Mechanical Stratigraphy and Stress History of Cap-rocks: Analysis of Exhumed Analogs in Central and South-eastern Utah and Implications for CCS*

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Abstract

Top-seal failure of subsurface waste storage systems such as those proposed for the mitigation of anthropogenic CO_2 accumulation can occur when pre-existing optimally oriented fault and fracture systems are reactivated or when new fractures are induced due to increased fluid pressures. The presence of discontinuities in seal lithologies affects their mechanical and hydrogeologic properties; migration of fluids or gas through mm- to cm-scale discontinuity networks can result in focused fluid flow within and across a caprock. We examine the mechanical and fracture stratigraphy of Paleozoic and Mesozoic analogues of failed cap-rocks exposed in central and south-east Utah to understand the nature and distribution of fluid flow pathways in various sealing lithologies. Each seal type has experienced a unique depositional and tectonic history, all are heterolithic, low permeability (0.001 to 0.12 D), and show evidence of fluid flow across the cap-rock through open-mode and shear fractures. We combine outcrop analysis with the unique loading history and resultant uniaxial strain model at each locality to understand the timing of fracture initiation and paleo-tectonic stress orientation, if it differs from the current dominant crustal stress orientation. Burial history models evaluated in this study suggest that most formations reach a maximum burial depth > 1.6 km and experience an overburden stress of up to 50 MPa. As lithostatic load increases with burial depth the potential for initiation of natural hydrofractures increases because the excess pressure above the hydrostatic gradient required for failure decreases. Once zones of weakness have been established within the cap-rock they exist as loci for future deformation and fluid flow.

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Mechanical stratigraphy and stress history of cap-rocks: Analysis of exhumed analogs in SE Utah and implications for CCS.

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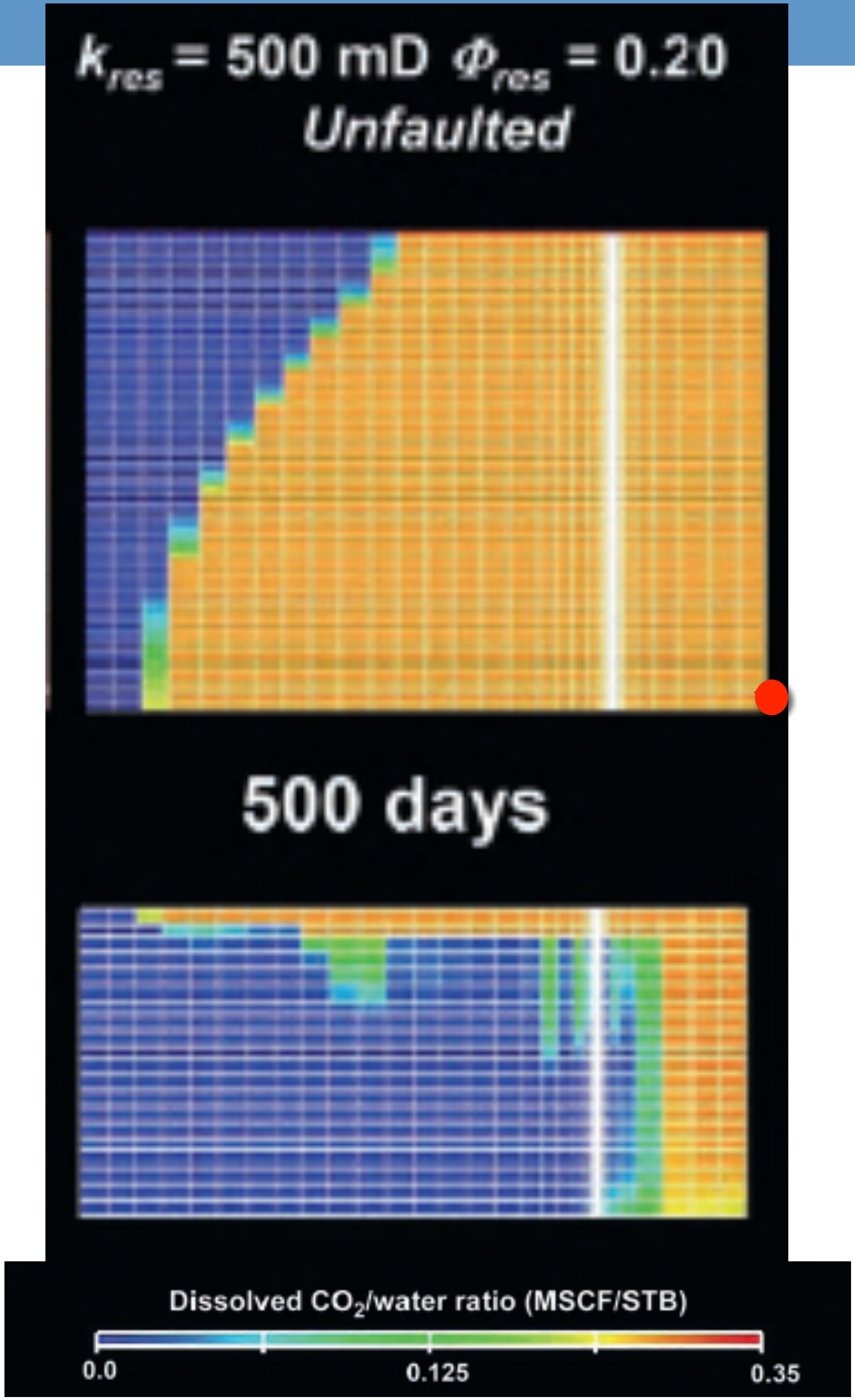
Overview

- Introduction
- Objectives
- Study locality
- Findings
  - Outcrop observations
  - Outcrop characteristics
  - Stress history modeling
- Implications



Pasala et al., 2013

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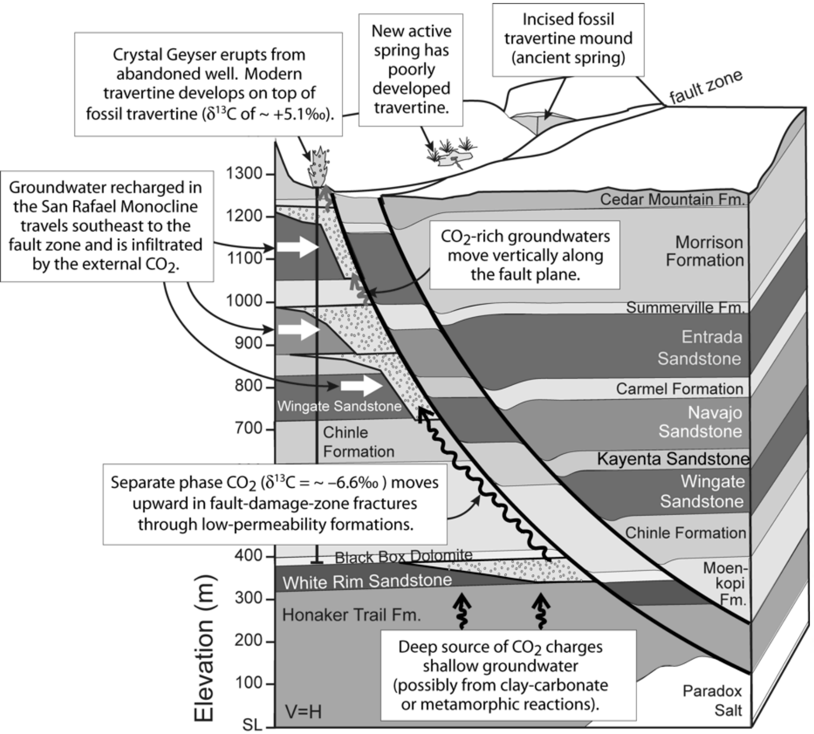
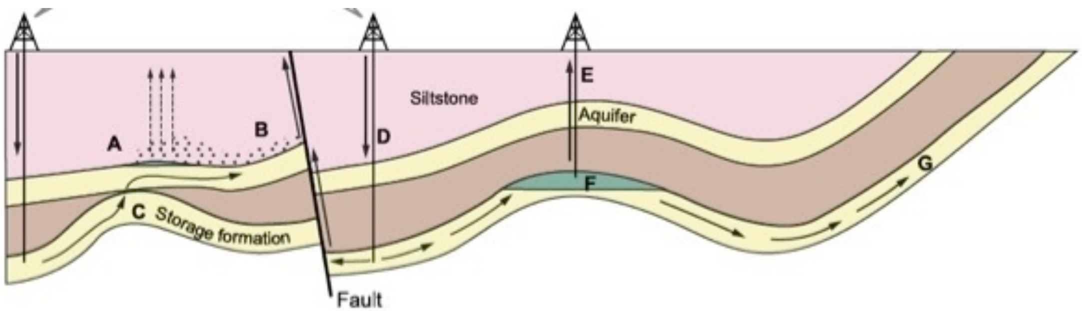
Research drivers

- CCS (CCUS) for global warming mitigation
- Seismicity associated with waste disposal & sequestration
- Unconventional resources



Heath et al., 2009; Williams, 2007



From: IPCC, 2005

- Leakage pathways and risks associated with large scale faults and faulty well bores recognized early
- Importance of interconnected micro- to meso-scale leakage pathways (cm to m) scale

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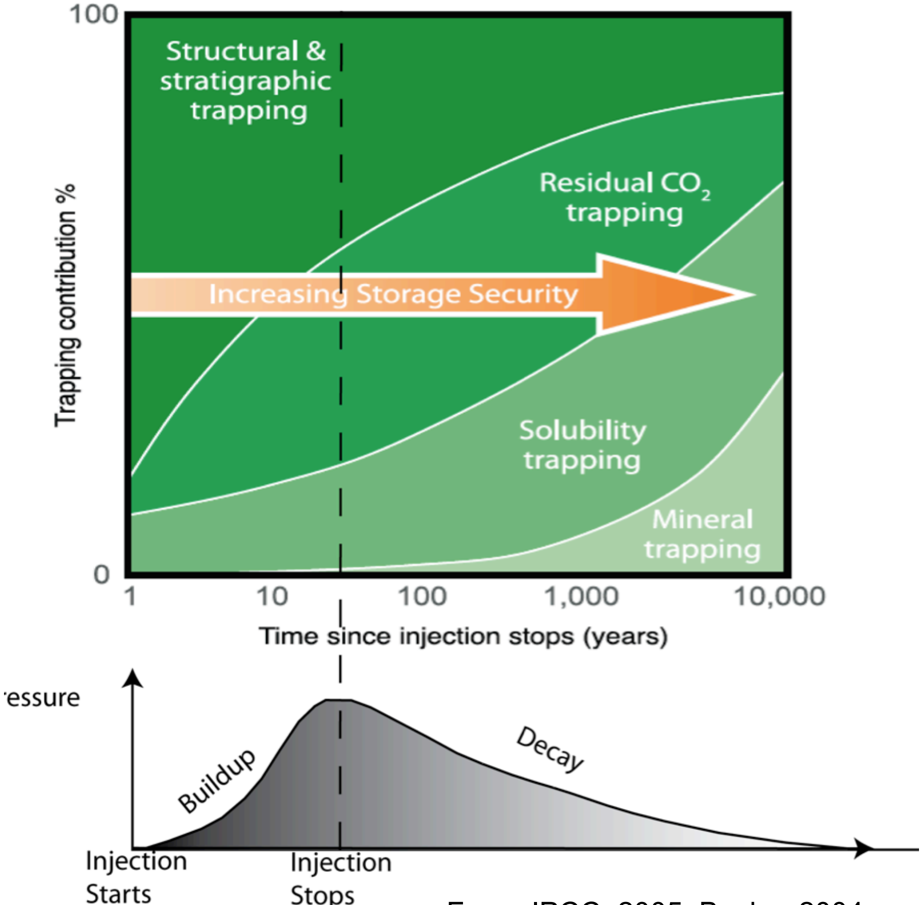
Research drivers

