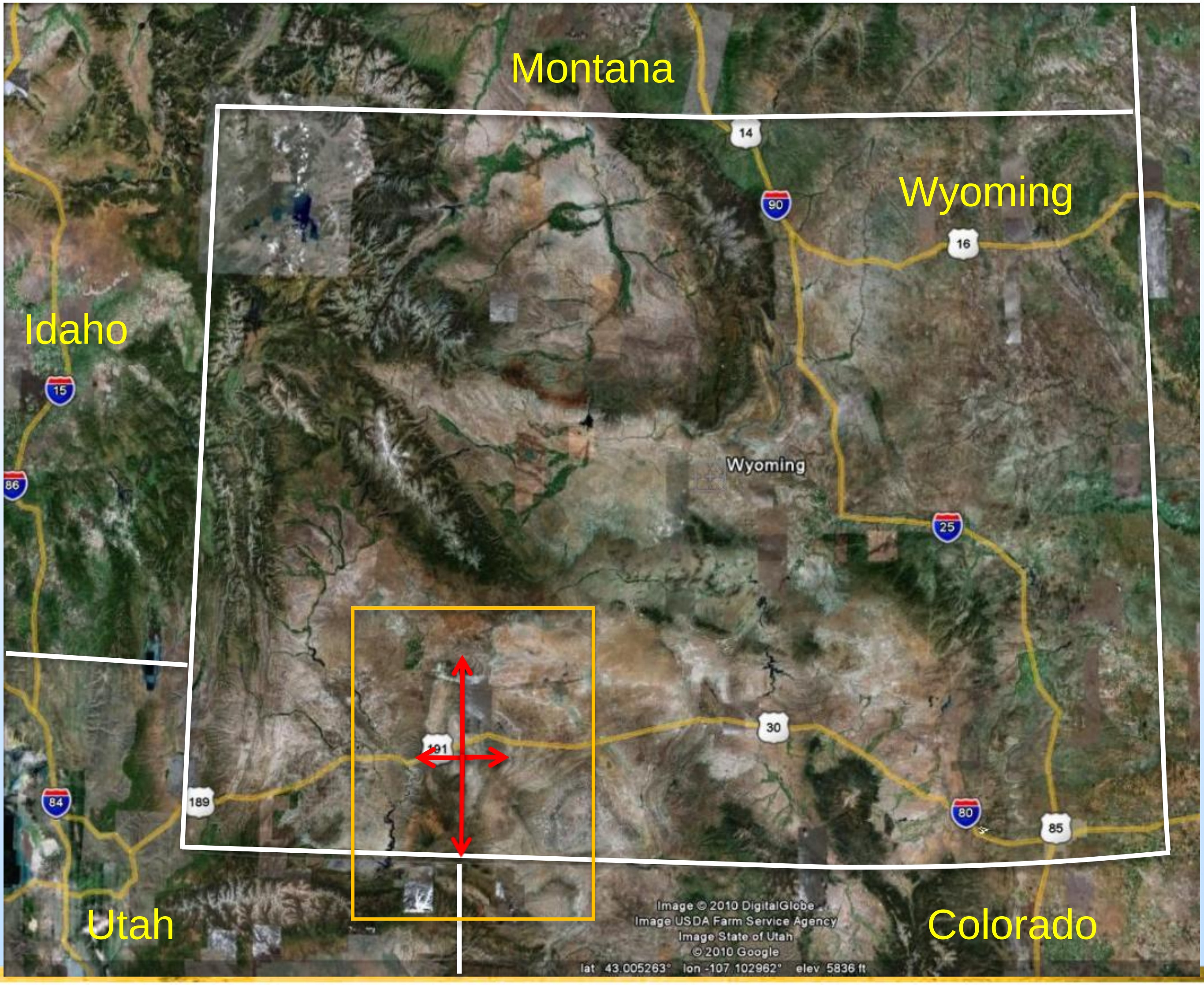
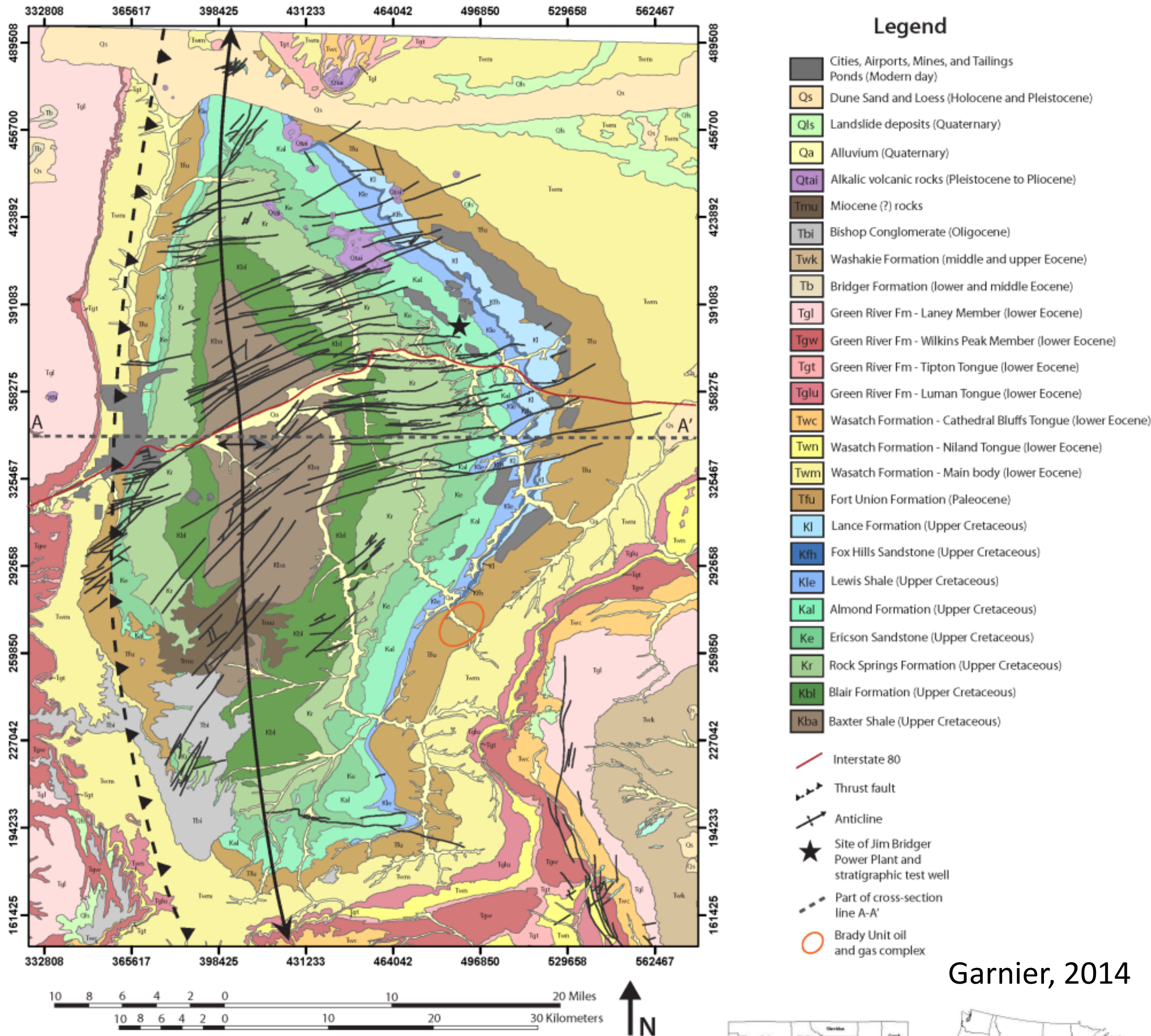
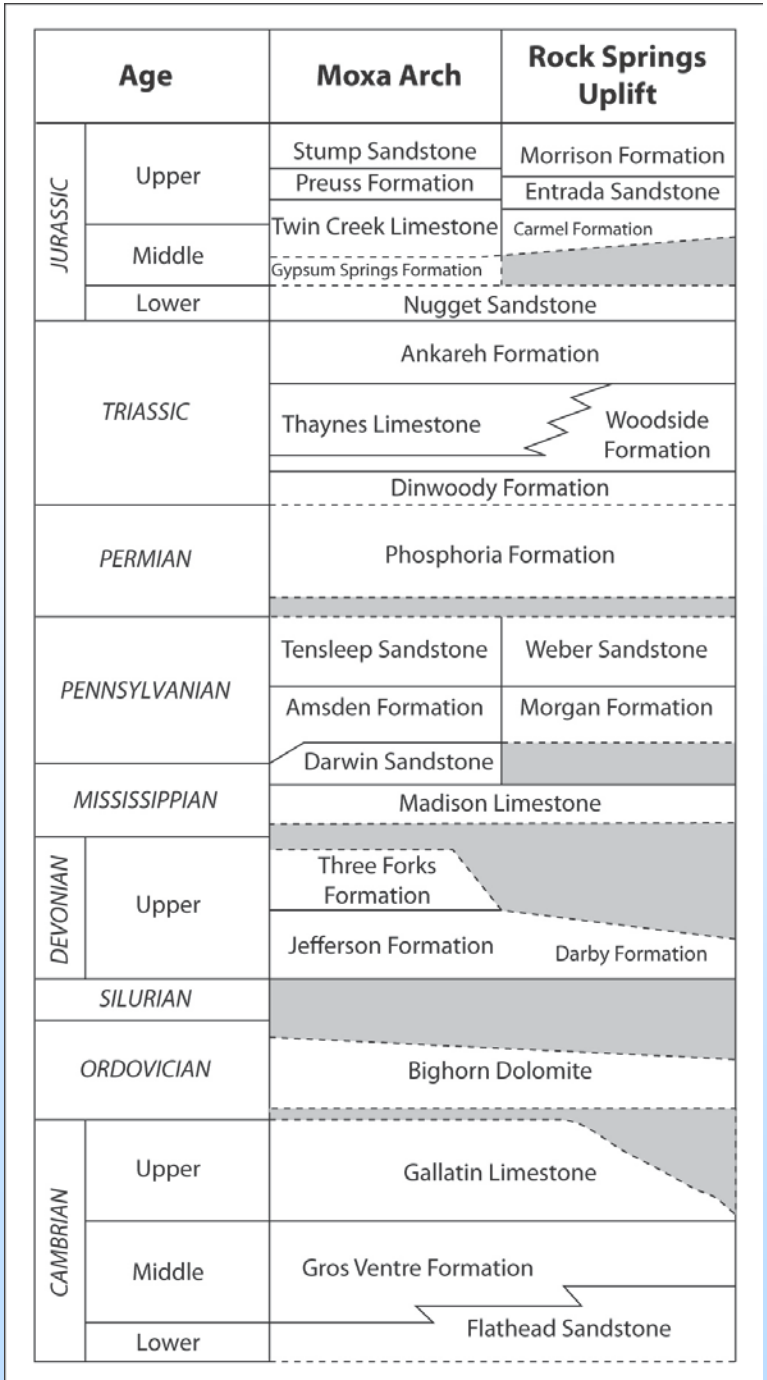


