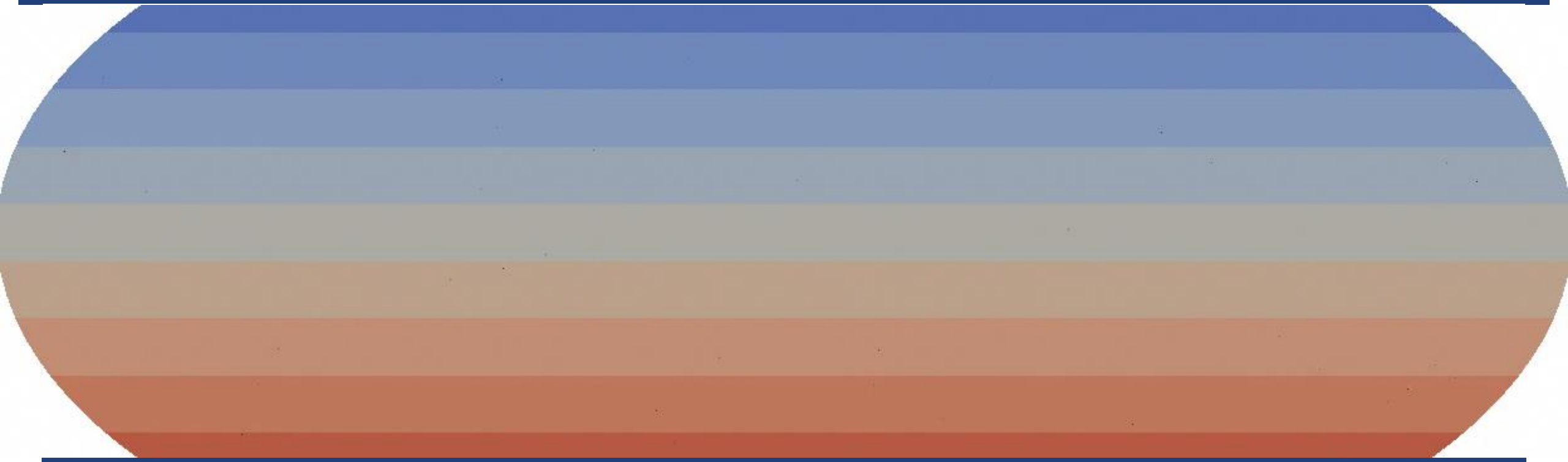

Numerical Modeling of Thermal Convection in Multiple Fractures

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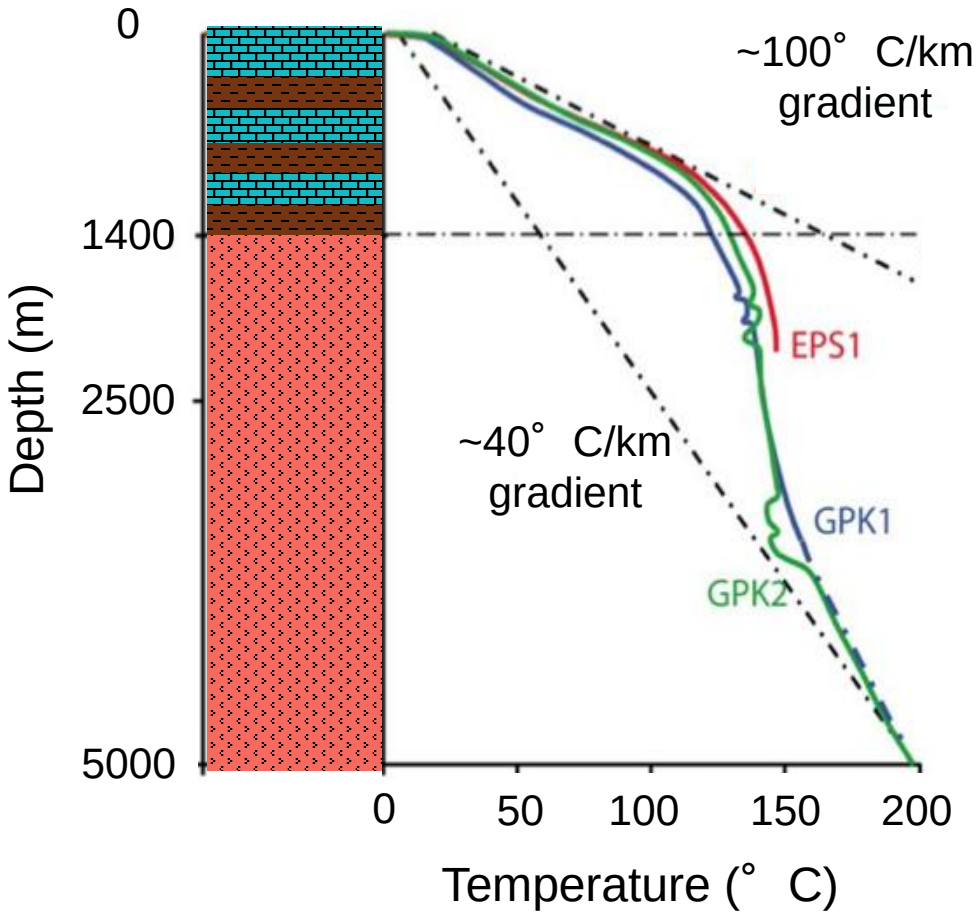
Natural Convection

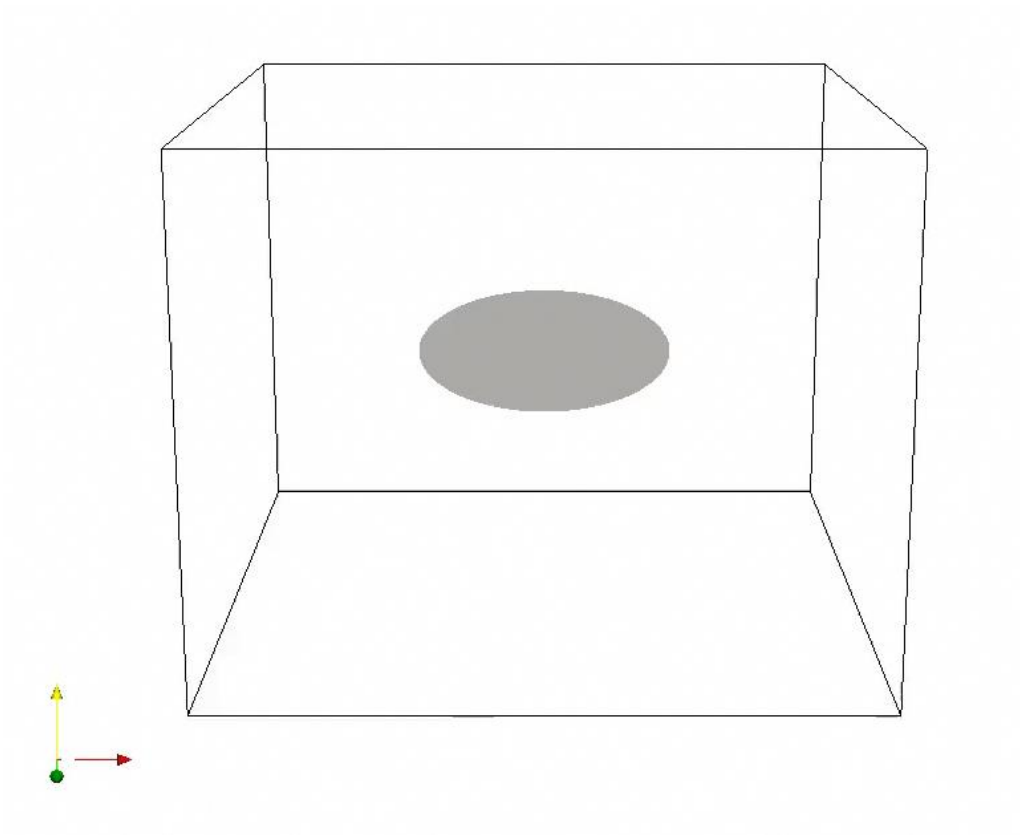
- Soultz-sous-Forêts
  - Geothermal gradient in crystalline basement cannot be entirely due to conduction
  - Basement rock permeability too low for Rayleigh convection
  - Fractures provide conduit for fluid
- Convection thought to occur within fractures



