CO_2 at the Interface: Nature and Dynamics of the Reservoir/Caprock Contact and Implications for Carbon Storage Performance

Project Number DE-FE0004844

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U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and
Infrastructure for CCS
August 14-16, 2014

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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?

Exposure of analog caprock-reservoir interface cut by fault

Outline:

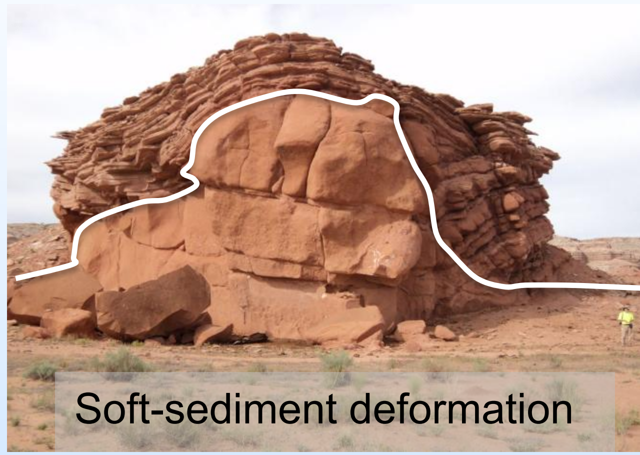
- Intro
- Organization
- Benefit to Program
- Project Overview
- Technical Status
- Accomplishments
- Summary
- Appendix

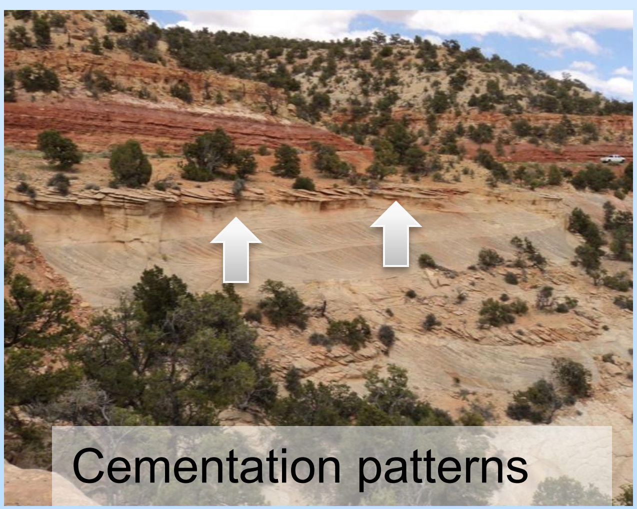
Importance of **Scale**: Examples of Interface Heterogeneity

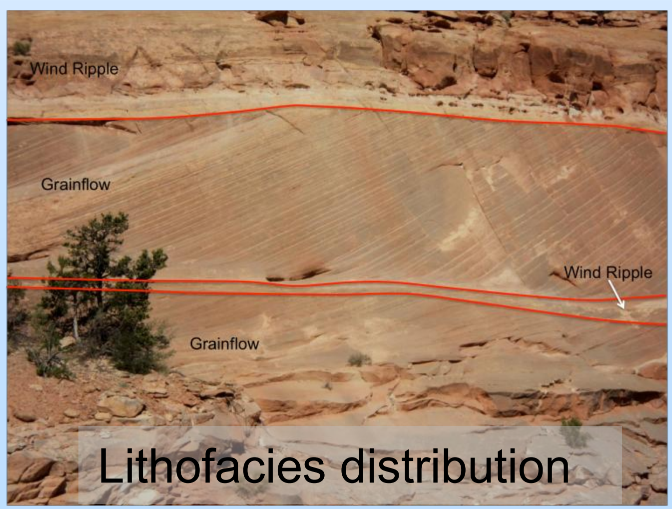
- Depositional
- Structural
- Diagenetic

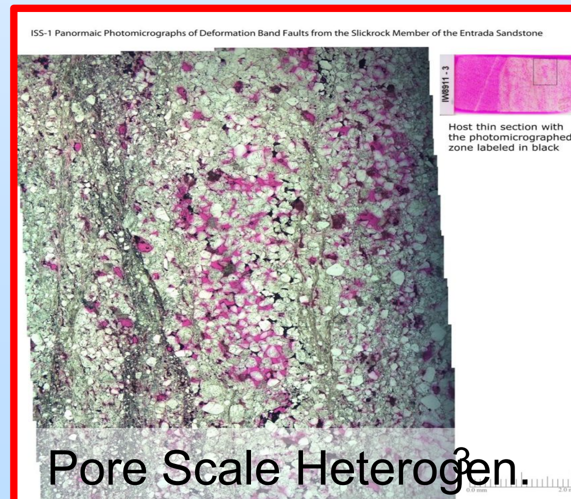
Focus for today's talk

1. Fracture Patterns
2. Deformation Bands
3. Porosity "Facies"

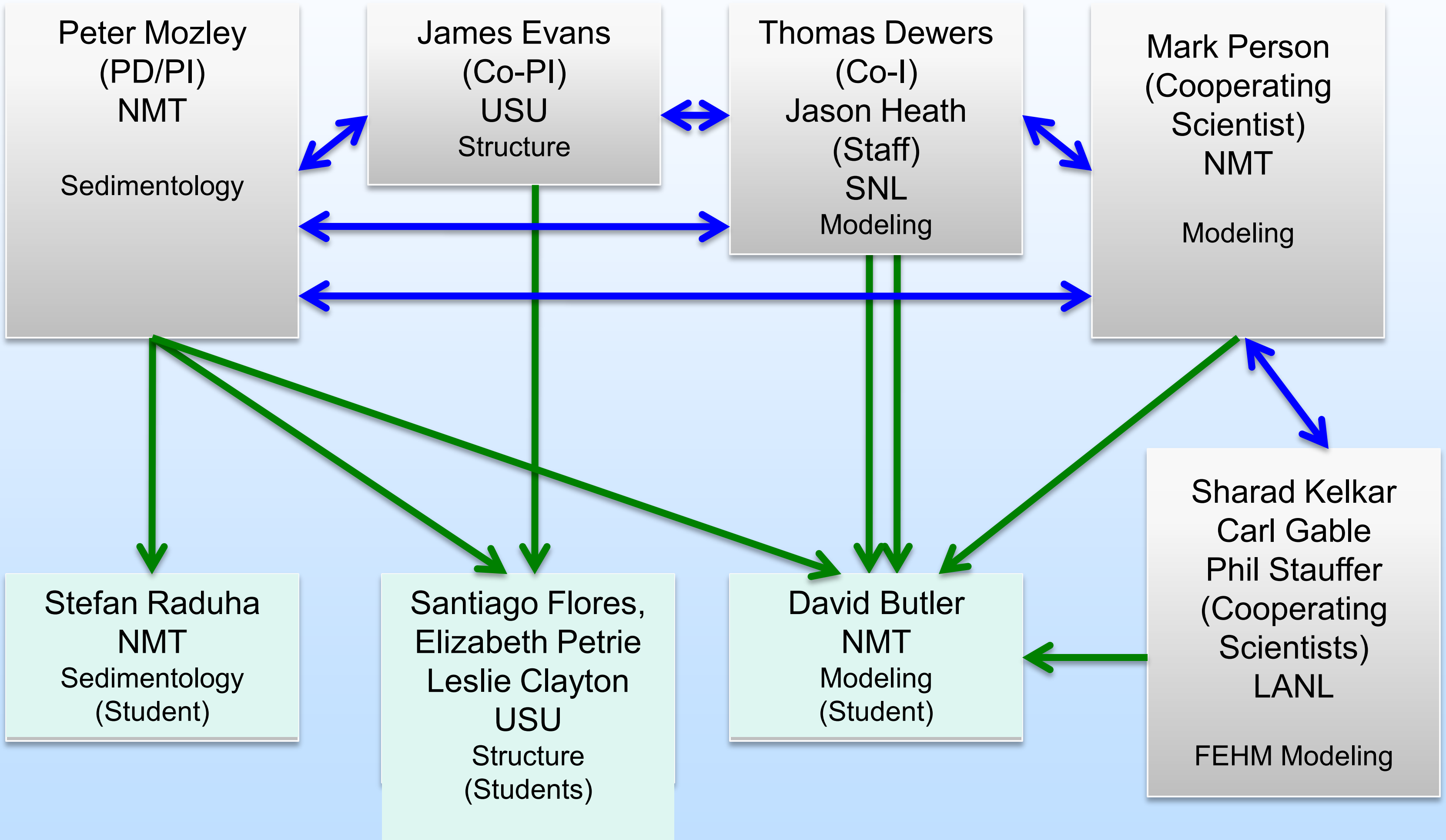








Organization: Team Interface



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**

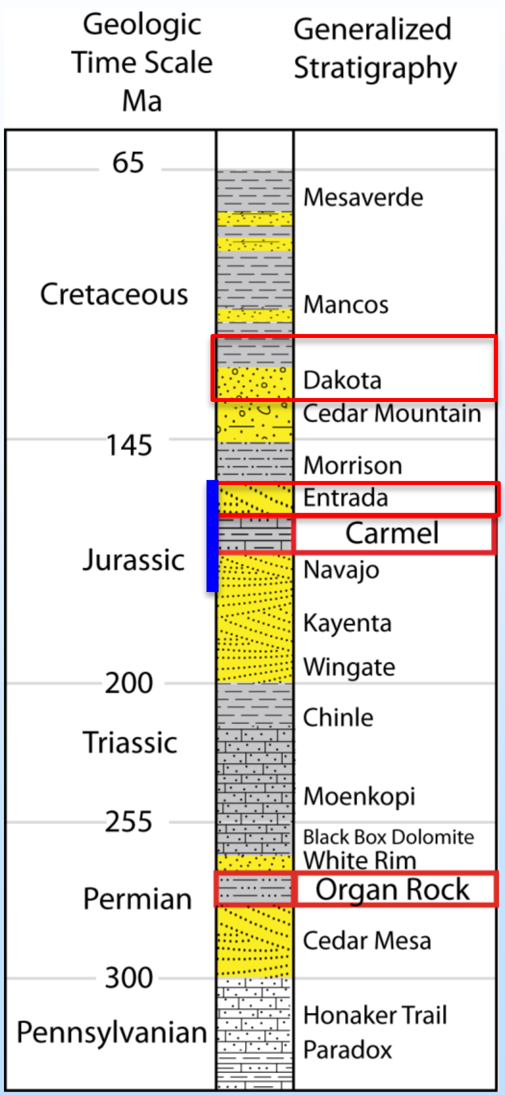
- Constrain potential interface transmissivity attending certain features (i.e. deformation band faults)
- Place occurrences within structural context, thus useful for risk assessment/site characterization efforts

