Correlations between a mudstone heterogeneity index and micromechanical properties in the Lower Mancos Shale

THE UNIVERSITY OF UTAH

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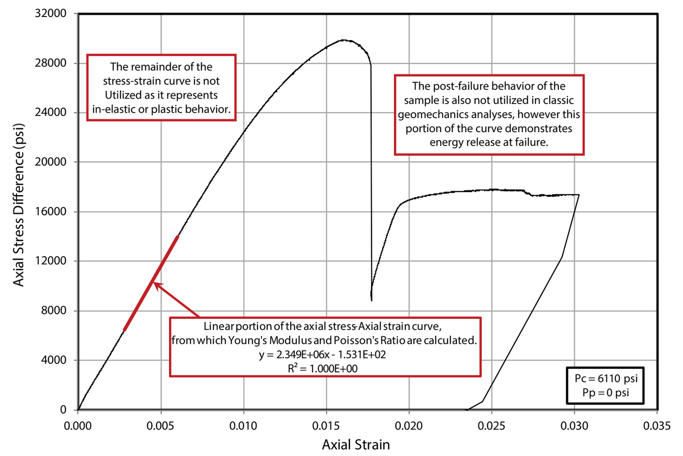
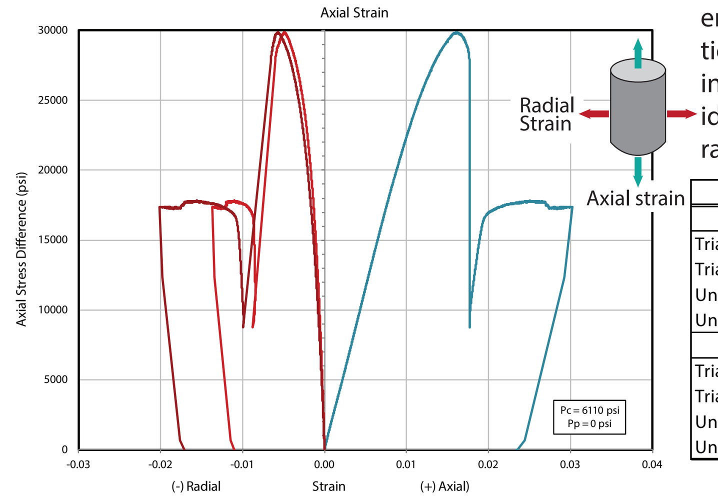
Geomechanics Background and Methodology

Classical Geomechanics Background

The linear portion of the stress-strain curve from compression testing represents elastic behavior and is used to calculate two commonly used elastic moduli: Young's Modulus, E, and Poisson's ratio, v. Results of E and v from TXC and UCS tests from the RGU and MCF cores are graphed below.

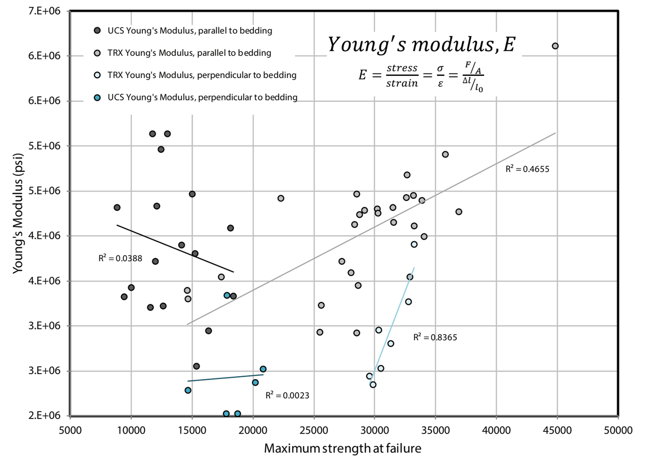


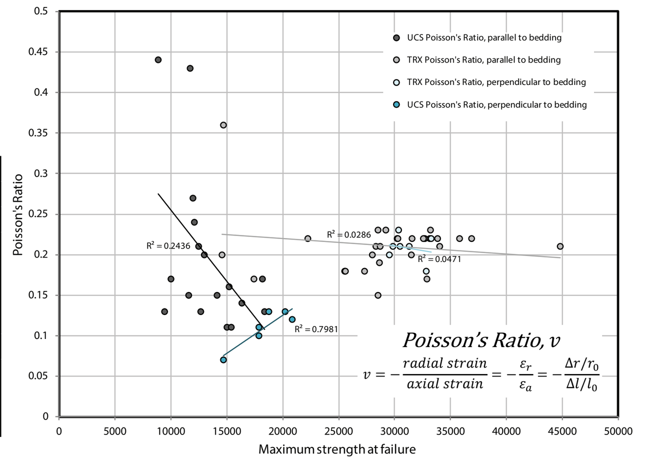


Relationships between max strength and elastic moduli from these tests are not always predictive (see table below).

Rocks behave as quasi-elastic brittle solids, meaning that they deform both elastically and plastically, as evidenced by the linear and non-linear portions of the axial stress-axial strain curves. Thus, damage threshold values identified along the entire curve, from crack initiation to post-failure, are examined herein in an attempt to identify predictive strength parameters.

