Interdisciplinary investigation of CO_2 sequestration in depleted shale gas formations

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Developing the Technologies and
Infrastructure for CCS

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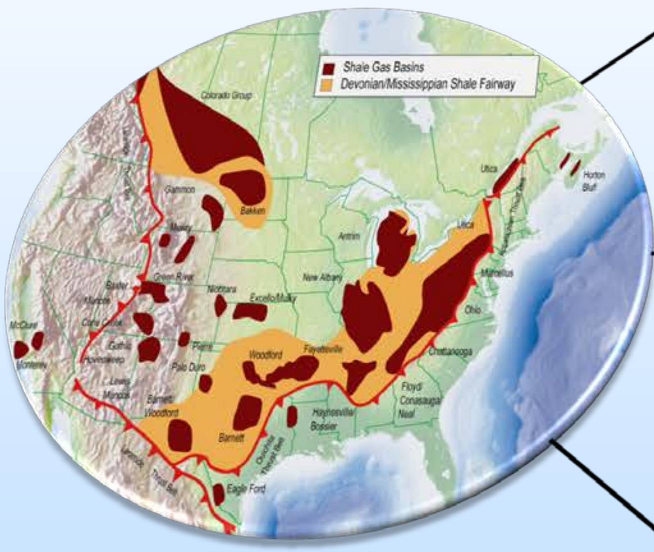
Presentation Outline

- Research Objectives and Benefits to the Program
- Technical Status
  - Transport
  - Storage
  - Geomechanics
- Summary / Accomplishments

Research Objectives and Benefits to the Program

- Spectacular development of shale gas plays in the US offers a massive opportunity for CCS applications in the near future.
- Effective CO_2 sequestration strategies rely on solid understanding of local fluid/rock properties under in-situ post-production conditions.
- Our work integrates laboratory and theoretical studies and aims at developing a realistic description of multi-scale transport, storage mechanisms and geomechanical behavior of gas shales.

Technical Status



Transport

- free/adsorbed CO_2
- permeability anisotropy
- role of fractures
- pore connectivity

Storage

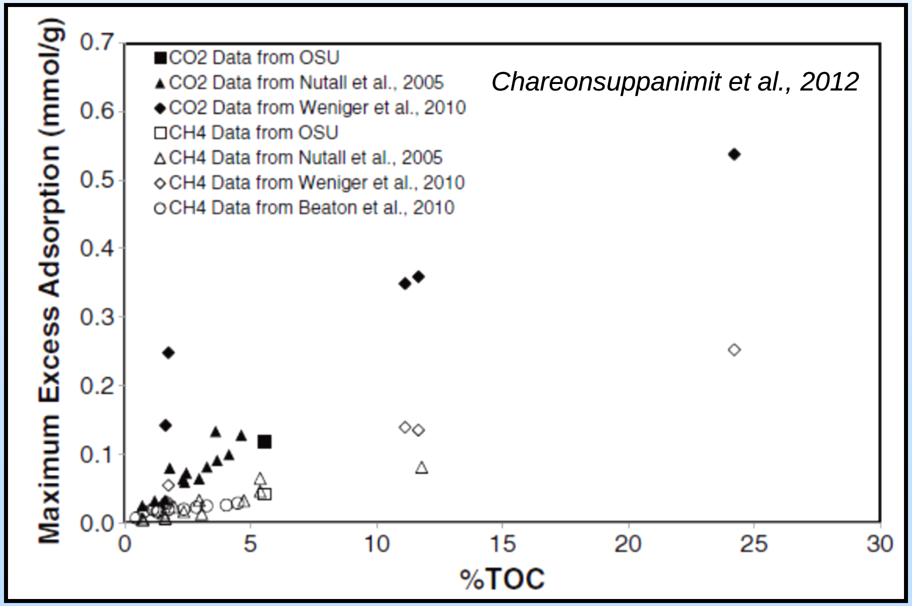
- free/adsorbed CO_2
- pore size distribution
- pore shape

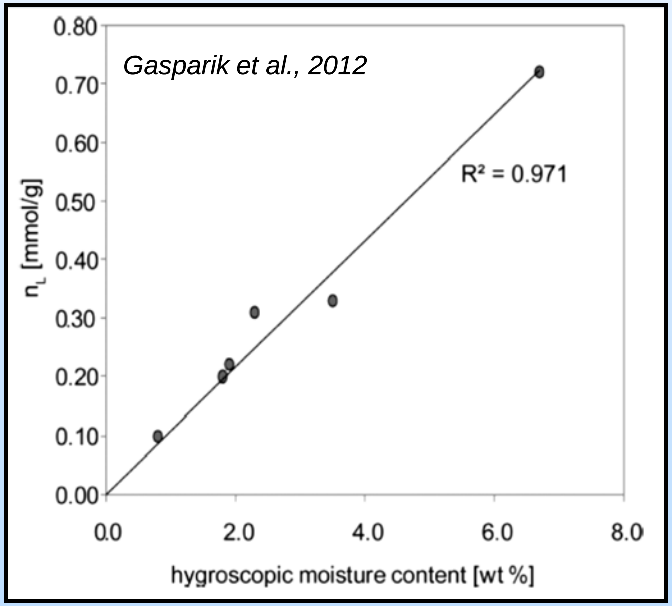
Geo-mechanics

- free/adsorbed CO_2
- instantaneous vs. time-dependent response

Adsorption

- Adsorption related to TOC, H_2O and clay content
- CO_2 adsorption sometimes significant
- Coupling between adsorption, transport and mechanical behavior in shales unclear

