

# CO<sub>2</sub> at the Interface: Nature and Dynamics of the Reservoir/Caprock Contact and Implications for Carbon Storage Performance

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National Energy Technology Laboratory  
Carbon Storage R&D Project Review Meeting  
Developing the Technologies and  
Infrastructure for CCS  
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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<sub>2</sub> 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

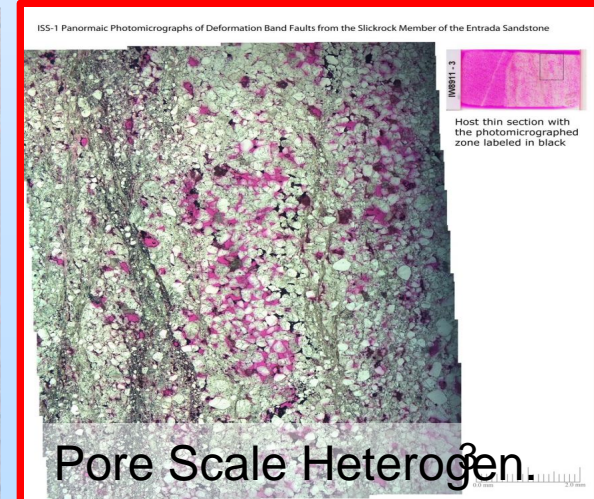
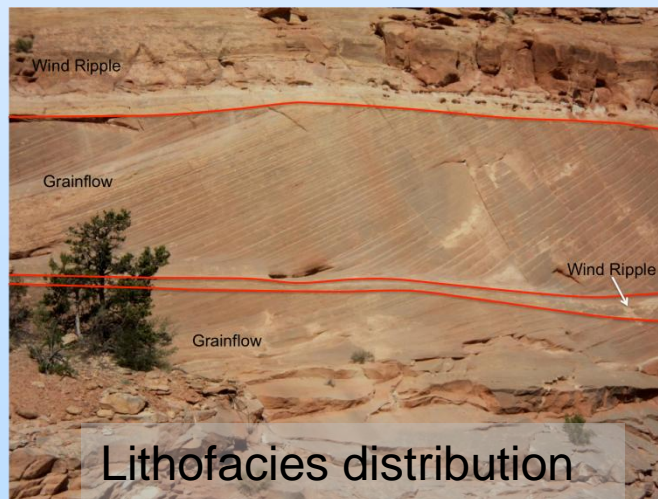
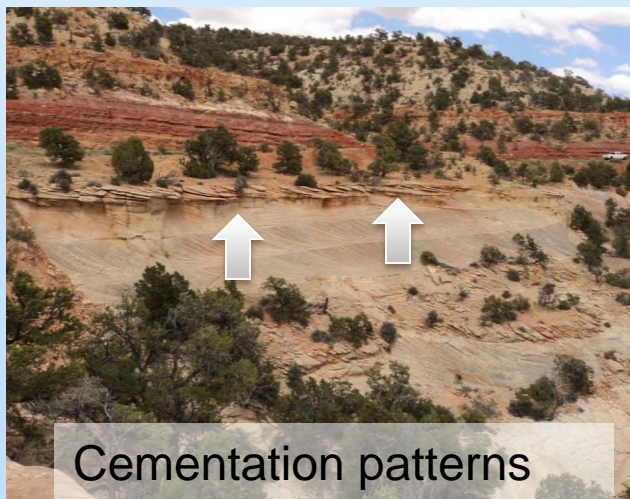
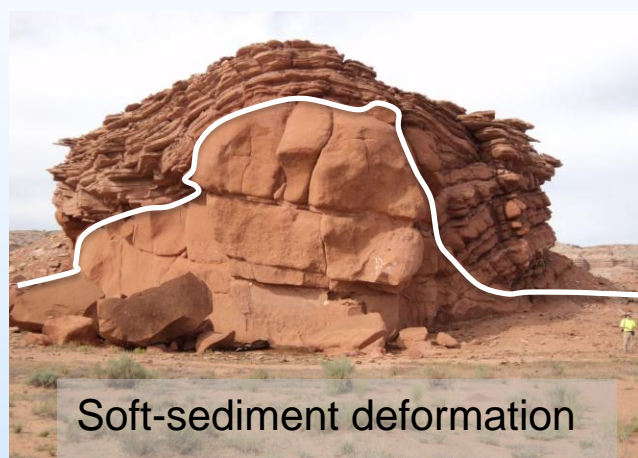


# Importance of **Scale**: Examples of Interface Heterogeneity

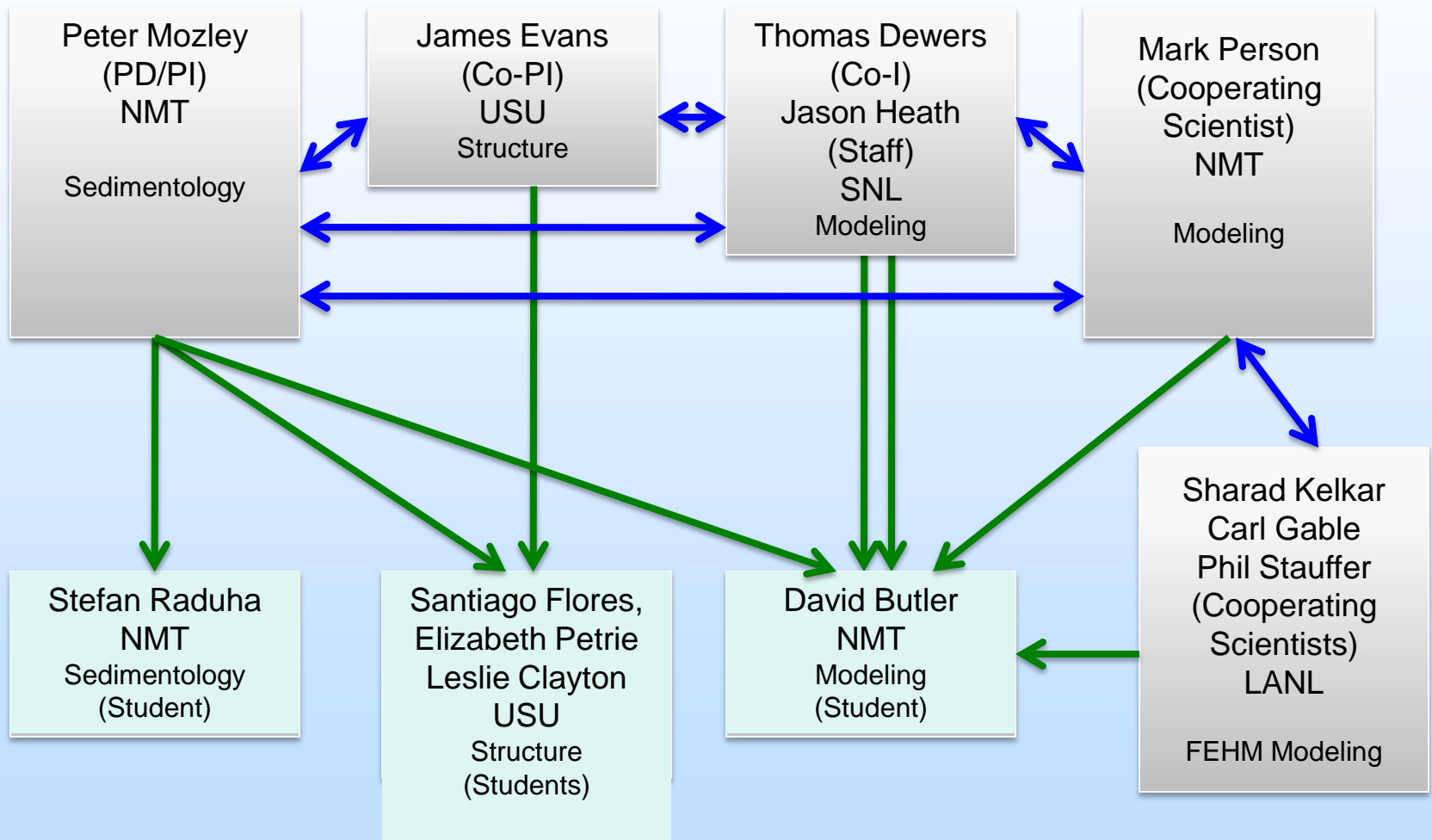
- Depositional
- Structural
- Diagenetic

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<sub>2</sub> storage capacity in geologic formations to within  $\pm 30$  percent.
  - Develop technologies to demonstrate that 99 percent of injected CO<sub>2</sub> 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<sub>2</sub> 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

