| 11. 19. 2020 |

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2020 SCCS Annual Affiliates Meeting

Characterizing local fracture aperture distributions in heterogeneous rock cores using X-ray CT and PET imaging

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Characterizing fracture apertures in reservoir rocks

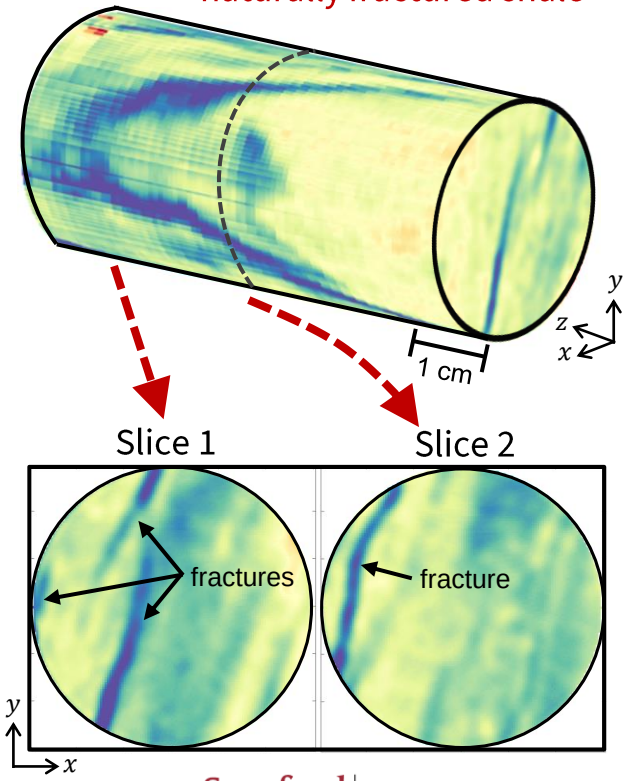
Importance:

- Understanding the internal structure of fracture apertures is important for applications such as CO_2 storage and the extraction of oil and gas from unconventional reservoirs
- This is because they are the main drivers for the chemical and physical interactions between the fluids, the fractures and the rock matrix

Major challenges:

- Rock cores exhibit strong heterogeneity at all scales (from nm to km)
- Fractures introduce additional complexities (e.g. coupled fracture-matric fluid flow) due to heterogeneous fracture distributions

Medical CT images of a naturally fractured shale



Characterizing fracture apertures in reservoir rocks

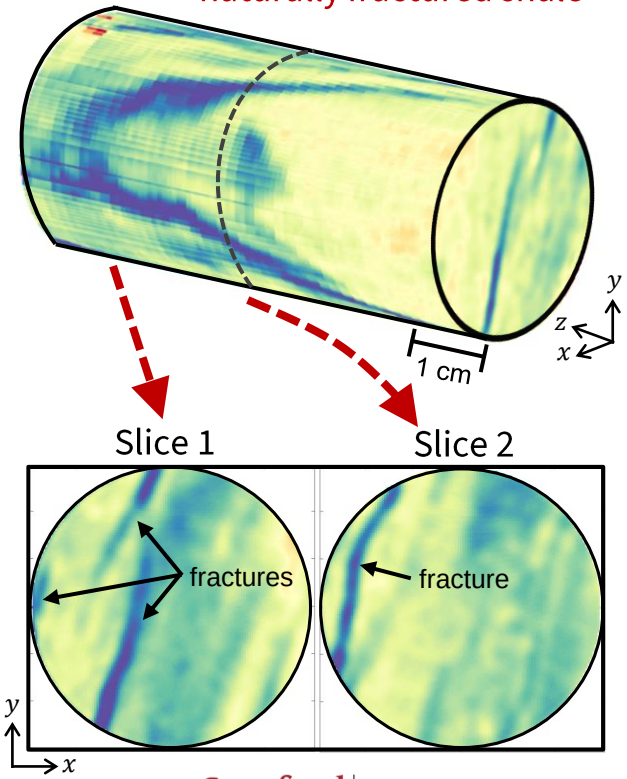
Work to date:

- Measurements of fracture aperture distributions at the core-scale have been mostly limited to relatively homogeneous rocks[1-3]

[1] Ketcham et al. **2010** *Geosphere* ; 6 (5): 499–514
[2] Huo et al. **2016** *Geosphere*. 12 (2): 558–571
[3] Wenning et al. **2019** *JGR: Solid Earth*, 124, 7320–7340

Advanced laboratory protocols needed to quantify the spatial structure of the complicated fractures embedded in heterogeneous rock matrix

Medical CT images of a naturally fractured shale



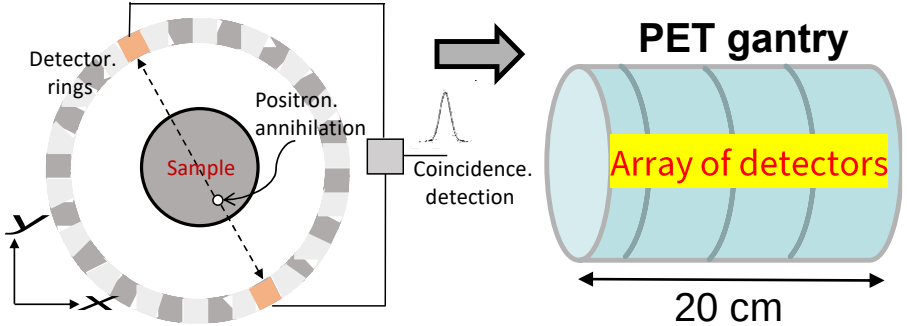
Our experimental techniques:

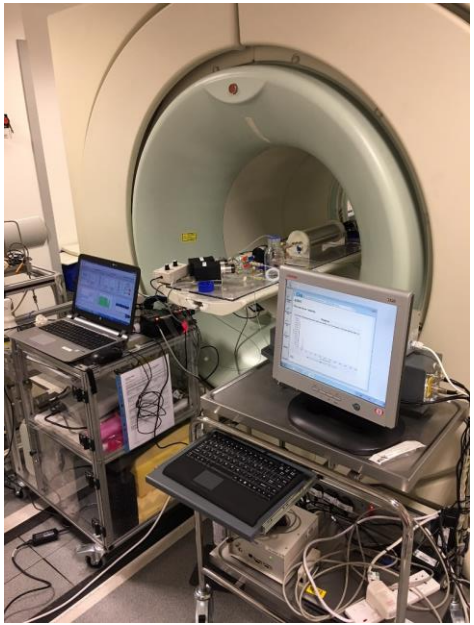
Positron Emission Tomography (PET)