Single Fracture

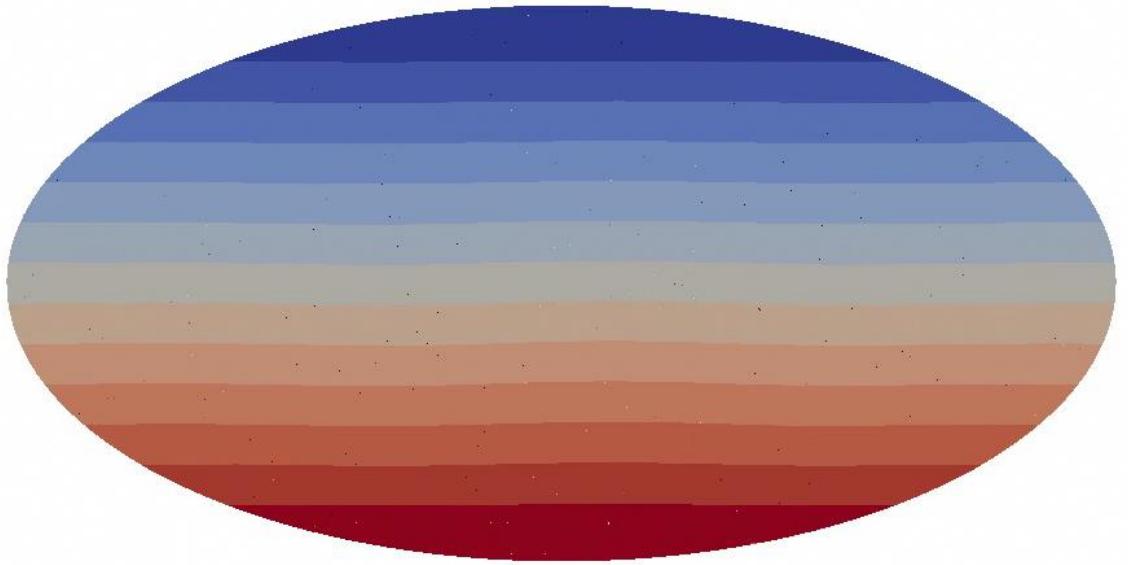
- Natural convection forms “cells”
- Key Factors:
  - Fracture aperture (0.5 & 0.75 mm)
  - Basal heat flow (85 mW/m^2)
  - Rock thermal conductivity (2 W/m/K)
- Low permeability host rock (10^{-18}m^2)
  - Closed loop system
  - Upward flow offsets downward flow

- Model: 4km height, 5km length, 5km width
- Fracture: 1km height, 2km length, variable aperture



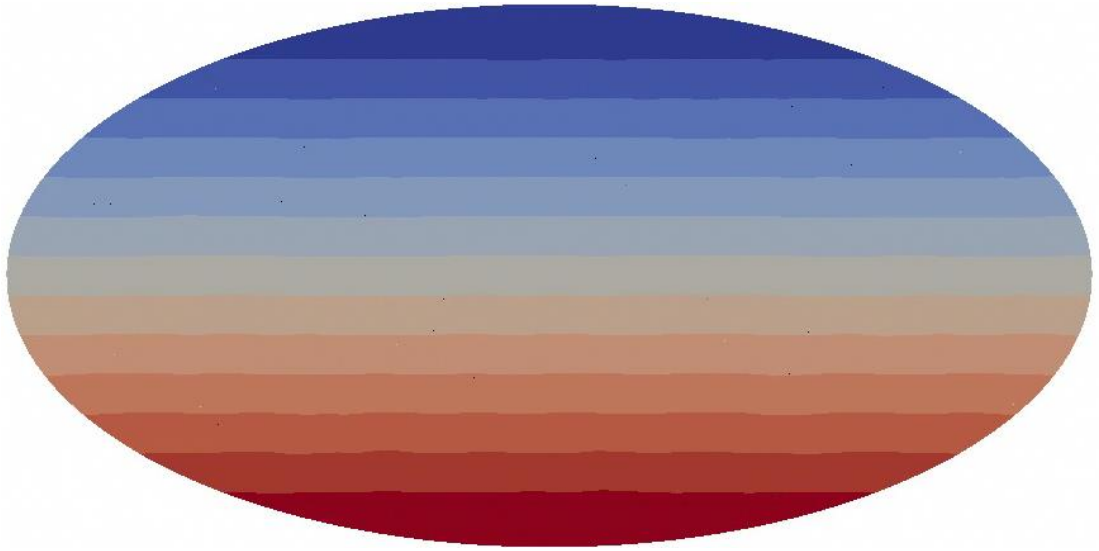
Single Fracture

Fracture aperture = 0.50 mm
Model time ≈ 20,000 years

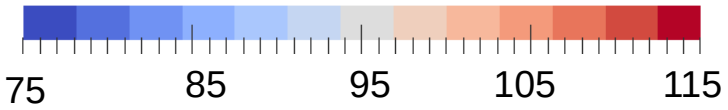


2 km

Fracture aperture = 0.75 mm
Model time ≈ 4,000 years



2 km



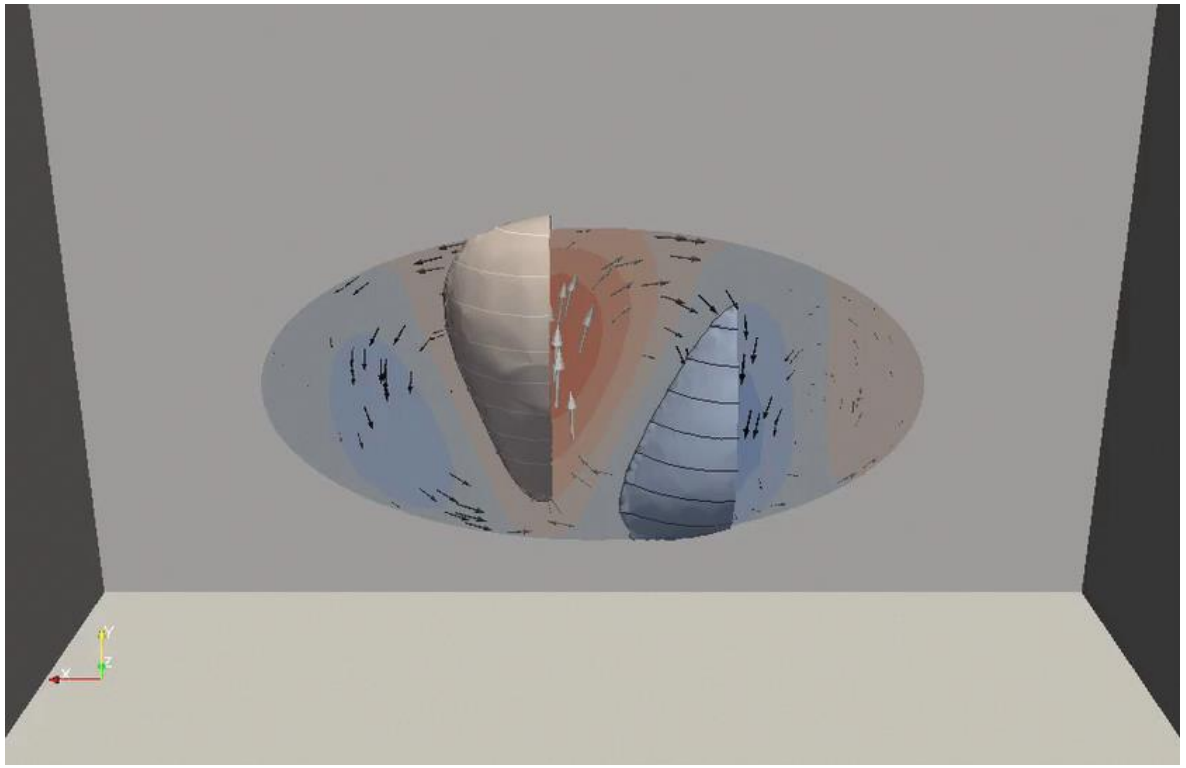
Temperature (°C)