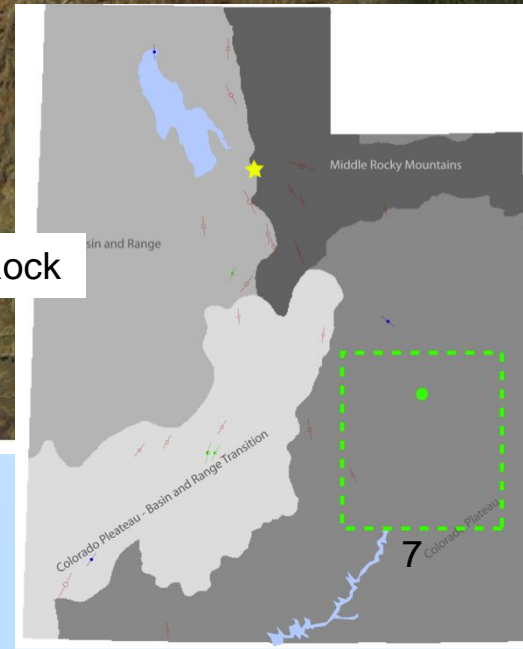
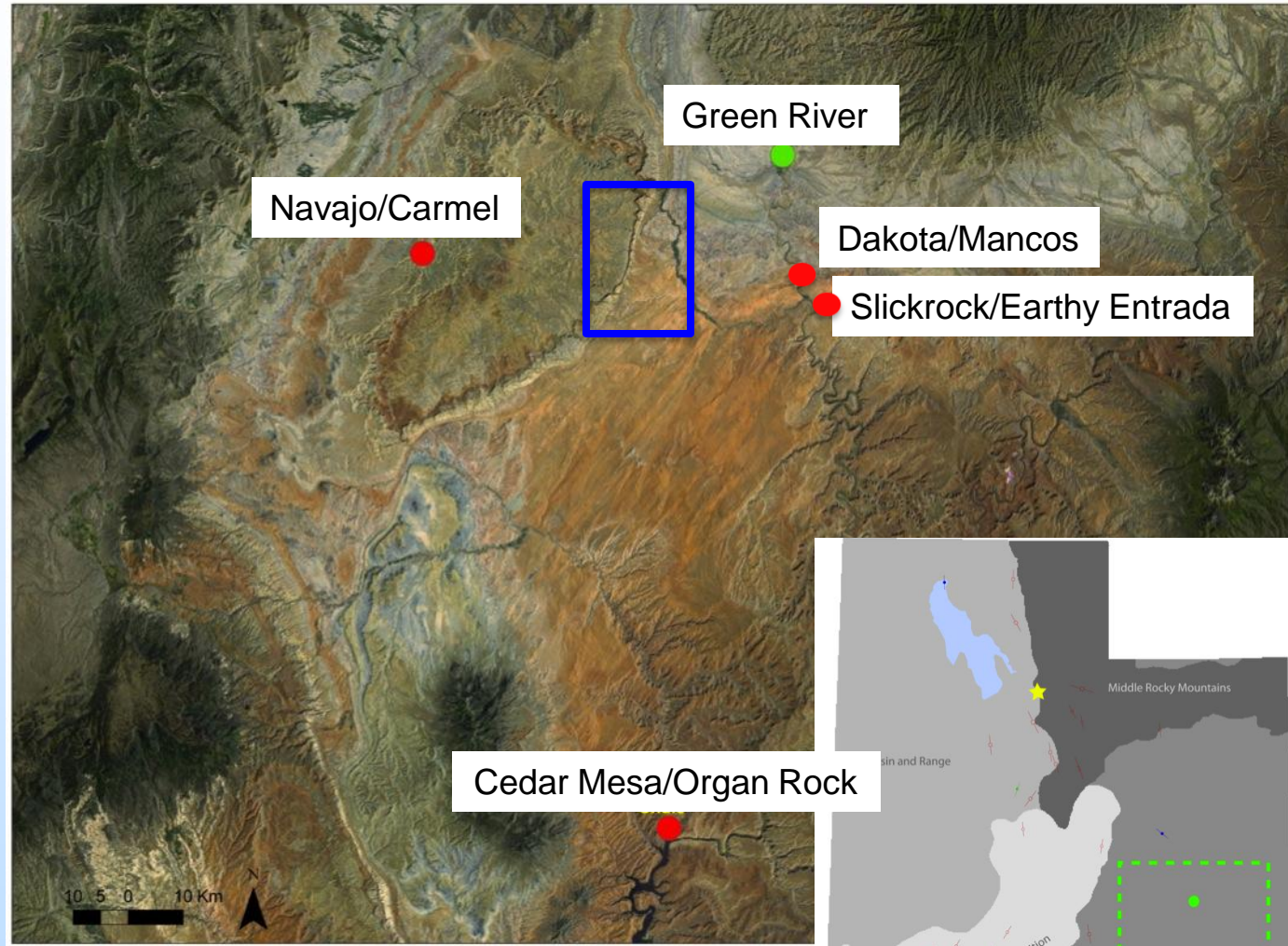
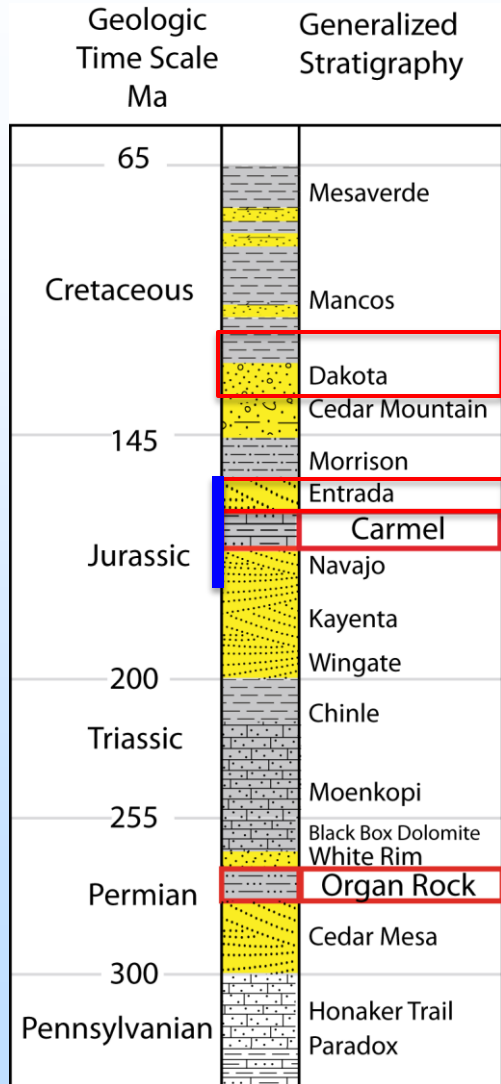
# Technical Status

- 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* 6

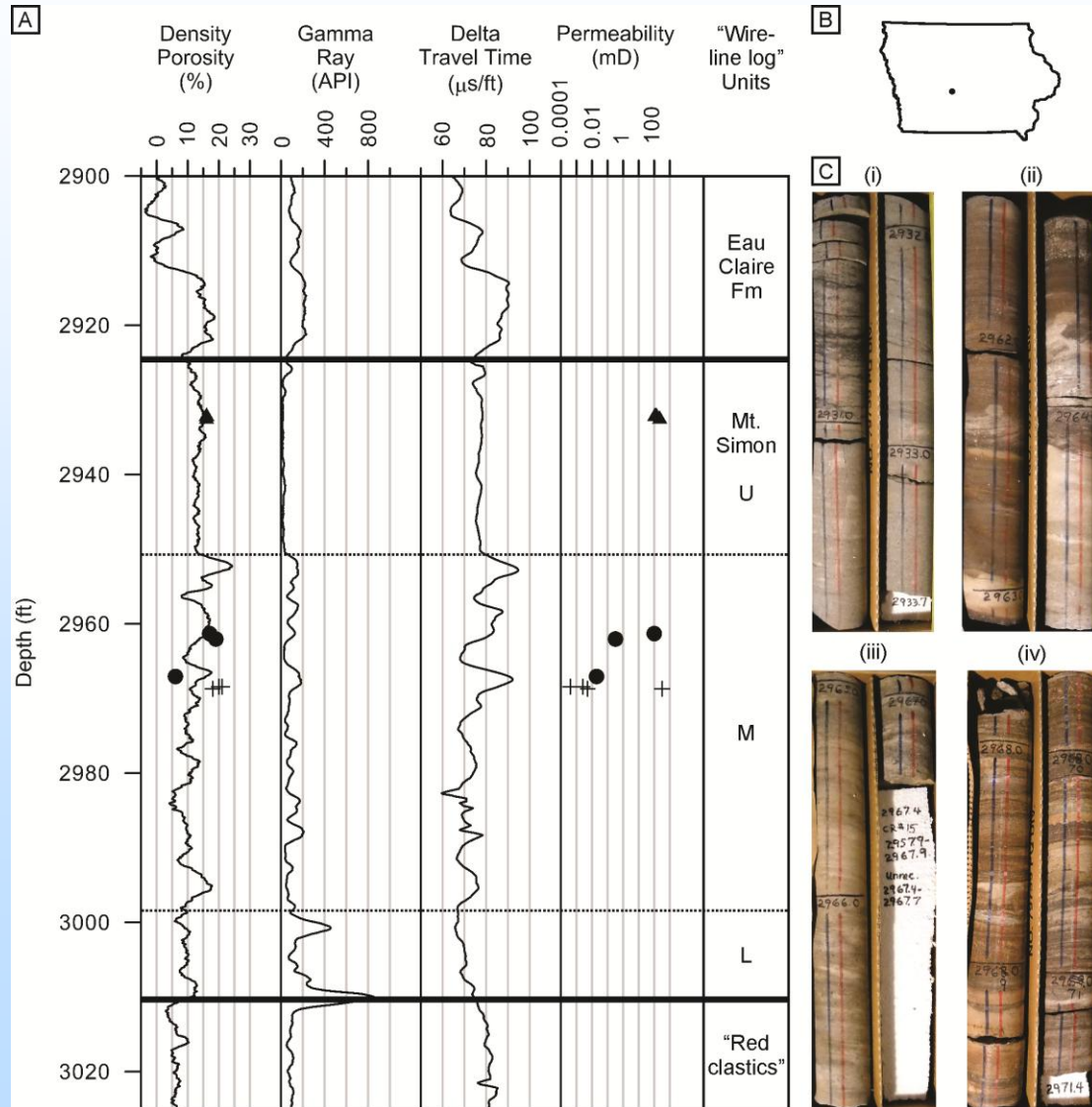
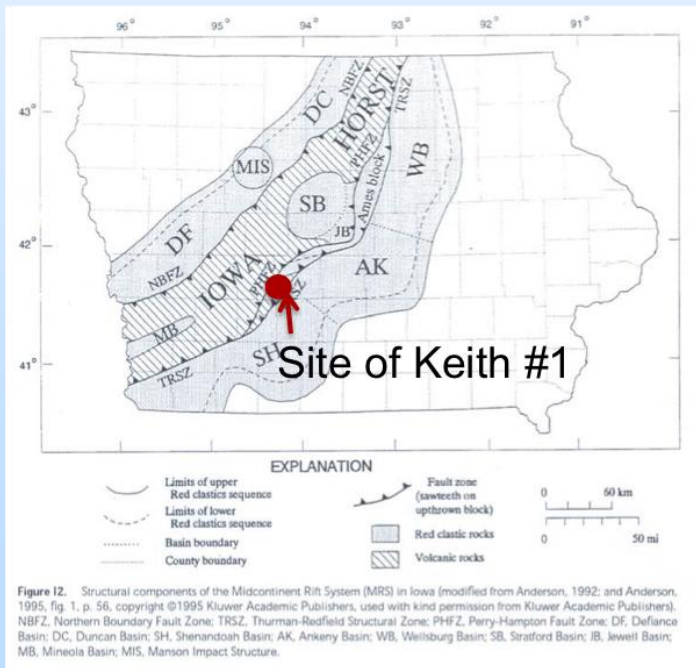
# Study Units: Overview