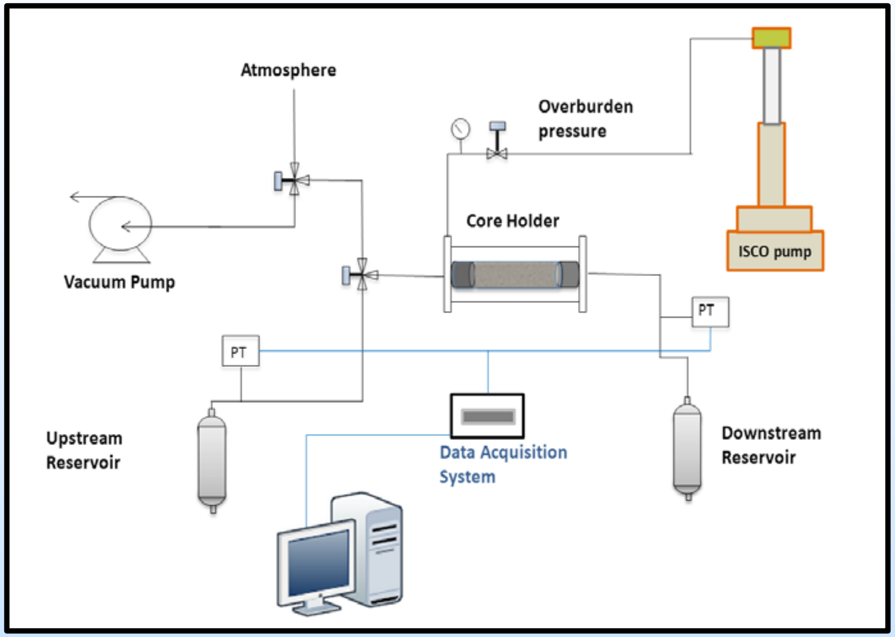


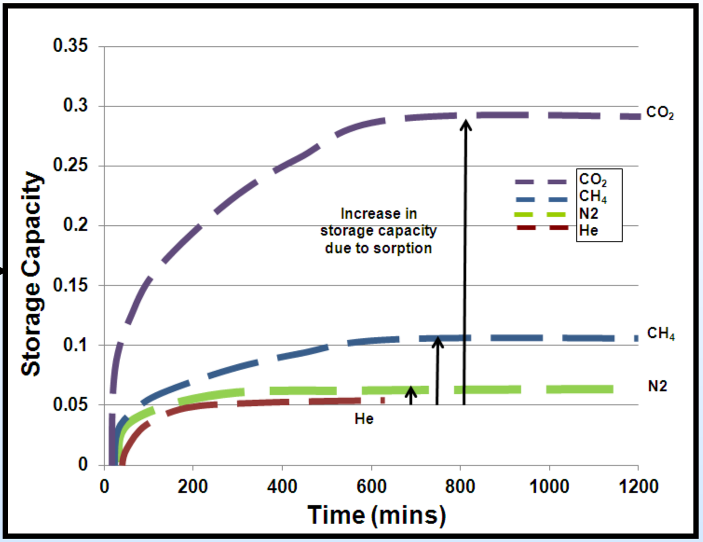


Transport

- Experimental work using pulse-decay method
  - Horizontal ("high") permeability versus vertical ("low") permeability
  - Separate rock permeability(k_∞), slippage effect, and adsorption
- Simulations
  - Comparing Brace (1968), Jones (1976) and history-match methods based on pulse-decay data
  - Non-equilibrium molecular dynamics 3D carbon network
  - Incorporate direct effect of adsorption

Transport





Simultaneous porosity, permeability, and sorption measurement

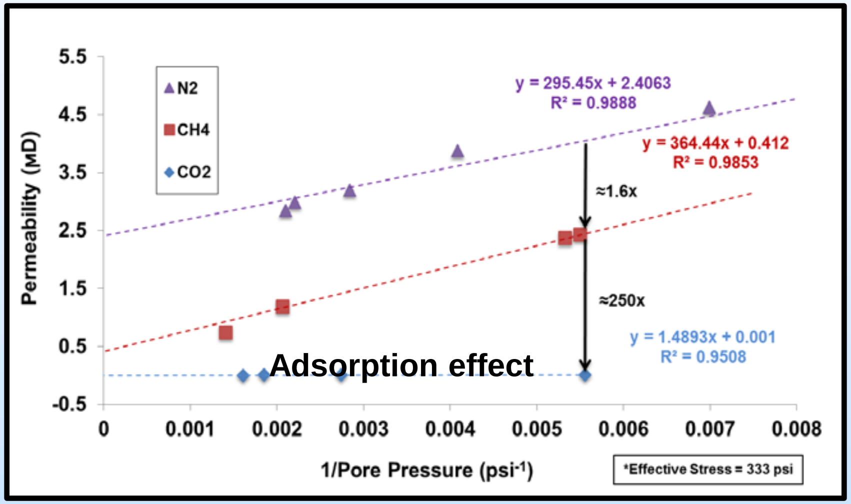
HORIZONTAL SAMPLES !

very little adsorption…

Transport

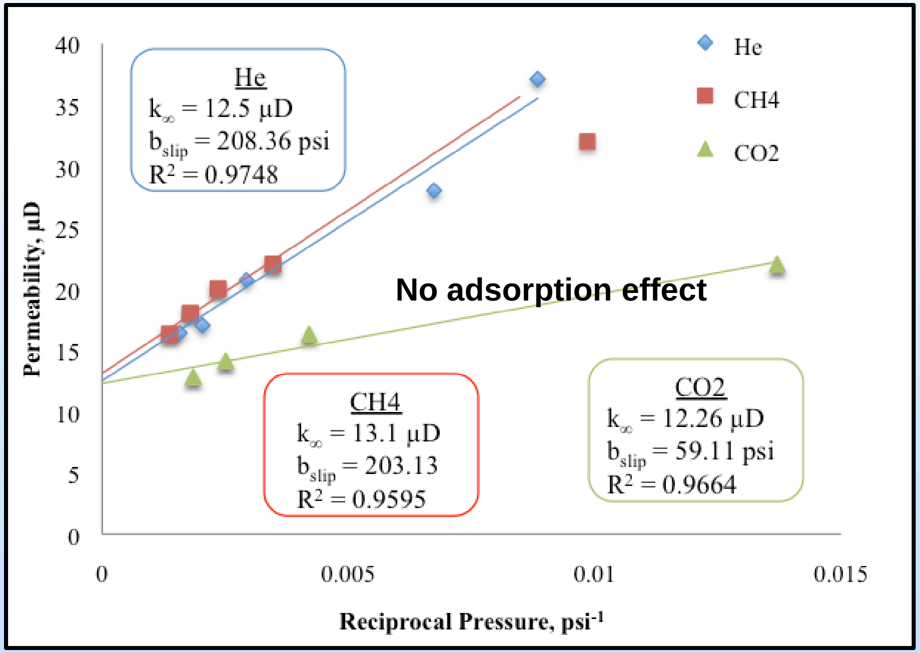
Horizontal permeability when exposed to N_2, CH_4, and CO_2

Barnett Shale



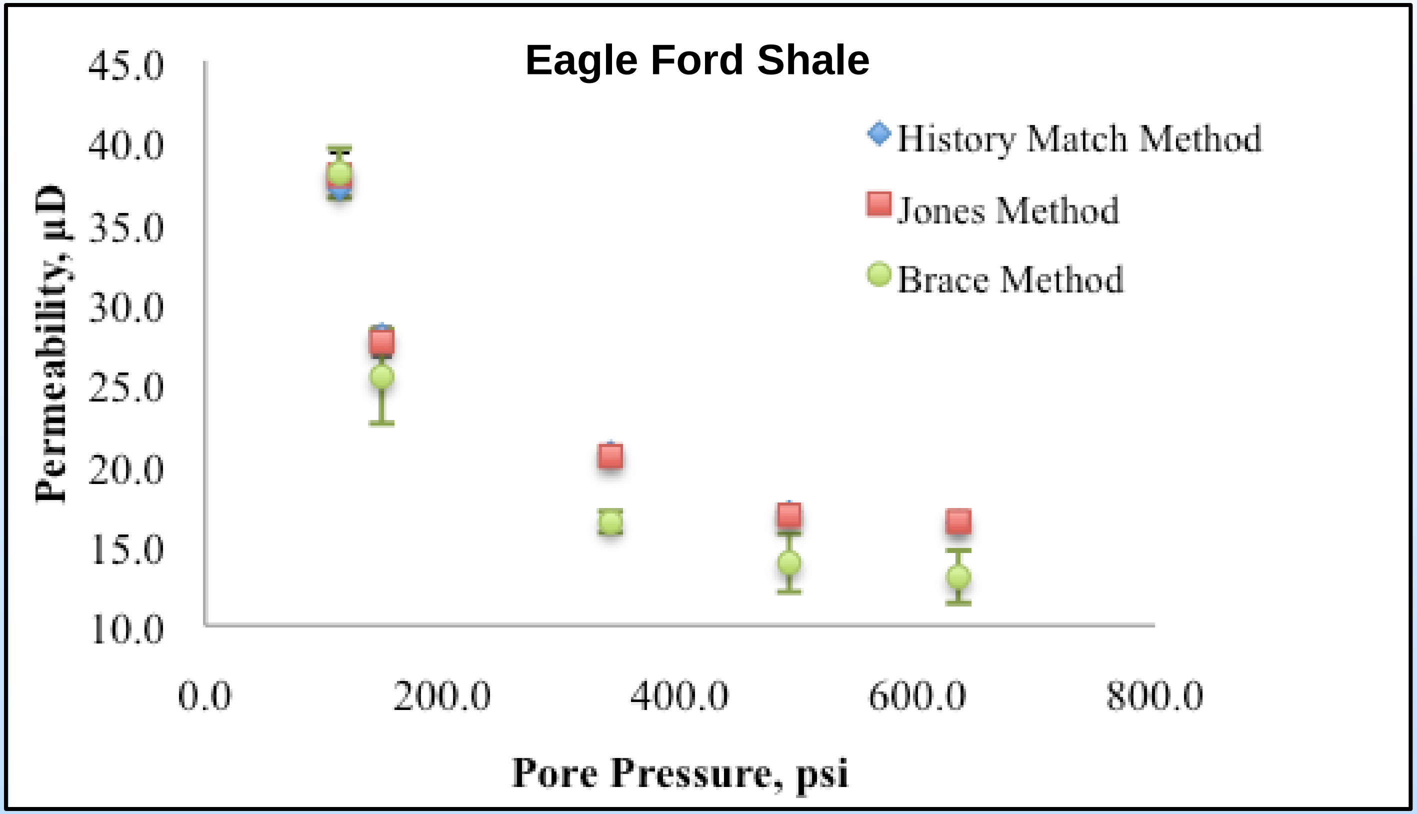
P_f =182 psia Effective Stress =333 psi	N_2	CH_4	CO_2
***K* (мD)**	4.02	2.41	0.009

