CO$_2$ at the Interface: Nature and Dynamics of the Reservoir/Caprock Contact and Implications for Carbon Storage Performance

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How well is the reservoir caprock interface described by a discrete boundary with simple (uniform) flow conditions?

How do inevitable structural, diagenetic and depositional heterogeneities at the interface influence transmission of CO$_2$ into the caprock?

Outline:

• Intro
• Organization
• Benefit to Program
• Project Overview
• Technical Status
• Accomplishments
• Summary
• Appendix
Importance of **Scale**: Examples of Interface Heterogeneity

- Depositional
- Structural
- Diagenetic

Focus for today’s talk
1. Fracture Patterns
2. Deformation Bands
3. Porosity “Facies”

Image descriptions:
- Soft-sediment deformation
- Fracture patterns and structural style
- Deformation Bands
- Cementation patterns
- Lithofacies distribution
- Pore Scale Heterogeneity
Benefits to Program

- Program goals being addressed:
  - Develop technologies that will support industries’ ability to predict CO\(_2\) storage capacity in geologic formations to within ±30 percent.
  - Develop technologies to demonstrate that 99 percent of injected CO\(_2\) remains in the injection zones.

- Project benefits:
  - Our results have the potential to significantly improve prediction of containment system effectiveness.

Project Overview:

- Goals:
  - To determine the influence of diagenetic and structural features of the reservoir/caprock interface on transmission of CO\(_2\) into and through the caprock.

- Objectives
  - Constrain potential interface transmissivity attending certain features (i.e. deformation band faults)
  - Place occurrences within structural context, thus useful for risk assessment/site characterization efforts
Technical Status

• Initial fieldwork to identify significant interface features and select study sites

• Collection of geological and petrophysical data from outcrop (Navajo/Carmel, Slickrock/Earthy facies in Entrada) and core (Mt. Simon/Eau Claire)

• Use geological and petrophysical data to construct conceptual geologic and permeability models

• Modeling efforts
  – Single phase
  – Multiphase

• Structural framework to predict likelihood of encountering at sequestration sites
Study Units: Overview

- Green River
- Navajo/Carmel
- Dakota/Mancos
- Slickrock/Earthy Entrada
- Cedar Mesa/Organ Rock
Study Units: Overview (cont’d)

- Mt Simon-Eau Claire Core from CAES core in Iowa
- Permeability, cap pressure, geomechanics

Precambrian Structure Map of Iowa and Location of CAES* Keith #1 Well

Site of Keith #1
I. Relating Fracture Conductivity to Structural Position

Cross section of San Rafael Swell, Utah, USA
Top Navajo Structural Contour Map
Curvature changes across fold limbs that creates changes in fracture patterns

Transverse fracture swarms 100’s m long

Concentrations of fractures near faults create pathways up to a km long

Fracture orientation wrt stress tensor controls fracture conductivity
II. Effects of Deformation Bands

• Most common strain localization feature found in porous sandstones (e.g., Navajo, Entrada, Mt. Simon)
• Form by: grain reorganization and/or comminution
• Typically 2 – 5 orders of magnitude lower K than host sand
• Can form capillary seals to supercritical CO$_2$
Deformation Bands:

• Localization in only certain sandstone facies (weak, highly porous)
• Constitutively a “transitional” behavior as seen in laboratory experiments
• Can compartmentalize sandstones, hinder injectivity

Yield and Failure Envelopes in Mt Simon Lithofacies

Laboratory shear bands in weak Mt Simon Facies

Dewers et al., 2014
Transition to Fractures

• Deformation band faults transition to shear fractures at interface

• Diagenetic alteration show these were open fractures
  – Bleaching
  – Mineralization
    • Carbonate cementation
    • Fe-oxide pseudomorphs of pyrite
    • Hydrocarbon inclusions
    • Can infer aperture history through petrography
Deformation Band/Fracture Transition, Slickrock/Earthy Entrada Facies

- 1 to 5 cm thick zone of deformation bands
- 2 to 30 mm thick zone of deformation bands
- 1 to 8 mm thick calcite mineralized fracture
- <1 to 1 mm thick calcite mineralized fracture
- Small normal fault with 1 to 2 mm thick calcite mineralized fracture
- Bleached zone
- Interface
Permeability Model

- Outcrop measurements map permeability onto lithology and structure

**Outcrop permeability measurements using TinyPerm™**
2D Single-Phase and Multiphase FE Modeling

- FEMOC (finite element method of characteristics) code (LANL) for single phase
- FEHM (Finite element hydrological mechanical (LANL) for multiphase

Meshing and boundary conditions for FE modeling of field site
Modeling Questions

1. Effect of small-scale architecture
   a) Fracture at Interface
   b) Deformation Band at Interface
   Caprock
   Reservoir
   Deformation Band
   0.25 m

2. Effect of degree of bypass
   c) 100% Fracture Penetration
   Caprock
   Reservoir
   d) 70% Fracture Penetration
Effect of Architecture (single phase results)

- When deformation band is at interface:
  - Greater compartmentalization
  - 2 orders of magnitude lower flux through fracture

- When fracture penetrates interface:
  - Greater flux through caprock
Multiphase Results

1. Effect of Architecture

2. Effect of Bypass
• Deformation-band faults:
  – often link to transmissive fracture networks in the caprock
  – can form capillary seals to CO$_2$
  – can compartmentalize the reservoir adjacent to the interface

• Field evidence of fluid transmission through caprock fractures:
  - Bleaching of iron
  - Enhanced carbonate mineralization above and within caprocks
III. Porosity Facies

• Detailed Petrography
• Mercury porosimmetry (here expressed as saturation versus pore diameter)

Eau Claire Caprock

Mt Simon Reservoir

Amount of “pink” proportional to pore volumes
On CO2 Capillary seals and residual trapping:

- Large capillary contrast at the interface between Eau Claire and Mt Simon
- Mt Simon has an extraordinary degree of sub-cm heterogeneity in pore- and pore-throat sizes
- Increased pore-body/pore-throat size ratio supports greater residual trapping

On Mt Simon storage potential:

- Connected porosity in Mt Simon Reservoir facies due to gypsum and (lesser) feldspar dissolution
- Evaporite dissolution thought to be from Pleistocene (ice sheet hydrology)
Accomplishments to Date

– Navajo/Carmel, Earthy/Slickrock Entrada
  • Geologic description and conceptual permeability models of interfaces for 6 Utah sites
  • 10s of km fracture density and orientation data
  • Single- and Multiphase phase modeling results
  • Detailed structure yields permeability distributions; may not “homogenize”

– Mt. Simon/Eau Claire
  • Core description, petrographic analysis and mercury porosimetry completed for 180 ft of Mt. Simon/Eau Claire (Dallas Center Structure, central Iowa)
  • Implications for capillary sealing and residual trapping
  • Diagenesis controls spatial reservoir quality
Appendix
Raduha, S., 2013, Influence of mesoscale features at the reservoir-caprock interface on fluid transmission into and through caprock: New Mexico Tech MS Thesis. (Available at ees.nmt.edu)

Butler, D., 2014, Effects of meso-scale deformation features at the reservoir-caprock interface: Implications for carbon capture and storage projects: New Mexico Tech MS Thesis (Available at ees.nmt.edu)