Test	Orientation	R^2
Young's Modulus		
Triaxial (TRX)	Perpendicular	0.8365
Triaxial (TRX)	Parallel	0.4655
Uniaxial (UCS)	Parallel	0.0388
Uniaxial (UCS)	Perpendicular	0.0023
Poisson's Ratio		
Triaxial (TRX)	Perpendicular	0.0471
Triaxial (TRX)	Parallel	0.0286
Uniaxial (UCS)	Parallel	0.2436
Uniaxial (UCS)	Perpendicular	0.7981





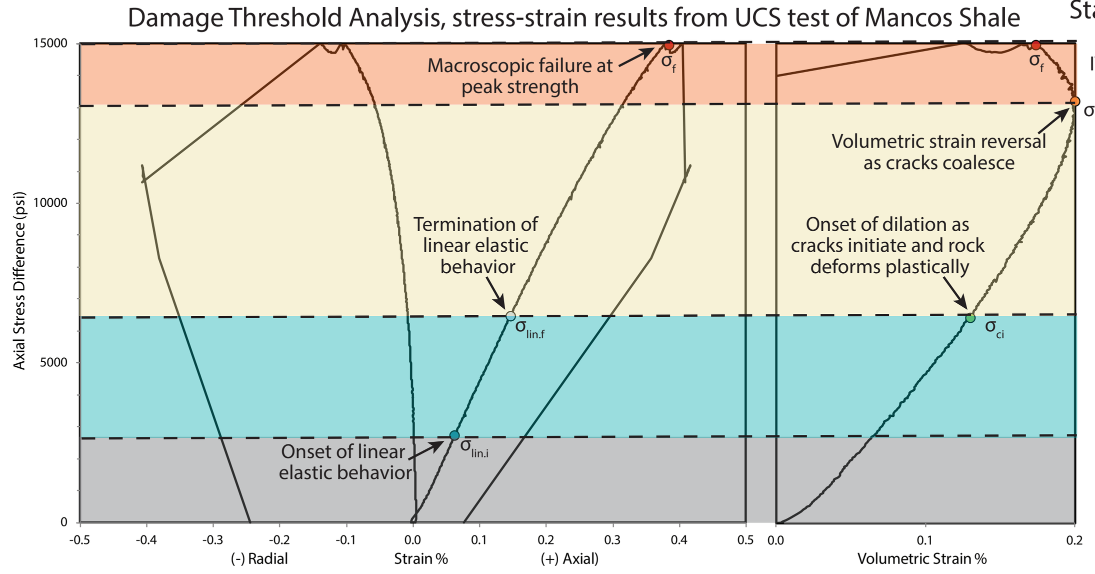
Damage Threshold Background and Methodology

Micro-structural features govern the location of crack tips during fracturing. Thus, micro-scale sedimentary heterogeneity is hypothesized to control fracture zone development (4-6). Throughout fracture zone development, damage threshold parameters along the stress-strain curve identify nucleation, propagation, and coalescence of micro-cracks (7-8). Damage thresholds were calculated using the methodologies described below.

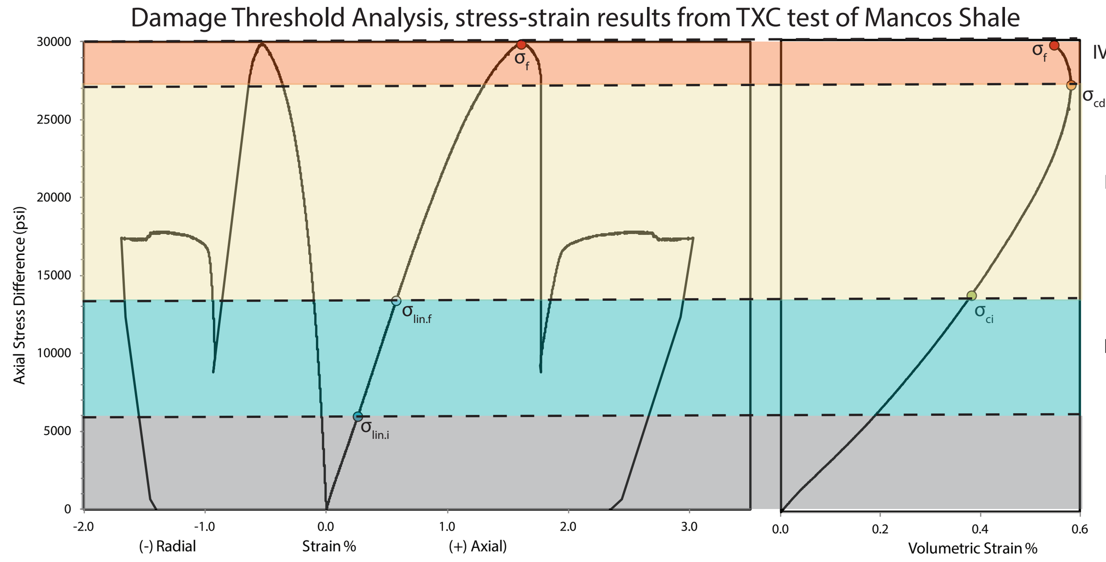
Crack Threshold	Methodology of calculation
Linear Elastic Initiation, $\sigma_{lin.i}$	Determined as the minimum stress value on the axial stress-axial strain curve, where R^2 ~1
Linear Elastic Termination, $\sigma_{lin.f}$	Determined as the maximum stress value on the axial stress-axial strain curve, where R^2 ~1
Crack Initiation, σ_{ci}	Determined as the maximum stress value of linearity on the volumetric strain-axial stress curve, where R^2 ~1
Crack Damage, σ_{cd}	Determined as the inflection point on the volumetric strain-axial stress curve
Peak Strength, σ_f	Determined as the maximum stress value on the axial stress-axial strain curve

