Unconventional Shale Hydraulic Fracturability-Effect of Porosity and Pore Shapes*

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Abstract

Hydraulic fracturing is a common practice used to dramatically improve the production of hydrocarbons from unconventional shale reservoirs. However, it is still not clear how micro-cracks initiate, grow, interact and coalesce into macro-fractures in unconventional shales. This article presents an experimental study investigating the effects of porosity and pore shapes on the crack generations and development. A better understanding of their effect on the frackability of unconventional shales will be useful in shale reservoir characterization and development, hydraulic stimulation design and other aspects of unconventional development. Fracturing increases the surface area of shale reservoirs and provides the flow channels for hydrocarbons extraction. This is usually achieved by pumping fracturing fluids into the rock to initiate and propagate cracks under tension. A large proportion of the energy required for crack initiation and propagation is consumed in the crack initiation stage. The presence of a stress-concentrating feature reduces the crack initiation energy.

During hydraulic fracturing, cracks propagate through the inhomogeneous rock matrix, which consists of grains of various minerals and pores present in the rock. Once a crack hits a pore, its tip blunts. To propagate any further the crack has to reinitiate, which is an energy intensive process. The exact amount of energy required, however, largely depends on the shape of the pores, as sharp corners within the pores act as stress concentrators, resulting in reduction in the energy for crack re-initiation. In this article, we used our state of art instruments to perform rock compressional tests on various shale samples from various basins in the world. The samples are imaged and then analyzed before and after tests to determine the size, the number, and the

shape of pores present within samples. A model based on statistical methods is developed to describe the effects of total number, size and shapes of pores on crack propagation. To simplify the model, some assumptions are made and verified experimentally. This model will be helpful in optimization of fracking jobs in the oil and gas industry.

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Unconventional Shale Fracability-Effect of Porosity and Pore Shapes

Naeem Minhas, Guodong Jin

Introduction

- Hydraulic fracturing revolutionised the unconventional oil and gas.
- It’s a hit and miss.
- 70% of the frac stages are not successful.
- Not fully understood.

Problem Statement

Recent fracability (brittleness) index calculation is largely skewed to mineral composition at the expense of rock fabric.