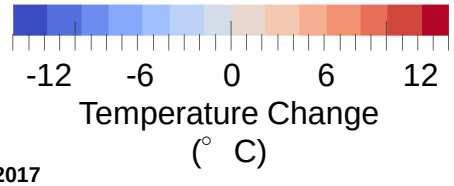
⇧ White arrow = upward flow

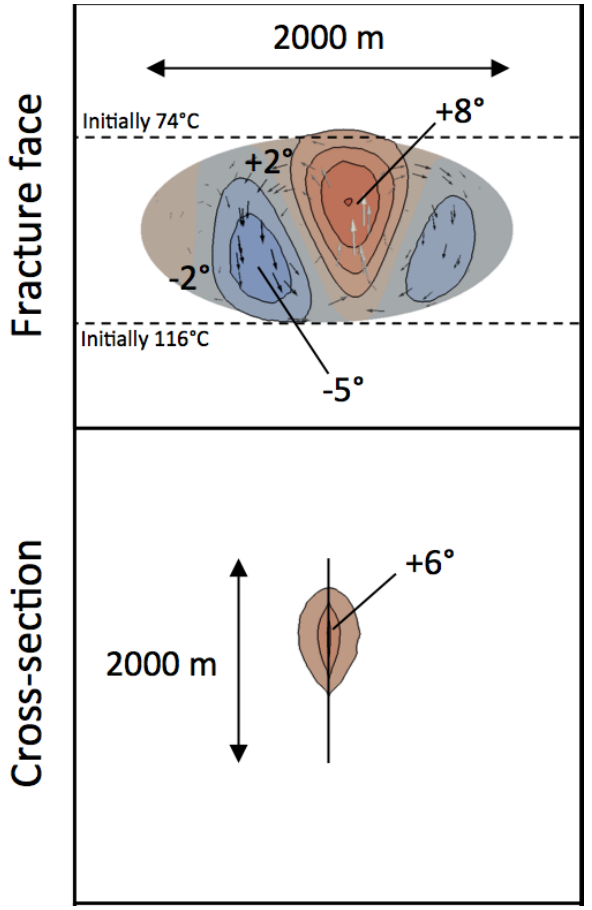
⇩ Black arrow = downward flow

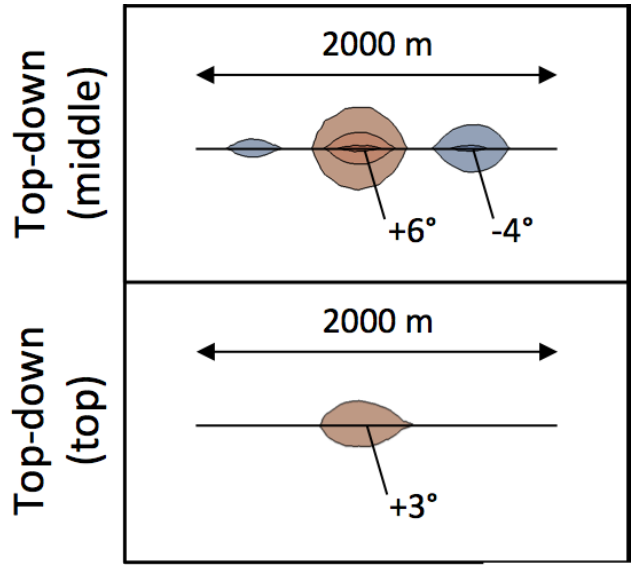
Single Fracture – slice through middle

Fracture aperture = 0.50 mm



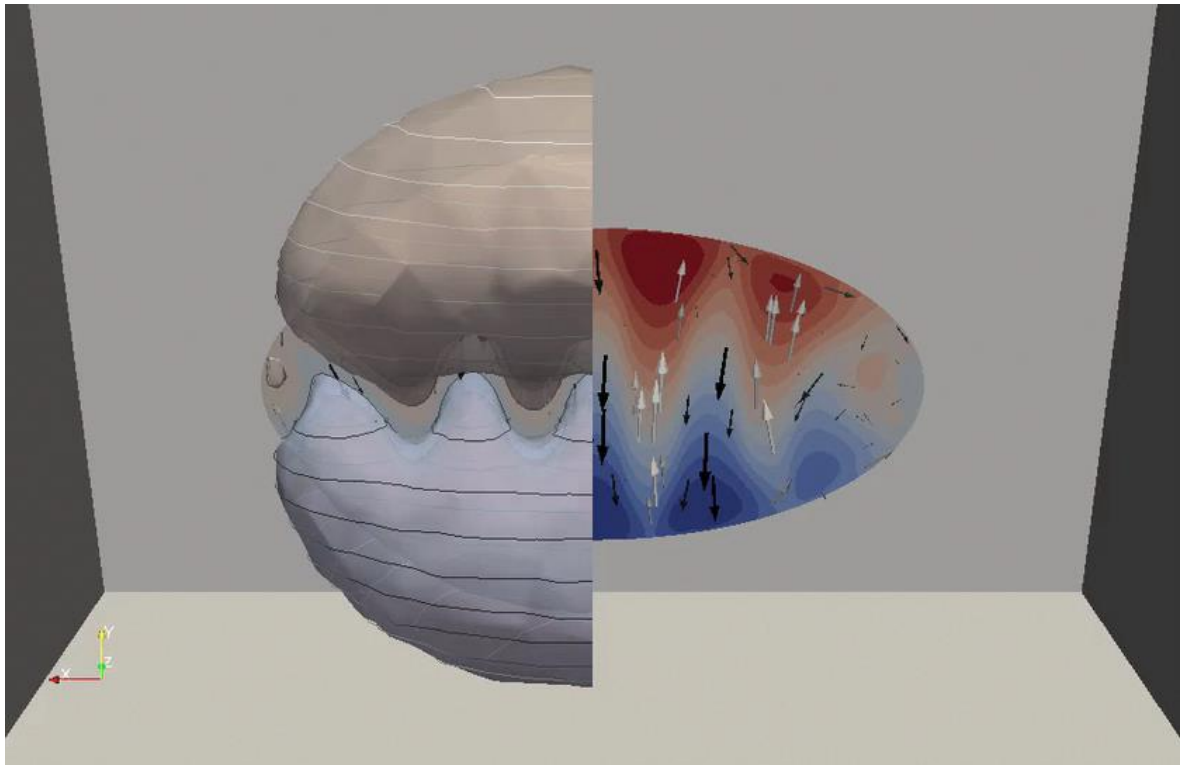


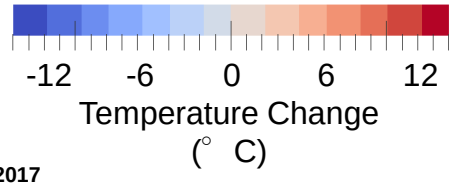


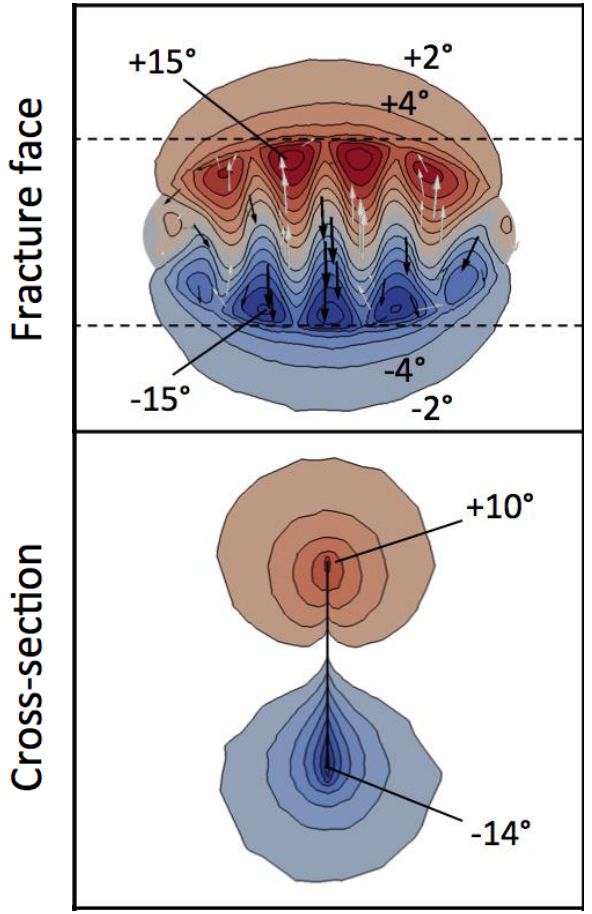


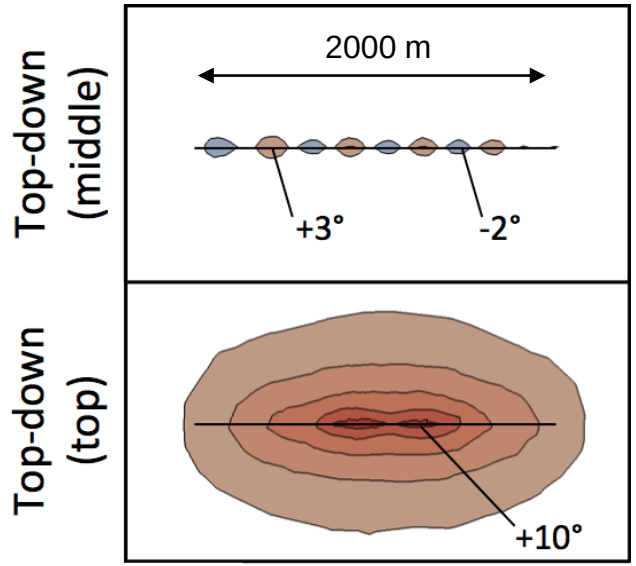