Damage threshold analysis was carried out on stress-strain results from 23 UCS tests. This preliminary analysis was completed on the MCF and RGU cores from the Uinta Basin, and the successful methods proposed herein will be utilized on plugs from the Lindrith, Lindisfarne, and FGF cores.

Damage Threshold Analysis, stress-strain results from UCS test of Mancos Shale



Damage Threshold Analysis, stress-strain results from TXC test of Mancos Shale



Samples utilized in this analysis:

Well ID	Sample No.	Orientation	Facies	Peak Strength
MCF 1-7	1	parallel	6.2	8788.23
MCF 3-7	2	parallel	4.2	12438.32
MCF4-6	3	parallel	4.2	12904.88
MCF 5-10	4	parallel	4.2	11673.10
MCF 6-3	5	parallel	6.3	18342.72
MCF 6-5	6	parallel	6.3	14955.47
MCF 7-6	7	parallel	3.3	12071.59
MCF 8-6	8	parallel	3.2	11952.32
RG 1-1	9	parallel	6.2	9956.89
RG 2-1	10	parallel	6.2	14097.06
RG 3-4	11	parallel	3.3	12611.31
RG 4-7	12	parallel	6.2	15191.06
RG 5-1	13	parallel	6.2	9397.78
RG5-5	14	parallel	6.2	11573.71
RG 6-6	15	parallel	3.2	16316.74
RG 7-1	16	parallel	6.2	18141.45
RGU 8-1	17	parallel	3.3	15338.28
MCF 1-1	18	perpendicular	6.2	17820.06
MCF 3-1	19	perpendicular	4.2	18751.31
MCF 4-1	20	perpendicular	4.2	20147.30
MCF 5-1	21	perpendicular	4.2	20787.84
MCF 7-3	22	perpendicular	3.3	17862.24
MCF 8-2	23	perpendicular	3.2	14643.51

6. admixed siliceous muddy v.f. sandstone — 4. discontinuous wavy laminated sandy mudstone — 3. continuous, curvy-laminated sandy mudstone