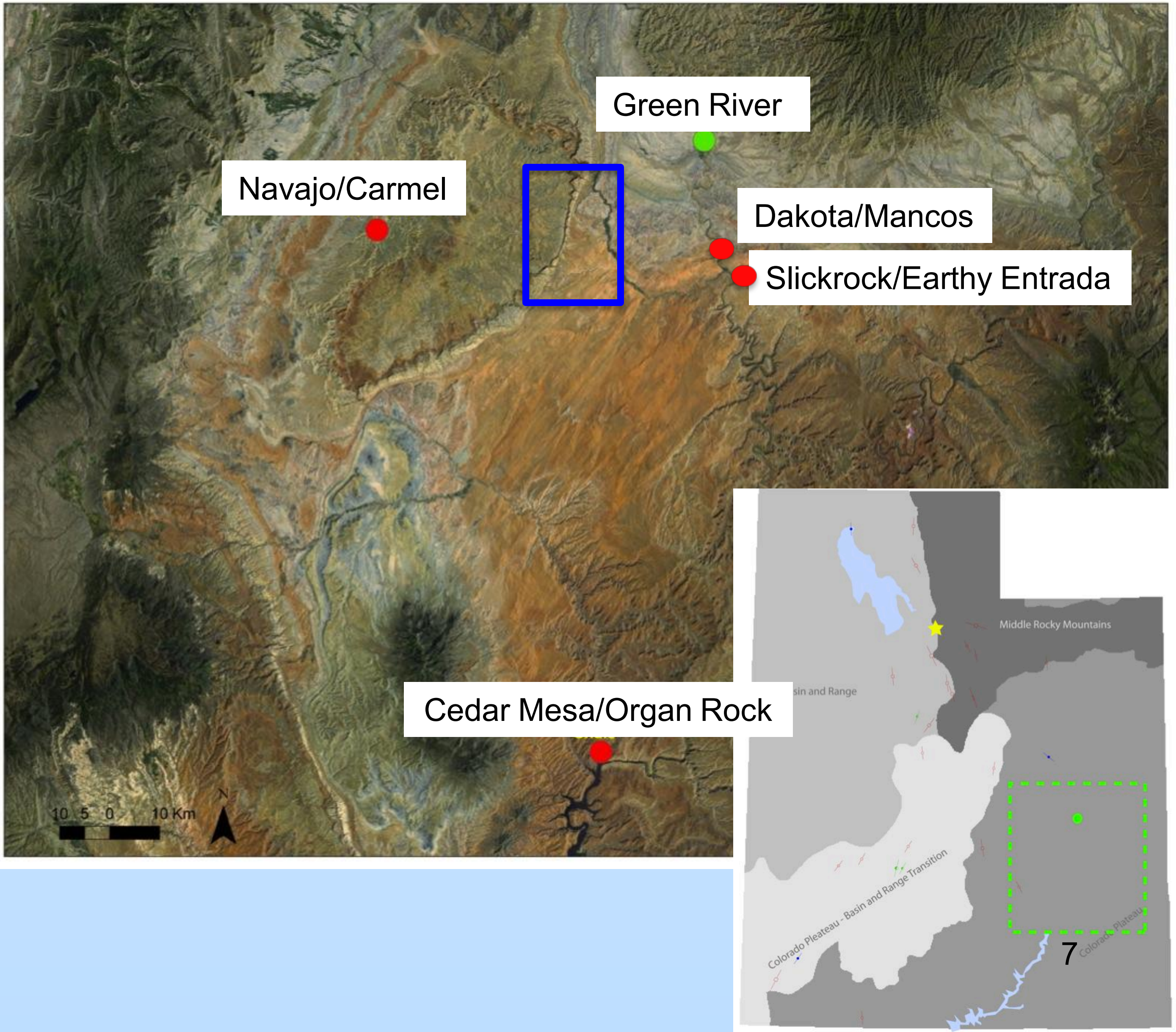
Technical Status

- 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

Reservoir-caprock analog and outcrop measurement of permeability

Study Units: Overview





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

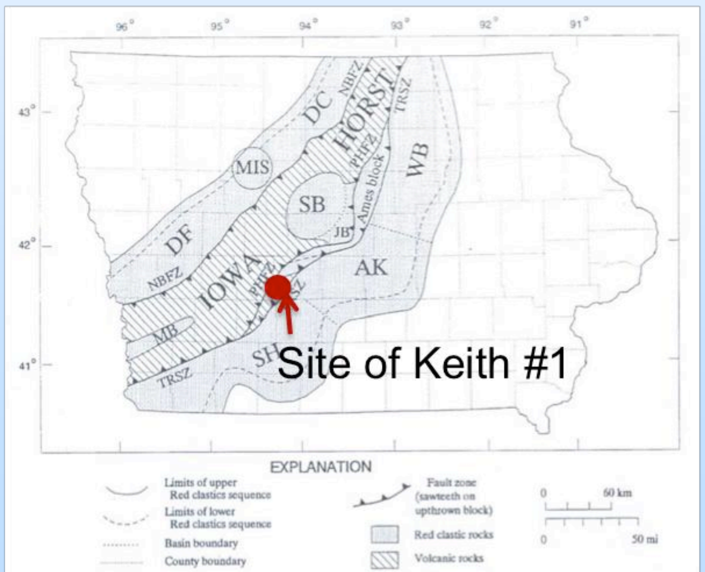
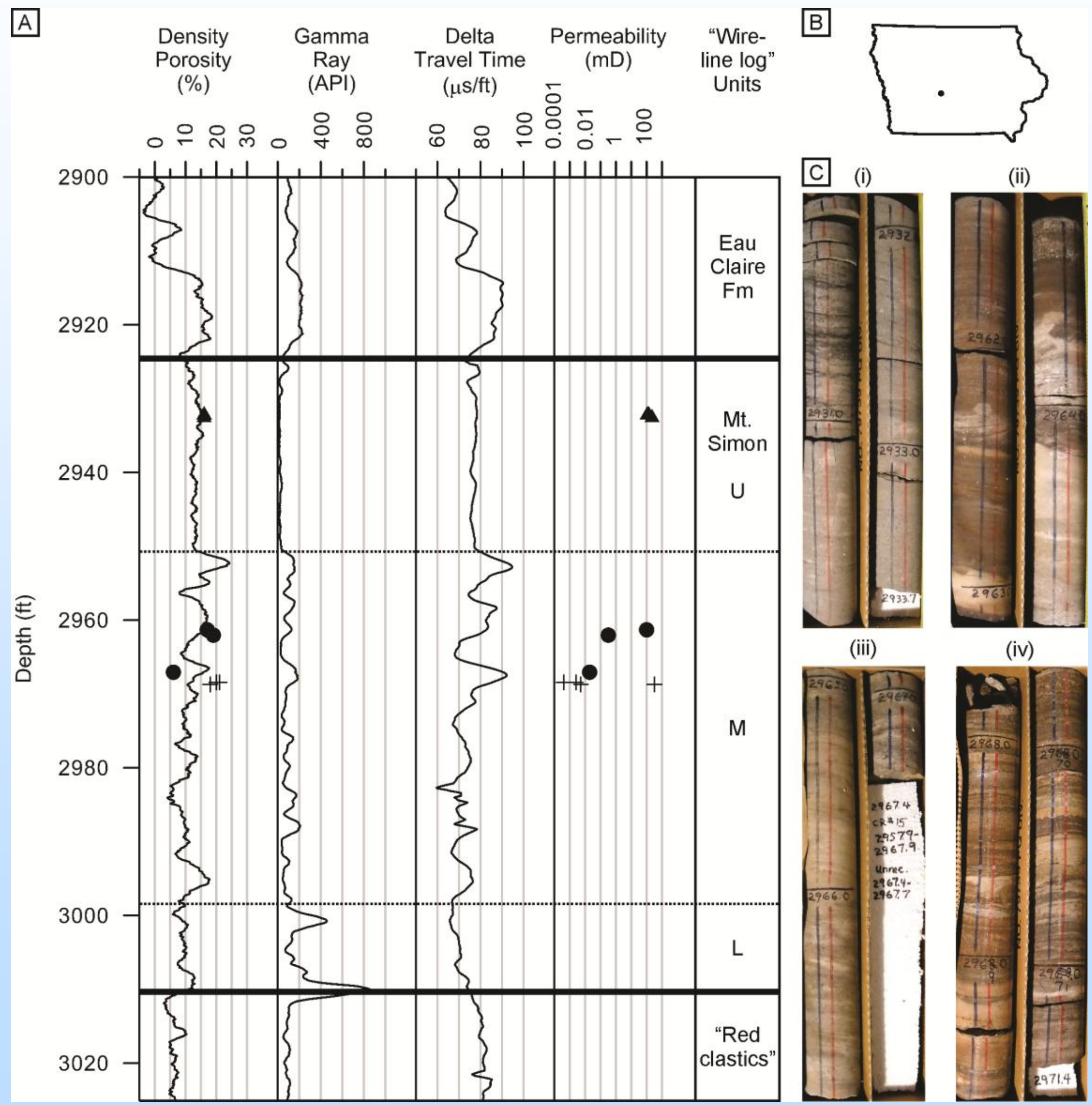
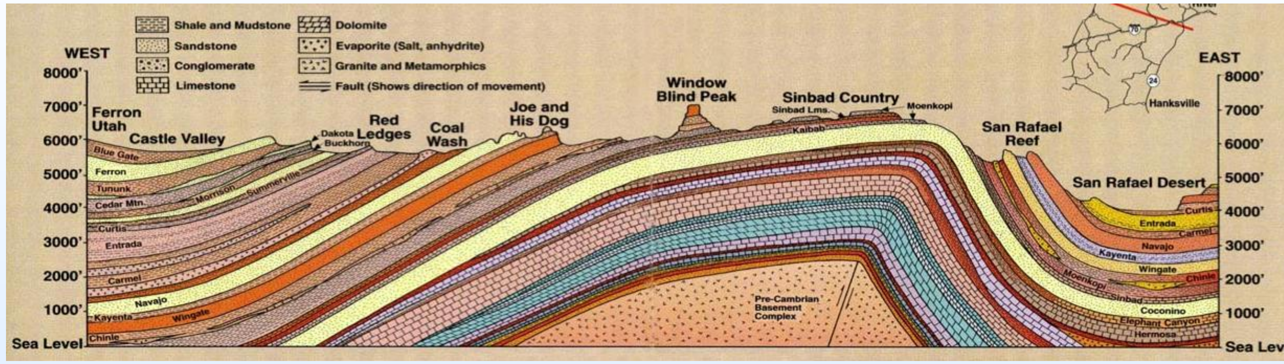


Figure 12. Structural components of the Midcontinent Rift System (MRS) in Iowa (modified from Anderson, 1992; and Anderson, 1995, fig. 1, p. 56, copyright ©1995 Kluwer Academic Publishers, used with kind permission from Kluwer Academic Publishers). NBFZ, Northern Boundary Fault Zone; TRSZ, Thurman-Redfield Structural Zone; PHFZ, Perry-Hampton Fault Zone; DF, Defiance Basin; DC, Duncan Basin; SH, Shenandoah Basin; AK, Ankeny Basin; WB, Wellsburg Basin; SB, Stratford Basin; JB, Jewell Basin; MB, Mineola Basin; MIS, Manson Impact Structure.



