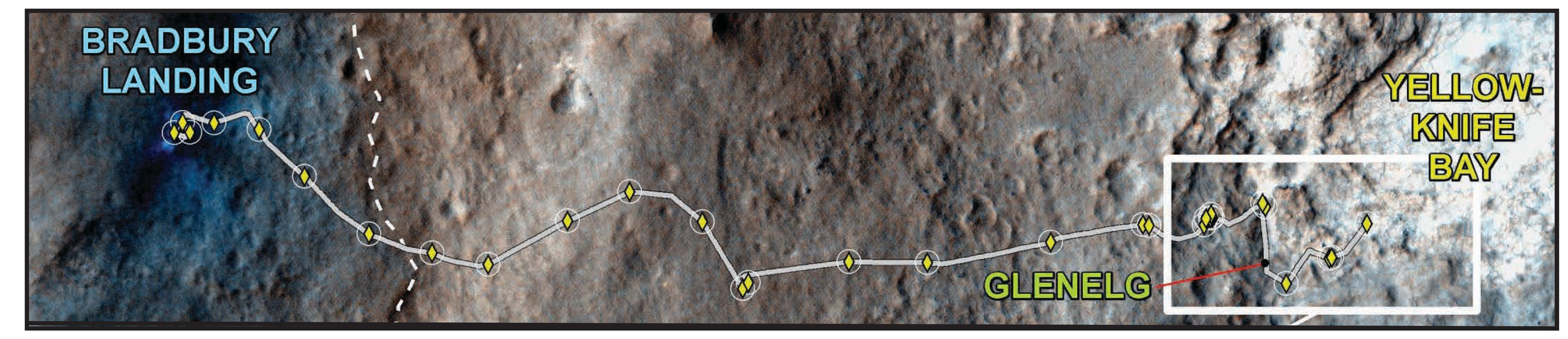
Burial History of the Yellowknife Bay Formation

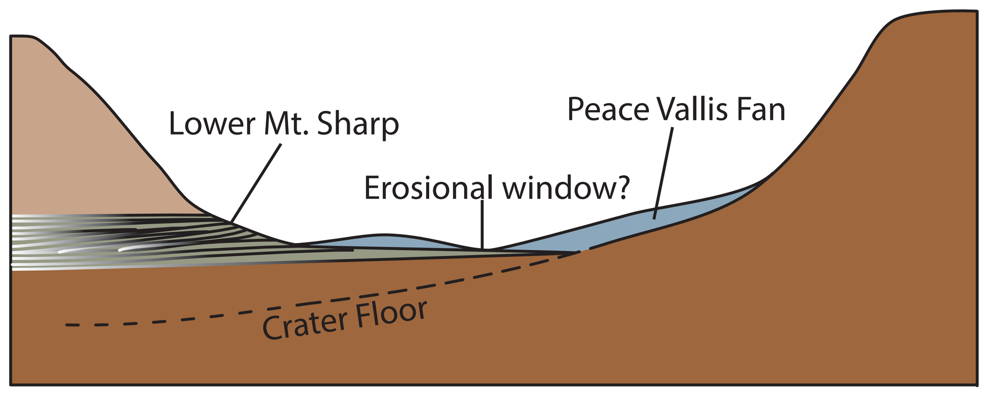
Insight from Fracture Morphology and Mechanics

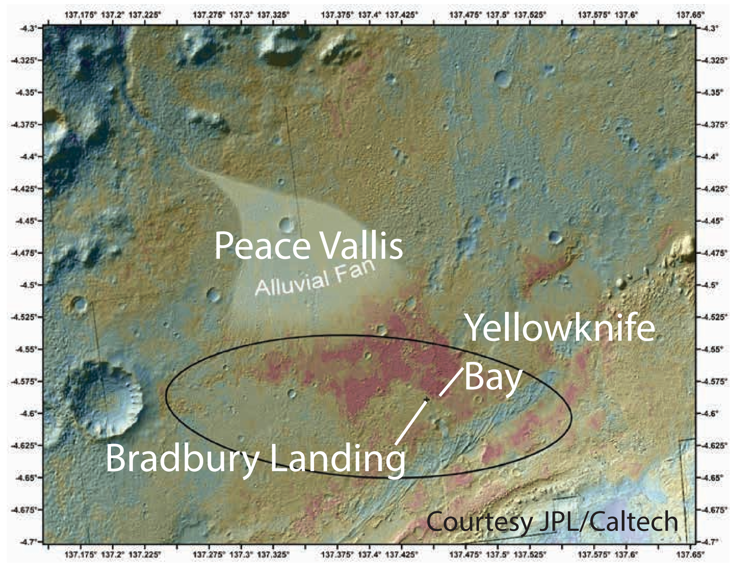
Tess E. Caswell (tess_caswell@brown.edu) and Ralph E. Milliken