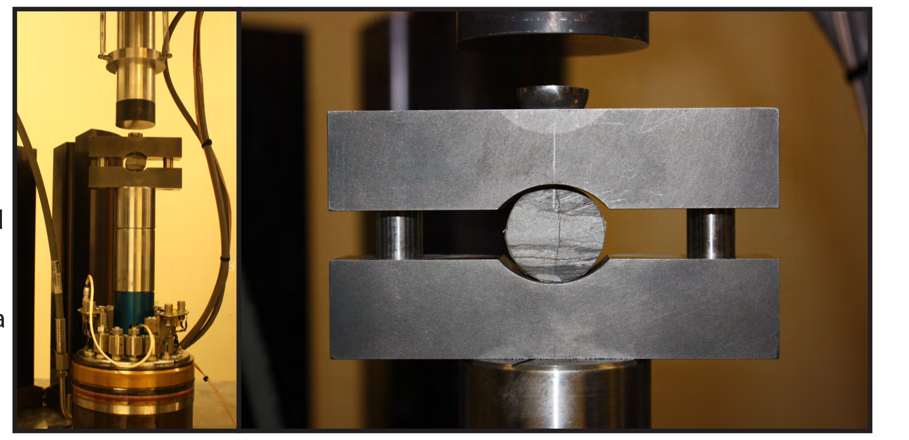
Post UCS-test plugs from MCF and RGU

Indirect Tensile Testing Background and Methodology

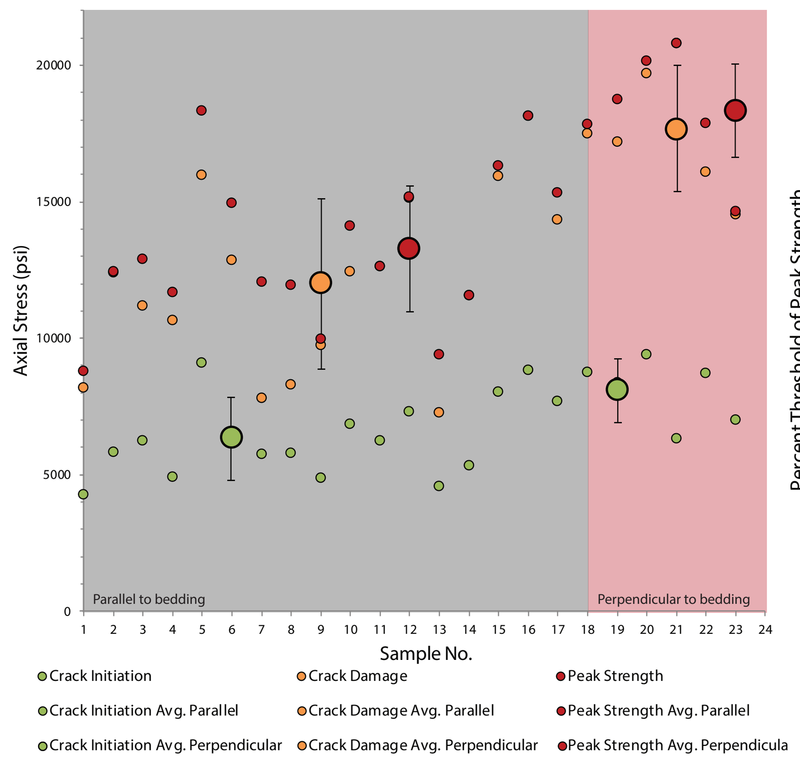
Indirect tensile testing was carried out on 126 disks from three cores of the Lower Mancos Shale. At least ten samples per facies (see stratigraphic columns on right hand panel) were chosen for analysis. 59 samples were wax-preserved directly from the wellbore of the Lindisfarne core, remained preserved until sample prep, and were re-preserved until each analysis was carried out.

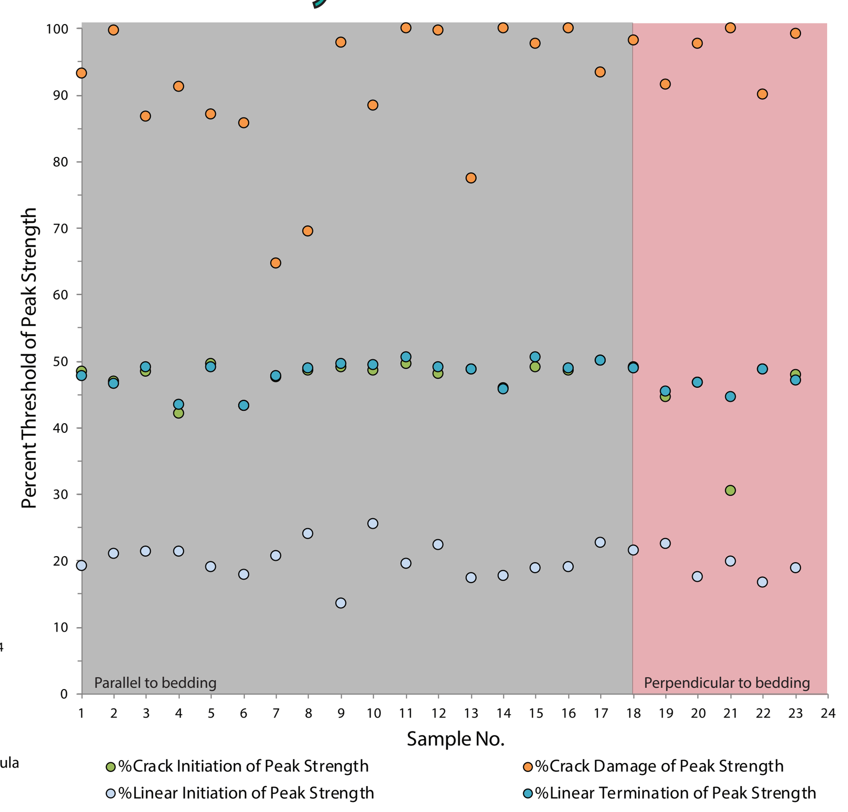
Analysis was completed according to ISRM Guidelines using a fixture machined to fit the triaxial unit at EGI at the Univesity of Utah with the following methodology:

- Samples were prepared at 1" diameter and 0.5" thickness
- CT scans were carried out in order to eliminate samples with extensive pre-existing flaws
- Mass, diameter, and width were recorded and density was calculated
- Each sample was marked where the point load would be placed
- Each sample was wrapped in 0.5" wide paper tape, per ISRM
- Each sample was loaded at a rate of $1x10^{-5}$ in/sec and force-time data were collected at 10 Hz until failure
- For each depth range, at least one parallel and one perpendicular to bedding sample was analyzed

