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Modeling the Effects of Chemical Reactions on the Elastic Properties of Rocks

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Outline

- Background
- Hypothesis
- Assumptions
- Model
- Results
- Summary
- Future Work

Motivation

- Monitoring and quantifying amounts of sequestered carbon dioxide
- Monitoring fluids/gases used for enhanced oil recovery

Background

- Hooke’s Law: Linear Elasticity
- Fluid Substitution:
  - Gassmann’s for Isotropy (1951)
  - Brown and Korringa’s for Anisotropy (1975) (theoretical)
- However, classical fluid substitutions break down when a chemical reaction causes a change in the microstructure (Vanorio, 2010)

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Hypothesis

Besides the compliance induced by the mechanical fluid substitution of a reactant, there is an additional compliance/stiffness induced by dissolution/precipitation respectively due to the chemical reactions of the reactant with the host rock.

$$C = C_{MECH} \pm C_{CHEM}$$

Hypothesis

- There is a saturation at which the rock frame becomes inert to the reactant known as the critical saturation
- Critical saturation is unique
- The bulk and shear moduli change at an exponential rate due to the chemical reaction

Assumptions

- Negligible change in porosity
  - No mechanical implications
  - Do not have to update mechanical fluid substitution models
- Assumptions of mechanical fluid substitution model
  - Pores in communication
  - Homogeneous

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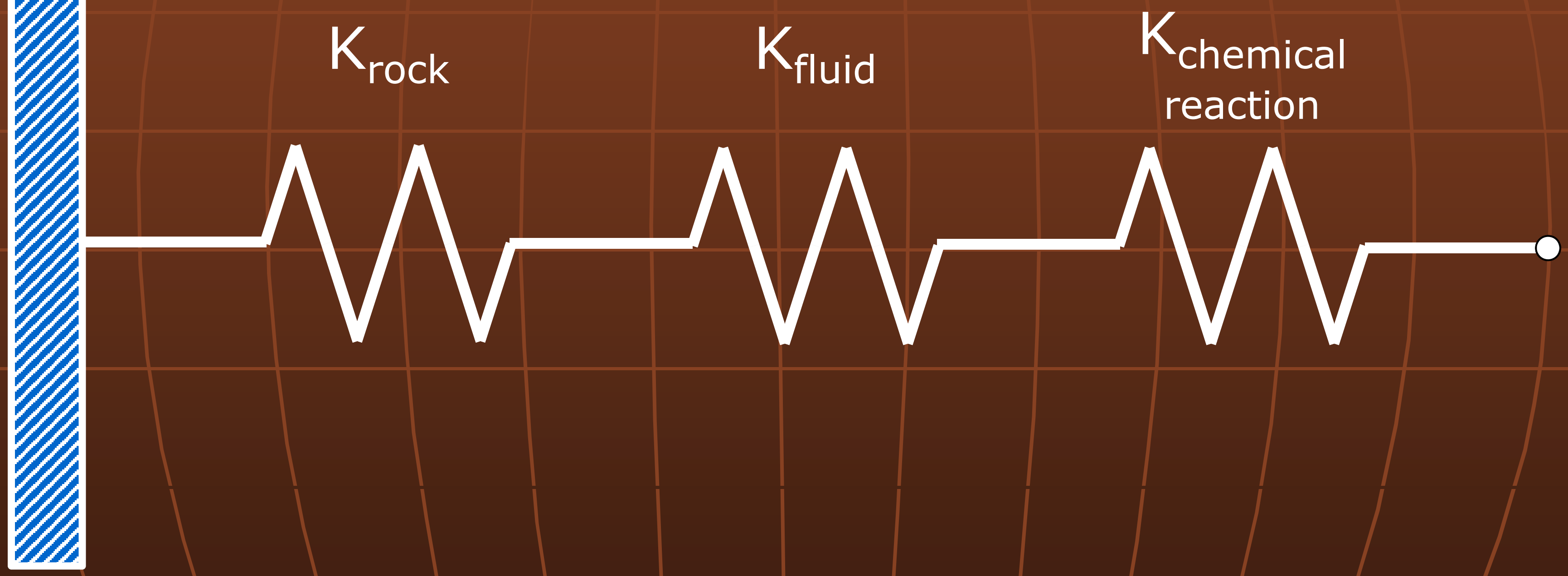
Schematic