Appendix

Table **A-1** Selected Expressions of Brittleness

Formula	Variable declaration	Test Method	Reference
$B_1 = (H_m - H)/K$	H and H_m are macro and micro-hardness, K is bulk modulus	Hardness test	[*Honda and Sanada*, 1956]
$B_2 = q\sigma_c$	q is percent of debris (<0.6 mm diameter); σ_c is compressive strength	Proto impact test	[*Protodyakonov*, 1962]
$B_3 = \varepsilon_{ux} \times 100\%$	ε_{ux} is unrecoverable axial strain	Stress strain test	[*Andreev*, 1995]
$B_4 = (\varepsilon_p - \varepsilon_r)/\varepsilon_p$	ε_p is peak of strain, ε_r is residual strain		[*Hajiabdolmajid and Kaiser*, 2003]
$B_5 = \tau_p - \tau_r/\tau_p$	τ_p and τ_r are peak and residual of shear strengths		[*Bishop*, 1967]
$B_6 = \varepsilon_r/\varepsilon_t$	ε_r and ε_t are recoverable and total strains		[*Hucka and Das*, 1974]
$B_7 = W_r/W_t$	W_r and W_t are recoverable and total strain energies		
$B_8 = \sigma_c/\sigma_t$	σ_c and σ_t are compressive and tensile strength	Uniaxial compressive strength and Brazilian test	
$B_9 = (\sigma_c - \sigma_t)/(\sigma_t + \sigma_c)$			
$B_{10} = (\sigma_c \sigma_t)/2$			[*Altindag*, 2003]
$B_{11} = (\sigma_c \sigma_t)^{0.5}/2$			
$B_{12} = H/K_{IC}$	H is hardness, K_{IC} is fracture toughness	Hardness and fracture toughness test	[*Lawn and Marshall*, 1979]
$B_{13} = c/d$	c is crack length, d is indent size for Vickers indents at a specified load; empirically related to H/K_{IC}	Indentation test	[*Sehgal et al.*, 1995]
$B_{14} = P_{inc}/P_{dec}$	P_{inc} and P_{dec} are average increment and decrement of forces		[*Copur et al.*, 2003]
$B_{15} = F_{max}/P$	F_{max} is maximum applied force on specimen, P is the corresponding penetration.		[*Yagiz*, 2009]
$B_{16} = H \times E/K_{IC}^2$	H is hardness, E is Young's modulus, K_{IC} is fracture toughness	Hardness, stress strain, and fracture toughness test	[*Quinn and Quinn*, 1997]
$B_{17} = 45° + \varphi/2$	φ is internal friction angle	Mohr circle or logging data	[*Hucka and Das*, 1974]
$B_{18} = Sin\varphi$			
$B_{19} = (E_n + v_n)/2$	E_n and v_n are normalized dynamic Young's modulus and dynamic Poisson's ratio defined in Eqs. 3-4.	Density and sonic logging data	Modified from [*Rickman et al.*, 2008]
$B_{20} = (W_{qtz})/W_{Tot}$	W_{qtz}, is the weight of quartz, W_{Tot} is total mineral weight.	Mineralogical logging or XRD in the laboratory	[*Jarvie et al.*, 2007]
$B_{21} = (W_{qtz} + W_{dol})/W_{Tot}$	W_{qtz} and W_{dol} are weights of quartz and dolomite, W_{Tot} is total mineral weight.		[*Wang and Gale*, 2009]
$B_{22} = (W_{QFM} + W_{Carb})/W_{Tot}$	W_{QFM} is weight of quartz, feldspar, and mica; W_{Carb} is weight of carbonate minerals consisting of dolomite, calcite, and other carbonate components. W_{Tot} is total mineral weight.		*Defined in this paper*

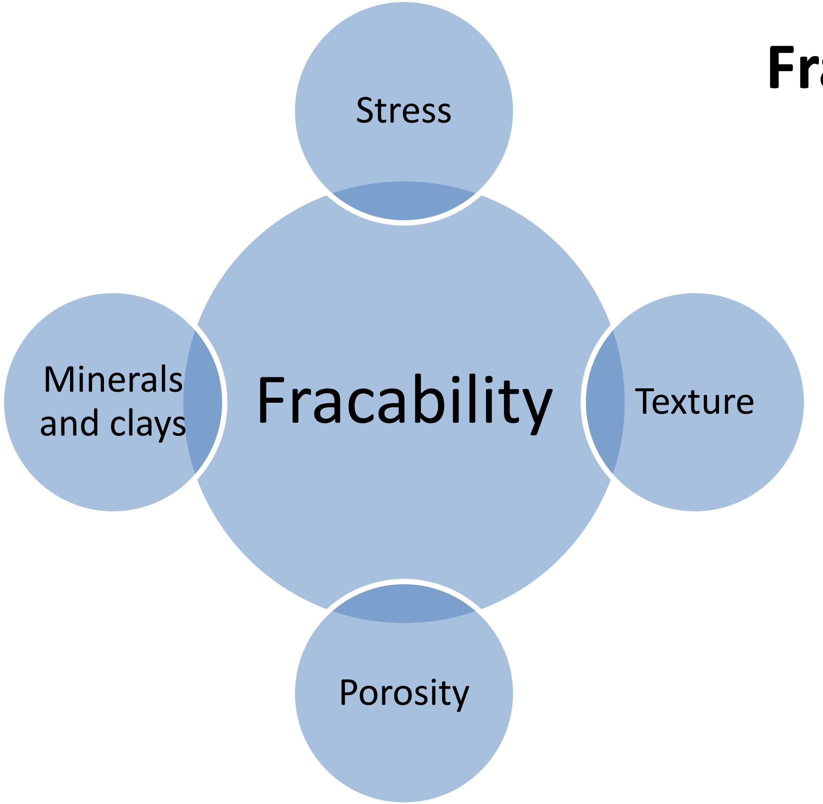
Selected Expressions of Brittleness
(SPE 168589)

21st [Jarvie et al., 2007]
B20= (Wqtz)/WTot Wqtz, is the weight of quartz, WTot is total mineral weight.