# Study Units: Overview (cont'd)

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

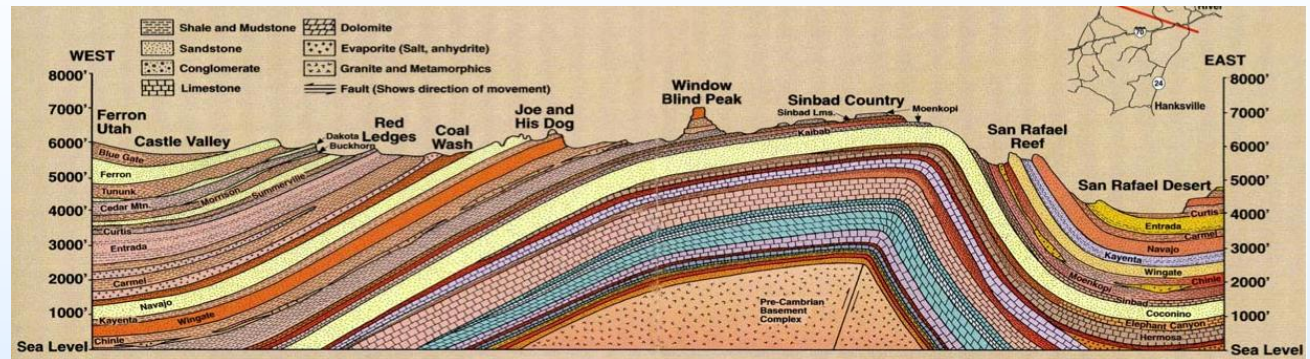
## Precambrian Structure Map of Iowa and Location of CAES\* Keith #1 Well



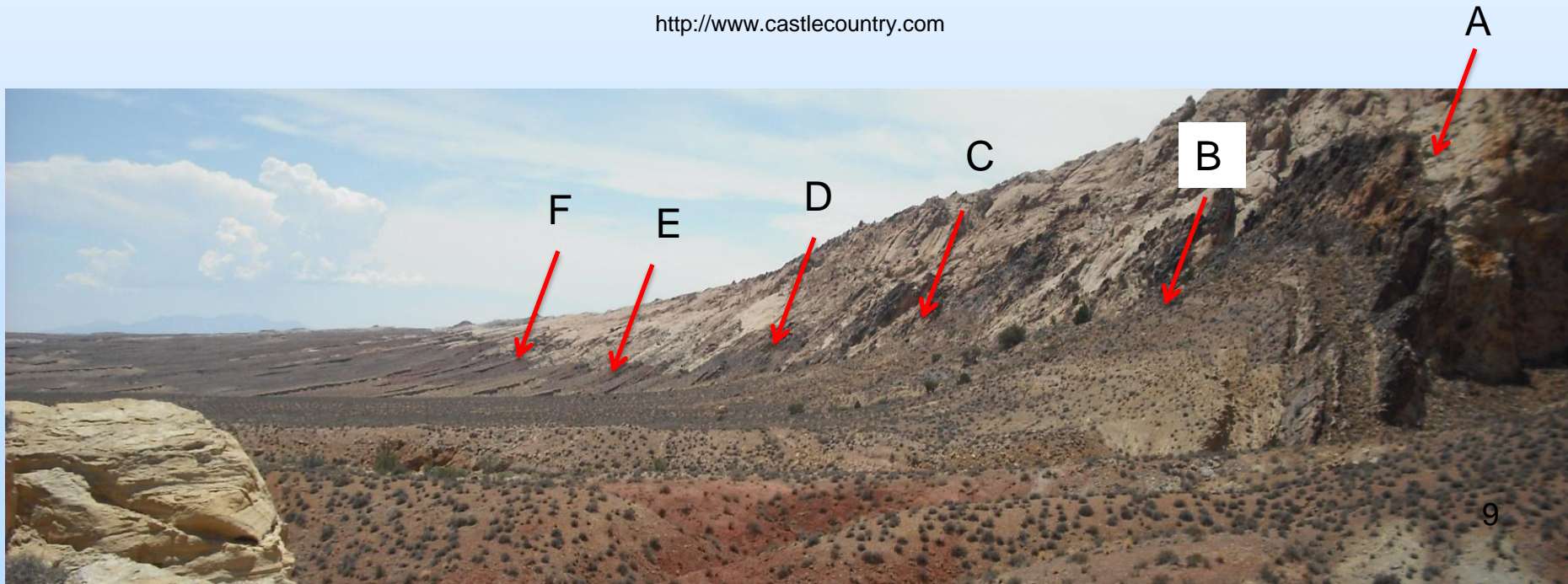
**Figure 12.** Structural components of the Midcontinent Rift System (MRS) in Iowa (modified from Anderson, 1992; and Anderson, 1995, fig. 1, p. 56, copyright ©1995 Kluwer Academic Publishers, used with kind permission from Kluwer Academic Publishers). NBZF, Northern Boundary Fault Zone; TRSZ, Thurman-Redfield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

# I. Relating Fracture Conductivity to Structural Position

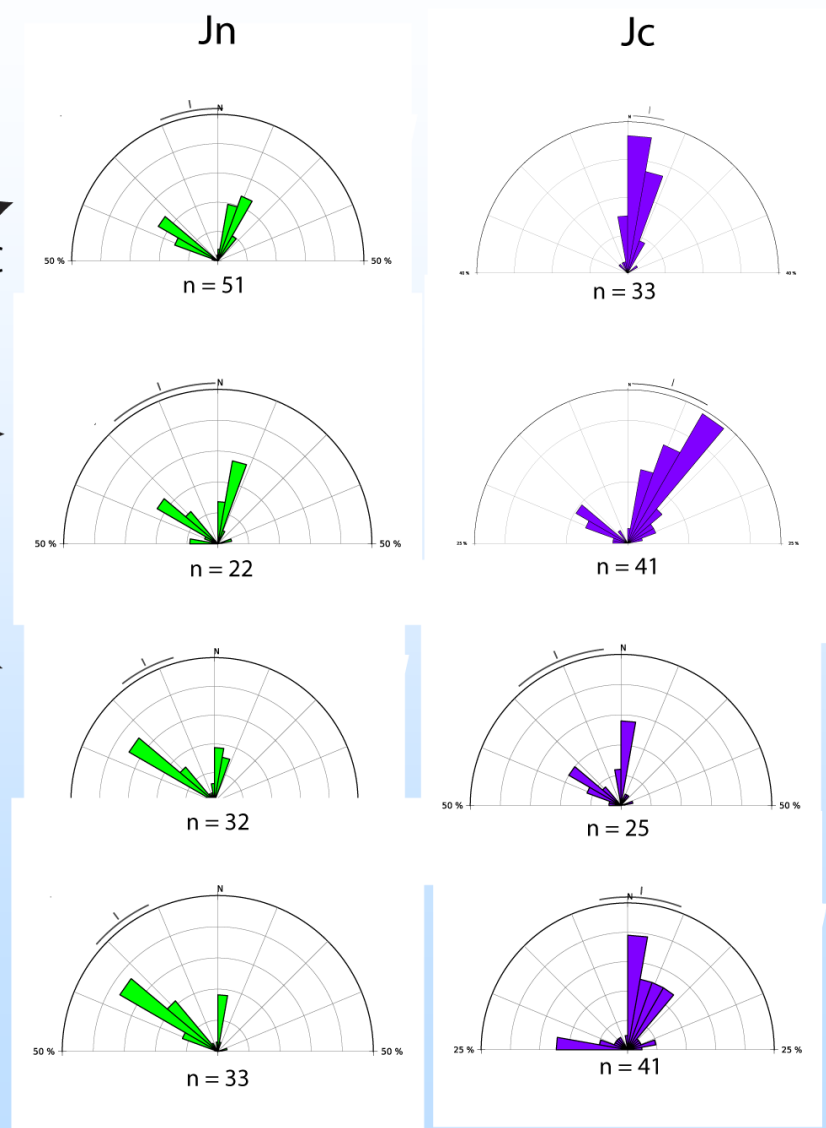
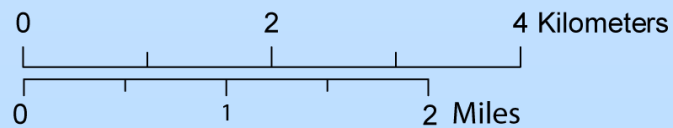
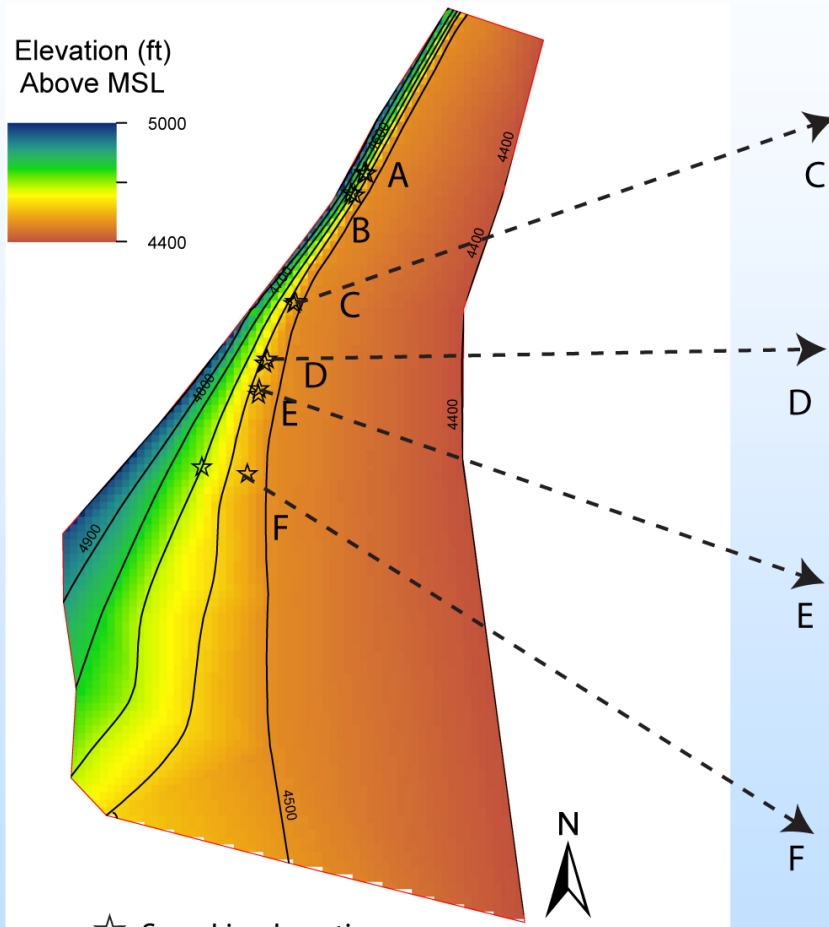
Cross section of San Rafael Swell, Utah, USA