I. Relating Fracture Conductivity to Structural Position

Cross section of San Rafael Swell, Utah, USA



http://www.castlecountry.com

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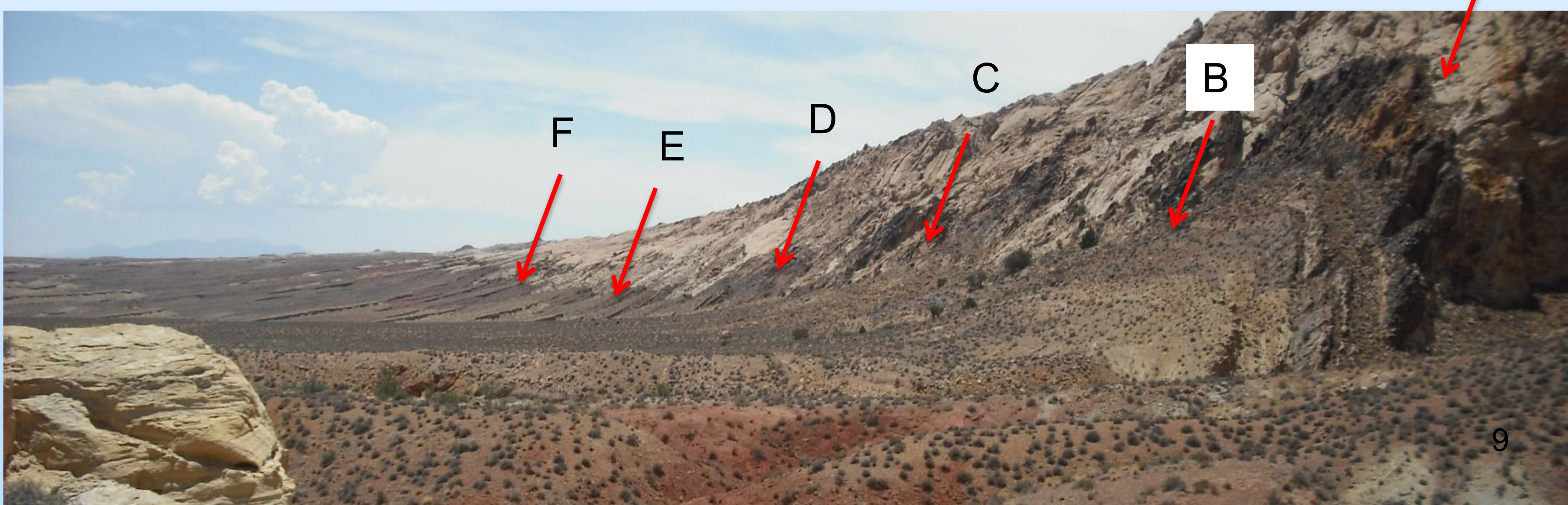
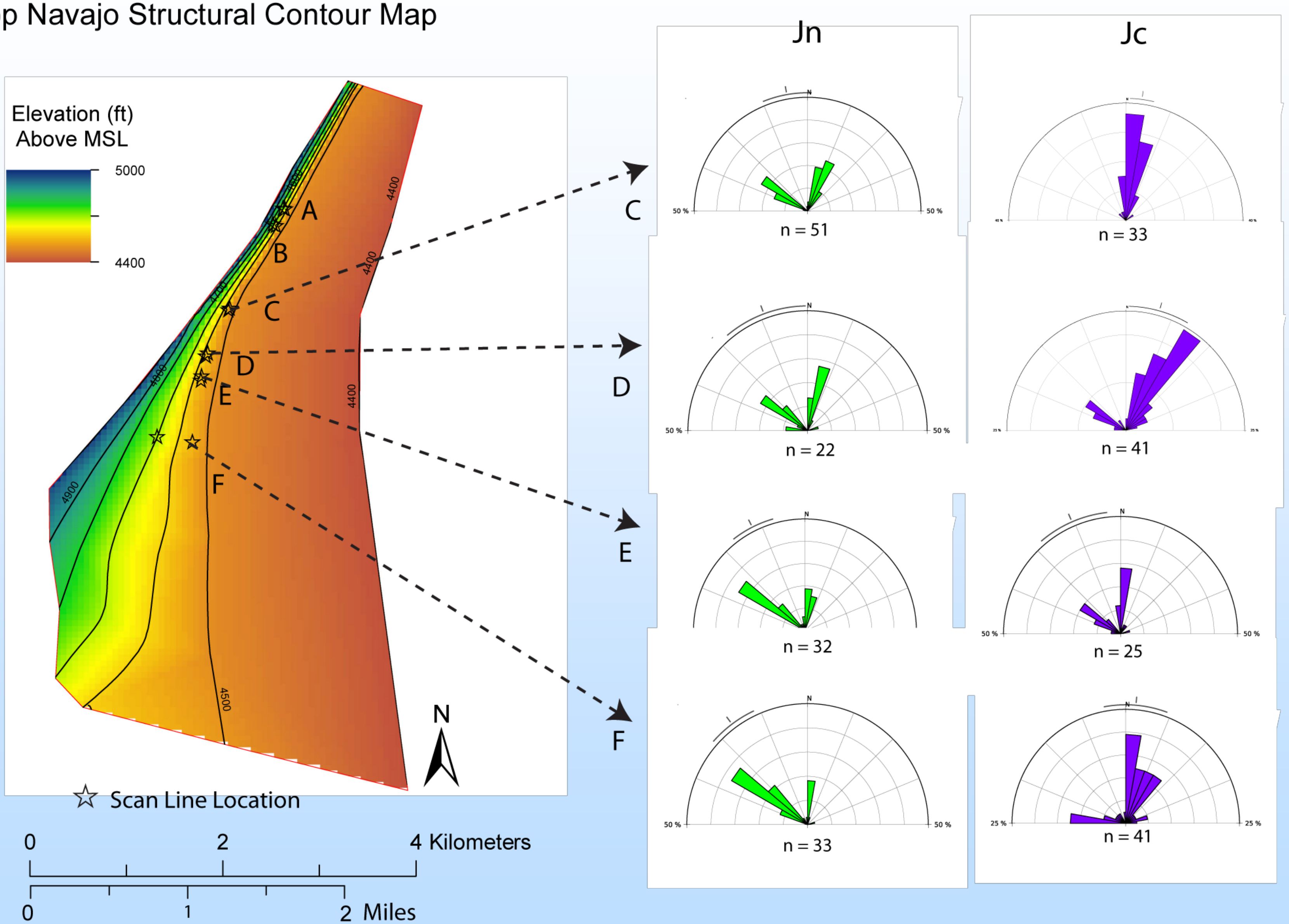
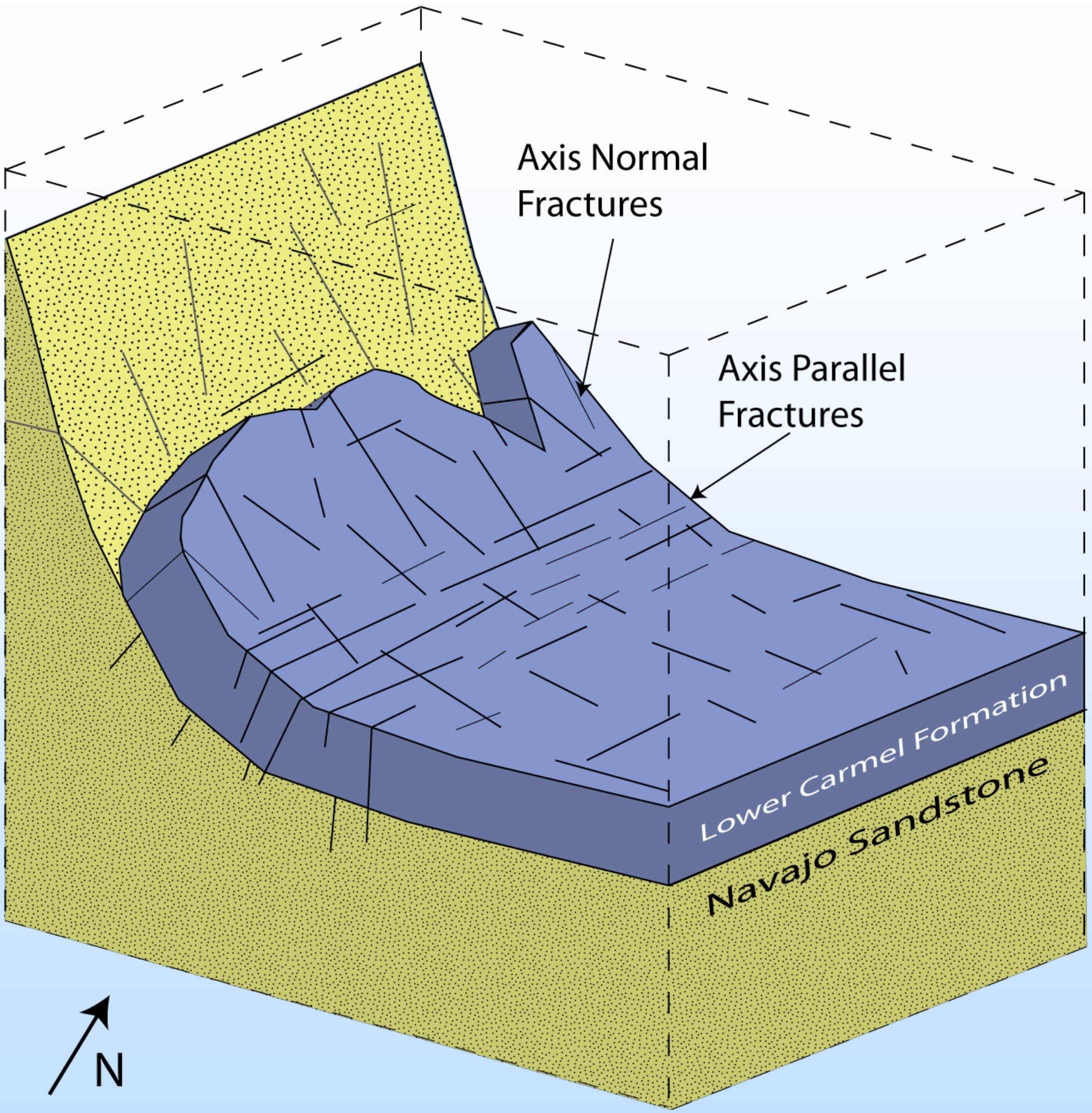


