Integrated Characterization of CO_2 Storage Reservoirs on the Rock Springs Uplift Combining Geomechanics, Geochemistry, and Flow Modeling

Project Number DE-FE0023328

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

Presentation Outline

- Technical status
  - Objectives
  - Geomechanics
  - Rock physics & seismic
  - Petrophysics
- Accomplishments to date
- Lessons learned
- Synergy opportunities
- Project summary

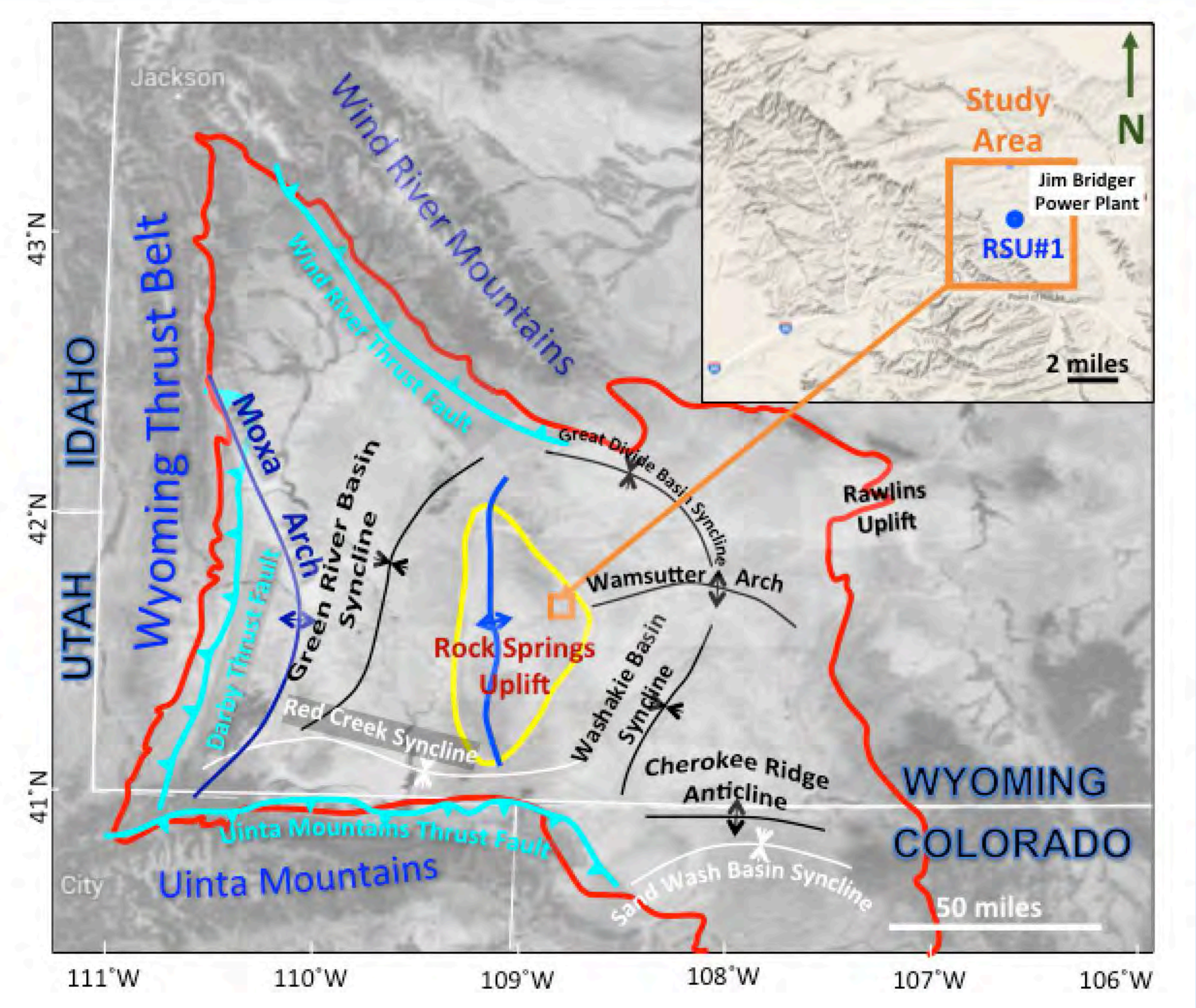
Technical Status

- **Overall Objective:** Improve understanding of the effects of CO_2 injection and storage on geomechanical and petrophysical properties.
  - Combines integrated, interdisciplinary methodology using existing data sets (Rock Springs Uplift in Wyoming)
  - Culminates in integrated workflow for potential CO_2 storage options

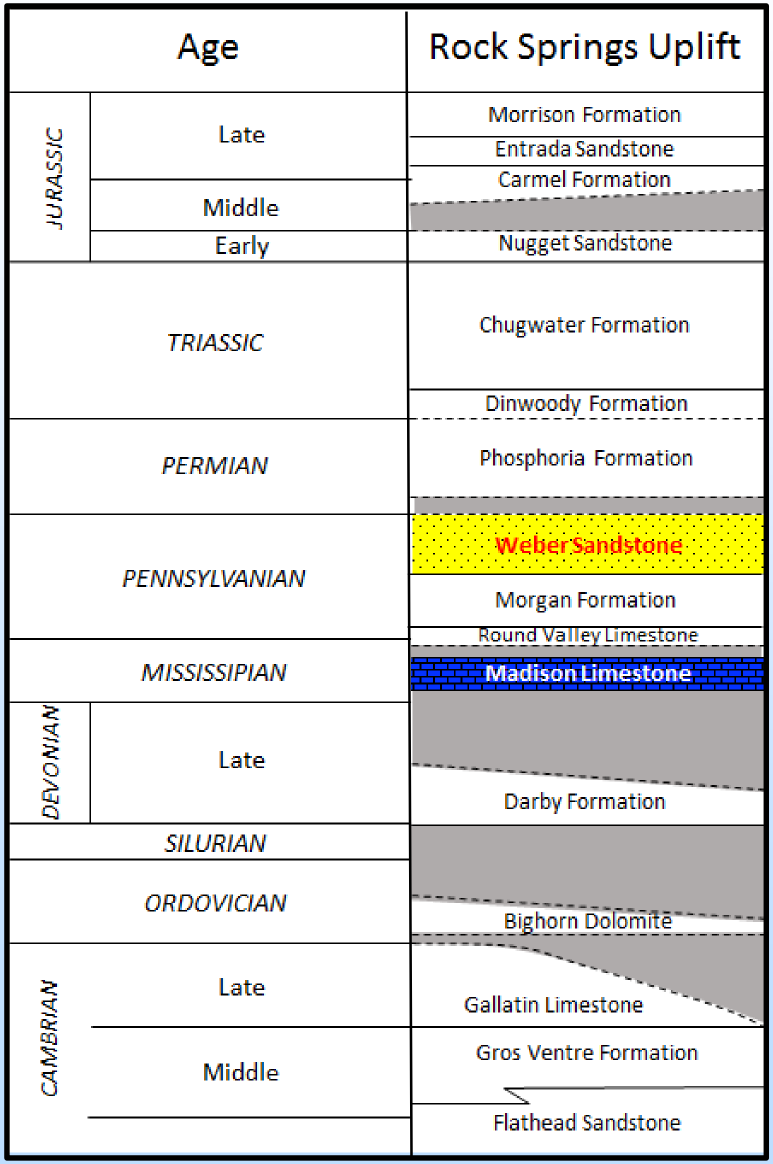
Multidisciplinary Team

- Vladimir Alvarado: Assistant Project Manager, Reservoir Engineering
- Erin Campbell: Structural Geology, Geomechanics, Wyoming Geology
- Dario Grana: Rock Physics
- John Kaszuba: Project Manager, Geochemistry
- Kam Ng: Geomechanics