Image from Google Earth



Garnier, 2014

Western WY stratigraphic column



← confining

← storage

← confining

← storage

modified from Love et al., 1993

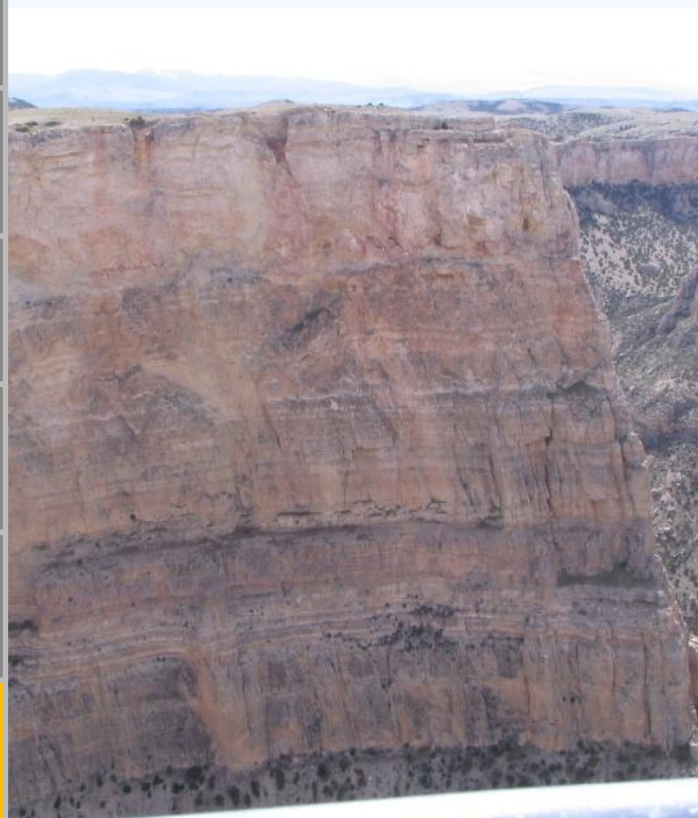
Tensleep/Weber
(Pennsylvanian)

Chugwater Grp.
Dinwoody Fm.
Phosphoria Fm.
Tensleep/Weber Ss.
Amsden Fm.
Madison Ls.

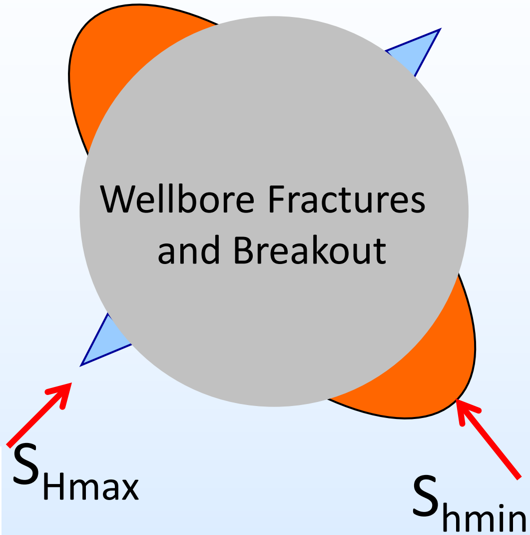
Madison Limestone

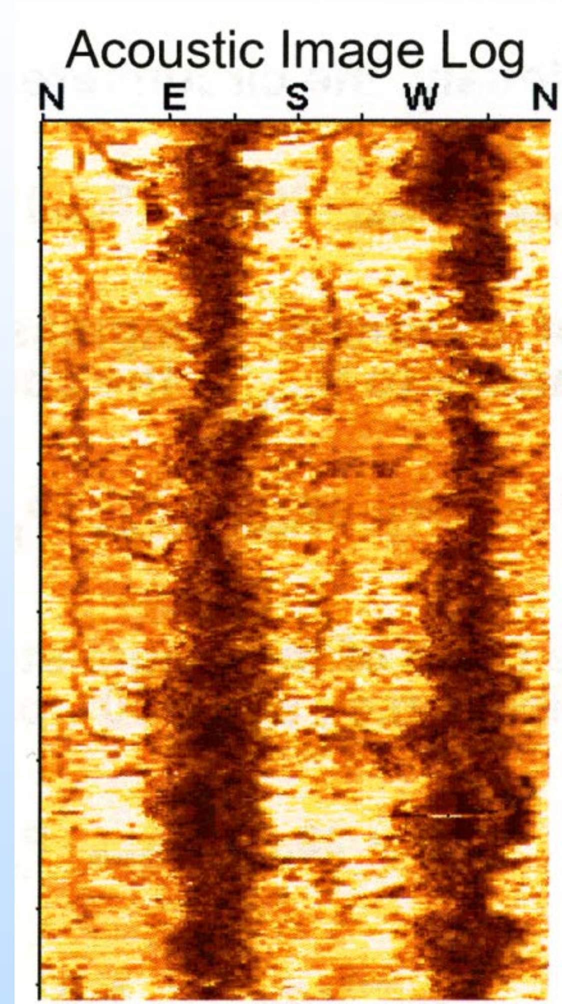
(Mississippian)

Chugwater Grp.
Dinwoody Fm.
Phosphoria Fm.
Tensleep/Weber Ss.
Amsden Fm.
Madison Ls.