22nd [Wang and Gale, 2009]
B21= (Wqtz+Wdol)/WTot Wqtz and Wdol are weights of quartz and dolomite, WTot is total mineral weight.

23rd [Jin et al., 2014]
B22= (WQFM+WCarb)/WTot WQFM is weight of quartz, feldspar, and mica; *WCarb* is weight of carbonate minerals *WTot* is total mineral weight.

Fracability: Texture Effects



Mineral phase distribution
Mineral grain size
Mineral Grain shape
Mineral Associations
Pore Size distribution
Pore Shapes

Mechanical Properties

- It all goes back to Mineralogy, texture and stresses acting on the rock

Porosity

- Generally considered to be good for fracability.
- Free ride for the crack for the length of the pore.
  - Longer the pore in that direction the longer the free ride.
- Hits the other side of the pore.
- Then what!!!
  - Depends on.
    - Shape
    - Orientation of the pore

Re-initiation of the crack required

Round pore

- Blunt crack-tip
- Required energy to re-initiate the crack close to the energy of re-initiation from a surface- VERY HIGH
- Crack is arrested

Sharp cornered pore

- Tip-radius same as the radius of the sharp corner.
- Re-initiation energy is small.
- Easy to propagate the crack further.

Effects of Porosity

- $$E_{FRAC} = \sum E_m + \sum E_b + \sum E_p$$

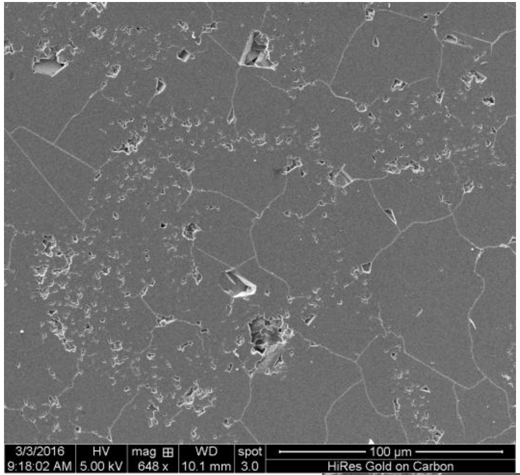
Where

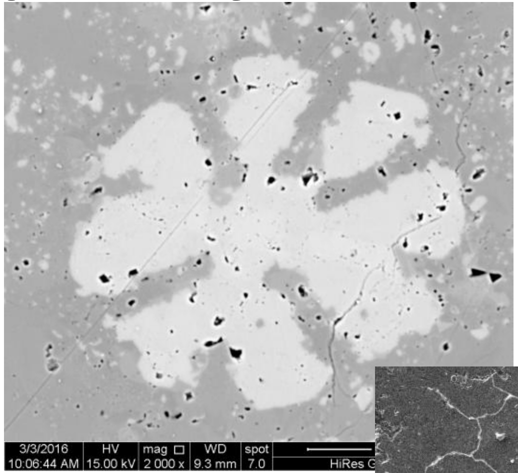
Em= Energy required to propagate the crack through mineral grains,
Eb = Energy required to propagate the crack though the grain boundaries and
Ep = Energy required to propagate the crack through the pore
Ep is supposed to be zero however. Crack tip gets blunted so re-initiation is required.
So