Rock Springs Uplift, WY



Target Formations

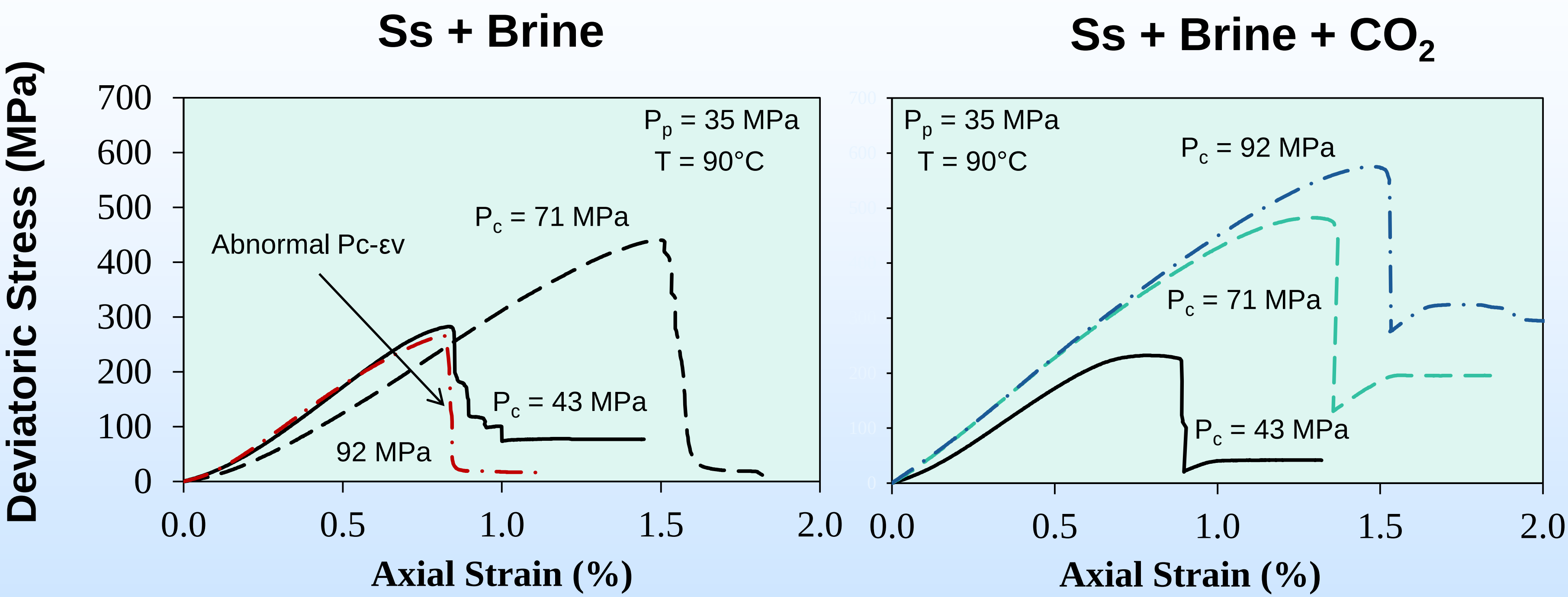


Weber Sandstone
(11,150 – 11,800 ft)

Madison Limestone
(12,225 – 12,650 ft)

Modified from Love et al. (1993)

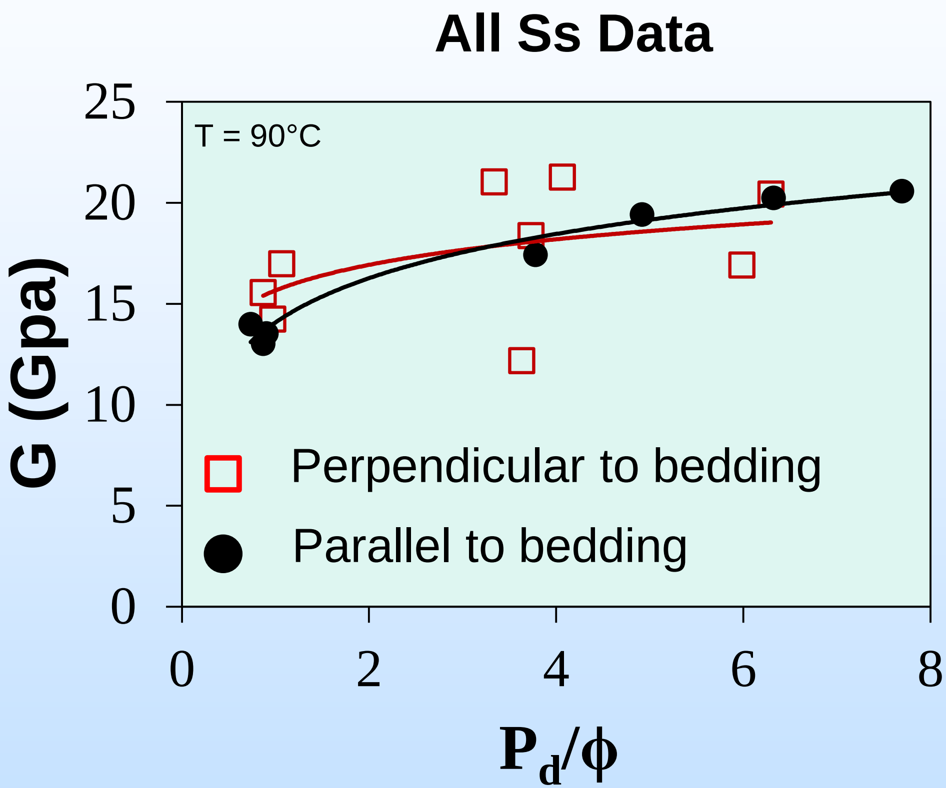
Geomechanical Results: Ss Perpendicular to Bedding

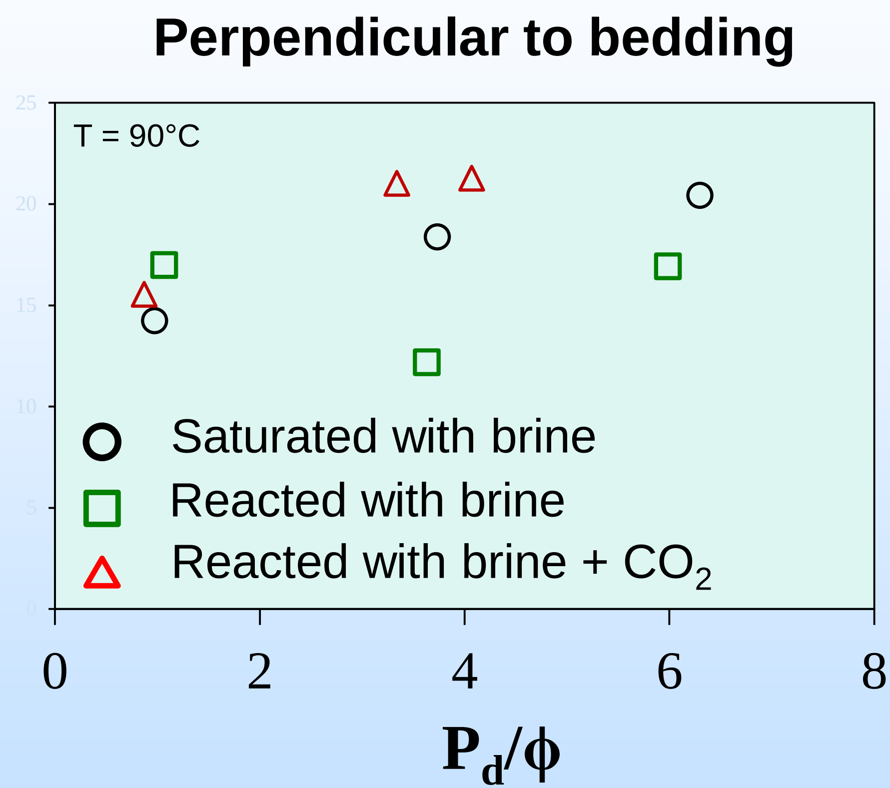


Brittle failure for sandstone reacted with brine and with brine + CO_2

Compiled from Yu et al., 2018, 2018 and 2018 (all submitted)

Geomechanical Results: Shear Modulus (G) of Ss

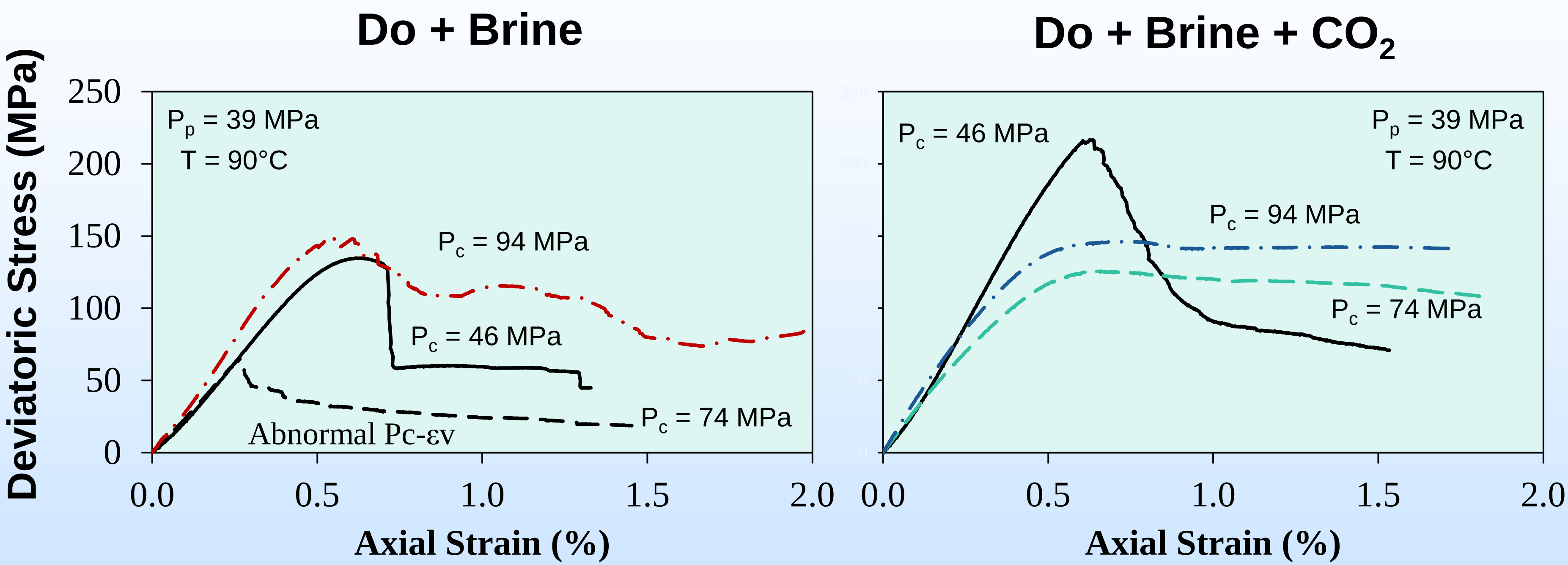




No significant effect due to reaction and anisotropy(?)

