Proceedings World Geothermal Congress 2026, Calgary, Canada, June 8—11, 2026

Bridging Fracture Structures and Flow: Inferring Heat Transport Pathways from Geometry via Topological Data Analysis

Hasumi T.[1, 2]*, Imoto Y.[3], Uda T.[4], Suzuki A.[1]

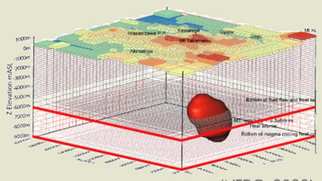
IFS, Tohoku Univ.[1]*, Grad. Sch. Eng., Tohoku Univ.[2]*, ASHBi, Kyoto Univ.[3], Fac. Sci., Univ. Toyama[4]

INTRODUCTION

Conventional geothermal reservoir model

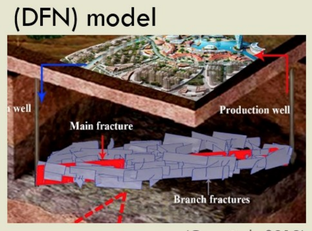
➡Focus on complex spatial shape of fractures

3D block model



(NEDO, 2022)

Discrete Fracture Network (DFN) model



(Guo et al., 2019)

Challenges

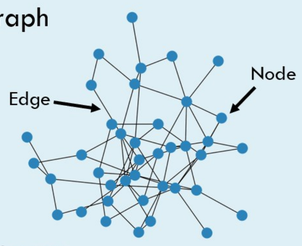
- Numerous parameters required
- Time-consuming model preparation
- High computational cost

Shift in perspective

New geothermal reservoir model

➡Focus on fracture connectivity

Graph



Advantages

✓Fewer parameters

✓Easy model preparation

✓Low computational cost

Background

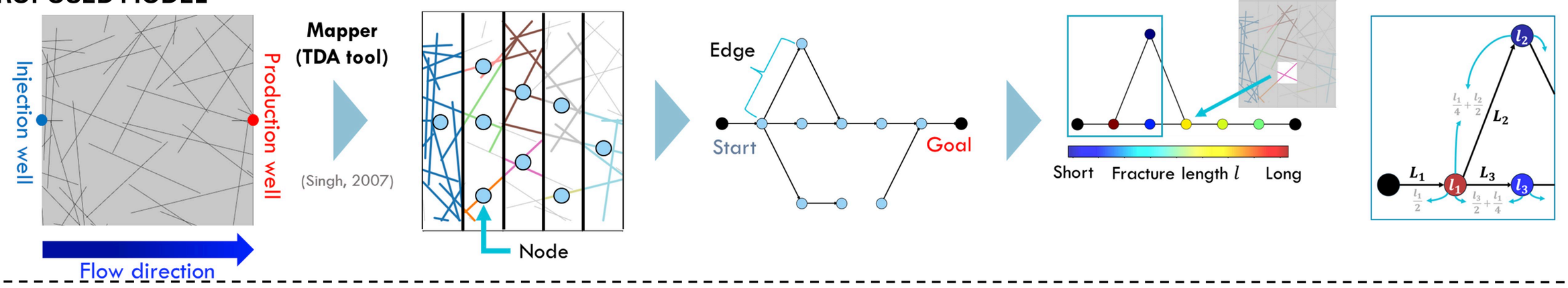
Fluid flow in geothermal reservoirs is controlled by fracture networks, but conventional models require many parameters, heavy preprocessing, and high computational cost.

OBJECTIVE

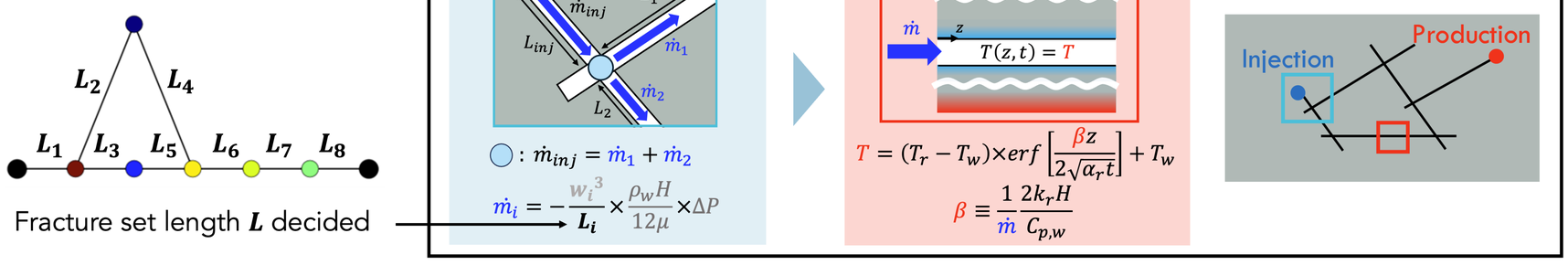
Shift the focus from detailed geometry to fracture connectivity and establish a simpler, more flexible representation of subsurface flow structures.

