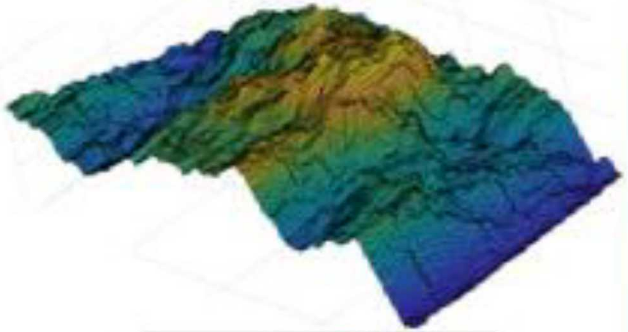
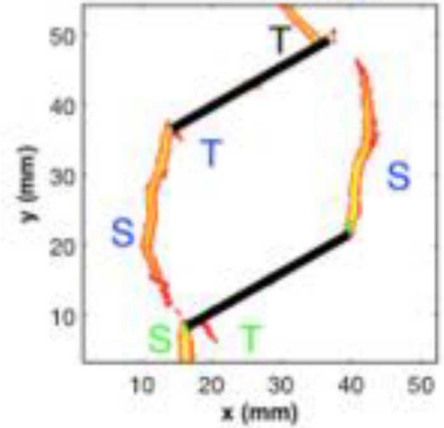
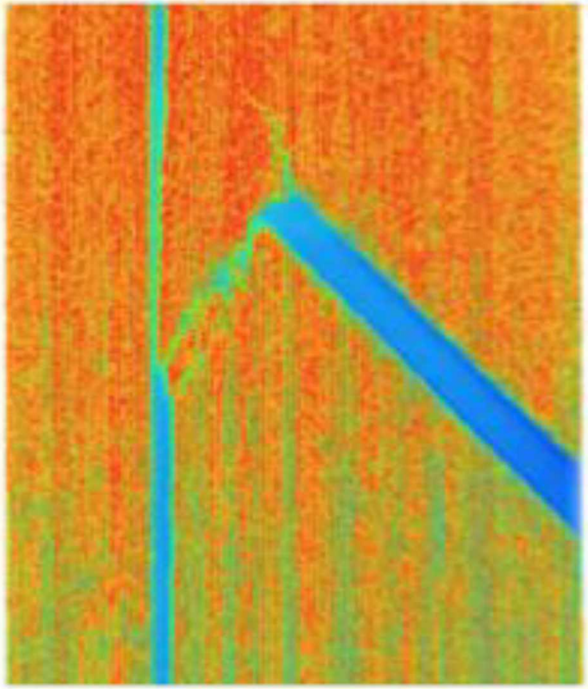
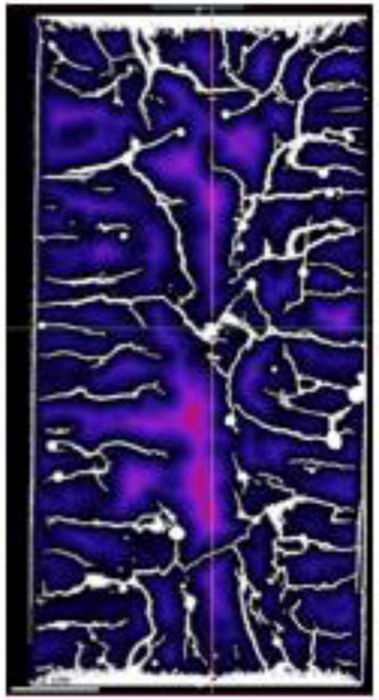
SAND2019-1747C

Damage Mechanics Challenge Workshop
February 20-22, 2019









Purdue University

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Welcome from the Organizing Committee

Laura Pyrak-Nolte

Purdue

Steve WaiChing Sun

Columbia

Hongkyu Yoon

Sandia

Antonio Bobet

Purdue

Thomas Siegmund

Purdue

Workshop Goal

***To gather theorists, computational scientists, and experimentalists to define and launch a numerical challenge to predict damage evolution, fracture geometry and signatures of failure in rock.**

Why Design a Challenge?

***1808 First Class of the Institut de France**

"*Give a mathematical theory verified by experiments of the double refraction which light undergoes in crossing different crystallized substances*"

Outcome: Malus found polarization in reflected light
Malus confirmed Huygen's formula for double refraction based on the wave theory of light
Beginning of the end of corpuscular optics

***1817 Academie des Sciences**

"*to explain the properties of light*"

Outcome: Frensel's theory for diffraction later demonstrated by Arago

***2019 Kaggle**

"*Can you predict laboratory quakes?*"

Outcome: in June

Workshop Approach

***To gather theorists, computational scientists, and experimentalists to define and launch a numerical challenge to predict damage evolution, fracture geometry and signatures of failure in rock.**

(1) have the participants present their computational approach for numerical simulation of damage;

(2) design a challenge problem that will be compared to laboratory experimental data on samples designed through *advanced manufacturing methods* to fail in controlled ways and with increasing complexity;

(3) define *a repeatable and unbiased metrics to quantitatively assess and measure* the quality of the theoretical and data-driven models, given the significant influence of inherent uncertainty and variability on the onset and mode of failures.

Some Questions to Think about ……

*What is the state of the art on computational methods for simulating damage in rock?

* What does each numerical approach provide for predicting or interpreting failure and fracture geometry in rock?

* Are there model parameters that are currently not measured or cannot be measured in the laboratory? What is the minimum required number of parameters?

* Do the models show that there are other experimental measurements that are needed or better ways of performing the measurements to monitor damage and fracture evolution?

* Are there *a repeatable and unbiased metrics to quantitatively assess and measure* the quality of the theoretical and data-driven models?

…… other questions.

Workshop Agenda

Tonight: Overview Presentations

Laura Pyrak-Nolte: Tensile Failure in "Geo-Architected Rock"

WaiChing Sun: Overview of numerical techniques at workshop

Brad Boyce: Lessons from Previous Challenges

Thursday: Invited Presentation on Different Computational Methods

Breakout Groups to Decide/Craft

*1st Challenge

*Data Needed for adequate/robust comparison

*Metrics for comparison

Friday: Refinements/Moving Forward/Writing

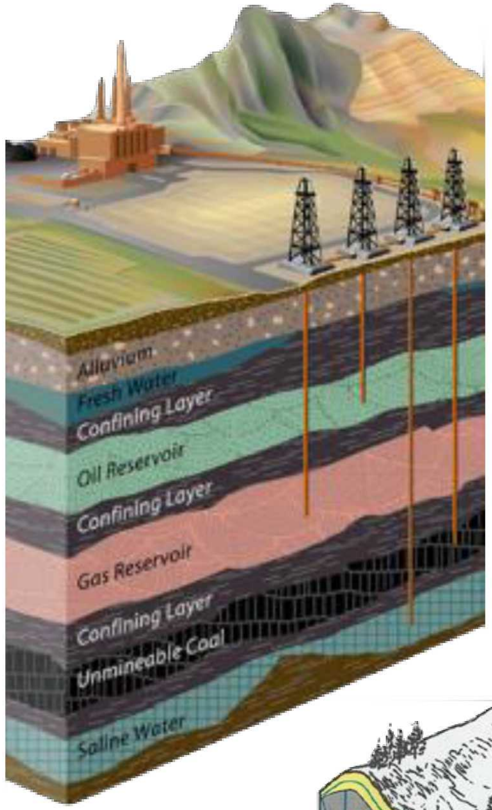
*Breakout Groups to Refine/Decide/Craft/Write

Why Advanced Manufacturing Methods?