Compiled from Yu et al., 2018, 2018 and 2018 (all submitted)

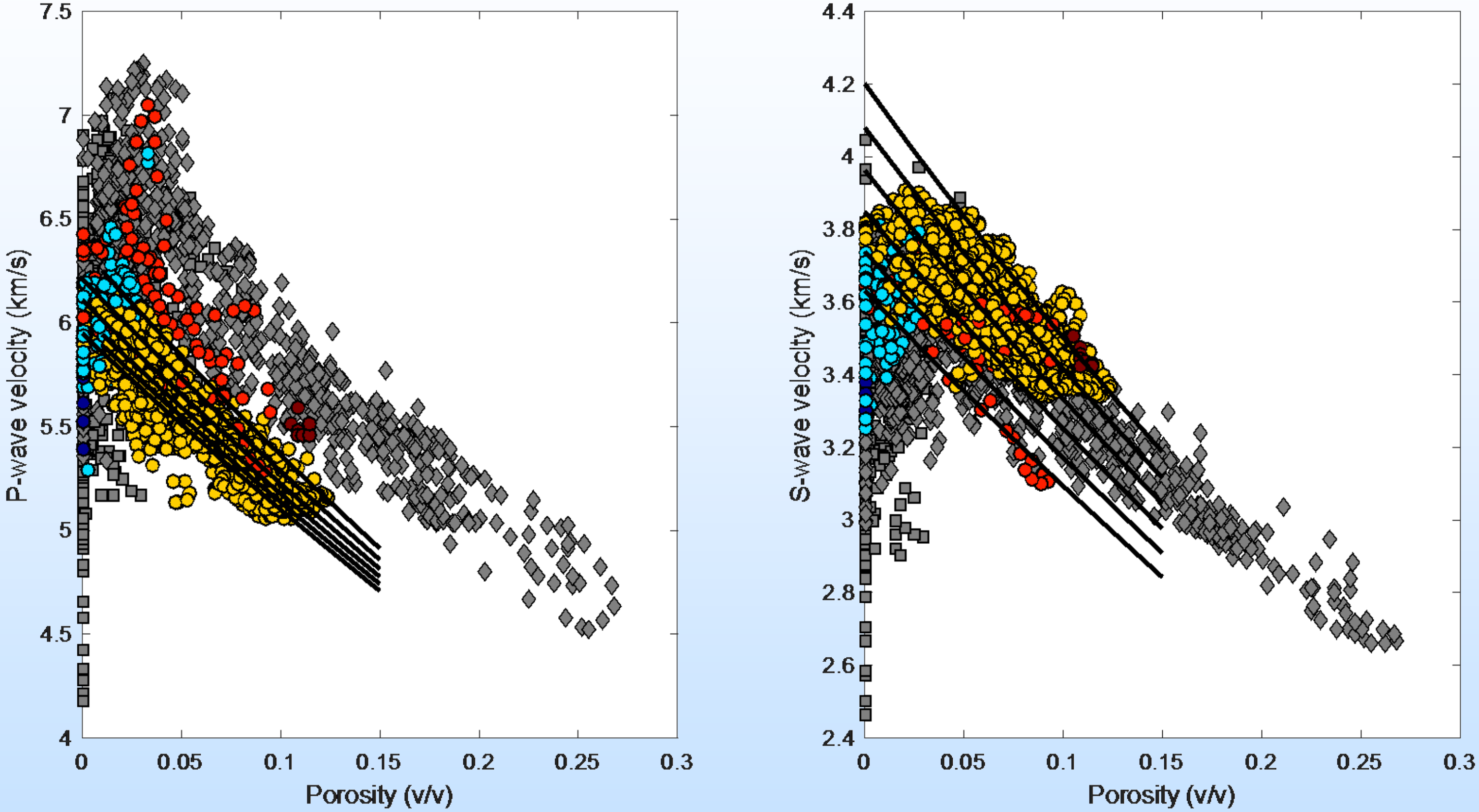
Geomechanical Results: Do Parallel to Bedding



Deformation changed from brittle to ductile at higher differential pressure. Effect of CO_2 on Young's modulus and Poisson's ratio indeterminate

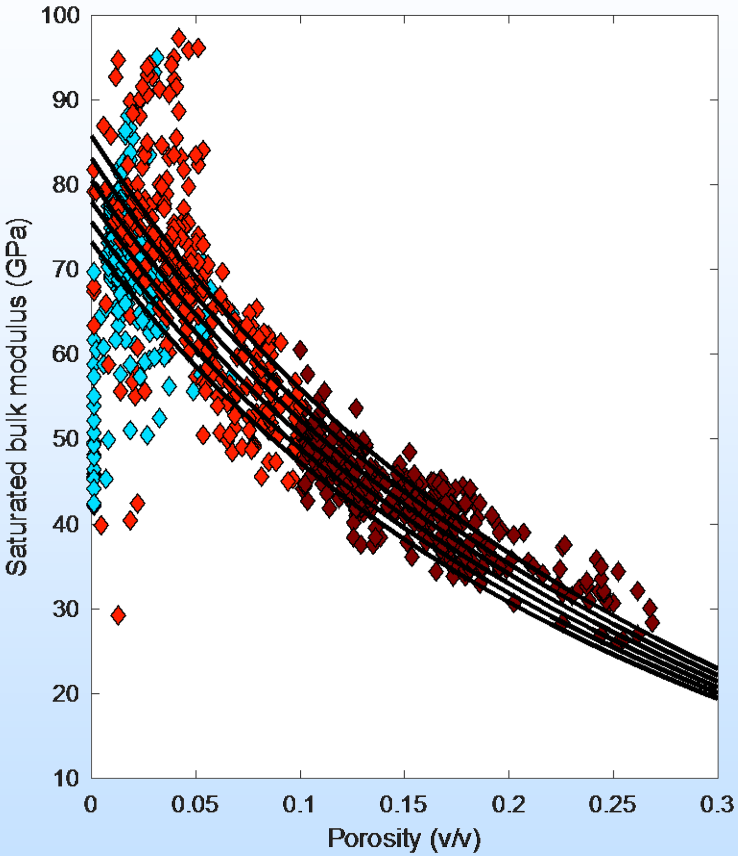
Compiled from Yu et al., 2018, 2018 and 2018 (all submitted)

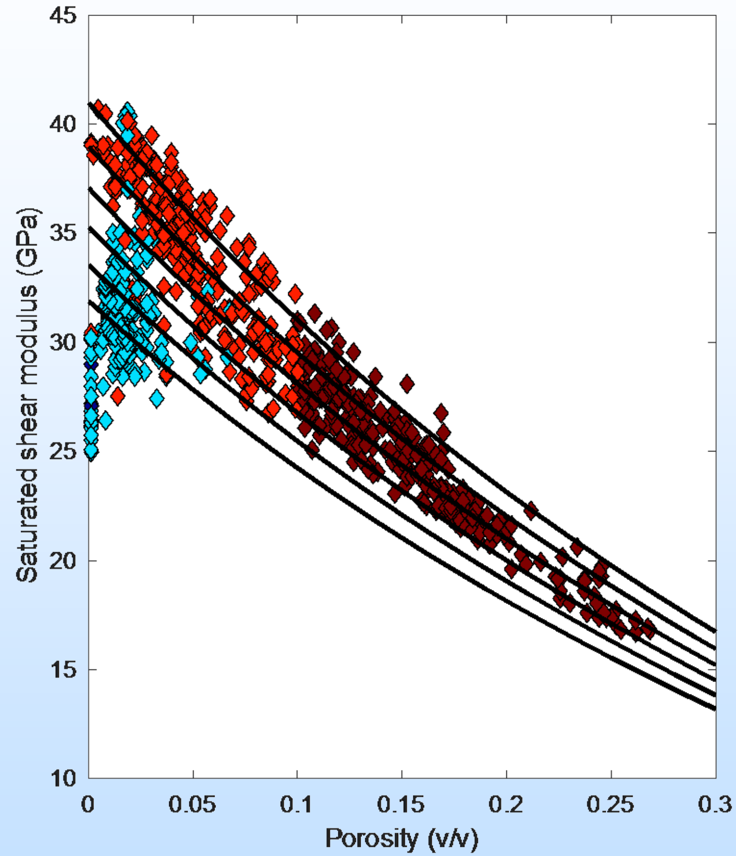
Rock Physics/Seismics
Elastic Properties



