Quantification of the 3D thermal anomaly in the orogenic geothermal system at Grimsel Pass

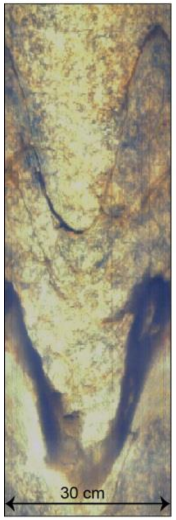
Christoph Wanner, Larryn W. Diamond, Peter Alt-Epping, Daniel Egli

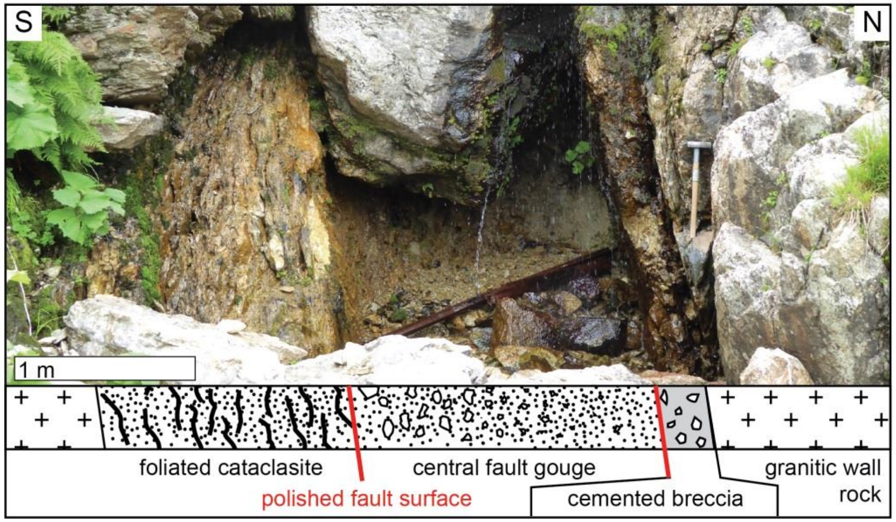
Rock-Water Interaction Group, Institute of Geological Sciences, University of Bern

Context NRP70 project

- Joint project between UniBE, Uni-Lausanne, and ETHZ
  “Exploration and characterization of deep underground reservoirs”
  - ➢ Investigation of water-conducting structures in the crystalline basement
  - ➢ Grimsel Pass hydrothermal system represents analogue for such structures in the crystalline basement in Northern Switzerland

Drill site at Grimsel Pass **Televiewer log** **Mapping of structures**

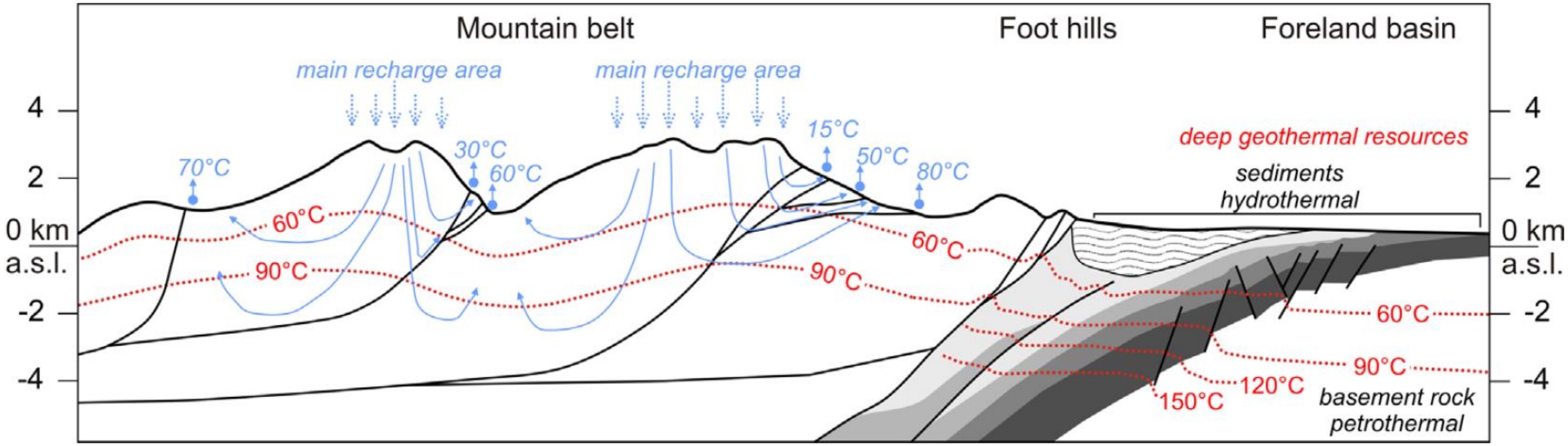




Context orogenic geothermal system

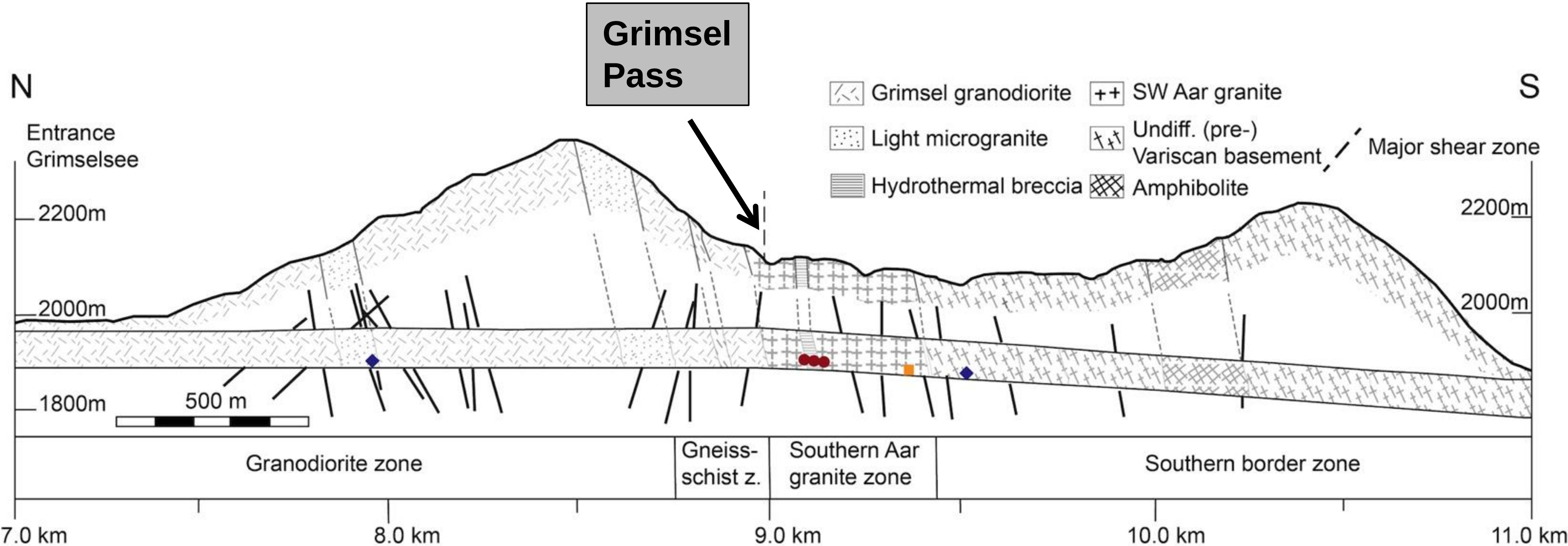
- Orogenic belts are recognized as low enthalpy geothermal plays
  - What is the potential of geothermal systems located in actual mountain ranges (i.e., orogenic geothermal systems)?
  - Numerical modeling study to quantify the 3D thermal anomaly of the Grimsel Pass geothermal system

Orogenic geothermal plays (Moeck, 2014)



