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Use of wireline logs to estimate strength of cap-rock lithologies

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Background

The presence of fractures in sedimentary rocks affect their mechanical and hydrogeologic properties. Understanding and modeling these properties is important for the accurate evaluation of petroleum as well as storage systems. This research is focused on characterizing the fracture properties and variability in the rock strength of cap-rock lithologies especially associated with the injection and storage of CO_2.

Research Drivers

- Results from active CO_2 injection offshore show lateral migration in heterogeneous lithologic sequences and under thin shale lenses (Chadwick, 2006).
- Geochemical changes indicate communication between an active CO_2 injection reservoir and an overlying reservoir separated by approximately 20 meters of shale and siltstone (Kharaka et. al 2009).
- Proposed CO_2 injection test site at Gordon Creek, UT - proposed reservoir is the Navajo Sandstone, with the Carmel Formation as the cap-rock.
- Assurance of the presence of impermeable cap-rock with capacity great enough to prevent the buoyancy driven upward migration of CO_2 over the appropriate time scales.
- Rock strength of cap-rock lithologies is typically derived from sonic logs, leak.off tests, and laboratory testing of rock strength – often limited to either subsurface data and/or limited samples sizes.

Understanding and Describing Cap-Rock Strength

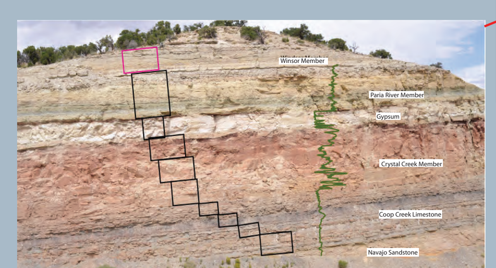
- Poisson's Ratio (n) - description of the compressibility of a material perpendicular to applied stress can be used to define the fracture index (F_I): F_I = (n/1-n) (Stump and Flemings, 2002).
- Young's Modulus (E) - description of the stiffness of a material, a higher Young's Modulus is associated with stiffer rocks which are more easily fractured

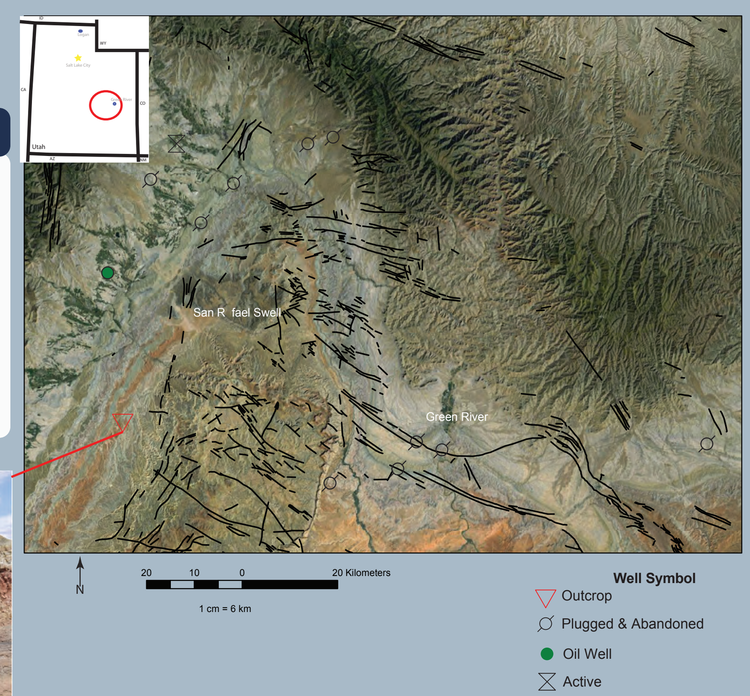
In this study we investigate how E and F_I might vary at the scale of a CO_2 injection site as well as their variability over stratigraphic intervals within a proposed cap-rock. The goal of this work is to establish a link between outcrop observations, well log signatures and rock strength properties in order to constrain risk in the design of CO_2 geosequestration systems and provide input data for forward modeling scenarios.