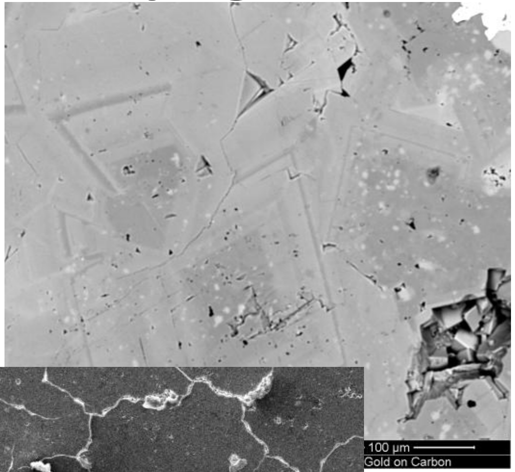
$$\sum E_p = \sum (E_i \times SF_p)$$

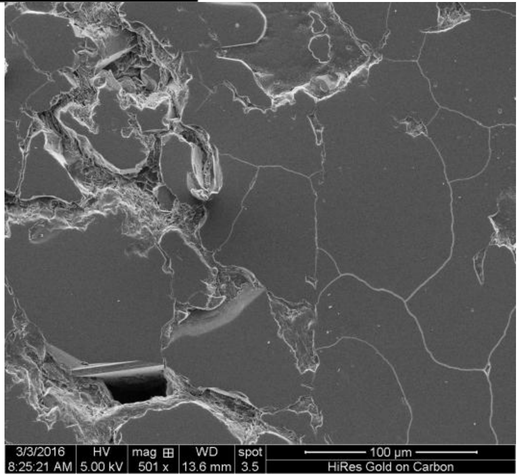
SF is the shape factor which is an indicator of stress concentrators within a particular pore. E_i is the energy required to initiate a crack from a flat surface.

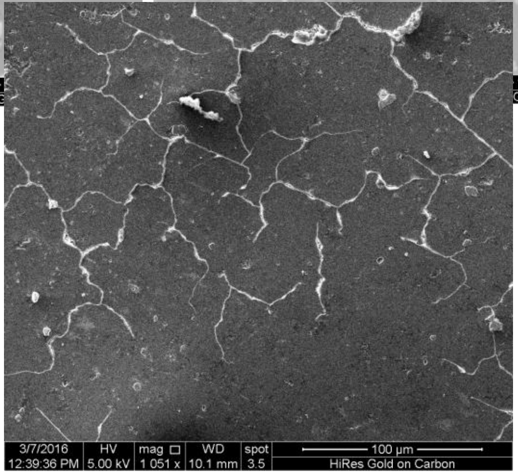
Effects of porosity on Crack Propagation