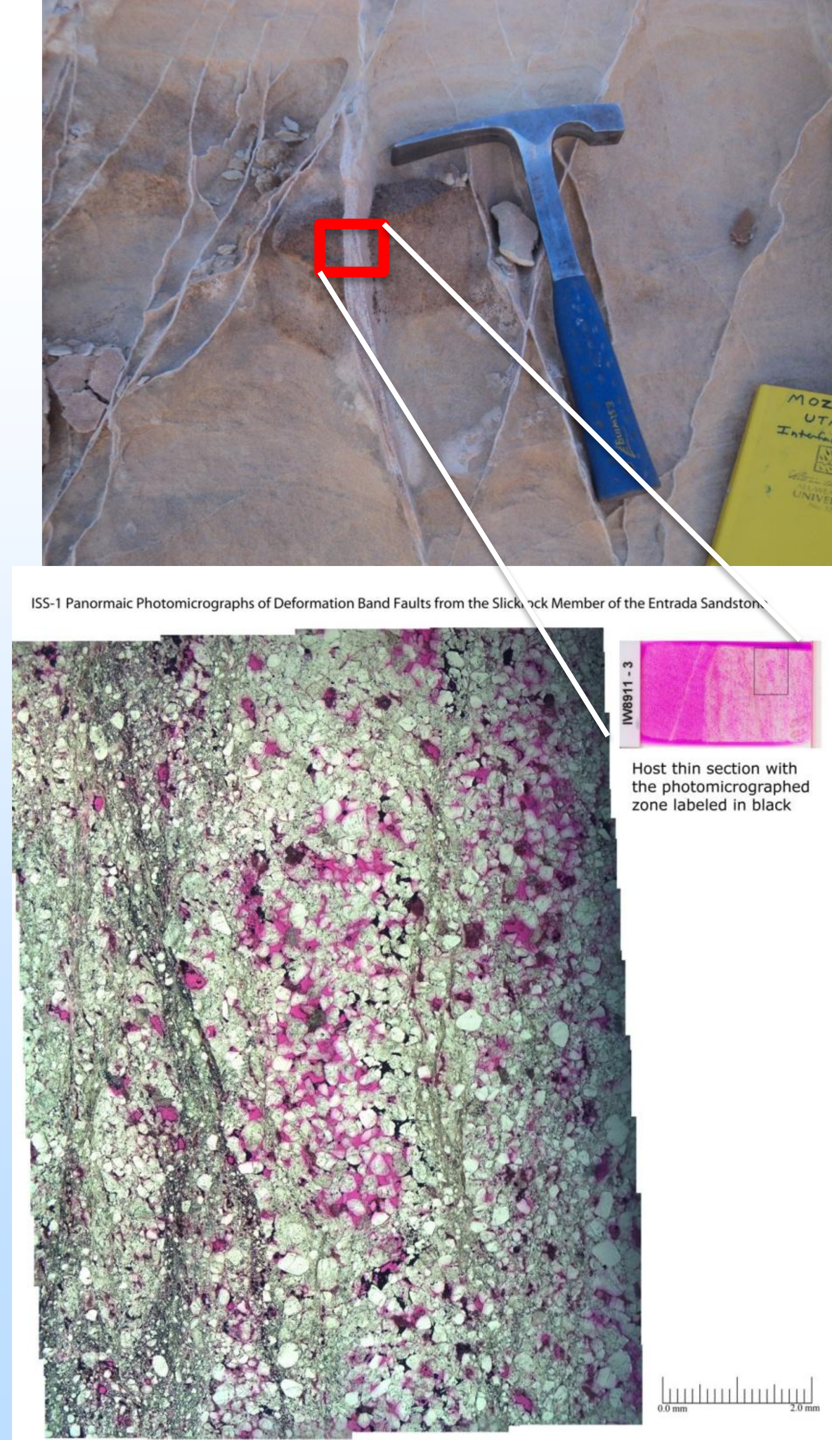
Top Navajo Structural Contour Map





- 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



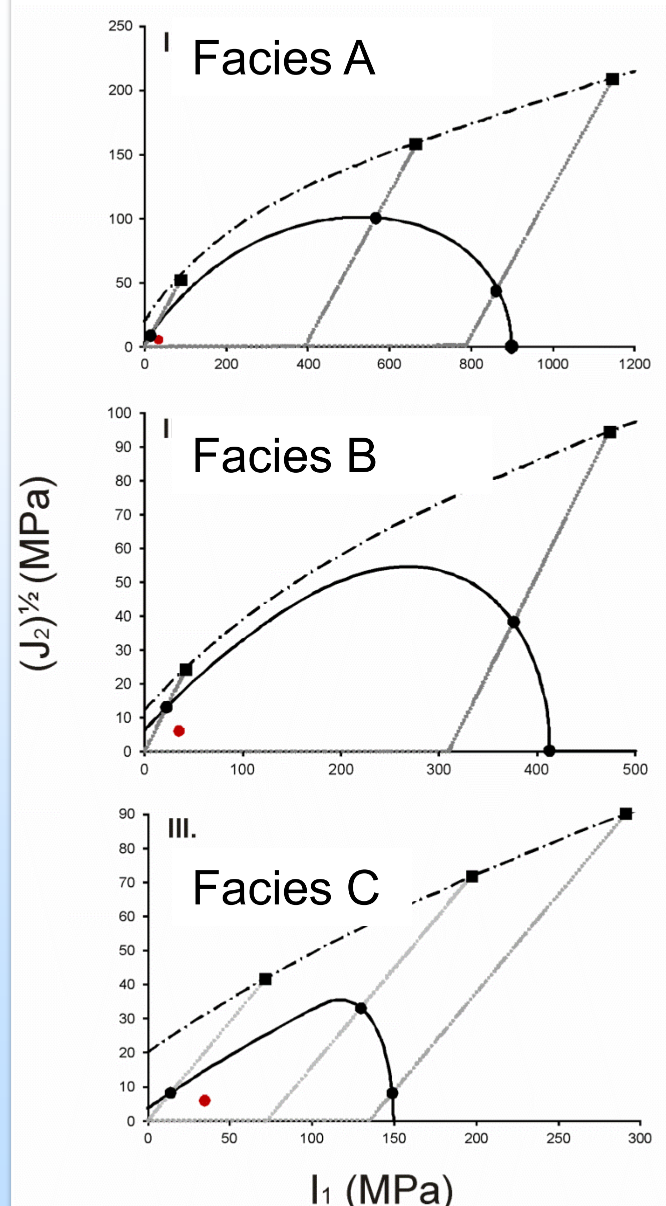
- Most common strain localization feature found in porous sandstones (e.g., Navajo, Entrada, Mt. Simon)
- Form by: grain reorganization and/or comminution
- Typically 2 – 5 orders of magnitude lower K than host sand
- Can form capillary seals to supercritical CO_2