- Fluid plume management - escape to overlying reservoirs, mineral rights or the atmosphere
- Induce seismicity events due to increased fluid pressure
- Understand the effect of changing rock properties



From: IPCC, 2005; Bachu, 2004

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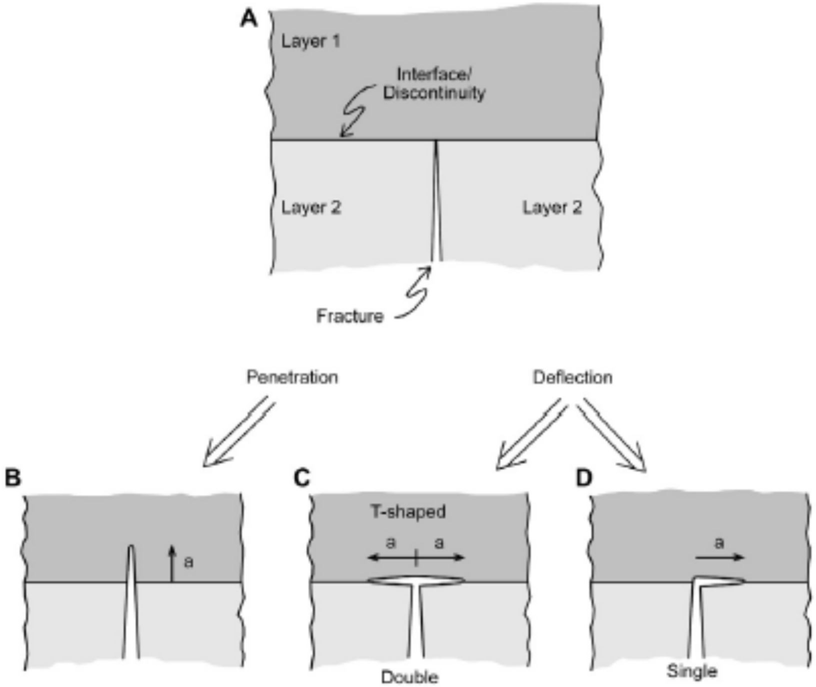
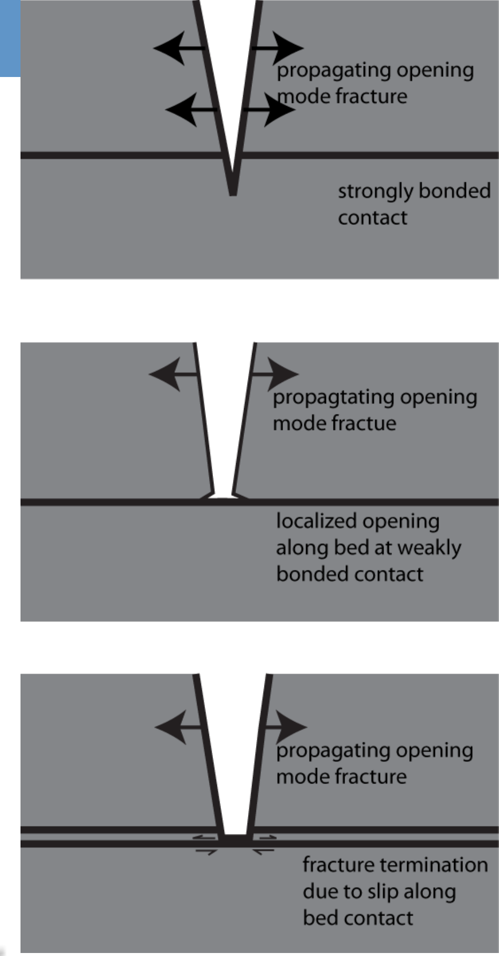
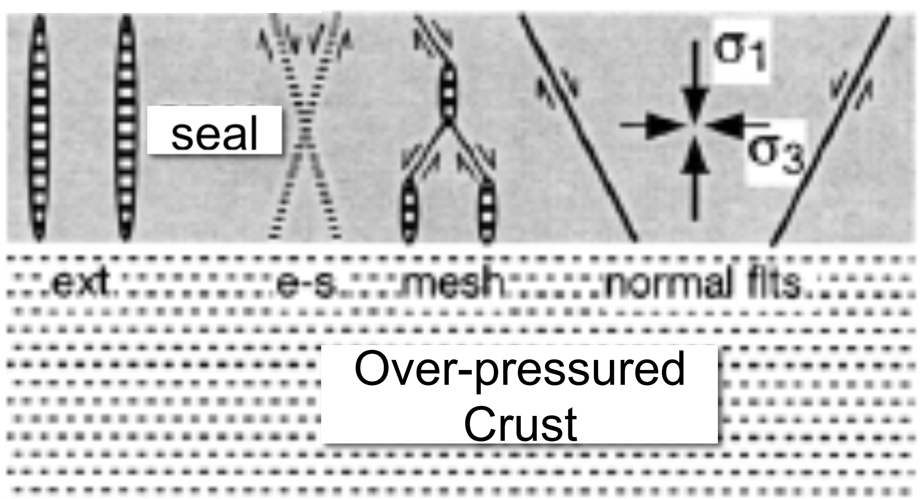
Fracture morphology at interfaces



From Larsen et al., 2010



From Cooke et al., 2006



From: Sibson, 2003

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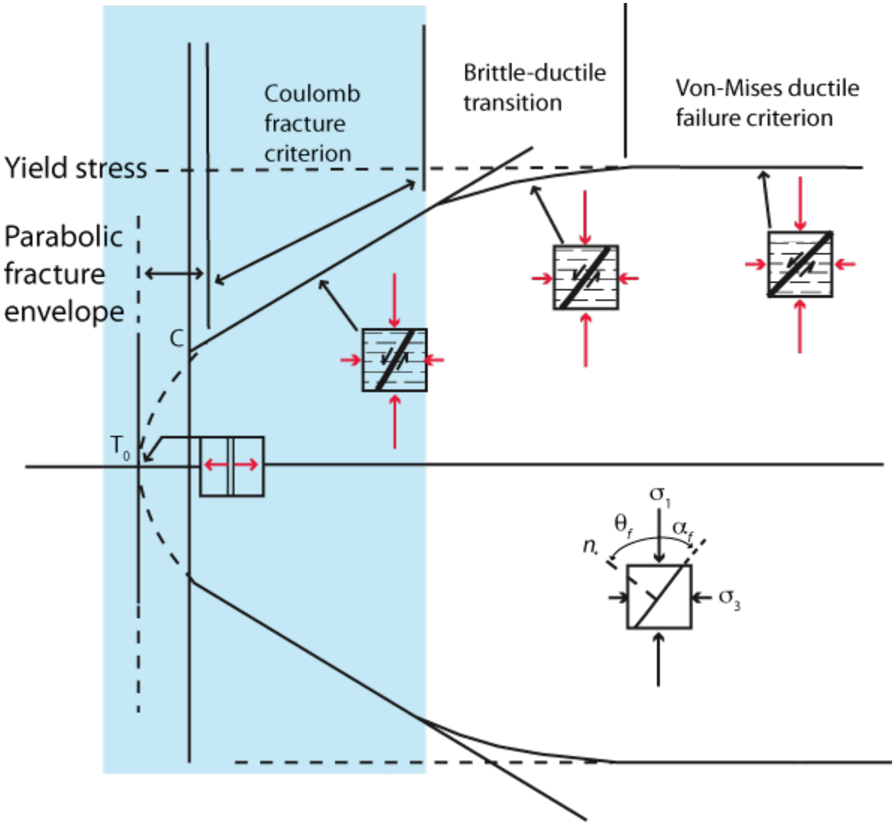
Methods

- Outcrop characterization
  - Scan lines
  - Mapping
  - Rock strength and air permeability
- Use burial history models to estimate S_v
- Stress history modeling using
  - Uniaxial strain model
  - Andersonian normal stress orientation
  - Mohr-Coulomb failure analysis with varied cohesive strength