Where does Yellowknife Bay fit in the stratigraphic record?

Stresses indicated by natural hydraulic fracturing allow us to estimate the minimum burial depth of the formation.





If contemporaneous with Lower Mt. Sharp...

- Late Noachian/Early Hesperian sediments
- Deeply buried prior to exhumation
- Habitable environment occurred early in Gale's history [1]

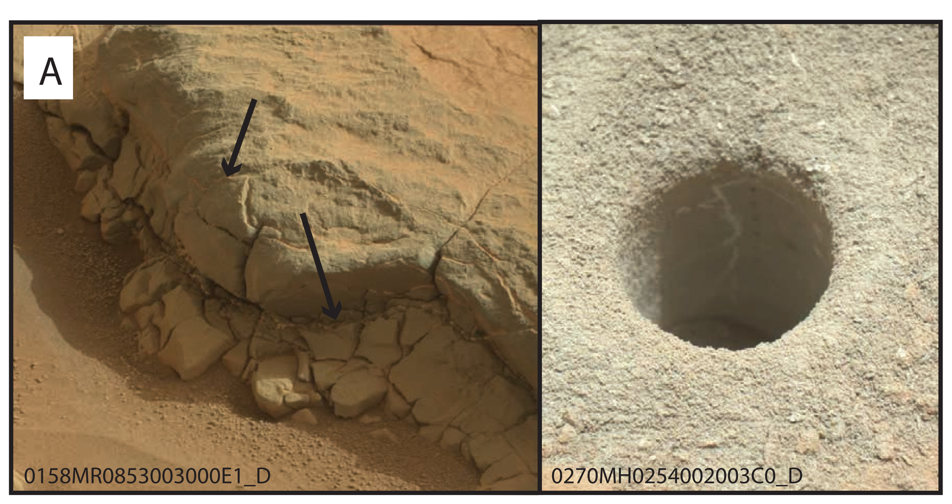
If contemporaneous with Peace Vallis...

- Some of the youngest sediments examined by Curiosity
- Never deeply buried
- Possible habitable environment during the Noachian [1]