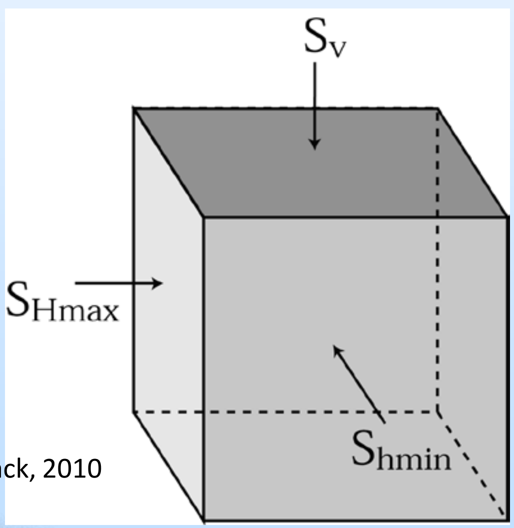
In Situ stress orientation





Orientation of S_{hmin} and S_{hmax}

Source = wellbore breakout, drilling induced fractures



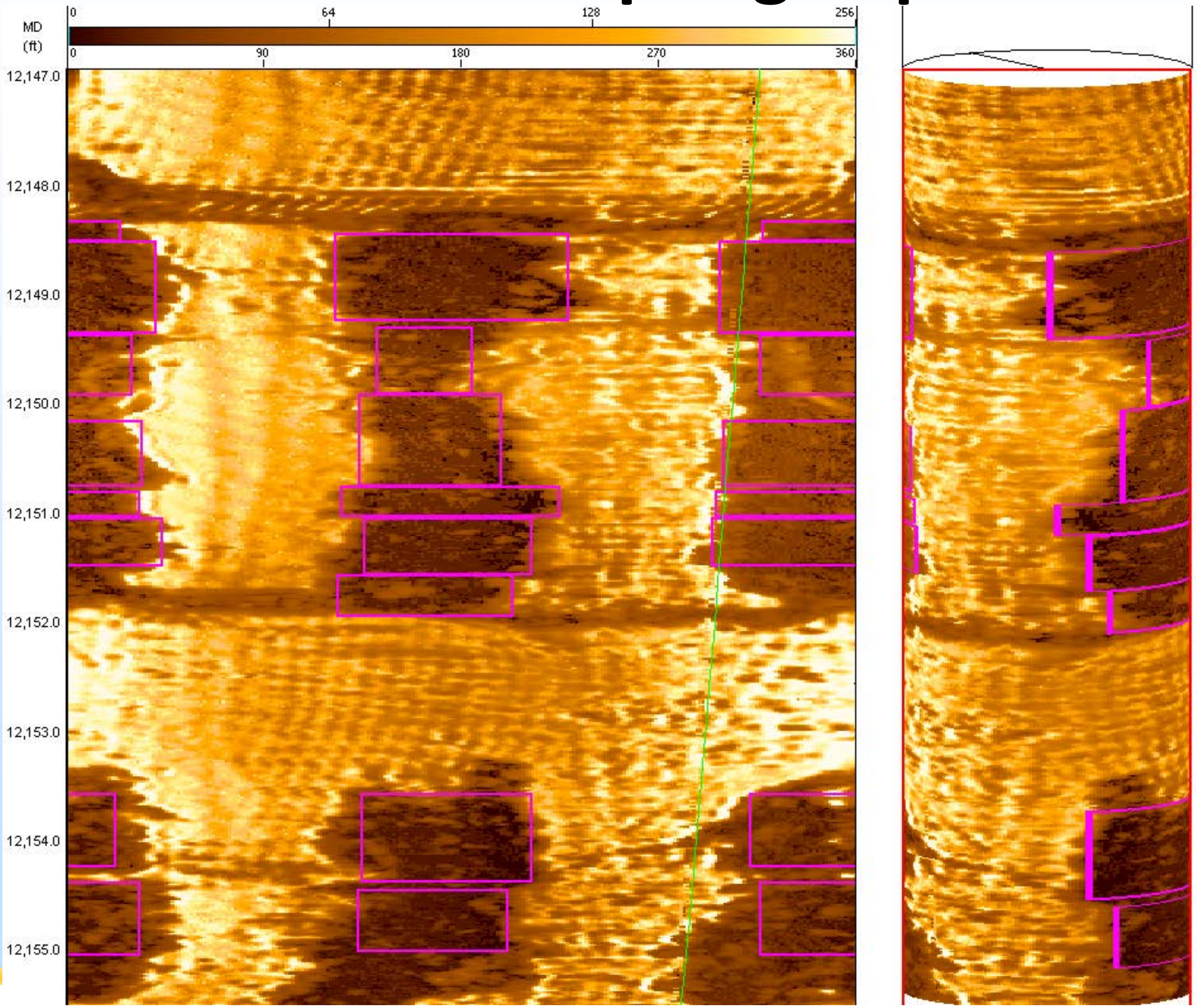
Zoback, 2010

Magnitude of S_{hmax}

Source = width of wellbore breakout or calculated

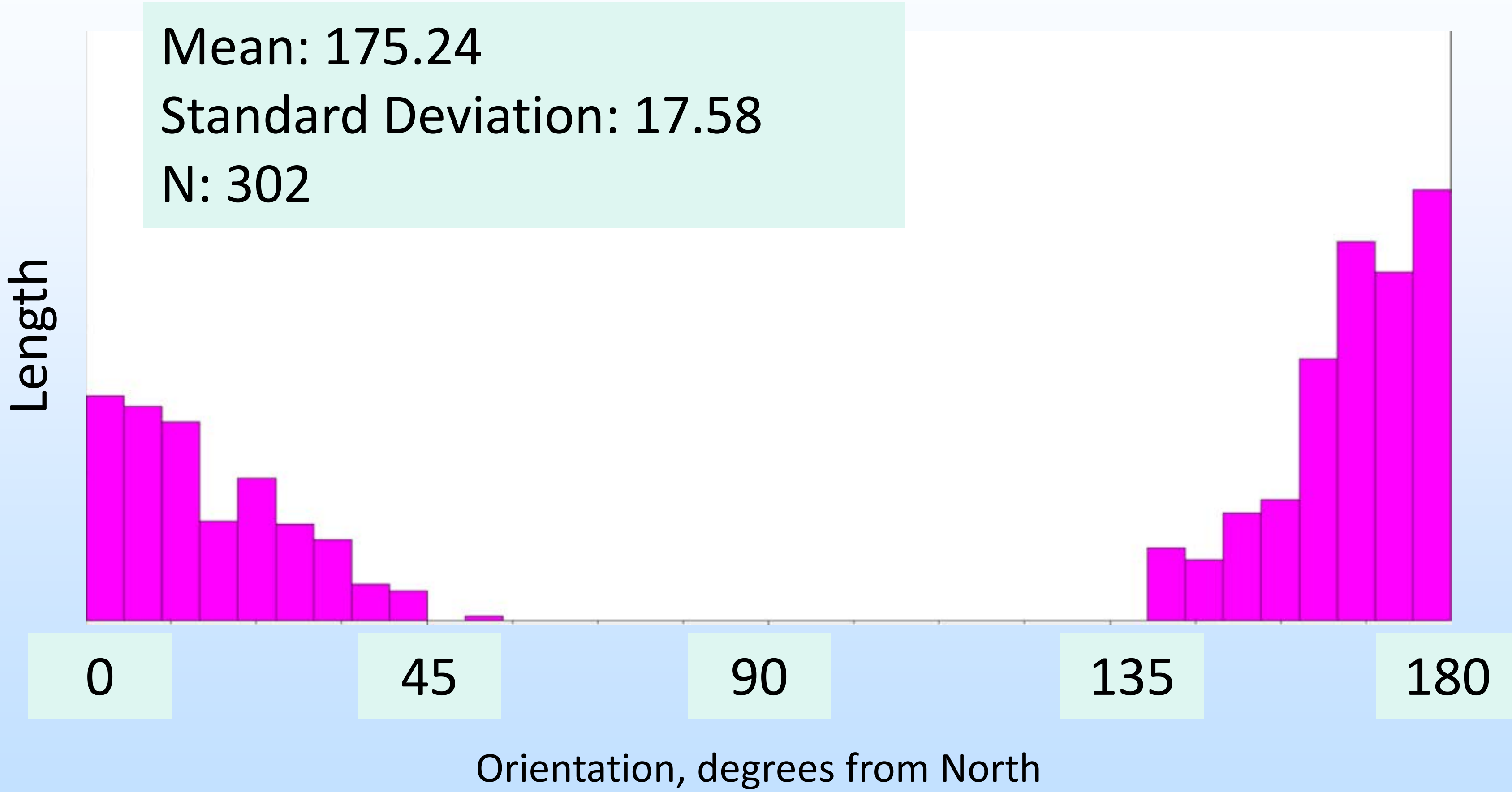
Image from GMI

Borehole Breakouts on Acoustic Image Log from Rock Springs Uplift

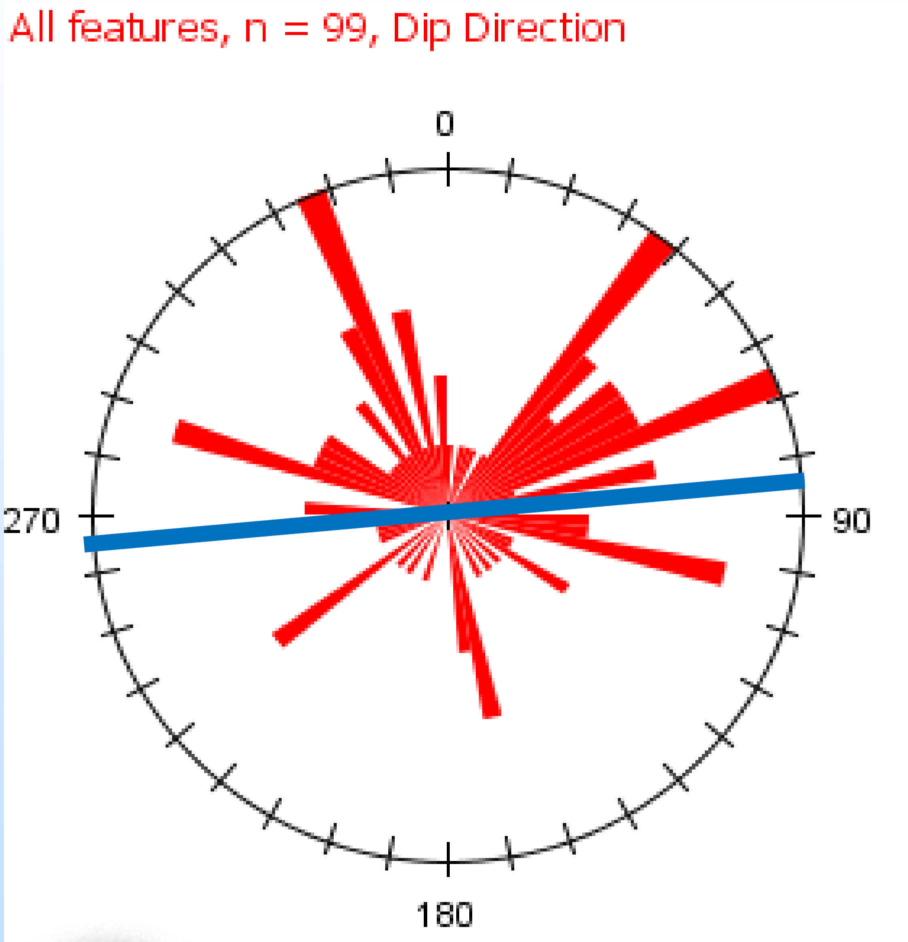


Shafer, 2013

Breakout Orientations



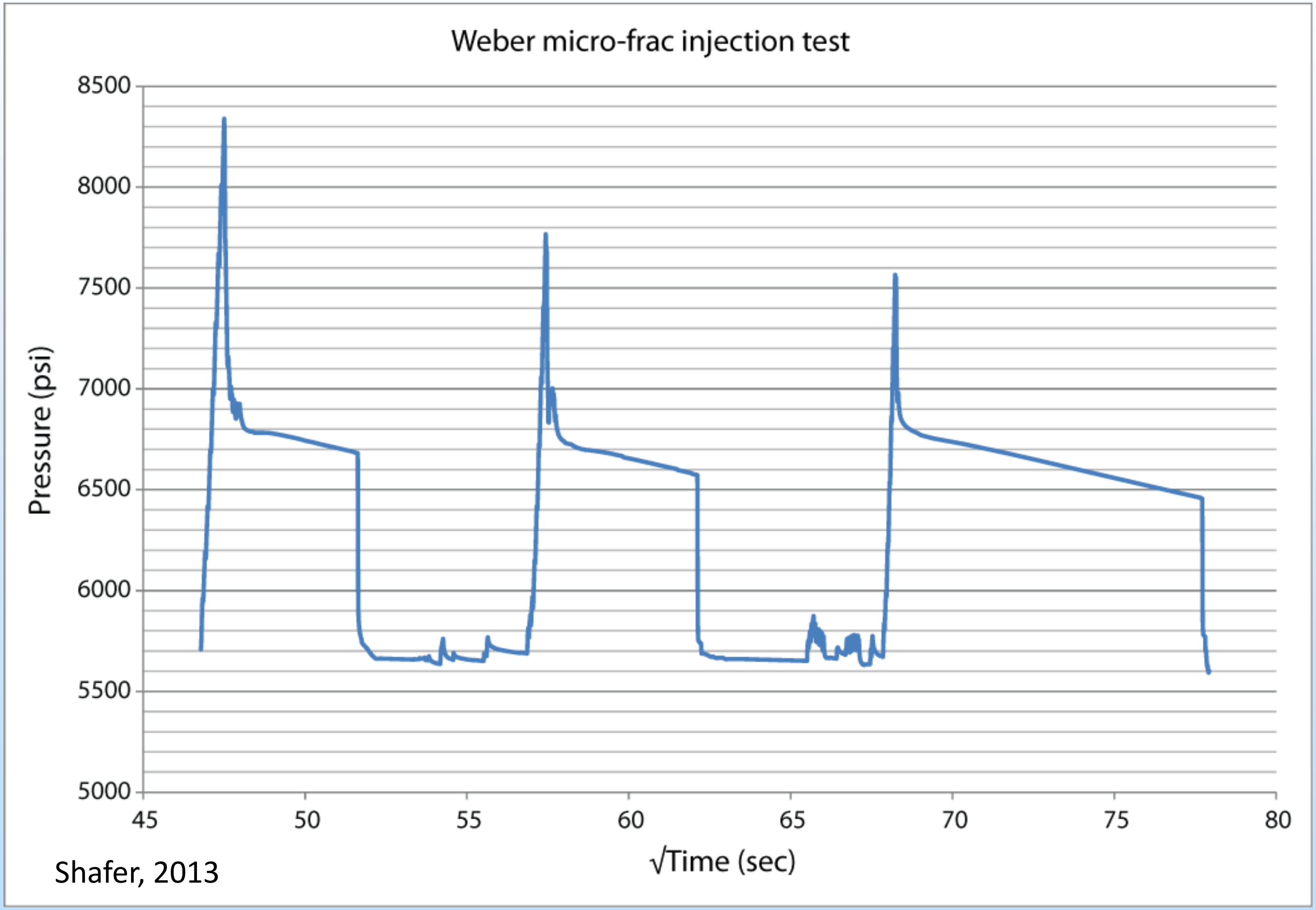
Permeable Fractures Expected at 085° ±18°