Modified from: Twiss & Moores

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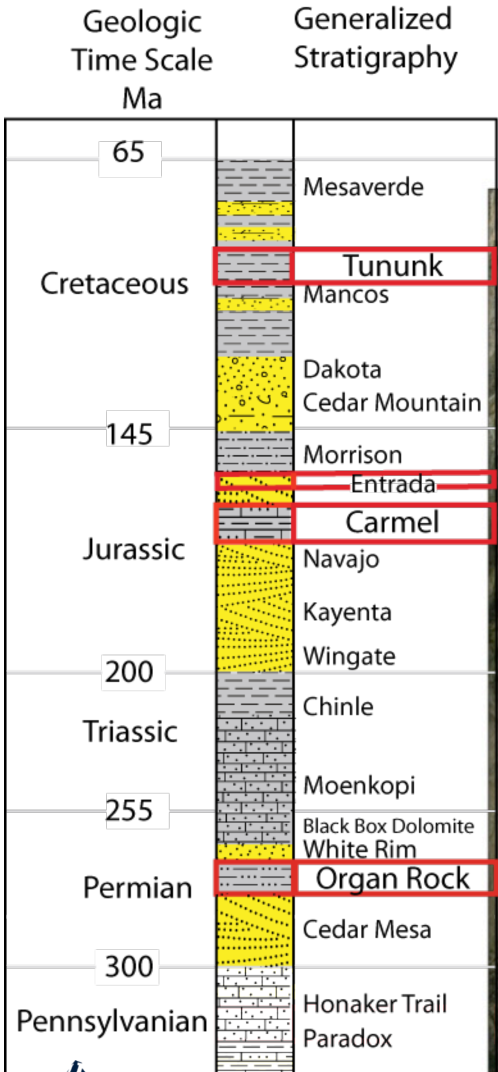
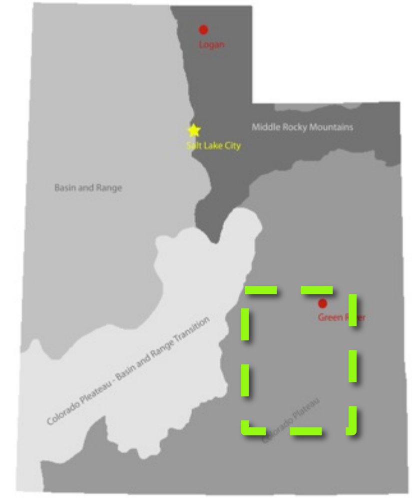
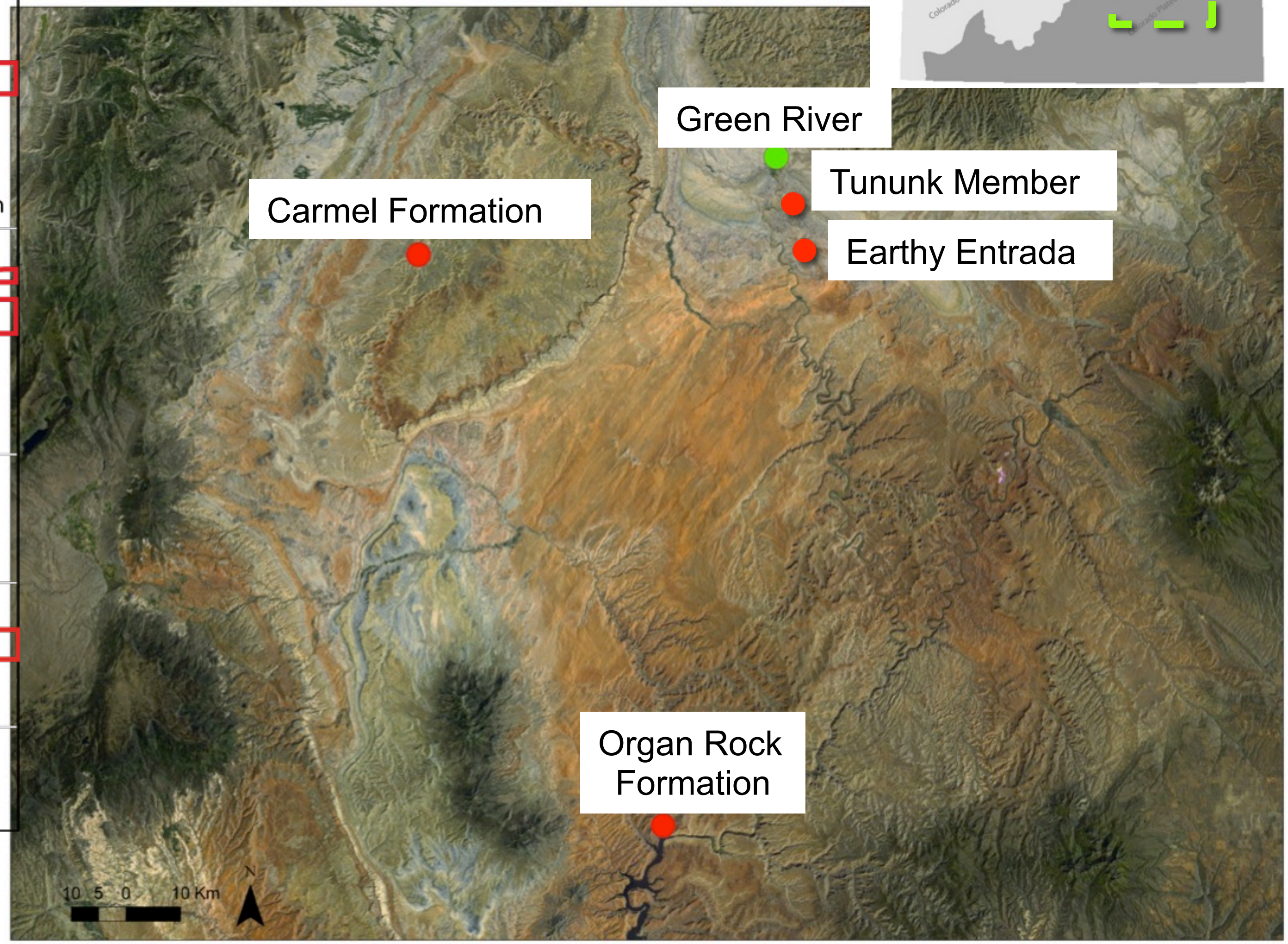
Study Locality







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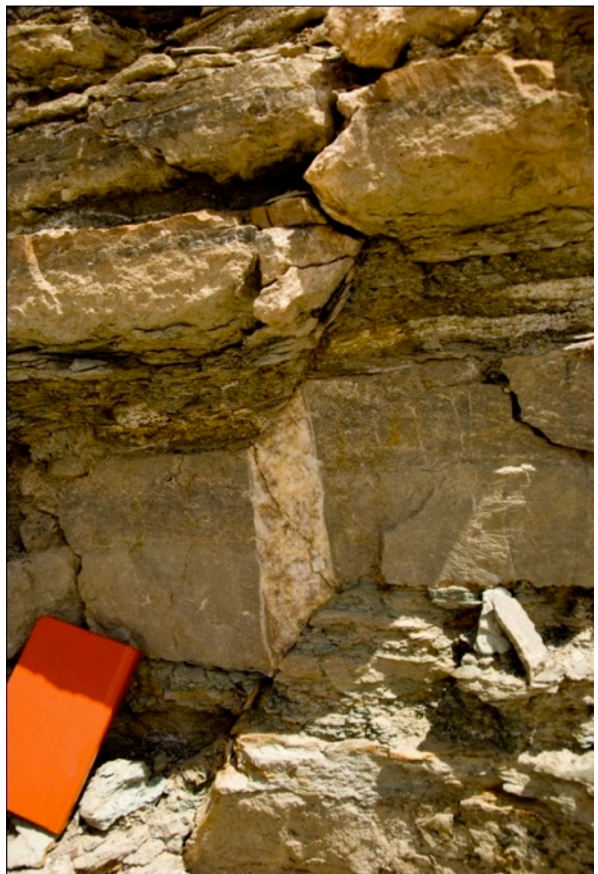
Outcrop Examples

Earthy Entrada

Carmel Fm.



Tununk Member

Organ Rock Formation

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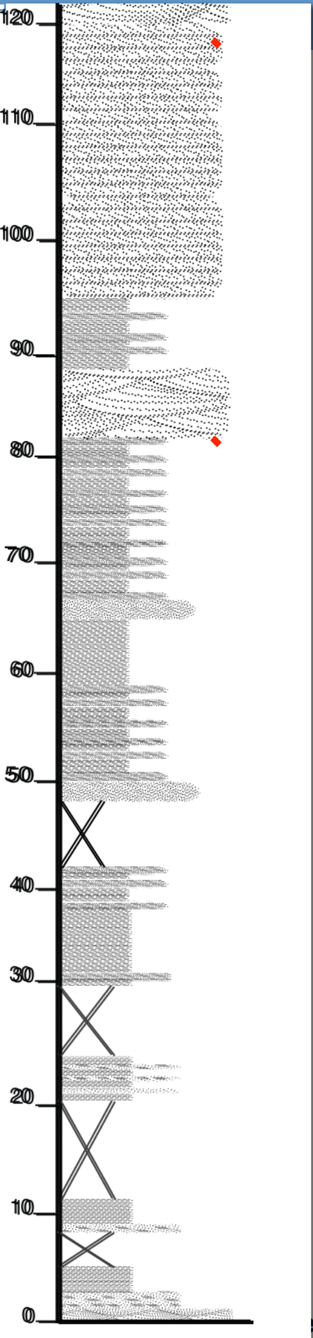
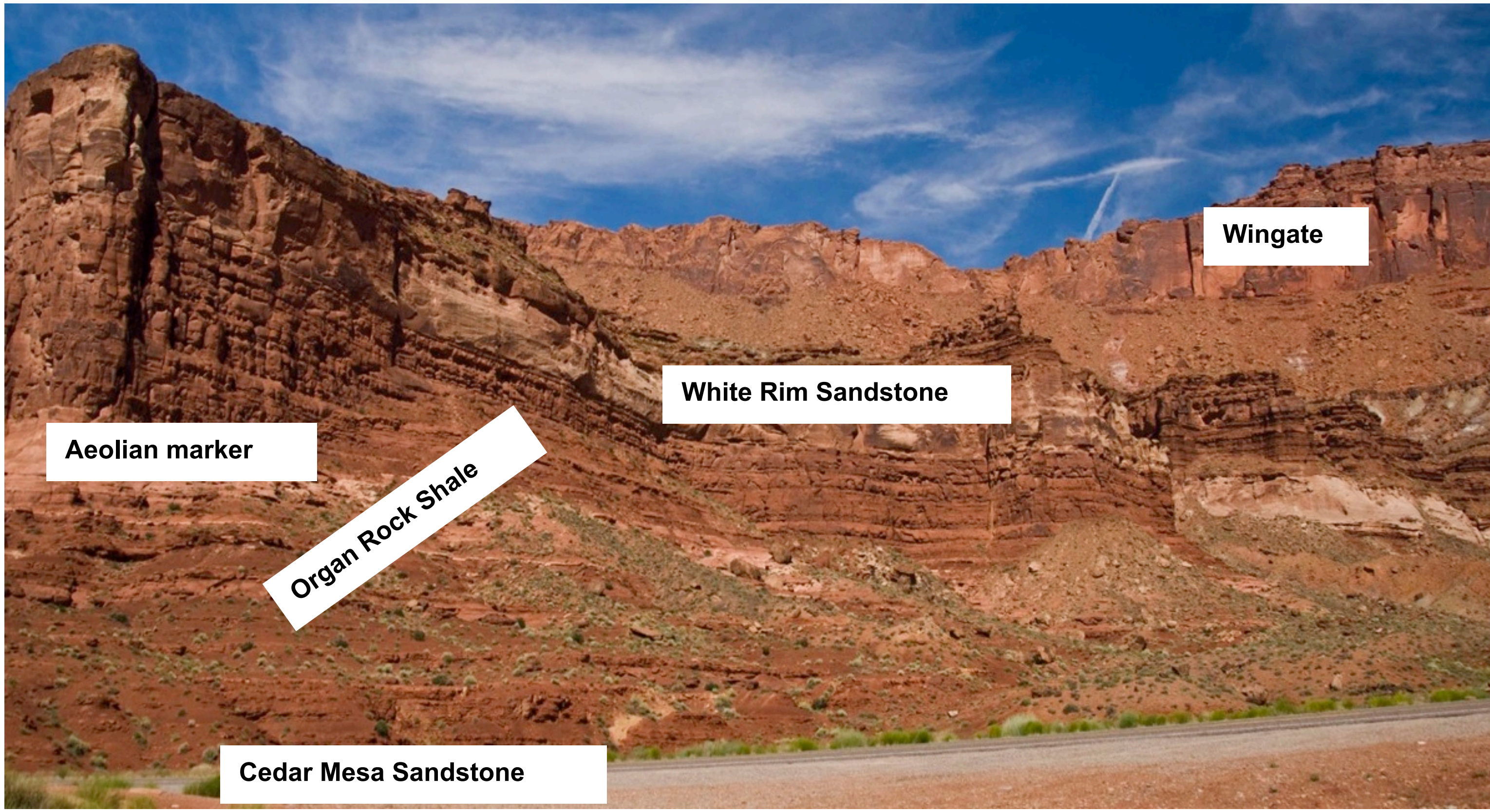
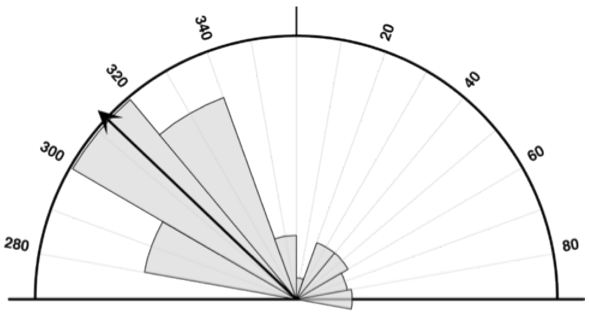