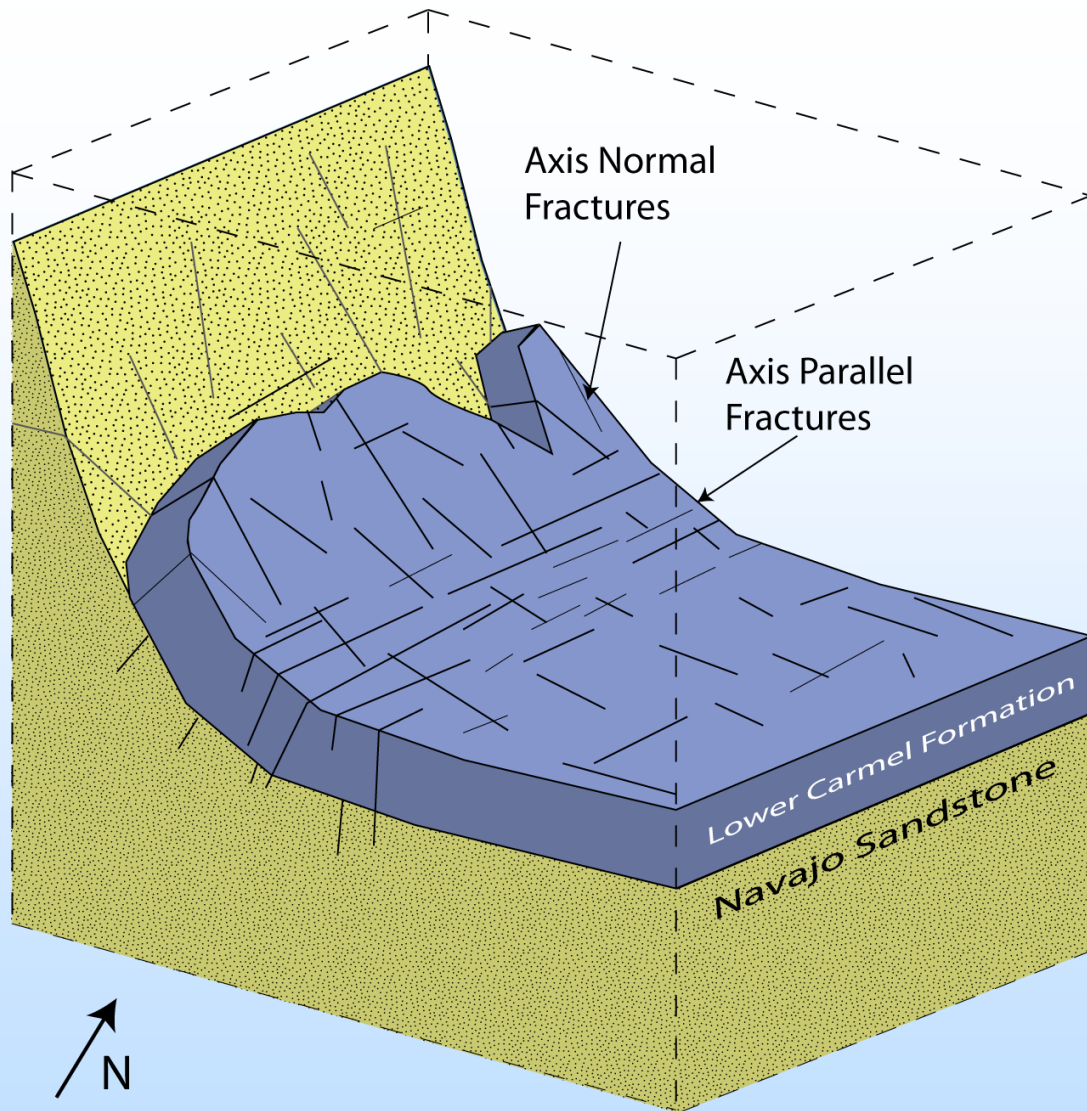


<http://www.castlecountry.com>



# 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<sub>2</sub>



ISS-1 Panomaic Photomicrographs of Deformation Band Faults from the Slicklock Member of the Entrada Sandstone



Host thin section with the photomicrographed zone labeled in black

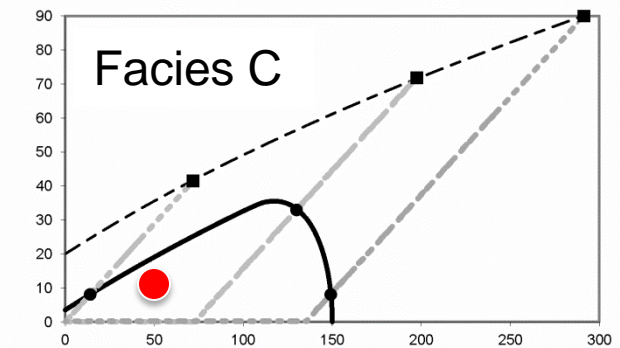
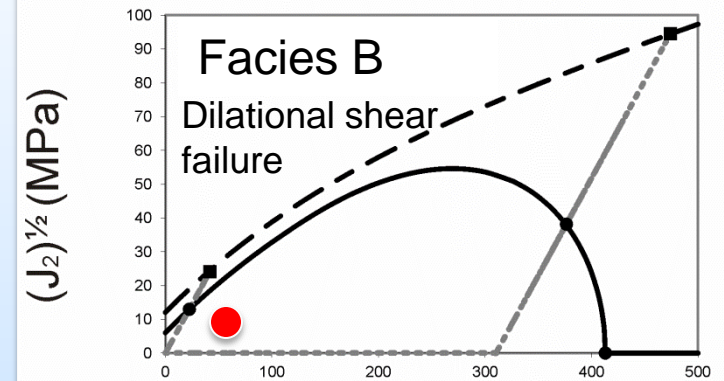
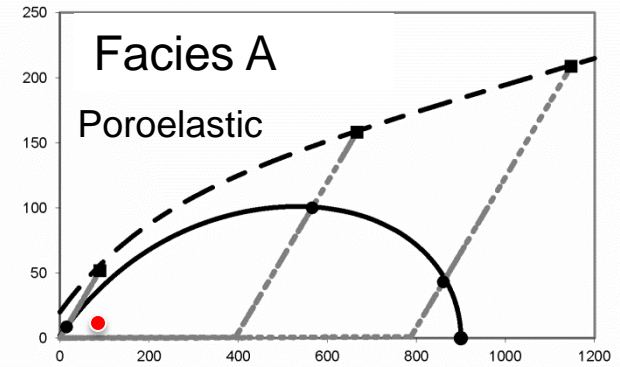
## Deformation Bands:

- 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



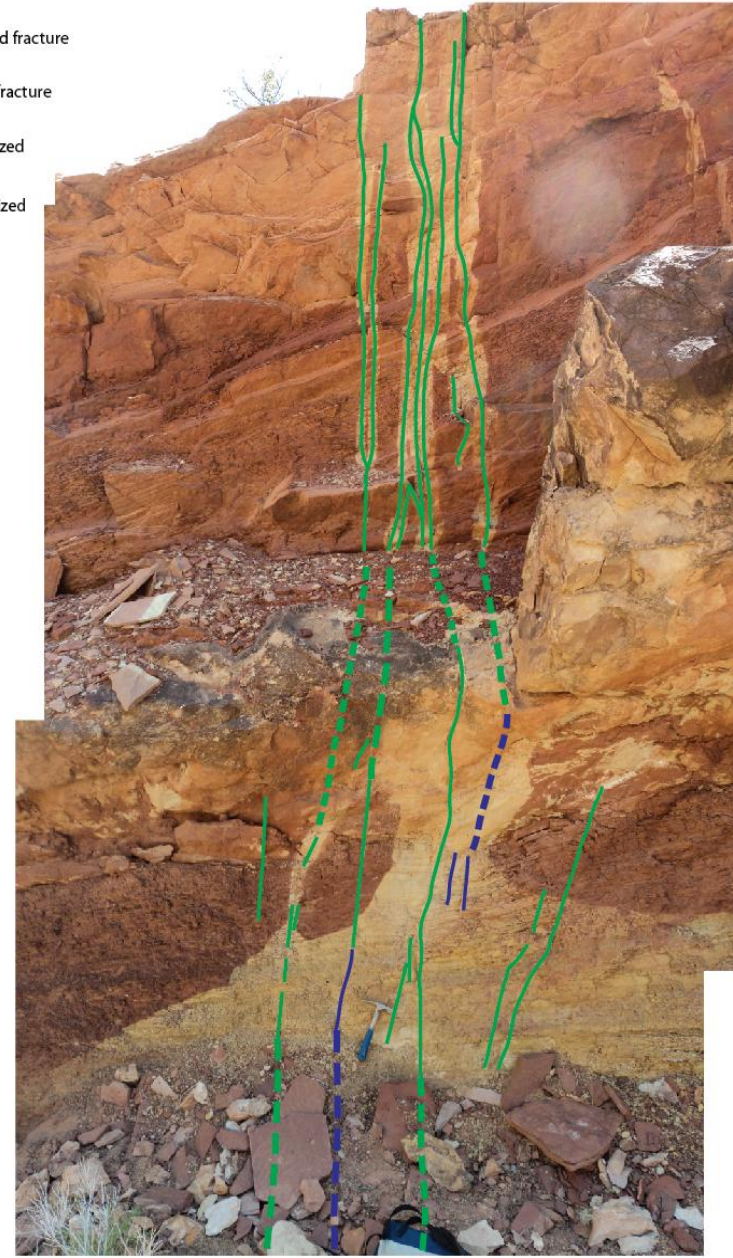
● Present stress state  $I_1$  (MPa)

