Fluid Substitution in Anisotropic Media: Seismic Monitoring of CO_2 sequestration

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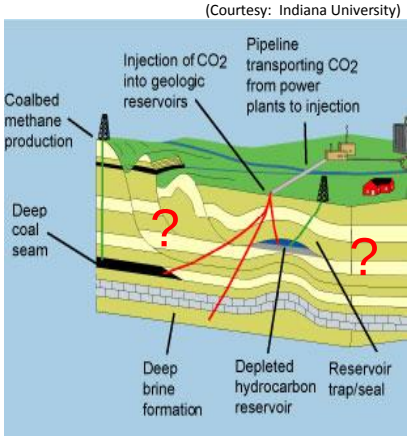
Motivation

- Improve understanding of sequestration site properties from seismic data
- Time-lapse seismic data successfully used to detect changes due to CO_2 injection
  - Where is the injected CO_2 going once injection begins?
  - What is the fate of CO_2: gas, liquid, or solid phases?

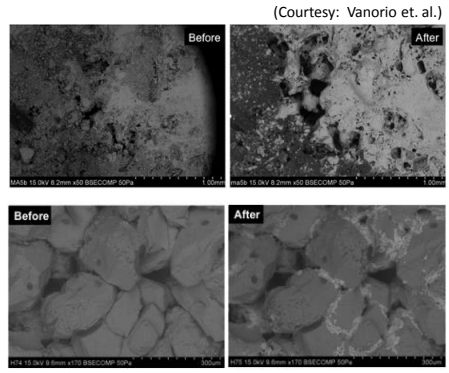
(Courtesy: Indiana University)



Introduction

- Some sequestration site changes due to CO_2 injection:
  - CO_2 displacing original formation fluid
    - Fluid substituted by fluid
  - Mineral dissolution
    - Solid substituted by fluid
  - Mineral precipitation
    - Fluid substituted by solid

(Courtesy: Vanorio et. al.)



- 3

Introduction

- Site changes ⇒ changes in elastic wave velocities
  - Detected in seismic data
  - Rock physics connection

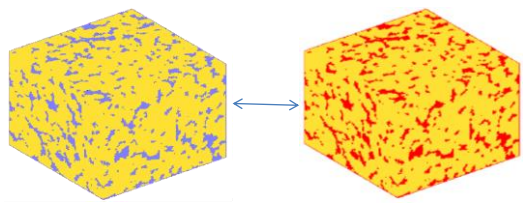
SUBSTITUTION IN ROCK PHYSICS

- $$elastic\ wave\ velocity = \sqrt{\frac{\boxed{elastic\ modulus}}{bulk\ density}}$$
- Elastic modulus: bulk (K), shear (μ)

- 4

Objective

- Better quantifying the seismic signature of pore-material in the sub-surface
  - Substitution from one pore material to another



PORE MATERIAL 1 PORE MATERIAL 2

- 5

Gassmann's fluid substitution: isotropic

EFFECTIVE BULK MODULUS WITH FLUID 1

EFFECTIVE BULK MODULUS WITH FLUID 2

- $$\frac{K_{sat1}}{K_{min} - K_{sat1}} - \frac{K_{fl1}}{\phi(K_{min} - K_{fl1})} = \frac{K_{sat2}}{K_{min} - K_{sat2}} - \frac{K_{fl2}}{\phi(K_{min} - K_{fl2})}$$

MINERAL BULK MODULUS

BULK MODULUS OF FLUID 1

POROSITY

BULK MODULUS OF FLUID 2

- $\mu_{sat1} = \mu_{sat2}$

EFFECTIVE SHEAR MODULUS WITH FLUID 2

EFFECTIVE SHEAR MODULUS WITH FLUID 1

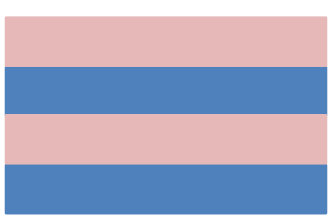
- 6

Gassmann's fluid substitution: isotropic

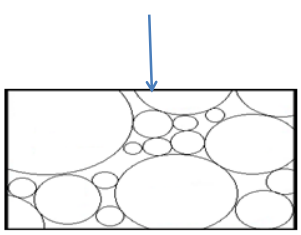
- Isotropic frame, isotropic mineral
- Fluid to fluid substitutions only
- Assumption: homogeneous pore pressure
  - Predicts **minimum change** in modulus due to substitution