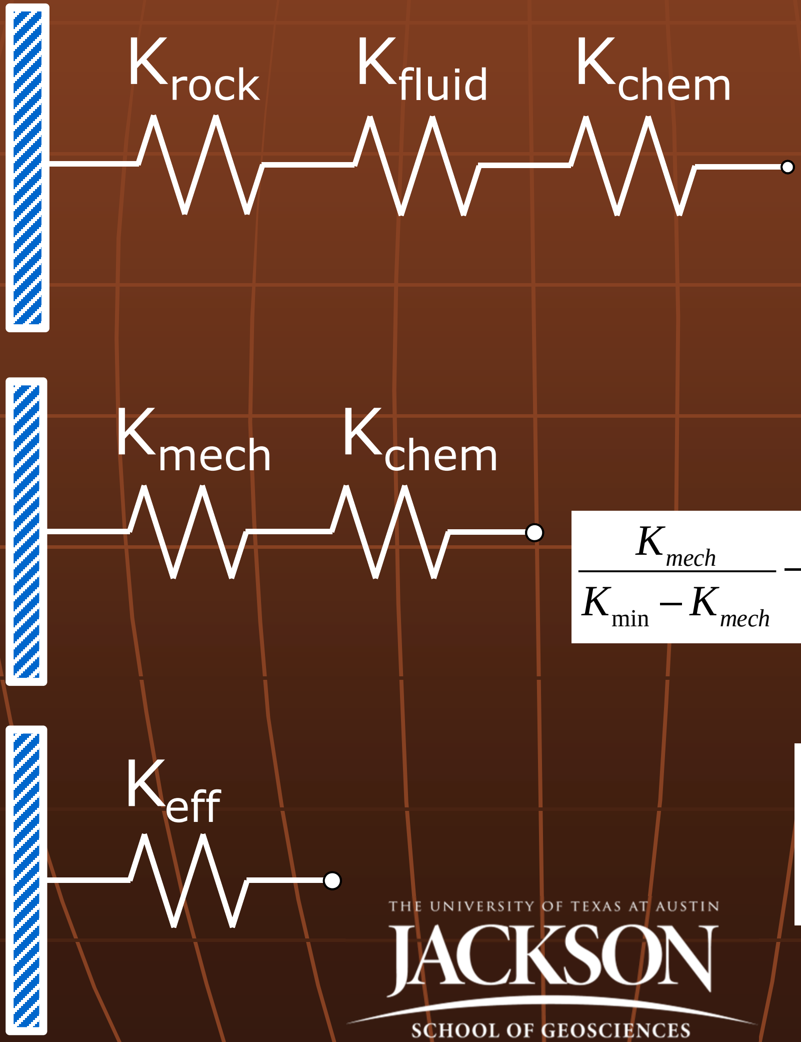
Model

STEP:

(1)

(2)

(3)



Uniform Mixture

$$K_{fl2} = \left(\frac{(1-S_R)}{K_{fl1}} + \frac{S_R}{K_R} \right)^{-1}$$

Patchy Mixture

$$K_{fl2} = (1-S_R)K_{fl1} + S_R K_R$$

Fluid Substitution

$$\frac{K_{mech}}{K_{\min} - K_{mech}} - \frac{K_{fl_2}}{\phi\left(K_{\min} - K_{fl_2}\right)} = \frac{K_1}{K_{\min} - K_1} - \frac{K_{fl_1}}{\phi\left(K_{\min} - K_{fl_1}\right)}$$

$$K_{eff} = \left(\frac{1}{K_{mech}} + \frac{1}{K_{chem}} \right)^{-1}$$

Model

- Let’s assume: $\phi_2 \approx \phi_1$
- Change in Vs caused by change in microstructure → Chemical Reaction

$$V_{s,1} = \sqrt{\frac{\mu_1}{\rho_1}} \qquad V_{s,2} = \sqrt{\frac{\mu_2}{\rho_2}}$$

- Therefore: $\boxed{\mu_2 = \rho_2 V_{s,2}^2}$

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Model

- Similarly with the bulk modulus

$$\boxed{K_2 = \rho_2 V_{p,2}^2 - \frac{4}{3}\mu_2}$$

- I hypothesize that: $C_2 = C_{2,mech} \pm C_{2,chem}$
- Remember: $C = \frac{1}{K} \rightarrow \frac{1}{K_2} = \frac{1}{K_{2,mech}} \pm \frac{1}{K_{2,chem}}$
- Therefore:

$$\boxed{\frac{1}{K_{2,chem}} = \pm\frac{1}{K_2} \mp \frac{1}{K_{2,mech}}}$$

Model

- Chemical reactions occur exponentially based on the Arrhenius Equation (Kotz et al, 2009)
- Elastic constants behave exponentially