*Dewers et al., 2014*








# Transition to Fractures

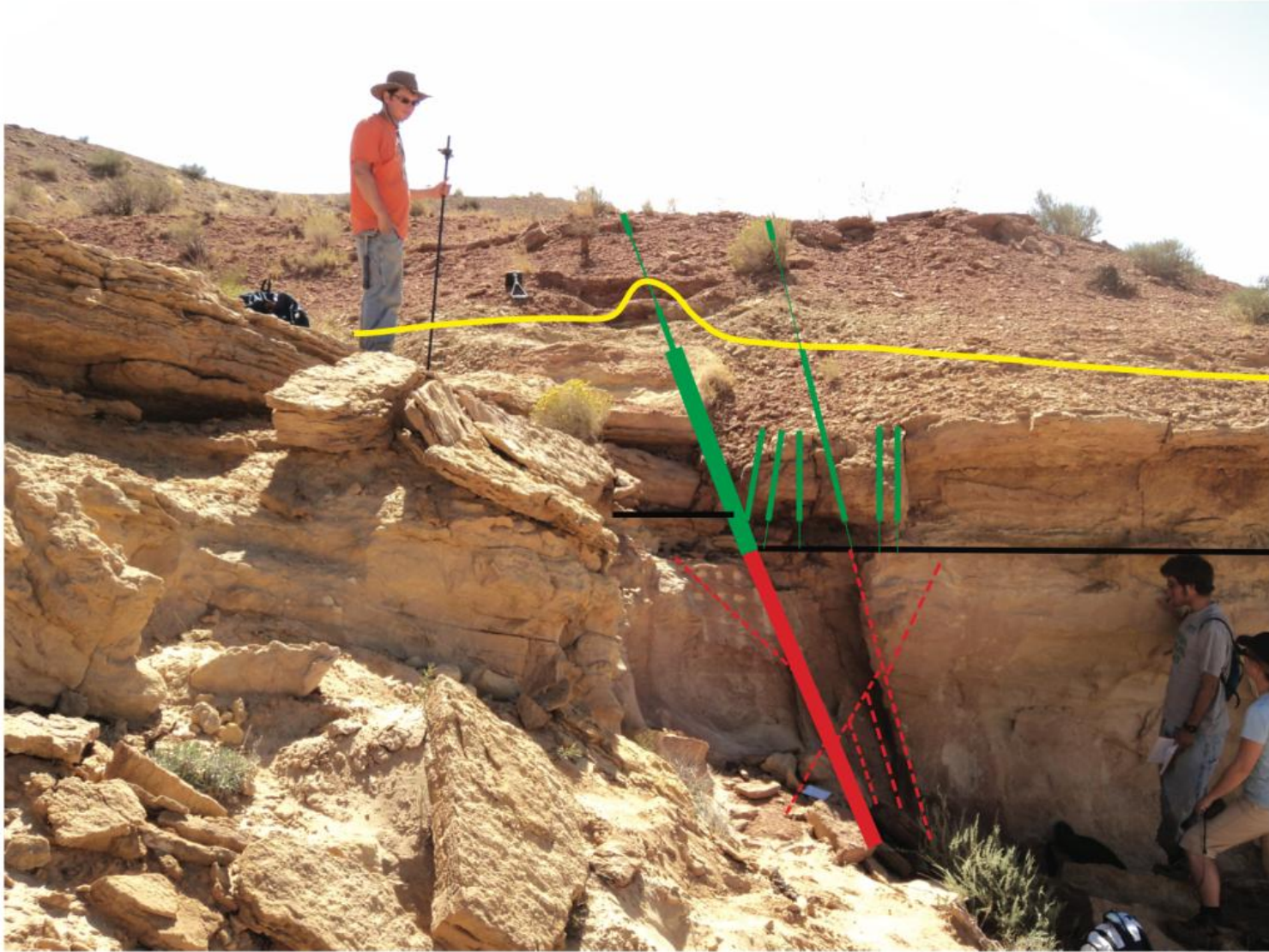
- Deformation band faults transition to shear fractures at interface
- Diagenetic alteration show these were open fractures
  - Bleaching
  - Mineralization
    - Carbonate cementation
    - Fe-oxide pseudomorphs of pyrite
    - Hydrocarbon inclusions
    - Can infer aperture history through petrography

- <1 to 30 mm thick mineralized fracture
- Inferred path of mineralized fracture
- 1 to 7 mm thick non-mineralized fracture
- Inferred path of non-mineralized fracture



# 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

	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 <sup>-8</sup>	
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<sup>-8</sup> 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

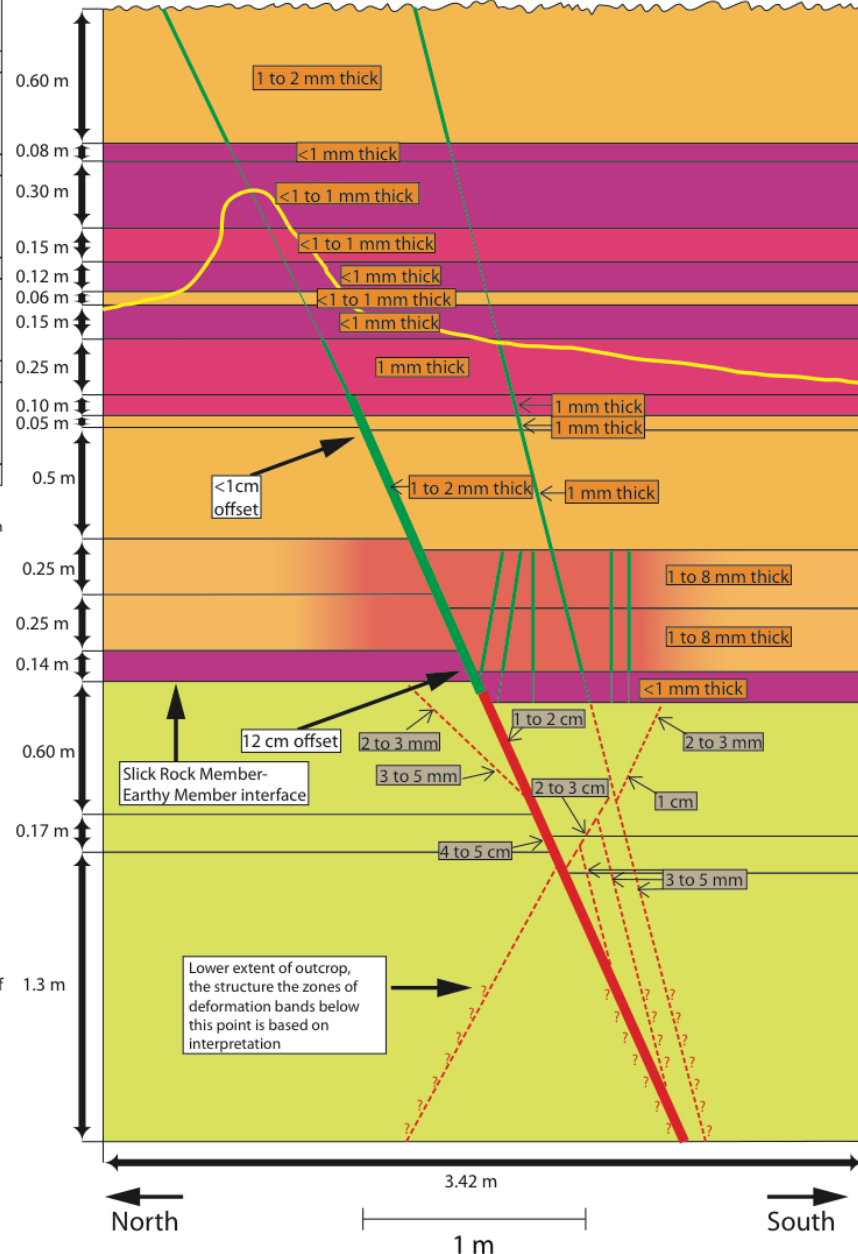
1 to 8 mm thick calcite mineralized fracture