Nuclear imaging technique that uses radioactive substances to visualize transport processes inside an opaque medium

- Detection of radio-tracers:

$$^{11}C \rightarrow {}^{11}B + b^{+} + u_e$$
$$b^{+} + e^{-} \rightarrow g + g$$





- Range of aqueous radiotracers (e.g., [11C]$NaHCO_3$, [18F]FDG)

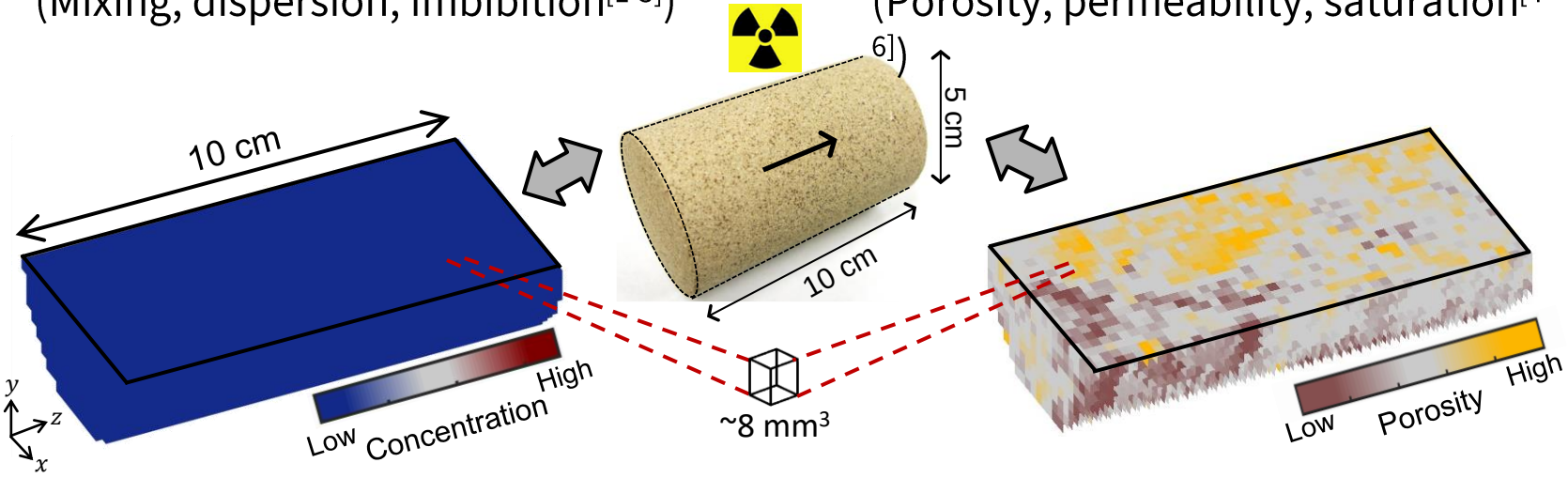
Our experimental techniques

Positron Emission Tomography

- 3D temporal concentration profiles (Mixing, dispersion, imbibition[1-3])

Medical X-ray Computed Tomography

- 3D distribution of static properties (Porosity, permeability, saturation[4-6])



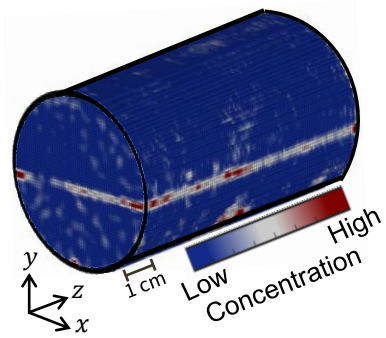
[1] Zahasky et al. **2018** *Adv Water Resour*, 115, 1-16
[2] Kurotori et al. **2019** *Chem. Eng. Sci.* 196, 366-383
[3] Zahasky et al. **2019** *Adv Water Resour*. 127, 39-52

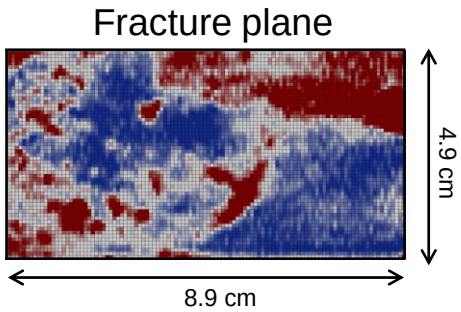
[4] Akin & Kovscek. **2003** *Geol. Soc.* 215 (1), 23-38
[5] Pini et al. **2012** *Adv Water Resour.* 38, 48-59
[6] Ni et al. **2019** *Int. J. Greenh. Gas Control*, 124, 86, 158-176

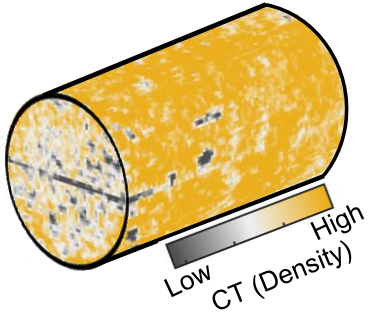
Our experimental techniques

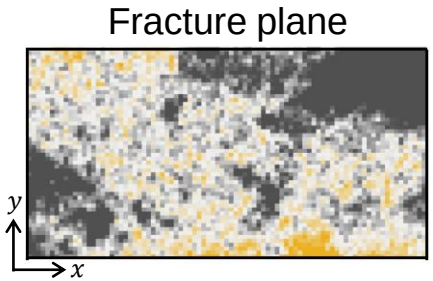
Positron Emission Tomography **Medical X-ray Computed Tomography**

Fractured Basalt









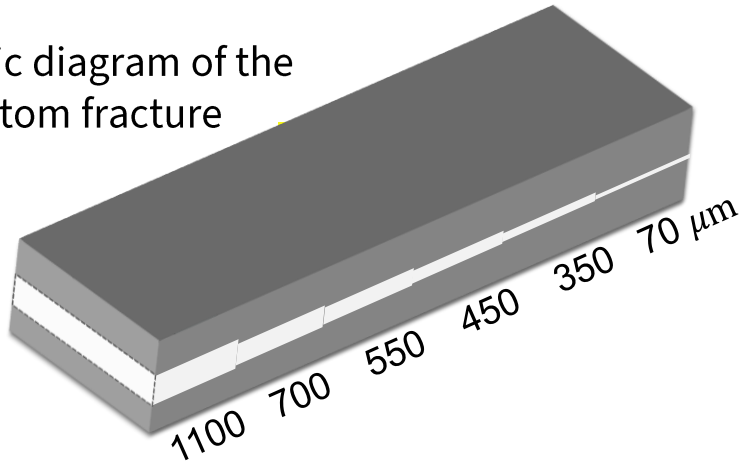
Goals:

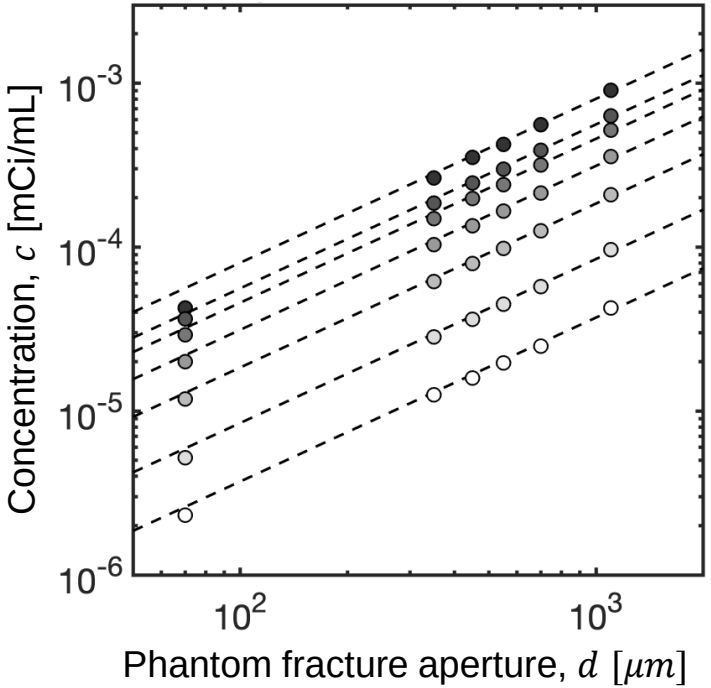
1. Develop experimental platforms to quantify aperture distributions using PET and CT
2. Evaluate the two imaging techniques by means of measurement noise and minimum detectable fracture

Methodology

PET fracture phantom experiment

Schematic diagram of the phantom fracture



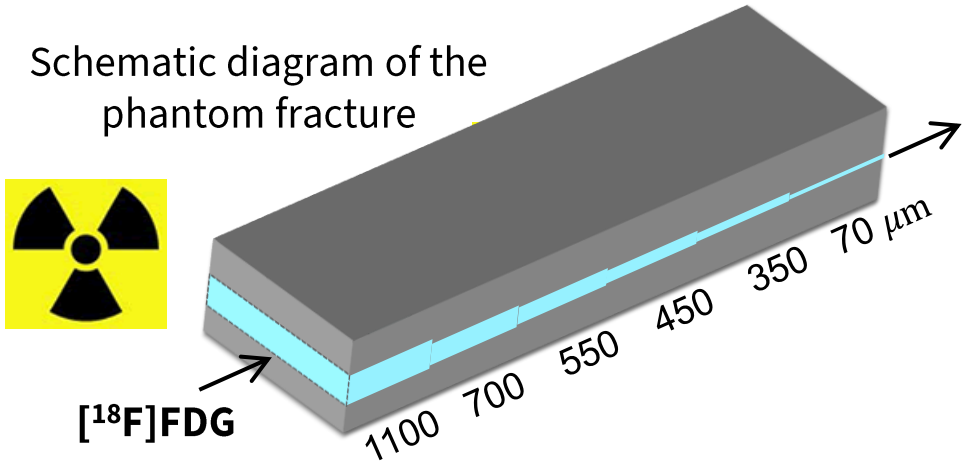


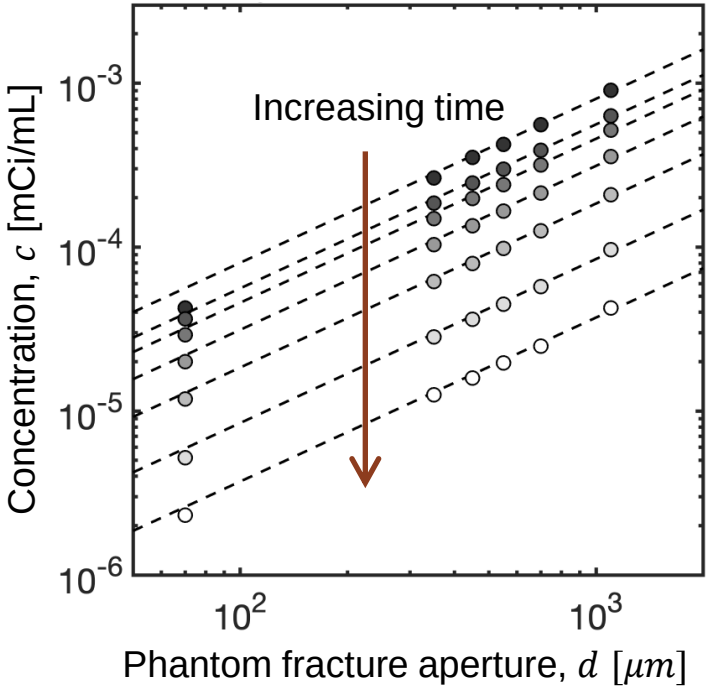
- Measured concentration decreases with time due to radiotracer decay
- PET concentration scales linearly with the size of the phantom aperture

Methodology

PET fracture phantom experiment

Schematic diagram of the phantom fracture





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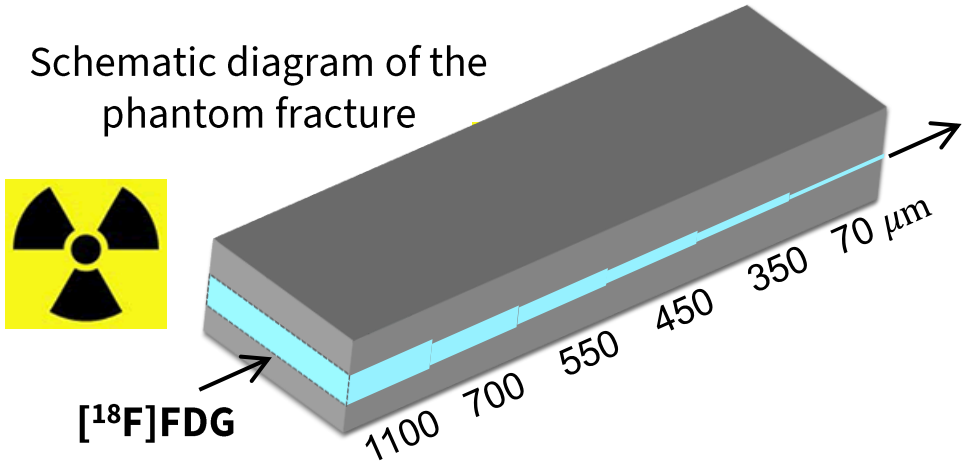