Organ Rock Formation



- Seal to the underlying Cedar Mesa Sandstone
- Coarsening up-ward interbedded siltstones & mudstones
- Deposited in near shore marine lowlands, braided streams & tidal flats

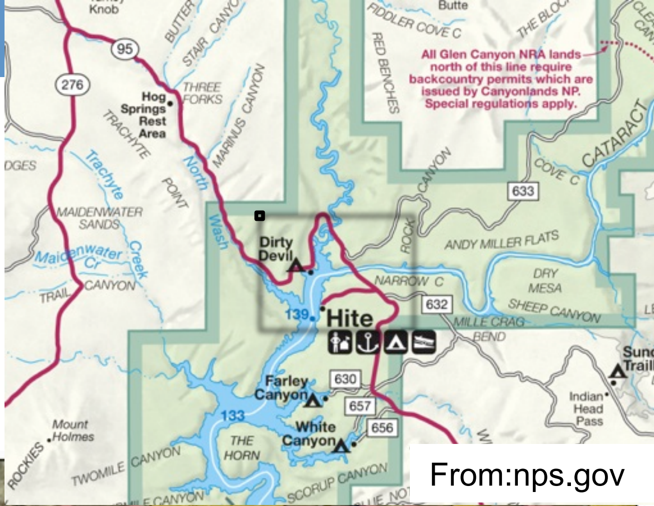
Cedar Mesa Discontinuities



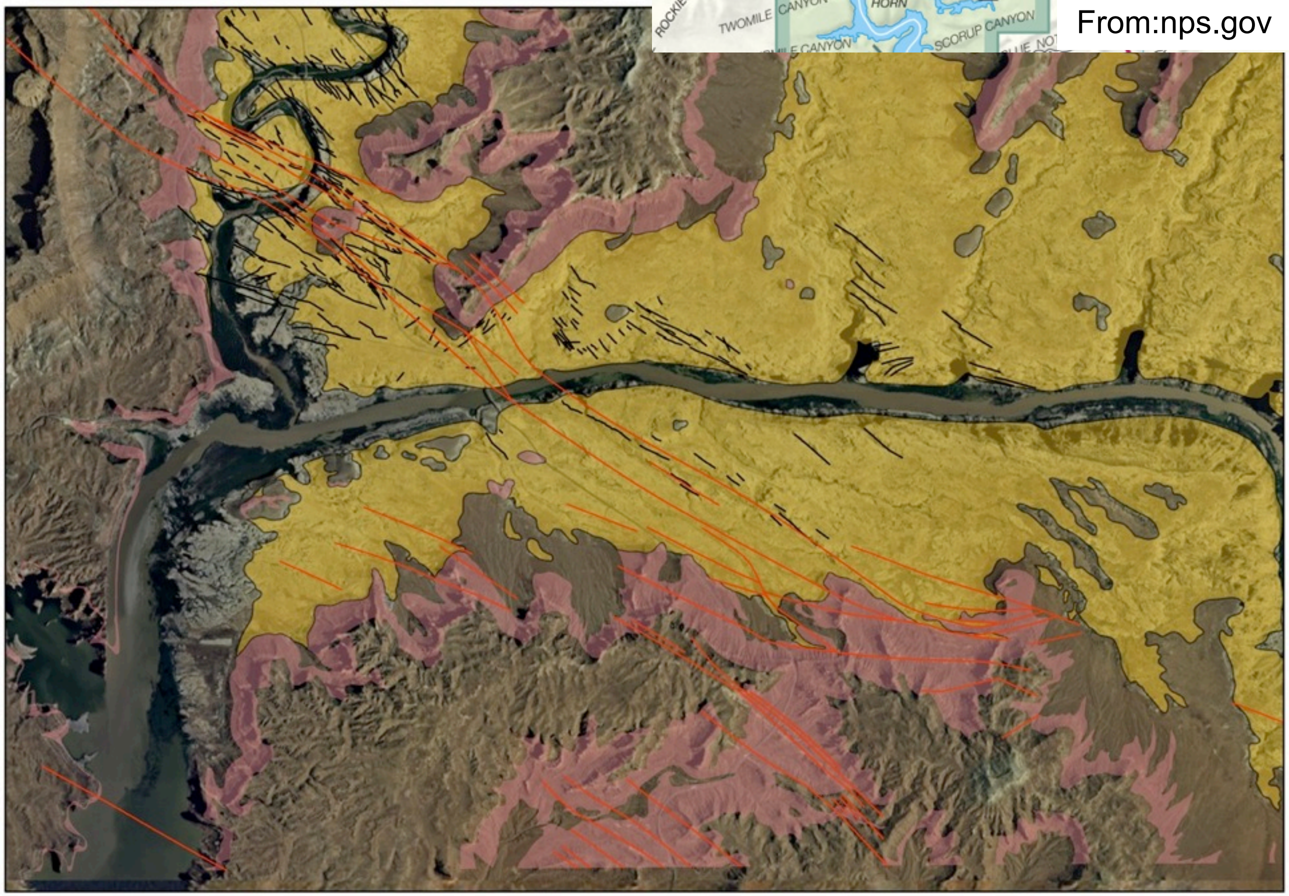
N: 342

Mean direction: 319°

Interval: 10°



From:nps.gov



Cedar Mesa Sst

Organ Rock Shale

Normal faults

Cedar Mesa joints

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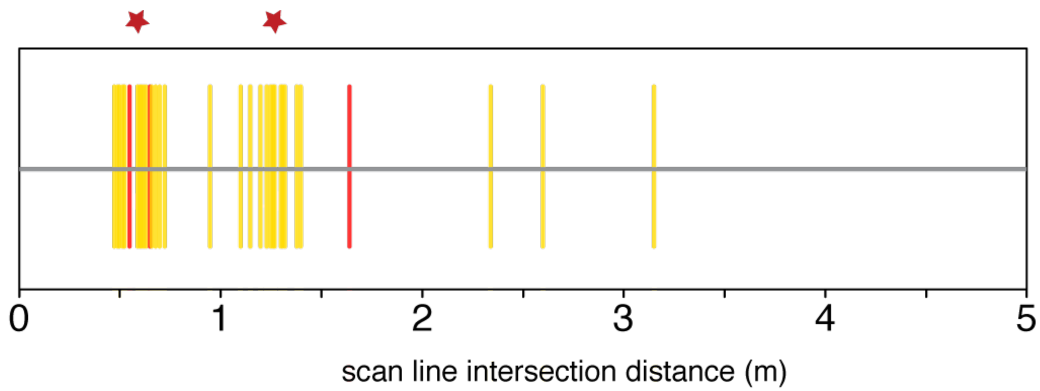
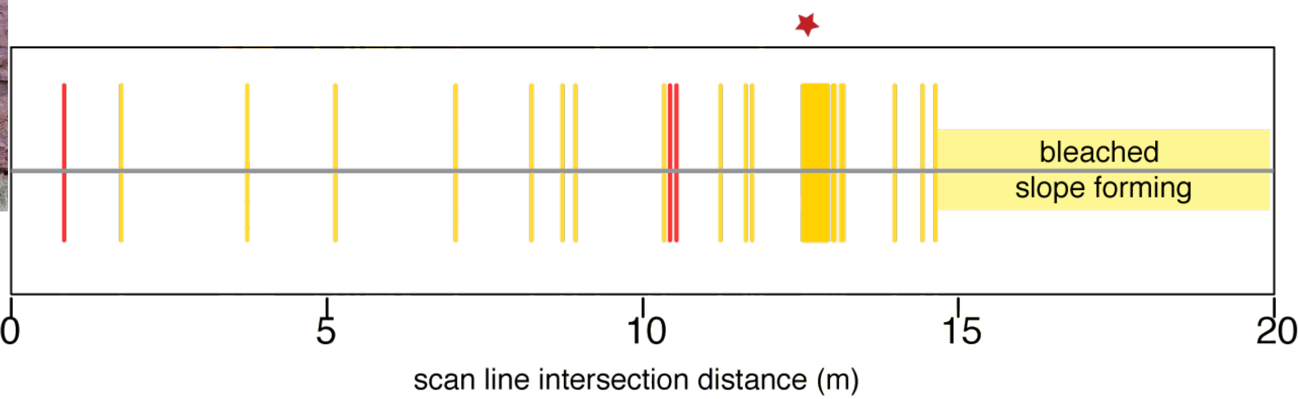
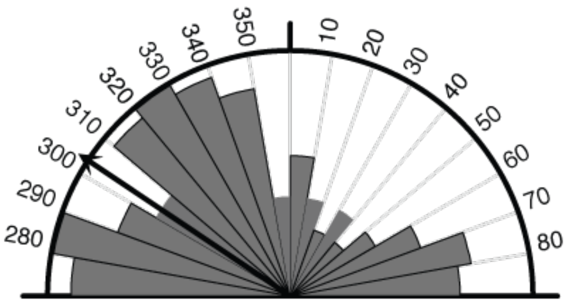
N 0 0.375 0.75 1.5 Kilometers