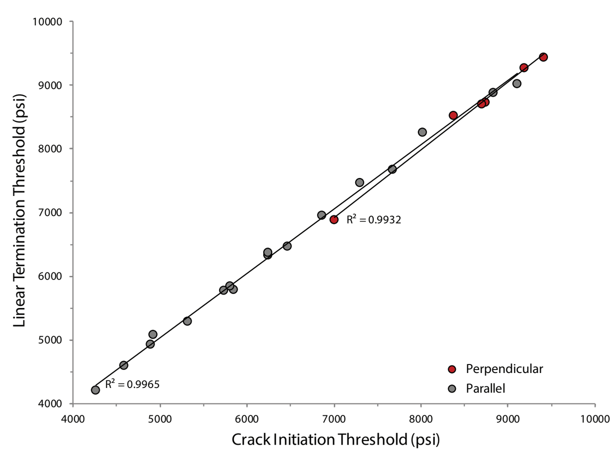


Damage Threshold Analysis

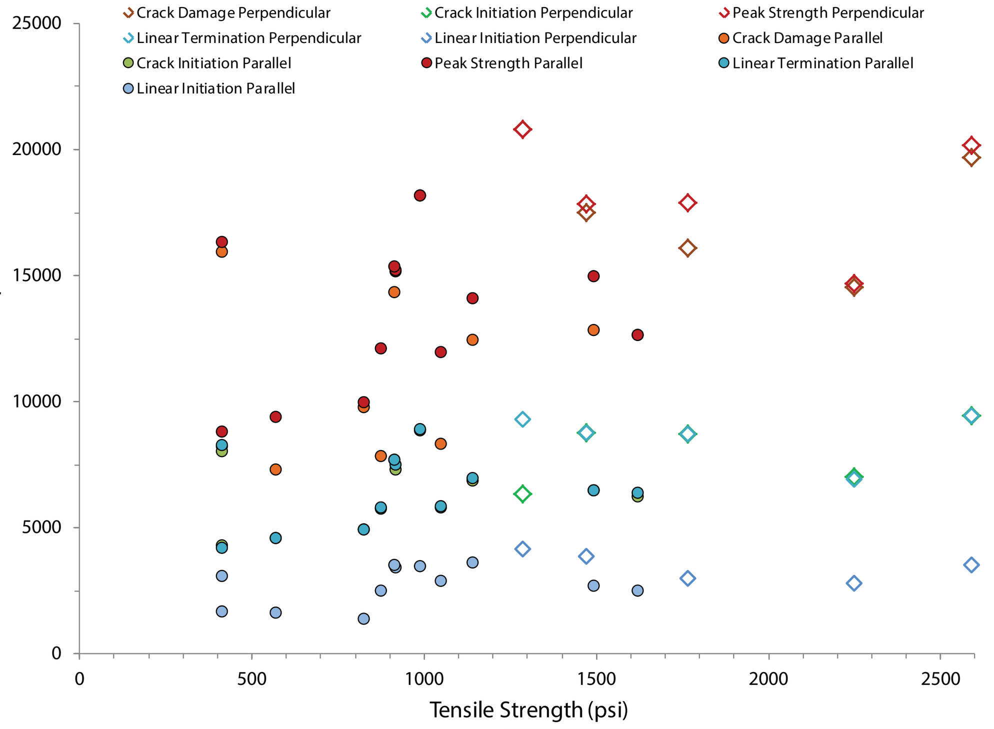




- Perpendicular to bedding samples have higher stress thresholds than those parallel to bedding.
- Crack initiation values successfully calculated: avg peak strength of parallel samples = 46%, perpendicular samples = 48%
- Crack damage values successfully calculated: avg peak strength of parallel samples = 90%, perpendicular samples = 96%
- Several crack damage values were equal to peak strength values, indicating very little stress accumulation between crack coalescence and macroscopic failure at peak strength.



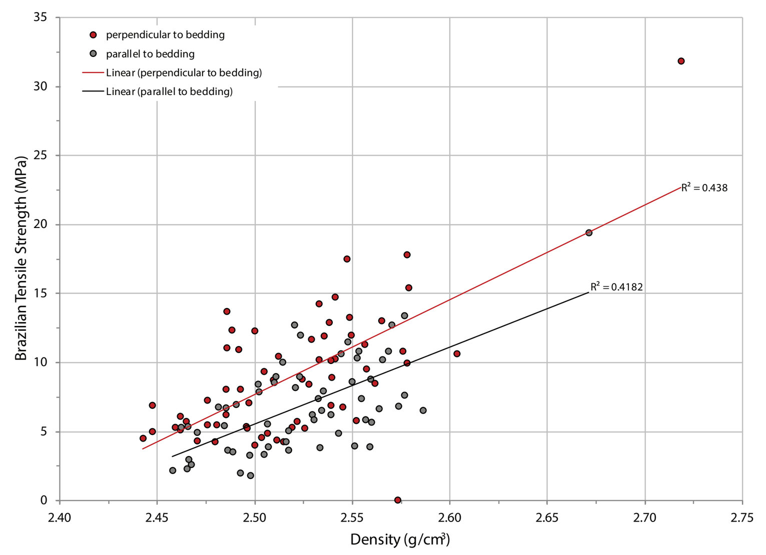
- Crack initiation and linear termination values fall within a maximum of 1.5 percent difference of one another, indicating that the onset of non-linear behavior on the axial stress-axial strain curve could be utilized to approximate crack initiation.