Single Fracture – slice through middle

Fracture aperture = 1.0 mm



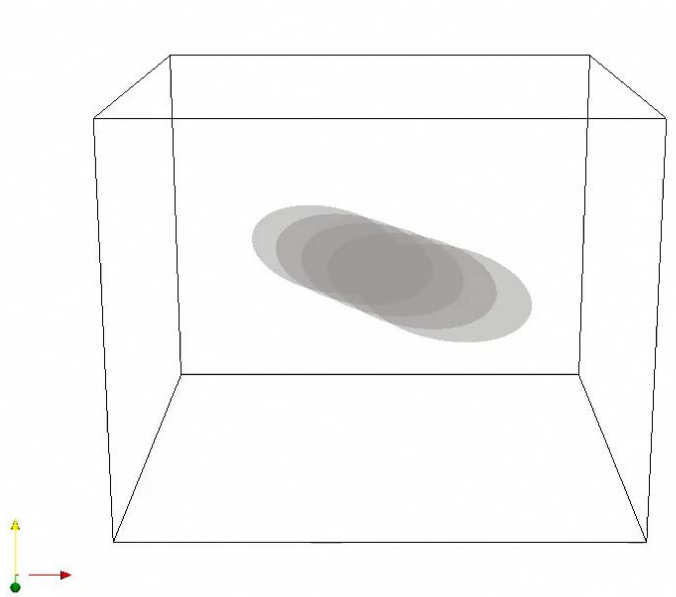


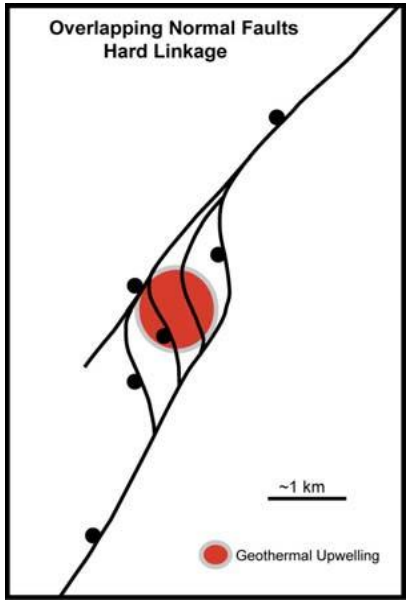


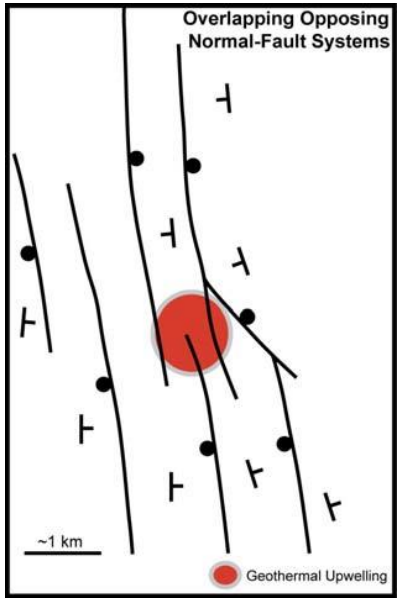


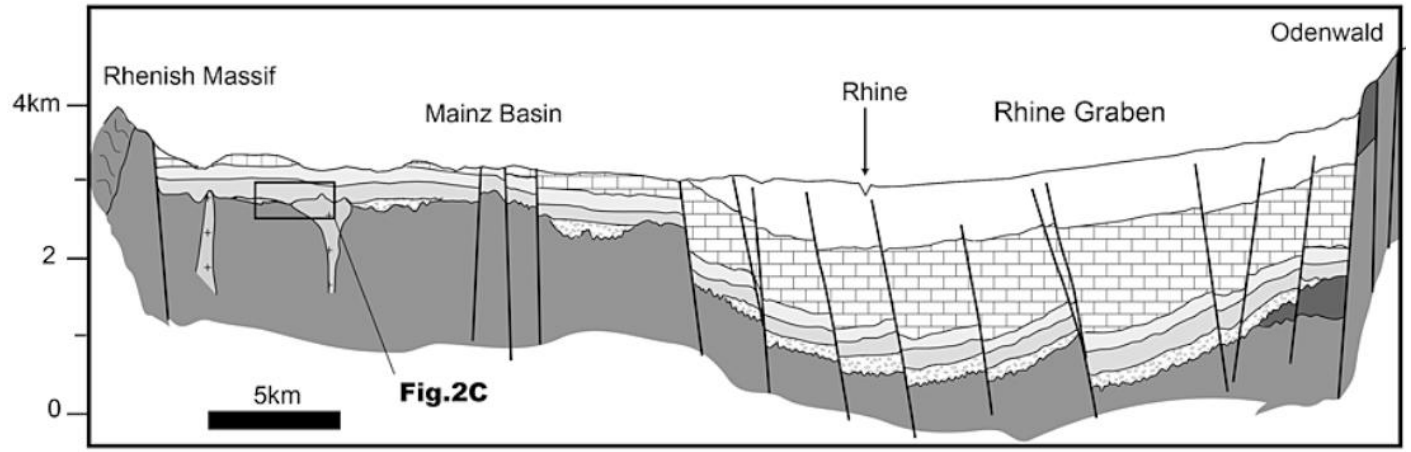
Multiple Fractures

- Fractures and faults typically come in sets
- Does a convecting fracture influence non-connected, neighboring fractures?