<1 to 1 mm thick calcite mineralized fracture

Small normal fault with 1 to 2 mm thick calcite mineralized fracture

Bleached zone

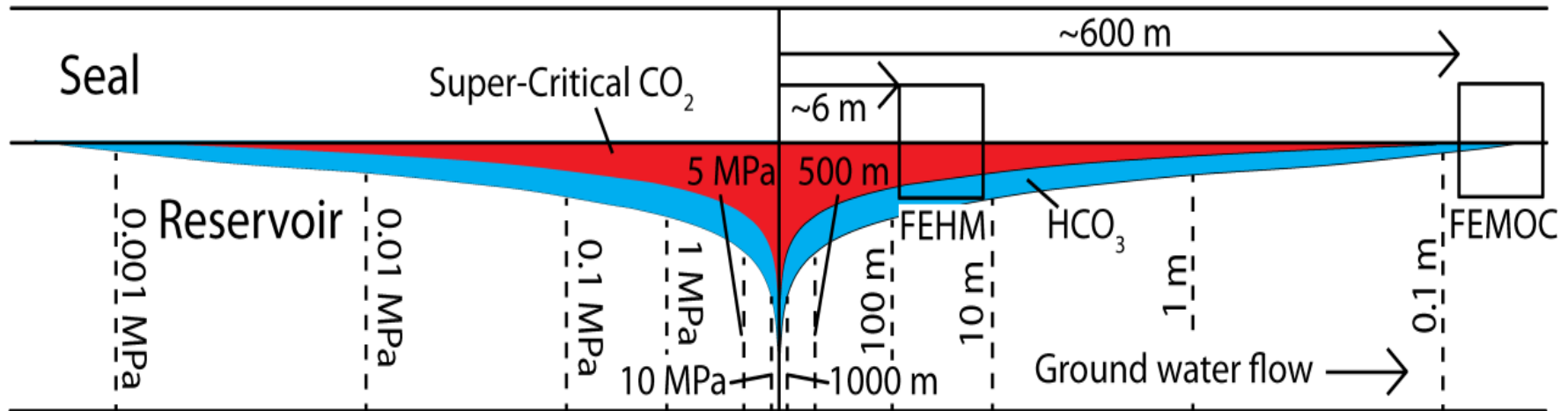
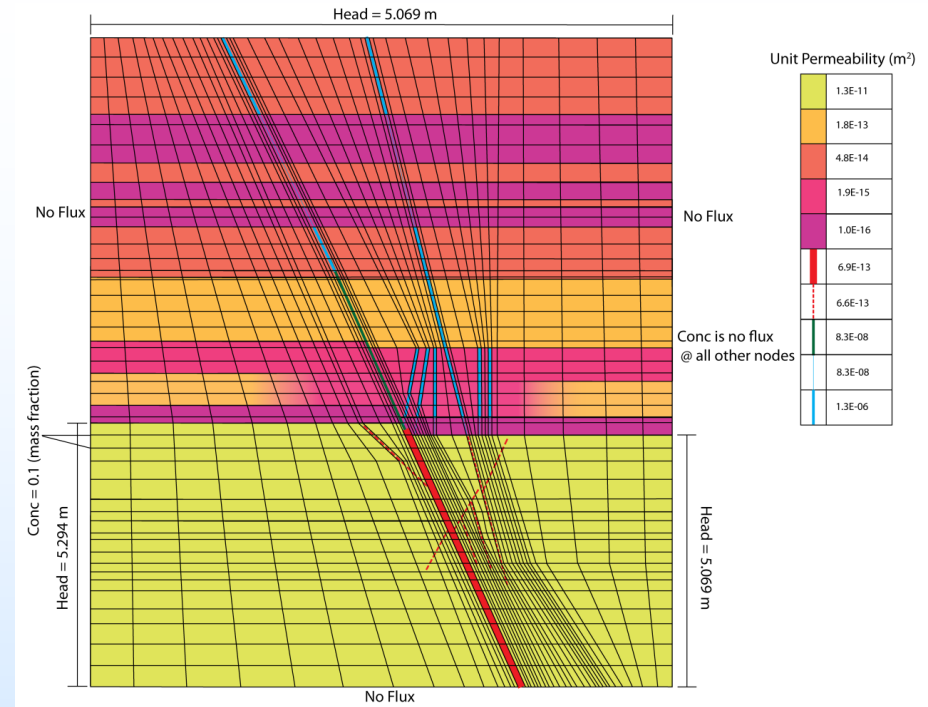
# mm Fracture thickness  
# mm Zone of deformation bands thickness