The Grimsel Pass geothermal system

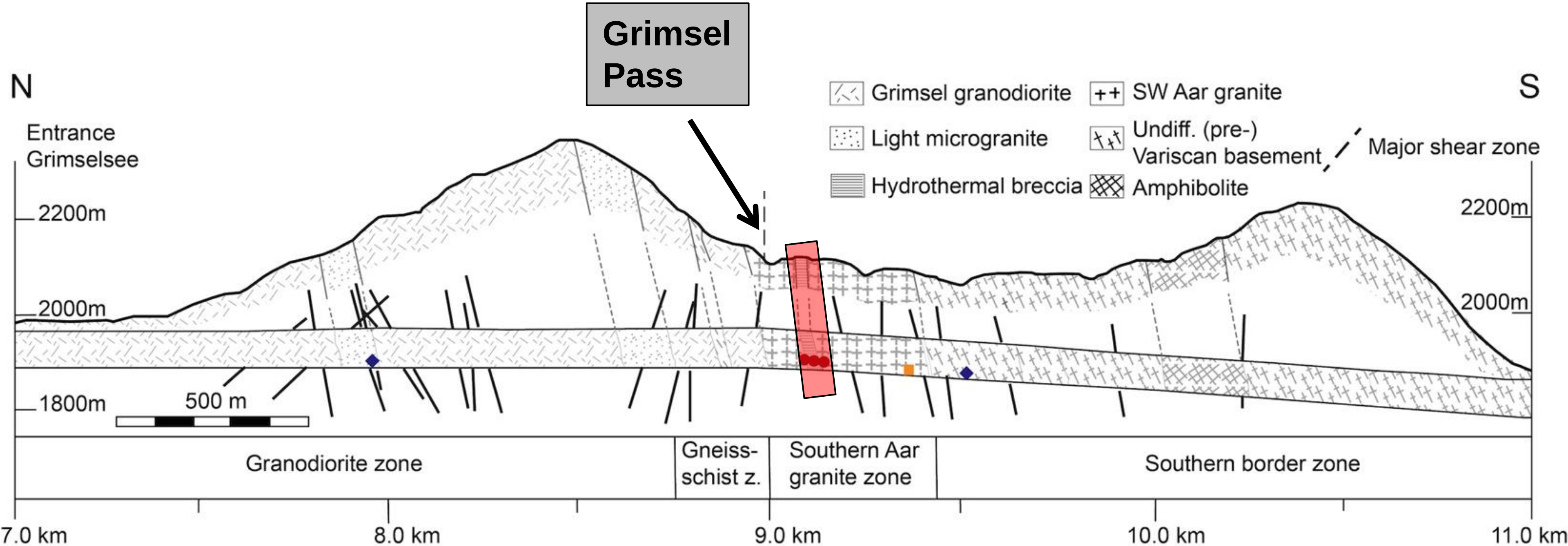
- Hydrothermal springs with T ≤ 28 ℃ are found beneath Grimsel Pass in the Transitgas AG tunnel
- Highest thermal discharges documented in the entire Alps (1900 m asl)
- Thermal springs occur over a narrow tunnel section only (<100 m)
- They are associated with the Grimsel Breccia Fault (GBF)



(Pfeifer et al., 1992; Waber et al., 2017)

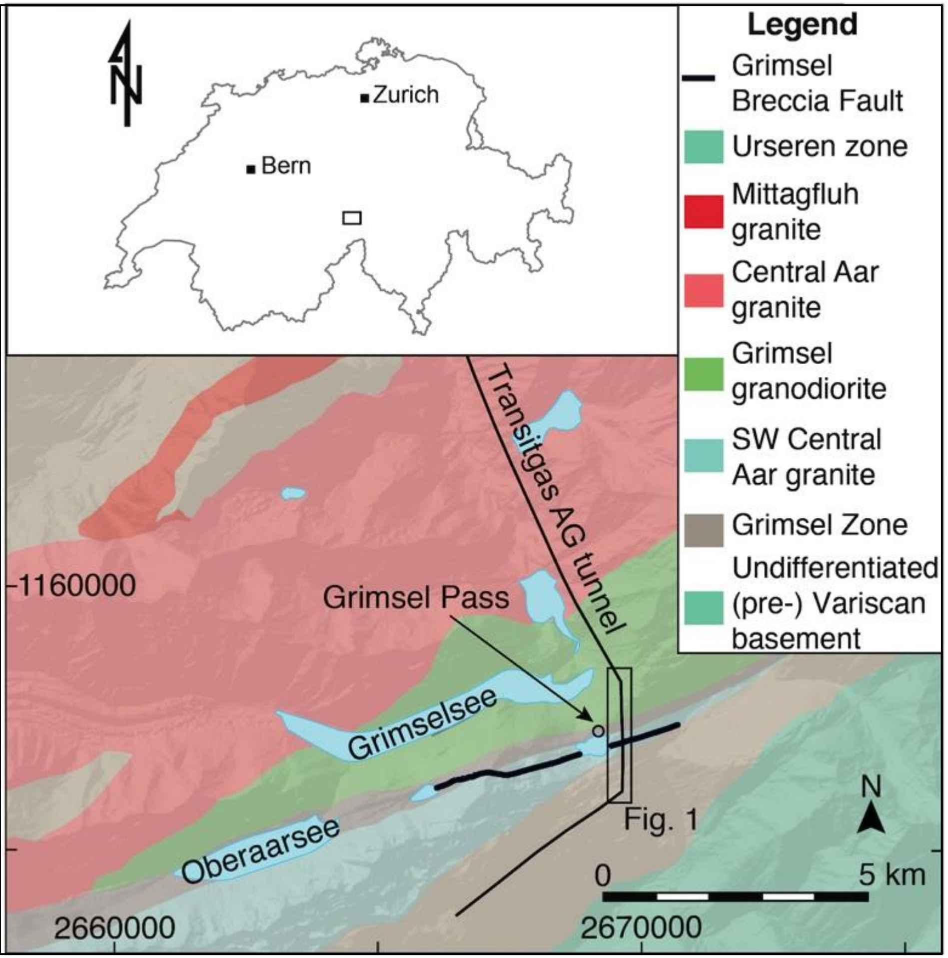
The Grimsel Pass geothermal system

- Hydrothermal springs with T ≤ 28 ℃ are found beneath Grimsel Pass in the Transitgas AG tunnel
- Highest thermal discharges documented in the entire Alps (1900 m asl)
- Thermal springs occur over a narrow tunnel section only (<100 m)
- They are associated with the Grimsel Breccia Fault (GBF)



(Pfeifer et al., 1992; Waber et al., 2017)

The Grimsel Breccia Fault



- Major WSW-ENE fault zone parallel to the Aar Massif
- Outcrops as a mineralized hydrothermal breccia

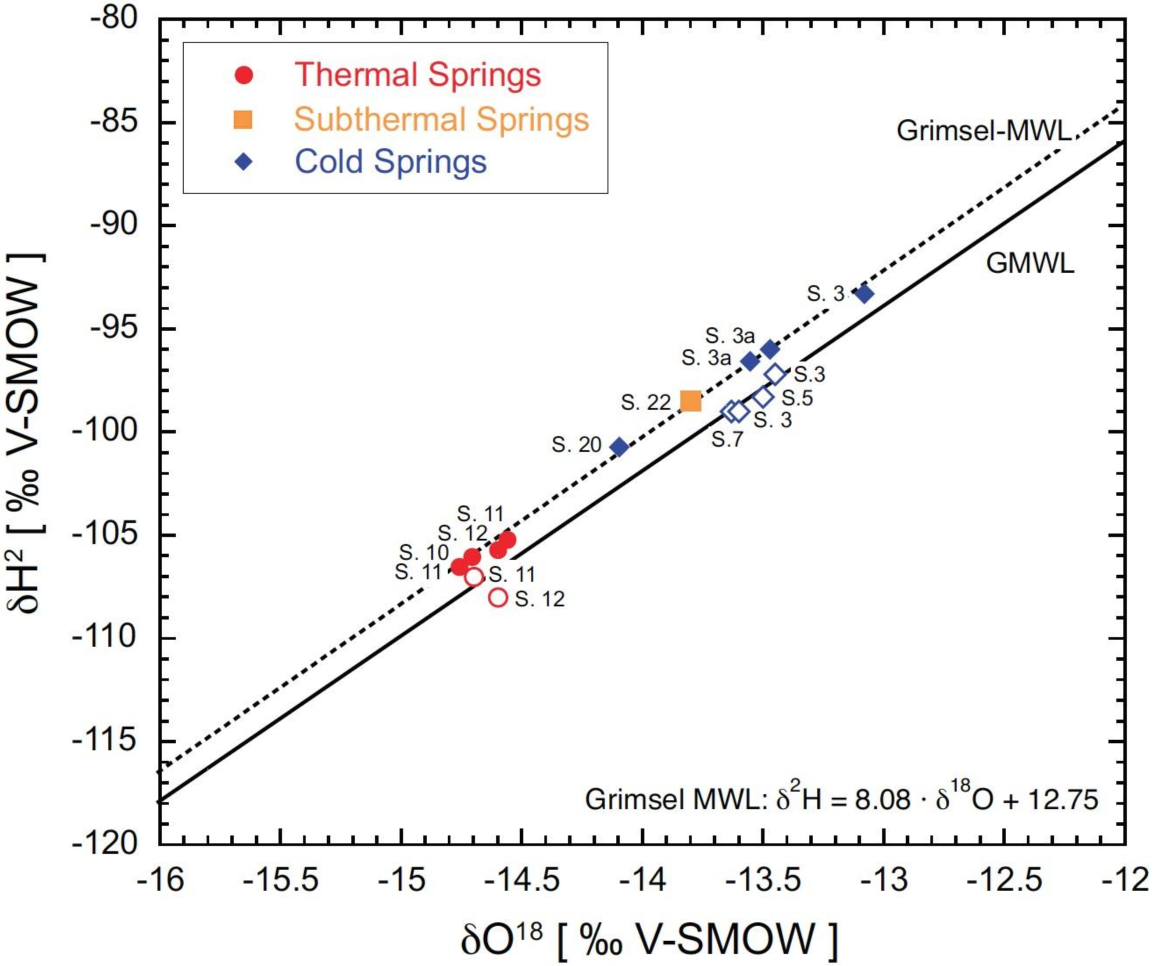
The Grimsel Breccia Fault

Breccia outcrop (Belgrano et al., 2016)