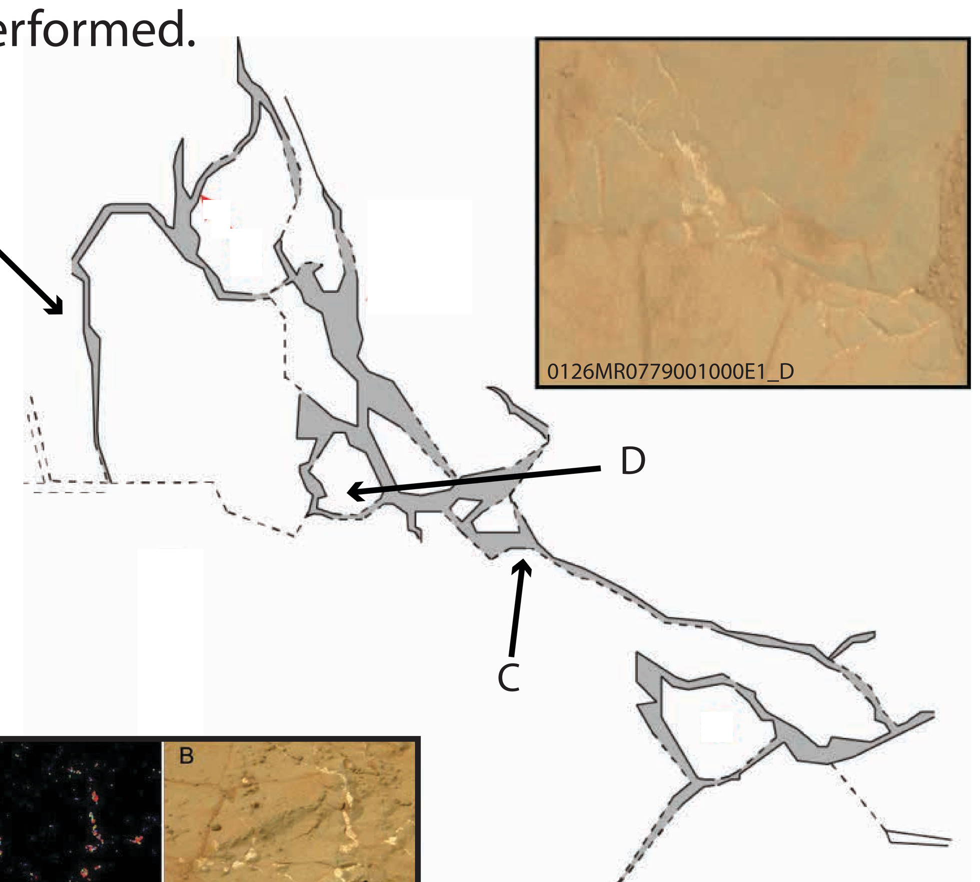
Constraining formation mechanism: observations

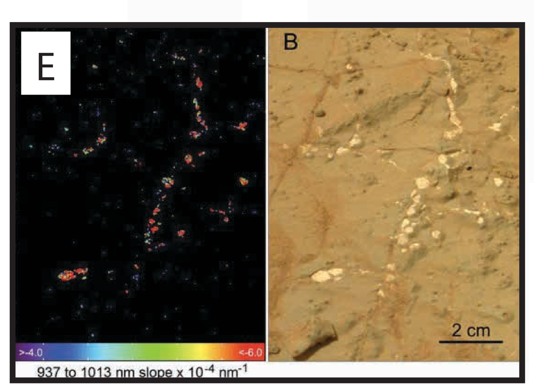
While ubiquitous fractures seen in YB are commonly referred to as veins, a quantitative morphologic analysis has not previously been performed.

Features of sulfate-filled fractures at Yellowknife Bay:
»Varied directions of propagation (A)
»Nonplanar fracture walls (B)
»Oblique intersections (C)
»Entrained, irregular blocks (D)
»Ca-sulfate fill confined to fractures (E)



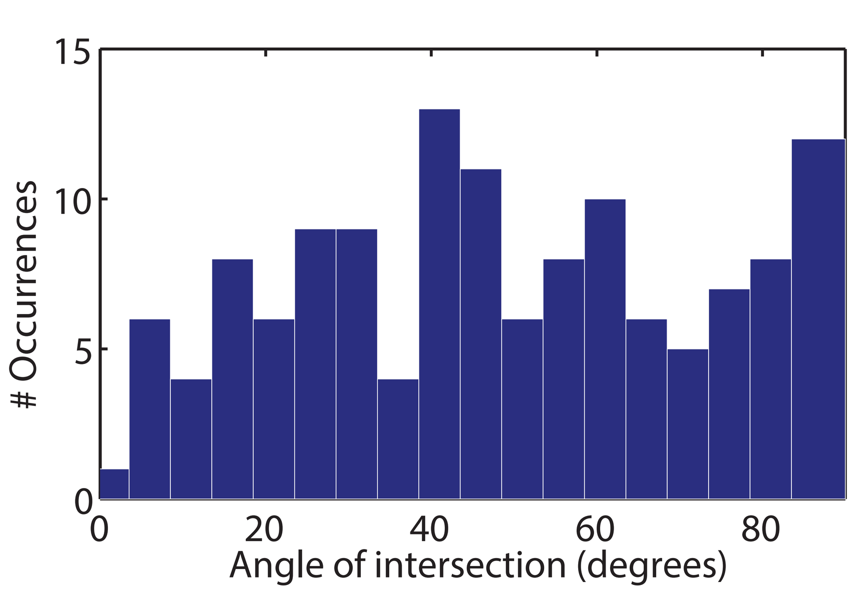
Vertical (right, John Klein), subhorizontal and horizontal (left, Selwyn) fractures indicate a driving force for fracture greater than lithostatic loading [2,3].