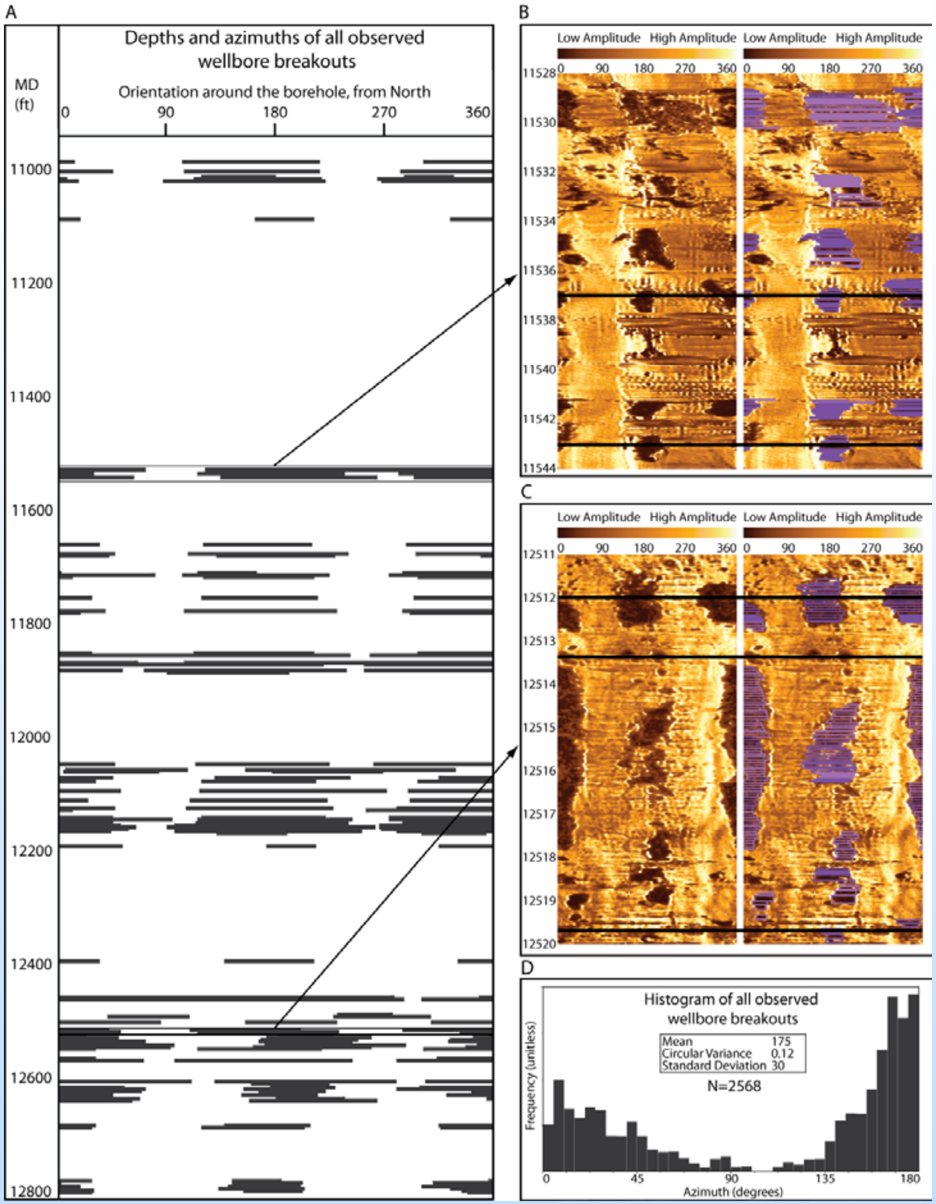


- Fractures in subsurface at the Rock Springs uplift exist in a variety of orientations
- S_{Hmax} orientation is ~085°±18°
- Fractures oriented parallel to S_{Hmax} are expected to be permeable

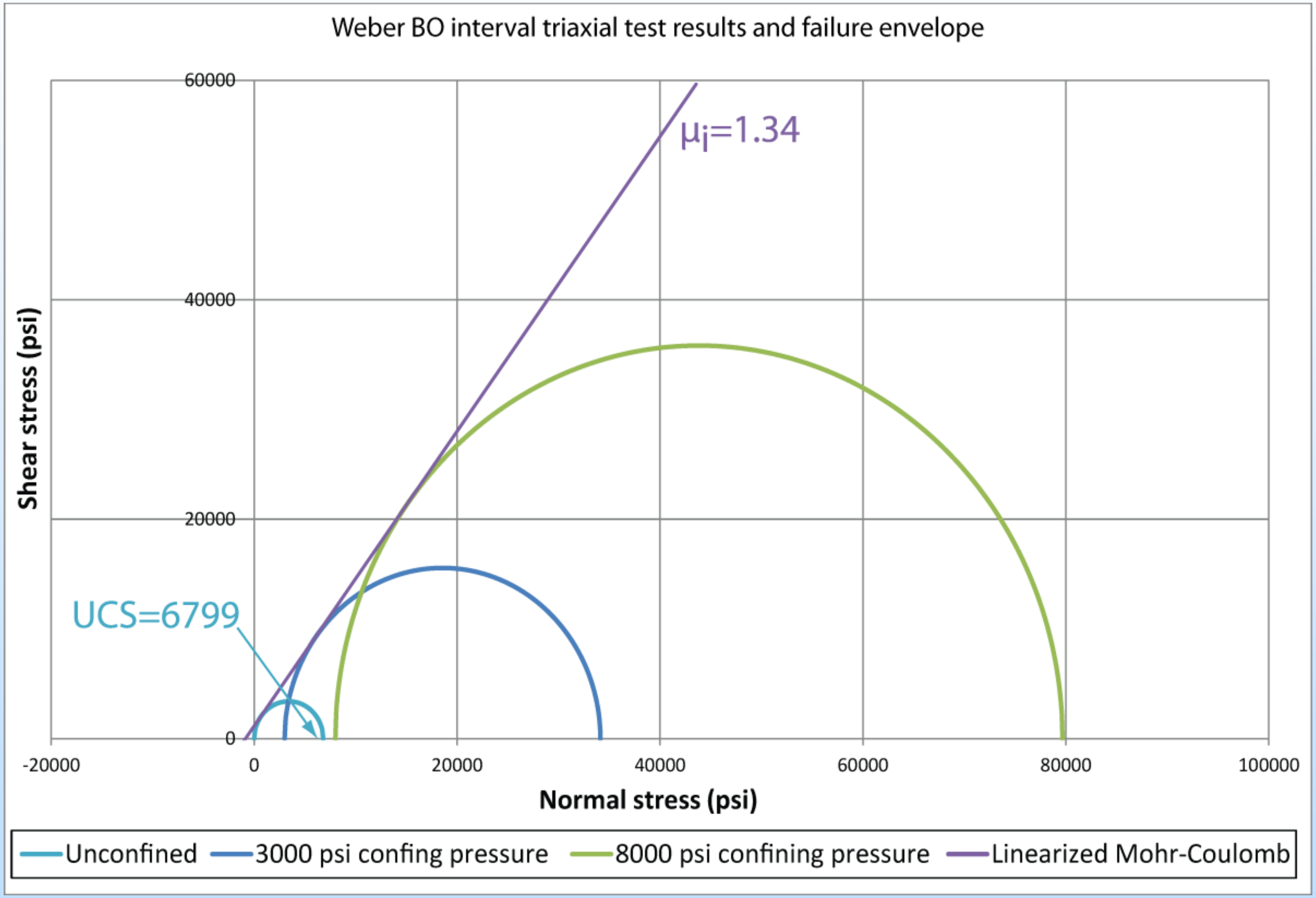
Shafer, 2013

Minifrac Data Available (Weber and Madison)




A
Depths and azimuths of all observed wellbore breakouts
MD (ft)
Orientation around the borehole, from North
0
90
180
270
360
11000
11200
11400
11600
11800
12000
12200
12400
12600
12800
B
Low Amplitude High Amplitude Low Amplitude High Amplitude
11528
11530
11532
11534
11536
11538
11540
11542
11544
C
12511
12512
12513
12514
12515
12516
12517
12518
12519
12520
D
Histogram of all observed wellbore breakouts
Mean 175
Circular Variance 0.12
Standard Deviation 30
N=2568
Frequency (unitless)
0
45
90
135
180
Azimuth (degrees)

Shafer, 2013



Weber BO interval triaxial test results and failure envelope
60000
40000
20000
0
-20000
0
20000
40000
60000
80000
100000
Shear stress (psi)
Normal stress (psi)
μi=1.34
UCS=6799
Unconfined
3000 psi confing pressure
8000 psi confining pressure
Linearized Mohr-Coulomb