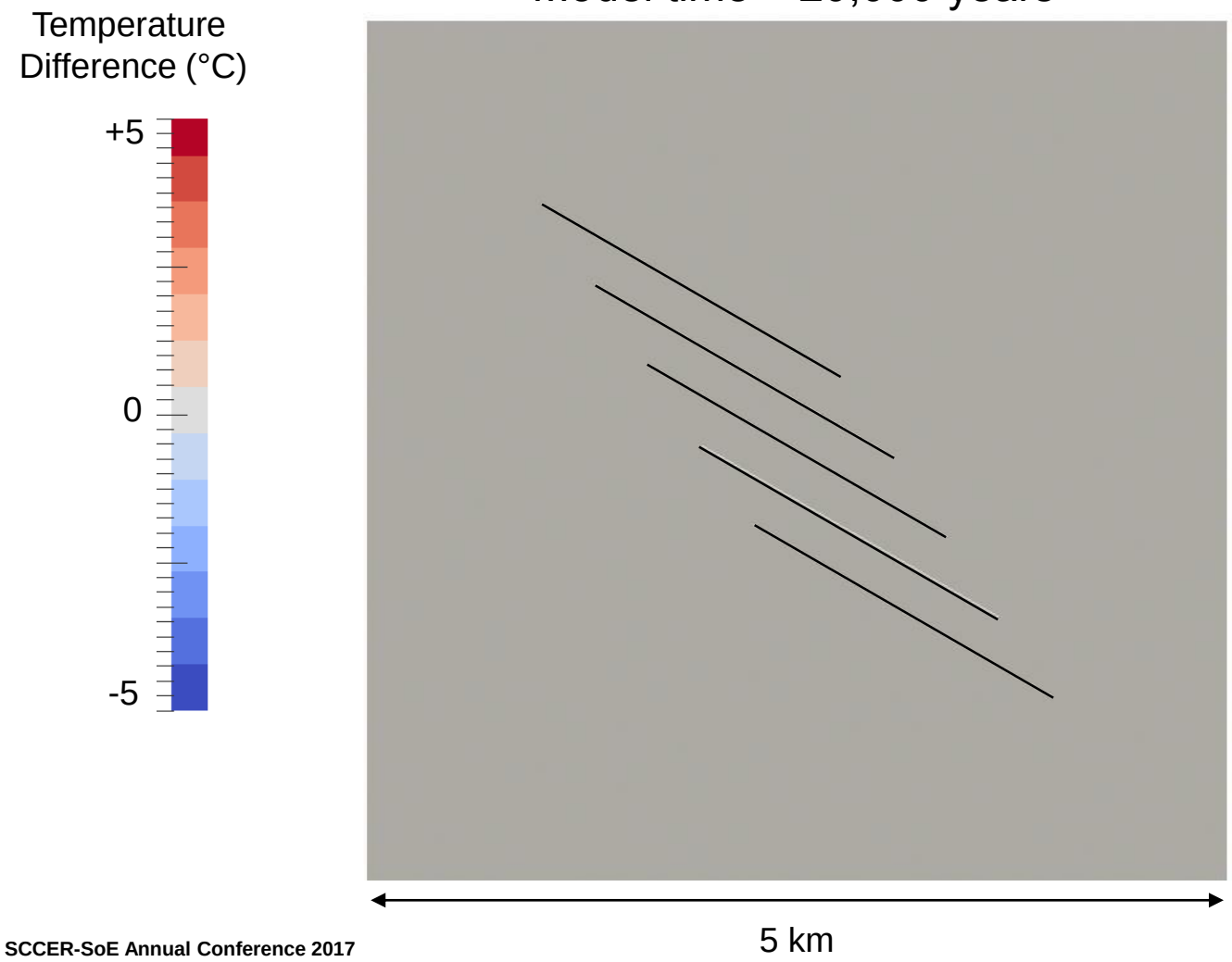


Left: Faulds et al. 2010, Characterizing Structural Controls of Geothermal Reservoirs in the Great Basin, USA, and Western Turkey
Right: Rouse et al. 2012, An exceptional rocky shore preserved during Oligocene (Late Rupelian) transgression in the Upper Rhine Graben (Mainz Basin, Germany)