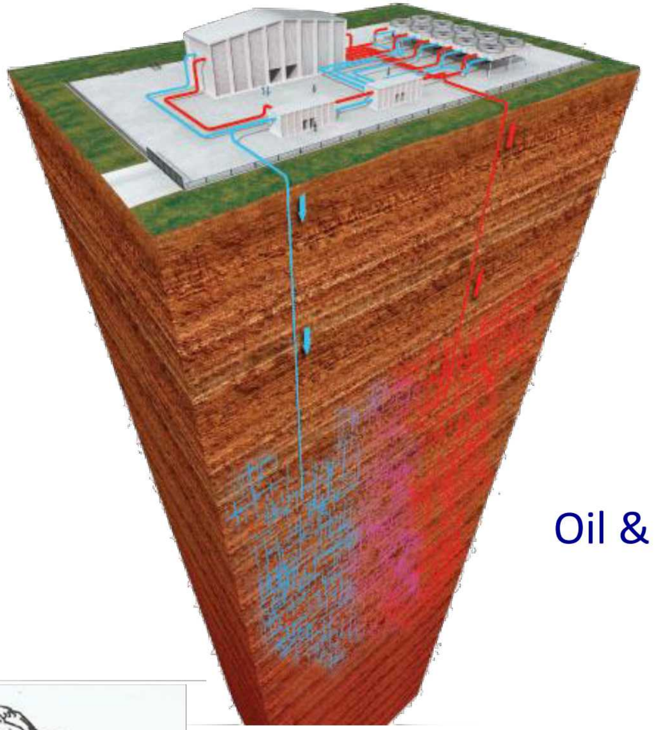
(2) design a challenge problem that will be compared to laboratory experimental data on samples designed through ***advanced manufacturing methods*** to fail in controlled ways and with increasing complexity;