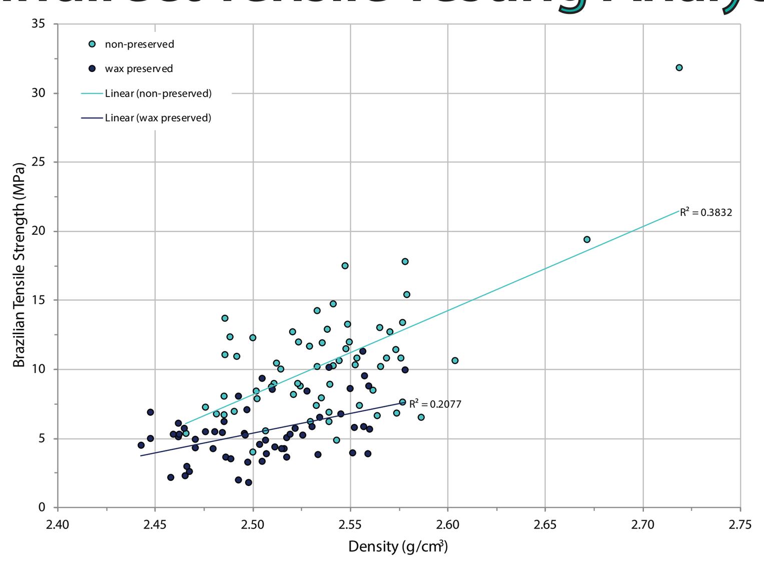


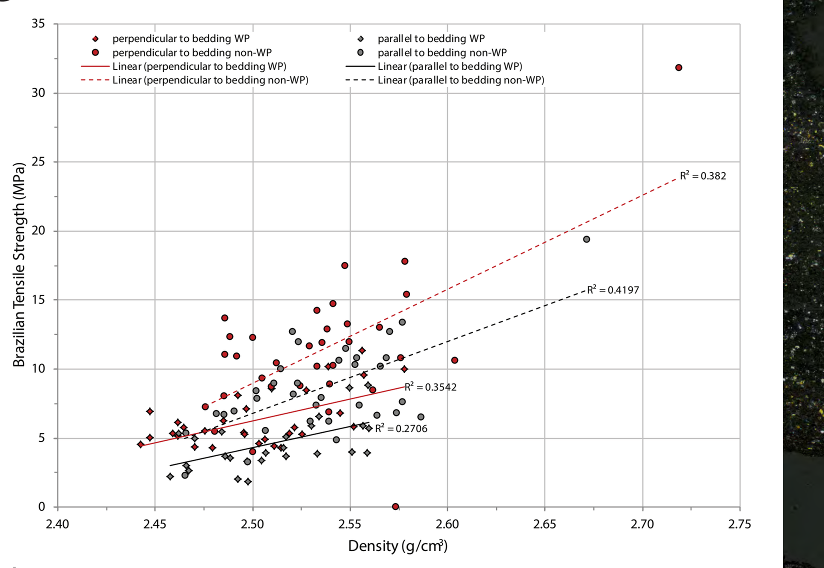
- Tensile strength has been correlated with the crack initiation threshold based on the hypothesis that crack initiation is a result of tensile stress concentration at a discontinuity or heterogeneity (9).
- However, no predictable relationship has been determined between threshold parameters and the tensile strength of mudstone samples in this study (see plot above right and table at right).
- These methods will be repeated on the samples from the remaining three cores once UCS tests corresponding to the indirect tensile test results reported herein have been completed.

Threshold Parameter	Parallel	Perpendicular
	R2	
Peak Strength	0.0749	0.0594
Crack Damage	0.0395	0.0584
Linear Termination	0.0397	0.0522
Crack Initiation	0.0412	0.1942
Linear Initiation	0.0829	0.3361

Indirect Tensile Testing Analysis







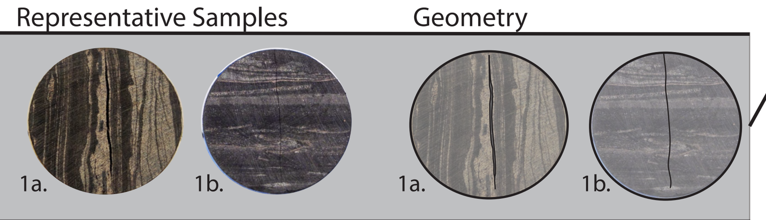
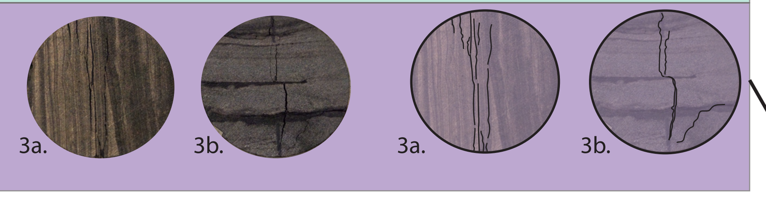
- Samples tested parallel to bedding fail at lower tensile strength values (avg=6.94 MPa, range=1.84 - 19.41 MPa) than those tested perpendicular to bedding (avg=9.01, range=4.08 - 30.89 MPa)