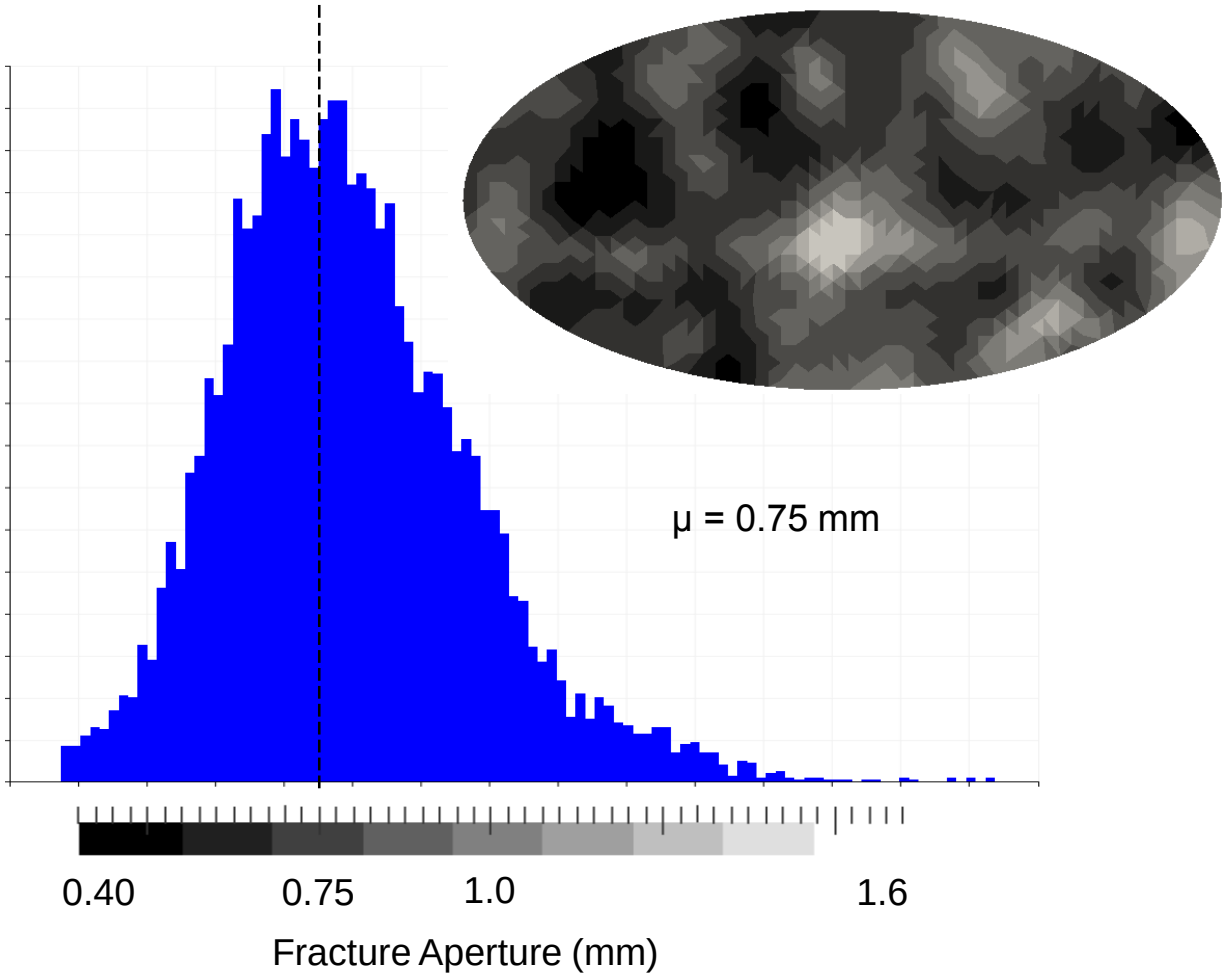
Multiple Fractures

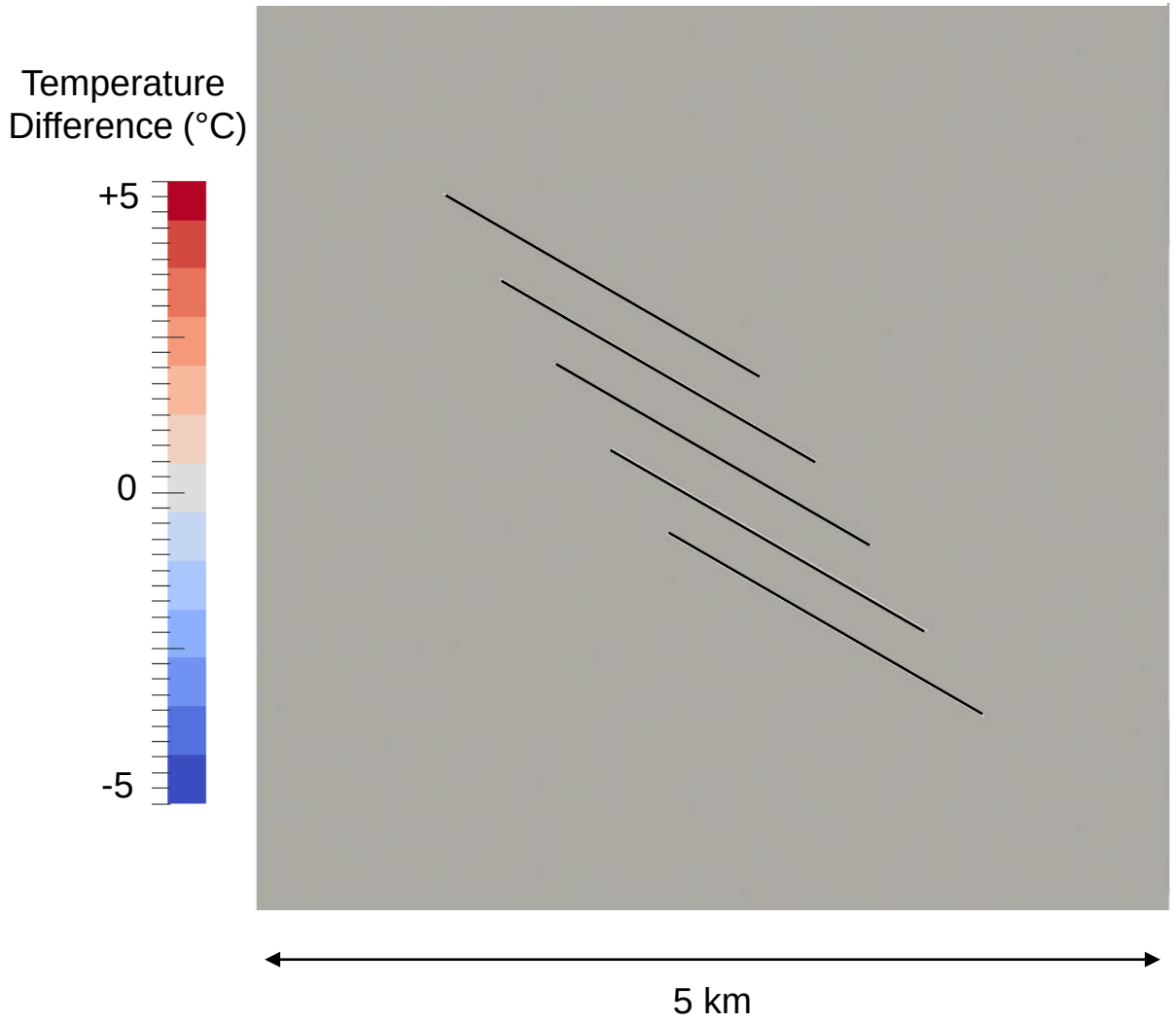
Fracture aperture = 0.50 mm
Model time ≈ 20,000 years