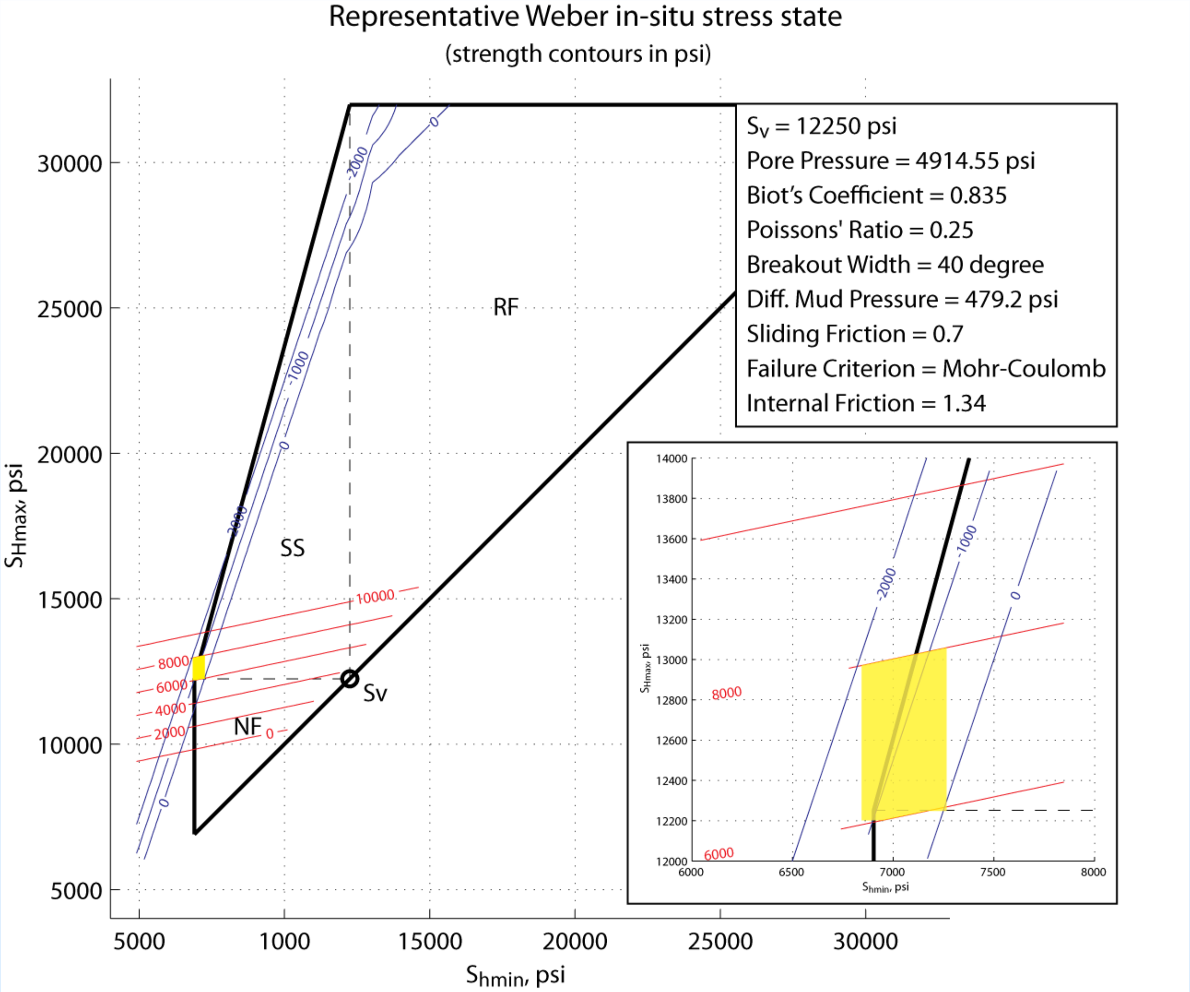
Shafer, 2013

Weber and Madison Geomechanics

Geomechanical Parameter	Weber	Depth Interval	Madison	Depth Interval
Vertical stress	12250 psi	11536.5 ft. MD	13380 psi	12512 ft. MD
BO investigation interval	11536.5-11543 ft. MD	NA	12511.5-12519.5 ft. MD	NA
Pore Pressure	4914.55 psi	11536.5 ft. MD	5380.15 psi	12512 ft. MD
Lowest mud weight experienced	5394 psi	11536.5-12810 ft. MD	6110 psi	12533-12810 ft. MD
UCS Range	6000-8000 psi	11536.5, 11543 ft. MD	5000-6000 psi	12512,12513,12519.5 ft. MD
SHmax azimuth	79°	10500-12807 ft. MD	79°	10500-12807 ft. MD
Shmin magnitude range	6844-7264 psi	11536.5 ft. MD	8240-9895 psi	12512 ft. MD
Biot range	0-1	NA	0-1	NA
Poissons ratio range	0.24-0.26	11536.5-11543 ft. MD	0.21-0.29	12512-12519 ft. MD
Internal friction	1.340	11536.5, 11543 ft. MD	0.624	12512,12513,12519.5 ft. MD
Breakout width	40-80°	11536.5, 11543 ft. MD	60-100°	12512,12513,12519.5 ft. MD
Coefficient of friction	0.6-1	NA	0.6-1	NA

Shafer, 2013

Weber in situ stress



Shafer, 2013

Integrated workflow

Well log analysis: formation evaluation, rock physics, and facies classification of petrophysical, elastic, and geomechanical properties (in situ condition)

Experiment: CO2 injection and pressure measurements to study geomechanical and geochemical effects (experiments based on possible reservoir fluid flow scenarios *)

Calibration of physics/chemistry models: rock physics, geomechanics, and geochemistry using well log data and lab experiments

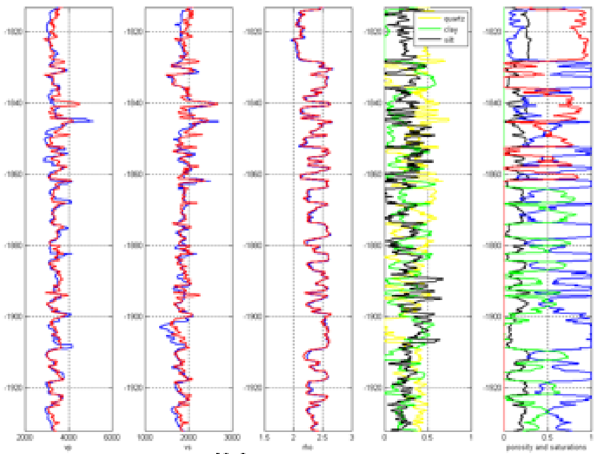
Statistical rock physics: simulation of different scenarios (according to *) and prediction of petrophysical, elastic, and geomechanical properties

Link with seismic and EM data at the reservoir scale

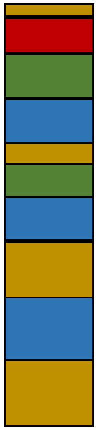
Time-lapse seismic and EM feasibility study

Multiple-scenario dynamic fluid flow simulation

Rock physics analysis

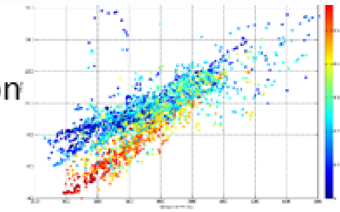


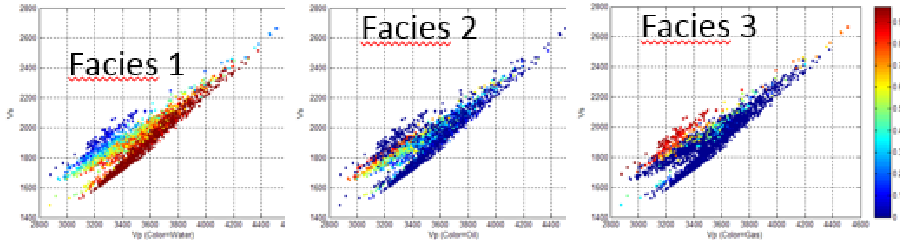
Well logs + Core analysis + Geology



Facies
Litho-fluid classes

Well log analysis
Rock property correlation





Rock physics / Geomechanics / Geochemistry models
(model calibration with lab experiments)

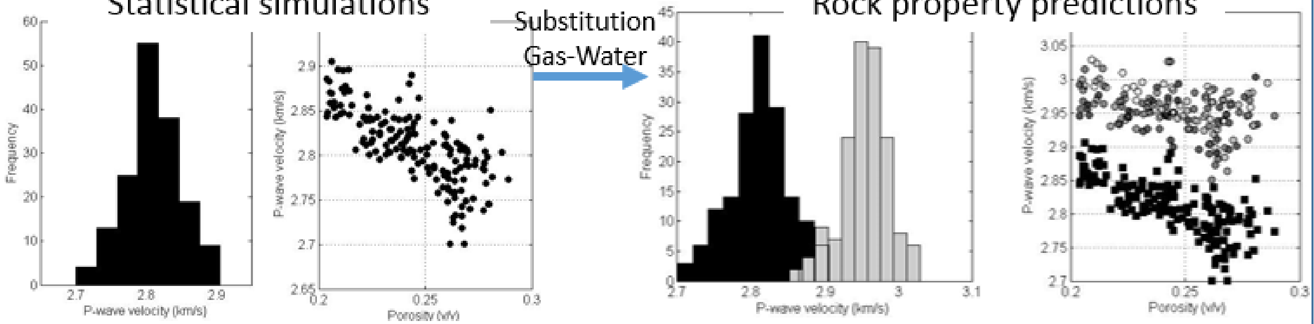
Definition of scenarios for rock property predictions:

- Fluid substitution
- Fracture modeling
- Chemical reactions
- Pore pressure changes

Statistical simulations

Scenario 1:
Substitution
Gas-Water

Rock property predictions

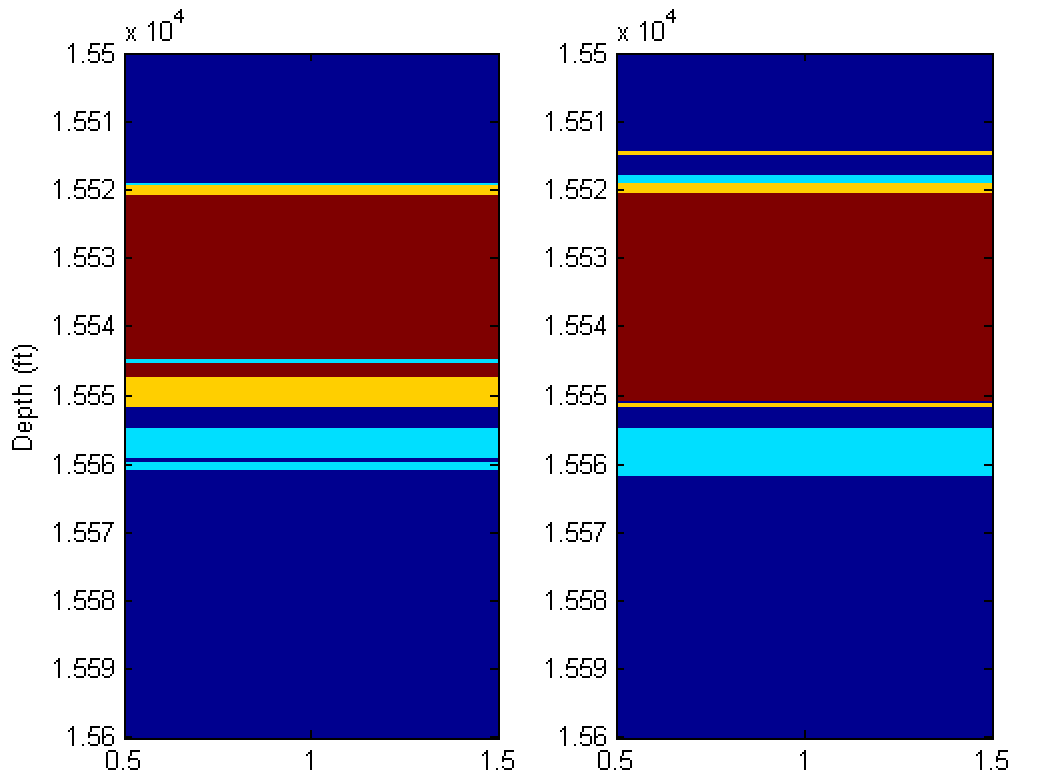


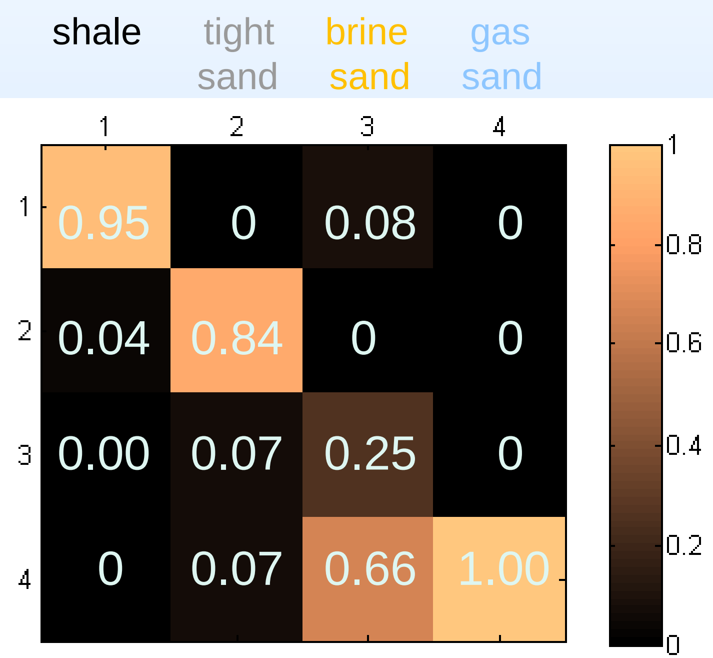
Monte Carlo simulations

Facies classification from elastic attributes

- Facies classification performed in elastic domain (well logs filtered at seismic frequency)