- Major SW-NE fault zone parallel to the Aar Massif
- Outcrops as a mineralized hydrothermal breccia
  - ➢ Fossil manifestation of the same hydrothermal system
- Age of breccia: 3.3 Ma (Hofmann et al., 2004)
  - ➢ Long lasting system
  - ➢ Formed at about 3 km depth
- $T_{formation}$= 165 °C (Hofmann et al., 2004)
  - ➢ T_{root} >> 165 °C

Hydrogeochemistry of thermal springs

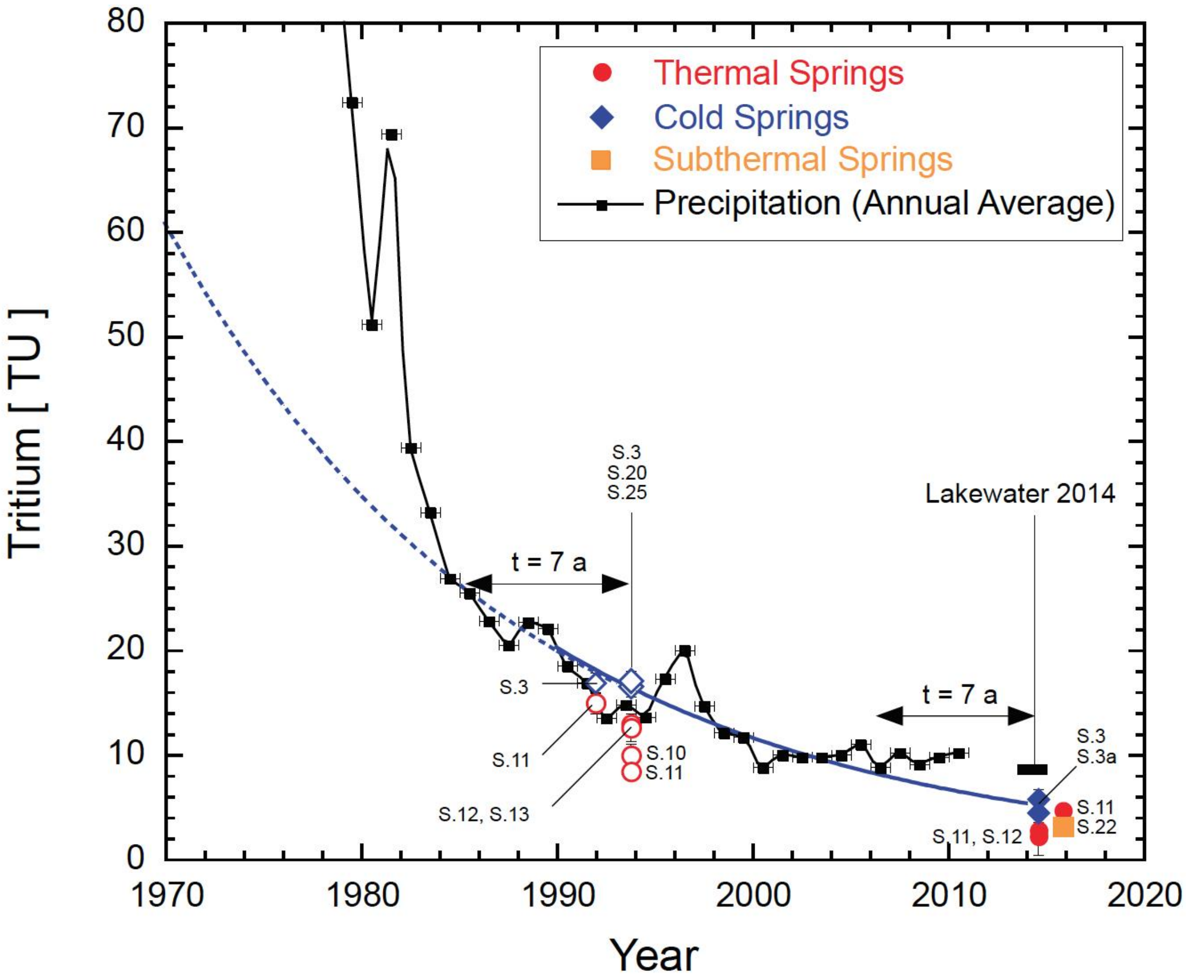
δ18O and δ2H analyses (Waber et al., 2017)



- Ca-HCO$_3$-SO$_4$ water type
- Meteoric origin
- Infiltration altitude: 2200–3000 m asl

Hydrogeochemistry of thermal springs

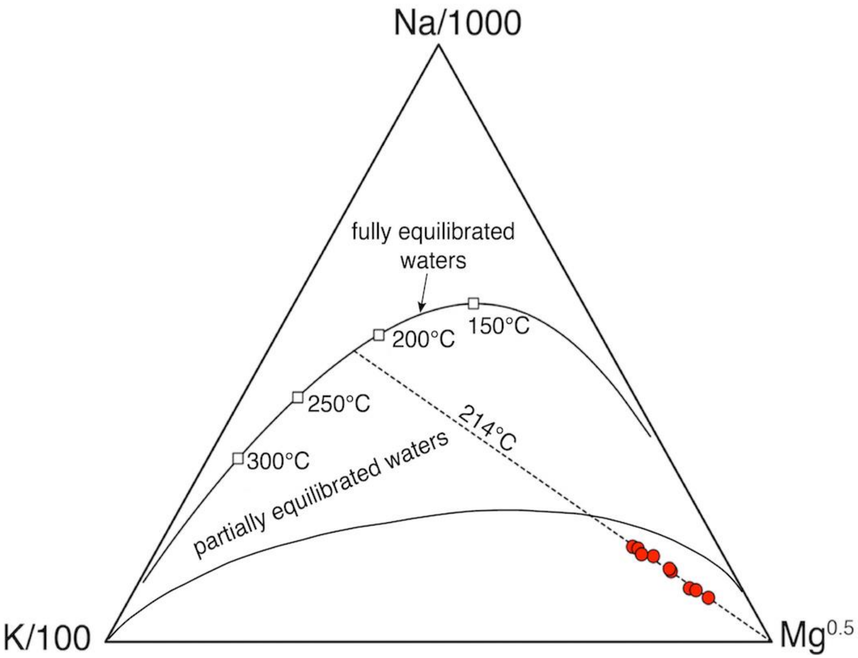
Tritium analysis (Waber et al., 2017)



- $Ca-HCO_3-SO_4$ water type
- Meteoric origin
- Infiltration altitude: 2200–3000 m asl
- Mixture between a young cold water and a deep geothermal component
- Geothermal component: 40–50%
- Spring temperatures without cold water component: 45–50 ℃