- 7

Anisotropic fluid substitution



LAYERING



OVERBURDEN

- Real subsurface:
  - Anisotropic frame, anisotropic minerals
- Hexagonal / VTI anisotropy
  - Thomsen parameters: **ε, γ, δ**

- 8

Anisotropic fluid substitution

- Gassmann (1951), Brown and Korringa (1975)
- $S_{ijkl}^{sat} = S_{ijkl}^{dry} - \frac{(S_{ij\alpha\alpha}^{dry} - S_{ij\alpha\alpha}^{min})(S_{\alpha\alpha kl}^{dry} - S_{\alpha\alpha kl}^{min})}{\left(S_{\alpha\alpha\beta\beta}^{dry} - S_{\alpha\alpha\beta\beta}^{min}\right) - \phi(1/K_{fl} - 1/K_{min})}$
- Limited measurements: **not all required inputs known**
- Approximate anisotropic fluid substitution (Bandyopadhyay & Mavko, 2009)
  - For vertical velocities in anisotropic media
  - Requires fewer inputs

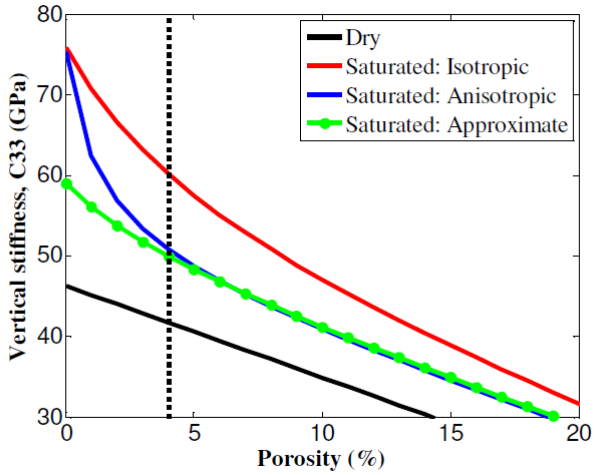
- 9

Approximate anisotropic fluid substitution

- $C_{3333}^{sat} - C_{3333}^{dry} \approx (K_{iso}^{sat} - K_{iso}^{dry})\left[1 - \delta \frac{(\frac{4}{3})C_{3333}^{dry}}{K_{min} - K_{iso}^{dry}}\right]$
- $C_{3333} = \rho V_p^2$
- $K_{iso} = \rho V_p^2 - \left(\frac{4}{3}\right)\rho V_s^2$
- δ measured from vertical and NMO P-wave velocities
- $K_{iso}^{sat} =$ saturated bulk modulus using isotropic Gassmann
- Positive $\delta \Rightarrow$ isotropic Gassmann overpredicts vertical velocities and vice-versa

- 10

Approximate anisotropic fluid substitution



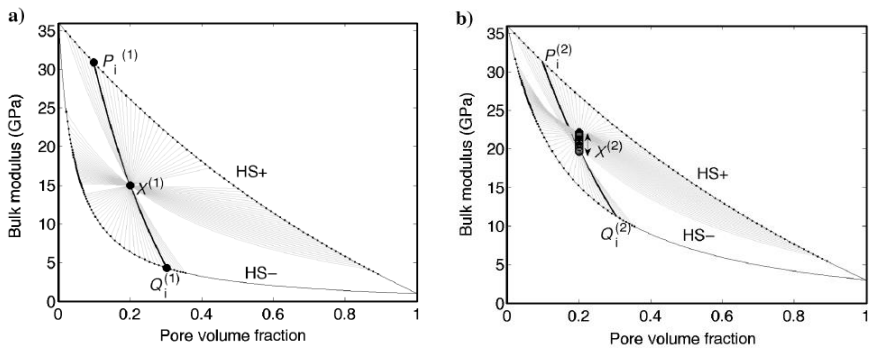
- 11

Bounds on fluid/solid substitution

- Gassmann substitution prediction unique
  - Assumption: absolute pore connectivity
- Real-life rocks: arbitrary pore connectivity
  - Gassmann: smallest change due to substitution
- Gibiansky & Torquato (1998)
  - Bounds on change due to fluid substitution
- Mavko & Saxena (2013)
  - Bounds on change due to solid/fluid substitution