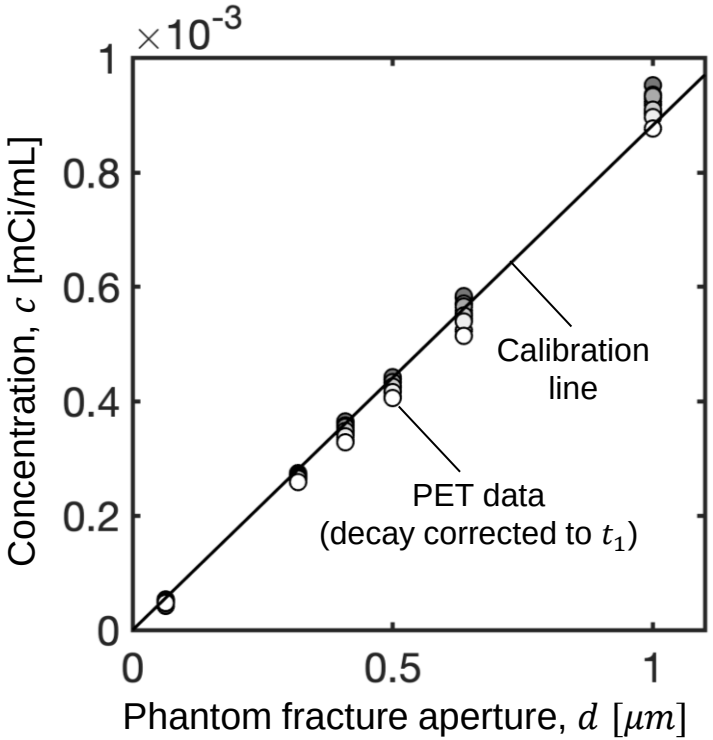

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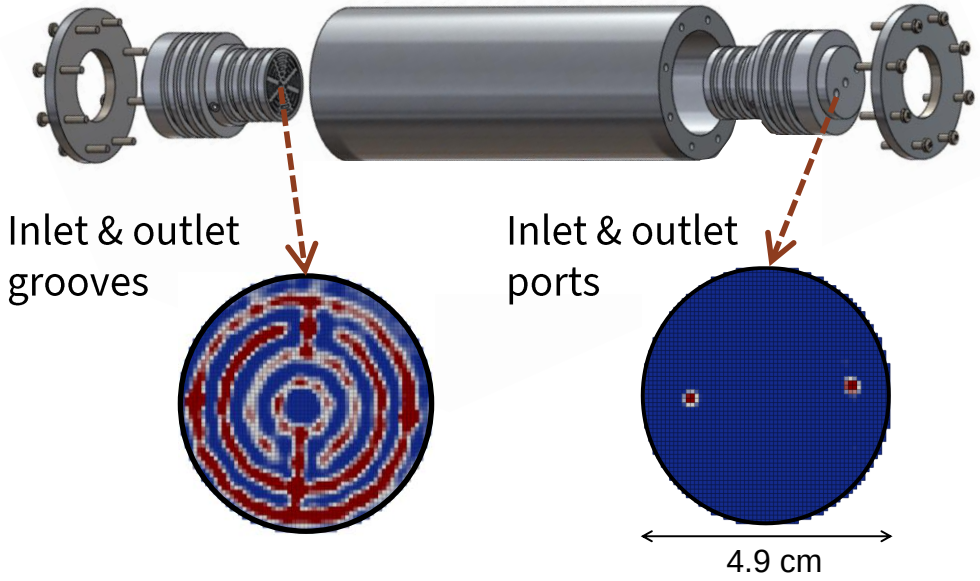
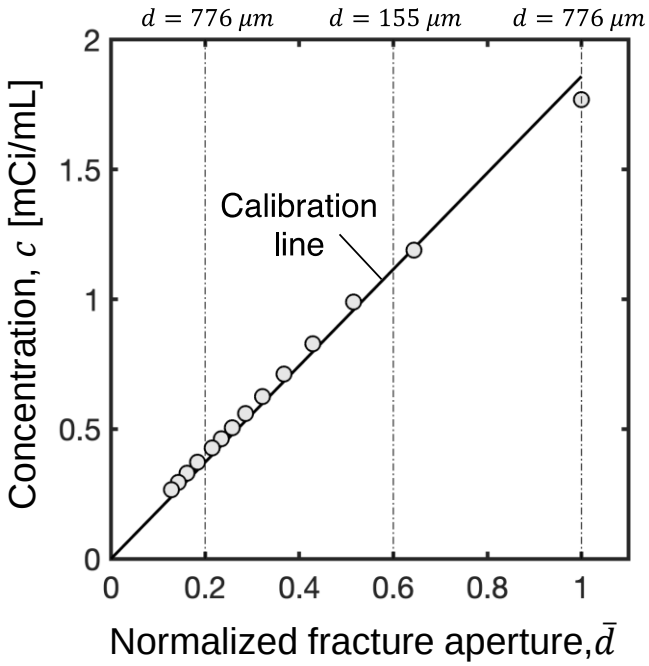
Methodology

How about experiments on real systems?