$$\boxed{K_{CHEM}, \mu_{CHEM}(S_R) = ce^{-aS_R} + b}$$

where S_R = reactant saturation,
a = rate of change, c = scalar, b = intercept

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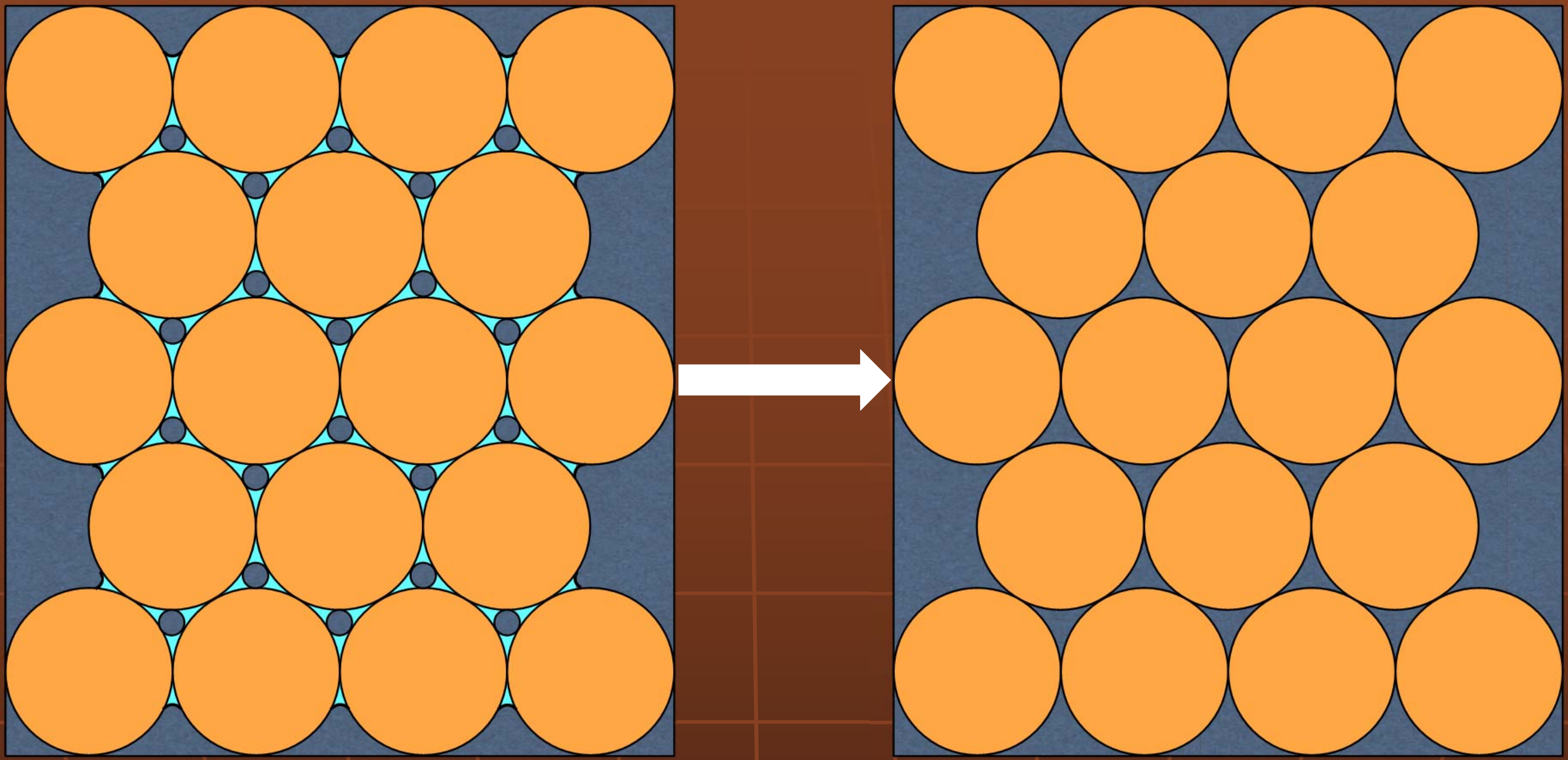
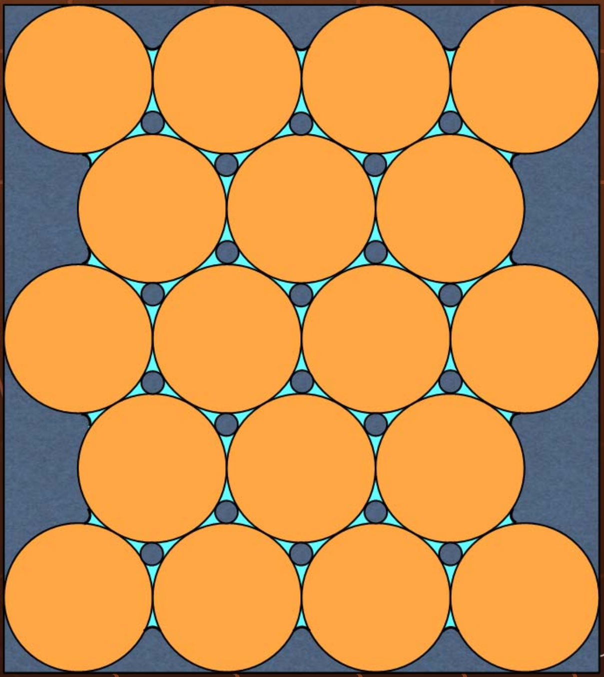