Actual log-facies Elastic facies

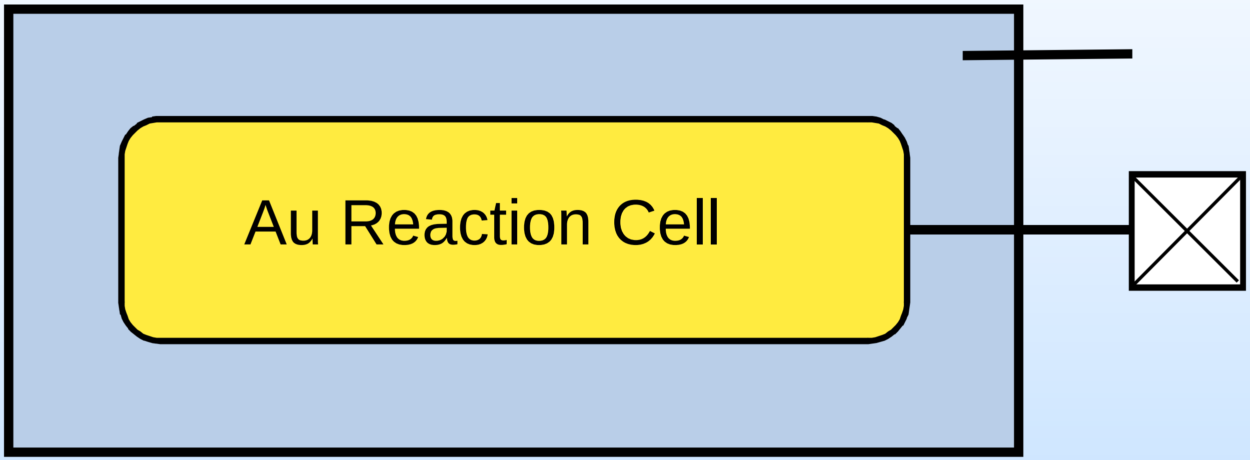




Methodology

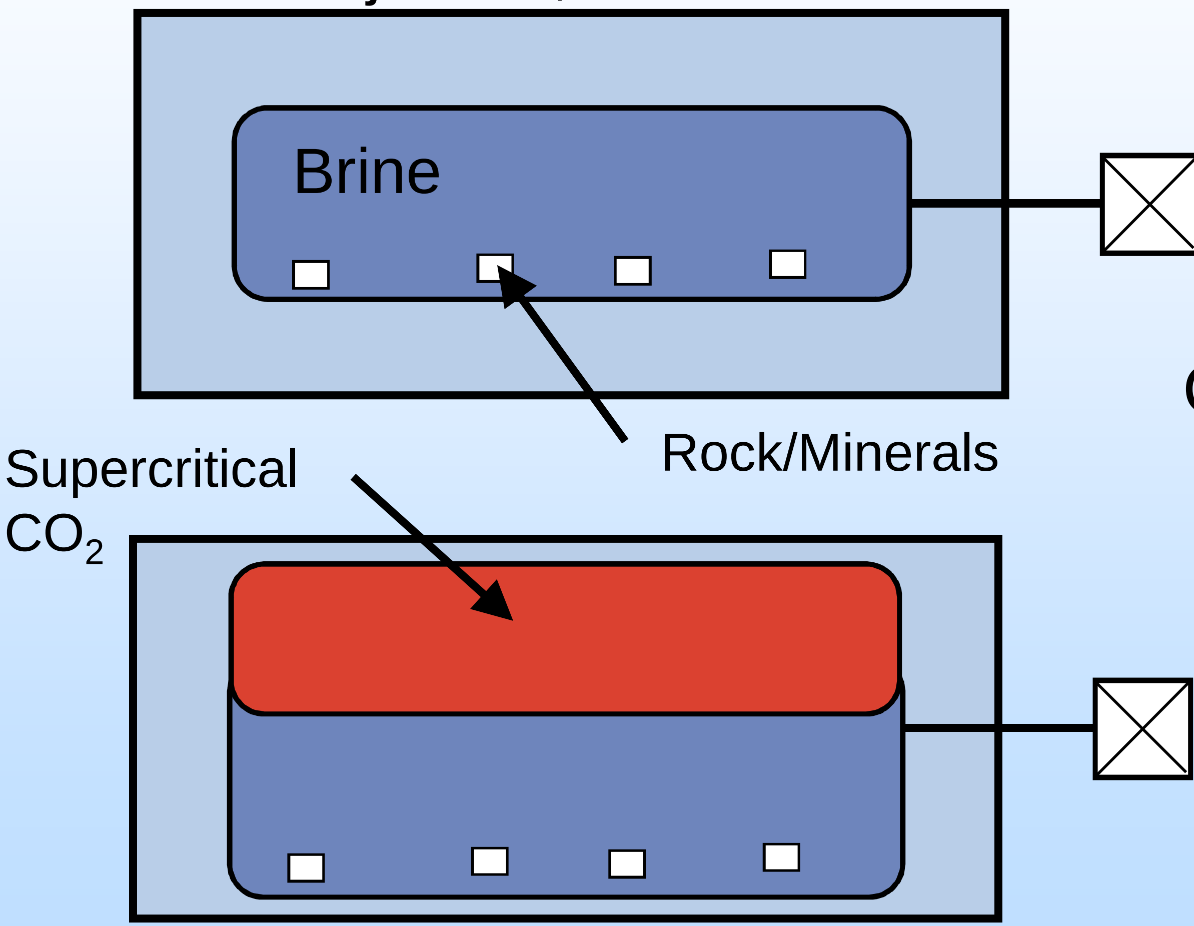
Geochemistry Experiments

Pressure Vessel



Methodology

Pre-injection, brine + rock

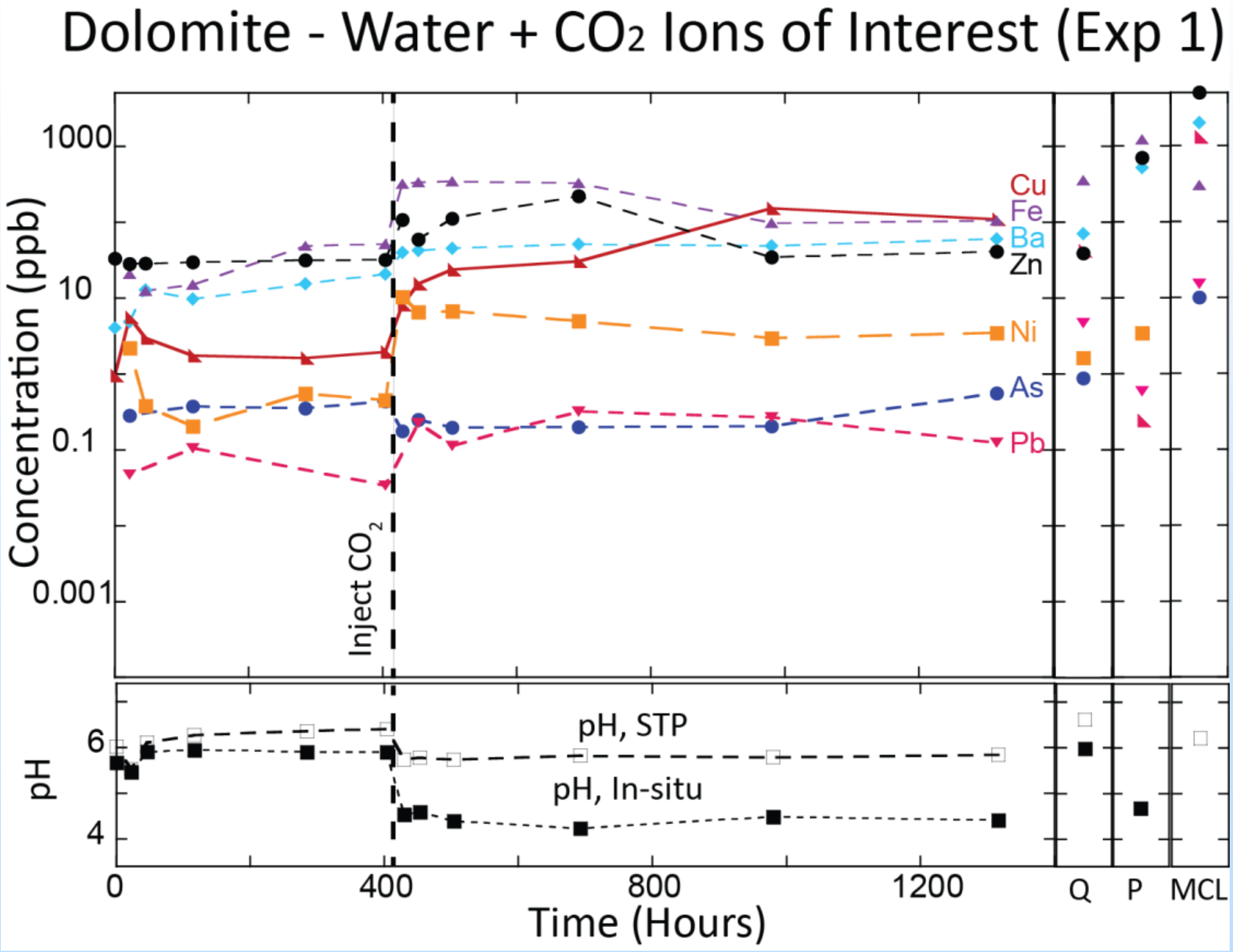


Post-injection, brine + rock + CO_2

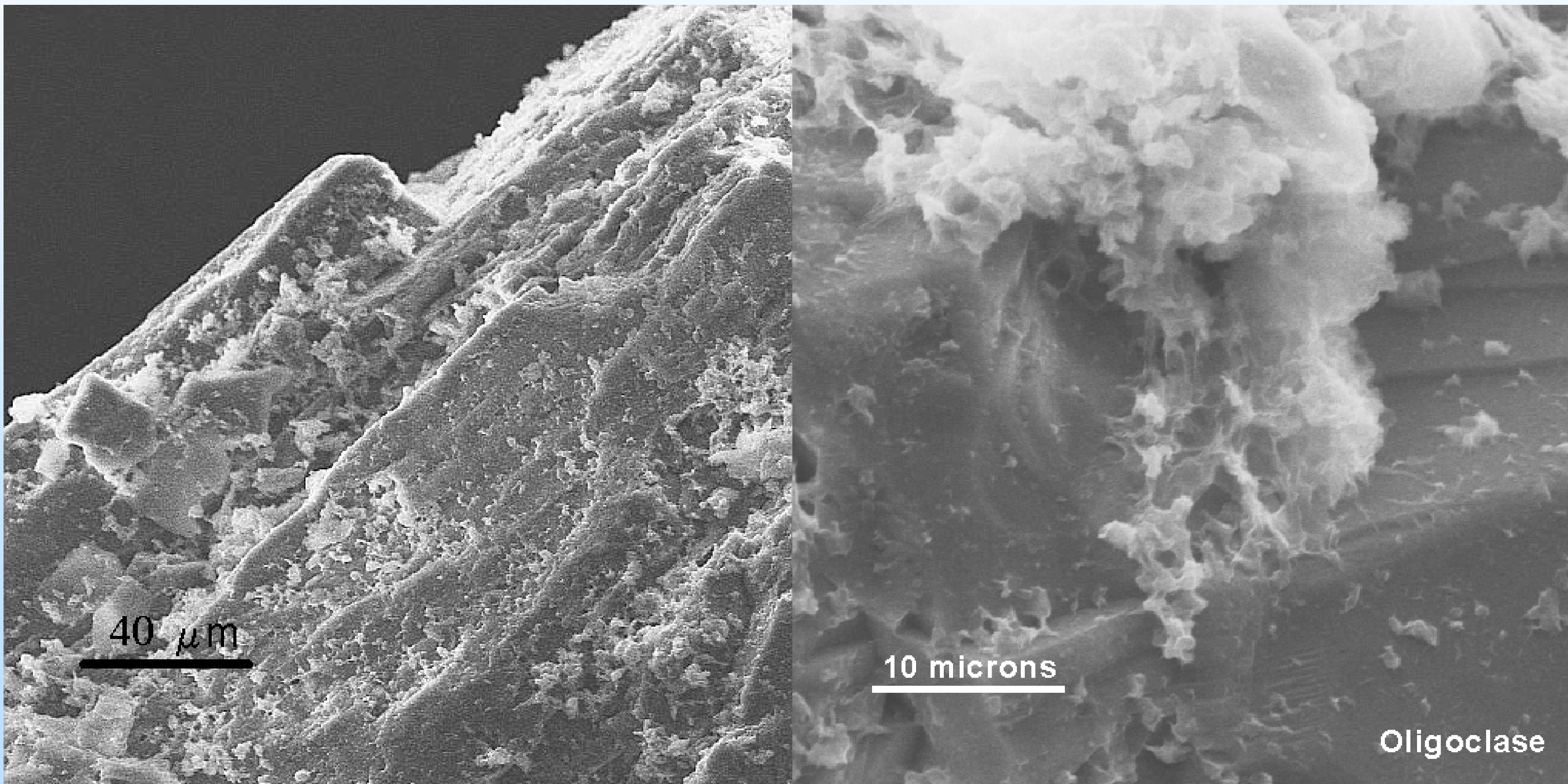
$CO_2(sc) \Leftrightarrow CO_2(aq)$

large ΔV

Methodology



Methodology



Methodology

Pc system

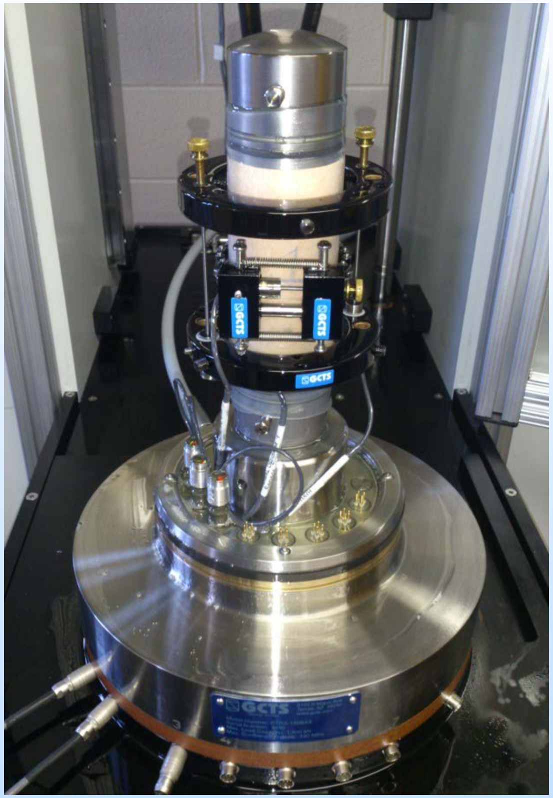
Coreflooding system

Flow-through experiments will be conducted also in saturation cells (not shown)

Task 4-Geomechanical Experiment

- To determine the effect of CO_2 on rock strength parameters
- Rock plugs from the Weber Sandstone and Madison Limestone
- Three subtasks:
  - Task 4.1: Triaxial experiments
  - Task 4.2: Evaluation
  - Task 4.3: Report of experimental results

Triaxial Equipment



Upgrade of Triaxial Equipment

- Temperature Control System up to 150°C
- Ultrasonic Velocity Measurement System
- Expected installation by mid of Jan 2015
- Capable of preforming tests on 1-in and 2-in diameter specimens

Expected Outcomes

- **Improve the accuracy of reservoir models**, by providing an understanding of the effect of CO_2 injection on crucial modeling input parameters, and offering quantitative statistical methods to identify reactive lithologies.
- **Help ensure 99% storage permanence**, by creating more accurate reservoir models predicting the direction of migration and the extent of the CO_2 plume.