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

Laboratory shear bands in weak Mt Simon Facies

Yield and Failure Envelopes in Mt Simon Lithofacies

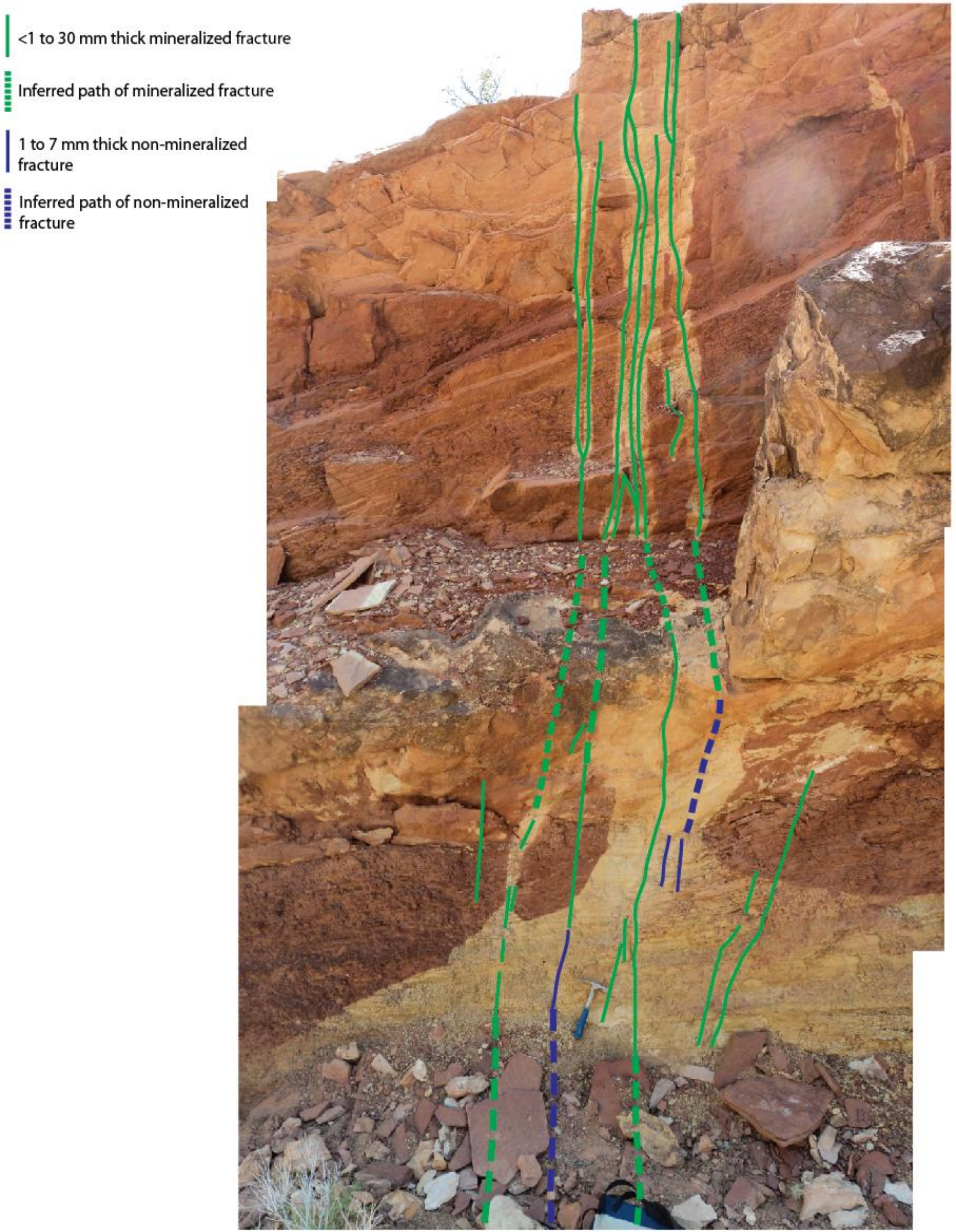


● Present stress state

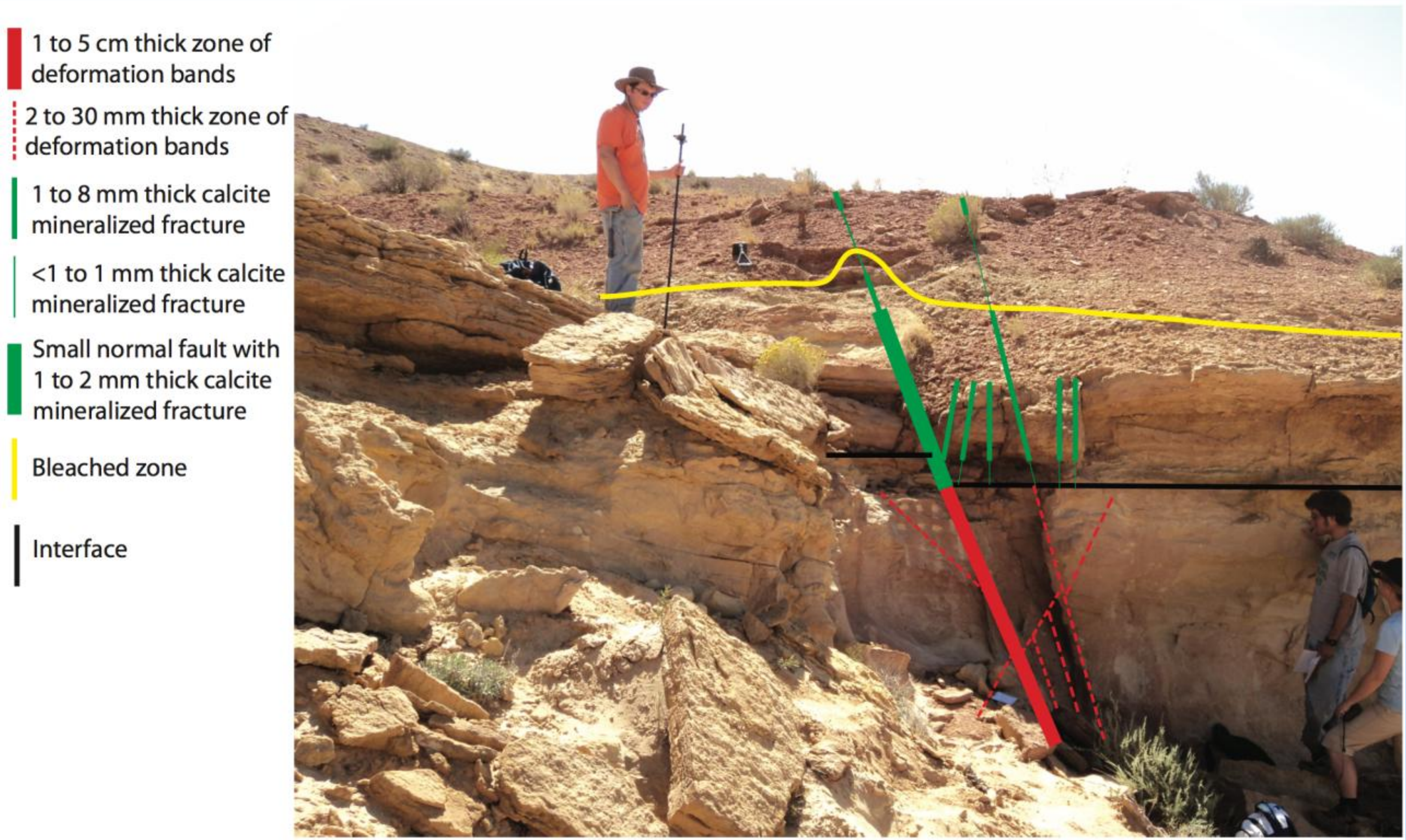
Dewers et al., 2014

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



Permeability Model

• Outcrop measurements map permeability onto lithology and structure

Outcrop permeability measurements using TinyPerm™

Unit Permeability (mD)

	TinyPerm II Measured Value	Corrected Value
Perm value:	12173	3528
Average:	12172.82	3527.82
Min:	849.57	360.83
Max:	31711.63	8992.61
n=26		
Perm value:	60	56
Average:	60.41	55.83
Min:	4.73	3.47
Max:	192.01	176.92
n=12		
Perm value:	2	1
Average:	1.87	1.37
Min:	1.87	1.37
Max:	1.87	1.37
n=1		
Perm value:	0.0055*	
Average:	0.0055	
Min:	0.001	
Max:	0.01	
n=N/A		
Perm value:	0.0005**	
Average:	0.0005	
Min:	$1x10^{-8}$	
Max:	0.001	
n=N/A		

*0.01 to 0.001 mD is a general permeability range for siltstone from Brace (1980)
**0.001 to $1x10^{-8}$ mD is a general permeability range for shales from Brace (1980)

Zone of Deformation Bands Permeability (mD)

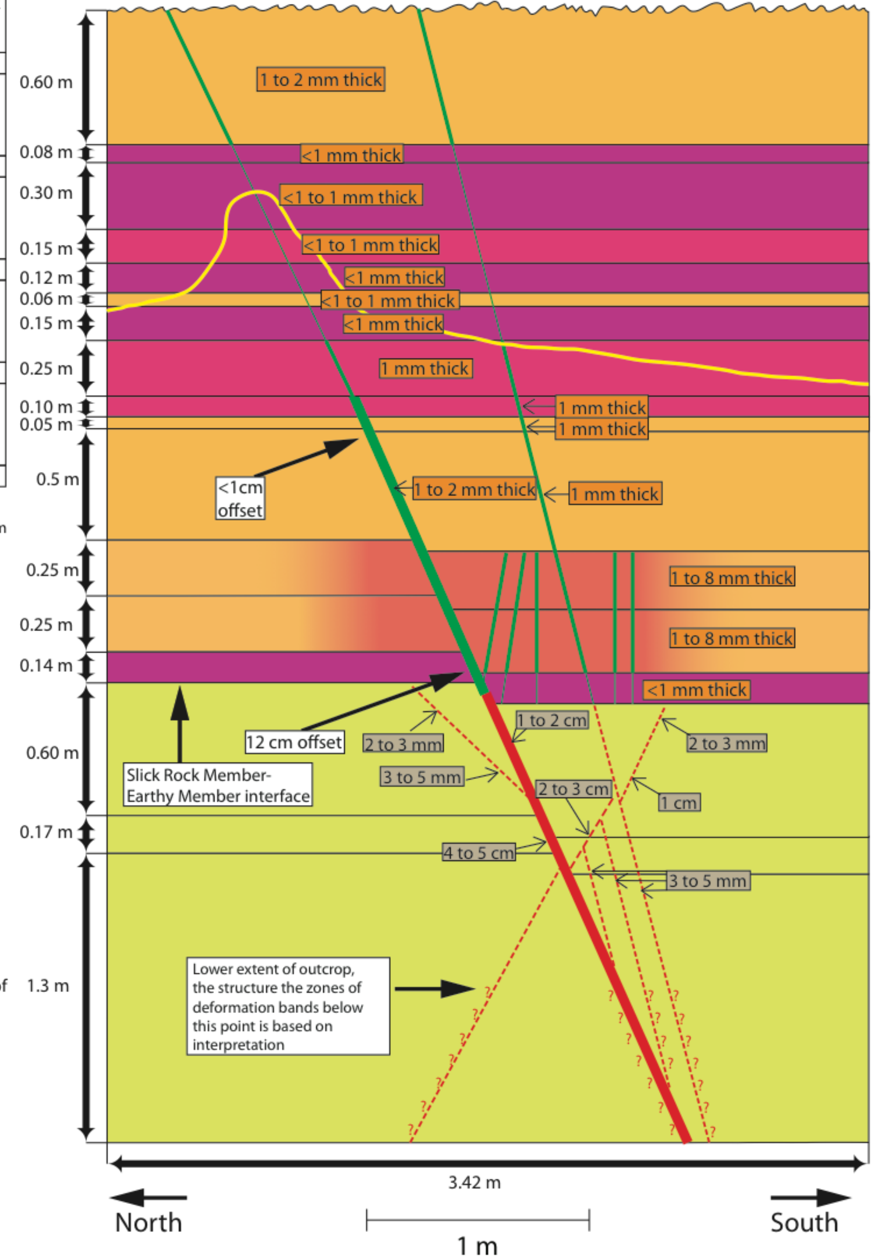
Perpendicular to Band

Perm value:	2
Average:	2.44
Min:	0.416
Max:	4.47
n=2	

Parallel to Band

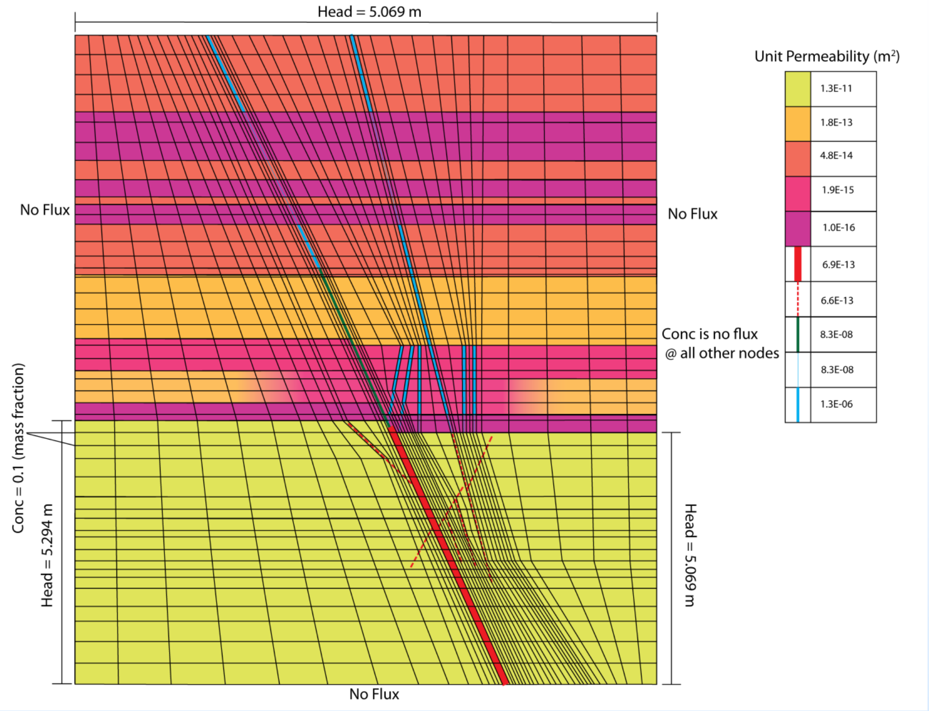
Perm value:	9
Average:	8.69
Min:	1.28
Max:	16.10
n=2	