AN EXAMPLE

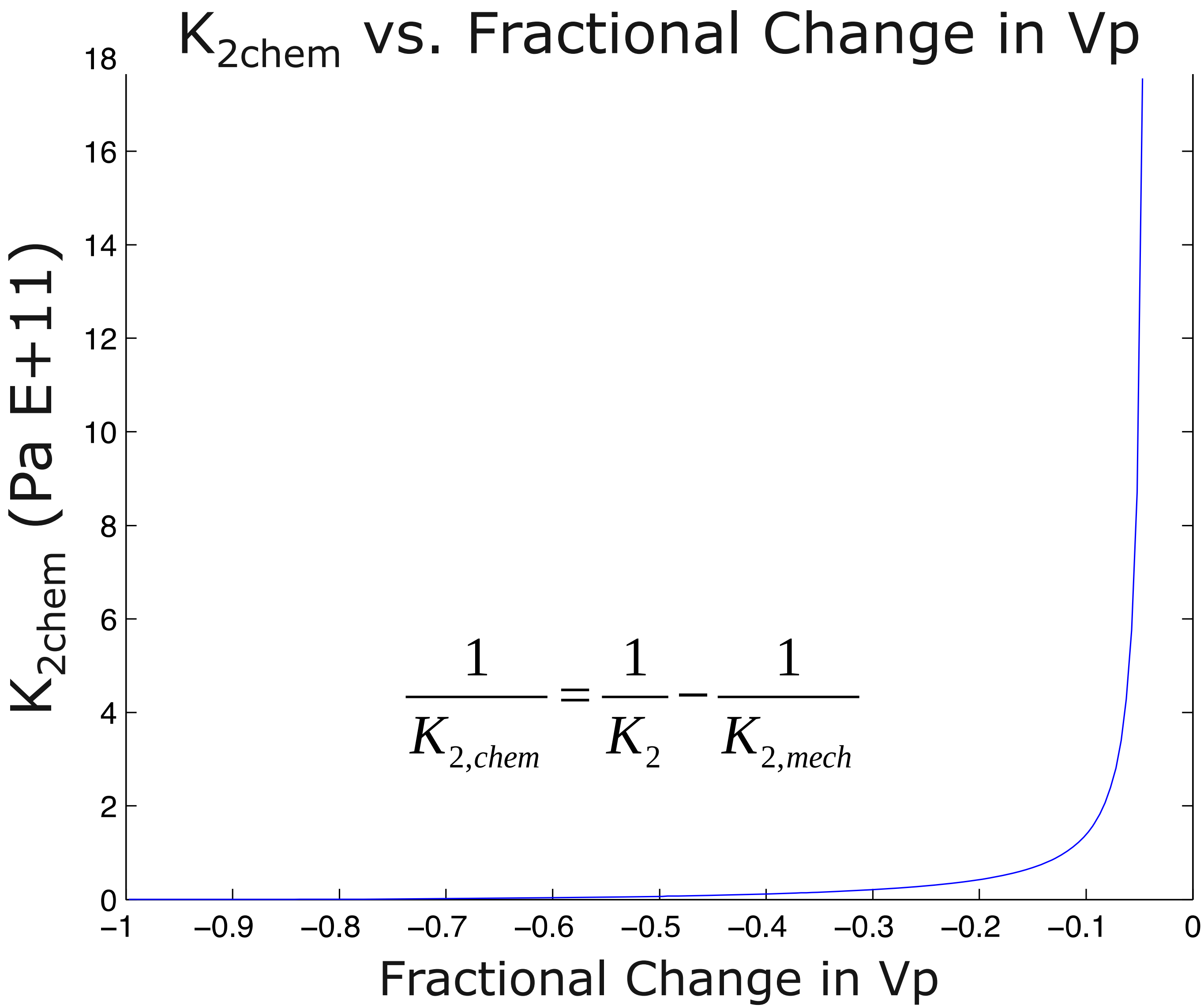
DISSOLUTION OF CALCITE CEMENT IN SANDSTONE – CO_2

Key Parameters

- Critical Saturation = Sc = 0.5
- Vs @ Sw=0 is 90% of Gassmann’s
- Vp @ Sw=0 is 85% of Gassmann’s