- **Increase our ability to predict storage capacity, toward the goal of ±30%**, by helping to generate reservoir models based on post-injection conditions of permeability and fracture density.
- **Include the state-of-the-art technique and workflow in DOE Site Selection or Initial Characterization stages of injection site characterization**.
- **Reduce the time and cost required to assess potential storage locations** by eliminating unsuitable sites earlier in the assessment process, using existing well log data, perhaps before drilling an expensive and time-consuming stratigraphic test well.

Products

- Site-specific project fact sheet on the NETL website.
- Data for inclusion in the NETL Energy Data eXchange (EDX),
  https://edx.netl.doe.gov/.
- Report on advanced statistical model, including updated mechanical stratigraphy and geomechanical model.
- Report on experimental plan describing the details of the geochemical-mineralogic experiments performed.
- Report of experimental results providing information on the nature and impacts of CO_2-water-rock reactions on geomechanical and petrophysical properties.
- Report summarizing experimental geomechanical procedures.
- Integrated methodology and prototype code (rock physics).
- Integrated methodology and prototype code (seismic reservoir characterization and monitoring)
- Integrated methodology and prototype code (fluid flow simulation)

Organizational Chart and Communication Plan

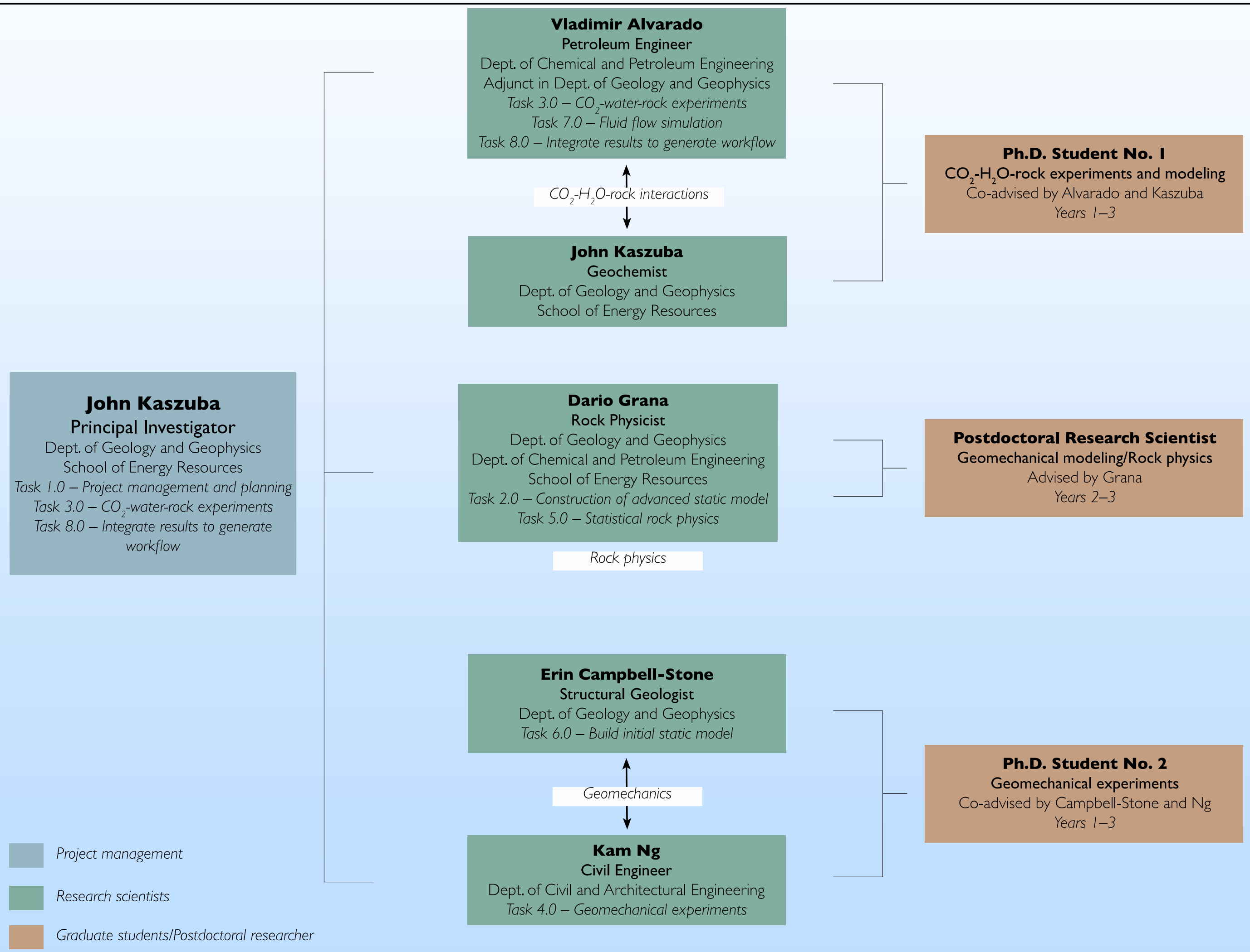


Figure 1. Organizational chart.