Importance of Understanding Fractures in the Subsurface

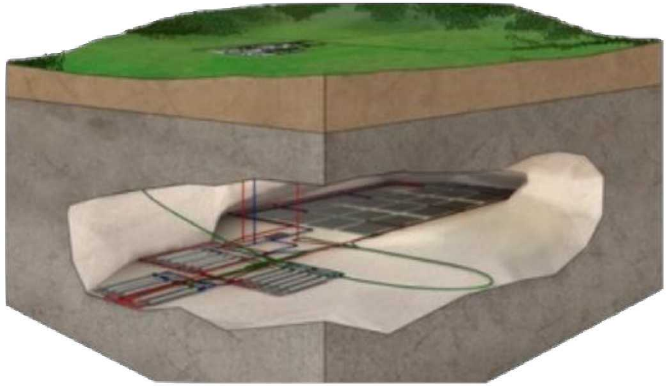
CO_2 Sequestration



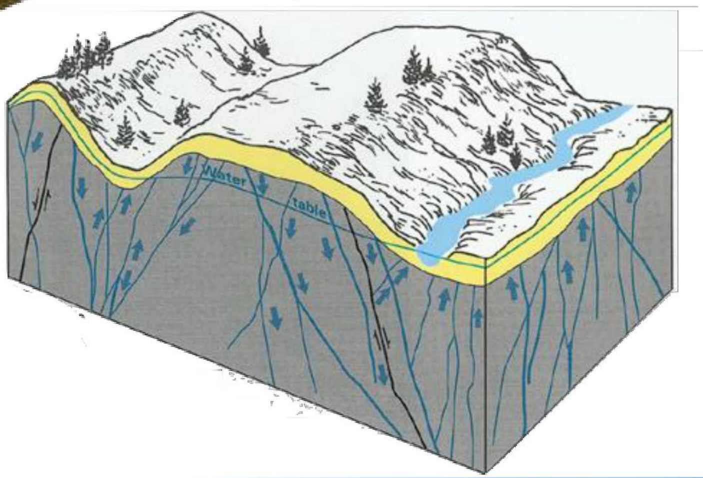
Geothermal Energy



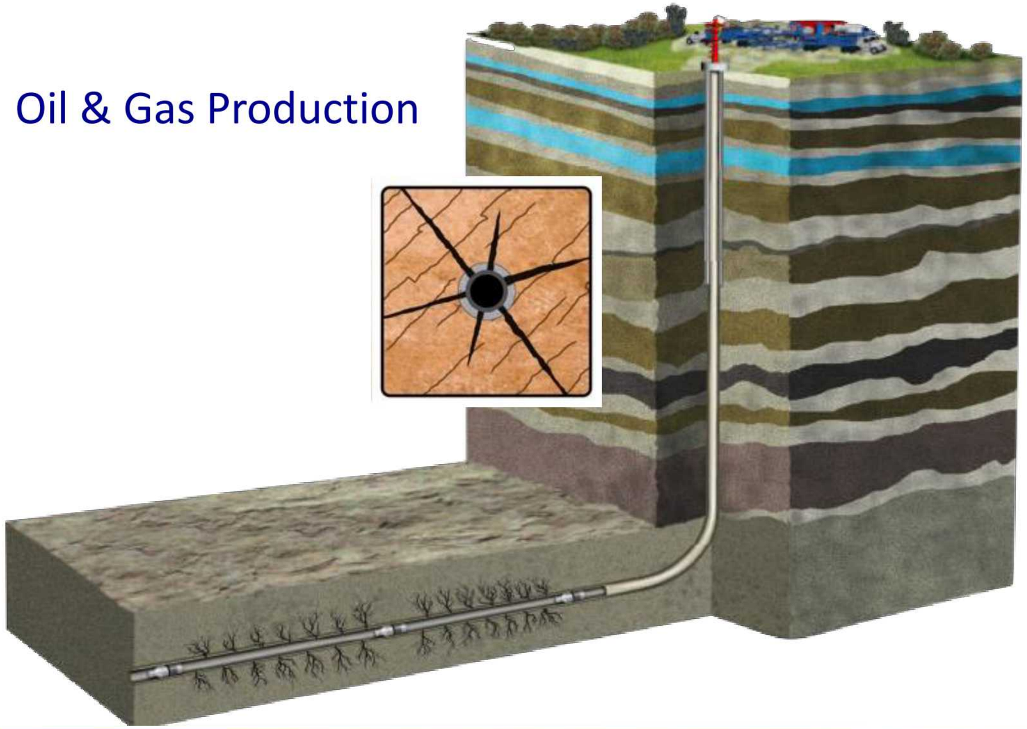
Waste Isolation



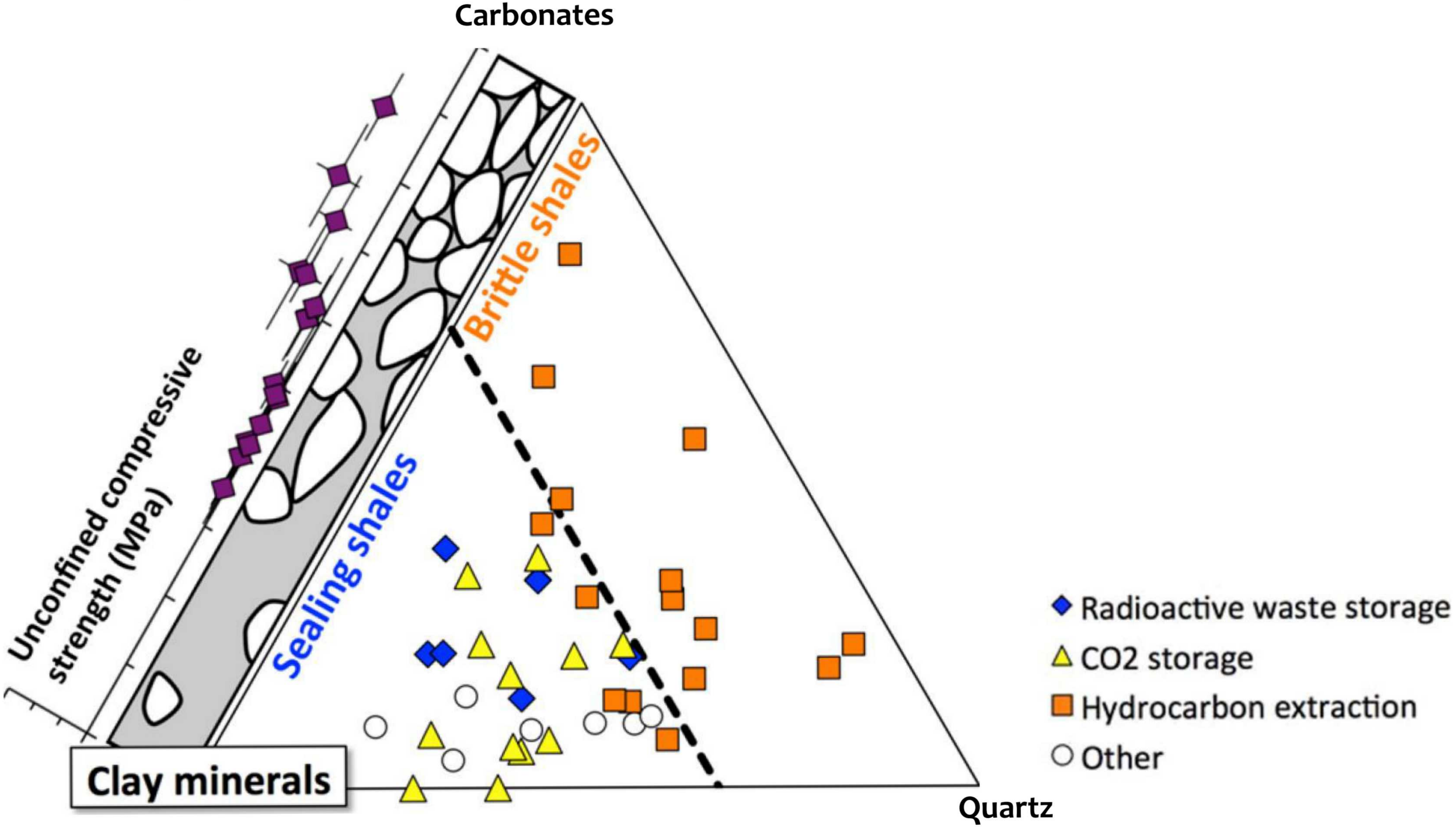
Aquifers



Oil & Gas Production



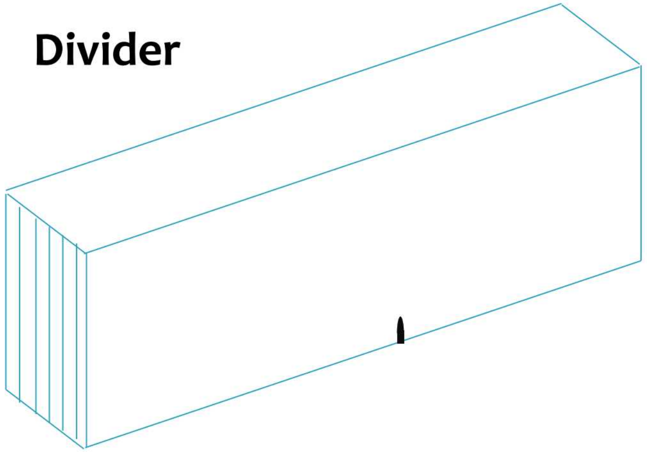
Rock Variability: “Shale”



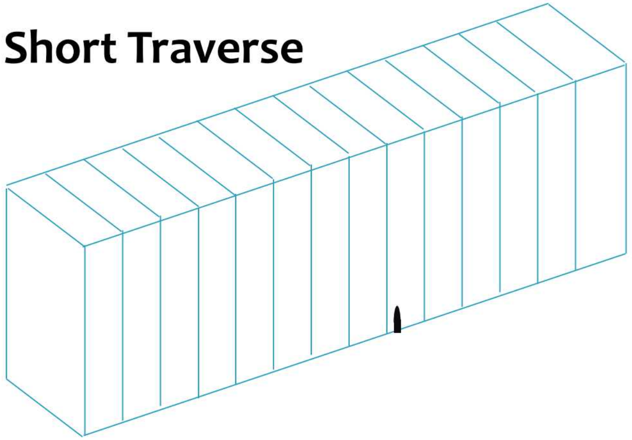
(Bourg et al., 2015)

Observations of Fracture Resistance in Layered Geological Media

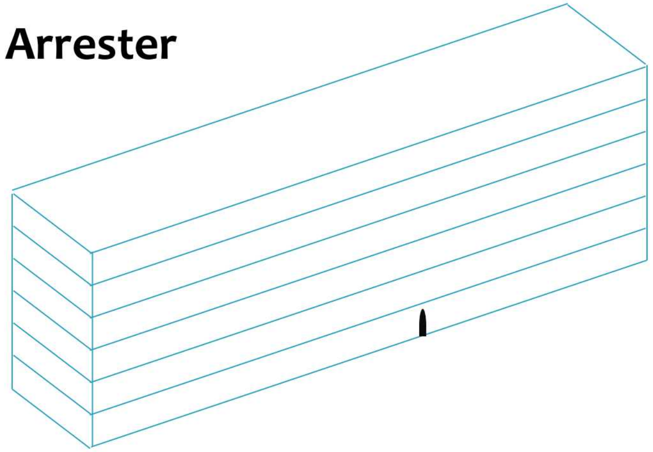
Divider



Short Traverse



Arrester

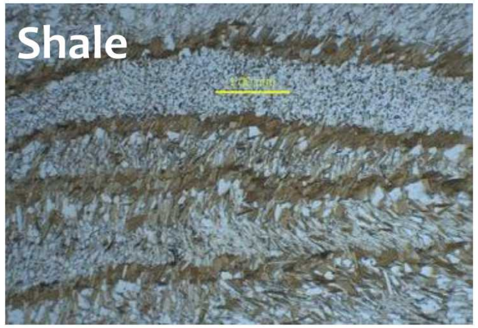


Divider > Arrester > Short Traverse

Divider ~ Arrester or Arrester ~ Short Traverse

Short Traverse < Divider ~ Arrester < Short Traverse

Chandler et al., 2016



Wikipedia

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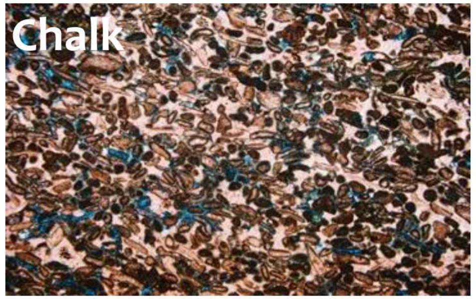


Pyrak-Nolte

Fracture Initiation, Growth & Propagation in 'Geo-Architected' Rock

Collaboration

Laura Pyrak-Nolte

Purdue

Liyang Jiang

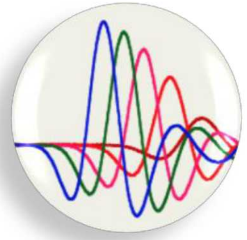
Purdue

Hongkyu Yoon

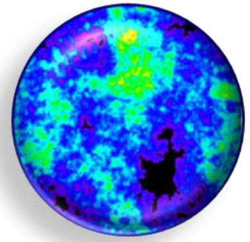
Sandia

Antonio Bobet

Purdue

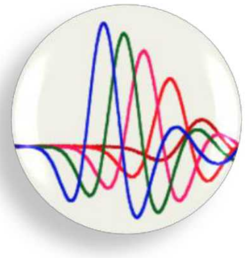


Geo-Architected Rock

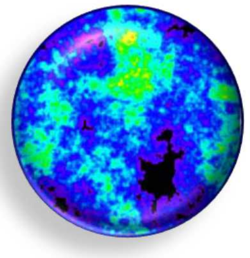


Tensile Failure of Geo-Architected Rock

What is needed for a benchmark data set?



Geo-Architected Rock



Tensile Failure of Geo-Architected Rock

What is needed for a benchmark data set?

Geo-architected Rock

A geo-architected rock is a rock analog that is fabricated and structured using conventional or unconventional methods to develop controlled features in specimens that promote repeatable experimental behavior.

Two Approaches

**Cast Gypsum*

**3D Printed Gypsum*

Geo-architected Rock

A geo-architected rock is a rock analog that is fabricated and structured using conventional or unconventional methods to develop controlled features in specimens that promote repeatable experimental behavior.