Study area

Jurassic Carmel Outcrop located ~1 km west of Exit 99, I-70 south-central Utah. GR log from off-set well 15 km north of outcrop

photo analysis this outcrop
photo analysis opposite side of I-70





Methods

Outcrop analysis

- Stratigraphic descriptions
- Scanlines
- 3D photo fracture analysis – Sirovision

Well log analysis

- Gamma Ray or Spontaneous Potential
  - lithology identification and correlation
- Sonic
  - derive V_p and V_s
    inverse of the sonic log data was taken to obtain
    P-wave velocity shear velocity was calculated
    using empirical relationships established by other workers
  - Derive density where no Bulk Density logs available
  - Calculate Poisson's Ratio
  - Calculate Young's Modulus
- Bulk Density
  - Calculate Young's Modulus

Log Calculations

Shear Velocity
(Castanga et al. , 1985)

Vs=(Vp/1.16)-1.36

Poisson's Ratio:

$nd=[(Vp/Vs)^2 - 2]/2[(Vp/Vs)^2-1]$

Young's Modulus:

$Ed=2rVs^2(1-nd)$

Density from Sonic
(SMT Kingdom calculation):

$D(l)=0.23\ msec/ft[(1x10^6/sonic(l)]^{0.25}$
where l is each log value

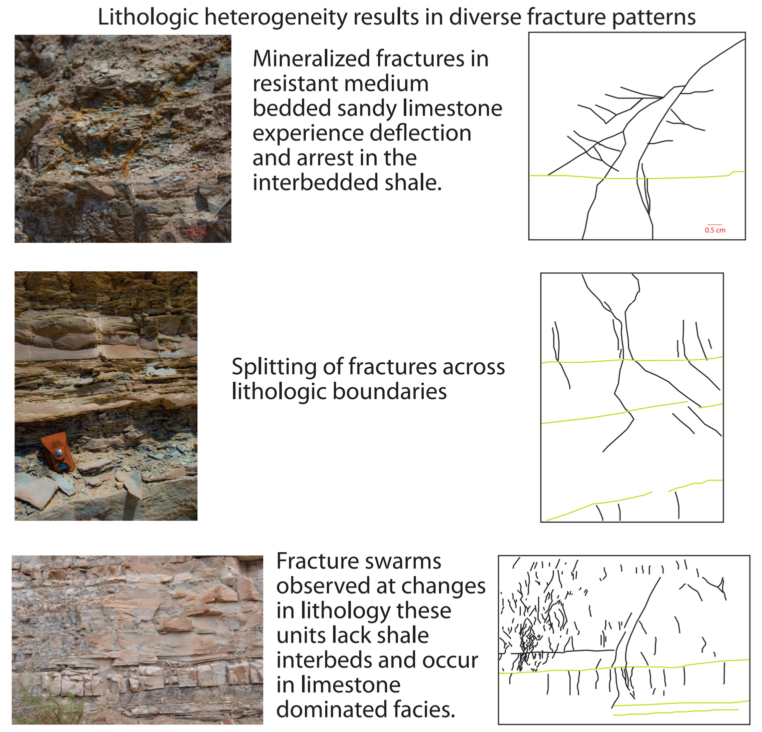
Vp P-wave velocity
Vs S-wave velocity
nd Poisson's Ratio dynamic
Ed Young's Modulus dynamic
r Bulk Density

Limitations

- No dipole sonic data available
- Rock strength estimated from vintage well log data; using sonic logs and empirical relationships established by previous workers; not a substitute for laboratory measurements of rock strength
- Log-based estimates are dynamic a more accurate measure of rock strength may be from static laboratory tests
- Likely provides a low estimate for rock strength

Outcrop Observations

Lithologic heterogeneity results in diverse fracture patterns



Mineralized fractures in resistant medium bedded sandy limestone experience deflection and arrest in the interbedded shale.