Hydrogeochemistry of thermal springs

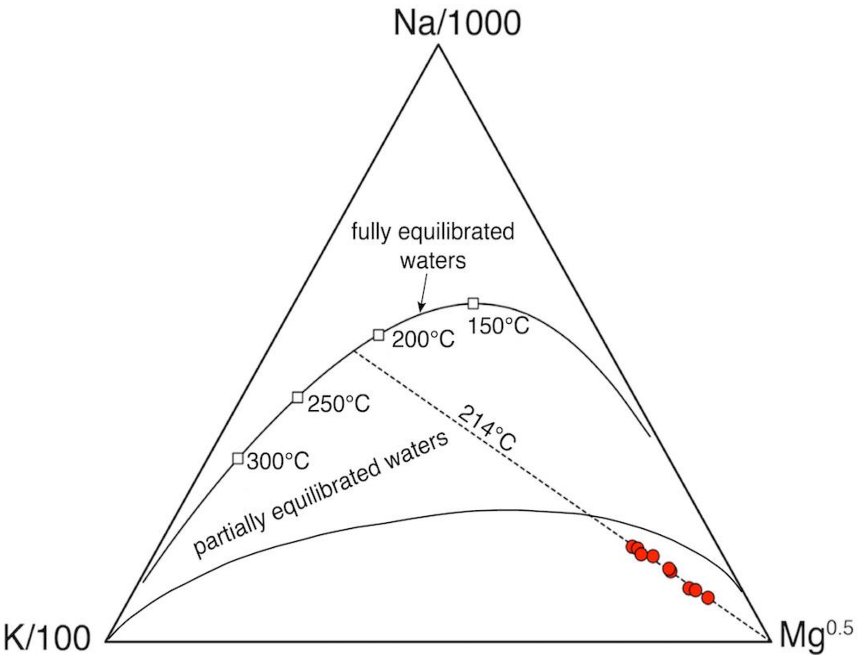
Solute geothermometry



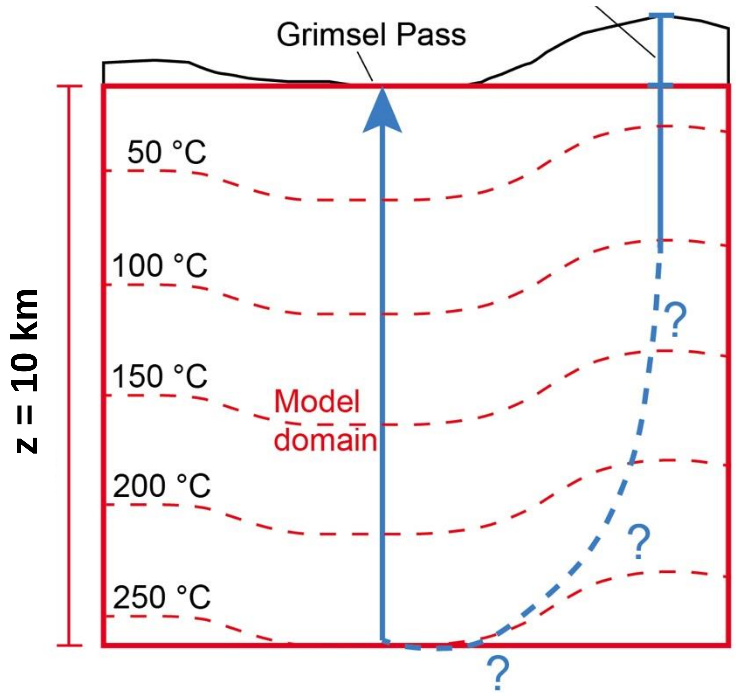
- Na-K geothermometer provides strong evidence that the circulating water reaches a temperature of at least 214 ℃, and more likely ~250 ℃

Hydrogeochemistry of thermal springs

Solute geothermometry



Infiltration model

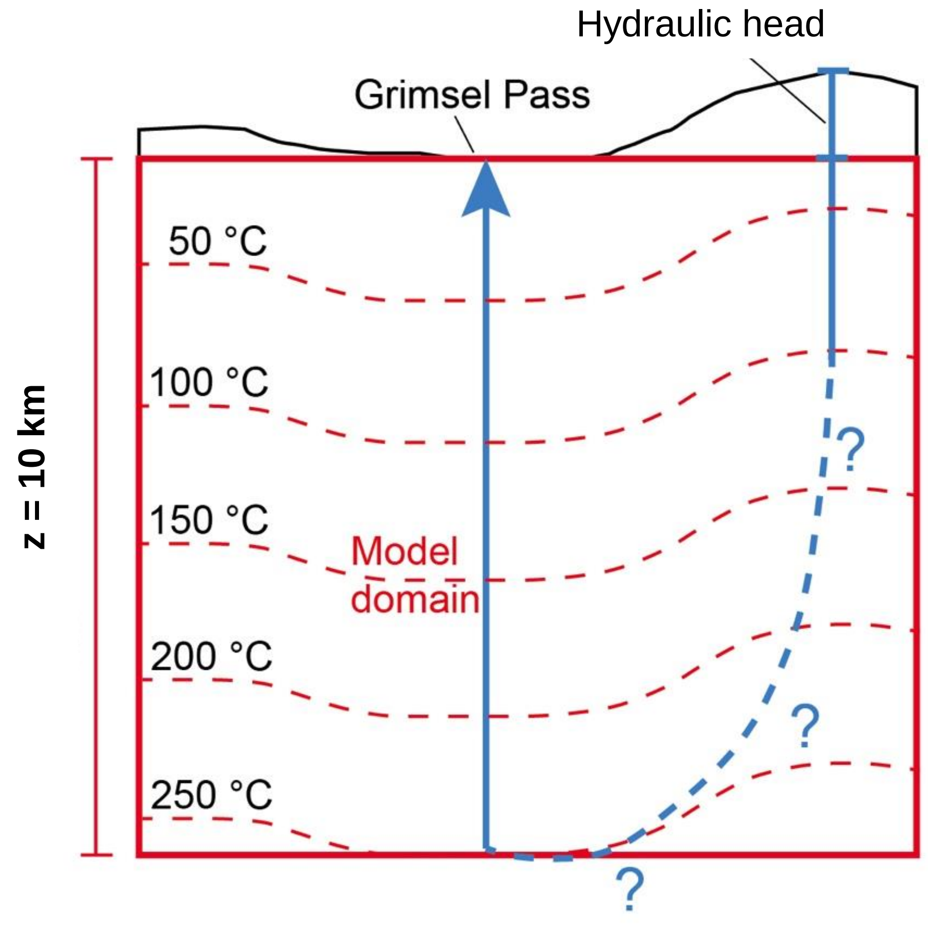


- Na-K geothermometer provides strong evidence that the circulating water reaches a temperature of at least 214 ℃, and more likely ~250 ℃
- Background geothermal gradient of 25 ℃ /km is the only heat source in the area
  - ➢ 10 km infiltration of meteoric water!

Model setup

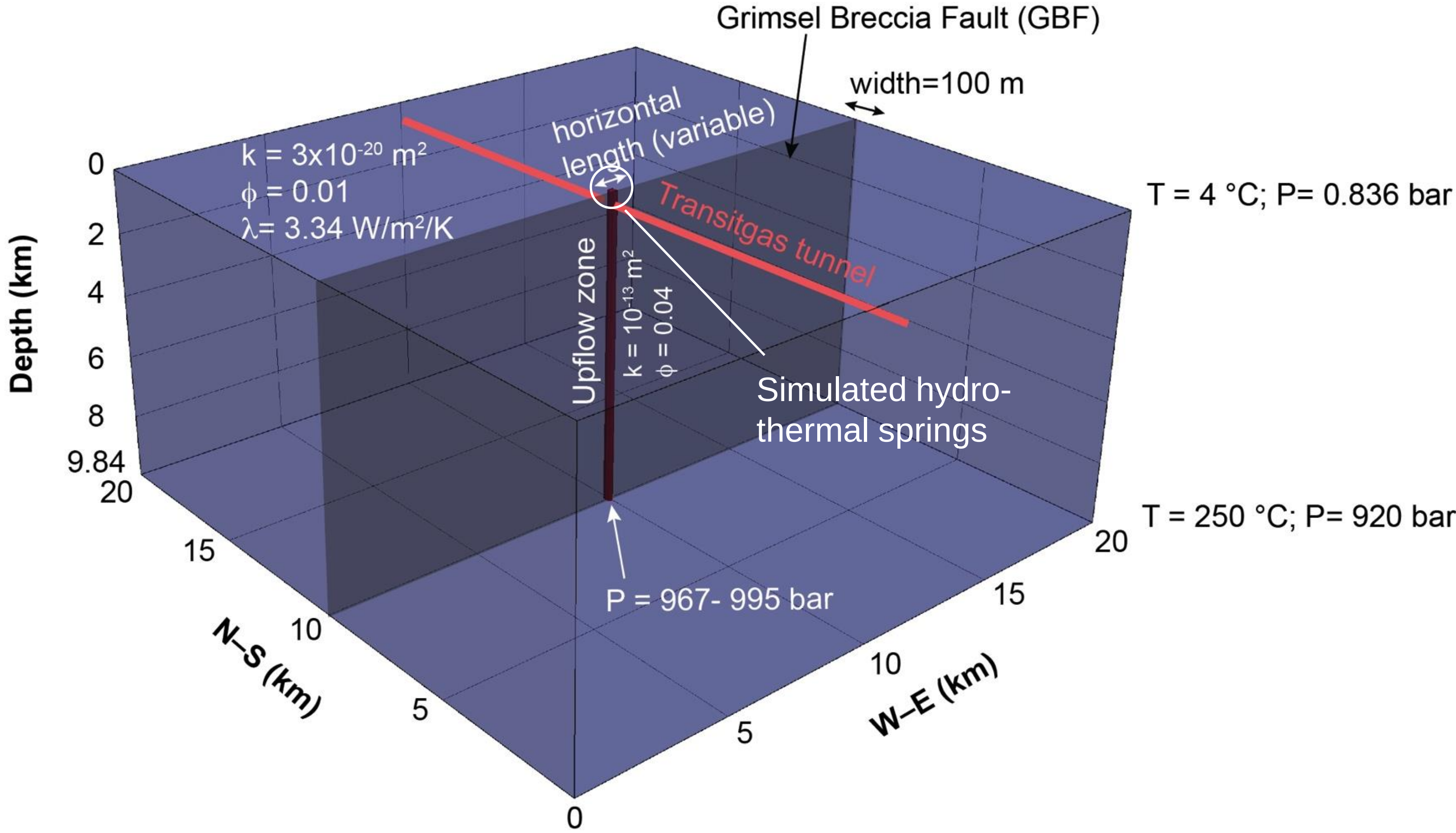
- Focus on upflow zone along the hydraulically active part of the Grimsel Breccia Fault
- Infiltration of meteoric water and surface topography was not explicitly considered
- Vertical model extent (z) constrained by the maximum fluid temperature (250 ℃)