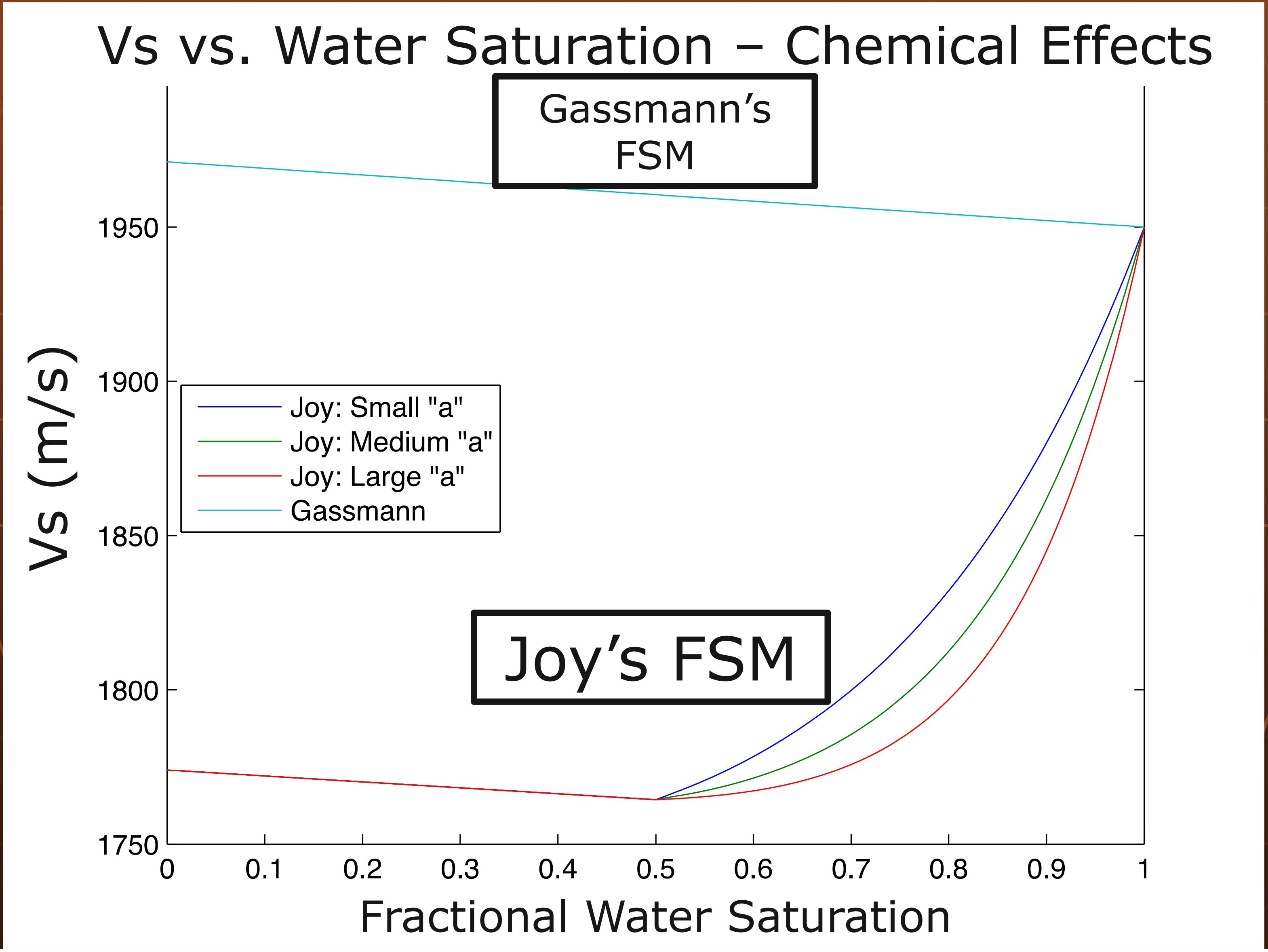


Results

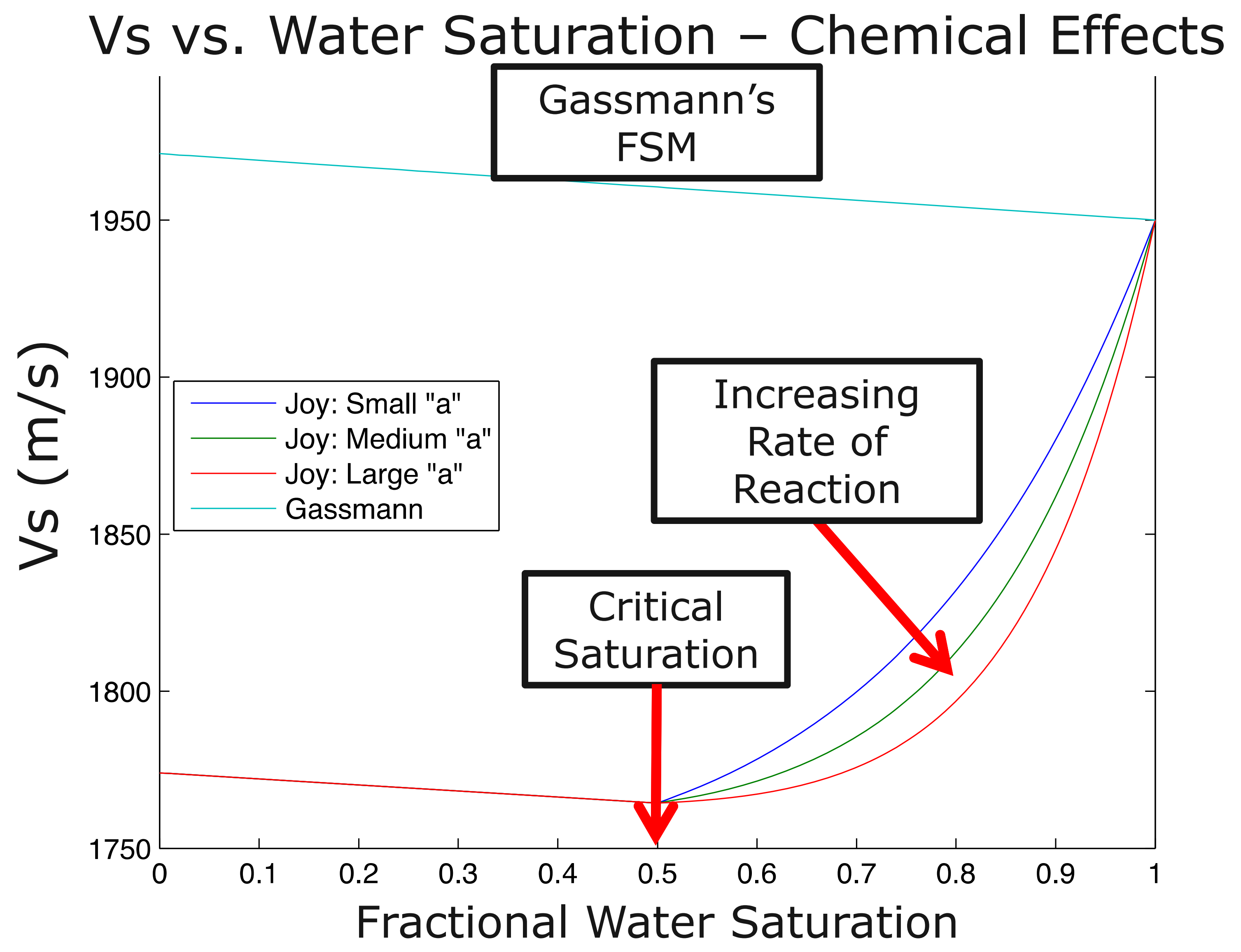


$$\frac{1}{K_{2,chem}} = \frac{1}{K_2} - \frac{1}{K_{2,mech}}$$

Results


Vs vs. Water Saturation – Chemical Effects
Gassmann's FSM
Joy's FSM
Joy: Small "a"
Joy: Medium "a"
Joy: Large "a"
Gassmann
Vs (m/s)
1750
1800
1850
1900
1950
Fractional Water Saturation
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Results