Well log data show clear trend in elastic properties. Ss (yellow dots) and Do (grey squares and grey diamonds) can be discriminated by absolute values of P-wave velocity and Vp/Vs

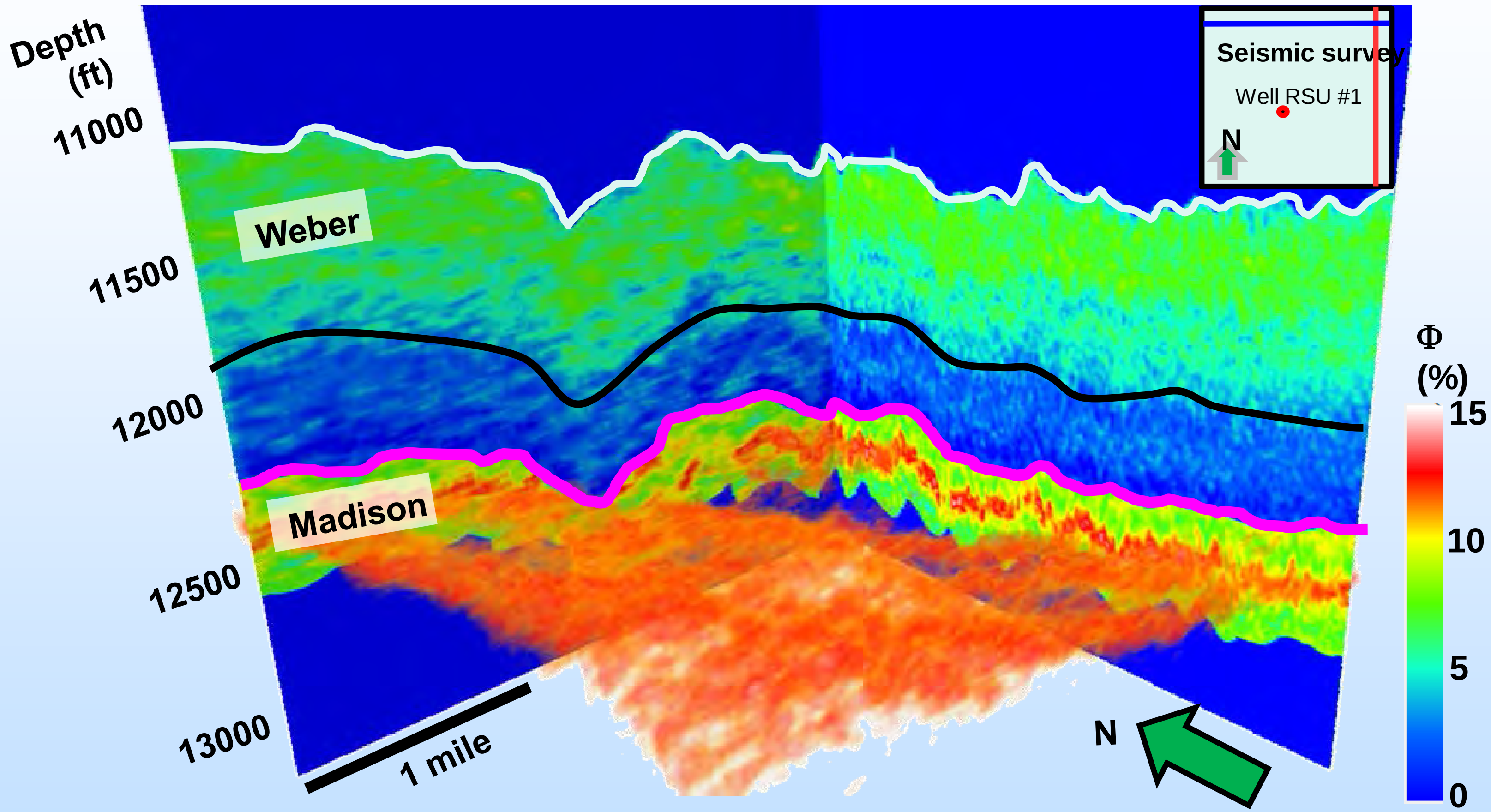
Rock Physics/Seismics Elastic Moduli





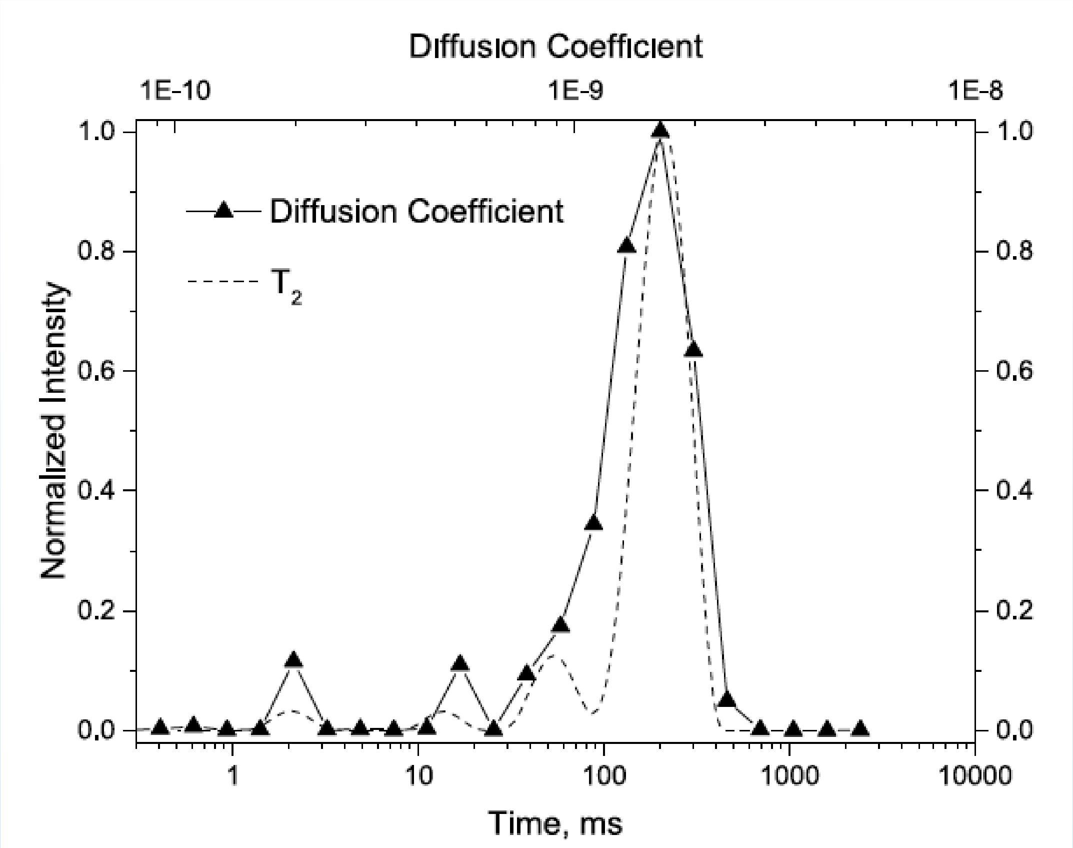
The trend also observed in the elastic moduli. In the Do the saturated-rock bulk and shear moduli decrease as a function of porosity

Rock Physics/Seismics
3D Porosity Model



By combining seismic inversion results and rock physics models, 3D model of porosity was computed for Weber Ss & Madison Ls.