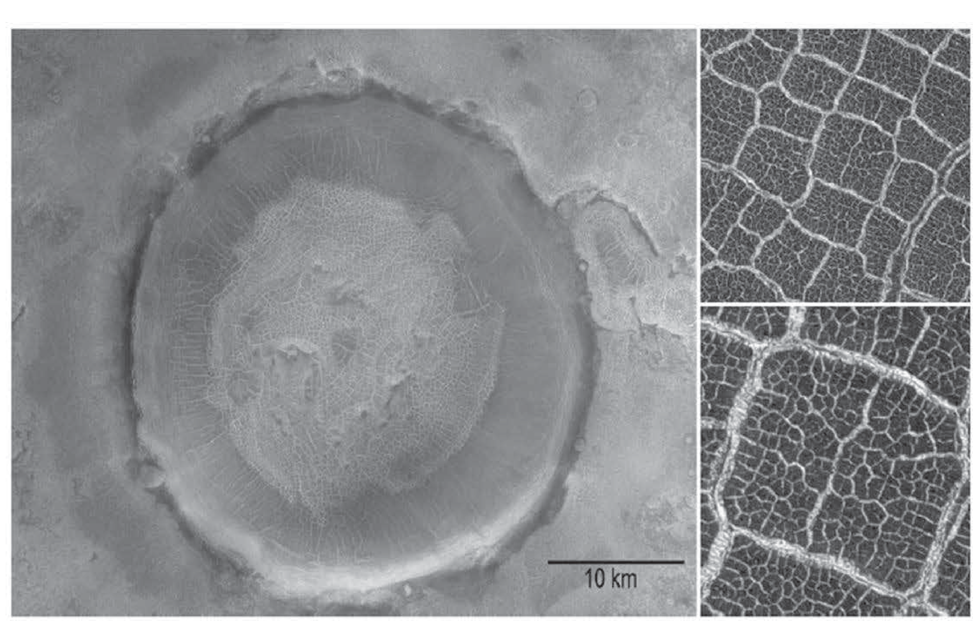




Confinement of Ca-sulfate to fractures (indicated by hydration state, left [4]) suggests rock well-lithified before fracture.

Quantifying intersection angles





(left) Histogram of cumulative intersections of a given angle (n=133). Compare to fracturing by thermal or desiccation processes, which produce a preferred intersection of 90° [5,6] (e.g., Crater Floor Polygons, right [13]).

Vein Networks
- Irregular wall morphology ✓
- Entrained blocks of host rock ✓
- Varied direction of propagation ✓

Dessication/Thermal Cracking
- Regular fracture spacing ✗
- Orthogonal intersections ✗

Constraining burial depth: fracture mechanics

The stress state of sediments in a confined basin can be used to estimate the burial depth at the onset of fracturing.

1) Calculate the vertical and horizontal stresses [7,8]