Conceptual model



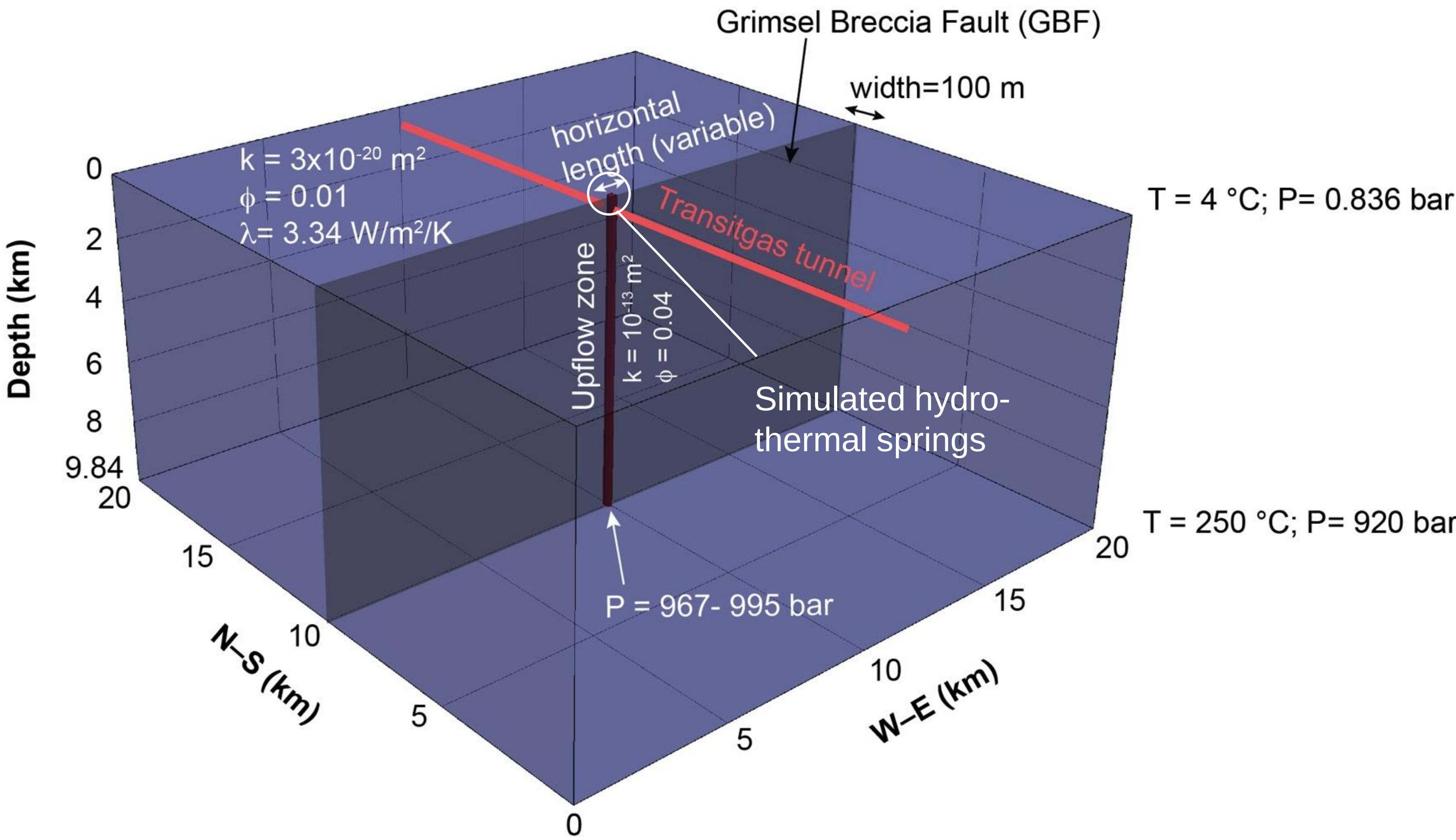
Model setup (TOUGH2)

- Large 3D domain (advective vs. conductive heat transport)
- Constant width of the GFB along the tunnel (100 m)
- Variable extent of the upflow zone parallel to the GFB (50-150 m)
- Maximum GFB permeability of 10^{-13} m^2 (based on hydraulic tests)



Model setup (TOUGH2)

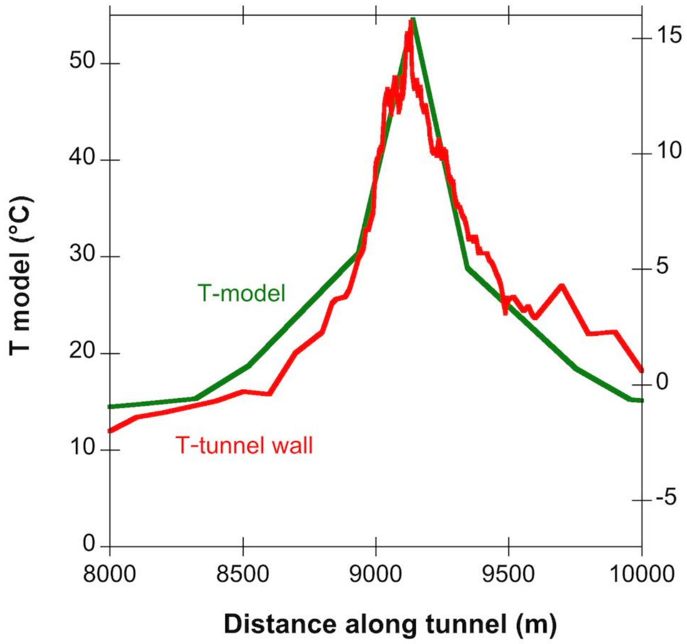
- Initial conductive temperature distribution (4 ℃ at surface, 25 ℃/km)
- Initial hydrostatic pressure distribution
- $P > P_{hydrostatic}$ below upflow zone; corresponding to the hydraulic head driving the system (500-800 m above tunnel)



Model calibration

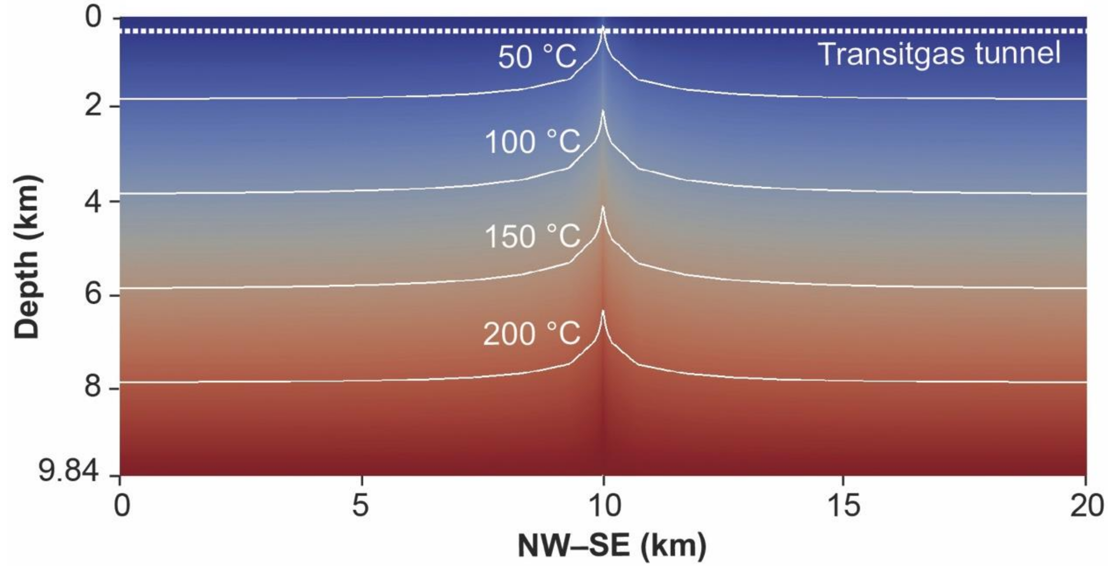
- Reconstructed discharge T of the geothermal fluid component (45–50 °C) can be matched when defining a hydraulic head of 800 m and a 75 m wide system
- The simulated temperature anomaly matches the measured temperature anomaly of the tunnel wall

Measured vs. modeled temp.