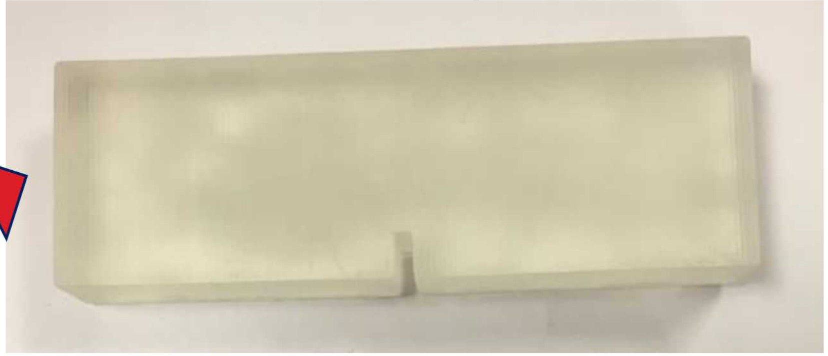
Two Approaches

**Cast Gypsum*

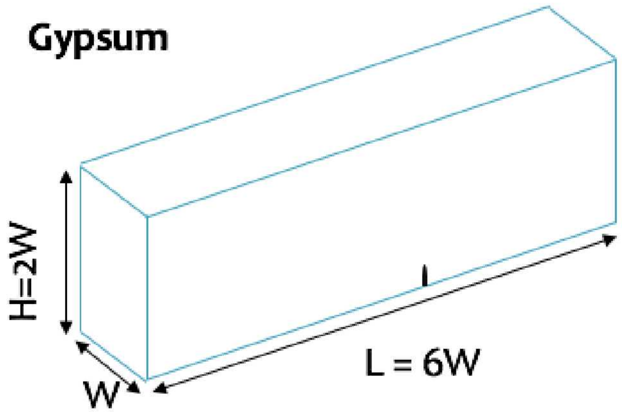
**3D Printed Gypsum*

'Geo-Architected' Rock: Cast Gypsum

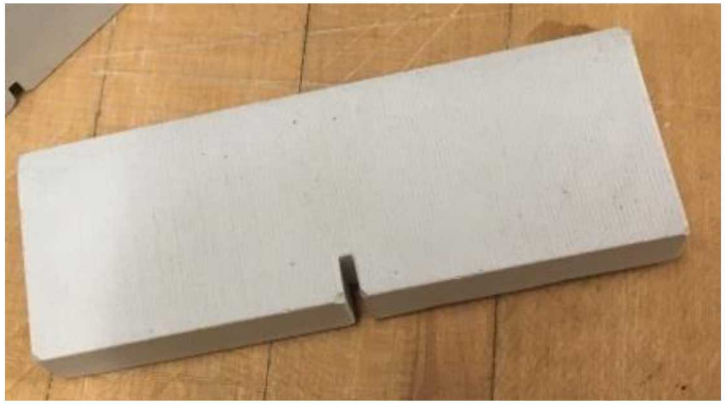
3D Printed PMMA Sample



Teflon Rubber Mold



Cast Gypsum



W = 12.7 mm
H = 25.4 mm
L = 76.2 mm

Notch Height = 0.4 W = 5.08 mm
Notch Width = 0.1 W = 1.27 mm
Notch Locations from Left End = 0.5 L = 38.1 mm

Geo-architected Rock

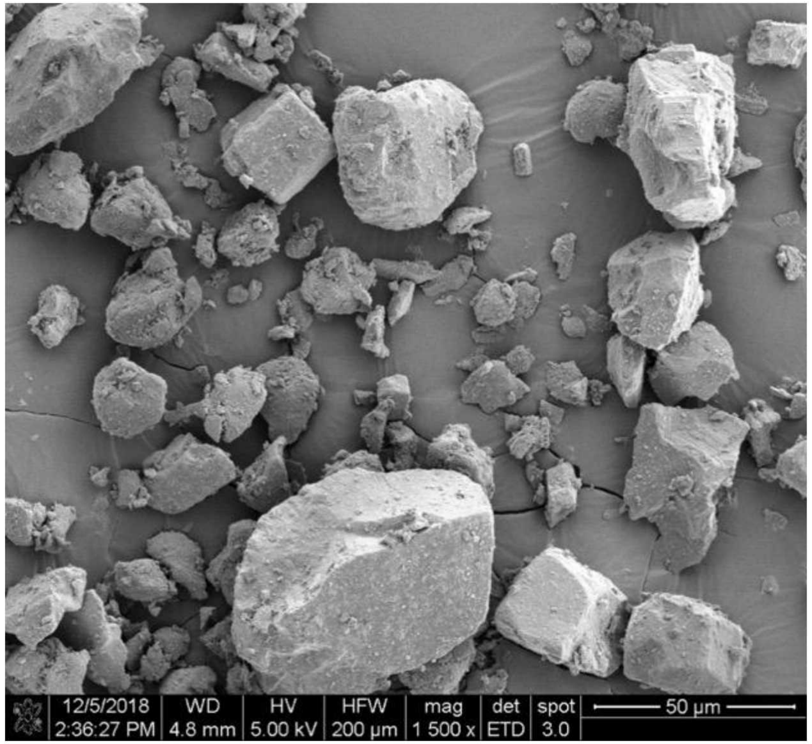
A geo-architected rock is a rock analog that is fabricated and structured using conventional or unconventional methods to develop controlled features in specimens that promote repeatable experimental behavior.

Two Approaches

**Cast Gypsum*

**3D Printed Gypsum*

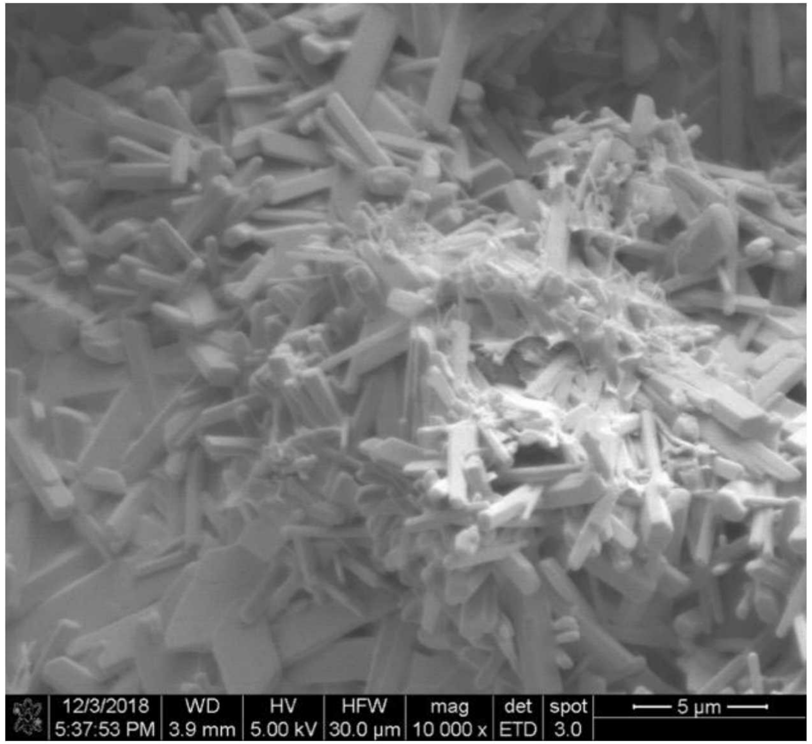
Geo-Architected Rock: Components of 3D Printed Rock



Bassanite powder

$2Ca_2SO_4 \bullet H_2O$

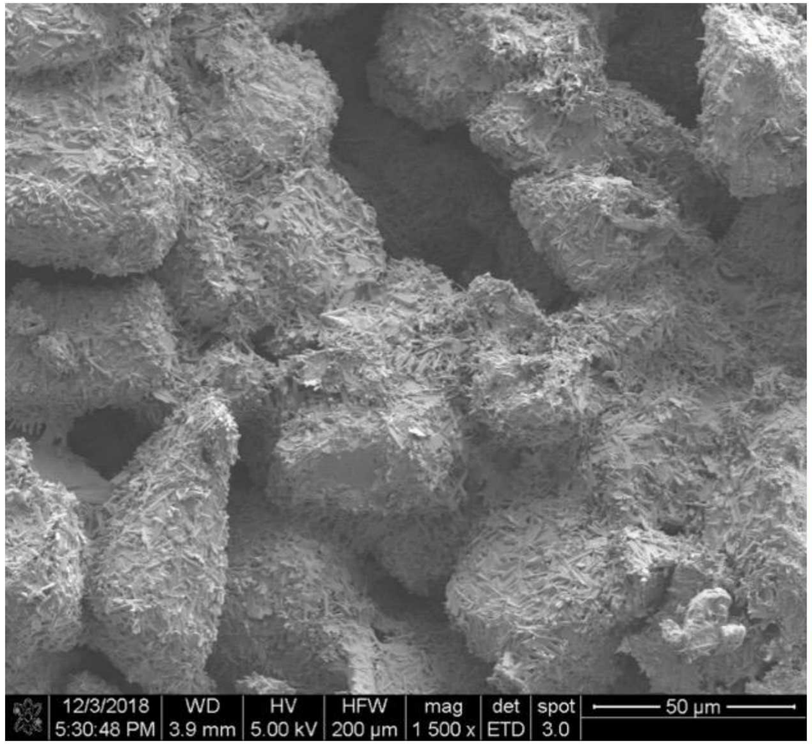
(Calcium Sulfate Hemihydrate)



Gypsum crystals form when binder is applied.