Modified from: Willis 2012 UGS; Glen Canyon NRA

Fracture character & distribution







N: 108
Mean Direction: 303.5°
Counting interval: 10°

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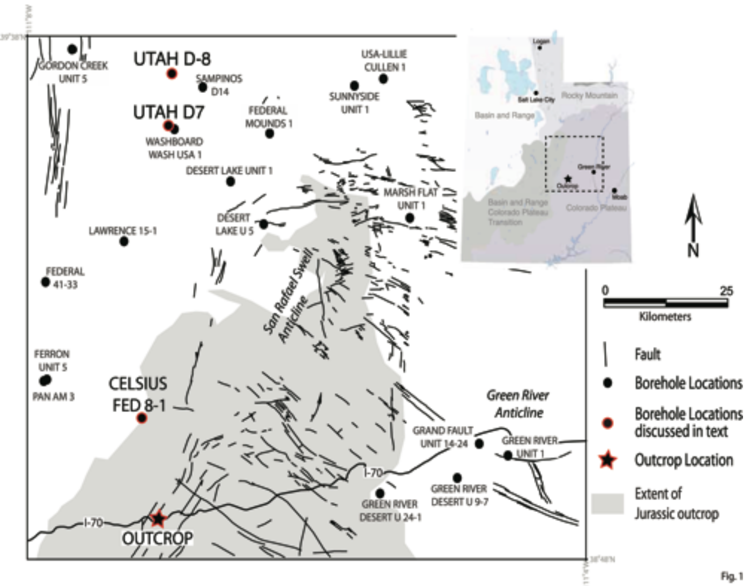
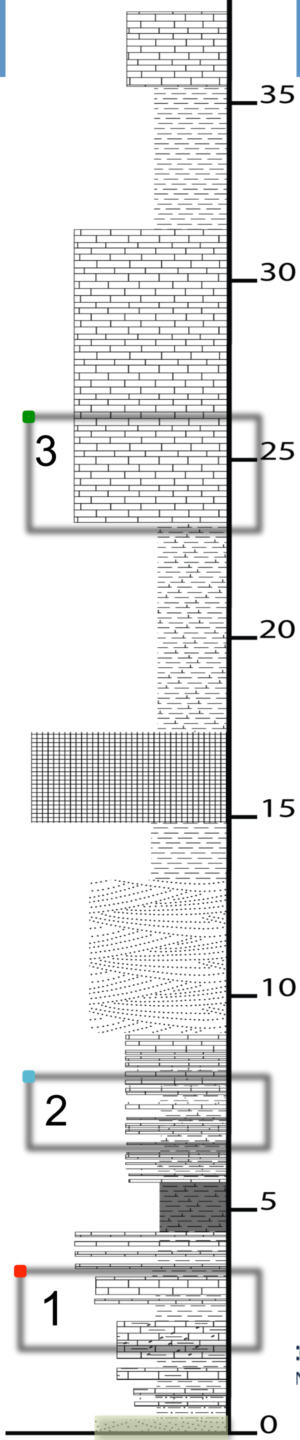
- Structural trend parallels fault and joint trend in underlying reservoir
- Bleaching and mineralization suggests fluid flow along fractures
- Fracture density increases with proximity to faults ★
- Rock strength and air permeability below detection limits

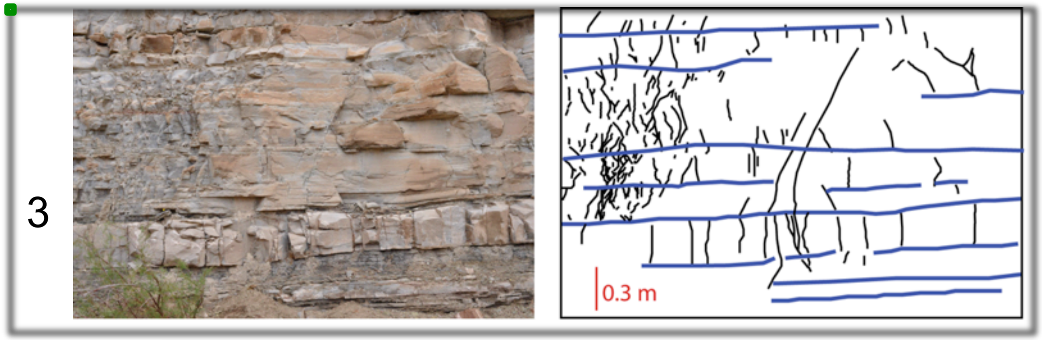


Jurassic Carmel Formation

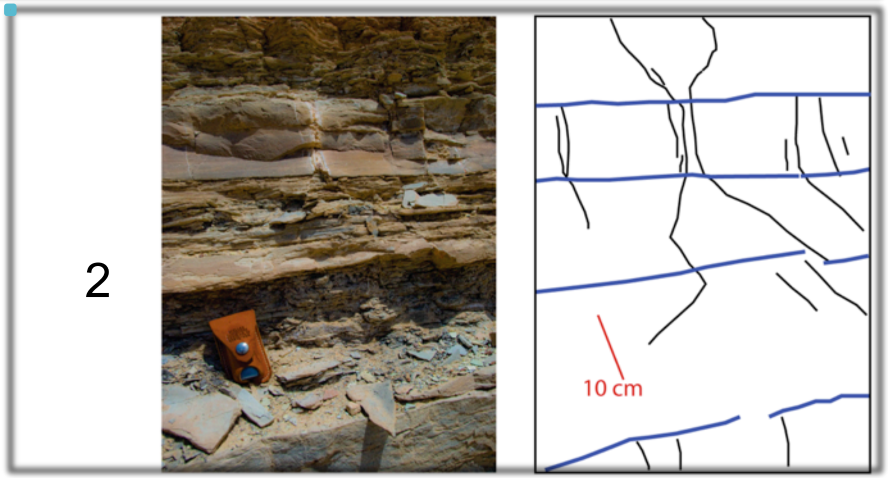
- Seal to the underlying Navajo Sandstone
- Mixed siliciclastic carbonate system
- Deposition in near shore marine to sabkha setting

Outcrop analysis

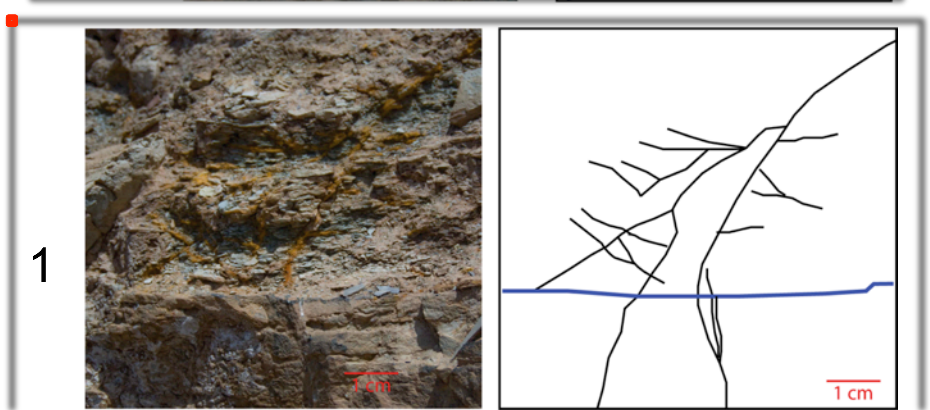




Fracture swarms associated with units lacking shale inter-beds and normal faults & spaced fractures

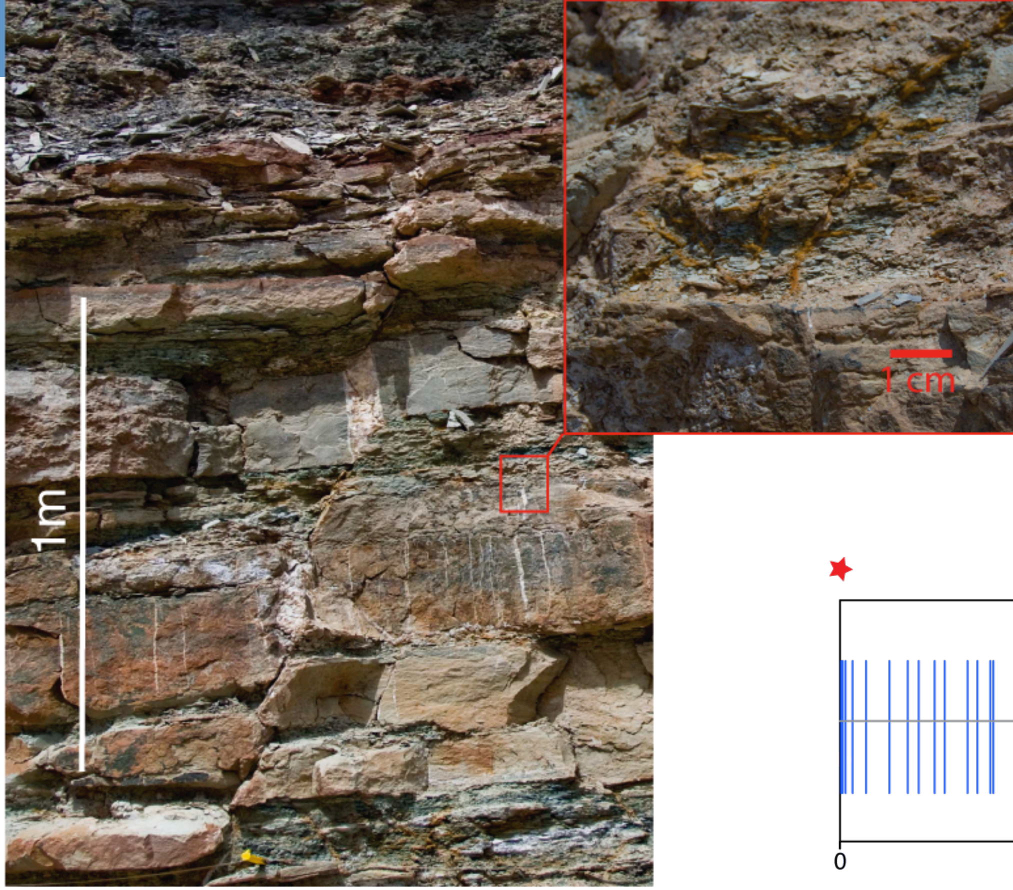


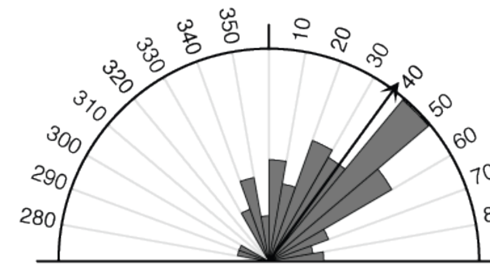
Splitting of fractures across lithologic boundaries