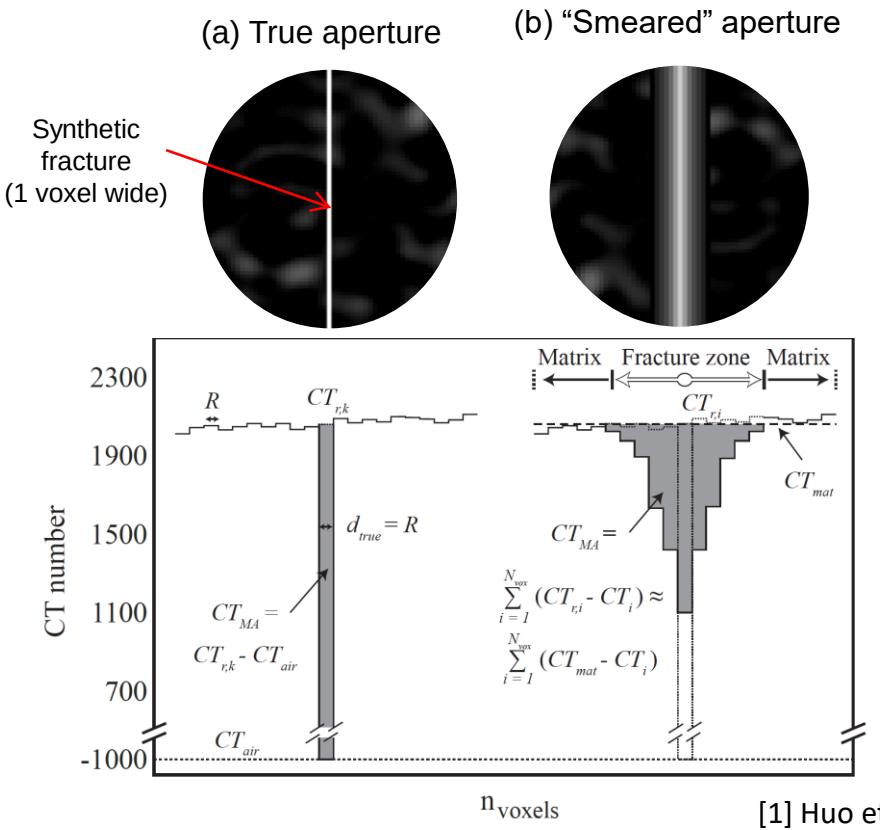




- Unique calibration line derived for each experiment based on grooves, ports at the inlet and outlet endcaps

Methodology: X-ray CT

The calibration free missing attenuation (CFMA) method[1]



- CT attenuation of rock's matrix smeared into the neighbouring voxels
- Due to various reasons, e.g. partial volume effects, finite volume width, oversampling
- CFMA assumes that this missing attenuation is fully conserved

CFMA expression

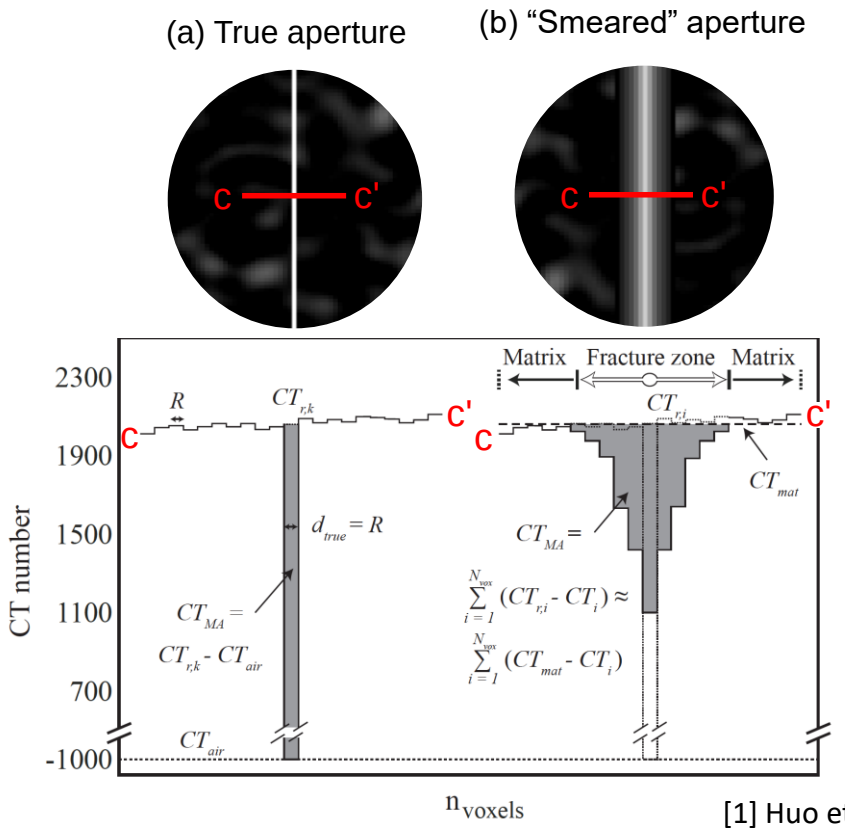
$$d = \frac{R \sum_{i=1}^{N_{vox}} (CT_{mat} - CT_i)}{CT_{mat} - CT_{air}}$$

Assumption: constant CT_{mat}

[1] Huo et al. **2016** *Geosphere*. 12 (2): 558–571

Methodology: X-ray CT

The calibration free missing attenuation (CFMA) method[1]



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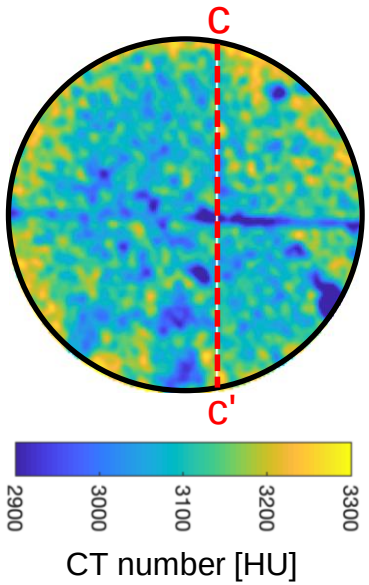
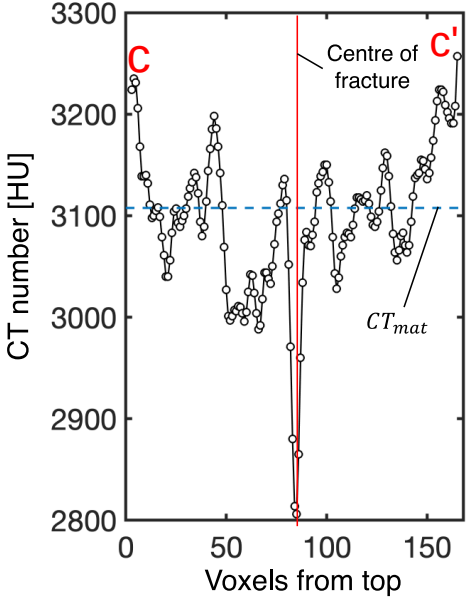
Methodology: X-ray CT

For heterogeneous rocks, the CFMA method does not work anymore…

e.g. Fractured Basalt

2D cross-sectional slice





- Local CT values of rock matrix can be very different in heterogeneous media
- Beam-hardening effects
- The CFMA formulation may lead to overestimation/underestimation of true apertures.