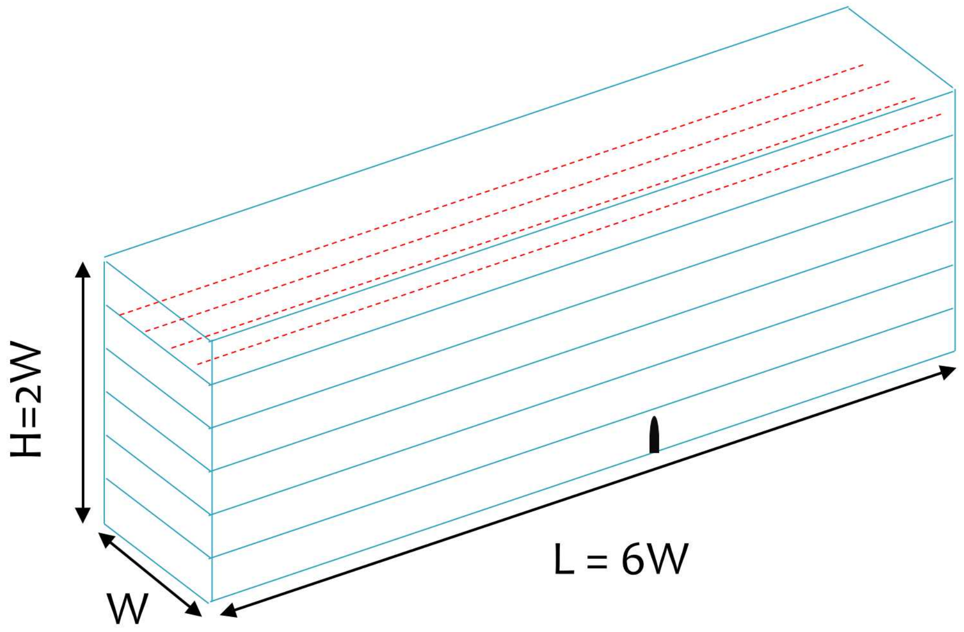
$CaSO_4 \bullet 2H_2O$

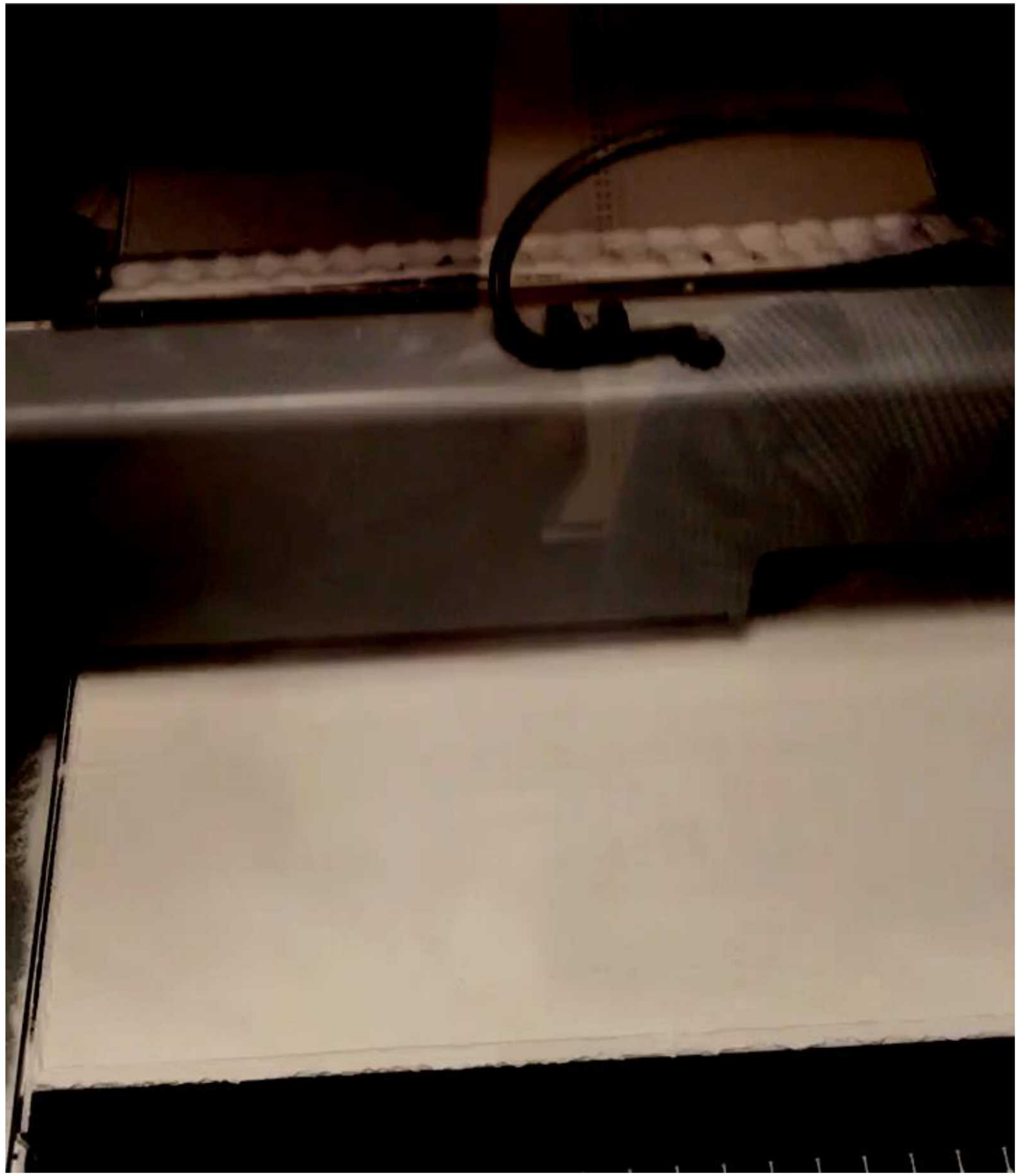
(Calcium Sulfate Dihydrate)



Gypsum crystals bond bassanite grains.

Geo-Architected Rock: 3D Printed Rock



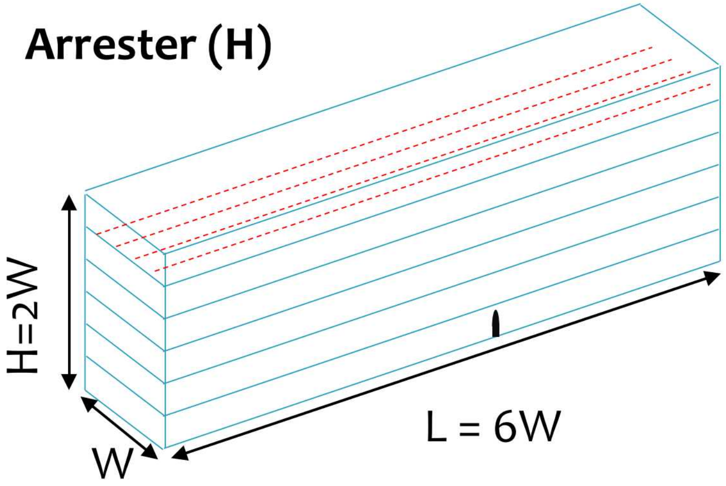


Red lines indicate binder printing direction.
Blue lines layer orientation. Layer thickness ~ 100 microns

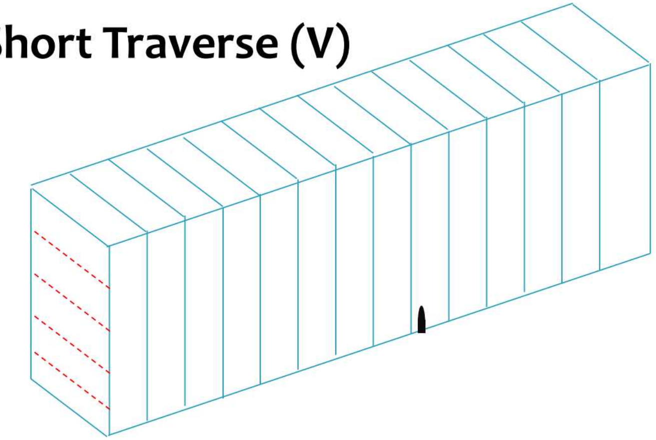
W = 12.7 mm	Notch Width = 0.1 V = 1.27 mm
H = 25.4 mm	Notch Height = 0.4 W = 5.08 mm
L = 76.2 mm	Notch Locations from Left End = 0.5 L = 38.1 mm

Geo-Architected Rock: 3D Printed Gypsum

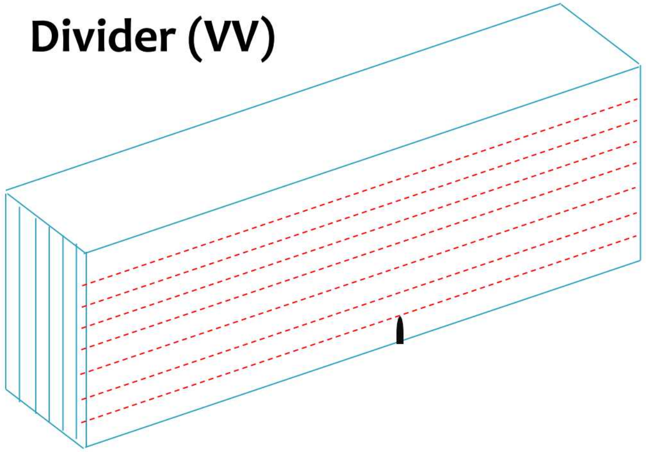
Arrester (H)