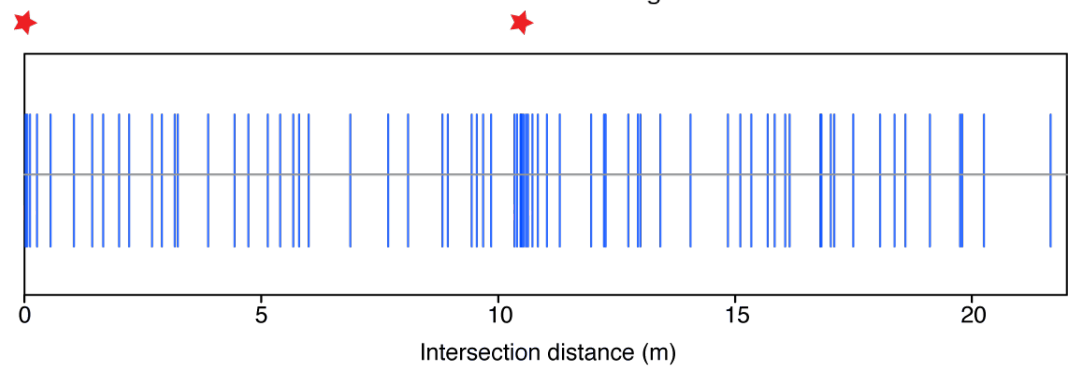
Deflection or arrest of mineralized fractures at interface

Carmel Formation

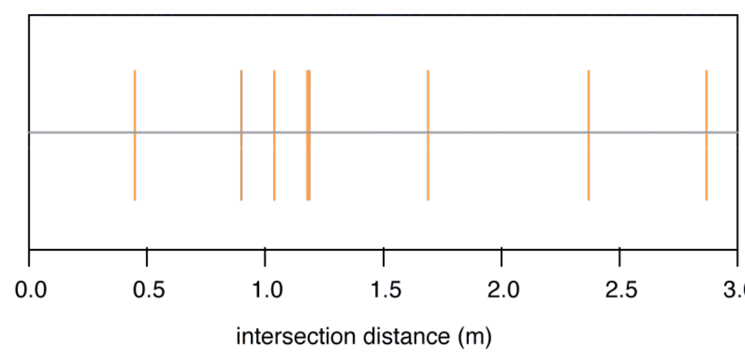




N: 132
Mean Direction: 36.3°
Counting interval: 10°



- Structural trend of veins parallels fault deformation bands in underlying reservoir
- Open-mode calcite veins
- Compressive strength range 15-65
- Air Permeability range > 0.01 D to 0.1 D



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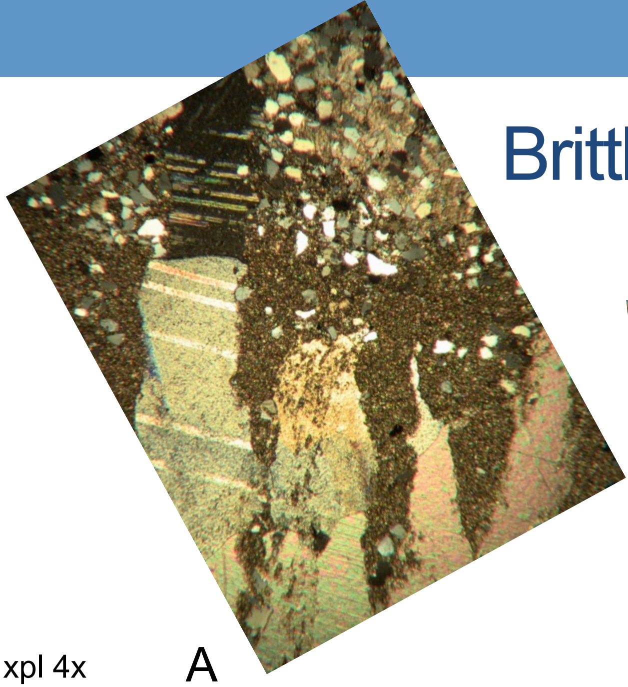
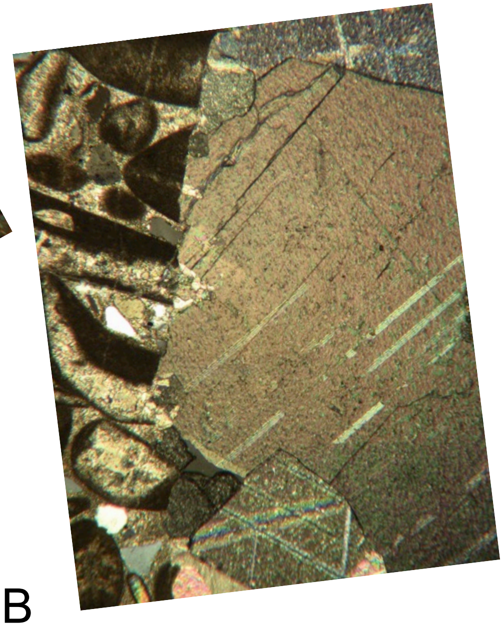
Brittle fractures



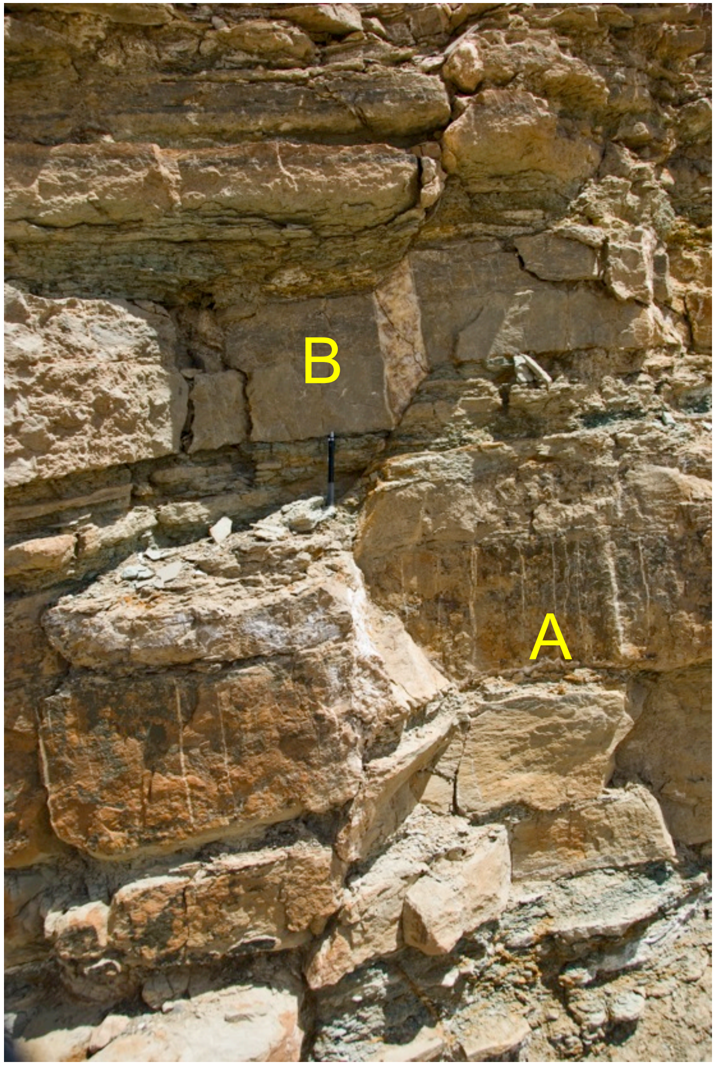
xpl 4x
field of view 4 mm

A



B

- Open-mode calcite veins with twinning lamellae
- Fracture opening & mineralization in the subsurface



13 cm

xpl 10x
field of view 2.5 mm

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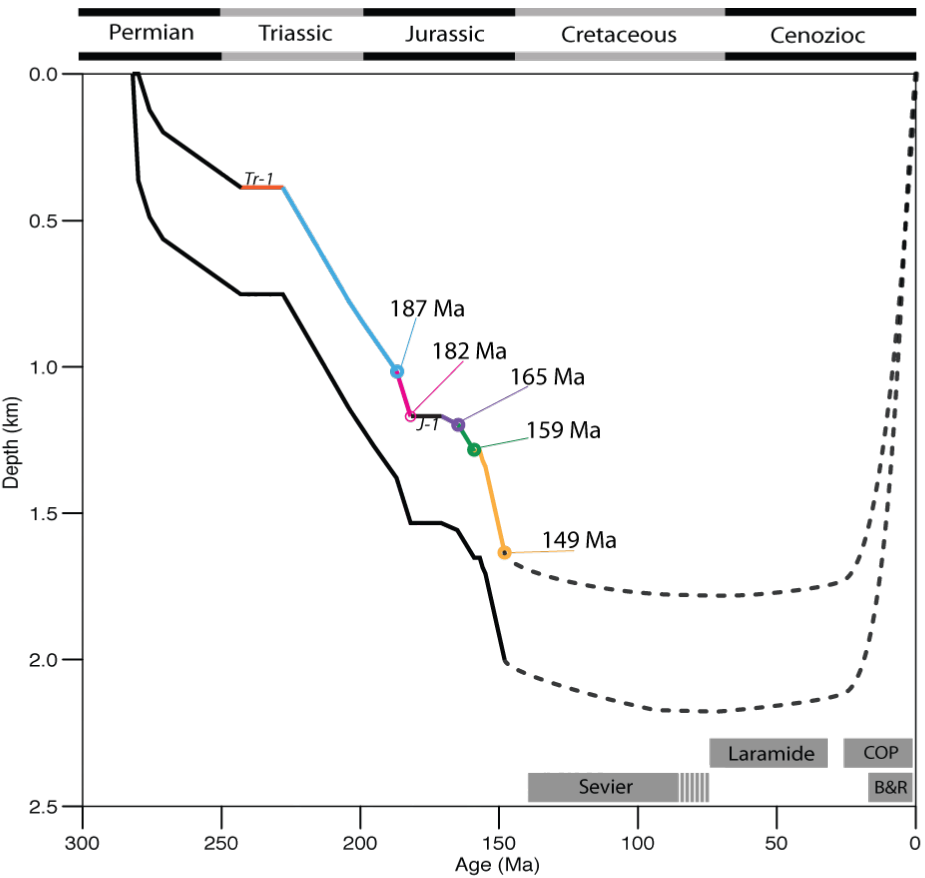
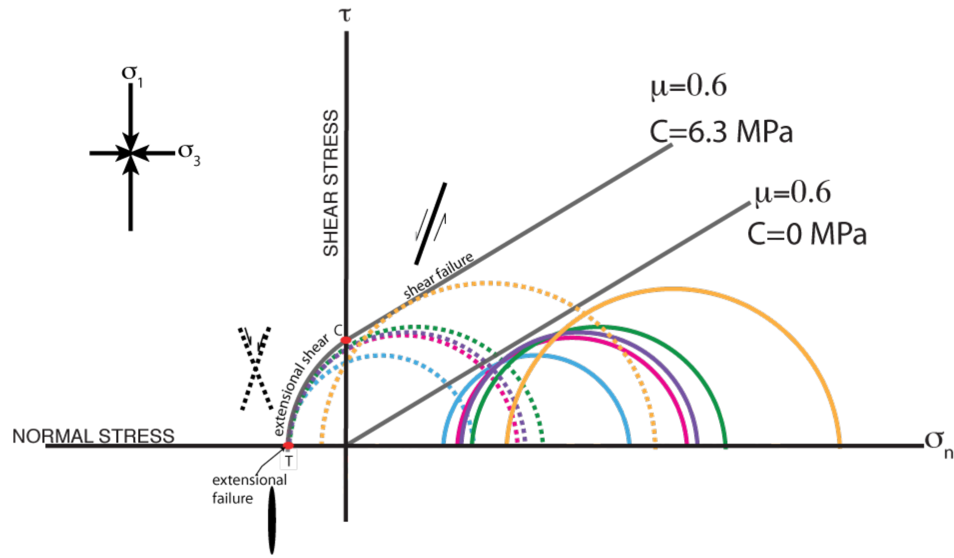
Organ Rock Formation – burial history