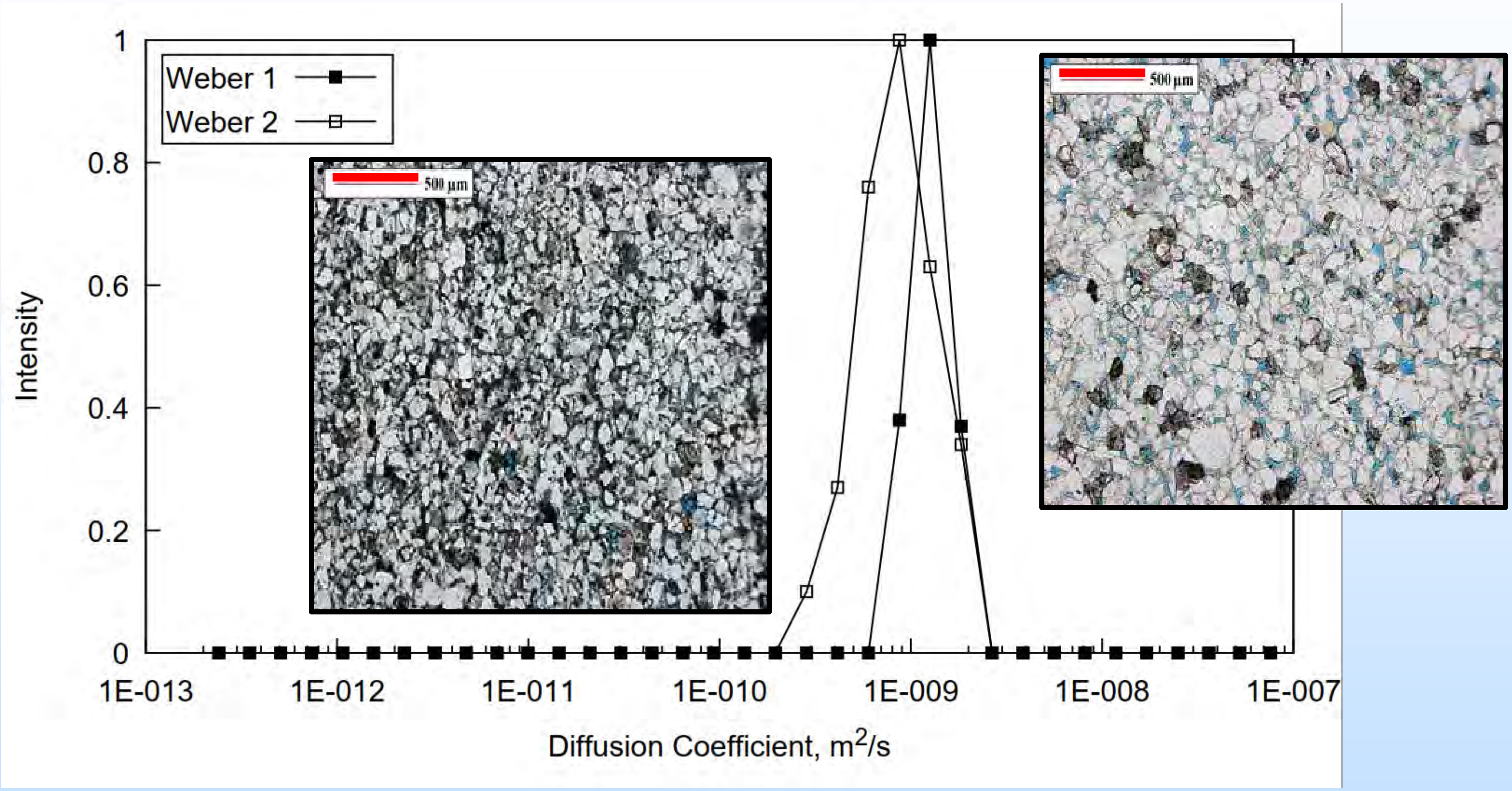
Petrophysics
NMR T_2 and Diffusion Coefficient



Diffusion coefficient distribution derived by regularized Inverse Laplace Transform method compares well to NMR T_2 distribution.

Wang and Alvarado 2018

Petrophysics
Diffusion Coefficient Weber Ss



Diffusion coefficient represents pore-size distribution. Quartz overgrowth and cements (calcite and anhydrite) in Weber 2 produces smaller diffusion coefficient.

Wang et al., 2018

Accomplishments to Date

- Completed geomechanical characterization of Weber Sandstone and Madison Limestone
- Completed detailed geophysical reservoir characterization
- Developed accurate rock physics modeling linking elastic and petrophysical properties
- Demonstrated that diffusion coefficient distribution is similar to NMR T2 distribution
- Used T2 distribution to characterize pore size distribution Weber Ss and Madison Ls
- **Two PhD students successfully defended, now postdocs**
- **Papers in refereed literature: 2 published, 1 in press, 3 in review, 2 in preparation**

Lessons Learned

- Difficulties in running high temperature and pressure triaxial experiments
- Need of high-resolution seismic data for seismic reservoir characterization
- Need of time-lapse seismic and electromagnetic data for reservoir monitoring
- **Reminder of the challenge of multiple disciplines on one project**

Synergy Opportunities

- Hosted Dr. P. Newell (University of UT) for seminar; potential collaboration with to model geomechanical data
- Integration of rock physics and reservoir characterization with laboratory experiments (Dr. M. Prasad, CSM)
- Integration of rock physics and reservoir characterization with fluid flow simulation (Dr. M. Wheeler, UT)
- **Special issue published in 2017, SEG journal *Interpretations* (Editor Dr. Grana, guest editors Dr's Alvarado, Wheeler, Prasad, and Kaszuba)**
- Collaboration with Center for Economic Geology Research, UW on JGR paper (McLaughlin, Bagdonas)

Project Summary

- Apparent effect of CO_2 on geomechanical behavior not observed on Weber Ss but on Madison Ss
- Accurate rock physics and seismic reservoir modeling improve the model predictions
- NMR T2 distribution and short time-limit diffusion coefficient distribution used to characterize Weber Ss and Madison Ls
- Geophysical responses to microstructural and petrophysical change for Weber Ss samples after CO_2 reaction not obvious

Questions?

Appendix

Benefit to the Program

- Program goals addressed:
  - Develop and validate technologies to ensure 99% storage performance
  - 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.

Benefit to the Program

- 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 estimated 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 CO2 injection, if successful, could increase the accuracy of subsurface models that predict the integrity of the storage reservoir.

Project Overview

Goals and Objectives

- Overall Objective: Improve understanding of the effects of CO_2 injection and storage on geomechanical, petrophysical, and other reservoir properties.
  1. Combines integrated, interdisciplinary methodology using existing data sets (Rock Springs Uplift in Wyoming)
  2. Culminates in integrated workflow for potential CO_2 storage operations

- 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

Project Overview

Goals and Objectives

- Specific Objectives (continued)

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 reacted reservoir rock and comparing the results to preexisting triaxial data available for reservoir rocks
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 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.

Organization Chart

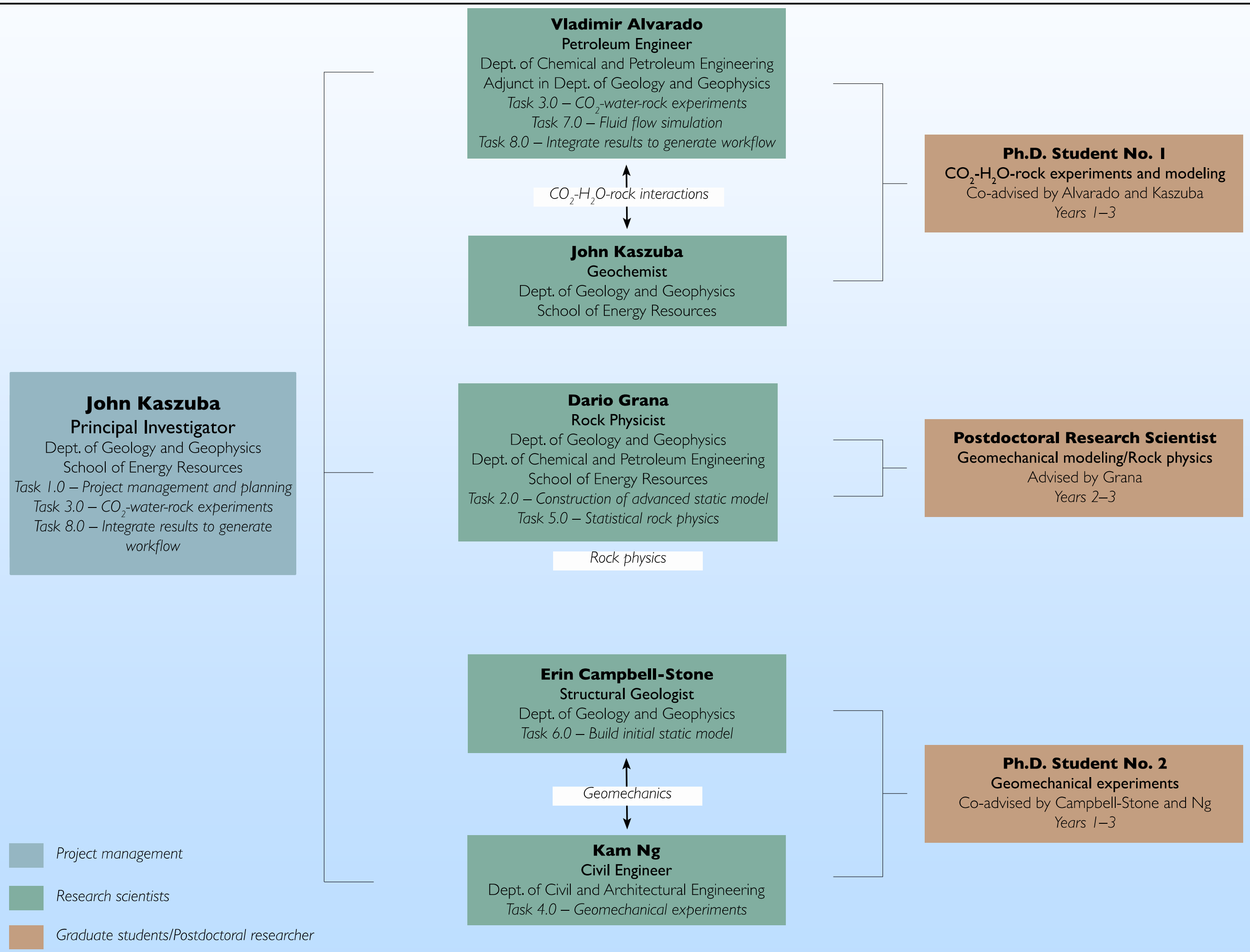
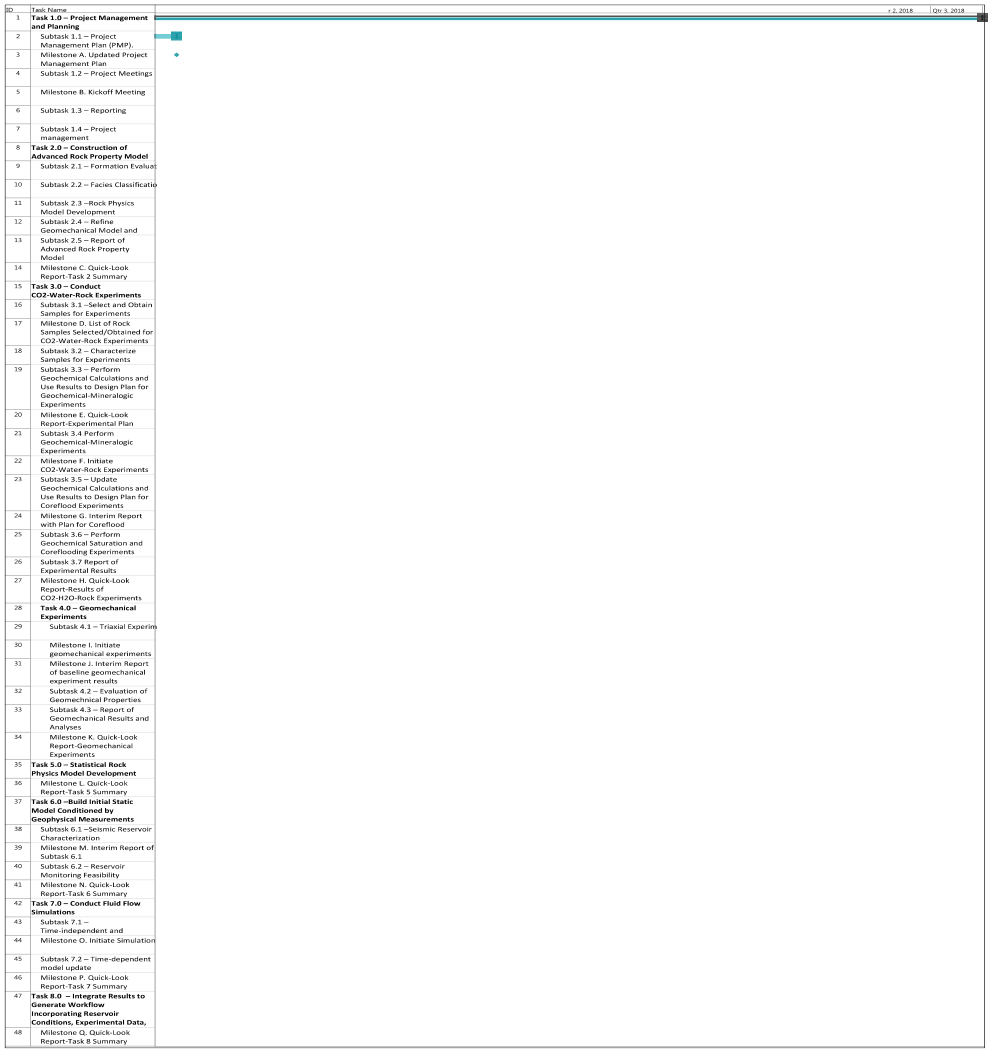