- 12

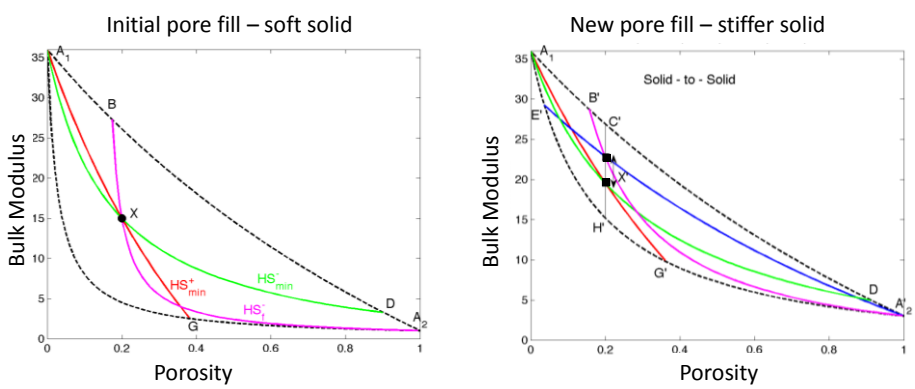
Bounds on fluid/solid substitution



- Substitution is non-unique
  - Range: uncertainty due to unknown micro-geometry

- 13

Bounds on fluid/solid substitution



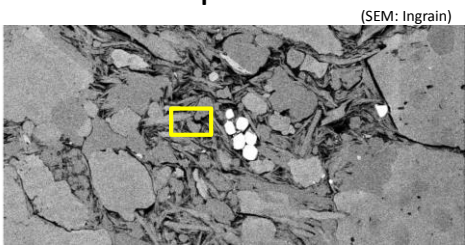
- 4 limiting cases anchored to mineral and pore end members

- 14

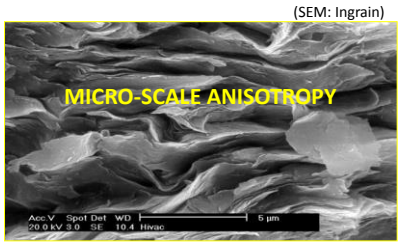
Bounds on substitution: micro-scale anisotropy

- Mavko-Saxena substitution bounds
  - Derived from embedded Hashin-Shtrikman constructions
  - Implicit assumption: isotropy at all scales
- What happens when our composite is anisotropic at sub-measurement scale?

(SEM: Ingrain)

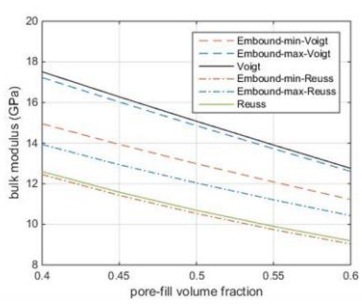


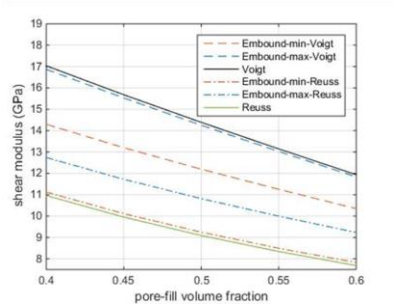
(SEM: Ingrain)



- 15

Bounds on substitution: micro-scale anisotropy





- Current substitution bounds not always approprite for micro-scale anisotropy

- 17

Summary and Conclusions

- Time-lapse seismic important tool for CO_2 sequestration monitoring
  - Rock physics connects seismic data to sequestration site properties
- Rock physics substitution models can describe common changes dues to CO_2 injection
- Ignoring anisotropy during substitution can lead to significant errors
- Substitution is not confined to fluids only
- Substitution is not unique

- 18

Aknowledgements

- Prof. Tapan Mukerji, Dr. Jack Dvorkin, Prof. Tiziana Vanorio
- Stanford Rock Physics and Borehole Geophysics group (SRB)

- 19

Thank you