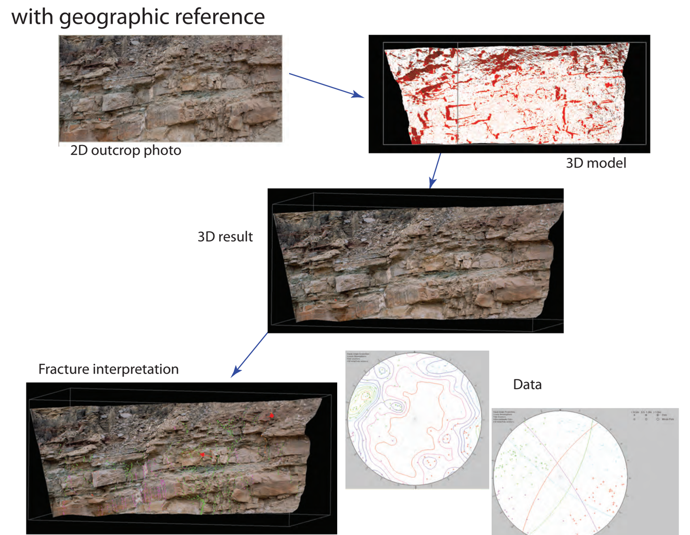
Splitting of fractures across lithologic boundaries

Fracture swarms observed at changes in lithology these units lack shale interbeds and occur in limestone dominated facies.

Sirovision

Photogammetry software enables the creation of 3D outcrop images
- Cost and time savings over Lidar survey
- Flexibility for photo analysis from meter scale to large scale photomosaics (100's of meters)

- Two photographs taken at a known distance from rock face with a set camera distance between each photo
- Siro3D uses camera calibration data, location and camera orientation to create an oriented 3D image
- SiroJoint the interpretation suite which provides output of discontinuity data with geographic reference



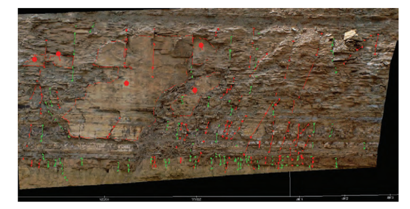
Stratigraphy

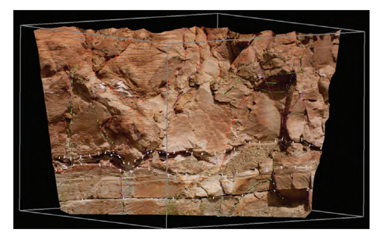
The Carmel Formation is a mixed silisiclastic carbonate system that unconformably overlies the Navajo Sandstone.

Unit A
Thin to med. bedded fossiliferous calcareous fine sand to siltstone, interbedded shale
Bed thickness increases up-section, abundant mineralized fractures.