Figure 1. Organizational chart.

Gantt Chart


ID
Task Name
r 2, 2018
Qtr 3, 2018
1 Task 1.0 – Project Management and Planning
2 Subtask 1.1 – Project Management Plan (PMP).
3 Milestone A. Updated Project Management Plan
4 Subtask 1.2 – Project Meetings
5 Milestone B. Kickoff Meeting
6 Subtask 1.3 – Reporting
7 Subtask 1.4 – Project management
8 Task 2.0 – Construction of Advanced Rock Property Model
9 Subtask 2.1 – Formation Evaluat
10 Subtask 2.2 – Facies Classificatio
11 Subtask 2.3 –Rock Physics Model Development
12 Subtask 2.4 – Refine Geomechanical Model and
13 Subtask 2.5 – Report of Advanced Rock Property Model
14 Milestone C. Quick-Look Report-Task 2 Summary
15 Task 3.0 – Conduct CO2-Water-Rock Experiments
16 Subtask 3.1 –Select and Obtain Samples for Experiments
17 Milestone D. List of Rock Samples Selected/Obtained for CO2-Water-Rock Experiments
18 Subtask 3.2 – Characterize Samples for Experiments
19 Subtask 3.3 – Perform Geochemical Calculations and Use Results to Design Plan for Geochemical-Mineralogic Experiments
20 Milestone E. Quick-Look Report-Experimental Plan
21 Subtask 3.4 Perform Geochemical-Mineralogic Experiments
22 Milestone F. Initiate CO2-Water-Rock Experiments
23 Subtask 3.5 – Update Geochemical Calculations and Use Results to Design Plan for Coreflood Experiments
24 Milestone G. Interim Report with Plan for Coreflood
25 Subtask 3.6 – Perform Geochemical Saturation and Coreflooding Experiments
26 Subtask 3.7 Report of Experimental Results
27 Milestone H. Quick-Look Report-Results of CO2-H2O-Rock Experiments
28 Task 4.0 – Geomechanical Experiments
29 Subtask 4.1 – Triaxial Experim
30 Milestone I. Initiate geomechanical experiments
31 Milestone J. Interim Report of baseline geomechanical experiment results
32 Subtask 4.2 – Evaluation of Geomechnical Properties
33 Subtask 4.3 – Report of Geomechanical Results and Analyses
34 Milestone K. Quick-Look Report-Geomechanical Experiments
35 Task 5.0 – Statistical Rock Physics Model Development
36 Milestone L. Quick-Look Report-Task 5 Summary
37 Task 6.0 –Build Initial Static Model Conditioned by Geophysical Measurements
38 Subtask 6.1 –Seismic Reservoir Characterization
39 Milestone M. Interim Report of Subtask 6.1
40 Subtask 6.2 – Reservoir Monitoring Feasibility
41 Milestone N. Quick-Look Report-Task 6 Summary
42 Task 7.0 – Conduct Fluid Flow Simulations
43 Subtask 7.1 – Time-independent and
44 Milestone O. Initiate Simulation
45 Subtask 7.2 – Time-dependent model update
46 Milestone P. Quick-Look Report-Task 7 Summary
47 Task 8.0 – Integrate Results to Generate Workflow Incorporating Reservoir Conditions, Experimental Data,
48 Milestone Q. Quick-Look Report-Task 8 Summary

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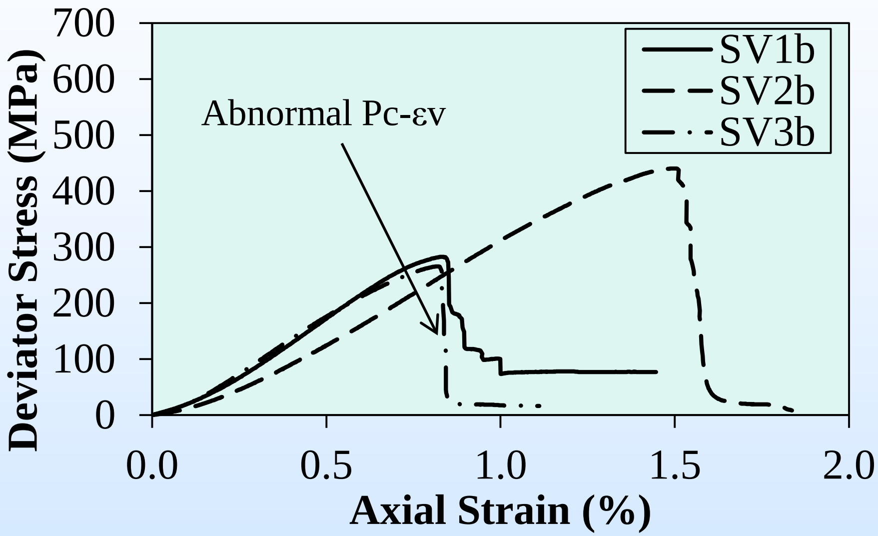
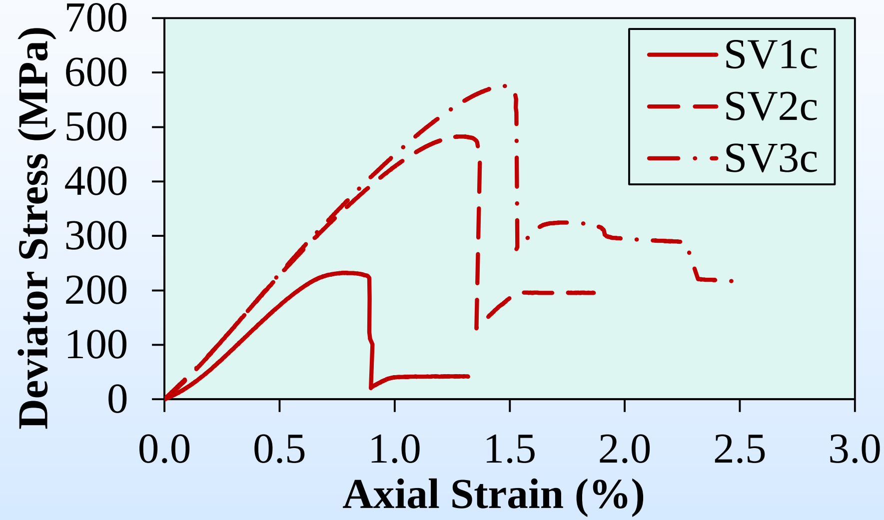
Appendix – Technical Data