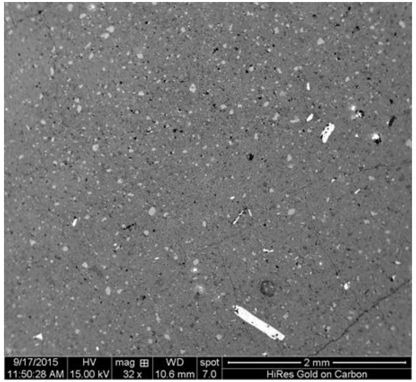


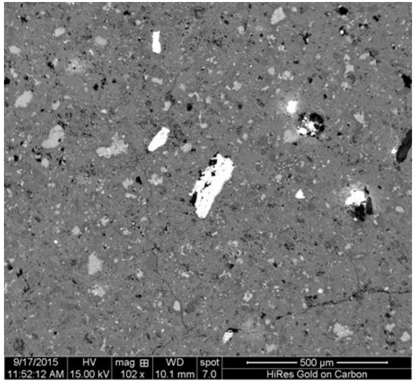


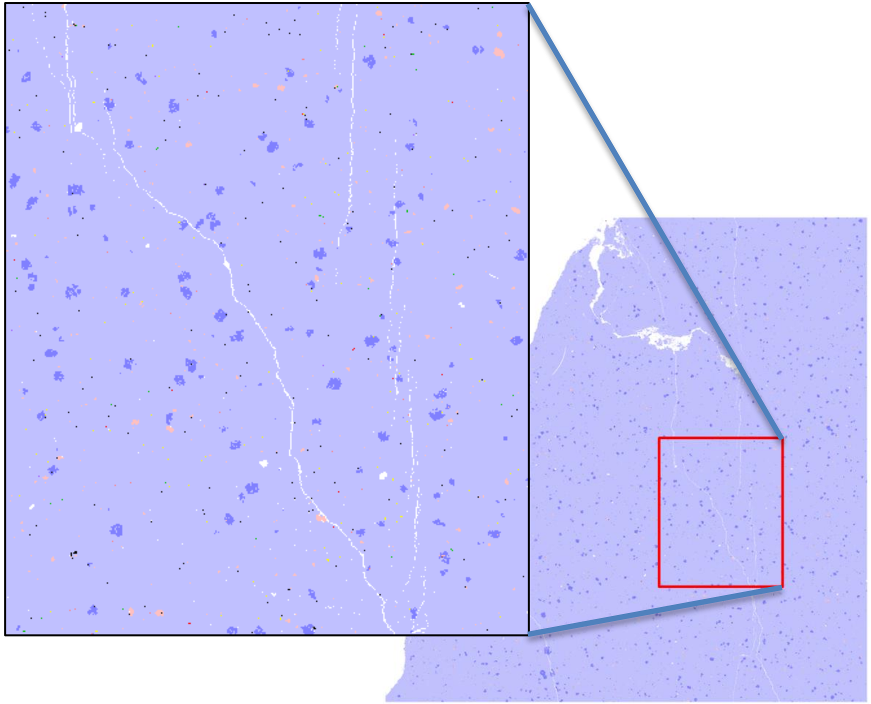
Effect of Mineral distribution

- Some hard minerals act as stress concentrators
- Cracks can initiate from them as they resist the deformation
- Crack deflection as they follow the grain boundaries.
  - Implications for mechanical properties/fracability
- The more hard mineral grains per unit area/volume, the bigger the effect