Eagle Ford Shale



Transport

Simulations based on pulse-decay data on horizontal cores

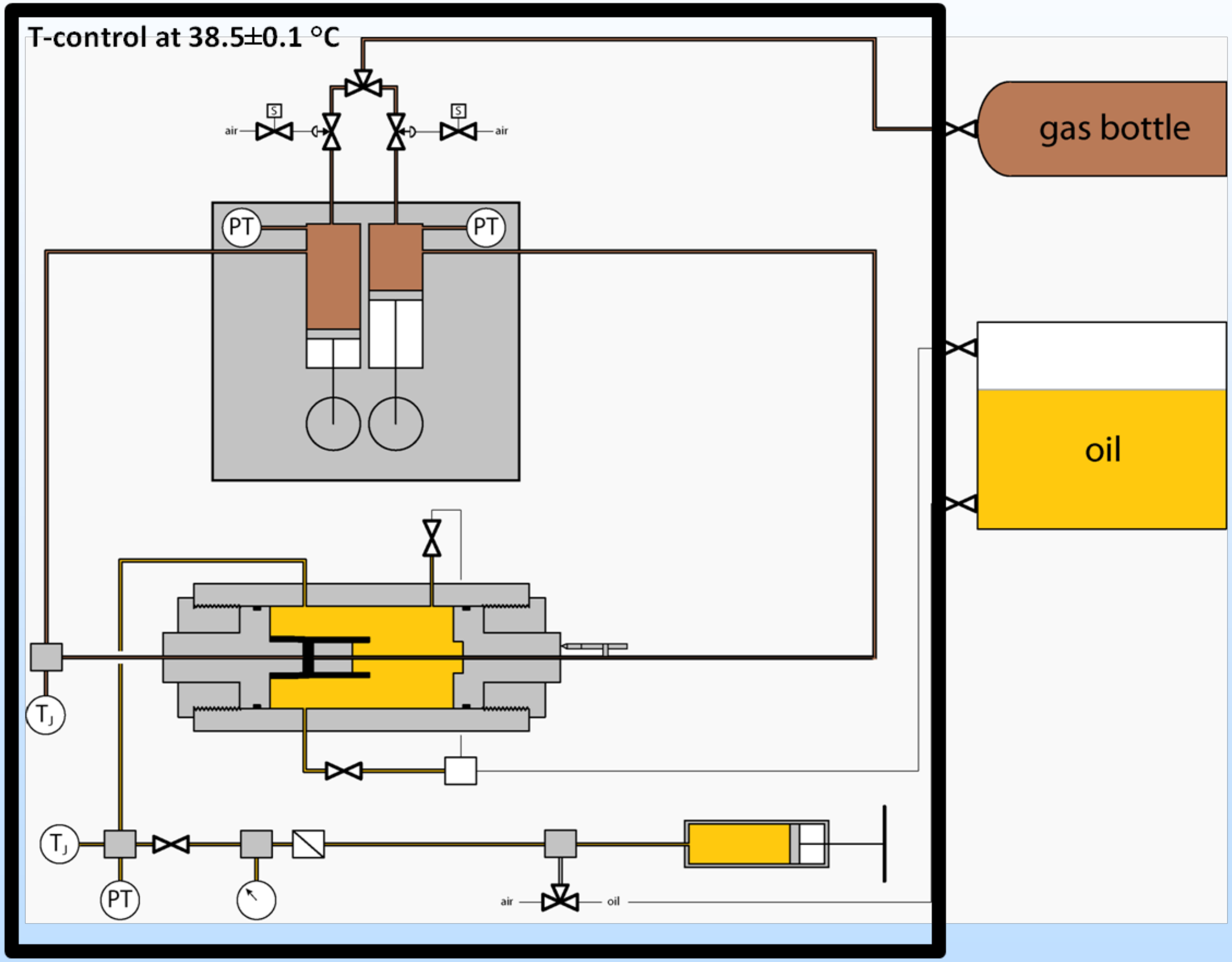


Transport

VERTICAL SAMPLES !