Calibrated model

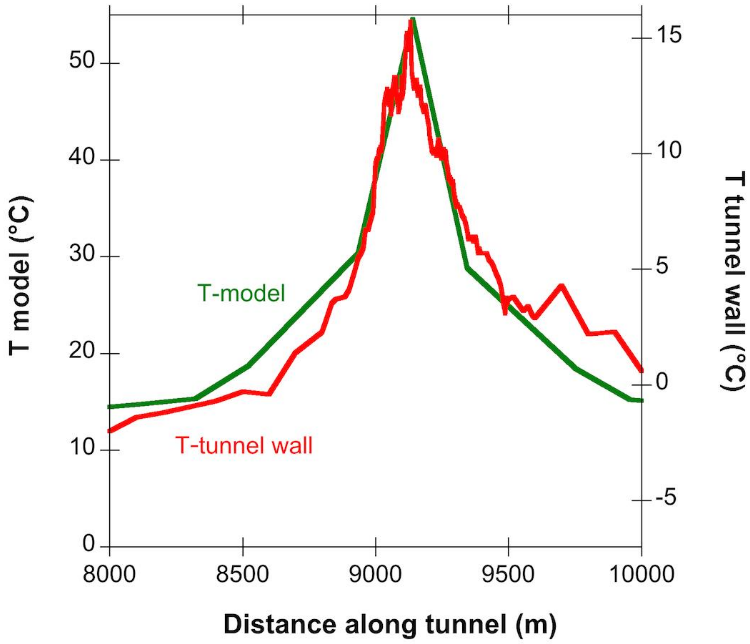
800 m hydr. head, 75 m horizontal length



Model calibration

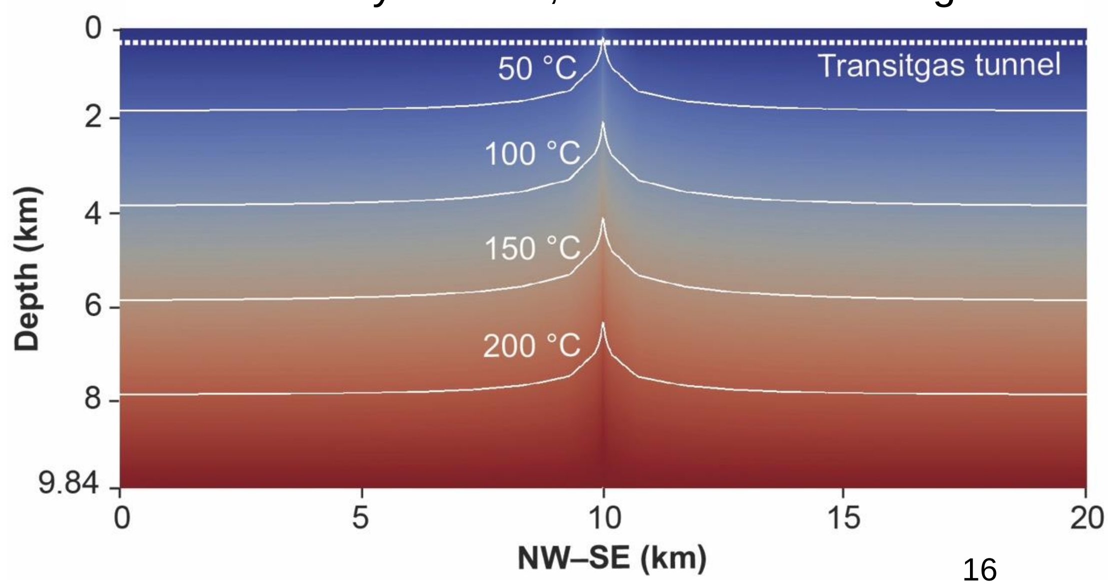
- Reconstructed discharge T of the geothermal fluid component (45–50 °C) can be matched when defining a hydraulic head of 800 m and a 75 m wide system
- The simulated temperature anomaly matches the measured temperature anomaly of the tunnel wall
  - ➢ No unique combination of 3D extent of the system and upflow velocity (permeability + hydraulic head)

Measured vs. modeled temp.



Calibrated model

800 m hydr. head, 75 m horizontal length

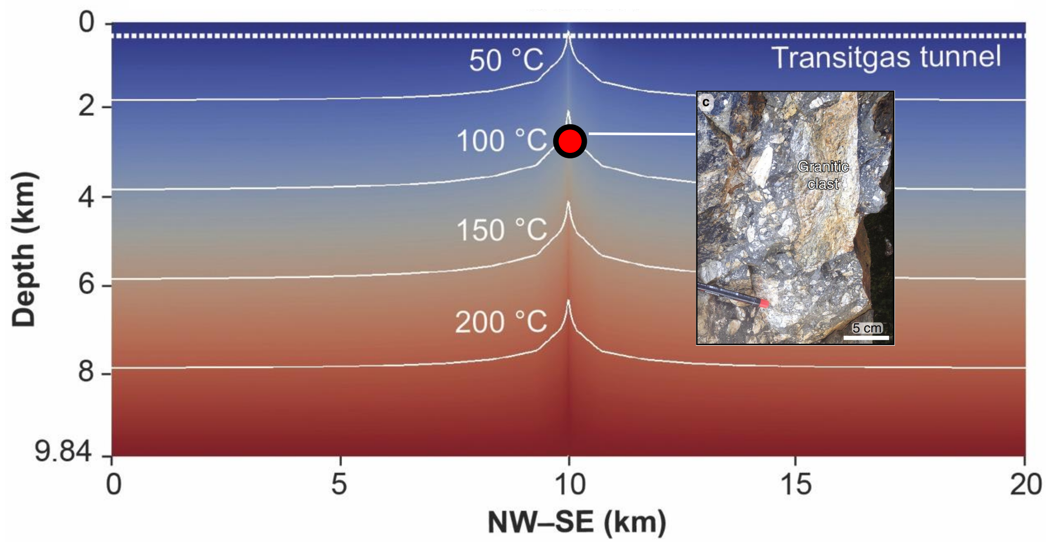


Model calibration

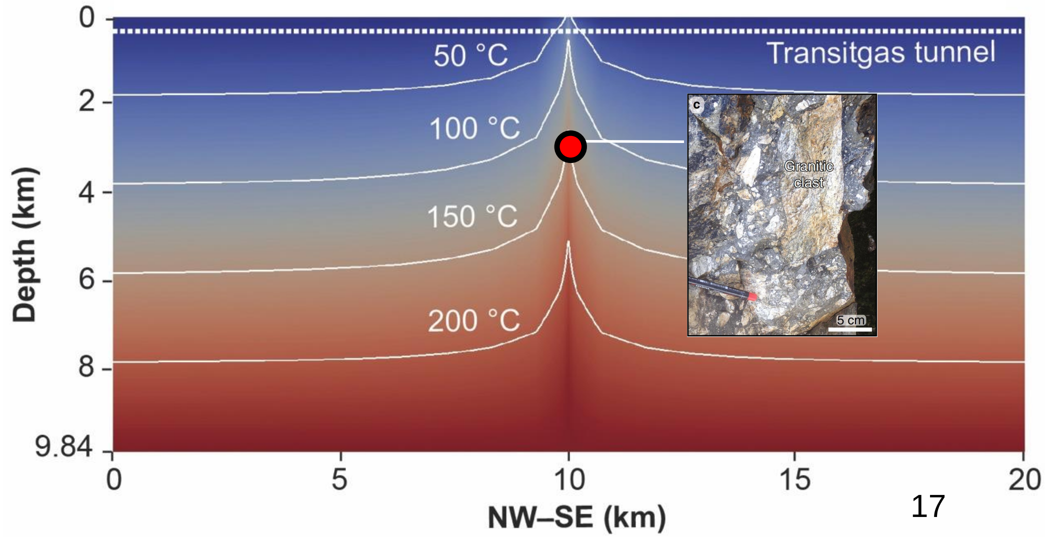
- $T_{breccia}$ (165 ℃ at 3 km depth) could not be matched simultaneously