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

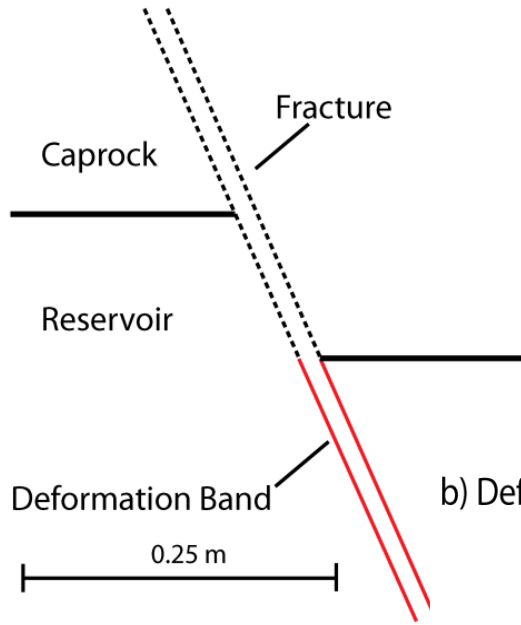


*Meshing and boundary conditions for FE modeling of field site*

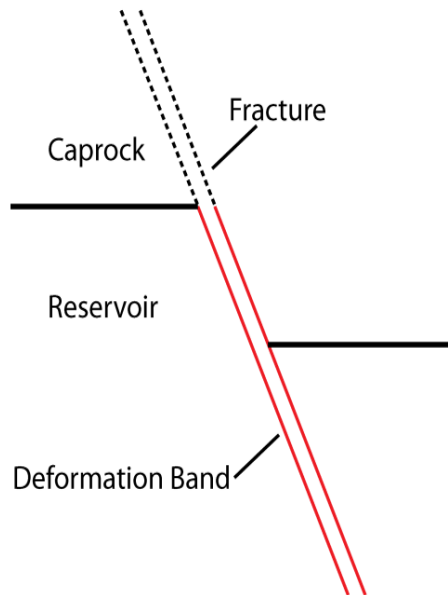
# Modeling Questions

## 1. Effect of small-scale architecture

a) Fracture at Interface

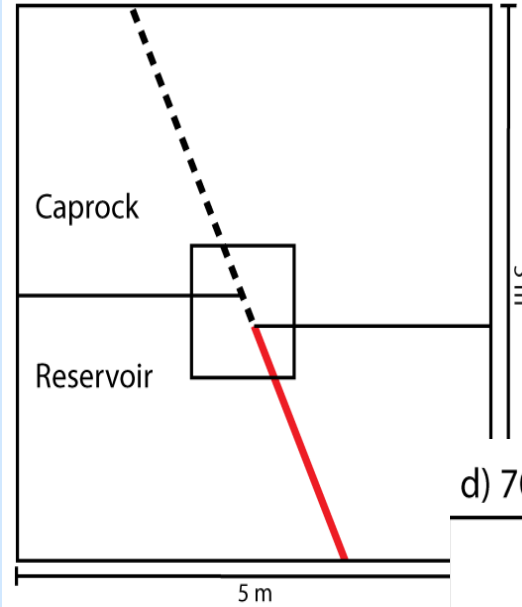


b) Deformation Band at Interface

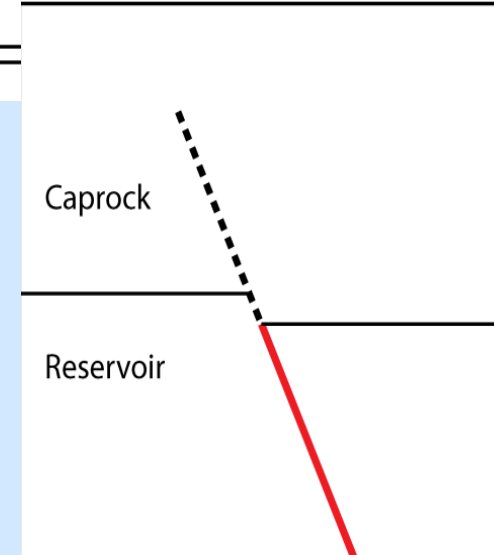


## 2. Effect of degree of bypass

c) 100% Fracture Penetration

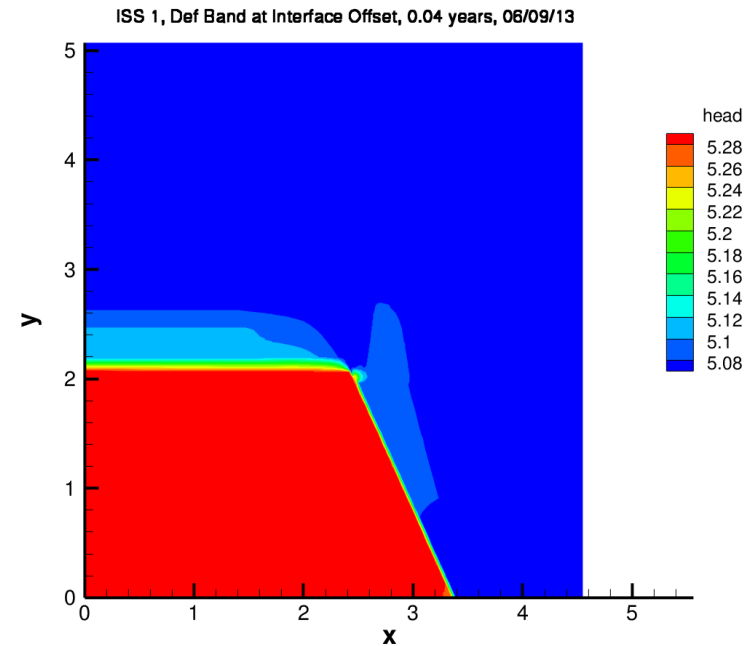


d) 70% Fracture Penetration

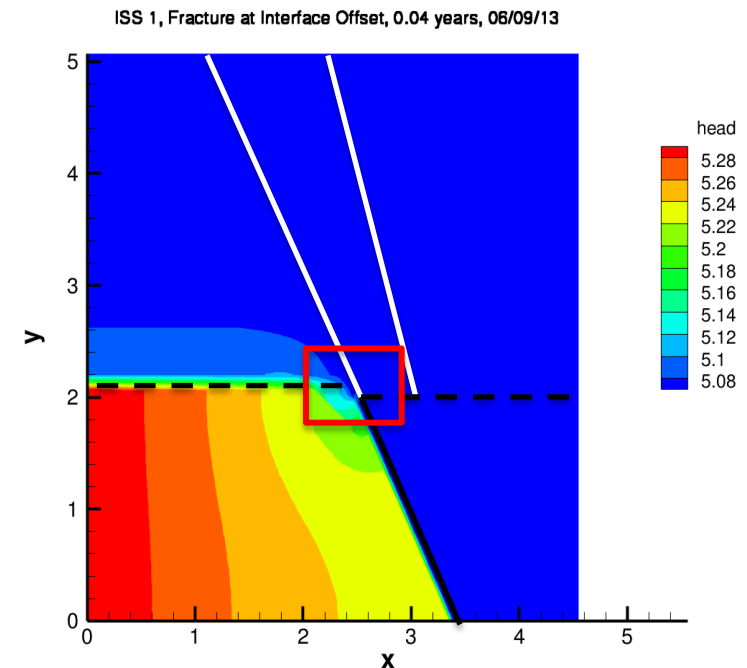


# Effect of Architecture (single phase results)

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



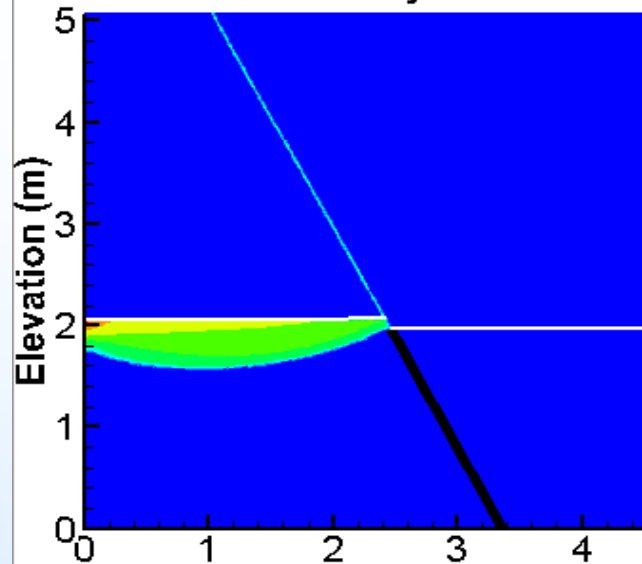
- **When fracture penetrates interface:**
  - Greater flux through caprock



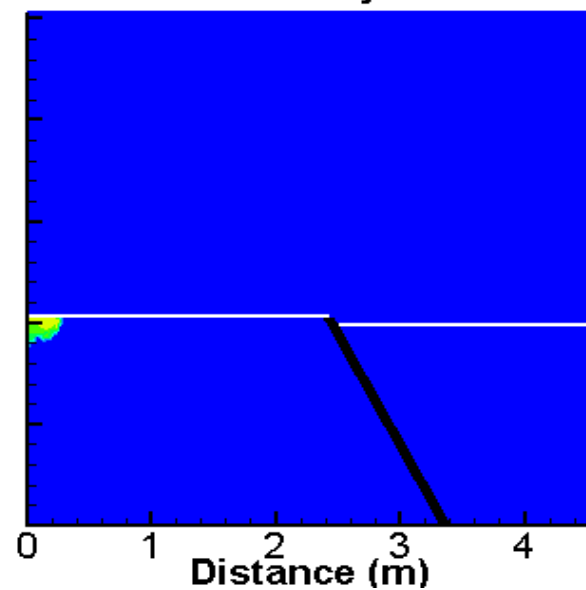
# Multiphase Results

## 1. Effect of Architecture

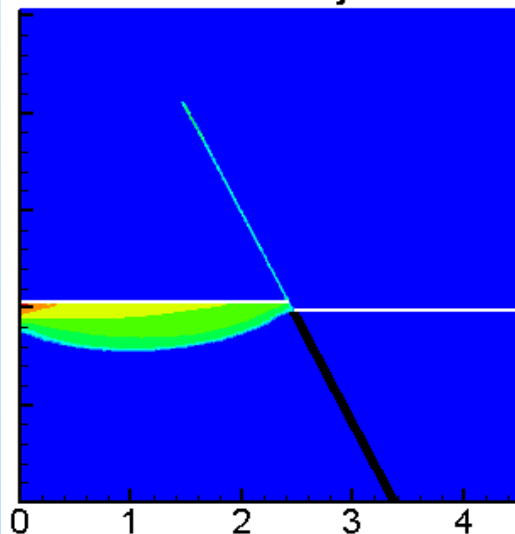
a) Multi-Phase  
100% Fracture Penetration  
Fracture at Interface  
Time = 0.13 days



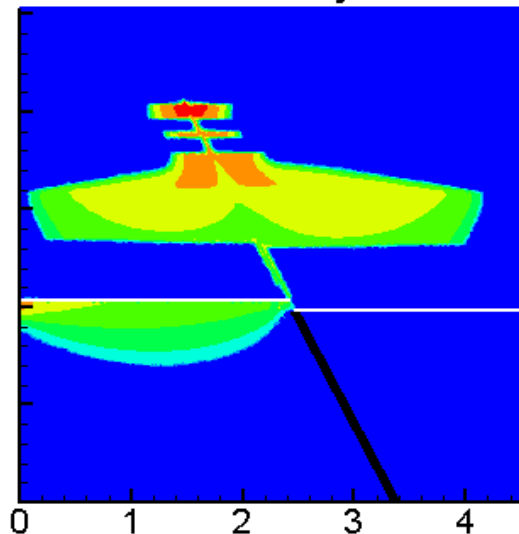
b) Multi-Phase  
100% Fracture Penetration  
Def. Band at Interface  
Time = 0.13 days



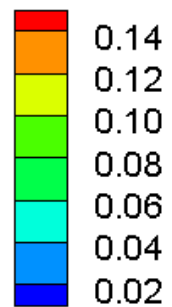
c) Multi-Phase  
70% Fracture Penetration  
Fracture at Interface  
Time = 0.13 days



d) Multi-Phase  
70% Fracture Penetration  
Fracture at Interface  
Time = 18.17 days



Super-Critical CO<sub>2</sub> Saturation



## 2. Effect of Bypass



- **Field evidence of fluid transmission through caprock fractures:**

- Bleaching of iron
- Enhanced carbonate mineralization above and within caprocks



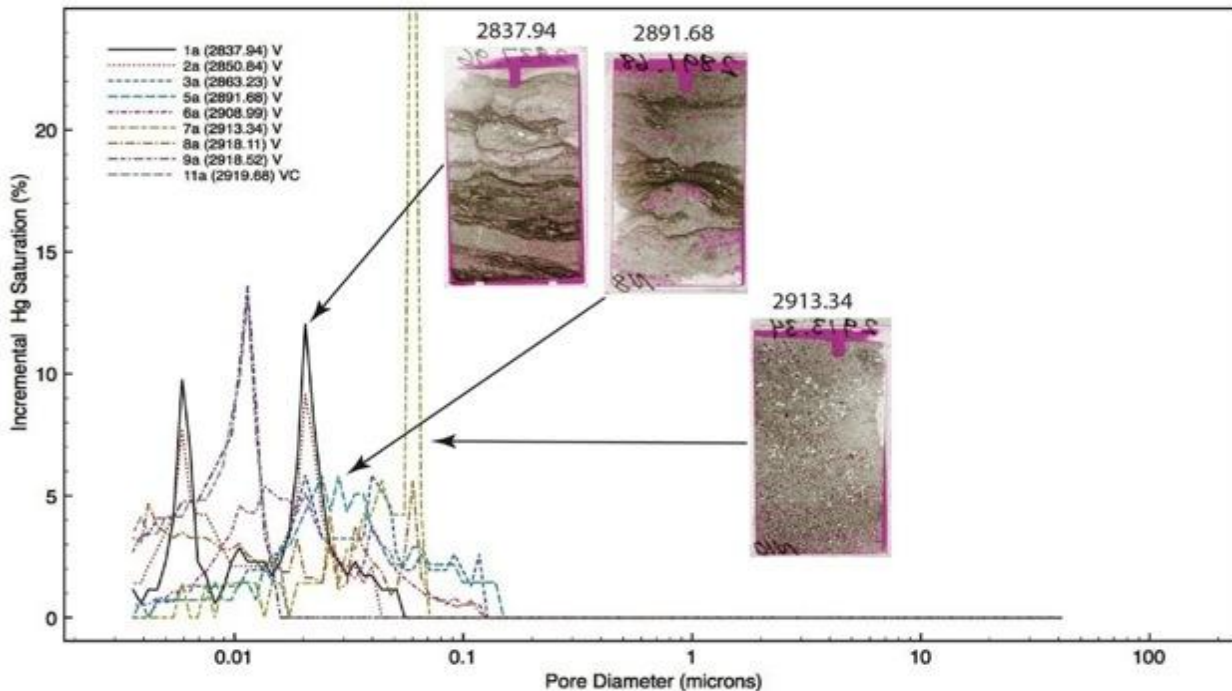
- **Deformation-band faults:**

- often link to transmissive fracture networks in the caprock
- can form capillary seals to CO<sub>2</sub>
- can compartmentalize the reservoir adjacent to the interface