Fracture aperture = 0.75 mm
Model time ≈ 4,000 years

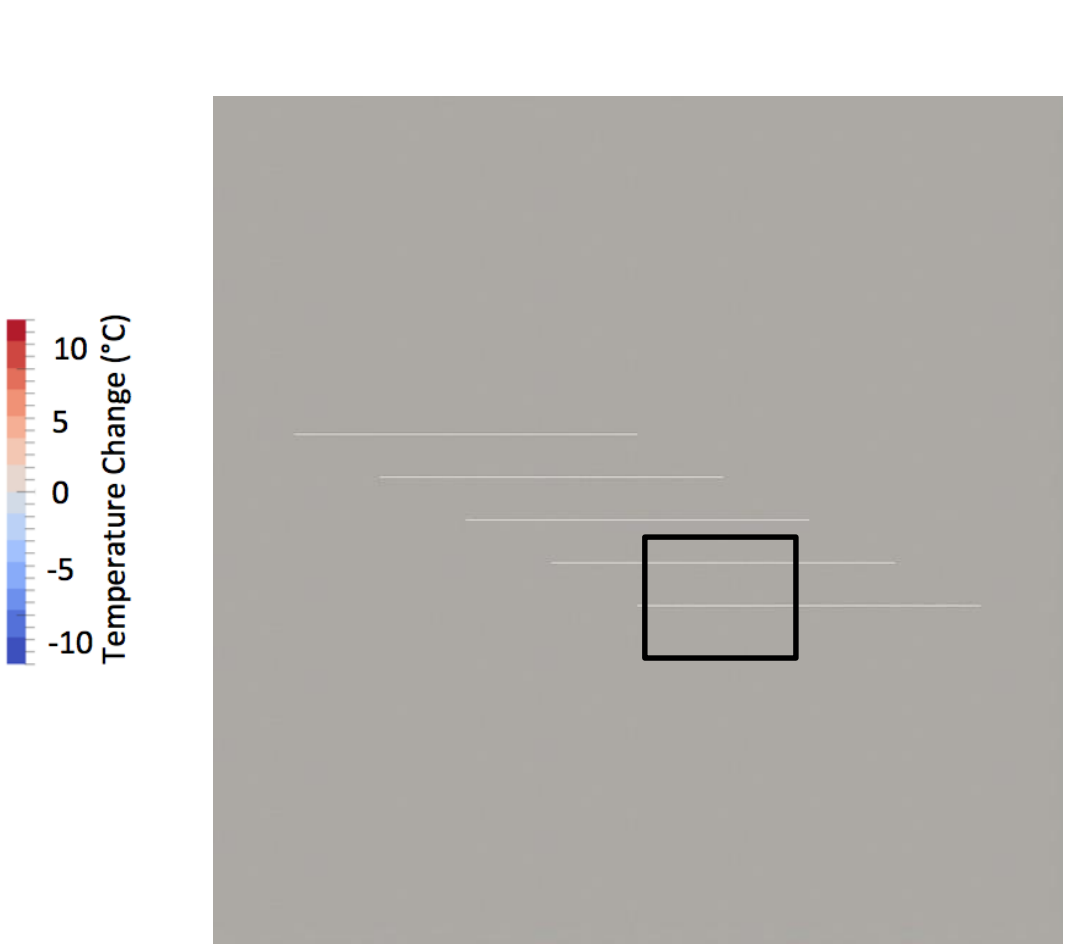


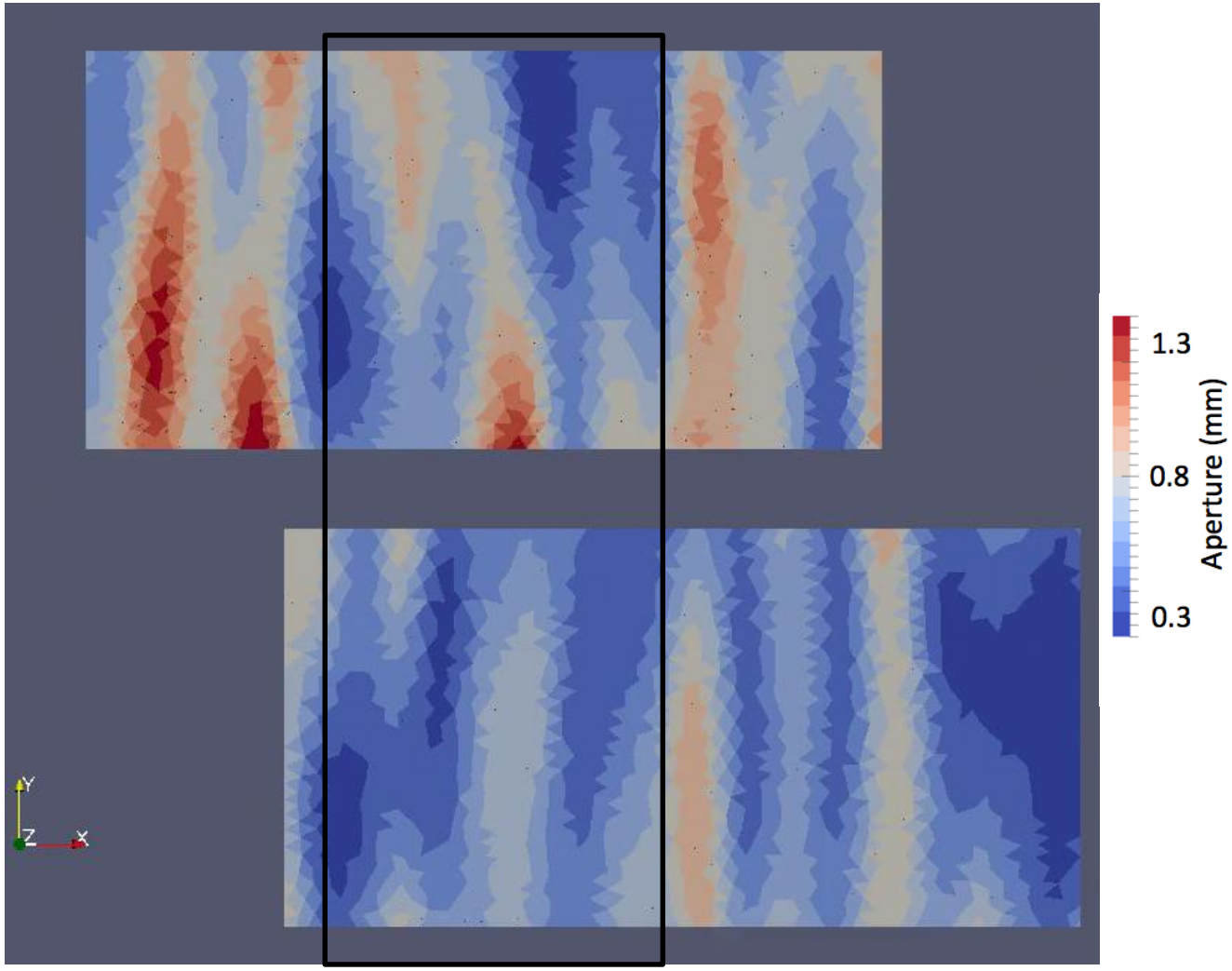
Multiple Fractures – Heterogeneous Aperture





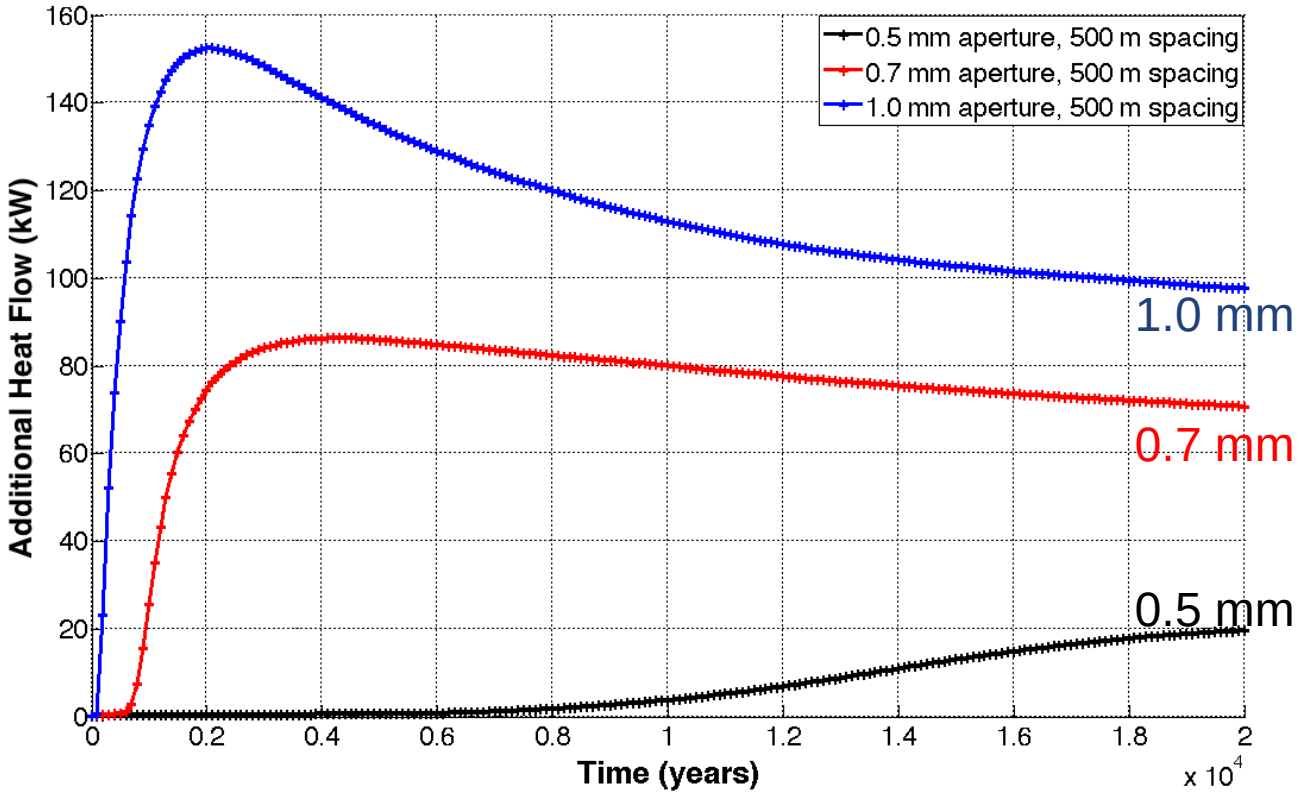
Multiple Fractures – Heterogeneous Aperture