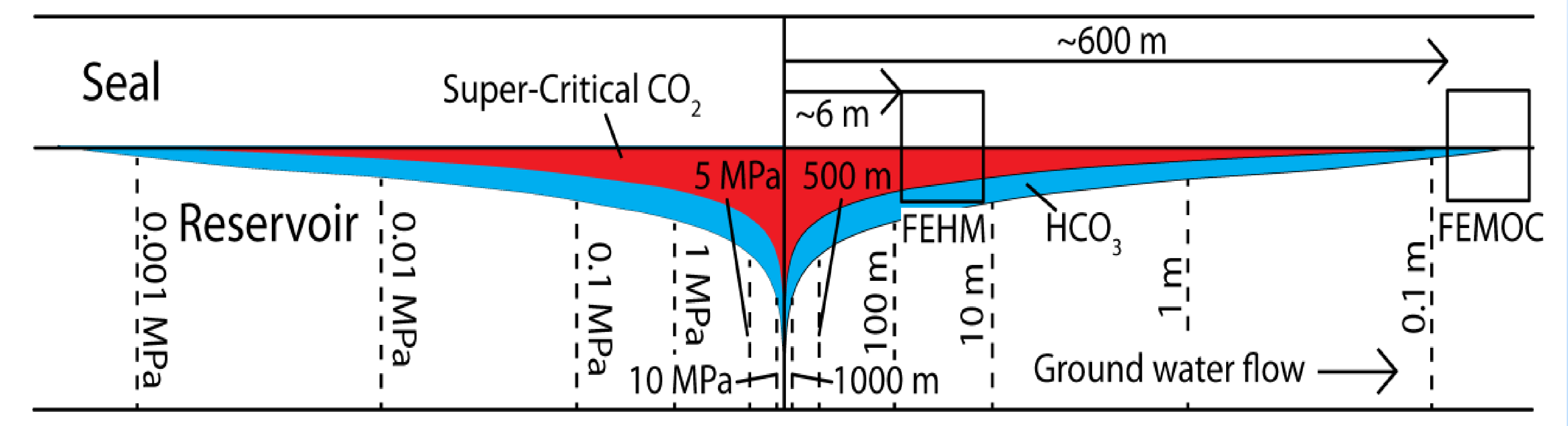
1 to 5 cm thick zone of deformation bands
2 to 30 mm thick zone of deformation bands
1 to 8 mm thick calcite mineralized fracture
<1 to 1 mm thick calcite mineralized fracture
Small normal fault with 1 to 2 mm thick calcite mineralized fracture
Bleached zone
mm Fracture thickness
mm Zone of deformation bands thickness



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

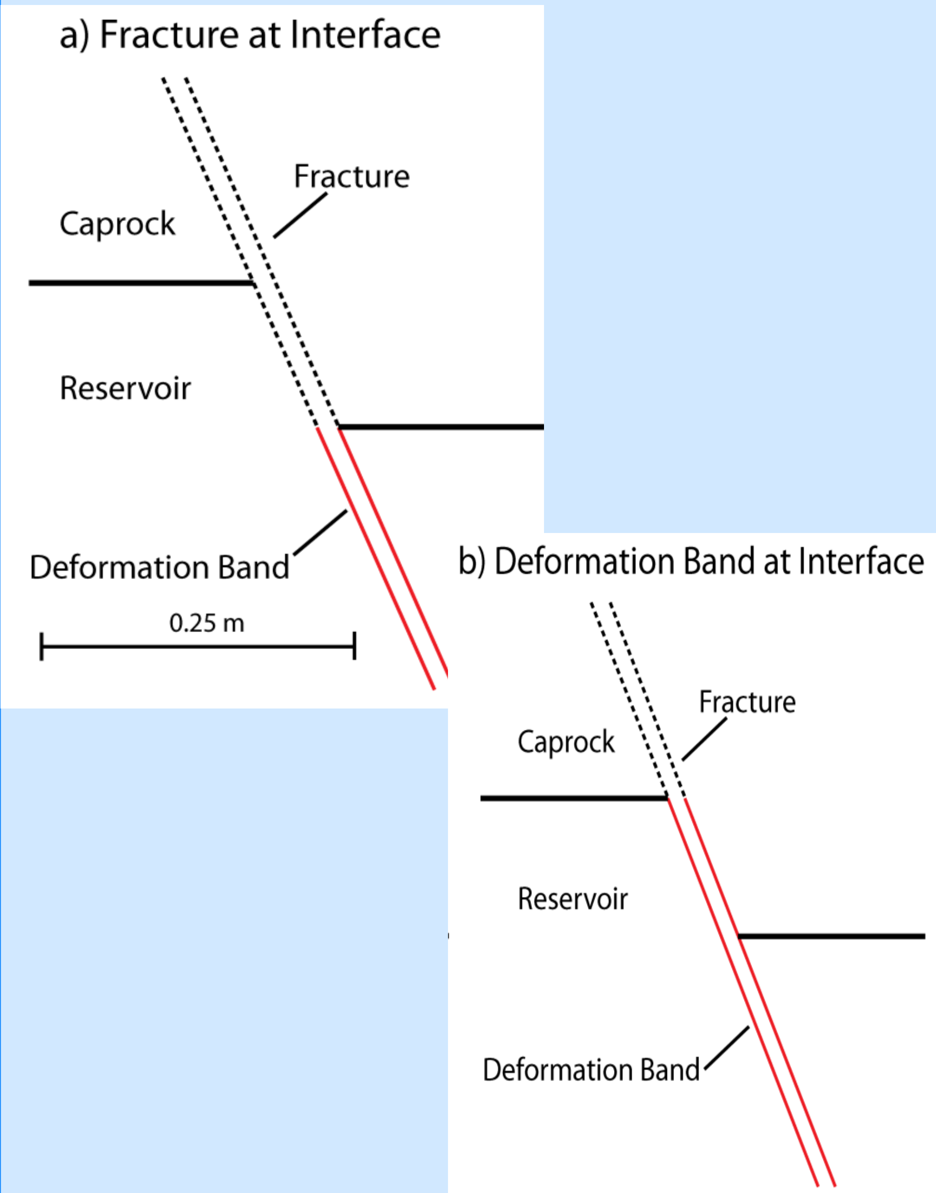




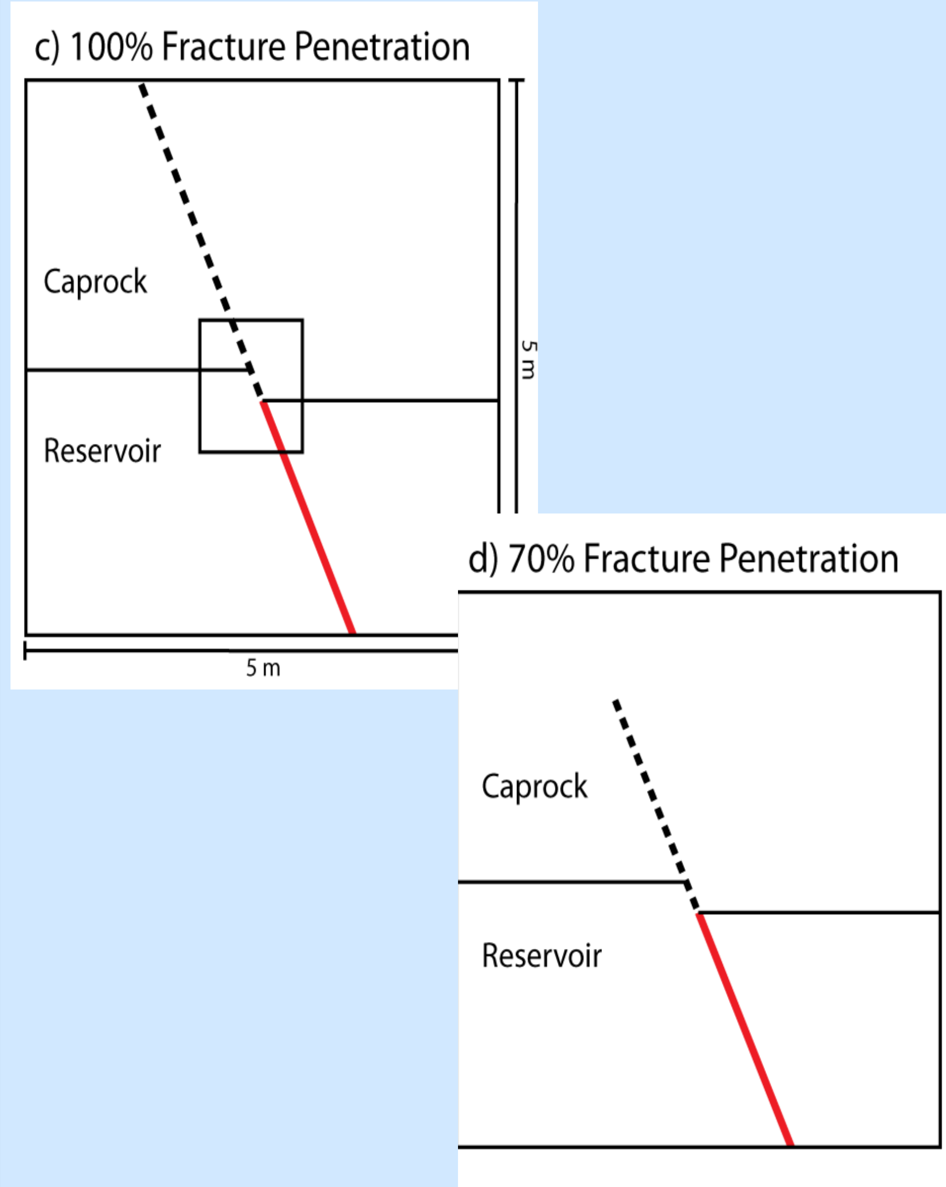
Meshing and boundary conditions for FE modeling of field site