Topological Data Analysis (TDA)

PROPOSED MODEL



An analytical thermohydraulic mode (D. B. Fox et al., 2016)



1. Formulate a mass balance equation ○ at each node on the graph
2. Calculate the mass flow rate ṁ of each fracture based on the characteristic length of the fracture set on each edge
3. Calculate the temperature T of the fluid flowing through the fracture based on the mass flow rate

VALIDATION

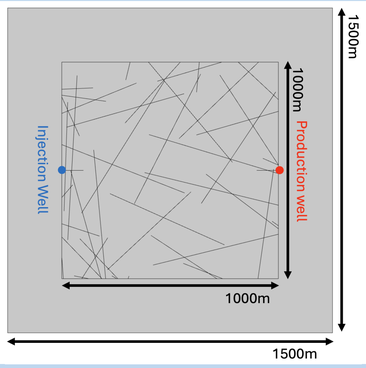
Statistical rules for creating DFN models (Wang et al., 2024)

Probability density function of fracture length *n(l)*

$$n(l) = \gamma l^{-a} \quad \text{for } l \in [l_{\min}, l_{\max}]$$

Total length of fractures per unit area *d*

$$d = \frac{1}{L^2} \int_{l_{\min}}^{l_{\max}} n(l)\, l dl$$

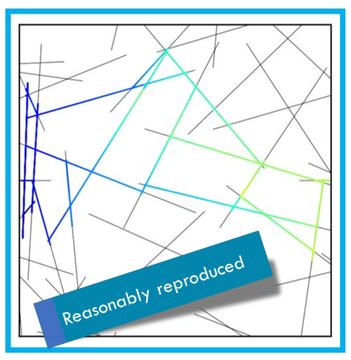


Simulation conditions

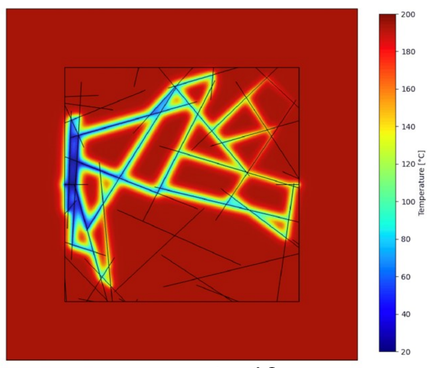
- Matrix thickness: 500 m
- Fracture aperture width: 1 mm
- Initial temperature: 200 °C
- Injection time: 10 years
- Injection temperature: 20 °C
- Injection pressure: 20 MPa
- Injection mass floe rate: 200 kg/s
- Maximum fracture length l_{max}: 800 m
- Minimum fracture length l_{min} : 500 m
- Power-low exponent a: 2.0
- d: 0.015
- Thermal conductivity of matrix: 2.7 W/m °C
- Thermal conductivity of fluid: 0.6 W/m °C
- Heat capacity of matrix: 1050 J/kg °C
- Heat capacity of fluid: 4300 J/kg °C
- Density of matrix: 2700 kg/m³
- Density of fluid: 1000 kg/m³
- Viscosity of fluid: 0.001 Pa s

RESULTS & DISCUSSION

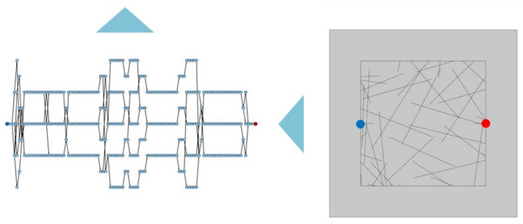
Fluid temperature filed estimation results