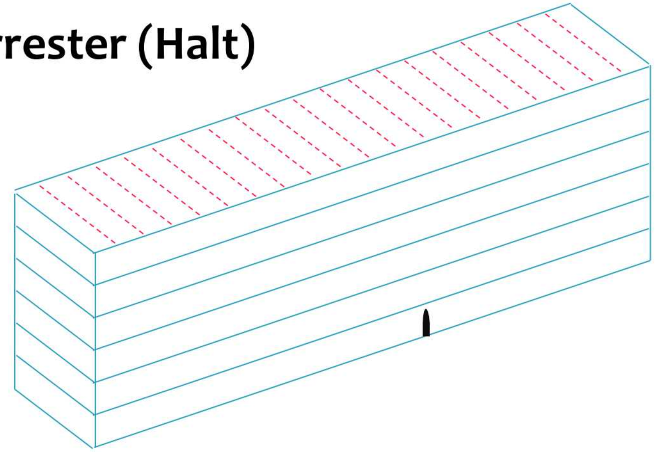
Short Traverse (V)



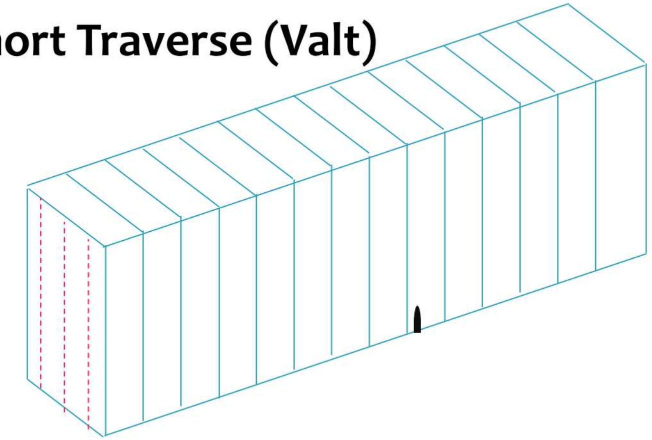
Divider (VV)



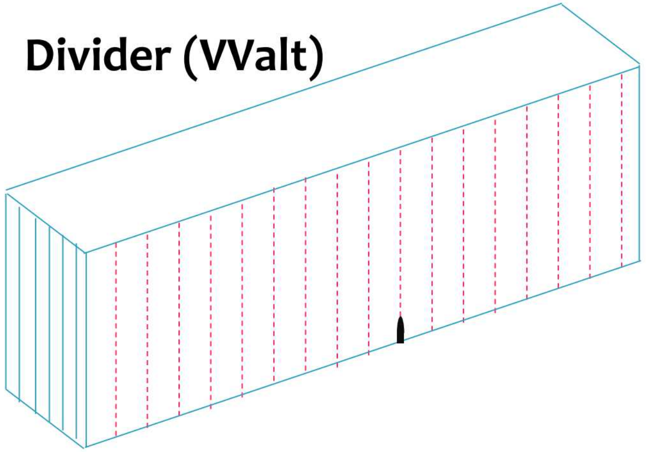
Arrester (Halt)



Short Traverse (Valt)



Divider (VValt)