Modeling Questions

1. Effect of small-scale architecture

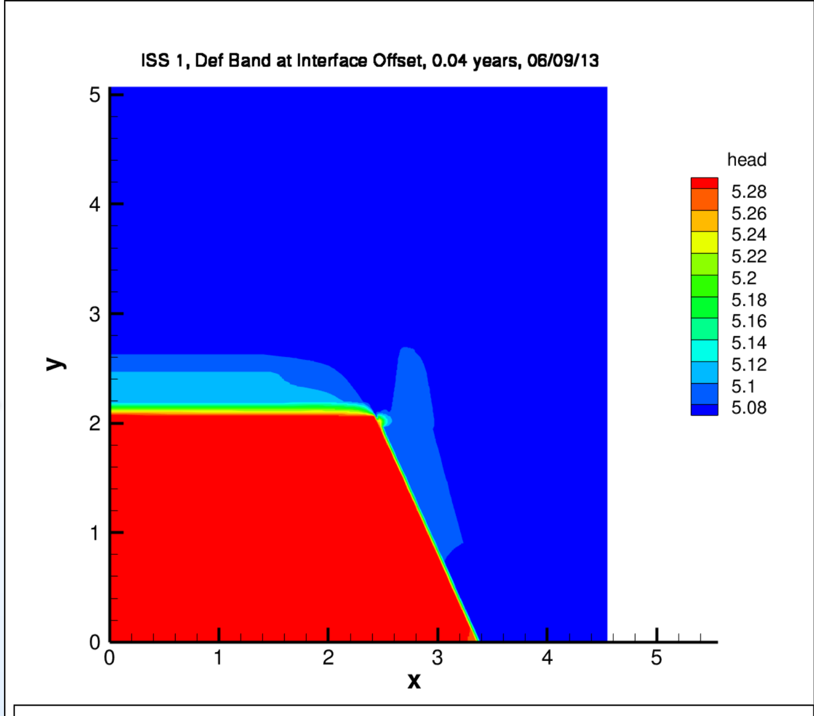


2. Effect of degree of bypass

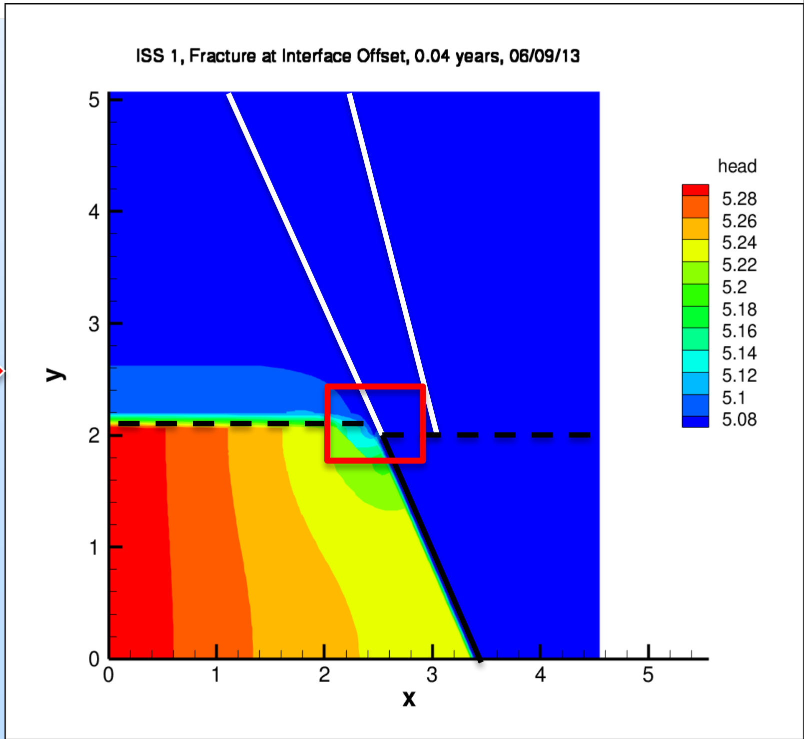


Effect of Architecture
(single phase results)

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



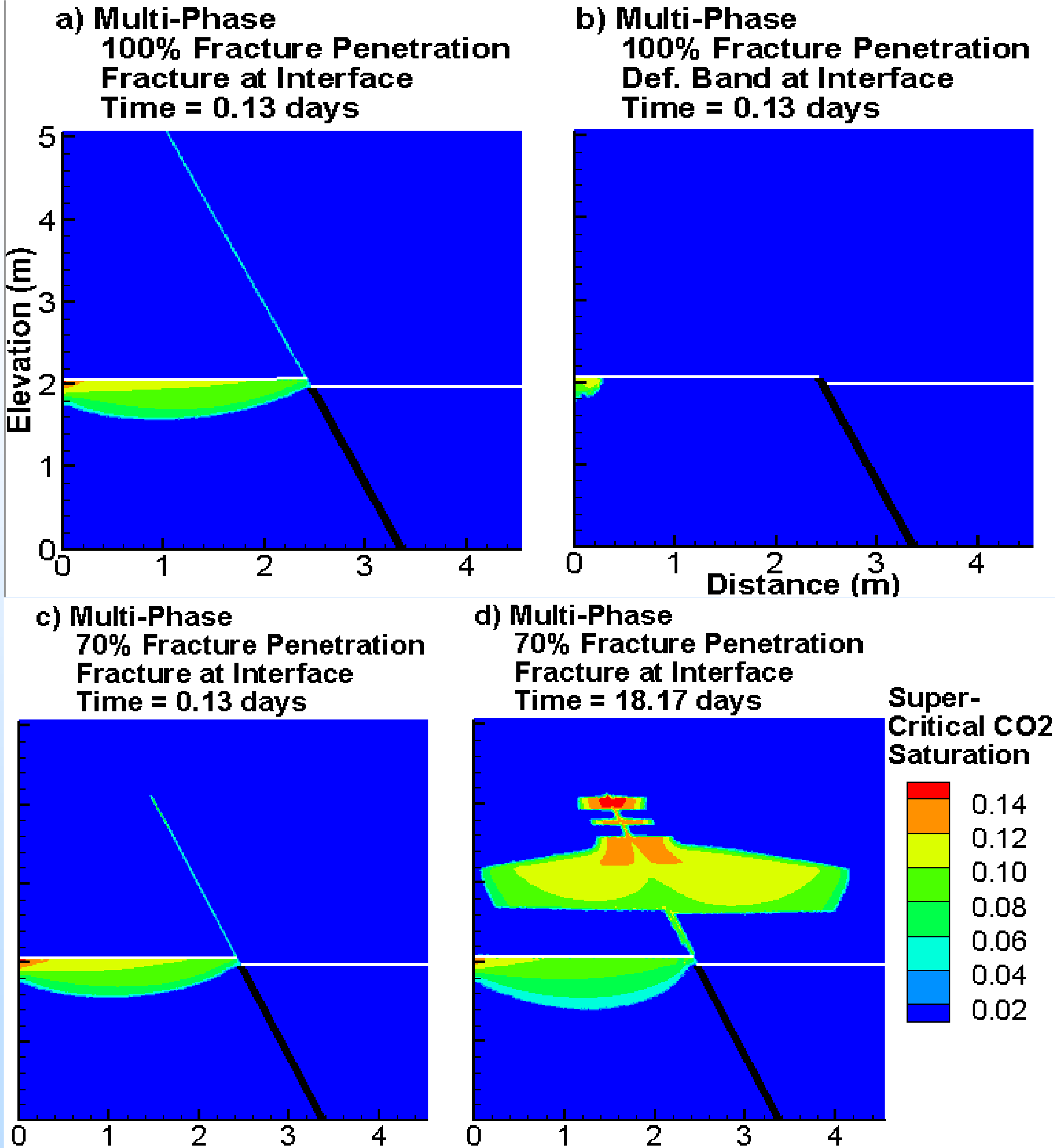
- **When fracture penetrates interface:**
- Greater flux through caprock



Multiphase Results

1. Effect of Architecture

2. Effect of Bypass



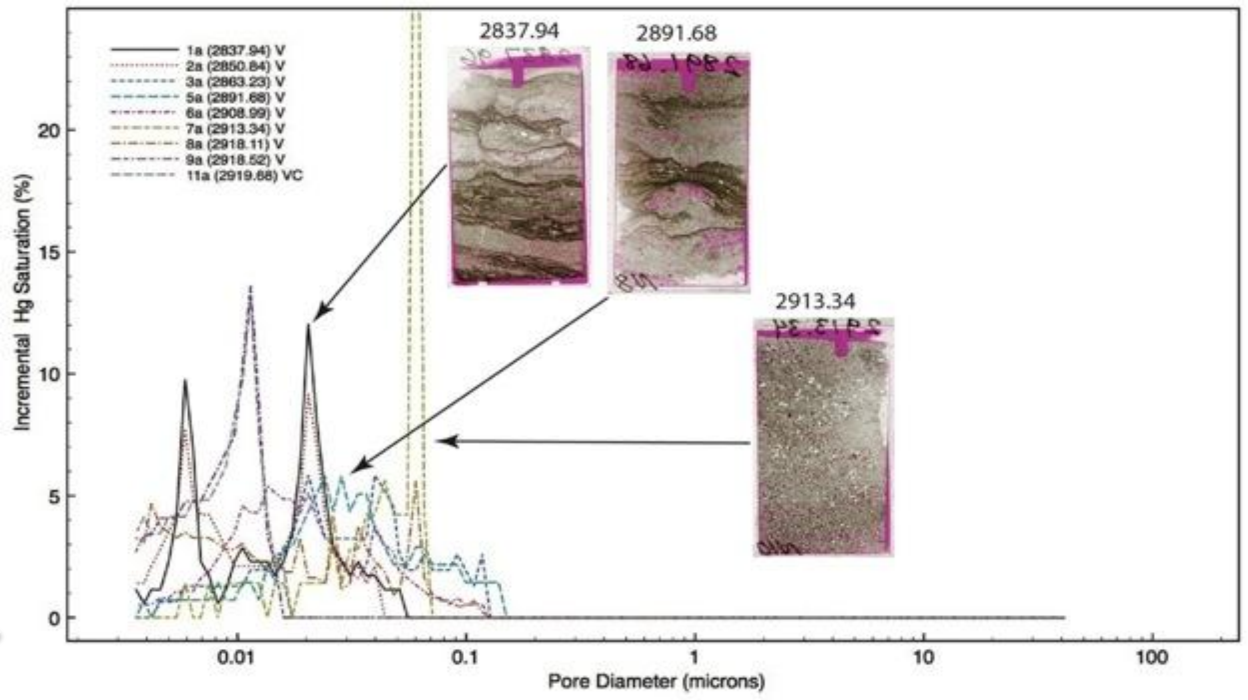
- **Field evidence of fluid transmission through caprock fractures**:
  - -Bleaching of iron
  - -Enhanced carbonate mineralization above and within caprocks