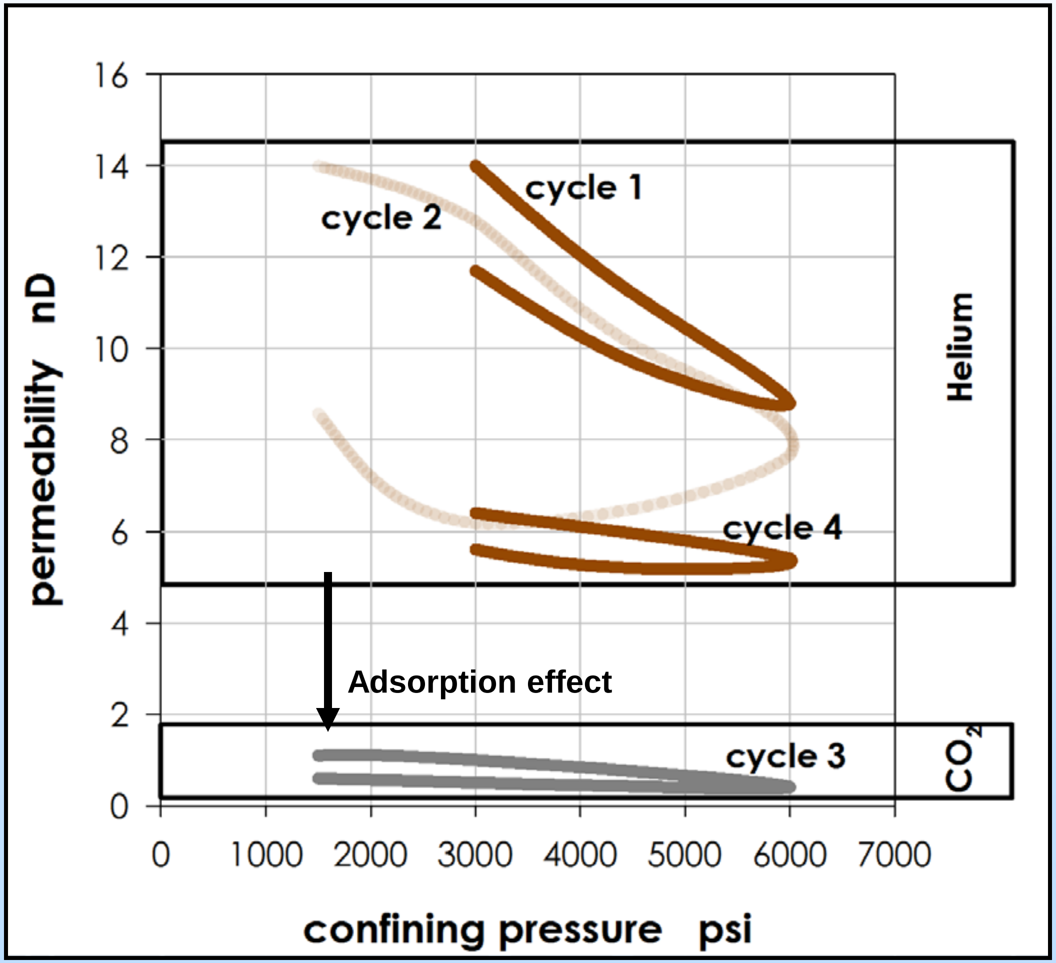
Eagle Ford Shale

disc

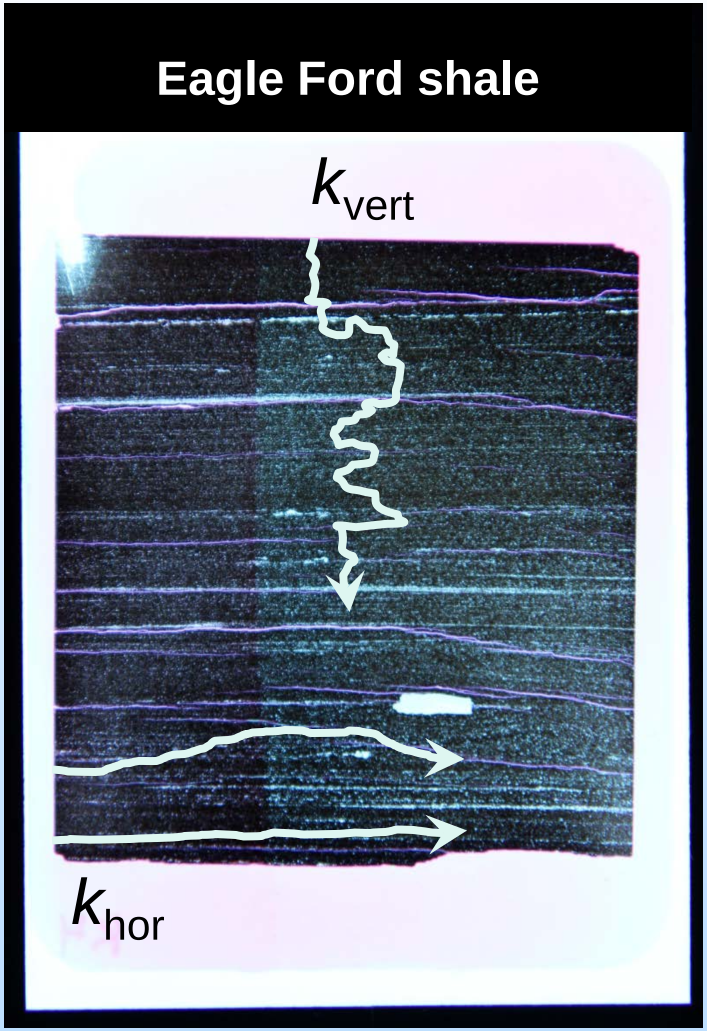


Transport

Vertical permeability when exposed to He and CO_2



Transport

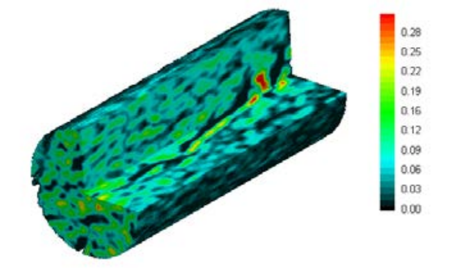


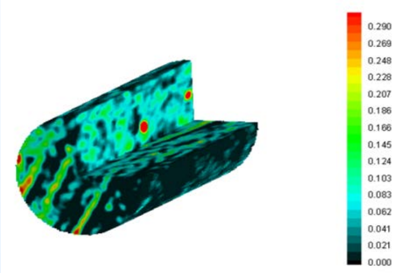
- $k_{hor} >> k_{vert}$ (orders of magnitude)
- related to fractures versus pores (refer to CT work reported previously)
- CO_2 adsorption causes direct and indirect reduction in *k*, *i.e.* ”blocking” versus “swelling”
- Strongly sample-dependent

Transport / Storage

Storage and transport of fluids in porous materials influenced by morphology -> pore connectivity, pore shape, size, and surface characteristics

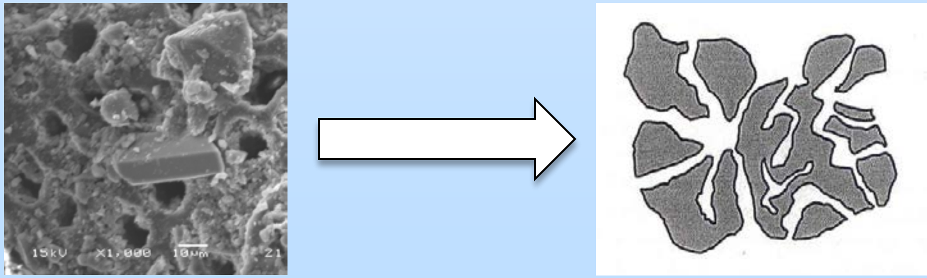
Eagle Ford





Haynesville

Realistic descriptions of local pore characteristics can be achieved by modeling of the solid material itself, and understanding pore structure including pore-size distribution, and pore-network connectivity