Task/Subtask Breakdown

- Task 1.0 – Project Management and Planning
- Task 2.0 – Construction of Advanced Rock Property Model
- Subtask 2.1 – Formation evaluation
- Subtask 2.2 – Facies classification
- Subtask 2.3 – Rock physics model development
- Subtask 2.4 – Refine geomechanical model and compare to facies
- Subtask 2.5 – Report of advanced rock property model
- Task 3.0 – Conduct CO_2-Water-Rock Experiments
- Subtask 3.1 – Select and obtain samples for experiments
- Subtask 3.2 – Characterize samples for experiments
- Subtask 3.3 – Perform geochemical calculations and use results to design plan for geochemical-mineralogic experiments
- Subtask 3.4 – Perform geochemical-mineralogic experiments
- Subtask 3.5 – Update geochemical calculations and use results to design plan for coreflood experimentsSubtask
- Subtask 3.6 – Perform geochemical saturation and coreflooding experiments
- Subtask 3.7 – Report of experimental results

Task/Subtask Breakdown

- Task 4.0 – Geomechanical Experiments
- Subtask 4.1 – Formation evaluation
- Subtask 4.2 – Facies classification
- Subtask 4.3 – Rock physics model development
- Task 5.0 – Statistical Rock Physics Model Development
- Task 6.0 – Build Initial Static Model Conditioned by Geophysical Measurements
- Subtask 6.1 – Seismic reservoir characterization
- Subtask 6.2 – Reservoir monitoring feasibility
- Task 7.0 – Conduct Fluid-flow Simulations
- Subtask 7.1 – Time-independent and two-way coupling simulations
- Subtask 7.2 – Time-dependent model update
- Task 8.0 – Integrate Results to Generate Workflow Incorporating Reservoir Conditions, Experimental Data, and Fluid-flow Simulations

Deliverables/Milestones/Decision Points

Task/ Subtask	Milestone ID/Description	Planned Completion	Verification Method*
1.0	A. Updated Project Management Plan	11/07/2014	Project Management Plan file
1.0	B. Kickoff Meeting	11/30/2014	Presentation file
2.0/2.5	**C. Summary of the activities and results from Task 2.0 for the advanced rock property model**	**8/31/2015**	**Quick-look report**
3.0/3.1	**D. List of rock samples selected/obtained for CO2-Water-Rock experiments to include pertinent sample properties (formation, lithology, depth, facies)**	**03/06/2015**	**List**
3.0/3.3	**E. Plan that describes the details of the geochemical-mineralogic experiments to be performed**	**04/30/2015**	**Quick-look report with plan**
3.0/3.4	**F. Initiate CO_2-Water-Rock experiments**	**05/30/2015**	**Email to FPM describing initiation**
3.0/3.5	**G. Plan for coreflood experiments**	**10/01/2015**	**Interim report to FPM with plan for coreflood experiments**
3.0/3.7	H. Report of analyses and results studied in the CO_2-Water-Rock experiments	04/14/2017	Quick-look report
4.0/4.1	**I. Initiate geomechanical experiments**	**10/01/2015**	**Email to FPM describing initiation**
4.0/4.1	**J. Report of baseline geomechanical experiment results**	**03/21/2016**	**Interim report to FPM with results of baseline geomechanical experiments**
4.0/4.3	K. Report of results and analyses of the geomechanical experiments	02/28/2017	Quick-look report
5.0	L. Summary of the activities and results performed in the rock physics model development and analyses in Task 5.0	10/31/2016	Quick-look report
6.0/6.1	**M. Report of Subtask 6.1 seismic reservoir characterization**	**08/30/2016**	**Interim report to FPM describing seismic reservoir characterization**
6.0/6.2	N. Summary of the activities and results performed in development and analyses of the initial static model, and the modeled petrophysical, geomechanical, and elastic response and implications for monitoring, performed in Task 6.0	12/29/2016	Quick-look Report
7.1	**O. Initiate Simulations**	**10/31/2015**	**Email to FPM describing initiation**
7.2	P. Report summarizing the activities and results performed in the simulations in Task 7.0	08/31/2017	Quick-look Report
8.0	Q. Report summarizing the workflow, accompanying documentation, and activities and results performed in Task 8.0 for the workflow definition and accompanying documentation.	08/31/2017	Quick-look Report

Milestones/Decision Points

BUDGET PERIOD PROJECT SUCCESS CRITERIA / DECISION POINTS

Success Criteria at Decision Points

Date	Decision Point	Success Criteria*
9/30/2015	End of Budget Period 1	Completion of the following milestones: Milestone C Milestone D Milestone E Milestone F
9/30/2016	End of Budget Period 2	Completion of the following milestones: Milestone G Milestone I Milestone J Milestone M Milestone O

Risk Matrix

POTENTIAL PROJECT RISKS

Technical Risks

Description	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Mitigation and Response Strategies
Geochemical experiments (Subtask 3.5) take longer and delay coreflood experiments (Subtask 3.7)	Moderate	Moderate	1) Identify and recruit graduate students earlier than normal 2) Employ existing pool of students to start experiments early
Challenges operating the triaxial test equipment after upgrades completed	Moderate	Moderate	The vendor, GCTS, will provide on-site technical installation and training
Computational costs for processing data	Low	Moderate	Availability of computer clusters in G&G, CPE, and SER

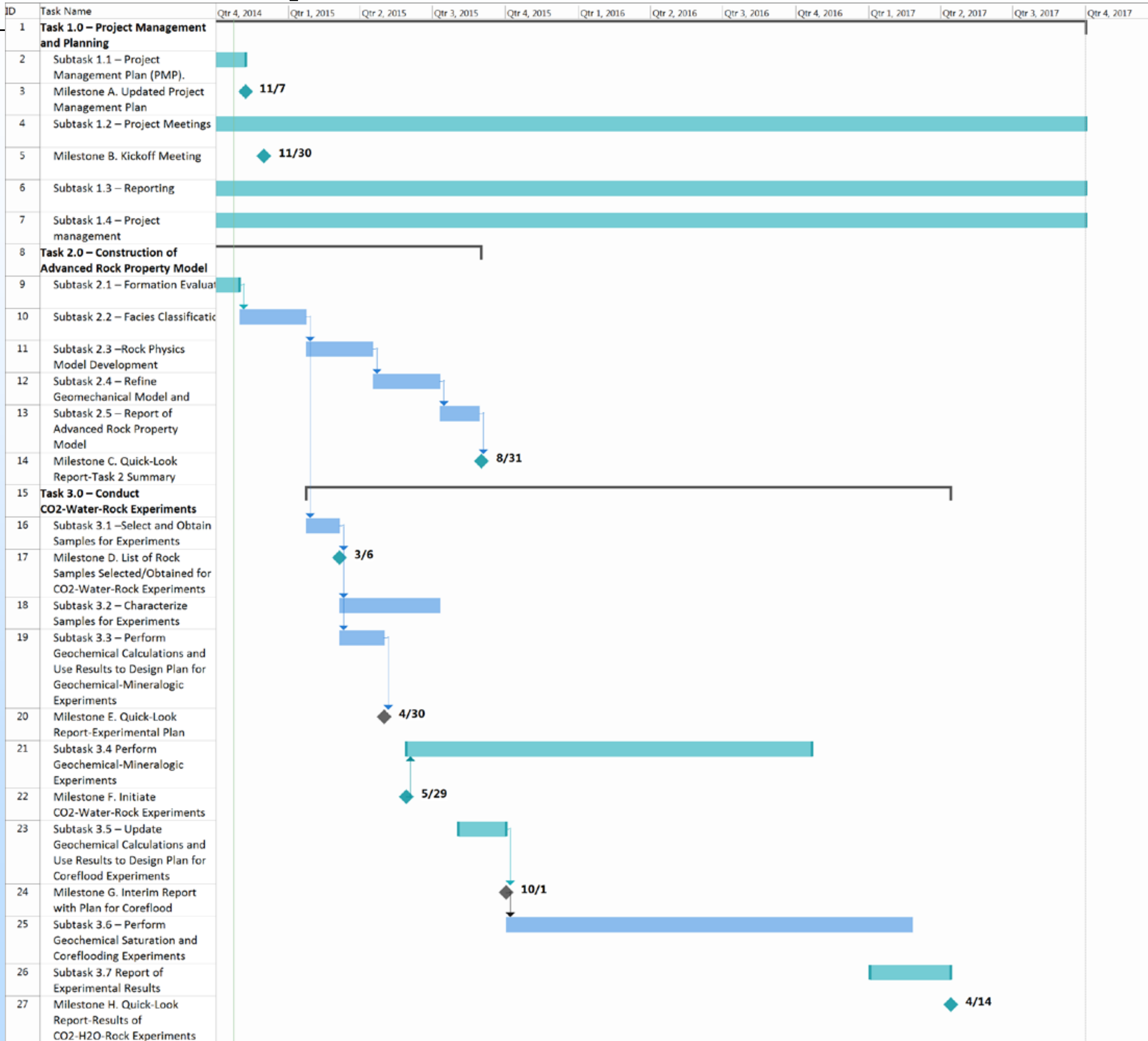
Resource Risks

Description	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Mitigation and Response Strategies
Identify and recruit qualified graduate students	Moderate	High	1) Each candidate recruited by two departments, effectively doubling applicant pool 2) Formal grad student recruiting program in place in G&G Dept.
Funding cycle and grad student matriculation out of sync	High	High	G&G's admissions program is flexible to accommodate grant cycles; students can be admitted year-round if necessary
Identify and recruit qualified postdoc	Moderate	Moderate	Postdoc not needed until year 2; recruitment period takes advantage of year 1
Backlogged coreflood experiments from other projects impact coreflood experiments for this project (Subtask 3.7)	Moderate	Moderate	Purchase essential components (Corelab-TEMCO parts) to construct dedicated core holders, as described in equipment section of Budget Justification
Data quality	Low	Moderate	RSU dataset was acquired via modern techniques. Post-processing of data to reduce noise can be performed using available methodologies at UW

Management Risks

Description	Probability (Low, Moderate, High)	Impact (Low, Moderate, High)	Mitigation and Response Strategies
Investigators in multiple departments	Moderate	Moderate	1) Time slot reserved for weekly meetings 2) Weekly project meetings, more frequent if necessary 3) Monthly technical presentations by investigators, grad students, and postdoc 4) Kaszuba and Grana are jointly appointed in SER, whose mission is to integrate different departments, specifically Geology & Geophysics (G&G) and Chemical & Petroleum Engineering (CPE) 5) Grana has a double appointment with G&G and CPE; Alvarado has an appointment in CPE and is an adjunct in G&G 6) Alvarado, Campbell-Stone, and Kaszuba have an established collaboration, as documented by published papers and serving as co-PIs on previous RSU work
Graduate students to perform work	Moderate	High	Same as 1) through 3) above
Postdoc to perform work	Low	Moderate	Same as 1) through 3) above
Chemical safety in lab	Low	High	UW Environmental Health and Safety Program, including formal training by UW ES&H staff, full-time EH&S professionals on-call, inspections by ES&H staff, waste disposal program in place with costs paid by UW and not individual investigators (provides incentive for proper disposal)
Waste disposal	Low	High	Same as above
Energized systems in lab	Low	High	Same as above, plus lab-specific and instrument-specific training by PI and his/her research group

Proposed Schedule



Proposed Schedule

Summary

- Data from the Rock Springs Uplift have been collated
- SOPO has been revised and team has initiated tasks as planned
- Upgrades of geomechanical system have been purchased
- Sample selection has been initiated
- Meetings and reporting schedules are set