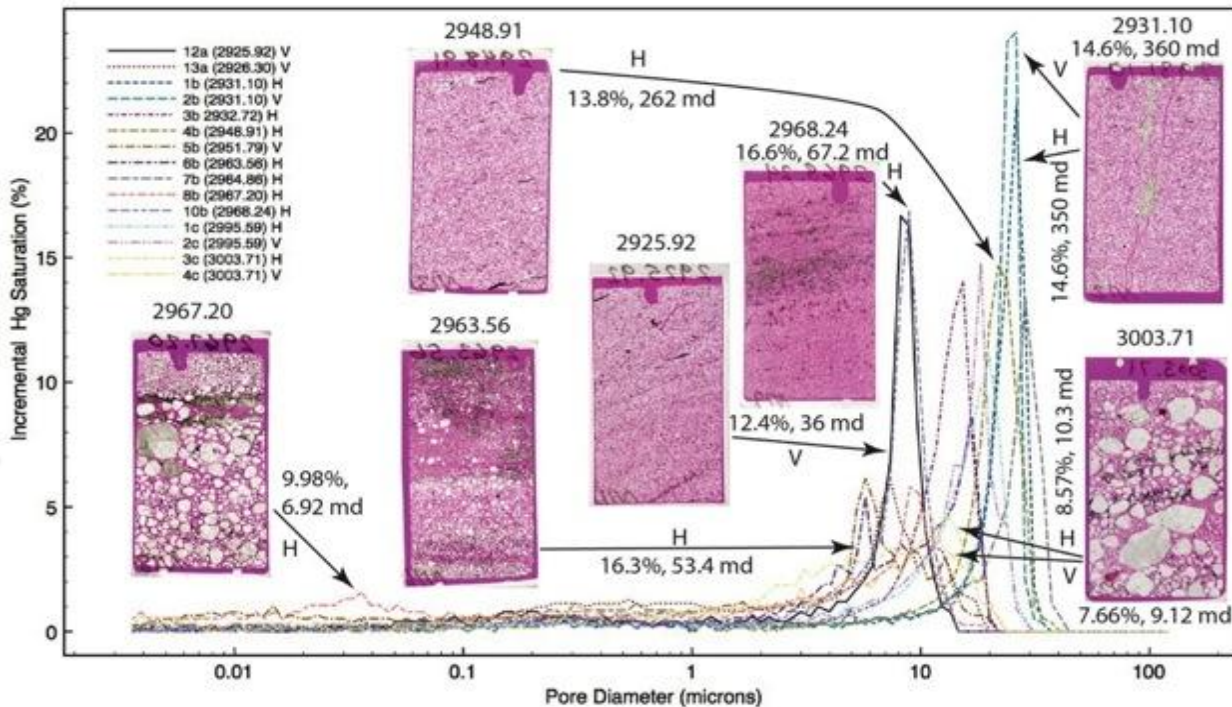
# III. Porosity Facies

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

**Eau Claire Caprock** →



**Mt Simon Reservoir** →



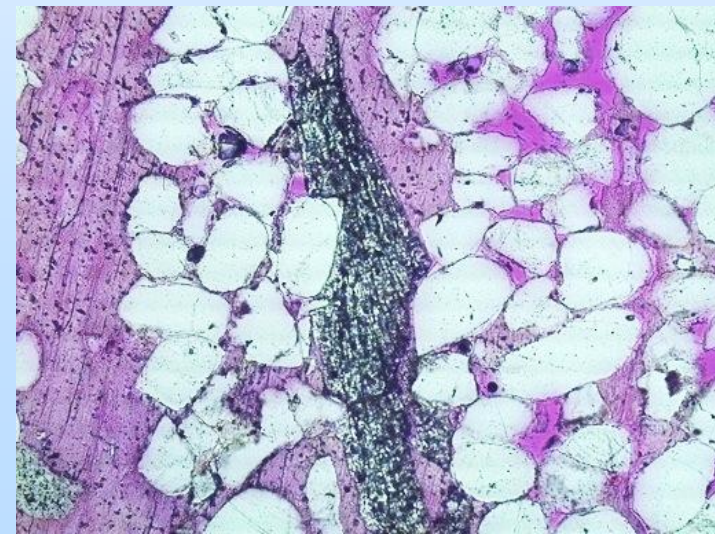
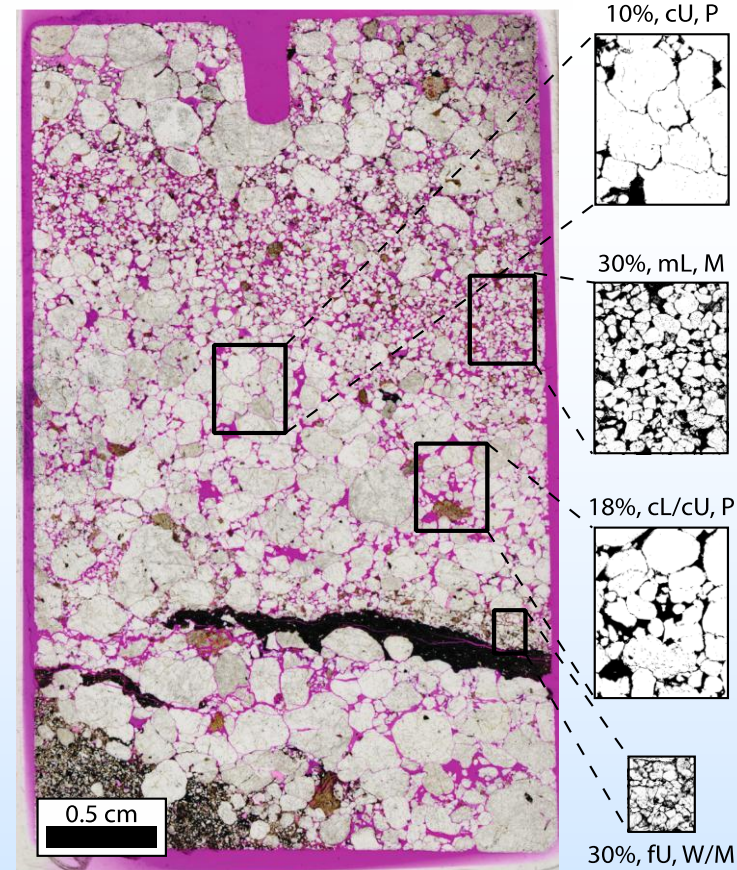
*Amount of "pink" proportional to pore sizes*

# On CO<sub>2</sub> 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”

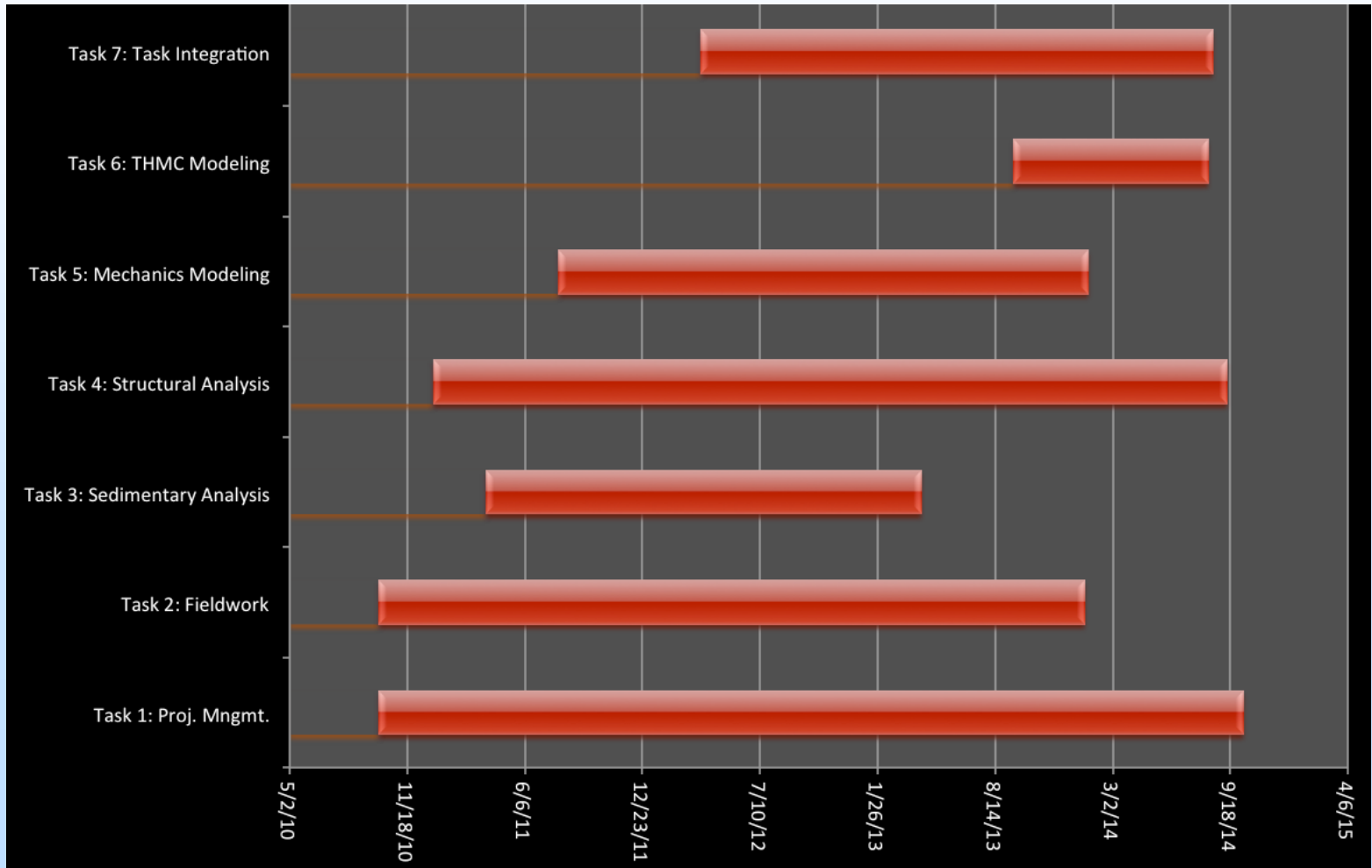
### – Mt. Simon/Eau Claire

- 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

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# Gantt Chart



# Bibliography

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*No peer reviewed publications generated from project yet.*

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](http://ees.nmt.edu))

Raduha, S, Butler, D., Mozley, P., Person, M., Evans, J., Flores, S., Heath, J., Dewers, T., 2013, Potential seal bypass features produced by deformation-band fault to opening-mode fracture transition at the reservoir-caprock interface: GSA Annual Meeting, Denver.

Mozley, P., Heath, J., Dewers, T., 2014, Origin and size distribution of porosity in the Mt. Simon Sandstone and Eau Claire Formation: Implications for multiphase fluid flow: AAPG Annual Meeting, Houston.