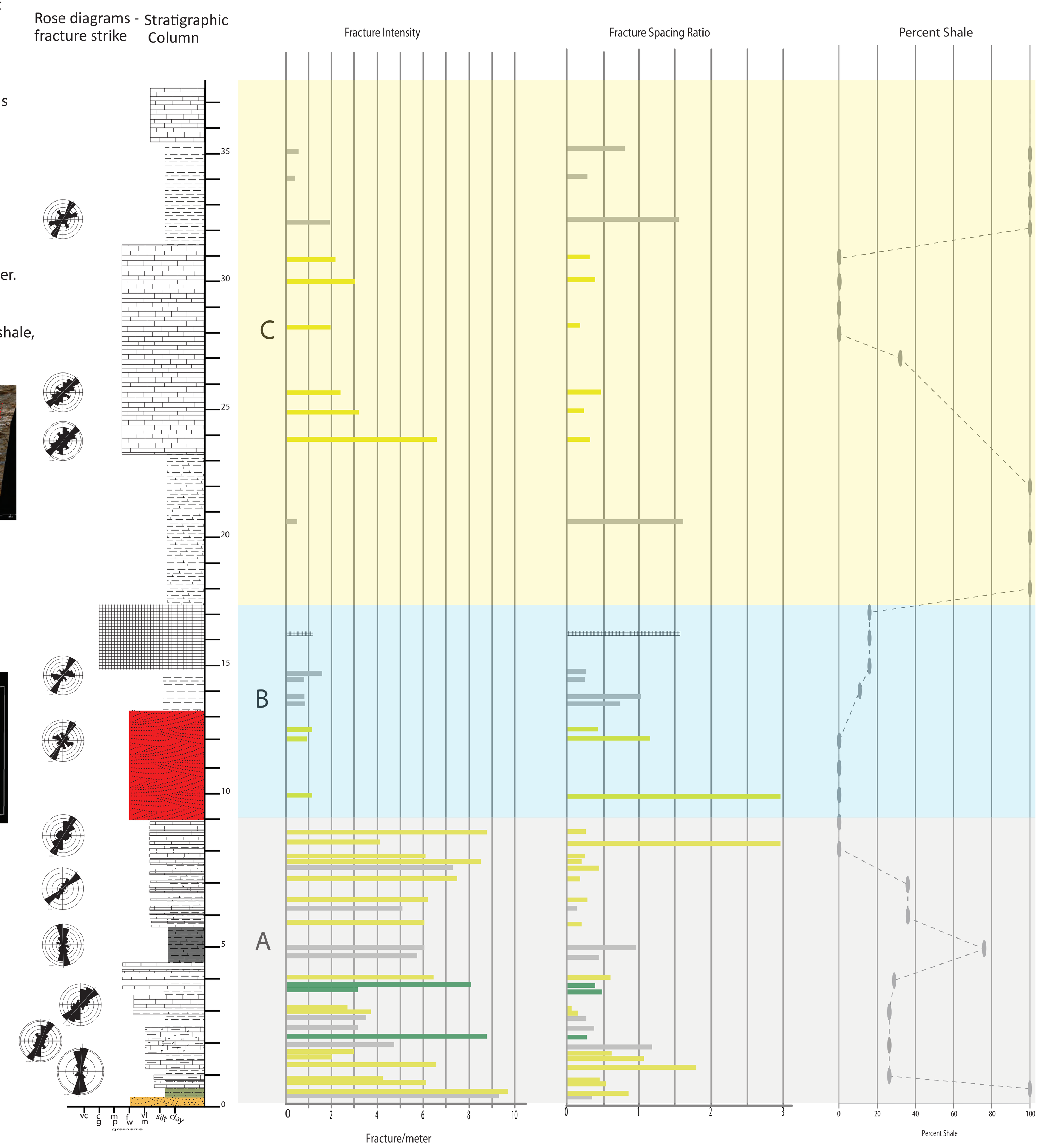
Unit B
Thick bedded gypsiferous red sandstone, cross-bedded, erosional basal contact. Maroon gypsiferous mudstone above & below sst bed, capped by thick gypsum layer.

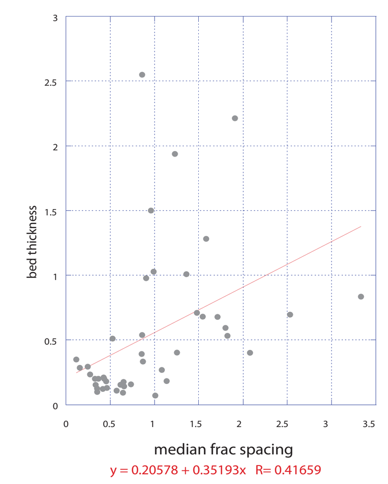
Unit C
Thin to med. bedded sandy limestone and shale, Some mineralized fractures in limestone beds.