Local Normal Faults

Basin and Range

Laramide

Sevier

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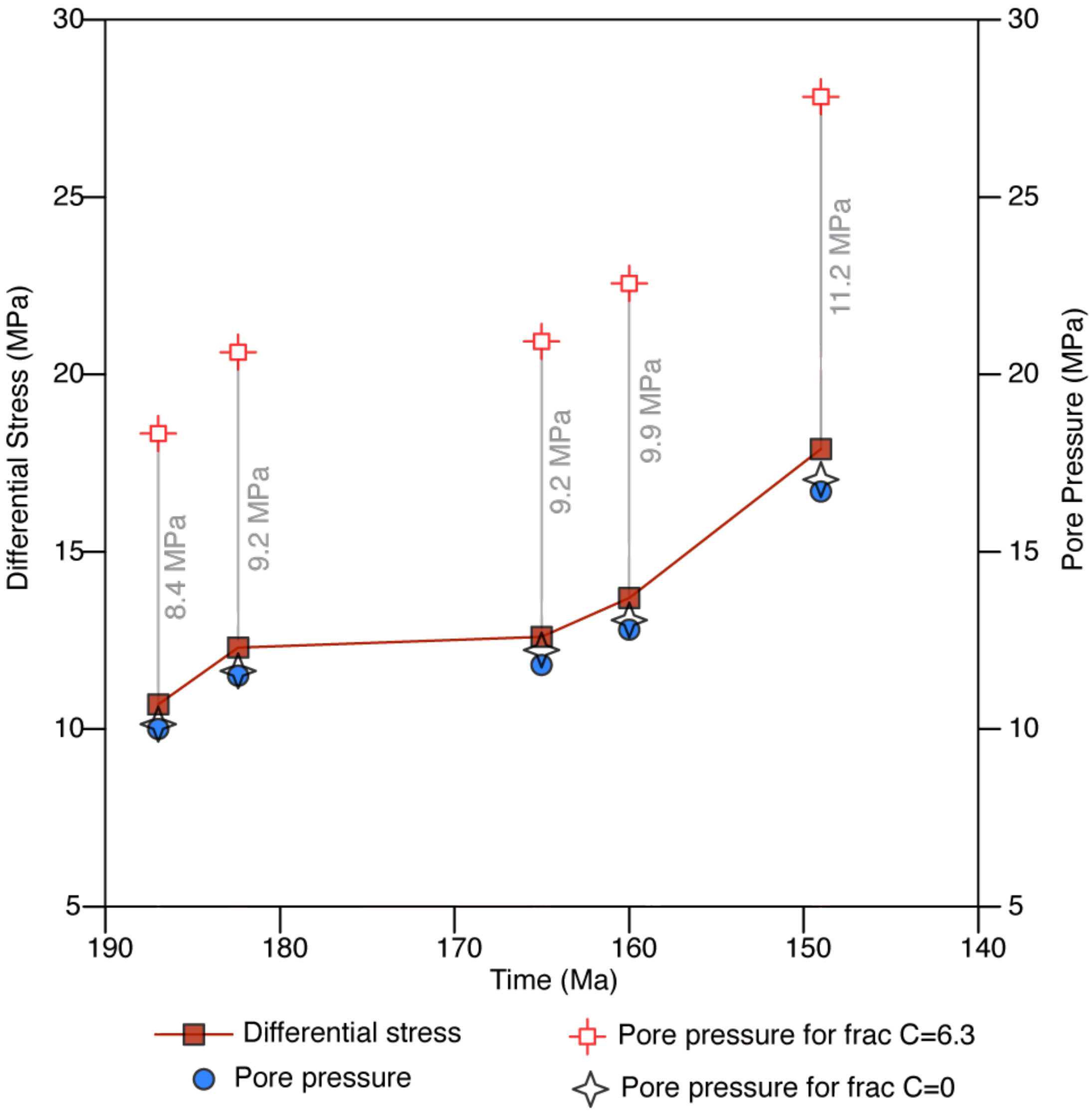
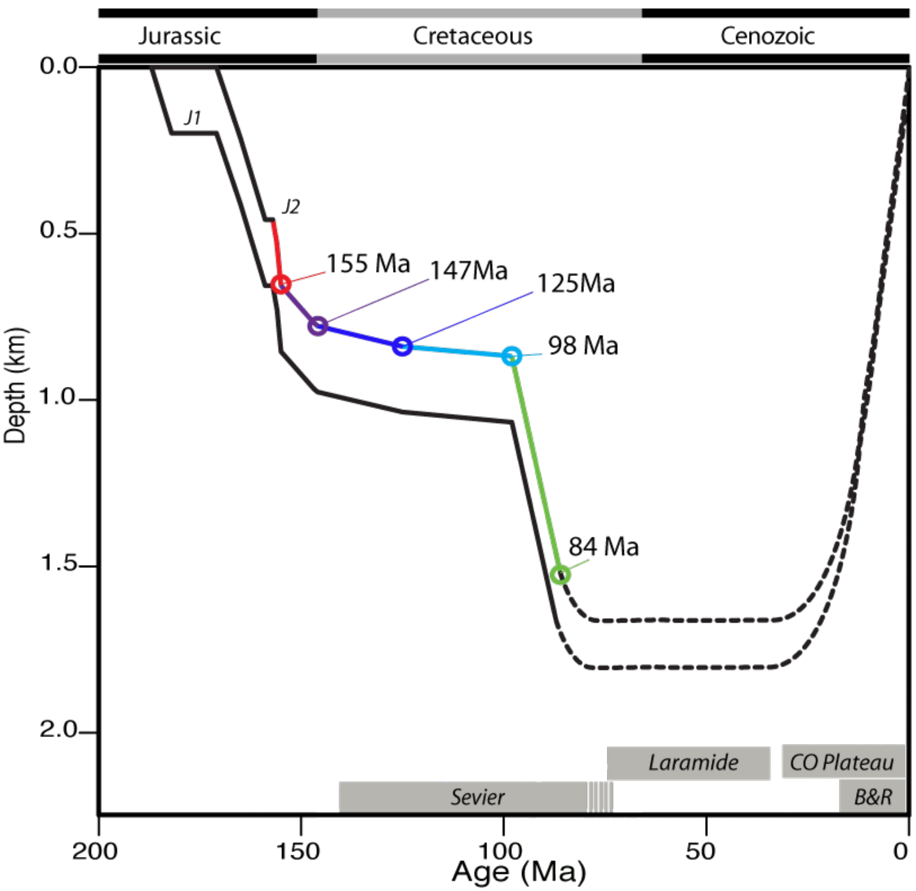
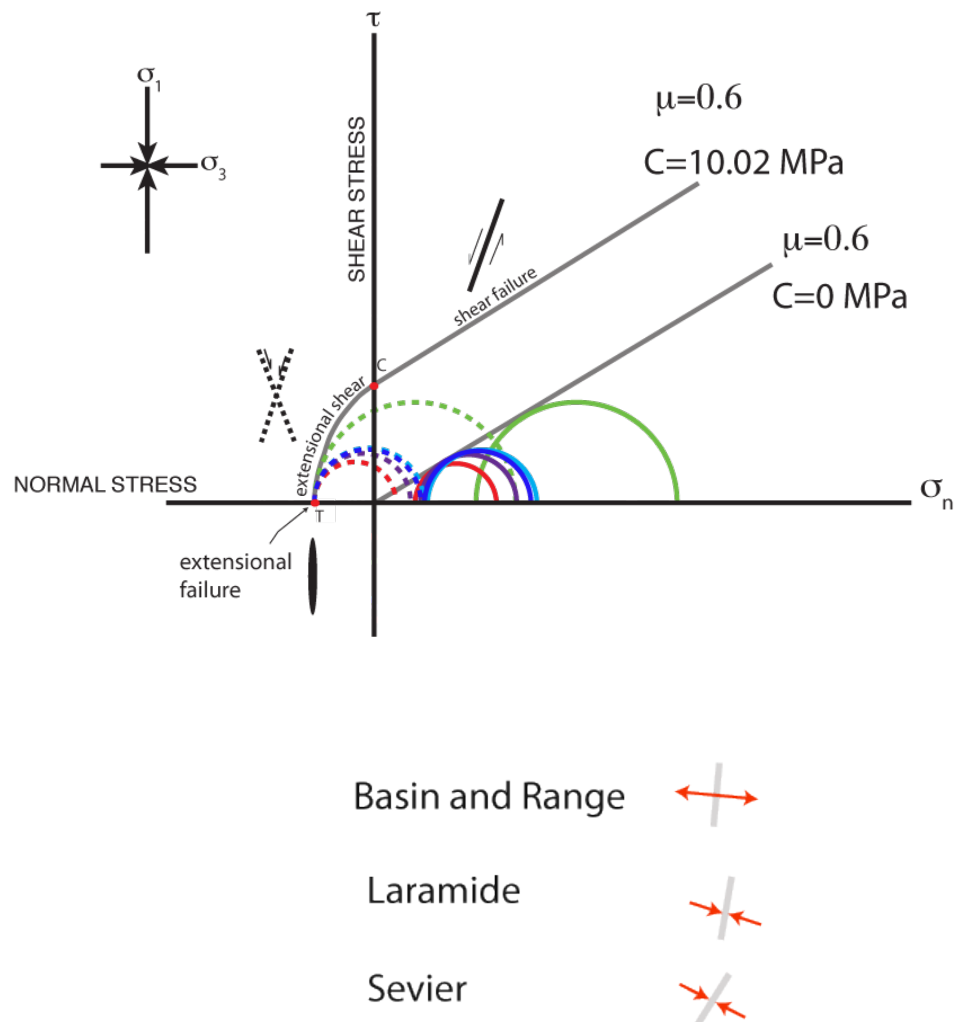
Organ Rock Formation - failure potential through time



Time (Ma)	ΔP_p at C=0	ΔP_p at C=6.3
187	0.2 MPa	8.4 MPa
	29 psi	1218 psi
184	0.2 MPa	9.2 MPa
	29 psi	1334 psi
165	0.6 MPa	9.2 MPa
	87 psi	1334 psi
160	0.4 MPa	9.9 MPa
	58 psi	1435 psi
149	0.4 MPa	11.2 MPa
	58 psi	1624 psi