COMSOL simulation result

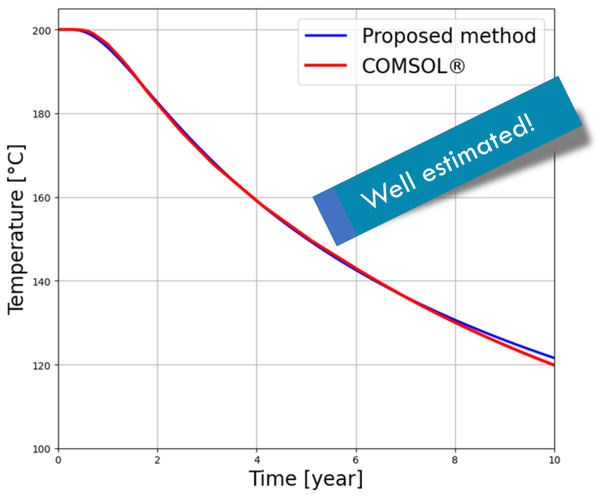


t = 10 years



- Successfully calculated the temperature field of the flow paths that extends from the injection well to the production well
- The detected flow paths were generally consistent with the COMSOL results
- However, since Mapper captures the connectivity from the injection well to the production well, it cannot capture the flow path in the opposite direction to this global direction.

Variation of *T* at the production well

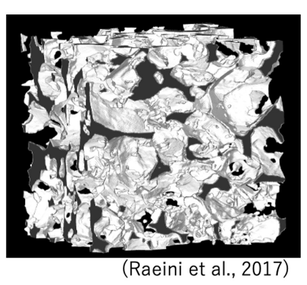


- Overestimation at 10 years possibly due to the analytical solution not accounting for thermal interference between fractures
- Error remains small (~5 °C) because convection dominates in this case
- Accuracy may decrease in conduction-dominated or densely fractured systems unless thermal interference is included

CONCLUSION

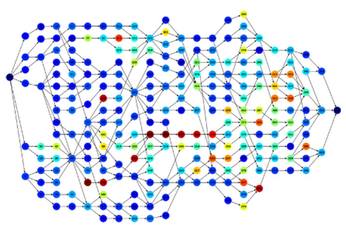
- Proposing a new numerical model for geothermal reservoirs using Mapper, a TDA tool
- Heat transfer analysis was performed on a graph, and fluid temperature changes were successfully estimated
- Permeability estimation has already been investigated within the same framework, and integration of both will lead to a multiphysics approach

Rock image data

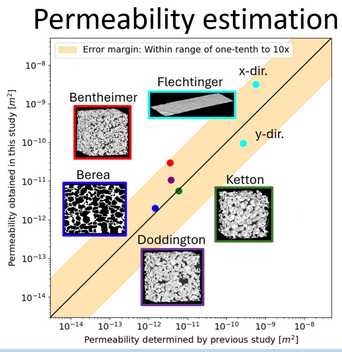


(Raeini et al., 2017)

Graph



Permeability estimation



Acknowledgements

This work was supported by the JSPS KAKENHI JP20H02676, JP22H05108, JP24K01413.

REFERENCES

Hyman, J.D., Hagberg, A., Srinivasan, G., Mohd-Yusof, J., and Viswanathan, H.: Predictions of First Passage Times in Sparse Discrete Fracture Networks Using Graph-Based Reductions, *Physical Review. E*, **96**, (2017), 013304.

Blunt, M., Jackson, M., Piri, M., and Valvatne, P.: Detailed Physics, Predictive Capabilities and Macroscopic Consequences for Pore-Network Models of Multiphase Flow., *Advances in Water Resources*, **25,** (2002), 1069–1089.

Wang, S., Zhang, L., Zhou, J., Yang, D., Han, Z., and Kong, Y.: Quantitative analysis of fracture network geometry on fluid flow and heat transfer in hot dry rock geothermal reservoirs, *Energy*, **313**, (2024), 133815.

Fox, D.B., Koch, D.L., and Tester, J.W.: An analytical thermohydraulic model for discretely fractured geothermal reservoirs, *Advances in Water Resources*, **52**, (2016), 6792–6817.

Singh, G., Mémoli, F., and Carlsson, G.: Topological methods for the analysis of high dimensional data sets and 3D object recognition, Eurographics Symposium on Point-Based Graphics, **2**, (2007), 91–100.