Methodology: X-ray CT

A *modified* calibration free missing attenuation (CFMA) method

CFMA[1]: $$d(CT_{r,k} - CT_{air}) = R \sum_{i=1}^{N_{vox}} (CT_{r,i} - CT_i) \quad [1]$$

Porosity[2]: $$\phi_i = \frac{CT_{water,i} - CT_{dry,i}}{CT_{water} - CT_{air}} \quad [2]$$

If CT number of the rock matrix ($CT_{r,i}$) is known, (fracture) porosity can also be obtained from:

$$\phi_i = \frac{CT_{r,i} - CT_i}{CT_{r,k} - CT_{air}} \quad [3]$$

Such that if $CT_i = CT_{air}$, $\phi_i = 1$
if $CT_i = CT_{r,i}$, $\phi_i = 0$

Combining Eqn. [1] and [3]:

$$d = \frac{R \sum_{i=1}^{N_{vox}} \phi_i \cancel{(CT_{r,i} - CT_{air})}}{\cancel{(CT_{r,i} - CT_{air})}} \quad [4]$$

Substitute Eqn. [2] into [4]:

Modified CFMA

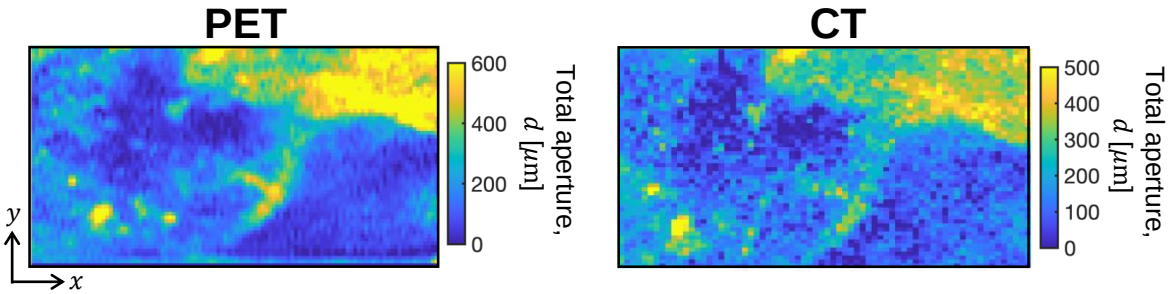
$$d = R \sum_{i=1}^{N_{vox}} \left[\frac{CT_{water,i} - CT_{dry,i}}{CT_{water} - CT_{air}} \right] \quad [5]$$

- No longer require the voxel CT number of rock matrix as input
- Effects of beam-hardening eliminated

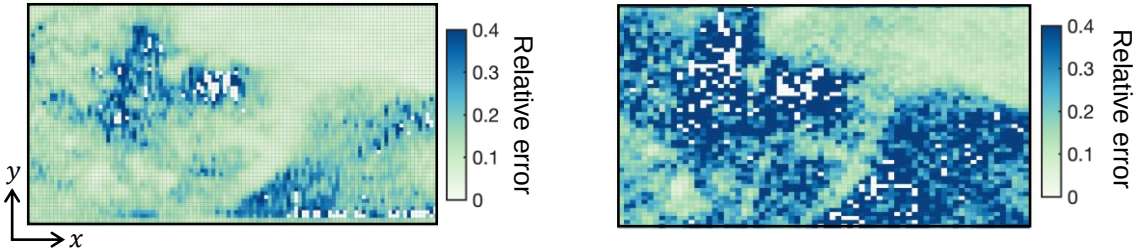
[1] Ketcham et al. **2010** *Geosphere*. 6 (5): 499–514
[2] Akin & Kovscek. **2003** *Geol. Soc.* 215 (1), 23-38

Fracture aperture & error maps: Fractured Basalt

Fracture aperture maps



Fracture (relative) error maps

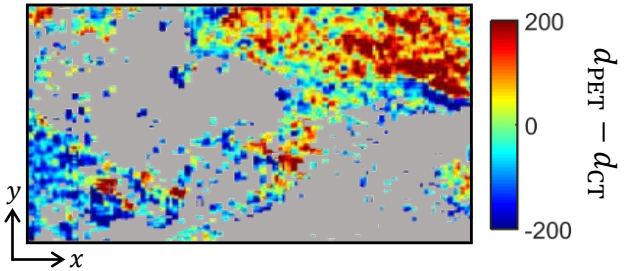


- Even saw-cut fracture can introduce a very heterogeneous distribution
- Overall distribution patterns of the fracture very similar
- CT aperture map much more scattered compared to PET
- CT aperture map gives higher errors particularly at voxels with smaller apertures

Spatial mapping of the local aperture values

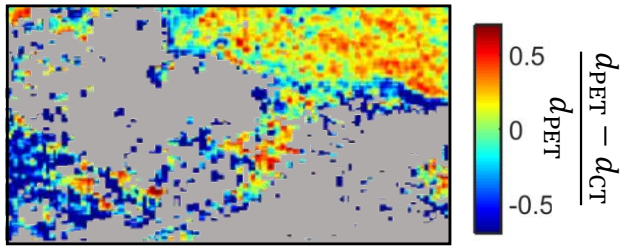
Absolute difference

$(d_{\mathrm{PET}} - d_{\mathrm{CT}})$



Relative difference

$(d_{\mathrm{PET}} - d_{\mathrm{CT}})/d_{\mathrm{PET}}$



- While the overall distributions are similar, the local aperture values are somewhat different
- $\bar{d}_{\mathrm{PET}} \approx \bar{d}_{\mathrm{CT}} = 250\ \mu\mathrm{m}$, but $\sigma_{\Delta} = 126\ \mu\mathrm{m}$

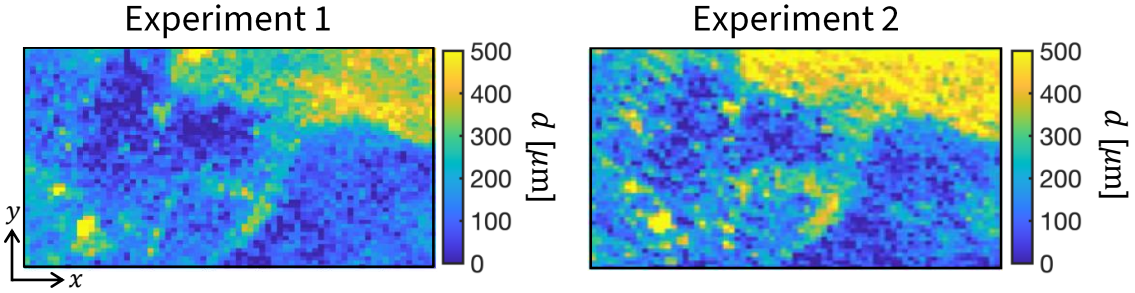
What are the possible causes of the deviation?