Vs vs. Water Saturation – Chemical Effects
Gassmann's FSM
Increasing Rate of Reaction
Critical Saturation
Joy: Small "a"
Joy: Medium "a"
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Gassmann
Vs (m/s)
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0.7
0.8
0.9
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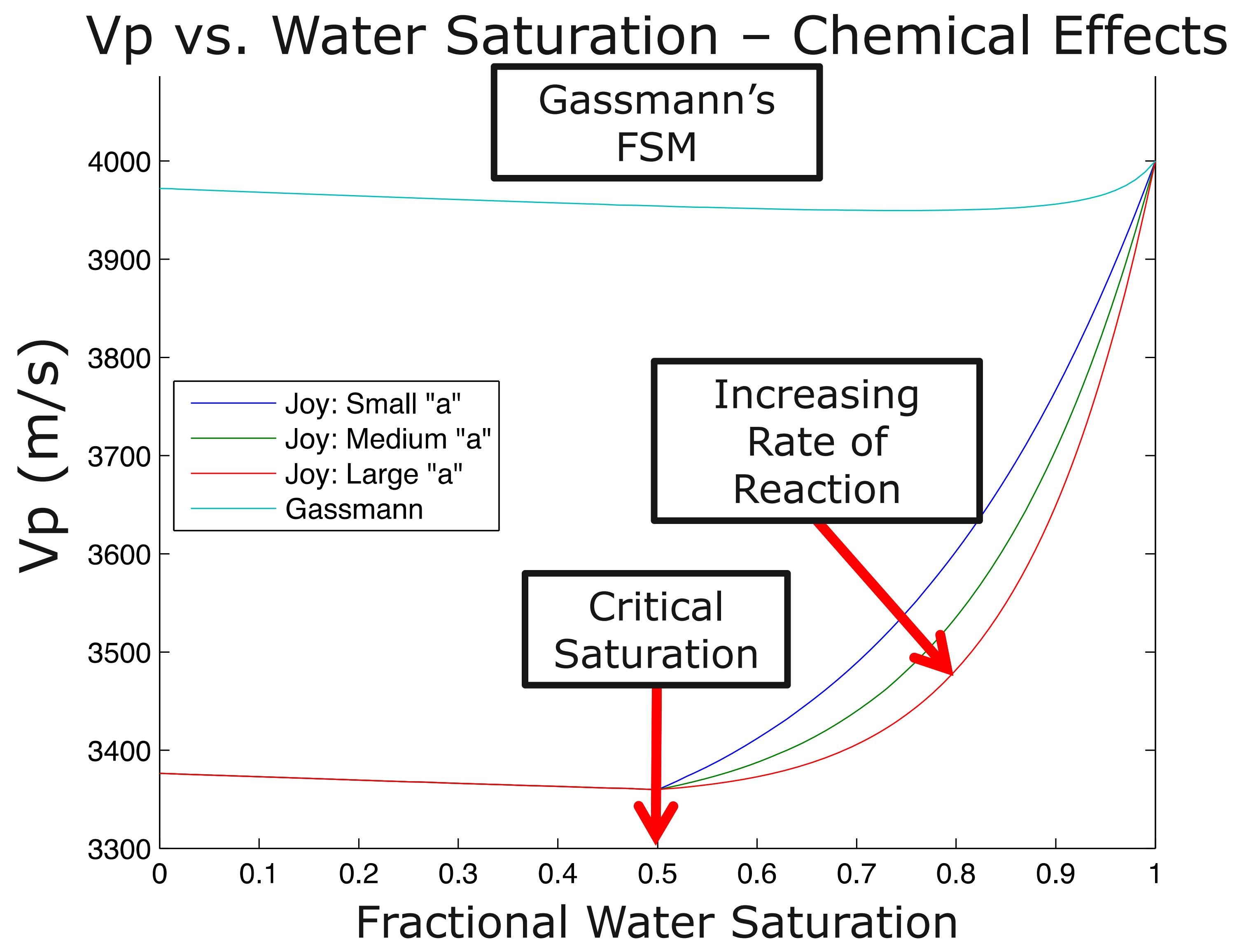
Fractional Water Saturation