Geo-Architected Rock

**Material Properties*

**Unconfined Compressive Stress Test*

**Ultrasonic Compressional & Shear Wave Measurements*

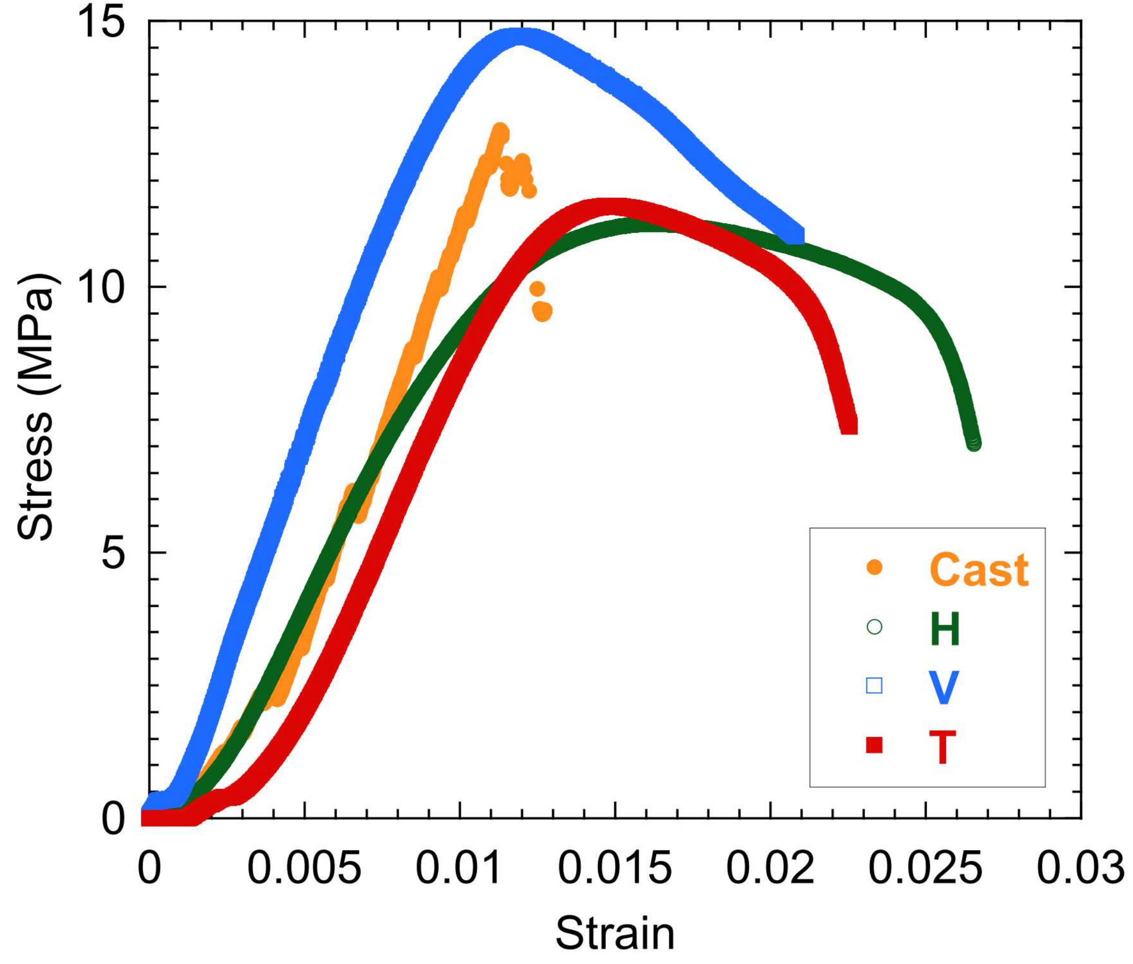
Geo-Architected Rock

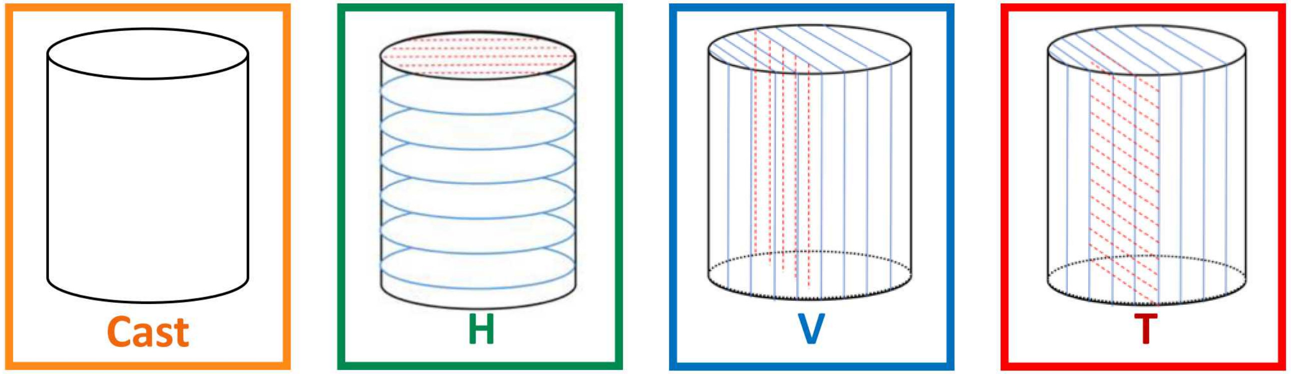
**Material Properties*

**Unconfined Compressive Stress Test*

**Ultrasonic Compressional & Shear Wave Measurements*

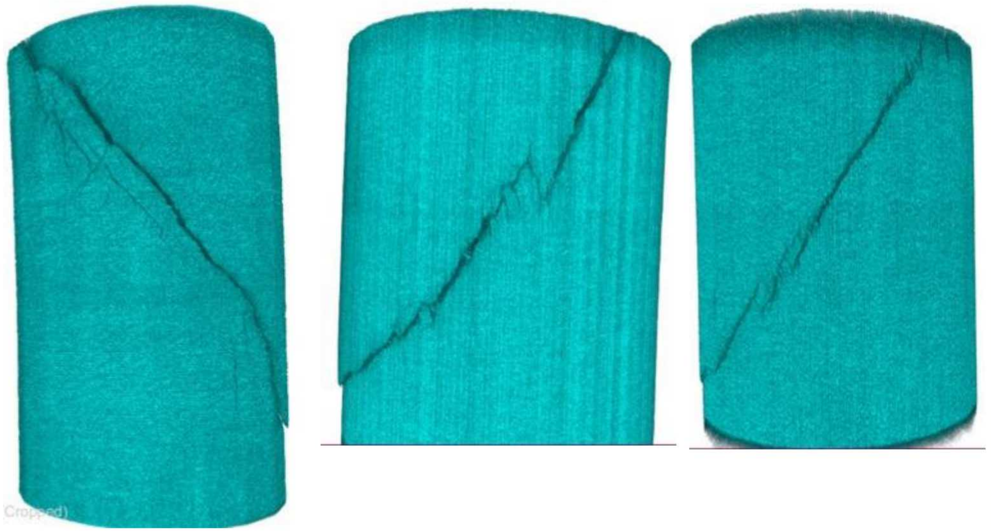
Material Properties: Unconfined Compressive Tests



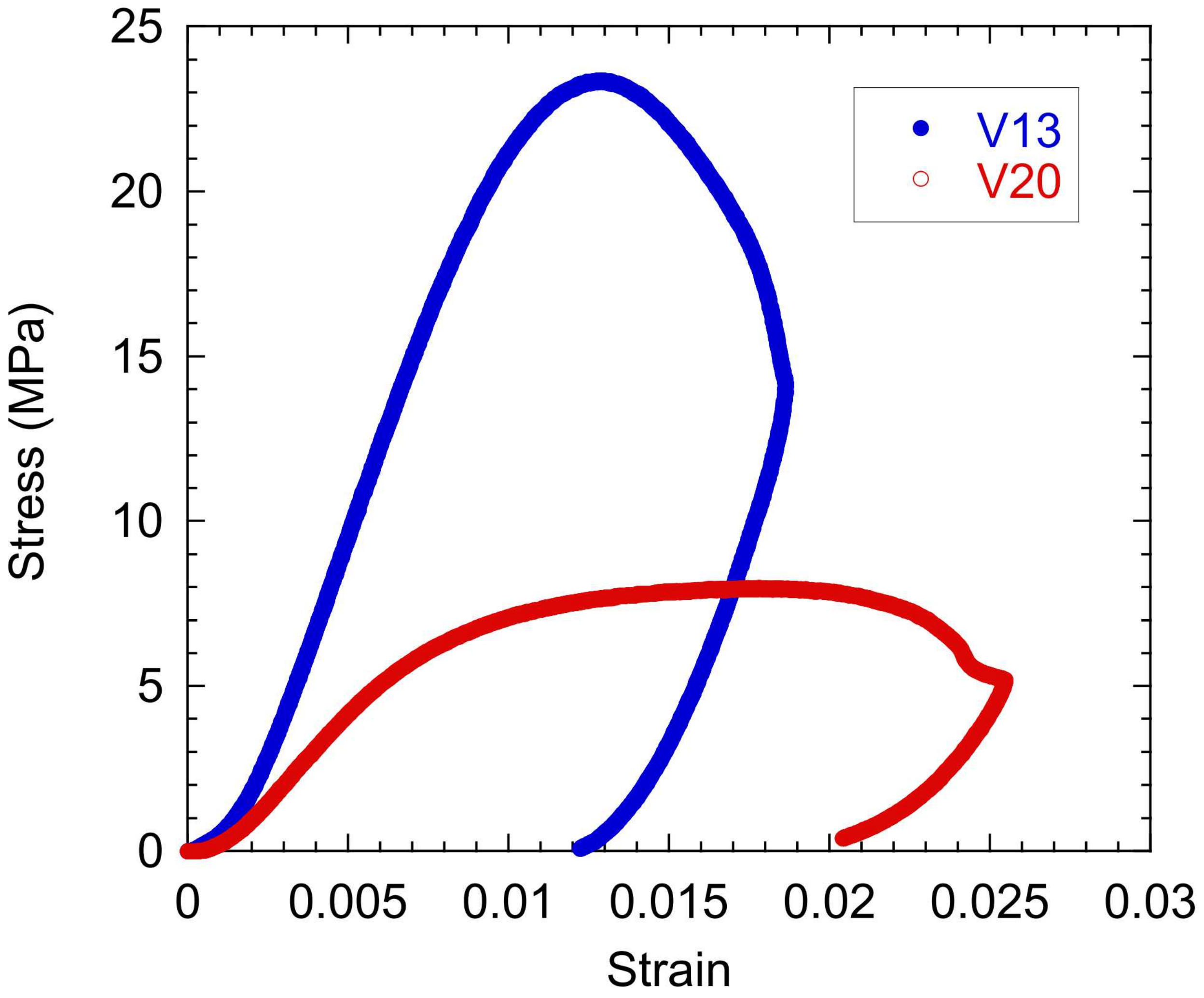


Photo

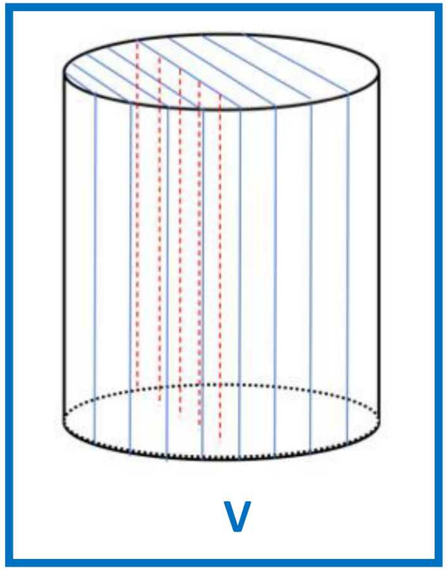
X-ray Tomographic Reconstructions

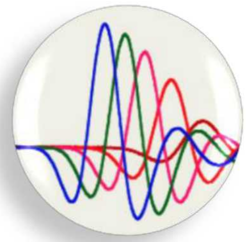


Material Properties: Uniaxial Compression Test

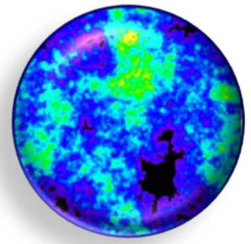


Components	V13	V20
Bassanite $2Ca_2SO_4 \bullet H_2O$	48.2	77.3
Gypsum $CaSO_4 \bullet 2H_2O$	51.8	22.7