- Flaw in the methods applied?
- Discrepancy introduced during core packing (e.g. when aligning the fracture faces between experiments)?

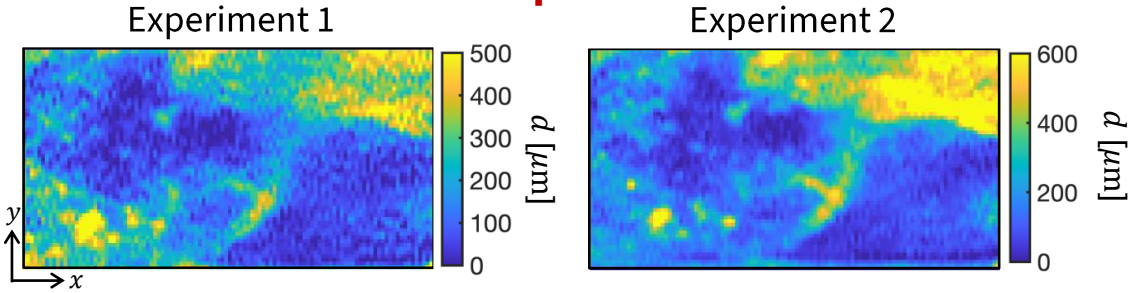
*Note the local aperture values below 99.5% confidence intervals have been segmented out (grey regions in the 2D maps)

Fracture aperture maps for repeated experiments

CT Repeats



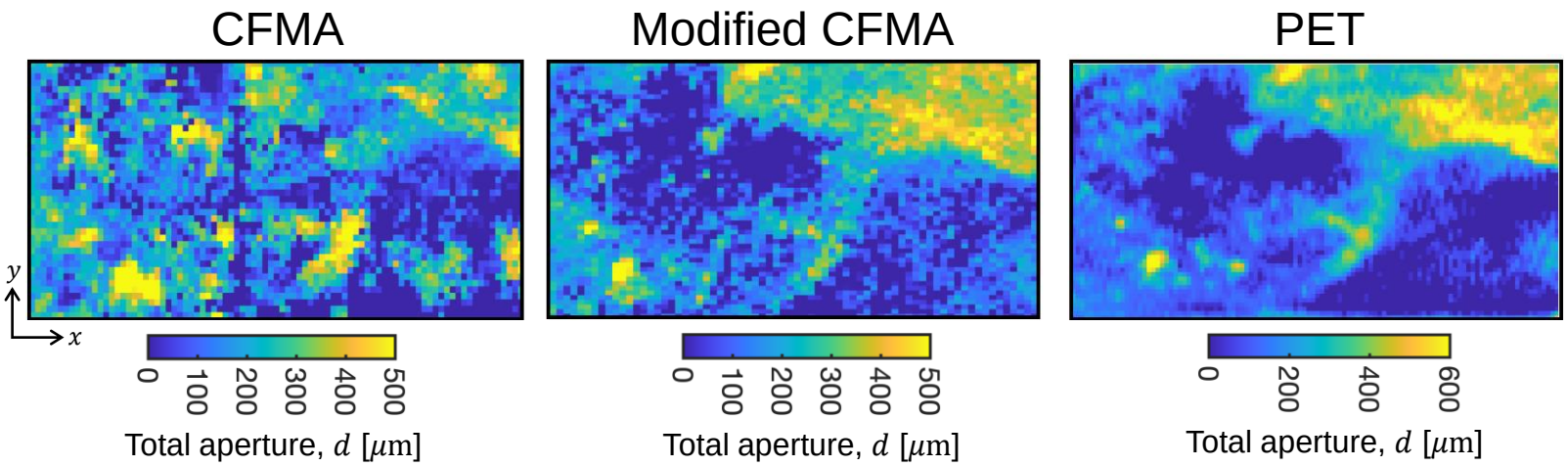
PET Repeats



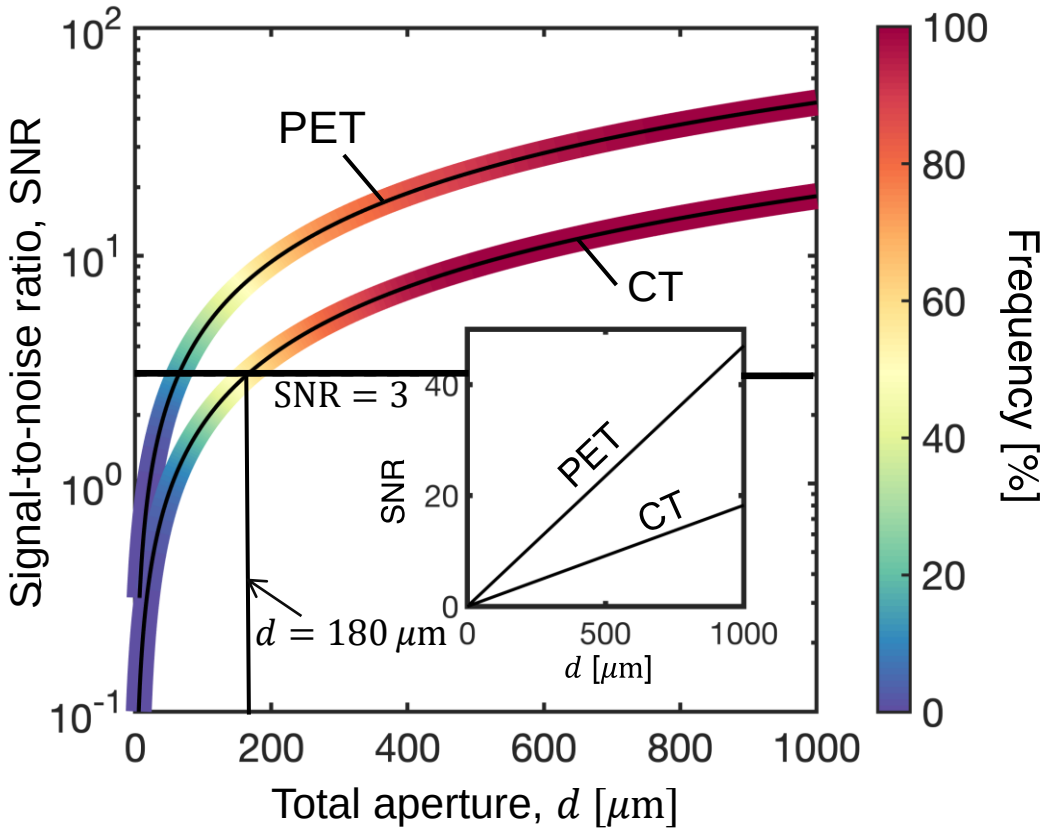
- Conditions of the experiments kept same, except the core was unloaded and repacked between experiments
- Even same imaging technique gives a difference in the local fracture aperture values
- Implying that these deviations are likely caused by variabilities in core packings