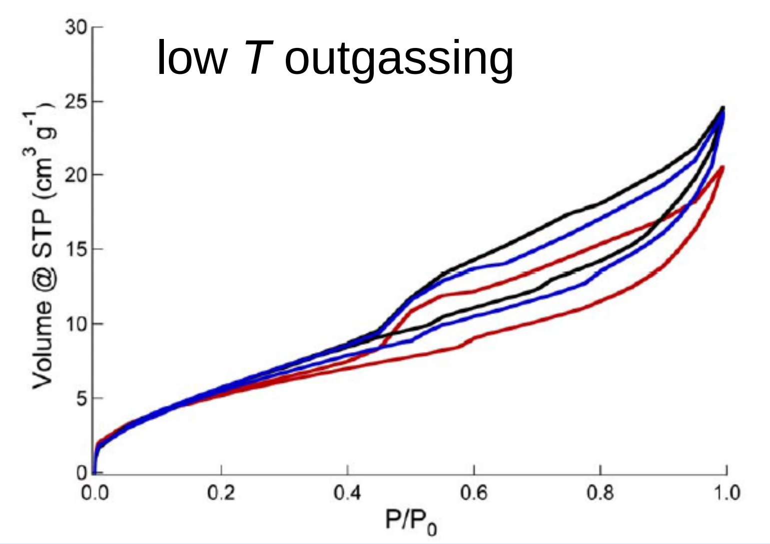


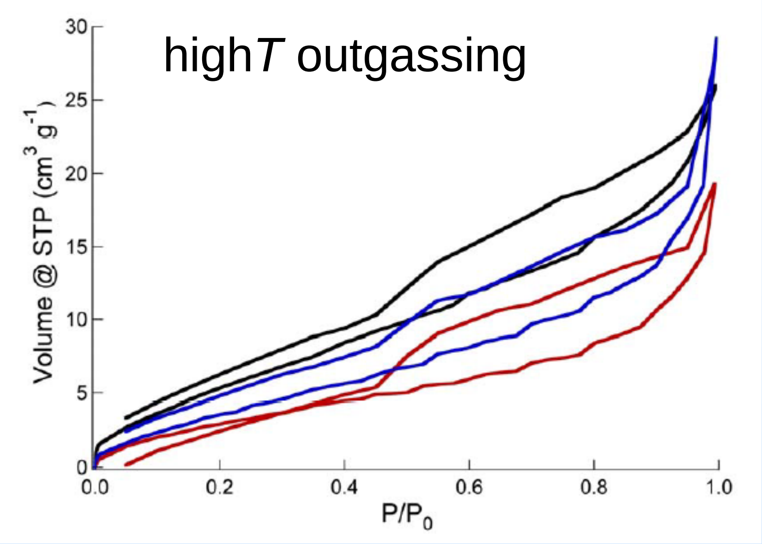
Storage

- Low pressure N_2 adsorption isotherms
  - Quantachrome Autosorb iQ2
- Sample: Eagle Ford shale
  - Pore size distributions
  - Create framework for modeling efforts
  - Link pore scale to fracture scale

Storage

Eagle Ford Shale

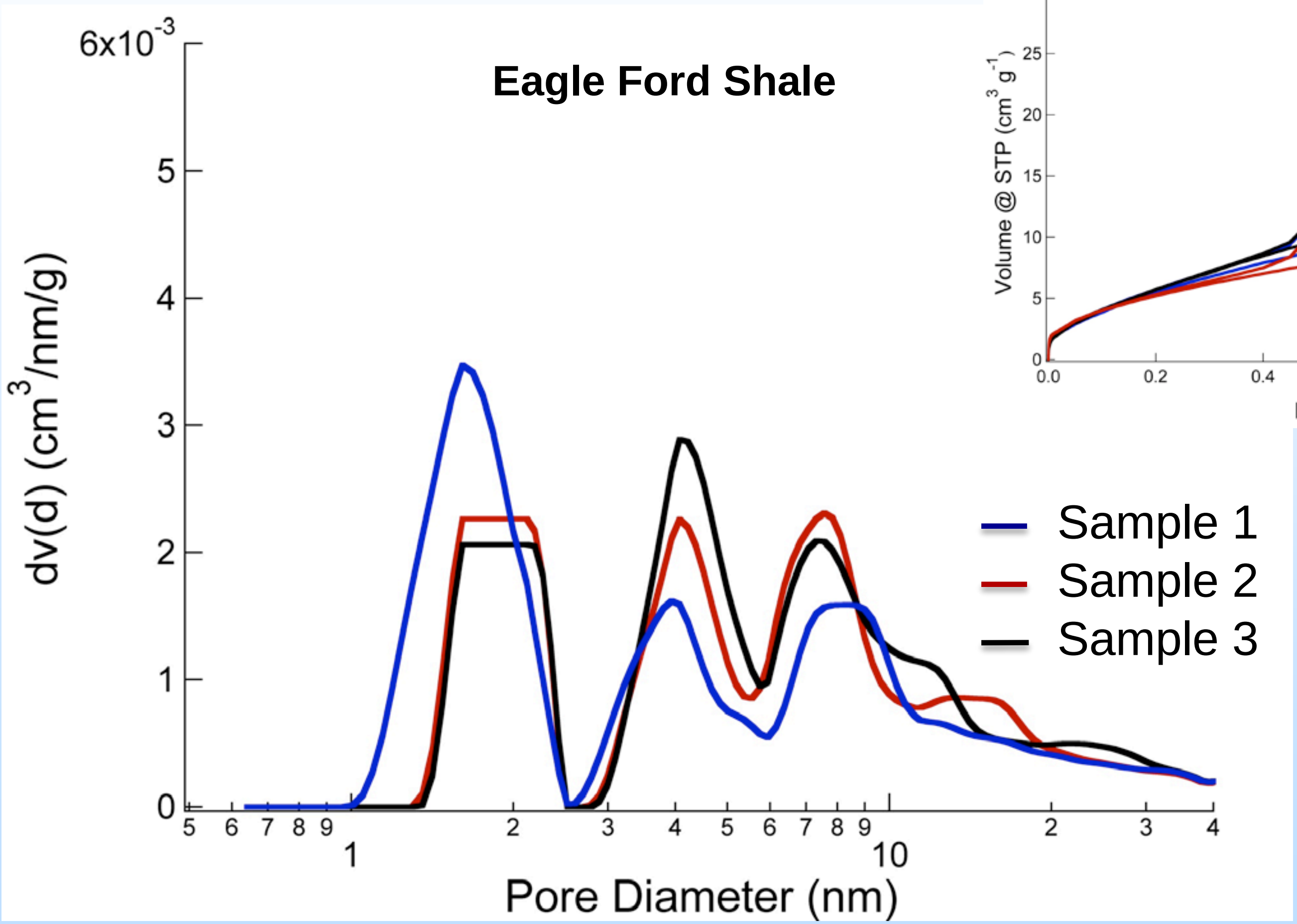




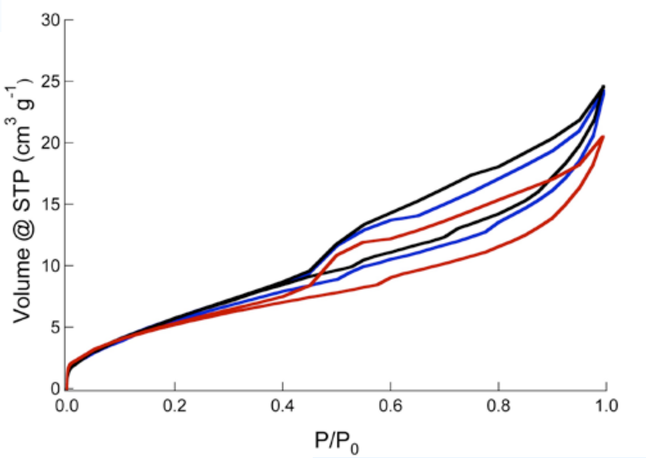
Improper outgassing can:

- Suggest heterogeneity in samples that may not exist
- Decrease apparent pore volume
- Lead to isotherms unsuitable for further analysis

Storage



Eagle Ford Shale
6x10^-3
5
4
3
2
1
0
dv(d) (cm^3/nm/g)
5 6 7 8 9 1 2 3 4 5 6 7 8 9 10 2 3 4
Pore Diameter (nm)
Sample 1
Sample 2
Sample 3

