Inverse analysis of fracture structures and flow for designing geological energy systems

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Design of Structure and Flow in the Earth Lab
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2007.4-2014.6 Undergrad~Ph.D. (Mechanical Eng/Environmental Studies, Tohoku U)
2014.6-2016.10 Postdoc (Geothermal group, Stanford)
2016.11-present Tenure track assistant professor (Fluid Science)
Design of Structure and Flow in the Earth Lab

Geothermal energy

Sustainable design?

STRUCTURE

FLOW

Static

Dynamic
1) How do structure and flow interact each other?
2) How to quantify fracture patterns?
3) Can we estimate structure or flow from the other data?
1) How do structure and flow interact each other?
RESEARCH TO FIELD DESIGN

Nature/Field → Experiment → Model

Model:
- Geometric
- Physical

Simulation → Prediction

Design
MICROFABRICATION APPROACH

Nature/Field

Experiment

Microfabrication

Model

Geometric

Physical

Simulation

Prediction

Microfluidics

3D printer
Core scale

**Moon rock**  
(Holloway, 2012)

**Coal rock**  
(Ju et al., 2014)

**Sandstone**  
(Ishutov et al., 2015)

**Single fracture surface**  
(Jiang et al., 2016)
FRACTURE NETWORK

Regional view

Satellite view

Field view

Fault zone

Minor fault zone

Reservoir simulation

Equivalent continuum model
(e.g., TOUGH2, FE-FLOW)

Discrete fracture network
(e.g., DFN, WORKS, FracMan)

Use 3D printer for validation
Scaling of fracture systems

(Castaing et al., 1996; Odling et al., 1999)

Min aperture / radius
0.2 / 1.6 mm

Max aperture / radius
1 / 8 mm
VisiJet ® EX200
3D Systems @Stanford 3-Dimensional Printing Facility (3D)

Base material:
  UV curable acrylic plastic
Support material:
  Hydrophobic wax
VALIDATION

CT scanning

Flow experimental results

Ideal 3D printing

Consistent with conventional theoretical studies (Jensen, 1991)

Suzuki et al., WRR, 2017
COMPARISON

CFD simulation

Equivalent permeability model

\[ K_x = \sum_j \frac{\eta_j^2 \eta_j L_j}{12 A_x} \]
- Areas of grid cell interfaces orthogonal to the x
- \( j \): Numbering of fractures
- \( \eta_j \): Aperture
- \( L_j \): Length of the fracture intersecting the interface of grid cells

Calculate flow rate by using Darcy’s law:

\[ Q_x = A_x \frac{K_x \Delta P}{\mu \Delta x} \]
- \( \Delta P/\Delta \): Pressure gradient
- \( \mu \): the viscosity of water

Good agreement

Need modification

Suzuki et al., TiPM, submitted
1) How do structure and flow interact each other?

*Microfabrication approach will help to understand.*
1) How do structure and flow interact each others?

Microfabrication approach will help to understand.

2) How to quantify fracture patterns?
QUANTIFICATION OF FRACTURE STRUCTURES

Quantitative tools for geometry
• intensity [Mauldon et al., 2001]
• length [Bour et al., 2002]
• density [La Pointe, 1988]
• fractal dimension [Bonnet et al., 2001]
• percolation thresholds [Mourzenko et al., 2005]
• topology of networks [Sanderson and Nixson, 2015]
  etc.
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Application

- material science [Hiraoka et al., 2016]
- data memory [Choudhury et al., 2012]
- RNA folding space [Mamuye et al., 2016]
- viral evolution [Chan et al., 2013]
- etc.
## Persistent Homology

### Thinning

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### Thickening

Persistence diagram

Software: HomCloud (Hiraoka and Obayashi)
PERSISTENT HOMOLOGY FOR FRACTURES

Fracture width

Fracture spacing

Matrix blocks

birth $\sim -$ width

dead $\sim$ spacing

# pairs = # blocks

Suzuki et al., GRL, submitted
**Discrete Element Method**

Numerical simulation

Model

- fracturing
- fluid flow

Hydration reaction

Results

Flow conditions

Estimation

FLOW

DATA

STRUC-TURE

Suzuki et al., GRL, submitted

(Shimizu and Okamoto, Contrib. Mineral Petrol. , 2016)
PERSISTENT HOMOLOGY ANALYSIS

Suzuki et al., GRL, submitted
PERSISTENT HOMOLOGY ANALYSIS

Suzuki et al., GRL, submitted
1) How do structure and flow interact each others?

Microfabrication approach will help to understand.

2) How to quantify fracture patterns?

Persistent homology will help.
CURRENT WORK

New 3D printer

KEYENCE
AGILISTA -3200

Base material:
UV curable acrylic plastic
Support material:
Hydrophilic plastic
**STRUCTURE**

- Measurement data
  - Tracer
  - Thermal response
  - Electrical resistivity etc.

**FLOW**

- Multiphysics
  - Chemical reaction (Precipitation/dissolution)
  - Anisotropic stress field
1) How do structure and flow interact each others?

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Persistent homology will help.