Comparisons of aperture maps from different methods

Conventional CFMA method fails to describe the spatial patterns of fracture heterogeneity

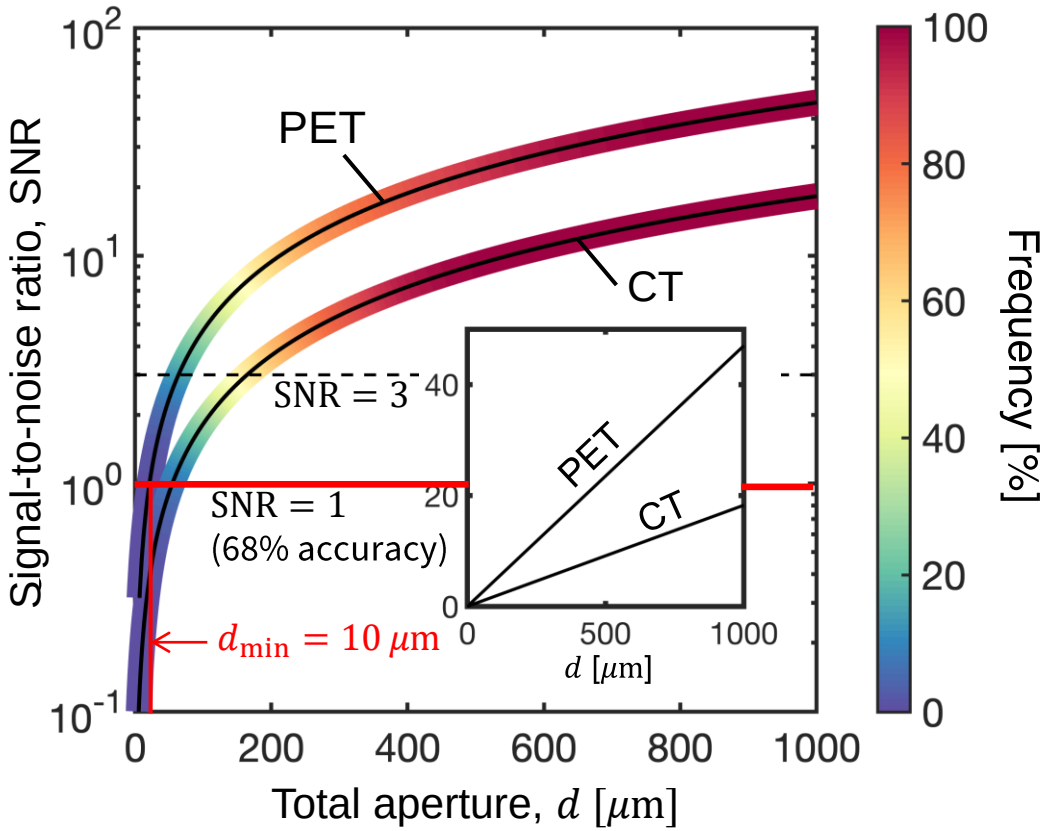


Signal-to-noise ratio (SNR) analysis



- $SNR_{PET} \gg SNR_{CT}$
- CT looses the sensitivity at low aperture regions:
  - $\sim$ 40% of the voxel CT numbers across the fracture plane has SNR < 3 ($d < 180\ \mu m$)
- Whereas, PET can detect minimum fractures (d_{min}) of about 10 μm with 68% accuracy (equivalent to SNR $= 3$)

Signal-to-noise ratio (SNR) analysis

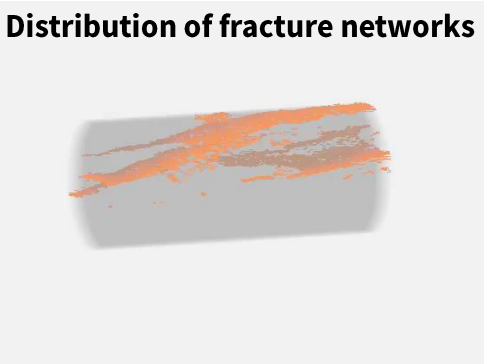


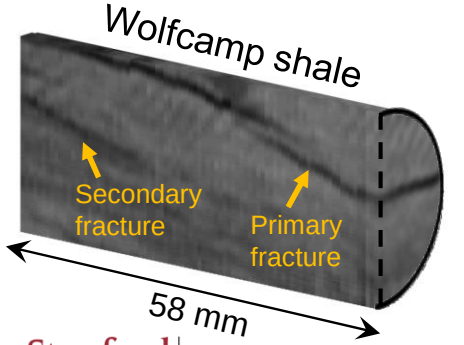
- $SNR_{PET} \gg SNR_{CT}$
- CT looses the sensitivity at low aperture regions:
  - ~ 40% of the voxel CT numbers across the fracture plane has SNR < 3 ($d < 180\ \mu m$)
- Whereas, PET can detect minimum fractures (d_{min}) of about 10 μm with 68% accuracy (equivalent to SNR = 3)

Concluding remarks

- Experimental workflows proposed to quantify fracture apertures in heterogeneous rock matrix using PET and X-ray CT
- The workflows successfully verified on a heterogeneous fractured Basalt core
- The conventional CFMA method fails to obtain accurate aperture maps; whereas the modified CFMA works well for heterogeneous systems
- PET represents a rigorous technique for characterizing fracture apertures because $SNR_{PET} \gg SNR_{CT}$, and can detects minimum fractures of ~ 10 μm

- **Next step:**
  Extend the protocol to natural fractures with more challenging fracture networks





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ACKNOWLEDGEMENTS

This work was supported as part of the Center for Mechanistic Control of Water-Hydrocarbon-Rock Interactions in Unconventional and Tight Oil Formations (CMC-UF), an Energy Frontier Research Center funded by the U.S. Department of Energy, Office of Science under *DOE (BES) Award DE-SC0019165.*

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