Results



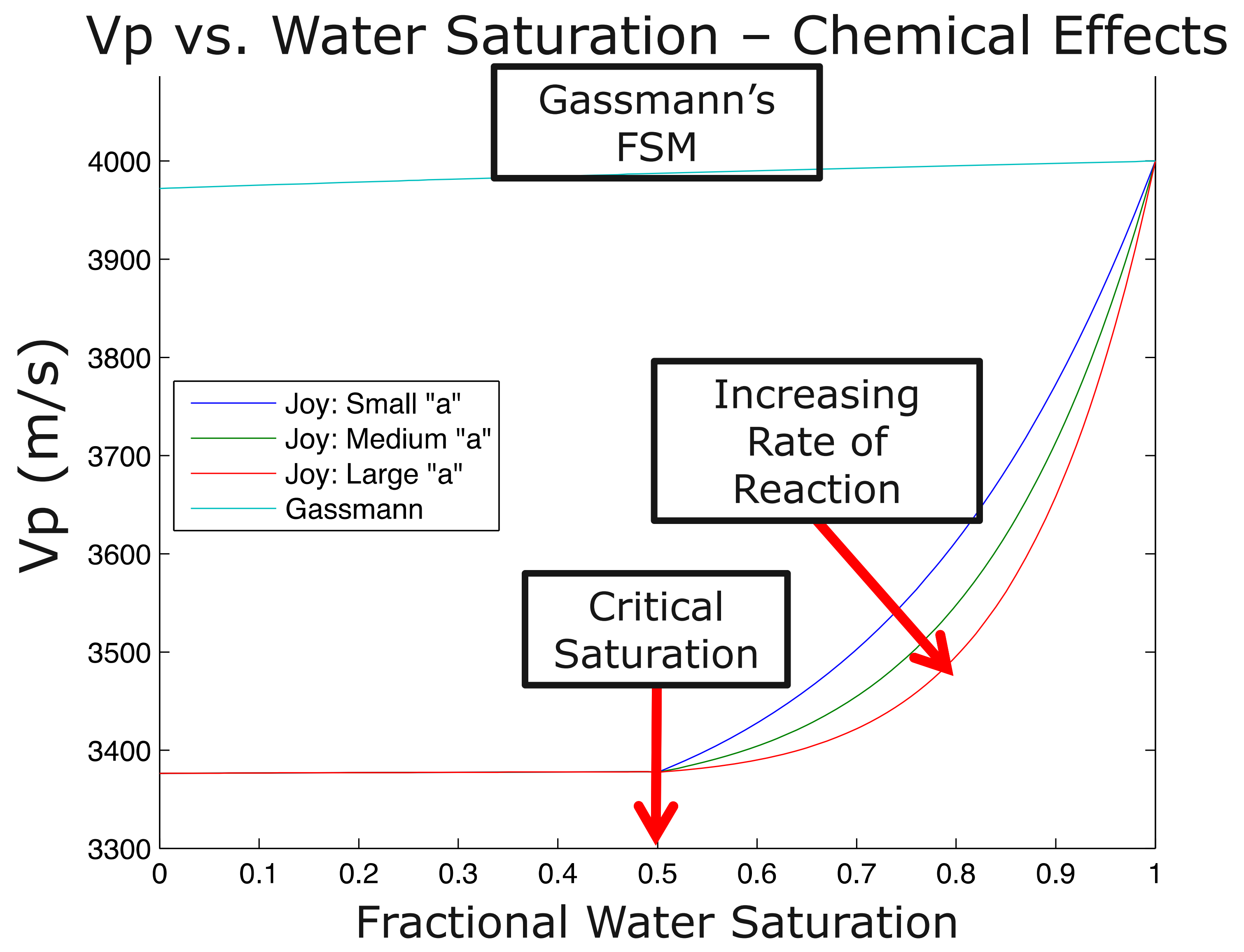
Vp vs. Water Saturation – Chemical Effects

Gassmann's FSM

Increasing Rate of Reaction

Critical Saturation

Results



Gassmann's FSM

Increasing Rate of Reaction

Critical Saturation

Summary

- Gassmann's fluid substitution model over/under predicts elastic moduli when chemical reactions occur (Vanorio, 2010)
- Fit the measured velocity profile by using Gassmann's FSM and adding an excess compliance/stiffness

$$C = C_{MECH} \pm C_{CHEM}$$

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Summary

- The chemical reaction occurs until a critical saturation
- The rate of change in elastic moduli and critical saturation are unique for each combination of rock and reactant
- Fully defined stiffness tensor for chemical fluid substitution

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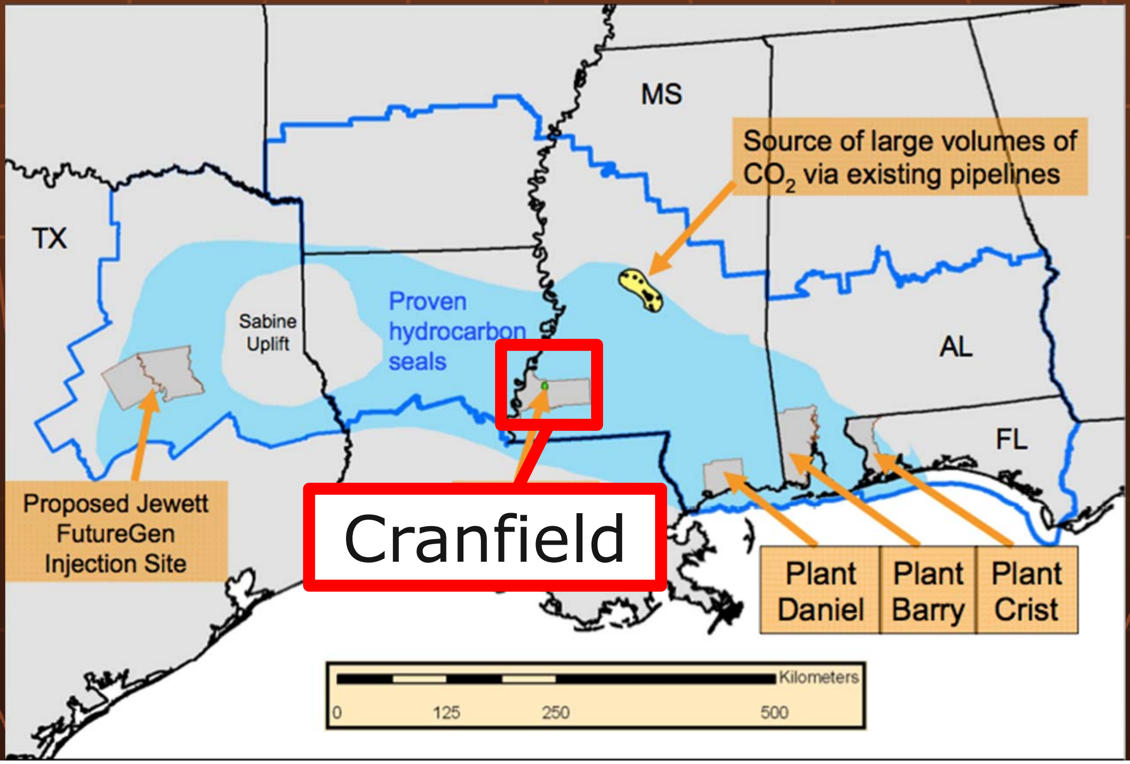
What’s Next?