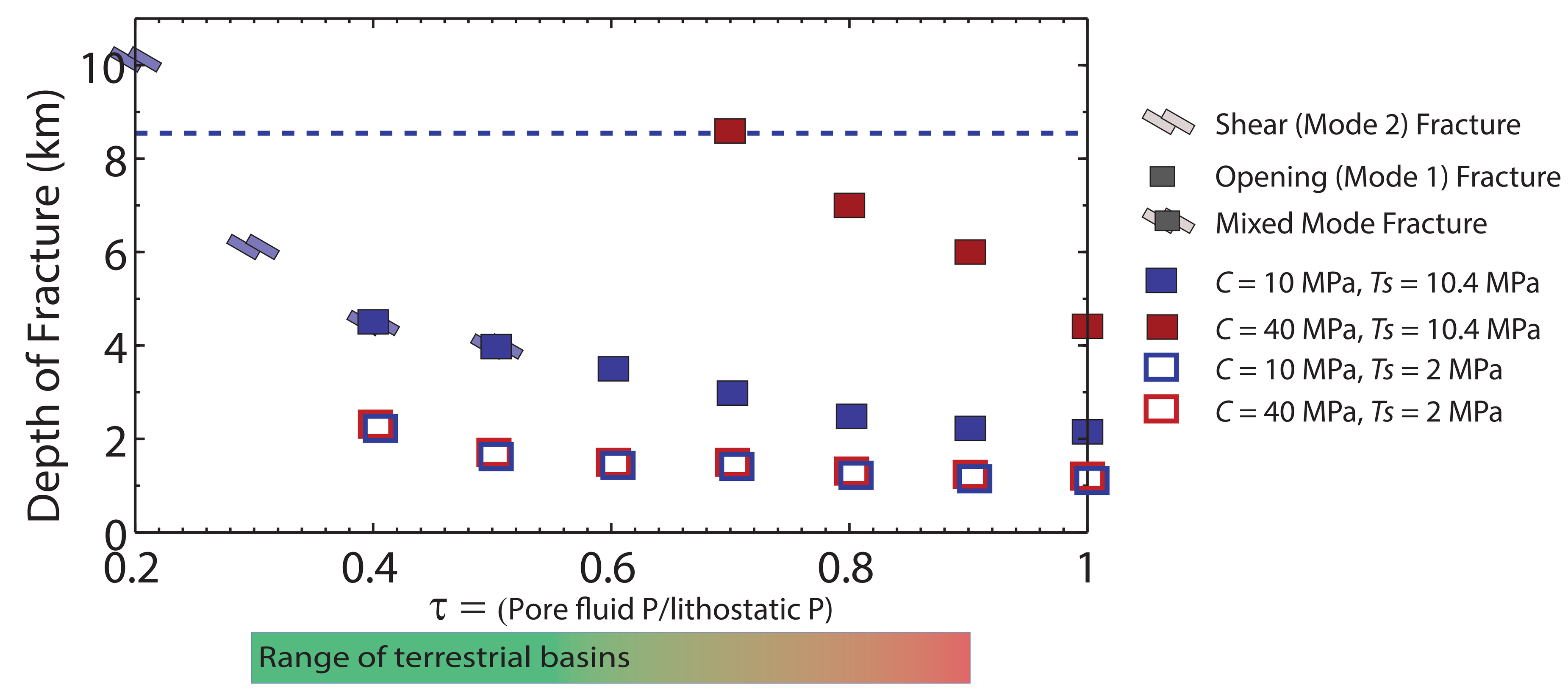
$$\sigma_{1,eff} = \sigma_V = \rho g d - P_f \qquad \sigma_3 = \sigma_h = \left[\left(\frac{\upsilon}{1-\upsilon}\right)\sigma_V - \left(\frac{E}{1-\upsilon}\right)\alpha\Delta T\right] - P_f \qquad P_f = \tau\sigma_V$$

ρ = Average density of overlying material
g = Gravity
d = Depth

υ = Poisson's ratio
E = Young's modulus
α = Coefficient of thermal expansion
ΔT = Geothermal gradient

τ = Ratio of pore fluid pressure to lithostatic (effects of lithification + poroelasticity).

2) From these, calculate differential stress ($\sigma_{1,eff} - \sigma_3$)
3) Calculate shear and normal stresses for all orientations within the sediments
4) Determine the conditions at which the stress state exceeds the Mohr-Coulomb failure envelope [12,14]