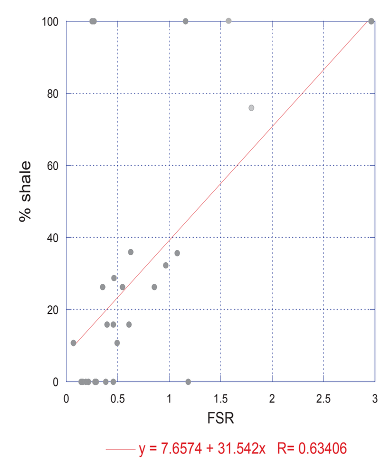


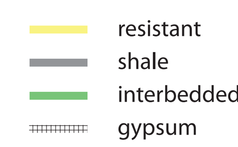


Fracture Analysis

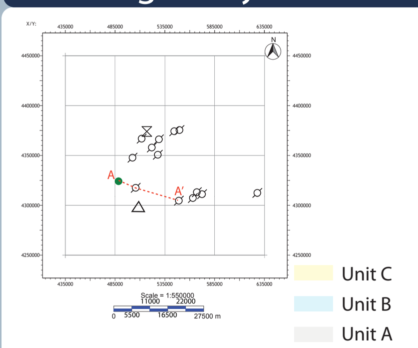




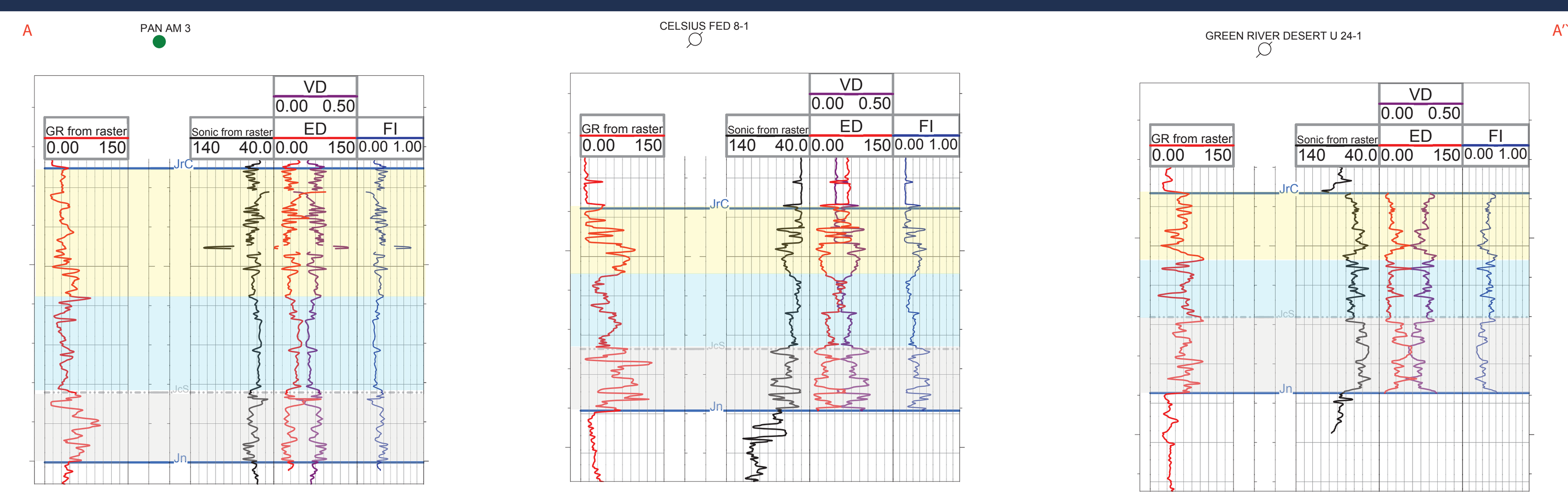




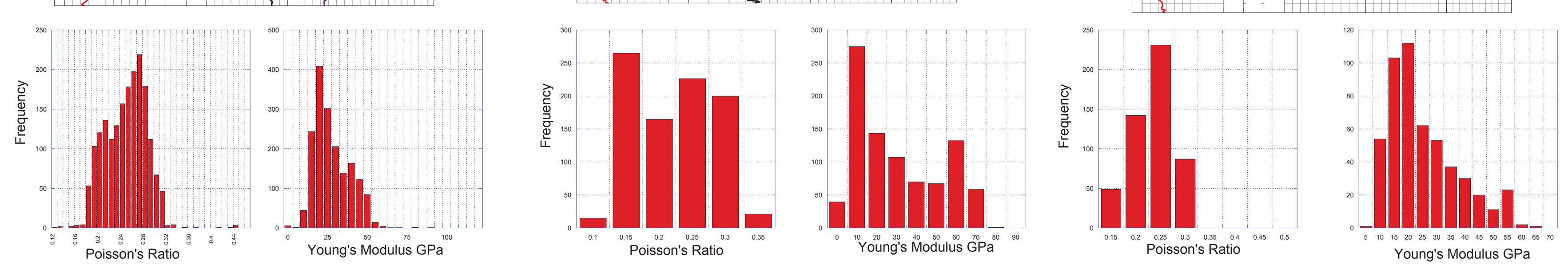
Well-log Analysis



- Gamma Ray, Sonic, and Bulk Density were digitized where available
- Poisson's Ratio, Young's Modulus, and Fracture Index derived from well log data over the entire Carmel