Geochemical Preparation	Sample ID	Depth (m)	(MPa)	(MPa)	P_d (MPa)	T (°C)
Group 1: Saturated with brine for 24 hours	SV1	3527.21	43.4	35.4	8.0	90
	SH1	3415.97				
	SV2	3527.24	71.0		35.6	
	SH2	3416.83				
	SV3	3527.08	91.7		56.3	
	SH3	3416.80				
Group 2: Aged with brine for 800 hours	SV1b	3415.6-3417.5	43.4	35.4	8.0	90
	SH1b	3413.8-3415.6				
	SV2b	3413.8-3415.6	71.0		35.6	
	SH2b	3413.8-3415.6				
	SV3b	3413.8-3415.6	91.7		56.3	
	SH3b	3413.8-3415.6				
	DH1b	3765.1-3767.0	46.2	39.3	6.9	93
	DH2b	3784.4-3786.2	73.8		34.5	
	DH3b	3763.4-3765.9	94.5		55.2	
Group 3: Aged with brine for 400 hours + CO_2 for 400 hours	SV1c	3413.8-3415.6	43.4	35.4	8.0	90
	SH1c	3413.8-3415.6				
	SV2c	3413.8-3415.6	71.0		35.6	
	SH2c	3526.4-3528.2				
	SV3c	3413.8-3415.6	91.7		56.3	
	SH3c	3413.8-3415.6				
	DH1c	3765.1-3767.0	46.2	39.3	6.9	93
	DH2c	3765.1-3767.0	73.8		35.6	
	DH3c	3765.1-3767.0	94.5		56.3	

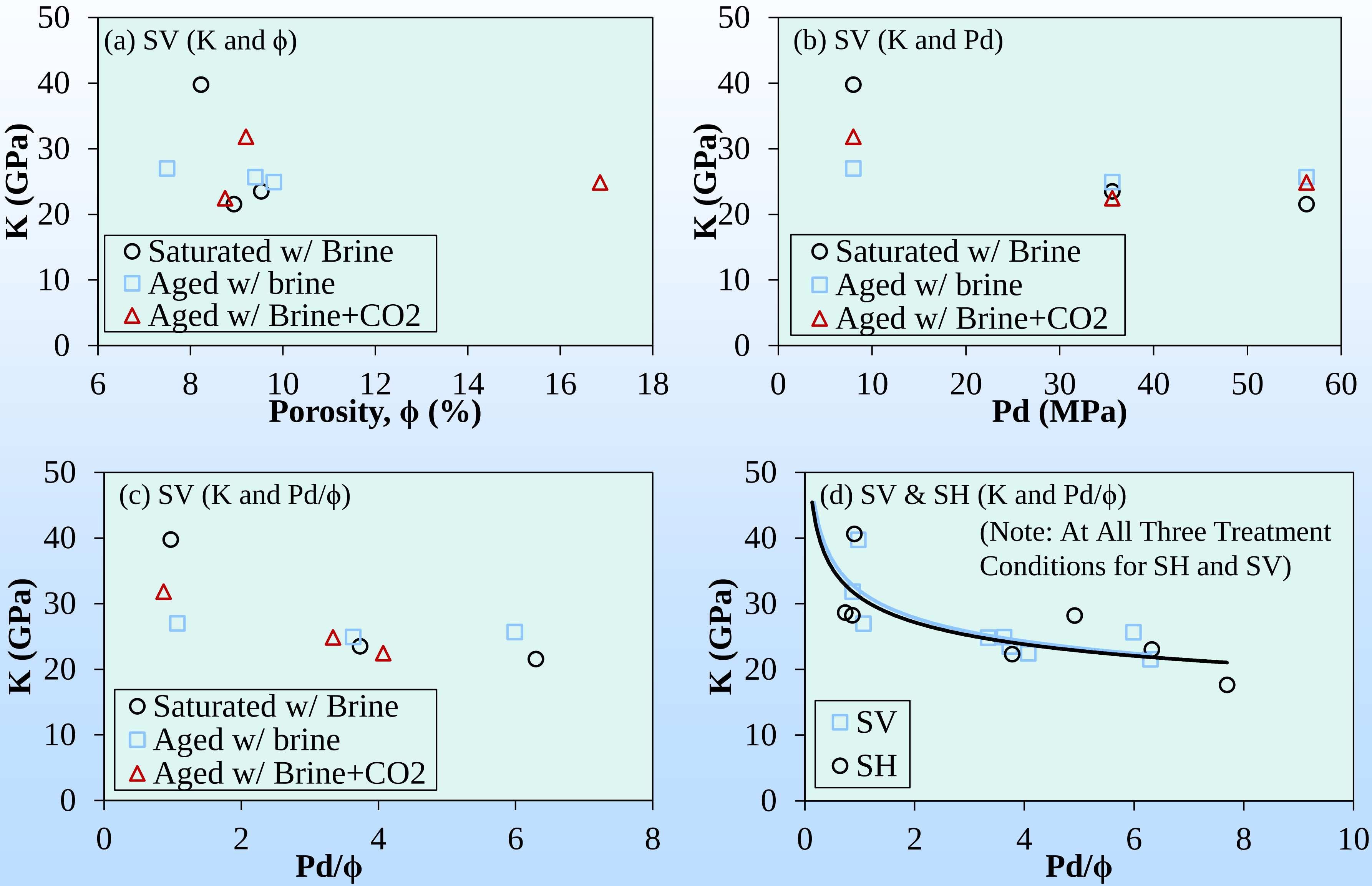
Geomechanical Results: Vertical Sandstone



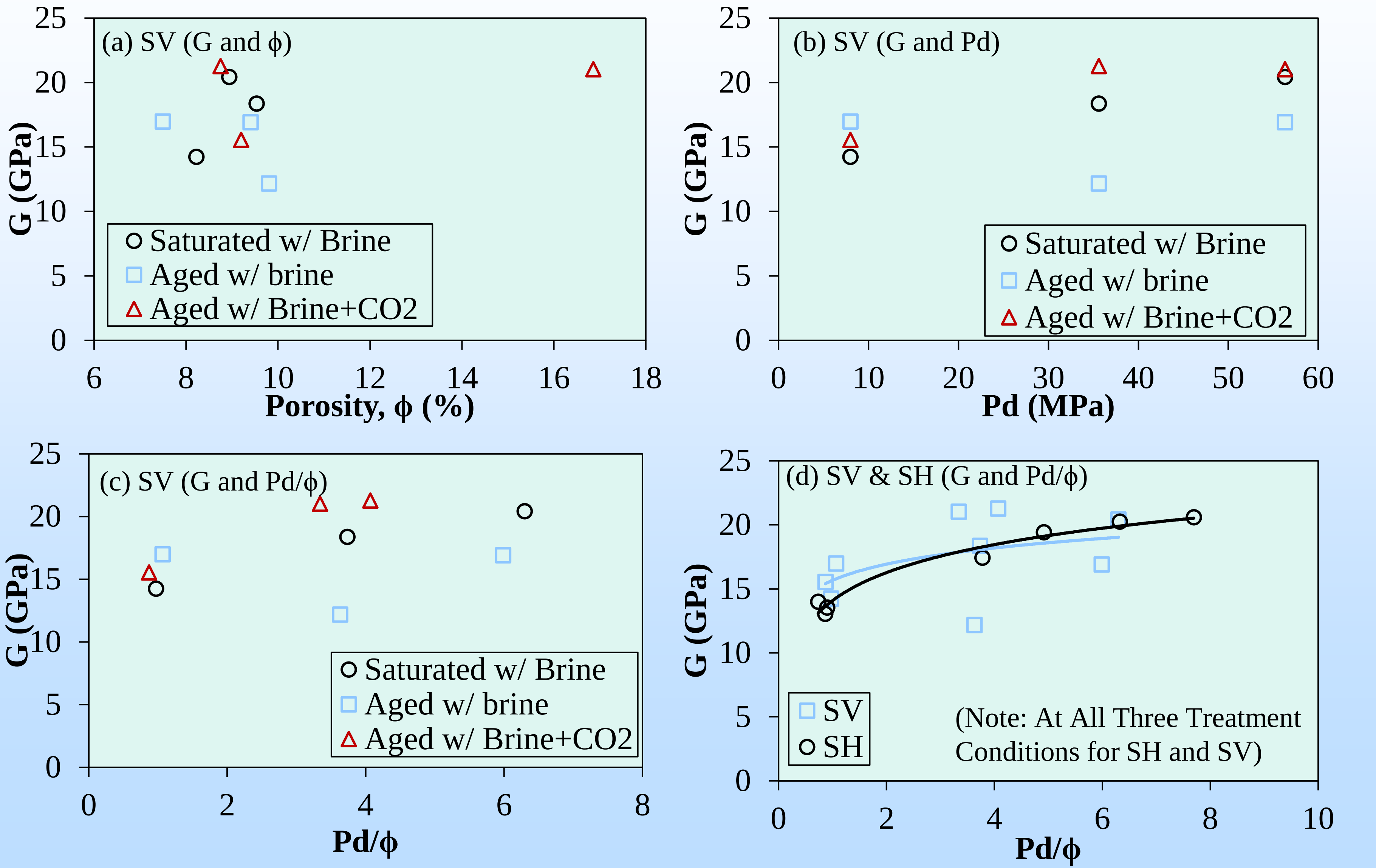


Sample ID	P_d (MPa)	ϕ (%)	E (GPa)	ΔE (%)	υ	$\Delta\upsilon$ (%)	σ_{pk} (MPa)	$\Delta\sigma_{pk}$ (%)
SV1b	8	7.494	42.1	-4.8	0.24	20.8	282.7	-17.9
SV1c		9.201	40.1		0.29		232.2	
SV2b	35.6	9.801	31.4	54.5	0.29	-51.7	440.3	9.6
SV2c		8.750	48.5		0.14		482.7	
SV3b[$]	56.3	9.404	41.6	18.3	0.23	-26.1	265.6	116.7
SV3c		16.859	49.2		0.17		575.6	