- Experiments: inject core plugs with CO_2 and test Vp and Vs
- Core plugs come from Cranfield, MS



(Meckel, 2008)

Cranfield, MS

- Plugged oil/gas well in 1965: Tuscaloosa formation
- Four way closure
- Seal integrity
- Detailed area study
- Time lapse seismic and well logs

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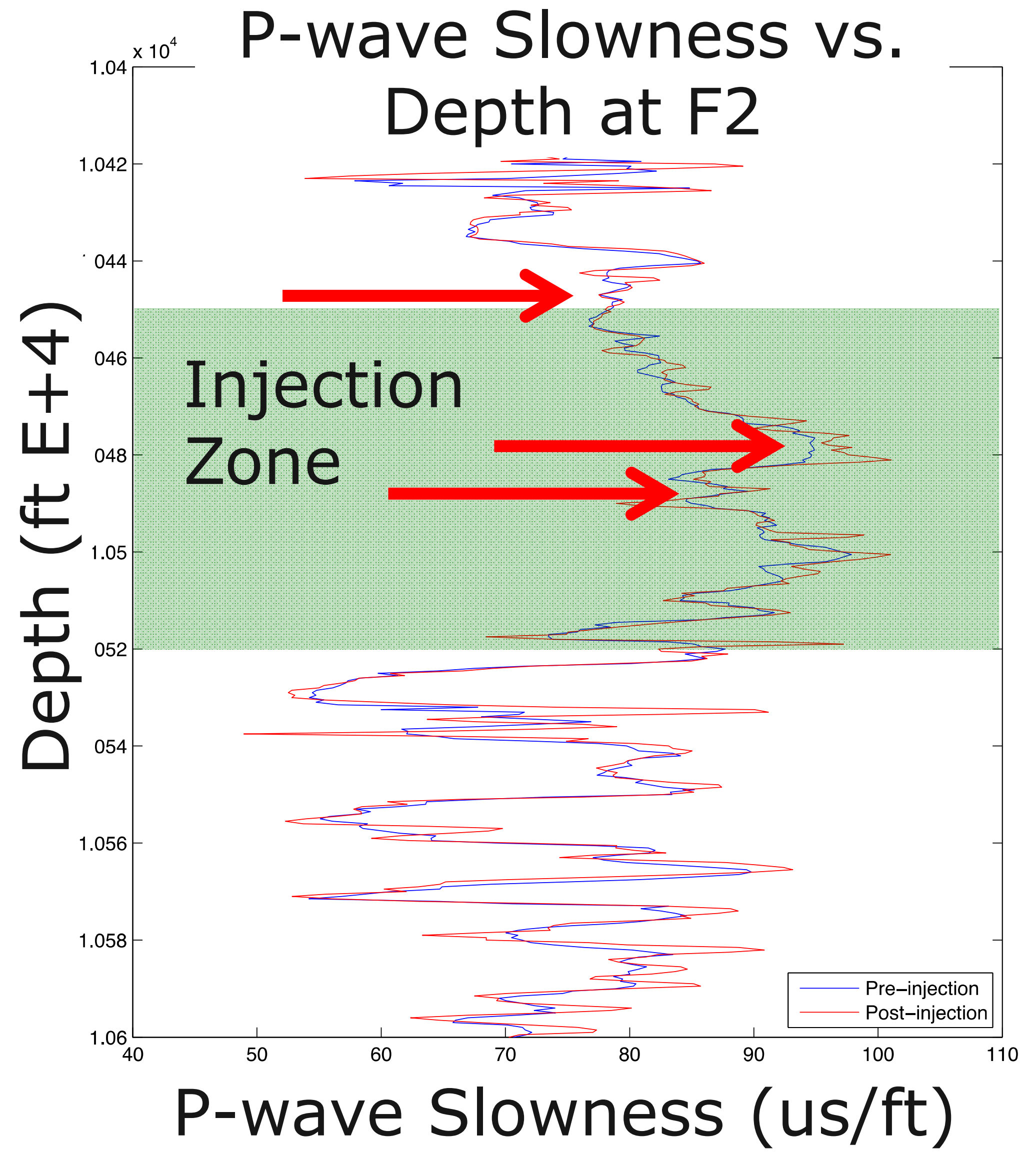
(Romanak, 2010)

Core Selection

- Poro. ≈ 20% (Kordi et al, 2010)
- Perm. ≈ 10 md (Kordi et al, 2010)
- Extensive carbonate cement (Acid test)
- Other cores to represent reservoir


P-wave Slowness vs. Depth at F2

Future Work

- Resolve forward problem: relate CO_2 saturation to elastic properties
- Invert time lapse seismic for CO_2 saturations
- Graduate!
- Off to BP!

Acknowledgments

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