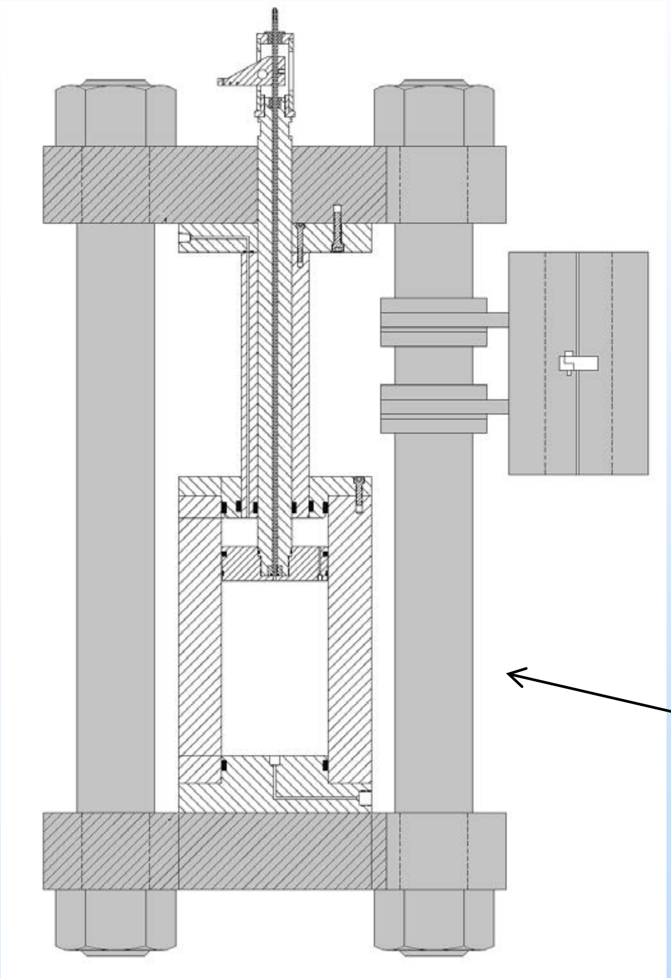


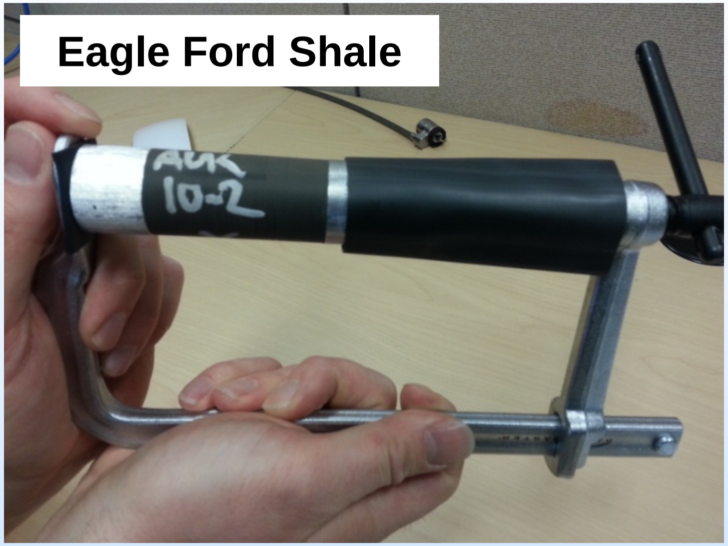
Volume @ STP (cm^3 g^-1)
30
25
20
15
10
5
0
0.0 0.2 0.4 0.6 0.8 1.0
P/P0

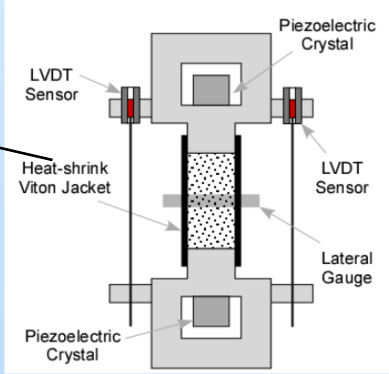
Geomechanics

- Storage: free phase in large pores/fractures and adsorption in nanoscale pores
- How do these phases affect long-term geomechanics? -> direct and indirect coupling
- Conduct creep experiments on samples equilibrated with CO_2