Effects of texture on fracture propagation

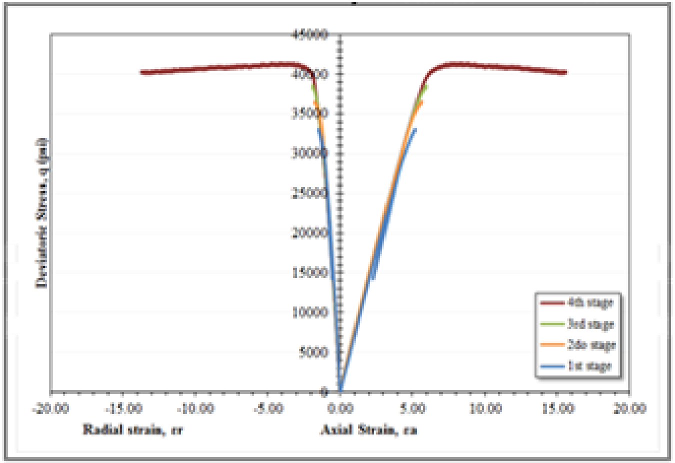




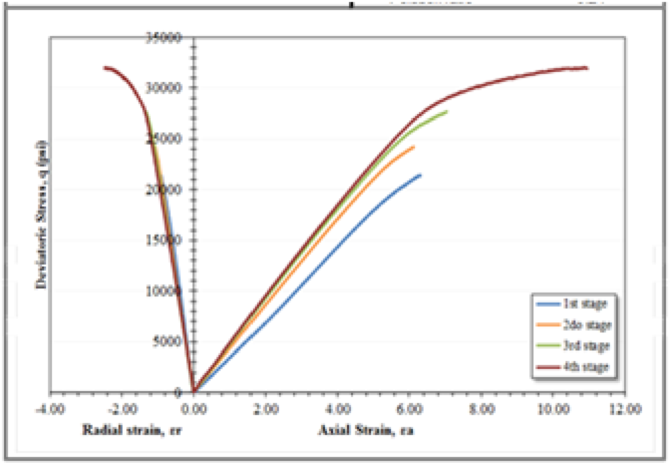


Mechanical Properties Results

Sample: **10V**
High Modulus
Low Strain,

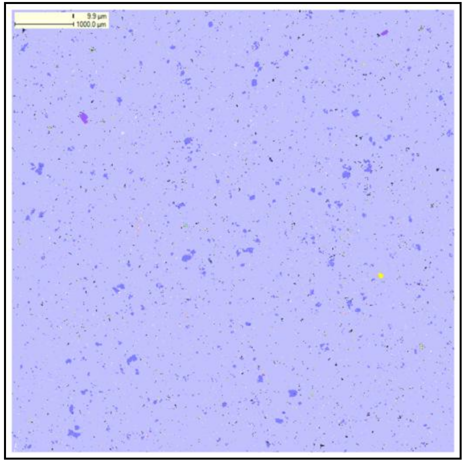


Sample: **4V**
Low Modulus
High Strain

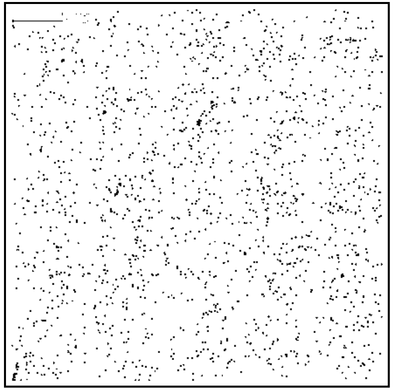


Mineral and Porosity Map

- 4V

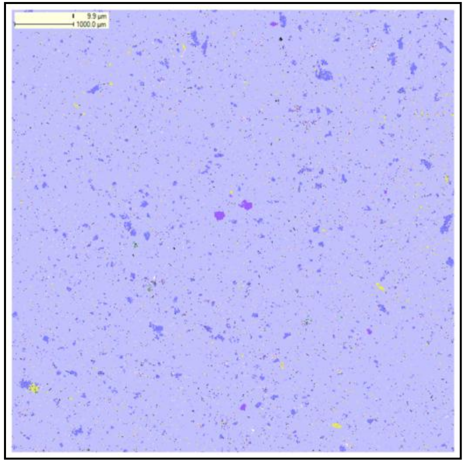


Mineral map