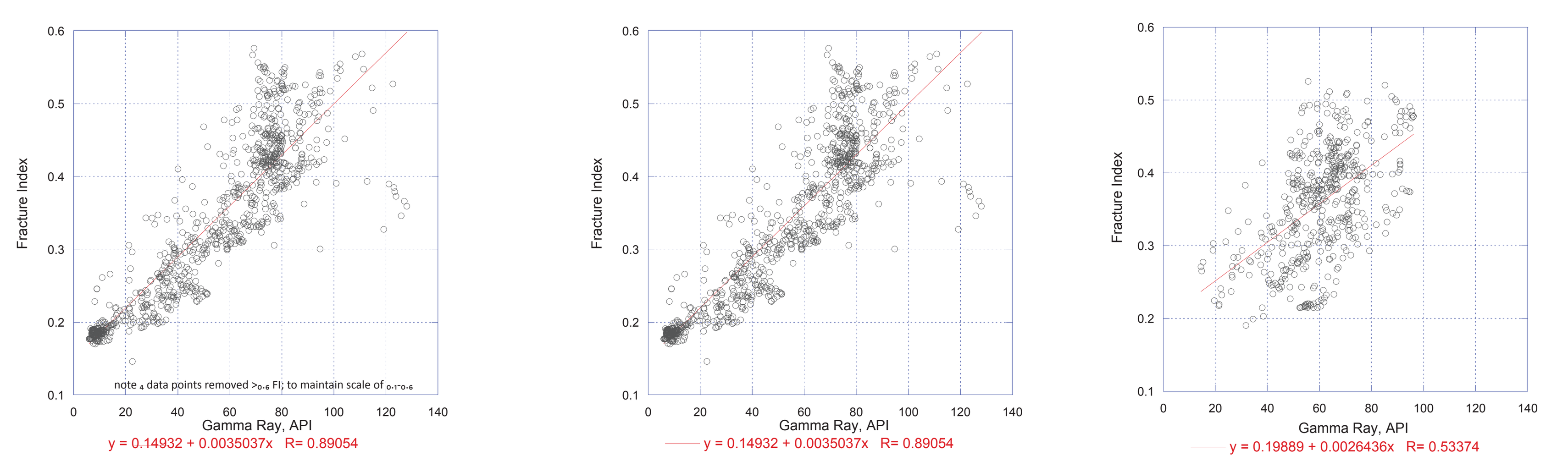


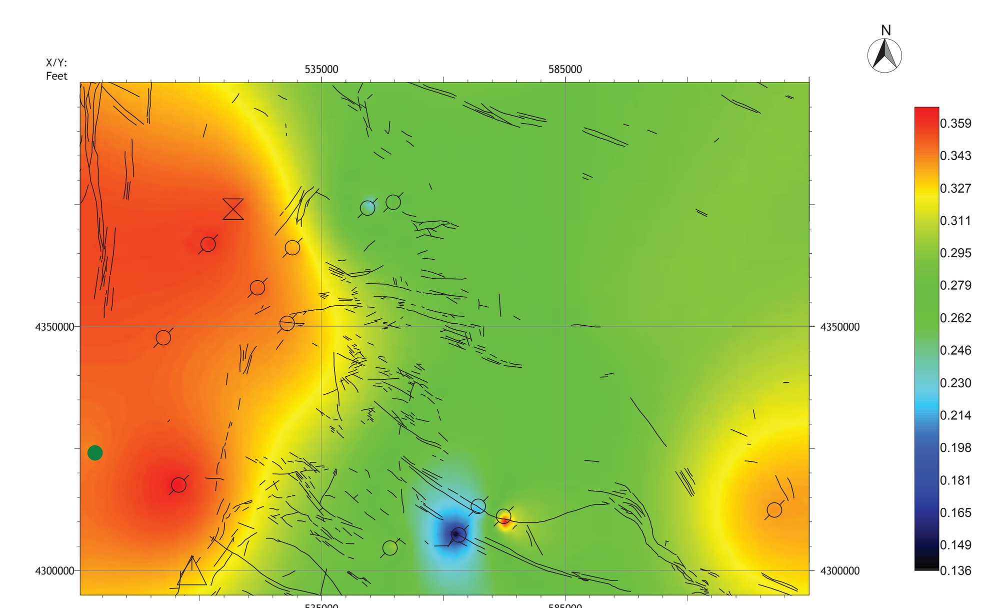
- Histograms of calculated nd & Ed – values fall within published ranges this rock-type