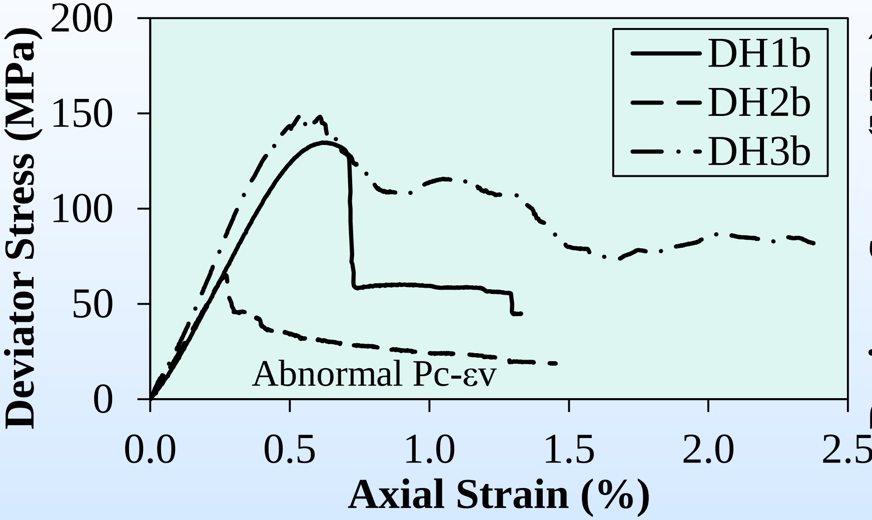
Geomechanical Results: Bulk Modulus (K) of Sandstone

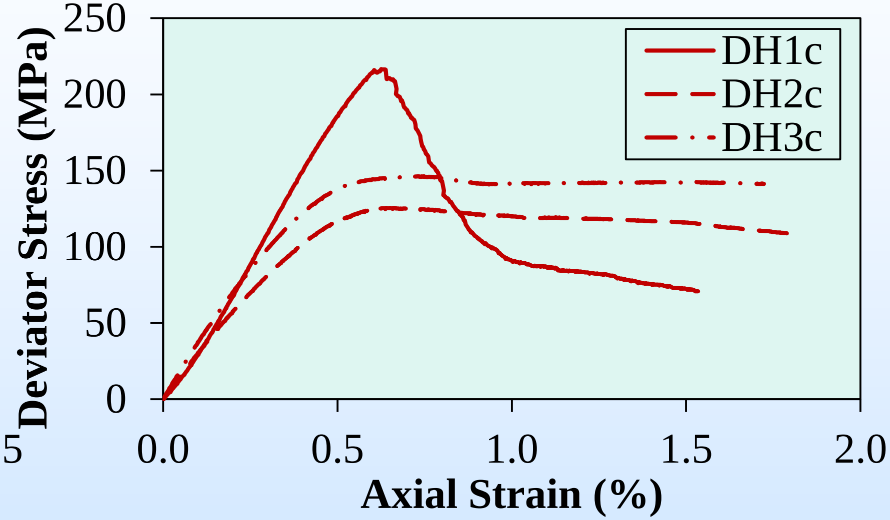


Geomechanical Results: Shear Modulus (G) of Sandstone



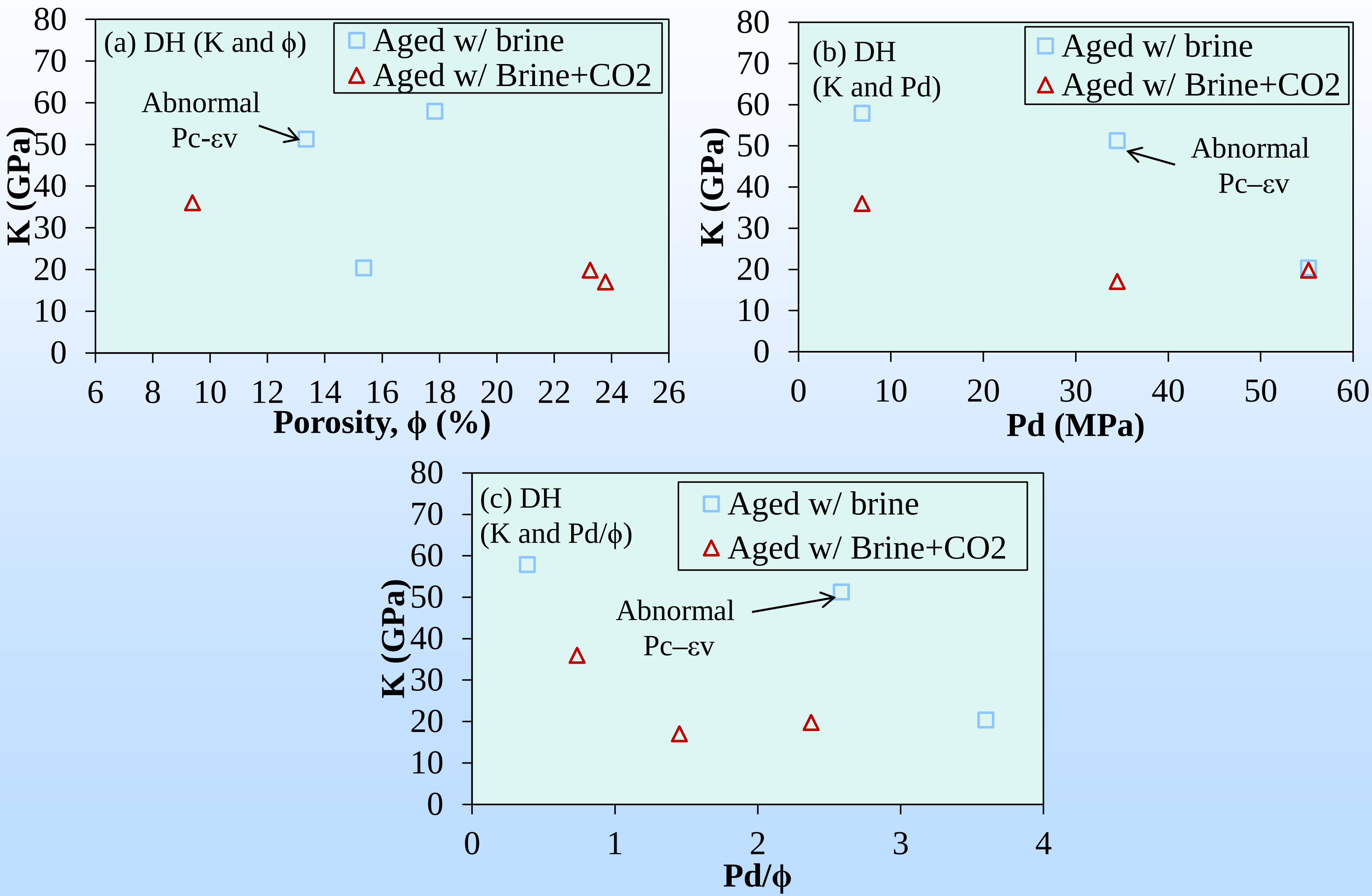
Geomechanical Results: Horizontal Dolomite





Sample ID	ϕ (%)	E (GPa)	ΔE (%)	υ	$\Delta\upsilon$ (%)	σ_{pk} (MPa)	$\Delta\sigma_{pk}$ (%)
DH1b	17.834	27.8	47.5	0.42	-26.2	134.7	60.7
DH1c	9.384	41.0		0.31		216.5	
DH2b$	13.345	24.6	-0.4	0.42	-38.1	65.2	92.6
DH2c	23.784	24.5		0.26		125.6	
DH3b	15.352	34.2	-13.2	0.22	13.6	150.0	-2.5
DH3c	23.256	29.7		0.25		146.2	

Geomechanical Results: Bulk Modulus (K) of Dolomite



Geomechanical Results: Shear Modulus (G) of Dolomite