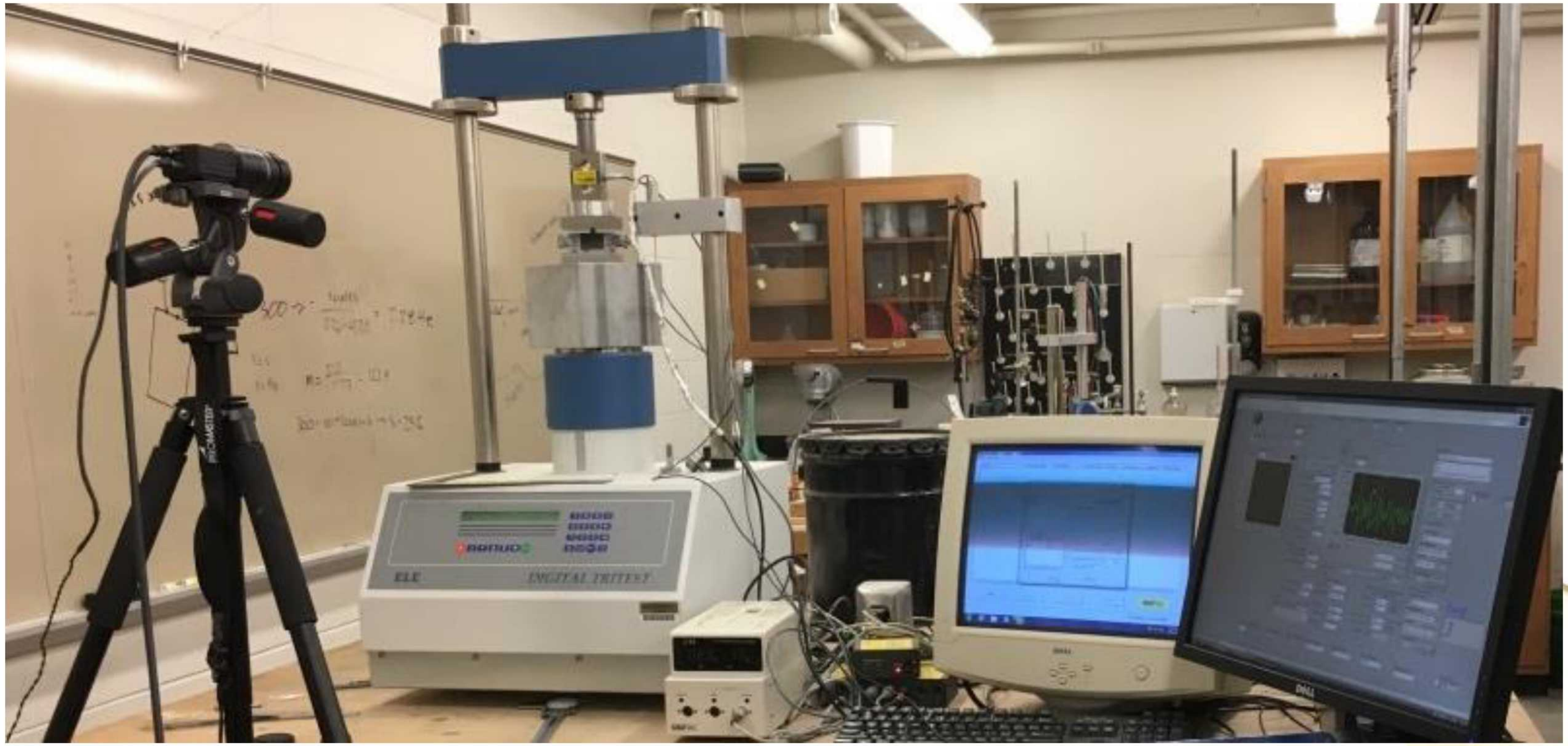
Geo-Architected Rock



Tensile Failure of Geo-Architected Rock

What do we need?

Three Point Bending Experiments: Tensile Crack Growth



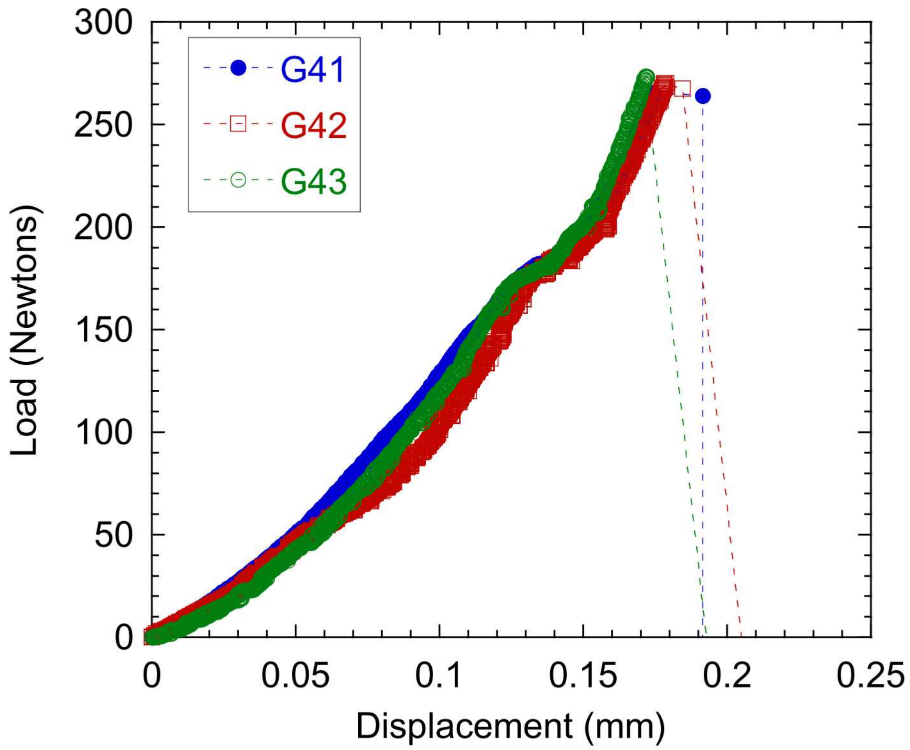
Digital Image Correlation (resolution 3.54 *um*)

Ultrasonic compressional and/or shear seismic waves
(1*MHz* central frequency, 5 *Hz* recording rate)

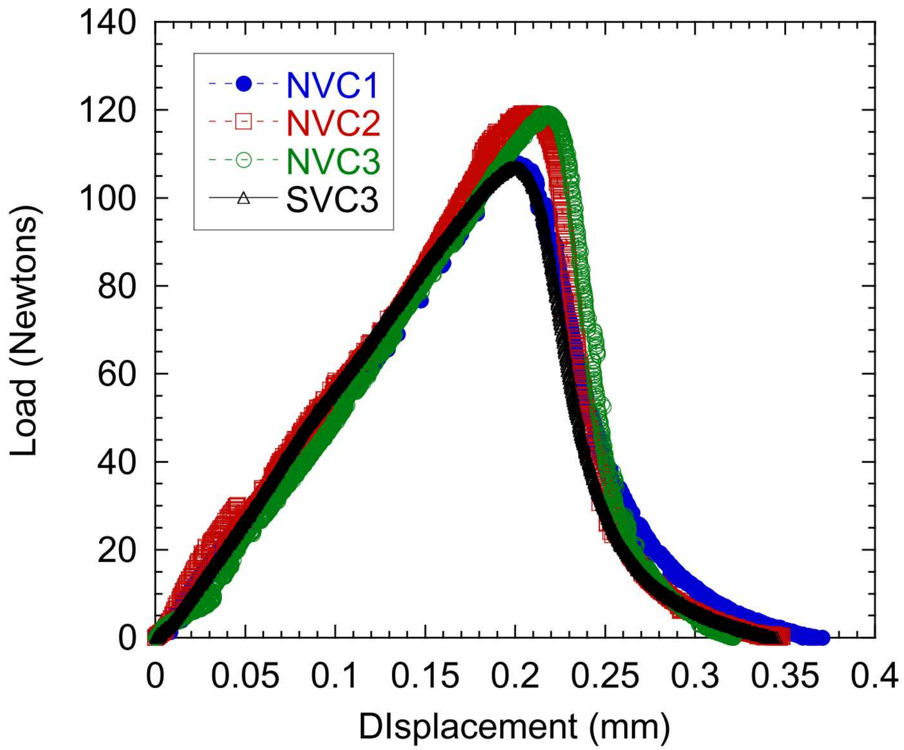
Displacement & Load
(recording rate: 0.03 mm/min at 5 *Hz, 0.5 mm/min at 10 Hz*)

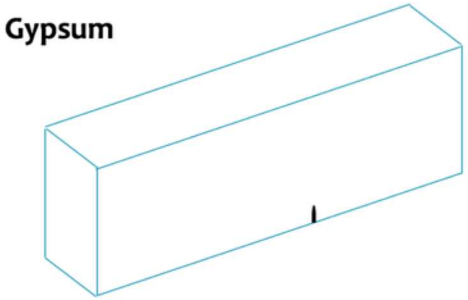
Three Point Bending Experiments: Repeatability

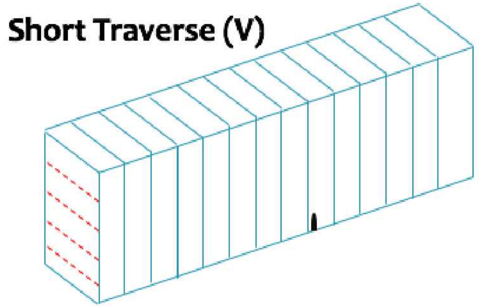
Cast Gypsum



3D Printed Rock







Summary

**Failure load is also dominated by mineral texture orientation.*

**3D Printed still have variability but less than natural samples*

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