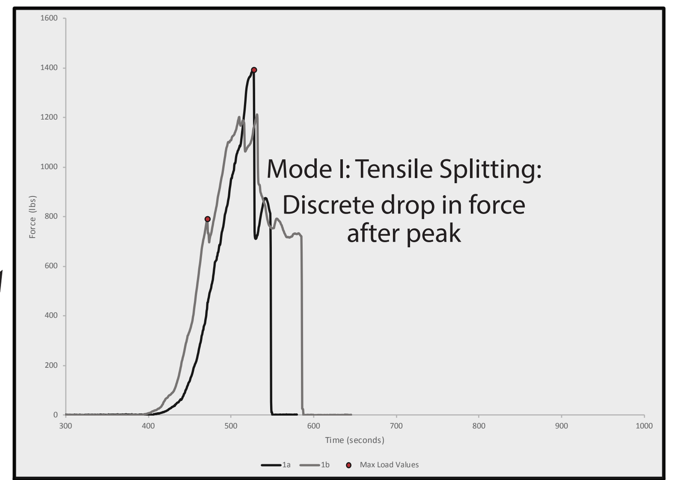
- Wax preserved samples fail at lower tensile strength values (avg=5.51 MPa, range=1.84 - 11.34 MPa) than non-wax preserved samples (avg=10.47, range=1.84 - 30.89 MPa)

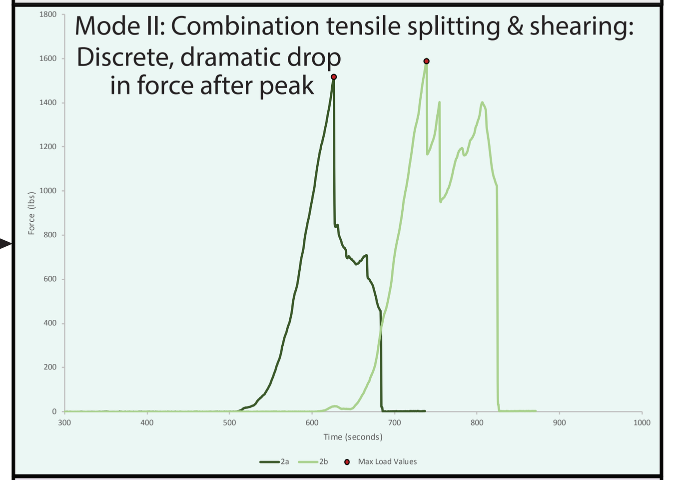
- Wax preserved samples failed in a step like pattern when tested perpendicular to bedding (Mode 3b, see failure mode table below); failure steps occurred between heterogeneities, commonly stepping across bedding planes

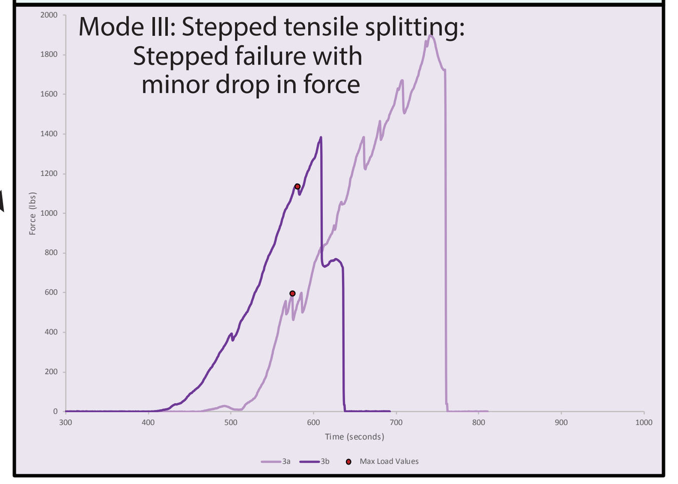
- Post-testing the wax-preserved samples commonly experienced fluid loss as shown in the photo on the right; no fluid loss was visible prior to testing or during sample preparation

Three modes of failure were observed across samples tested. These modes of failure span a variety of strength values and MHI parameters.

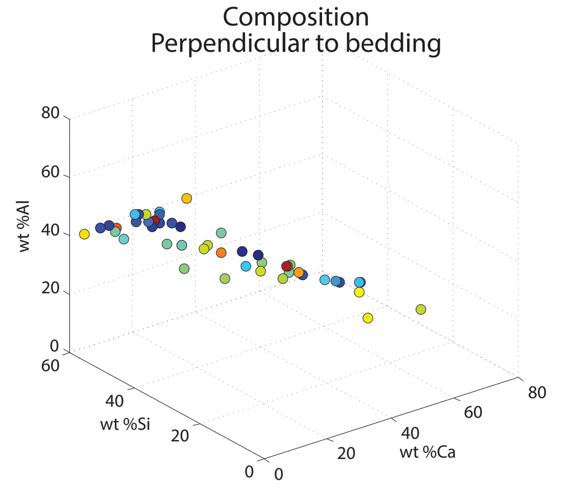
Main failure mode	Sub-failure mode	Representative Samples / Geometry
1. Tensile splitting	a. Splitting parallel to laminations b. Splitting perpendicular to laminations	
2. Combination tensile splitting and shearing	a. Splitting parallel to laminations and shearing sub-perpendicular to laminations b. Splitting perpendicular to laminations and shearing sub-parallel to laminations	
3. Stepped tensile splitting	a. stepping parallel to laminations b. stepping perpendicular to laminations	