Poisson's Ratio	Young's Modulus GPa	Poisson's Ratio	Young's Modulus GPa	Poisson's Ratio	Young's Modulus GPa
Min = 0.12	Min = 1.38 GPa	Min = 0.13	Min = 7.29 GPa	Min = 0.16	Min = 9.8 GPa
Max = 0.45	Max = 93.3 Gpa	Max = 0.37	Max = 88.2 Gpa	Max = 0.35	Max = 67.2 Gpa
Std = 0.04	Std = 11.2 GPa	Std = 0.06	Std = 21.2 GPa	Std = 0.04	Std = 12.3 GPa

- Strong correlation observed between GR and FI – suggesting a lithologic control on fracture distribution and a means of predicting FI from GR

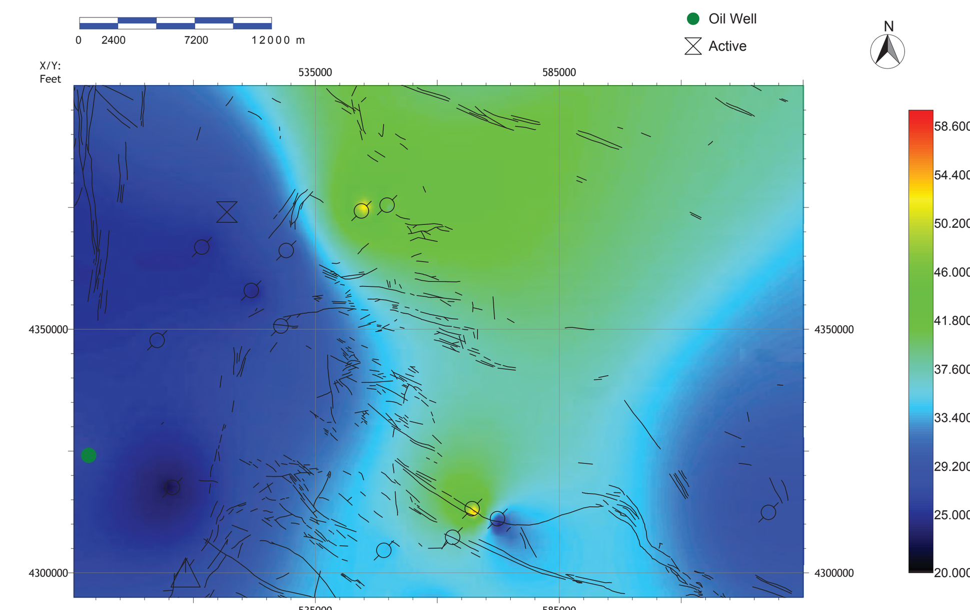




Fracture Index - Unit A - Geometric Mean

Scale = 1:240000

Well Symbol
Outcrop
Plugged & Abandoned
Oil Well
Active



Young's Modulus - Unit A - Geometric Mean

Results

Integration of outcrop and well log data of the Jurassic Carmel Formation shows :

- Fracture orientation changes slightly up section but maintains a NNE orientation
- Fracture intensity decreases with increased bed thickness and shale content
- Strong correlation between Fracture Index and gamma ray values – indicating a lithologic control
- Variability in Fracture Index and Young's Modulus observed from well logs at an injection project scale.

Proof of concept – variability observed in fracture distributions associated with lithologic changes can be identified in outcrop and well logs. Integration of these data types enable quantification of geomechanical properties: this can lead to robust modeling of cap-rock strength prior to and over the life of an injection project.

Remaining Questions

- How does lithologic heterogeneity at the meter scale change local responses to stress?
- How does meter scale fracture variability affect fluid flow through cap-rock lithologies?
- What defines the changes in the observed discontinuity patterns at the bed scale - grainsize distribution, clay content, cement type?
- Is variability observed in Fracture Index and Young's Modulus due to proximity of fault or primary sedimentologic changes?
  Further sub-divide the lithofacies based on mineralogy, grain-size distributions, cement type, percent clay
  Micro-scale fracture analysis
  Fluid inclusions for pressure and temperature of mineralized veins
- Core analysis -
  Fracture intensity and distribution analysis
- Whole rock geochemistry

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