Carmel Formation – burial history





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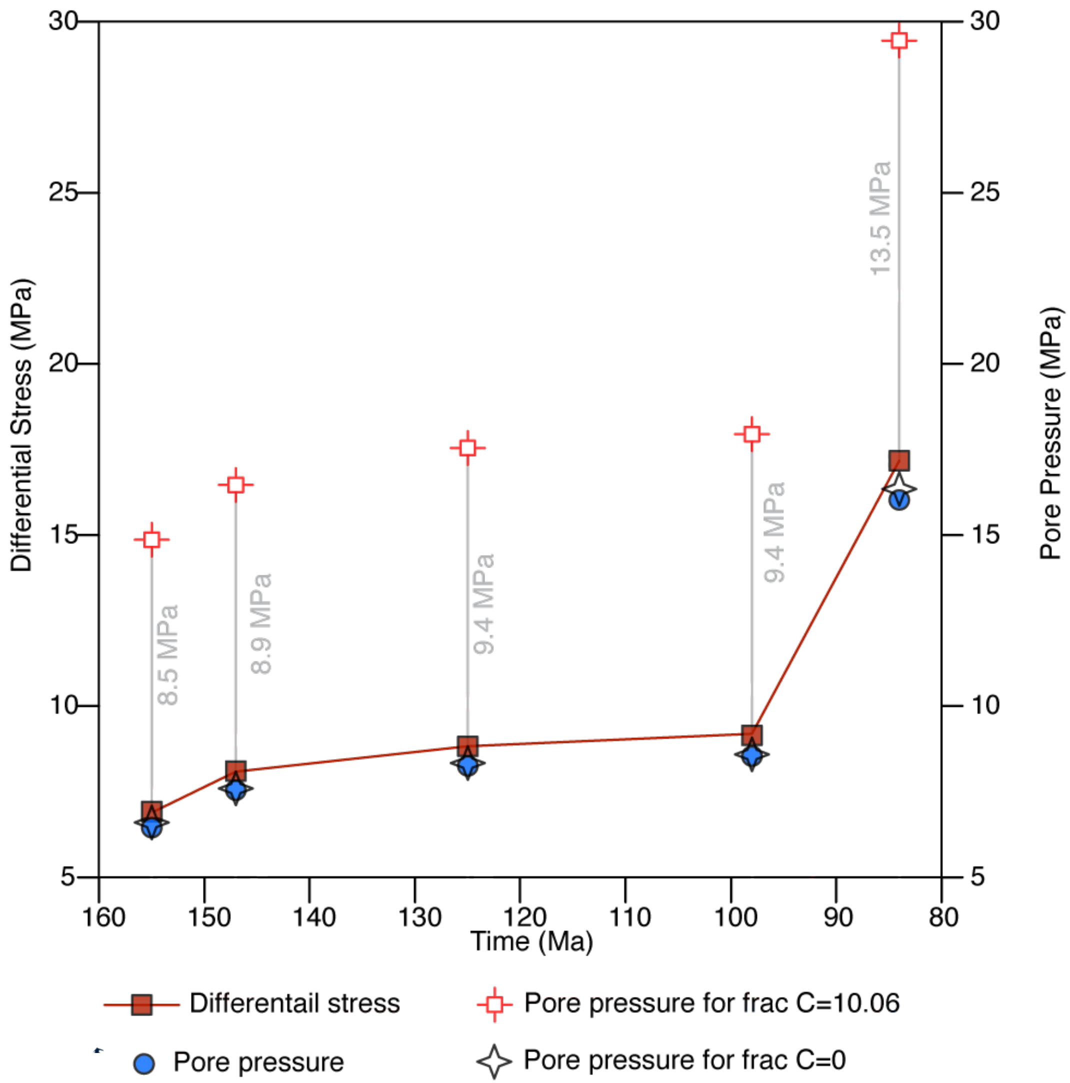
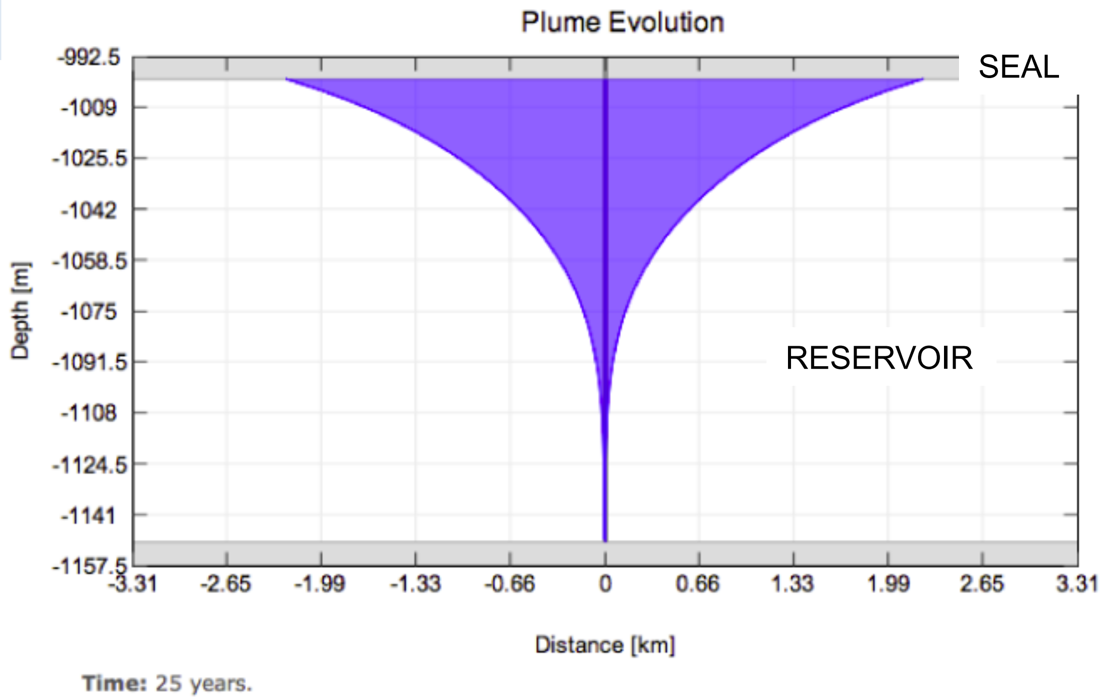
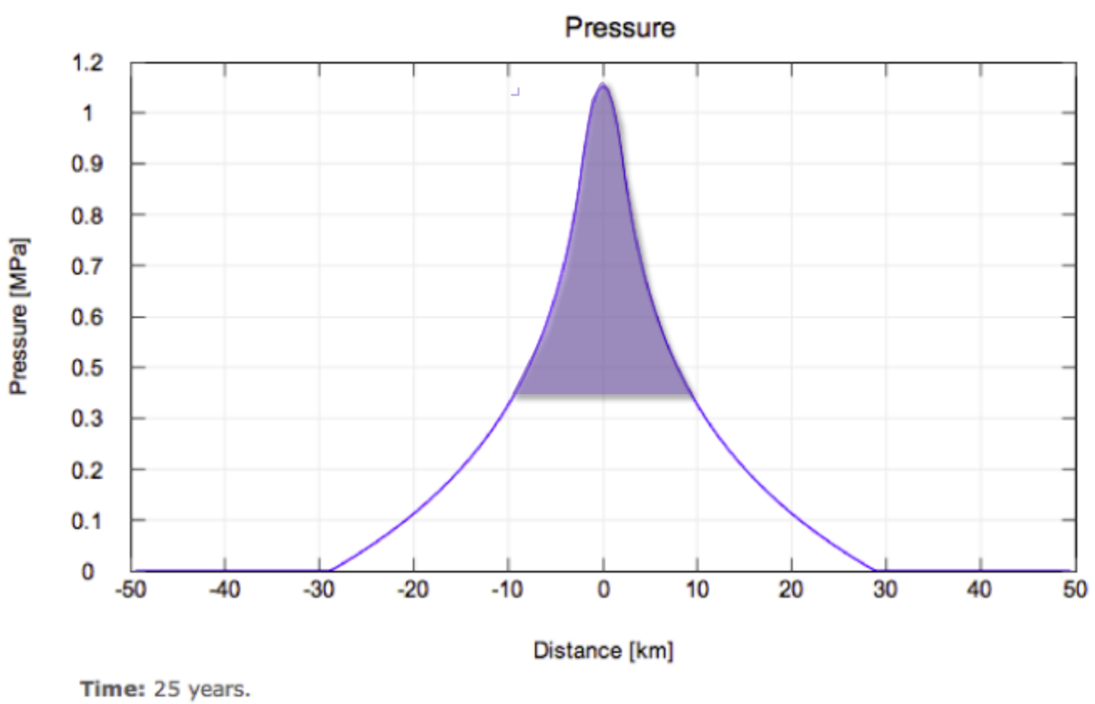
Carmel Formation - failure potential through time



Time (Ma)	ΔP_p at C=0	ΔP_p at C=10.1
155	0.2 MPa	8.5 MPa
	29 psi	1232 psi
147	0.1 MPa	8.9 MPa
	14.5 psi	1290 psi
125	0.2 MPa	9.4 MPa
	29 psi	1363 psi
98	0.1 MPa	9.5 MPa
	14.5 psi	1377 psi
84	0.4 MPa	13.5 MPa
	58 psi	1958 psi

Pressure Modeling





Parameters	
Permeability	0.05 Darcy
Brine Residual Saturation	0.3
Porosity	0.3
Top Depth	1000 m
Reservoir thickness	150 m
Injection rate	1 Mt/yr
Simulation time	50 years

http://monty.princeton.edu/CO2interface/index.html

Princeton Subsurface Hydrology Research Group
Carbon Dioxide Sequestration Simulator

- ◇ Variability in lithology and bed thickness
- ◇ Continuation, deflection, and termination of fractures at lithologic interfaces
- ◇ Lower fracture density in fine grained lithologies
- ◇ Failure at depth for C=0 at or very near hydrostatic pore pressure

Carmel Formation

- Highest fracture densities in thinly bedded units
- Mineralized and altered fractures throughout
- Low permeability and variable rock strength

Organ Rock Shale

- High fracture density adjacent to fault
- Bleaching and mineralized fractures adjacent to faults
- Permeability and rock strength below resolution limits

Conclusions

- At depth low cohesive strength rocks are very near failure –
  - Mechanical failure can be induced by small changes in pore pressure
  - Stress history important - pre-existing planes of weakness will fail prior to formation of new fractures (Gale, et al., 2007 & Gale, 2008)
  - Understanding orientation will allow prediction of failure direction
- Pressure front extends far from injection point
  - Buoyant plume may encounter meso- to micro-scale fractures (Pasala, et al., 2013)
- Pressure front exceeds change in pore pressure necessary for failure of cohesionless material

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Sirovision Software – University Grant
http://monty.princeton.edu/CO2interface/

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