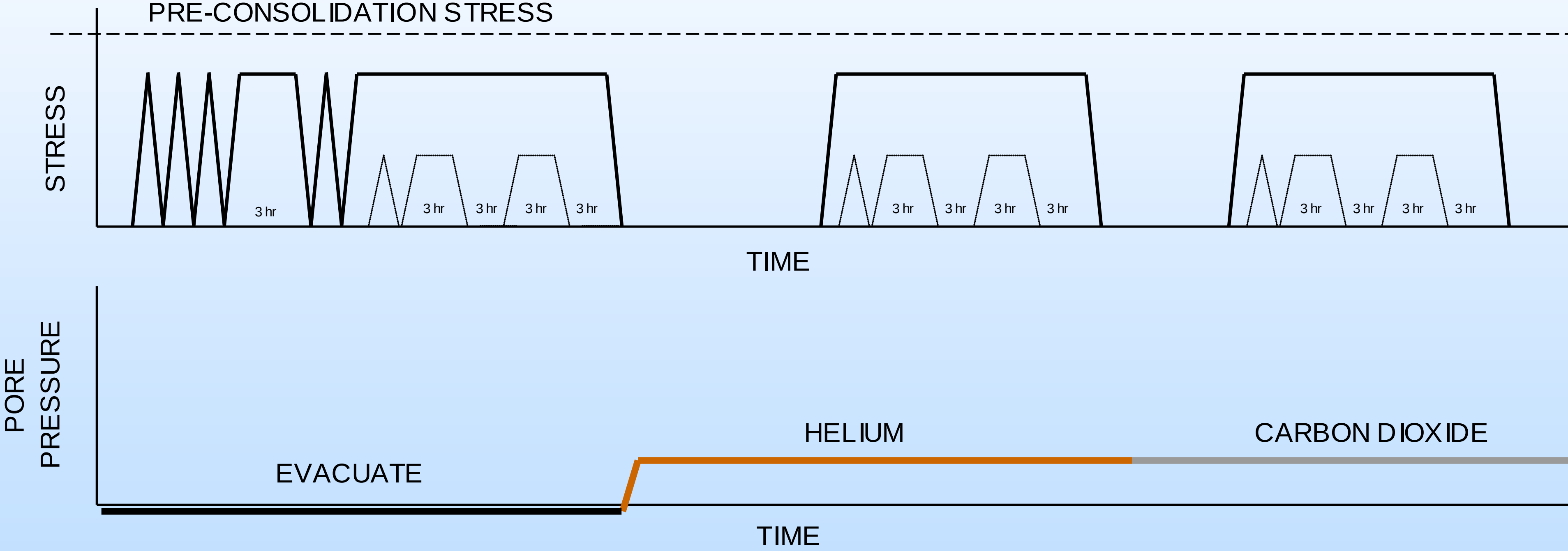
Geomechanics





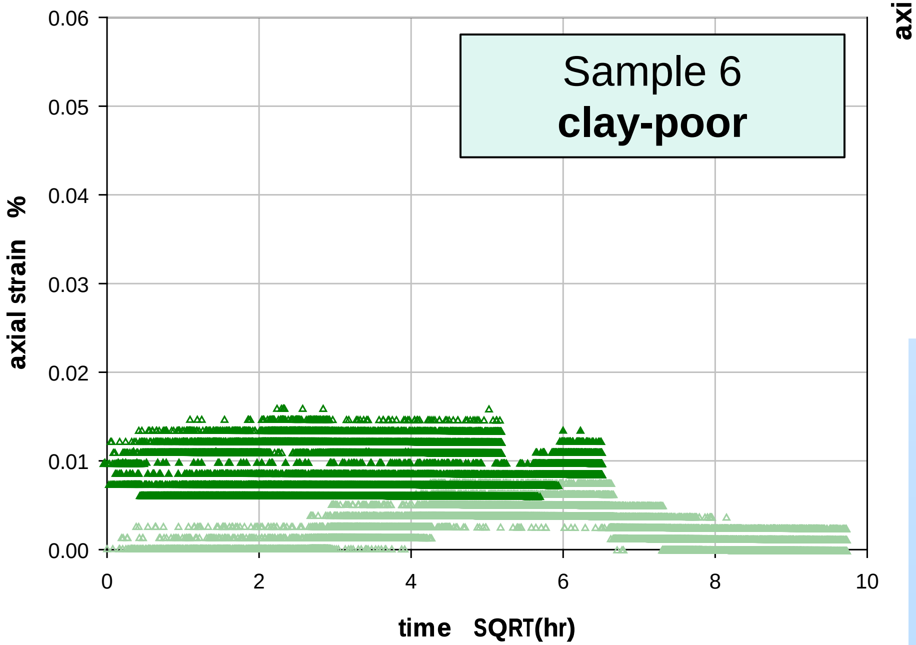


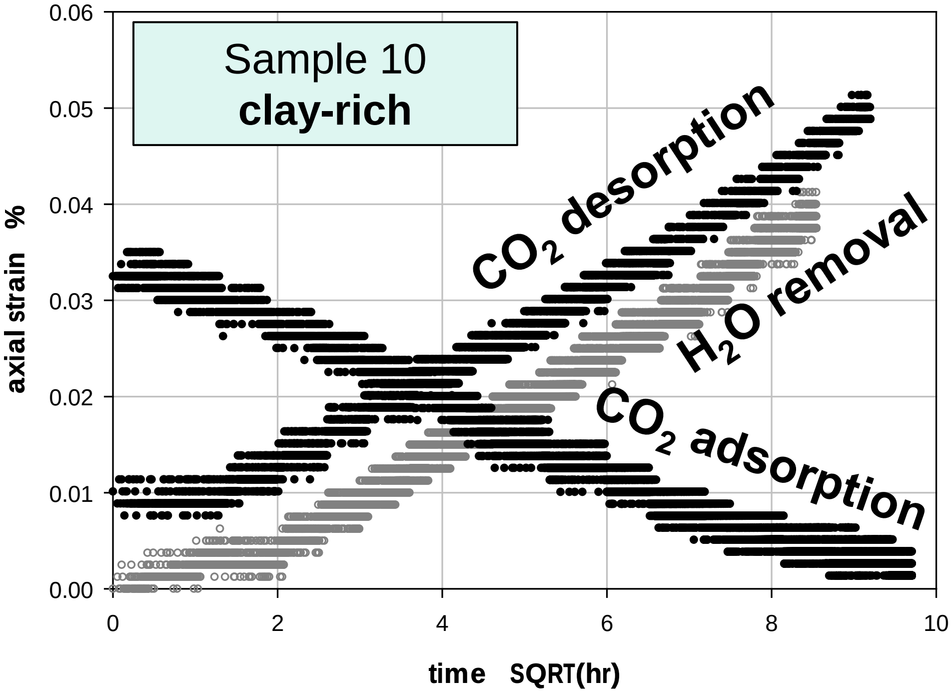
Geomechanics



Geomechanics

Evacuation and exposure to CO_2 at 3 MPa

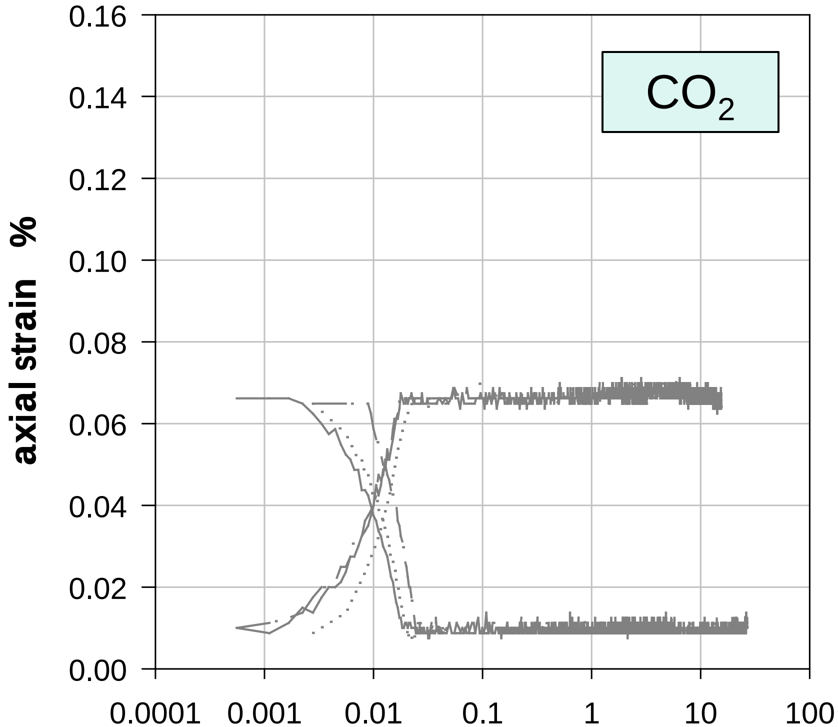




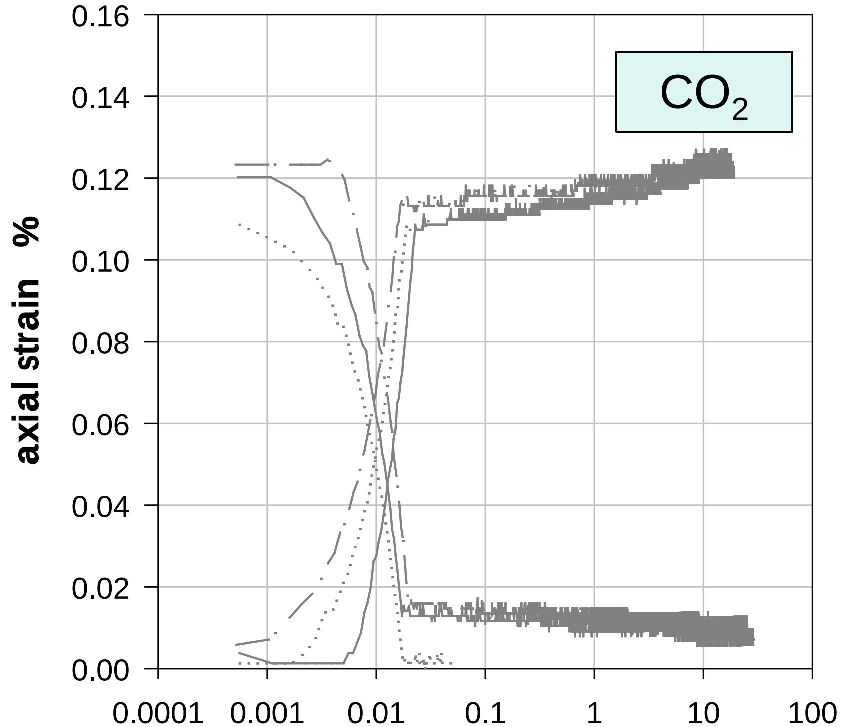
SampleID	Depth (m)	TOC	QTZ	CARB	CLAY	OTHER
5	3781	0.79	31.65	51.19	10.32	6.35
6	3816	2.11	3.72	86.05	7.44	0.59
10	3884	5.32	17.80	45.54	24.43	6.44