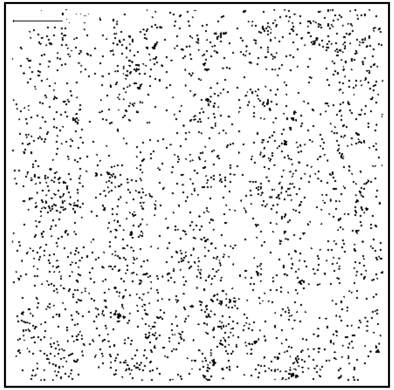


Porosity

- 10V

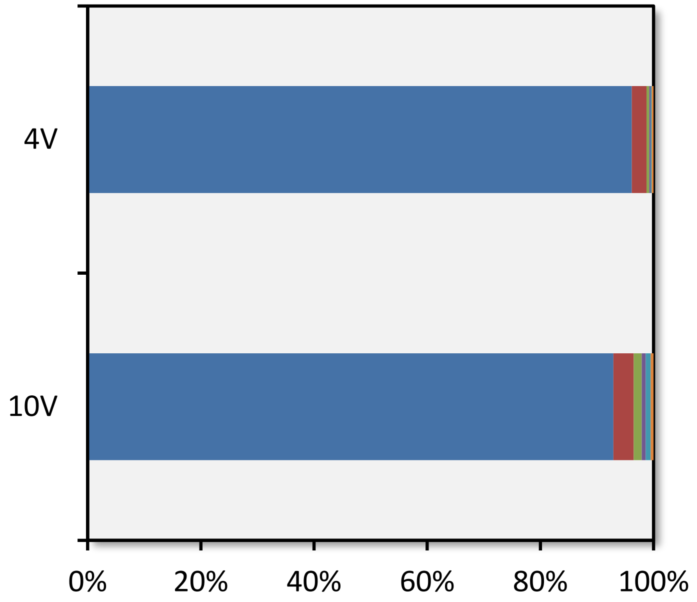


Mineral map



Porosity

Mineralogy and Porosity

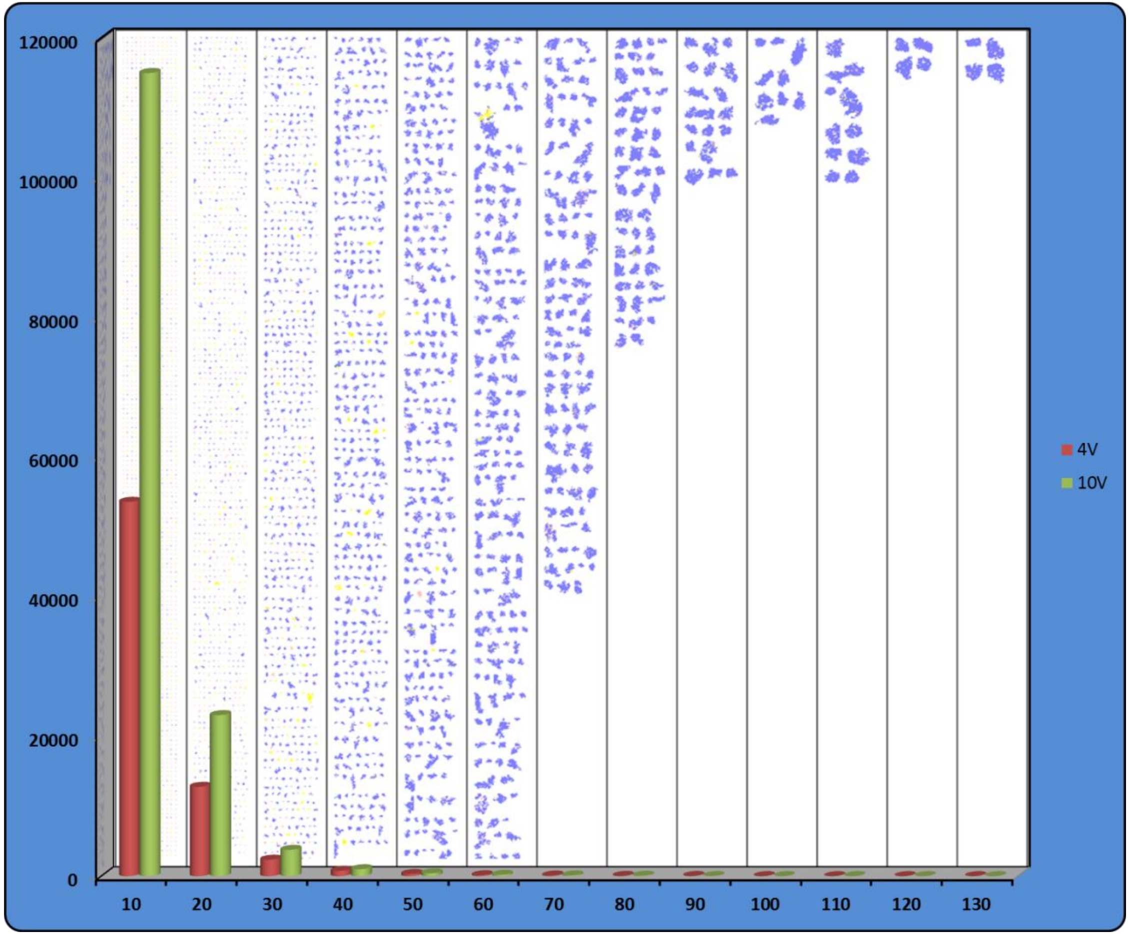


Almost no clay content in either of the samples

Minerals	4V	10V	Hardness
Calcite	96.1	93.0	3
Dolomite	2.6	3.6	3.5
Quartz	0.5	1.4	7
Gypsum/Anhydrite	0.2	0.7	3.5
Pyrite	0.2	0.9	6.5
Porosity	0.35	0.5	
Hardness*	3.0	3.1	
BI**	0.005	0.014	

