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 CO₂ 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.
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\(^{[1-3]}\)


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Advanced laboratory protocols needed to quantify the spatial structure of the complicated fractures embedded in heterogeneous rock matrix
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:
  \[ ^{11}C \rightarrow ^{11}B + ^{+} + e \]
  \[ ^{+} + e \rightarrow + \]

- Range of aqueous radiotracers (e.g., \([11C]NaHCO_3\), \([18F]FDG\))
Our experimental techniques

**Positron Emission Tomography**
- 3D temporal concentration profiles (Mixing, dispersion, imbibition\textsuperscript{[1-3]})

**Medical X-ray Computed Tomography**
- 3D distribution of static properties (Porosity, permeability, saturation\textsuperscript{[4-6]})

\[ x \quad y \quad z \]

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

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

\[ d = 776 \, \mu m \]
\[ d = 155 \, \mu m \]

Concentration, \( c \) [mCi/mL]

Normalized fracture aperture, \( \tilde{d} \)
Methodology: X-ray CT

The calibration free missing attenuation (CFMA) method

- 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

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

Assumption: constant \(CT_{\text{mat}}\)

Methodology: X-ray CT

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Methodology: X-ray CT

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

**e.g. Fractured Basalt**

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

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

If CT number of the rock matrix (\(CT_{r,i}\)) is known, (fracture) porosity can also be obtained from:
\[\phi_i = \frac{CT_{r,i} - CT_{i}}{CT_{r,k} - CT_{air}} \] \[3\]

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

Combining Eqn. [1] and [3]:
\[d = \frac{R \sum_{i=1}^{N_{vox}} \phi_i (CT_{r,i} - CT_{air})}{(CT_{r,i} - CT_{air})} \] \[4\]

Substitute Eqn. [2] into [4]:

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

- 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
Fracture aperture & error maps: Fractured Basalt

Fracture aperture maps

PET

CT

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
\( (d_{\text{PET}} - d_{\text{CT}}) \)

Relative difference
\( (d_{\text{PET}} - d_{\text{CT}})/d_{\text{PET}} \)

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

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

Experiment 1

Experiment 2

PET Repeats

Experiment 1

Experiment 2

- 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

- **CFMA**
- **Modified CFMA**
- **PET**

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Signal-to-noise ratio (SNR) analysis

\[
\text{SNR}_{\text{PET}} \gg \text{SNR}_{\text{CT}}
\]

- CT loses the sensitivity at low aperture regions:
  - \( \sim 40\% \) of the voxel CT numbers across the fracture plane has SNR < 3 (\( d < 180 \ \mu\text{m} \))

- Whereas, PET can detect minimum fractures (\( d_{\text{min}} \)) of about 10 \( \mu\text{m} \) with 68\% accuracy (equivalent to SNR = 3)
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- CT loses the sensitivity at low aperture regions:
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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 $\text{SNR}_{\text{PET}} \gg \text{SNR}_{\text{CT}}$, and can detect minimum fractures of $\sim 10 \, \mu m$

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

[Image of fracture networks and Wolfcamp shale with highlighted primary and secondary fractures]
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