Geomechanics

Sample 6
clay-poor



Sample 10
clay-rich



Mechanical response:

- Elastic (biggest effect)
- Viscoelastic (significant effect – clay rich)
- fluid migration effect (up to 15% effect)

Summary / Accomplishments

- Transport
  - Insights into separating rock permeability from slip flow and adsorption effects, plus composition-dependence and effects of scale.
  - Further understanding of basis of permeability anisotropy, and relation to direct and indirect effects of adsorption and rock fabric.
- Storage
  - Practical constraints on determination of PSD by N_2 adsorption techniques – effects of outgassing / role of residual fluids.
- Geomechanics
  - Identification of combined effects of rock fabric and adsorption in time-dependent deformation and stress relaxation – clays are key.

Appendix

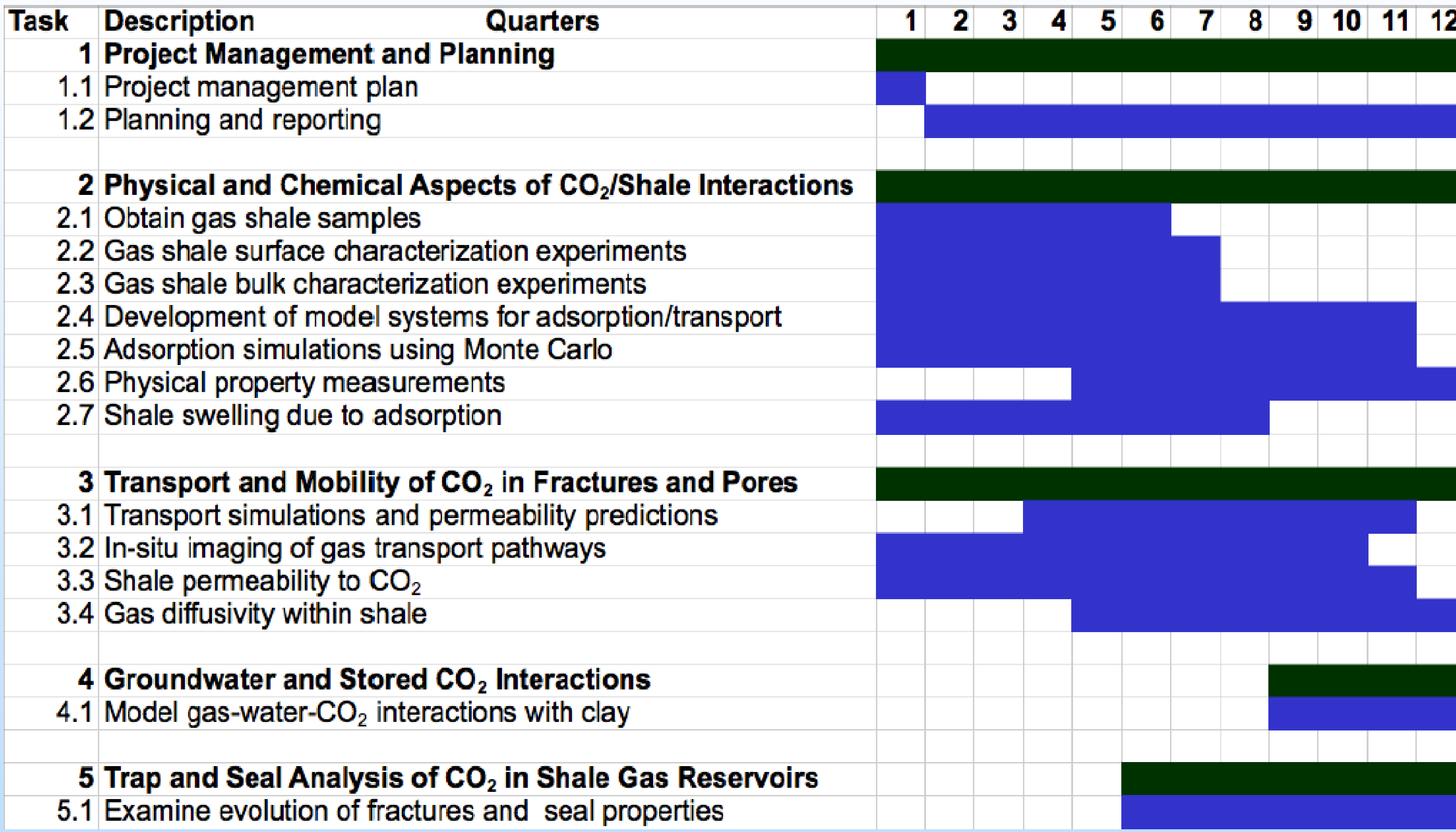
– Organizational Chart
– Gantt Chart
– Bibliography

Organization Chart

Stanford University, School of Earth Sciences

- PI: Professor **Mark D. Zoback**, Department of Geophysics,
  - Dr. Sander Hol (Postdoctoral Scholar), Dr. Julia Reece (Postdoctoral Scholar), Rob Heller (PhD student)
- Co-PI: Professor **Anthony R. Kovscek**, Energy Resources Engineering Department,
  - Bolivia Vega (Research Assistant), Dr. Cindy Ross (Research Associate), Hamza Aljamaan (PhD student) and Khalid Alnoaimi (PhD student)
- Co-PI: Assistant Professor **Jennifer Wilcox**, Energy Resources Engineering Department,
  - Dr. Mahnaz Firouzi (Postdoctoral Scholar), Dr. Dawn Geatches (Postdoctoral Scholar), and Dr. Erik Rupp (Research Associate)

Gantt Chart



Task
Description
Quarters
1 2 3 4 5 6 7 8 9 10 11 12
1 Project Management and Planning
1.1 Project management plan
1.2 Planning and reporting
2 Physical and Chemical Aspects of CO_2/Shale Interactions
2.1 Obtain gas shale samples
2.2 Gas shale surface characterization experiments
2.3 Gas shale bulk characterization experiments
2.4 Development of model systems for adsorption/transport
2.5 Adsorption simulations using Monte Carlo
2.6 Physical property measurements
2.7 Shale swelling due to adsorption
3 Transport and Mobility of CO_2 in Fractures and Pores
3.1 Transport simulations and permeability predictions
3.2 In-situ imaging of gas transport pathways
3.3 Shale permeability to CO_2
3.4 Gas diffusivity within shale
4 Groundwater and Stored CO_2 Interactions
4.1 Model gas-water-CO_2 interactions with clay
5 Trap and Seal Analysis of CO_2 in Shale Gas Reservoirs
5.1 Examine evolution of fractures and seal properties

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