3) Can we estimate structure or flow from the other data?
Tracer test solute tracer (e.g., dyes, radioactive, …)

Preferential paths  
(Hawkins et al., 2017)
Fracture aperture estimation

Fracture nm - cm

Minimum aperture in a flow path = critical aperture (Nishiyama et al., 2017)
Fracture
nm - cm

Minimum aperture in a flow path
= critical aperture (Nishiyama et al., 2017)

Nano-/microparticle tracers

- DNA-embedded particles
  → make barcode

* Various materials
  → Use in Extreme environments

* Small devices
  → possibility ∞
1. Preparing particles
2. Creating micro structures
3. Flow test under microscope
4. Measuring particle concentration
Fluorescent nano-/microparticles

500 nm green fluorescent
(Corpuscular Inc., New York, USA)

silica (2.0 g/cm³)
0.25 mg/ml
2D micromodel

1. Create mask
2. Etch silicon wafer
3. Cover glass

micro CT scan data of sandstone

rock grain
pore

EXPERIMENT

(Alaskar et al., Proc. SGW, 2013)
**Apparatus**

- Water tank
- Flow rate: \(3.19 \times 10^{-4} \text{ cm}^3/\text{s}\)
- Water head difference: \(~2 \text{ m}\)
- Tracer injection
- Microscope
- Micromodel
- Microtube

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Suzuki et al., Proc. SGW, 2018
Tunable resistive pulse sensor: qNano (Izon Science Inc.)

* particle diameter, volume, effective surface charge, Zeta potential

(Platt et al., 2012)
Matrix

Fracture

50 μm
EXPERIMENTAL RESULTS

SEM images of droplets at outlet

TIME: 12 h  TIME: 18 h  TIME: 36 h

Suzuki et al., Proc. SGW, 2018
Estimation of concentration from SEM images

\[
\text{Concentration} = \frac{\text{Green}}{\text{Green} + \text{Blue}}
\]

EXPERIMENTAL RESULTS

Suzuki et al., Proc. SGW, 2018
Tracer response obtained from qNano

EXPERIMENTAL RESULTS

Suzuki et al., Proc. SGW, 2018
Estimation method for critical aperture

Fracture aperture

\[ b_1 > b_2 > b_3 \]
PROPOSED METHOD

\[ b_1 < d < b_2 \]

\[ b_2 < d < b_1 \]

\[ b_1 > b_2 > b_3 \]

path 1

path 2

path 3
Estimation method for critical aperture

Suzuki et al., Proc. SGW, 2018
**PROPOSED METHOD**

**Estimation method for critical aperture**

- Particle size [nm]
- Critical aperture [nm]
- Permeability [m²]
  \[ k_i = \frac{b_i^2}{12} \]
- Flow rate [m/s]
  \[ q_i = -k_i \cdot \mu \cdot \nabla P \]
- Travel time [sec]
  \[ t_i \]
- Path length [m]
  \[ L_i = \frac{q_i}{t_i} \]

Suzuki et al., Proc. SGW, 2018
1) How do structure and flow interact each others?

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3) Can we estimate structure or flow from the other data?

Particle tracers will estimate critical fracture aperture.
Topological fracture characterization

3D printing fractures

Fractional derivatives in mass/heat transfer equation

My Ph.D.

Aperture estimation by particle tracers

Supercritical fluid fracturing simulation

Microfluidics for salt precipitation due to CO2 injection

Surface area estimation by tracer/thermal breakthrough

Machine learning for permeability distribution estimation

Application

TOPIC 1

TOPIC 2

TOPIC 3
Design of Structure and Flow in the Earth Lab

fundamental

3D printing fractures

Topological fracture characterization

Fractional derivatives in mass/heat transfer equation

Aperture estimation by particle tracers

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Machine learning for permeability distribution estimation

Miyazawa (M1)

Cui (M1)

Liu (D1)

Huong (M2)

Yamaguchi (B4)
Topological fracture characterization

3D printing fractures

Fractional derivatives in mass/heat transfer equation

Physical meaning of fractional derivatives

$0 < \gamma < 1$
Supercritical fluid fracturing simulation

Liu (D1)

Design of Structure and Flow in the Earth Lab

Two phase flow

Fracture propagation

Microfluidics for salt precipitation due to CO2 injection

Huong (M2)

Double nodes
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Surface area estimation by tracer/thermal breakthrough

Yamaguchi (B4)

Machine learning for permeability distribution estimation

Fracture surface area estimation

Injection well B9

Production well B4

Error

Learning curve
Fifteenth International Conference on Flow Dynamics, Sendai, Miyagi

November 7 - 9, 2018
Sendai International Center

JSPS Postdoctoral Fellowships for Research in Japan
Inviting Excellent Researchers from Other Countries to Japan
THANK YOU

anna.suzuki@tohoku.ac.jp
Size distribution measured by qNano

Analyzed sample before injection

EXPERIMENTAL RESULTS
Sustainable design for geothermal systems

Collaboration: Geothermal company

Sparse data
(temperature, pressure, tracer ...)

Network estimation
Future prediction
Sustainable design

Geothermal field = Fracture network