- **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

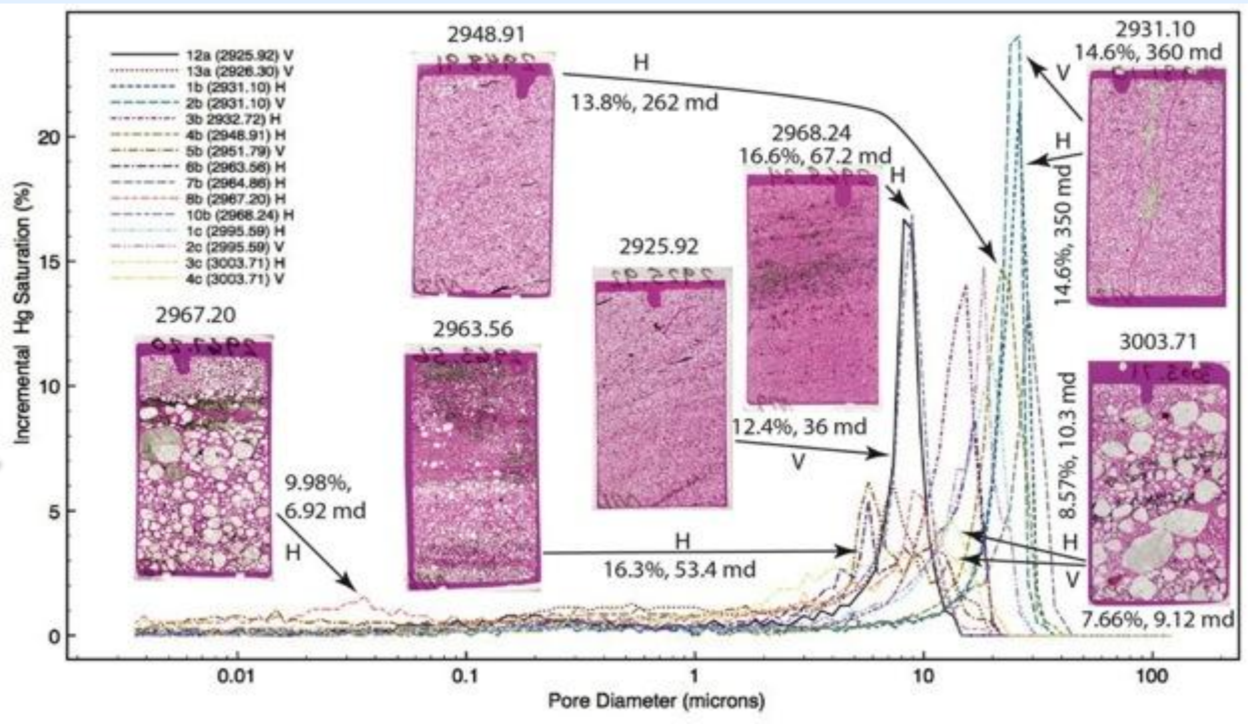
III. Porosity Facies

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

Eau Claire Caprock



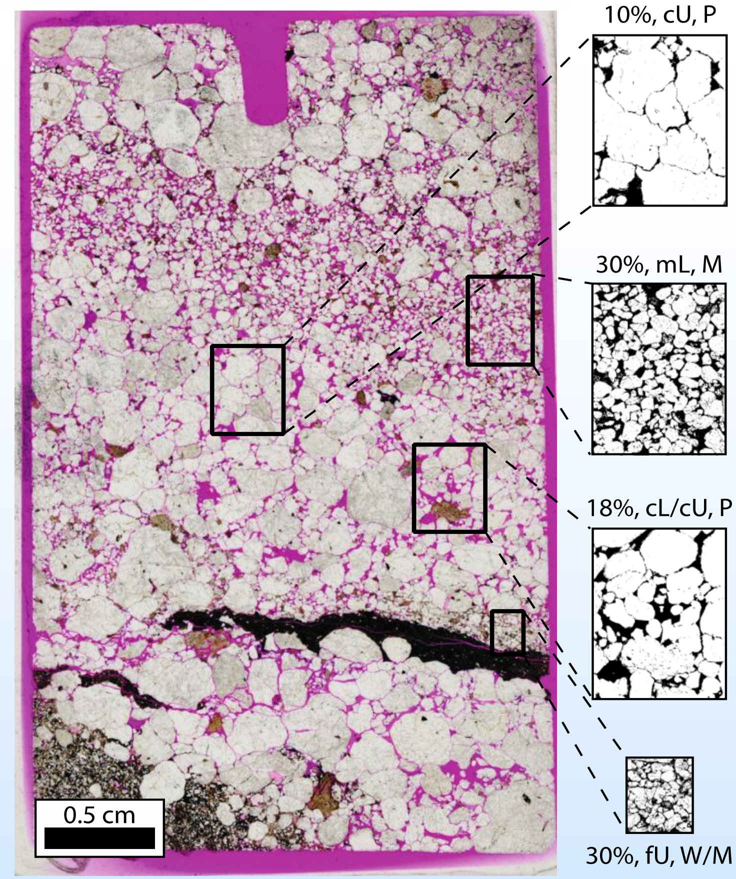
Mt Simon Reservoir



Amount of "pink" proportional to pore volumes

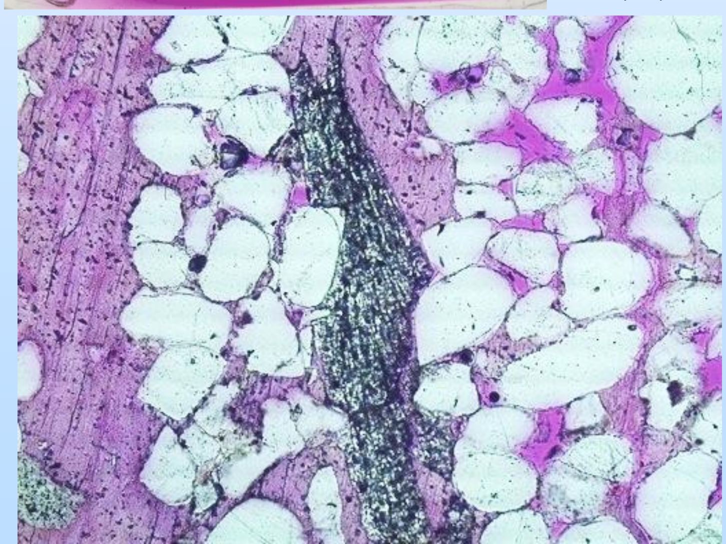
On CO2 Capillary seals and residual trapping:

- 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)

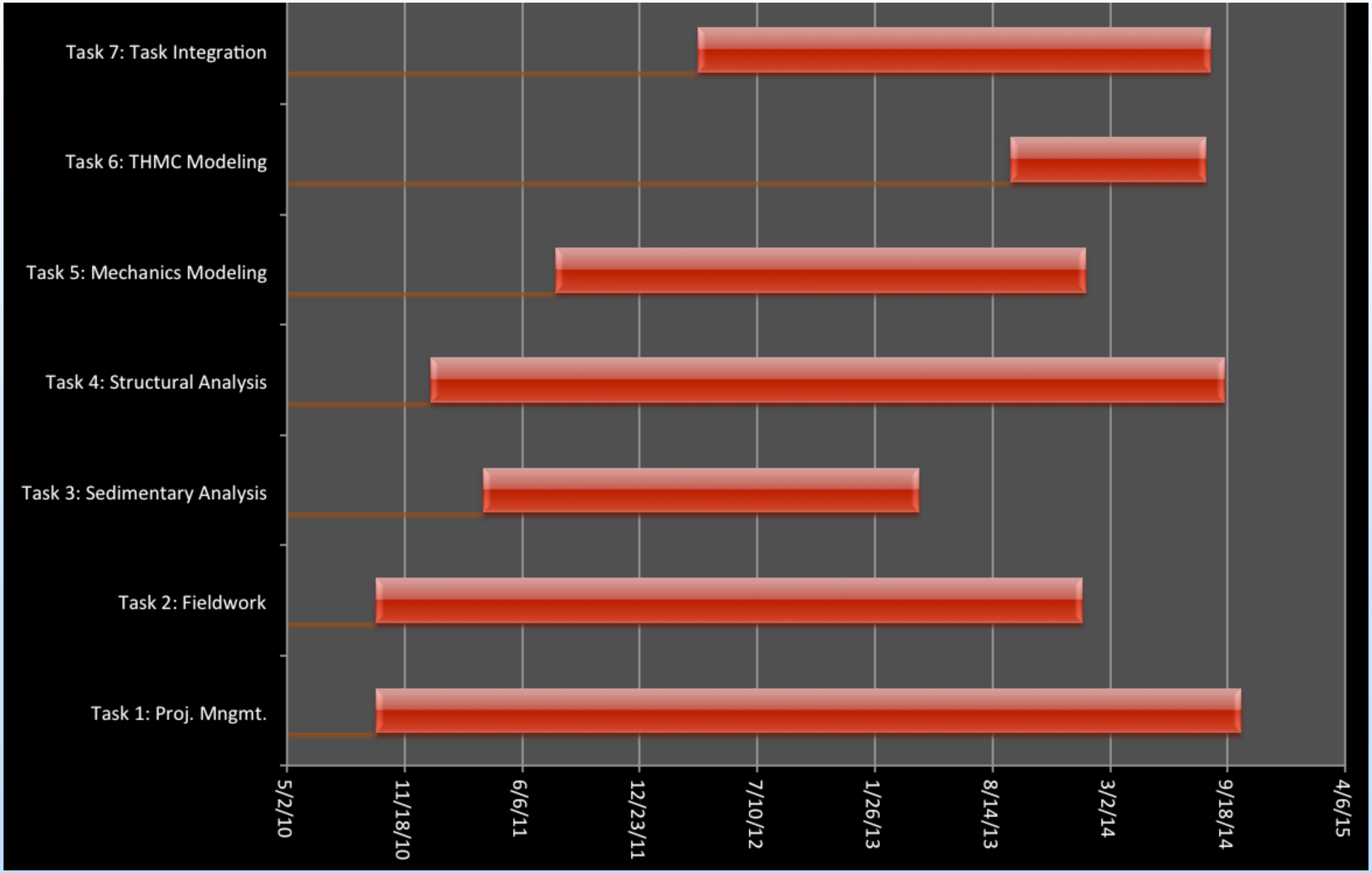


Accomplishments to Date

- 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

Gantt Chart



Task 7: Task Integration
Task 6: THMC Modeling
Task 5: Mechanics Modeling
Task 4: Structural Analysis
Task 3: Sedimentary Analysis
Task 2: Fieldwork
Task 1: Proj. Mngmt.
5/2/10
11/18/10
6/6/11
12/23/11
7/10/12
1/26/13
8/14/13
3/2/14
9/18/14
4/6/15

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