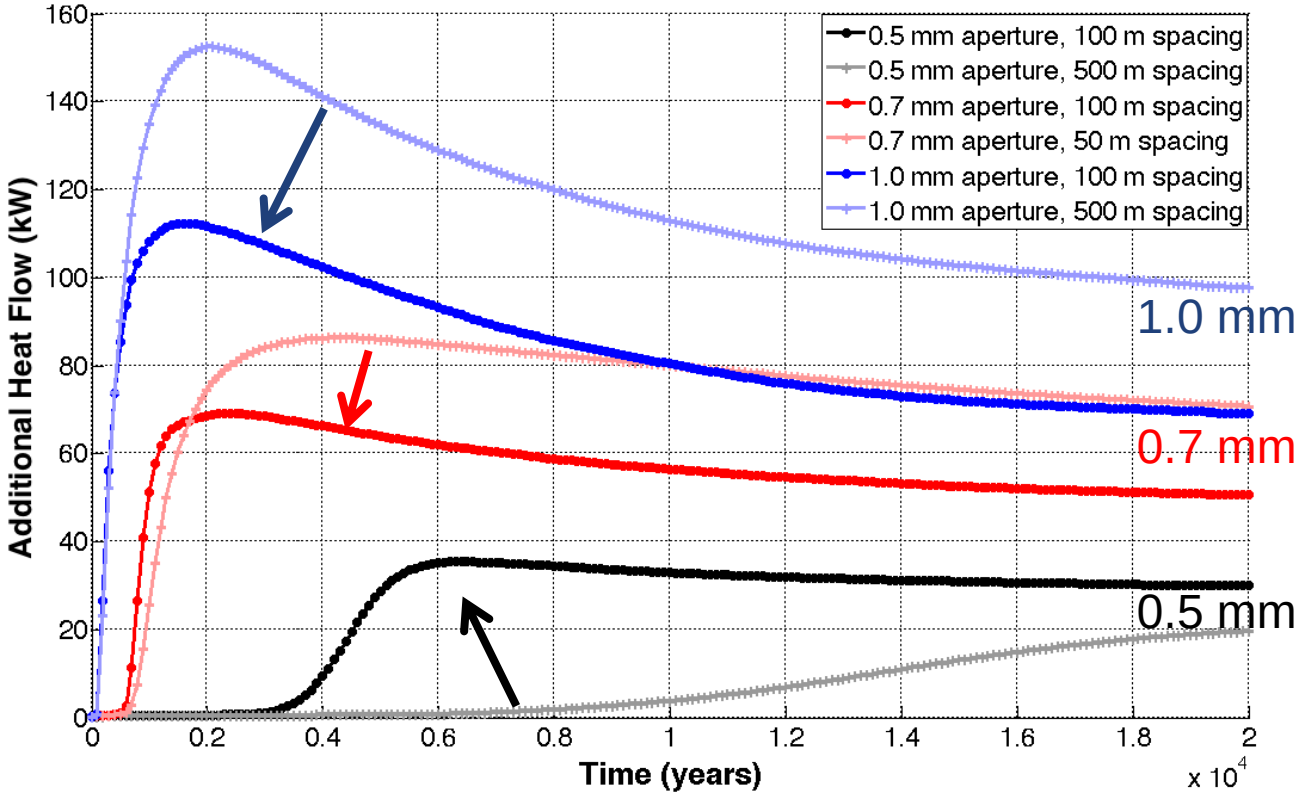
Heat Flow Through Fractures

- Increasing fracture perm…
  - convection initiates earlier
  - transports more heat



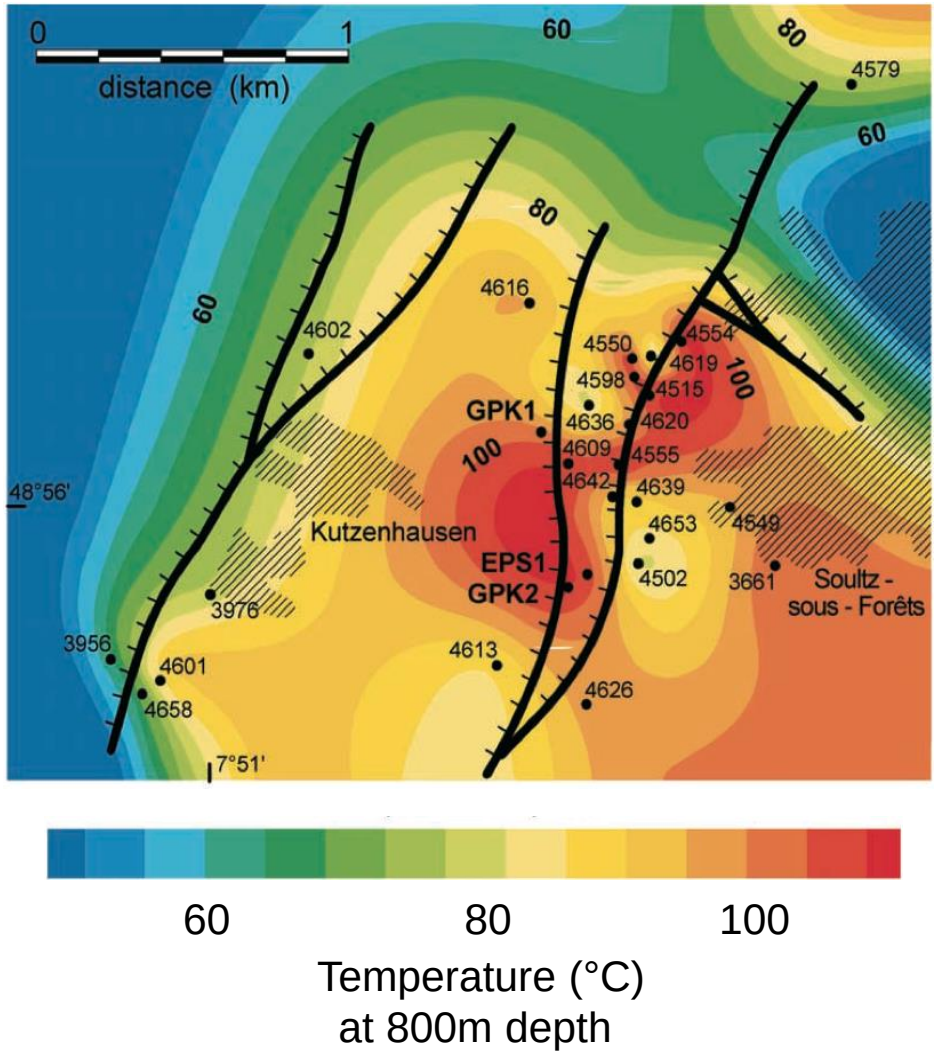
Heat Flow Through Fractures

- Increasing fracture perm…
  - convection initiates earlier
  - transports more heat
- Decreasing fracture spacing…
  - convection initiates earlier
  - Enhanced heat flow in low-perm fractures
  - Reduce heat flow in high-perm fractures



Conclusions

- Convection “syncs” across fractures
- Large-scale convection and temperature anomaly patterns emerge
- Fundamental behavior of convection in basement rock
- Aid in site selection



Thank you