The Mohr-Coulomb Failure Envelope

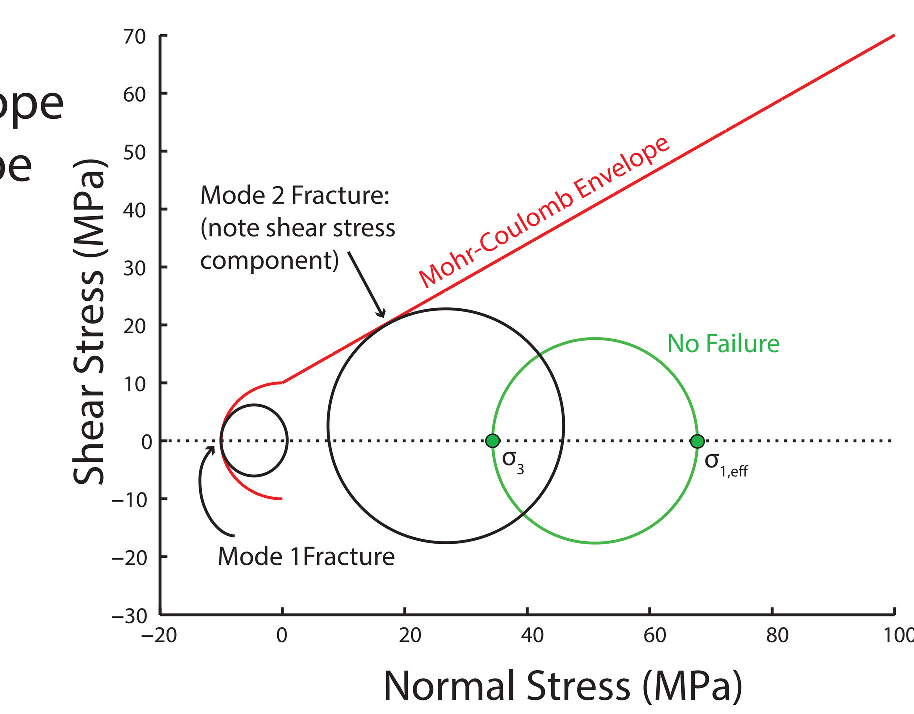
When does fracture occur? The Mohr-Coulomb Failure Envelope incorporates the mechanical properties of the rock to describe the stresses that lead to fracture.

The compressional envelope is determined by the resistance of the rock to shear.

$$\sigma_S = C + \mu\sigma_V$$

σ_S = Shear Stress
C = Cohesion
μ = Coefficient of friction

The tensile envelope is set by the tensile strength (*Ts*) of the rock.



Discussion

Fracture morphology is consistent with natural hydraulic fracturing (i.e., a vein network).

The stress state required to produce fracturing tells us that:
» even a "weak" mudstone requires burial by >1 km for fracturing to occur.
» stronger mudstone requires relatively high pore fluid pressure to fracture at < 5 km depth.

The sediments at Yellowknife Bay must have been buried >1 km to generate the observed fractures, indicating that these rocks are contemporaneous with Lower Mount Sharp.

This analysis can be improved by better constraining the properties of the rocks at Yellowknife Bay.
» Future work includes testing analog samples to more accurately estimate τ, *C* and *Ts*.

[1] Grotzinger, J.P. et al. (2014) Science, 343.6169, 1242777 [2] Schieber, J. et al. (2013), GSA Fall Mtg., 45(7), p39 [3] Schieber, J. (2014) AAPG 2014 ACE, #90189 [4] Vaniman, D.T. et al. (2014), Science, 343.6169, 1243480 [5] Weinberger, Ram (1999), J. Struct. Geol., 21.4,379-386 [6] Aydin, A. and DeGraff, J.M. (1988), Science, 239.4839, 471-476 [7] Engelder, T. (1993), Stress Regimes in the Lithosphere, Princeton U. Press, NJ [8] Van der Pluijm, B.A. and Marshak, S. (2004) Earth Structure, N.W. Norton, NY [9] Squyres, S.W. and Kasting, J.F. (1994) Science, 265, 744-749 [10] Corkum, A.G. and Martin, C.D. (2006) J. Rock Mech. & Mining Sci., 44, 196-209 [11] Hahn, B.C. et al. (2011) LPSC 42, #2340 [12] Lin, W. (1983) UCRL-53419, Lawrence Livermore National Lab, CA [13] El Maarry, M.R. et al (2010) J. Geophys. Res, 115, E10006 [14] Corkum, A.G. and C.D. Martin (2007) Int. J. Rock Mech. Min. Sci, 44, 196-209.