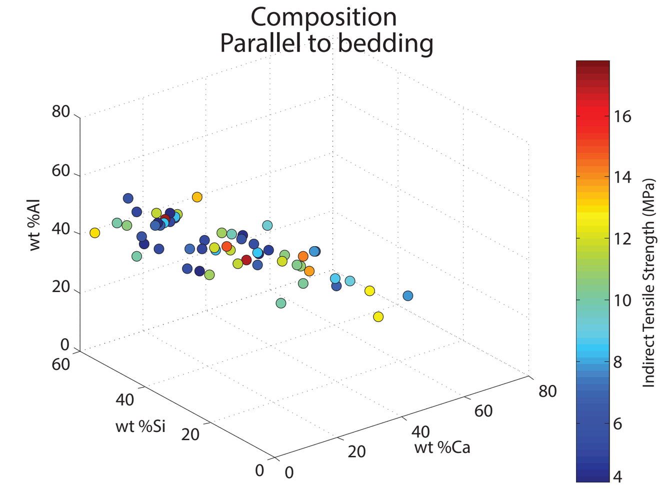


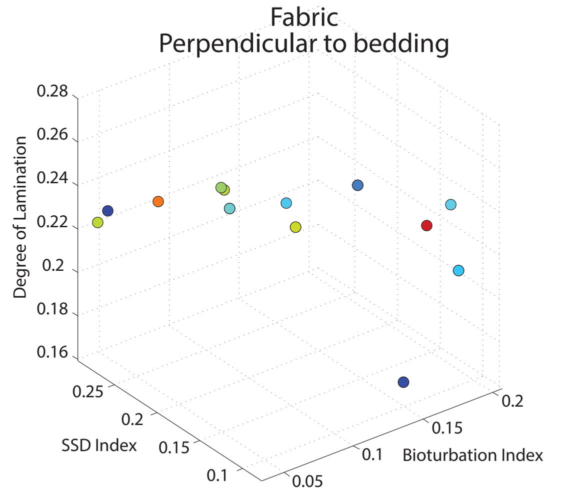


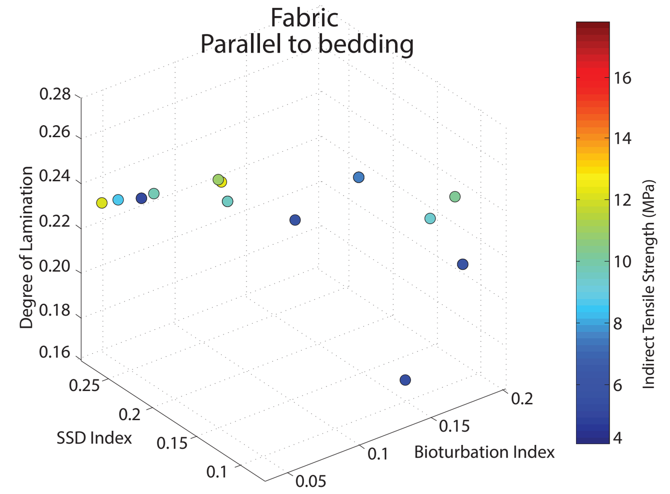


Relationships between the MHI and Indirect Tensile Strength (ITS) Results









- Al-rich samples have the lowest ITS values while Ca-rich sample have higher ITS values for both parallel and perpendicular to bedding samples.

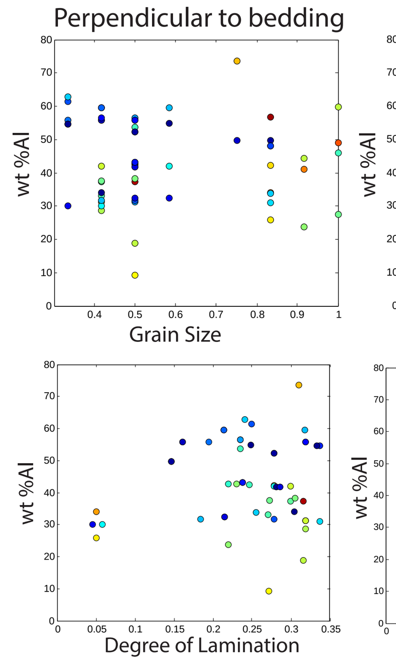
- The highest ITS samples have approximately proportionate mixtures of the three endmember composition values.

- The combination of fabric parameters reveals weak trends in distribution of strength values, likely due to lack of samples that contain an expression of all three endmembers.

- Low ITS, Al-rich, clay-rich mudstones perpendicular to bedding indicate weak bedding planes in fine mudstones, while higher ITS values correspond to Al-rich and sand rich samples measured parallel to bedding, suggesting strength in heterolithic layering.

- Low ITS values correspond with Al-rich, strongly laminated samples again suggesting weak bedding planes in fine mudstones tested perpendicular to bedding.

Perpendicular to bedding



Parallel to bedding