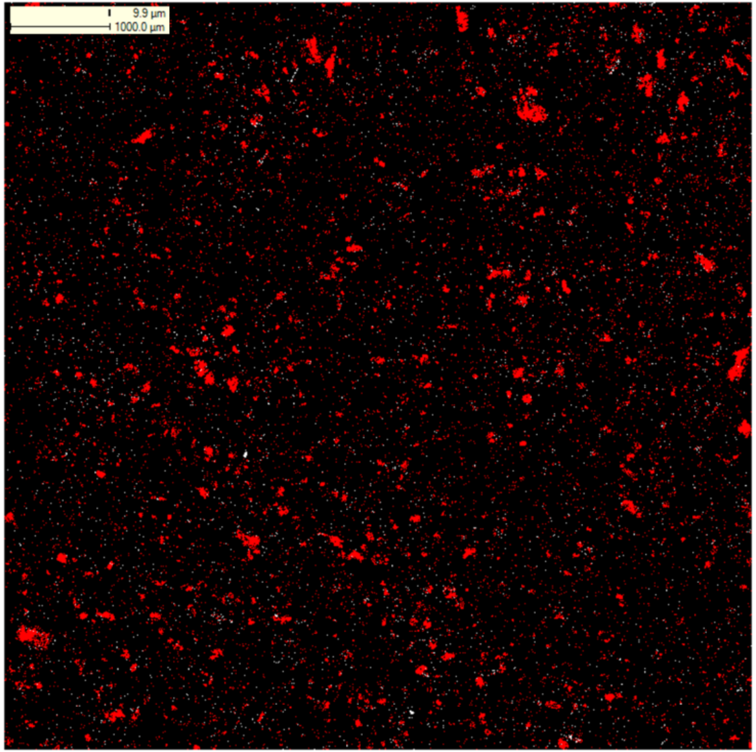
*Calculated hardness,
**Brittleness index (Jarvie et al., 2007)

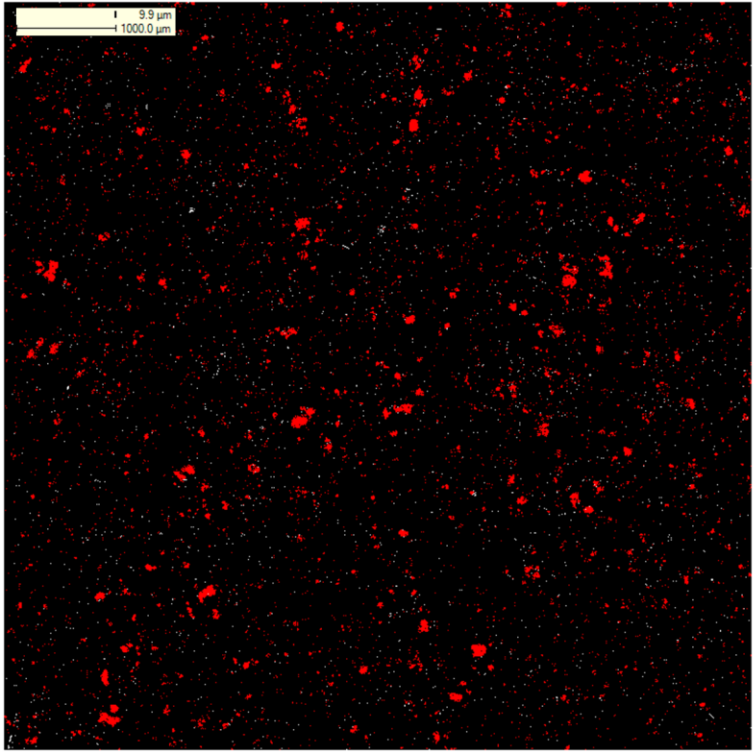
Particle Size Distribution



Dolomite + Quartz + Pyrite

10V





4V

Conclusions

- Porosity can be good or bad depending on.
  - Shape
  - Orientation
- Larger the number of pores the bigger the effect
  - Not necessarily the total porosity
- Mineralogy: Mineral distribution, grain size effects the crack propagation and mechanical properties.

Texture in Important.