  ➢ Upflow rate was likely higher when the breccia was formed 3.3 Ma ago

Current system



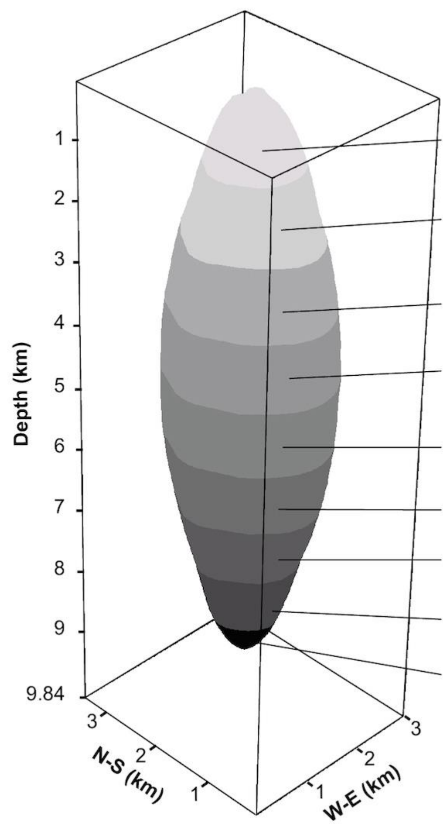
Fossil system



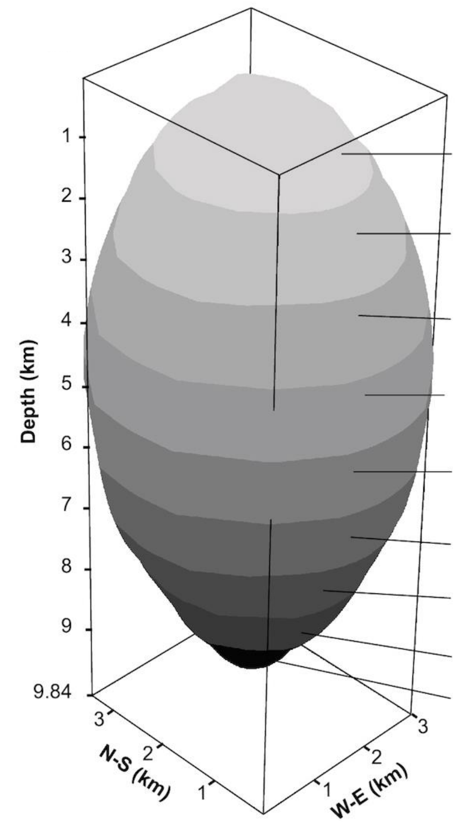
Thermal anomaly of the system

- Temperature difference of the calibrated model: $\Delta T = T_{steady\_state} - T_{initial}$

Current system (ΔT=10°C)



Fossil system (ΔT=10°C)

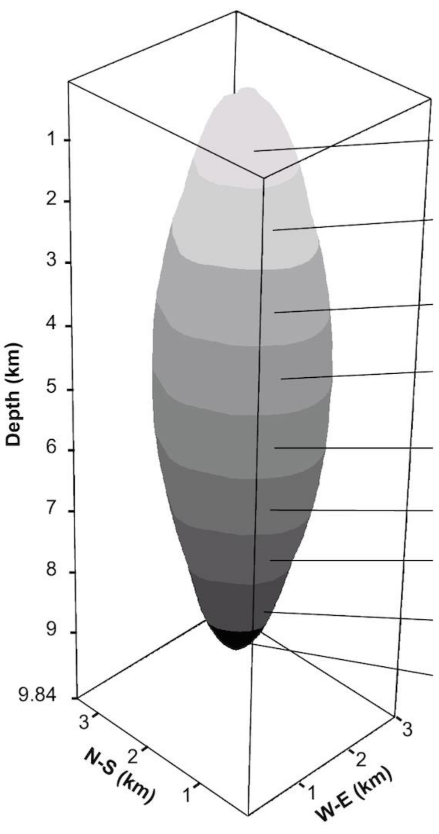


Quantification of heat excess per km

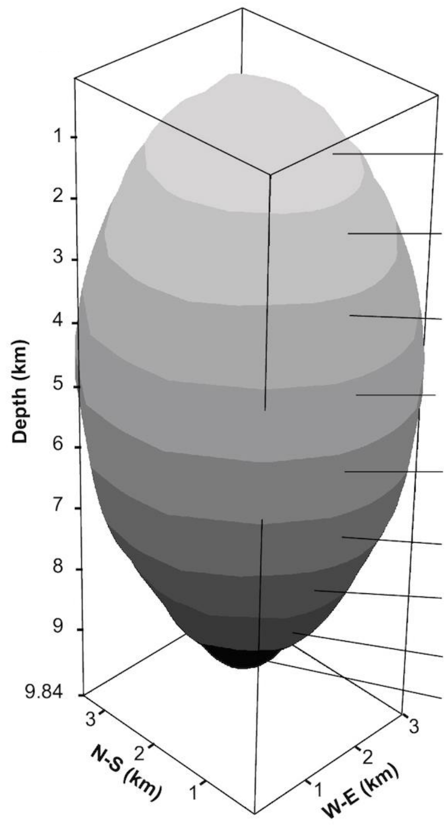
- Temperature difference of the calibrated model: $\Delta T = T_{steady\_state} - T_{initial}$
- Heat excess calculated from thermal anomaly of the calibrated model:

$$H = \sum_i C_P \cdot \delta \cdot V_i \cdot \Delta T_i$$

Current system (ΔT=10°C)



Fossil system (ΔT=10°C)

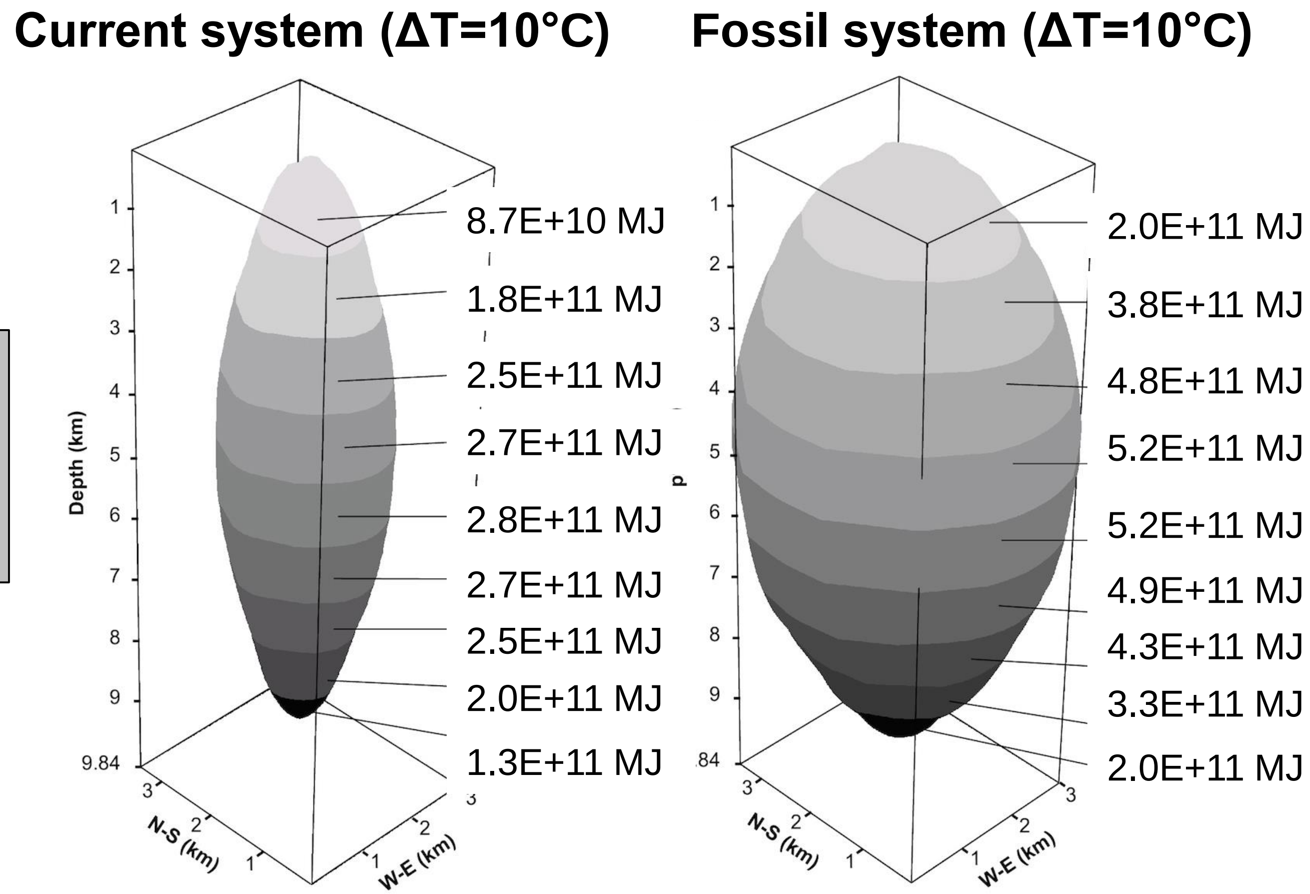


Quantification of heat excess per km

- Temperature difference of the calibrated model: $\Delta T = T_{steady\_state} - T_{initial}$
- Heat excess calculated from thermal anomaly of the calibrated model:

$$H = \sum_i C_P \cdot \delta \cdot V_i \cdot \Delta T_i$$

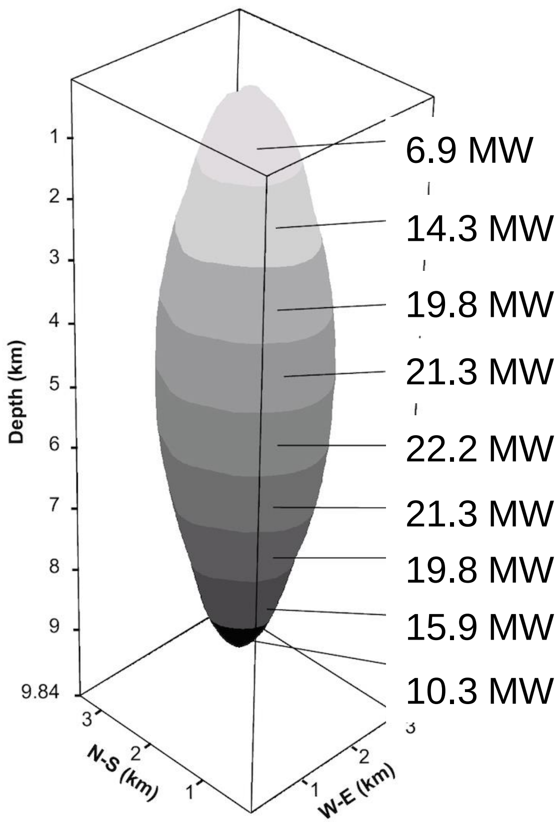
Thermal anomaly of the fossil system was roughly double the one of the current system



Theoretical power output over 20 years

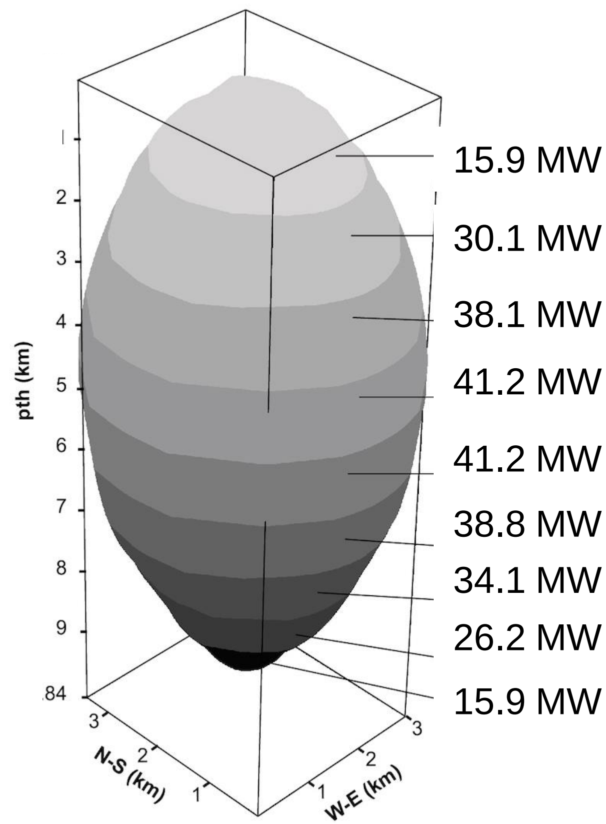
- Over 20 years and assuming a geothermal recovery factor of 5%, heat excesses over 1 km depth range correspond to significant theoretical power outputs

Current system (ΔT=10°C)



➢ 7–22 MW

Fossil system (ΔT=10°C)



➢ 16–41 MW

Rock-Water Interaction
www.geo.unibe.ch/rwi

Summary and conclusions

UNIVERSITÄT BERN

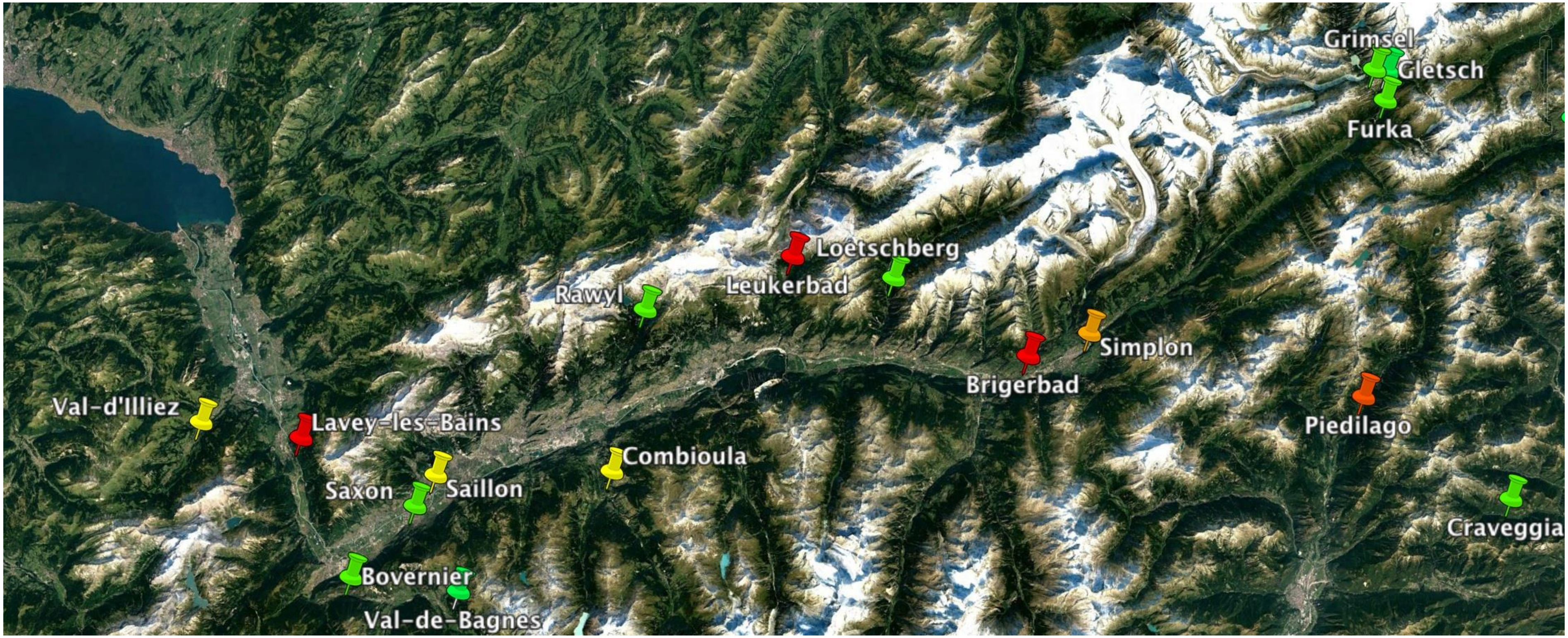
- The Grimsel Pass hydrothermal system has been active over the last 3.3 Ma
- The thermal anomaly is controlled by the geometry of the upflow zone and the upflow velocity
- Orogenic geothermal systems can lead to significant thermal anomalies

Summary and conclusions

- Exploration for orogenic geothermal systems should focus on high topography areas where hydraulic head gradients and hence upflow rates are at maximum values

  - ➢ Canton of Vallais and in surrounding valleys of the Central Alps

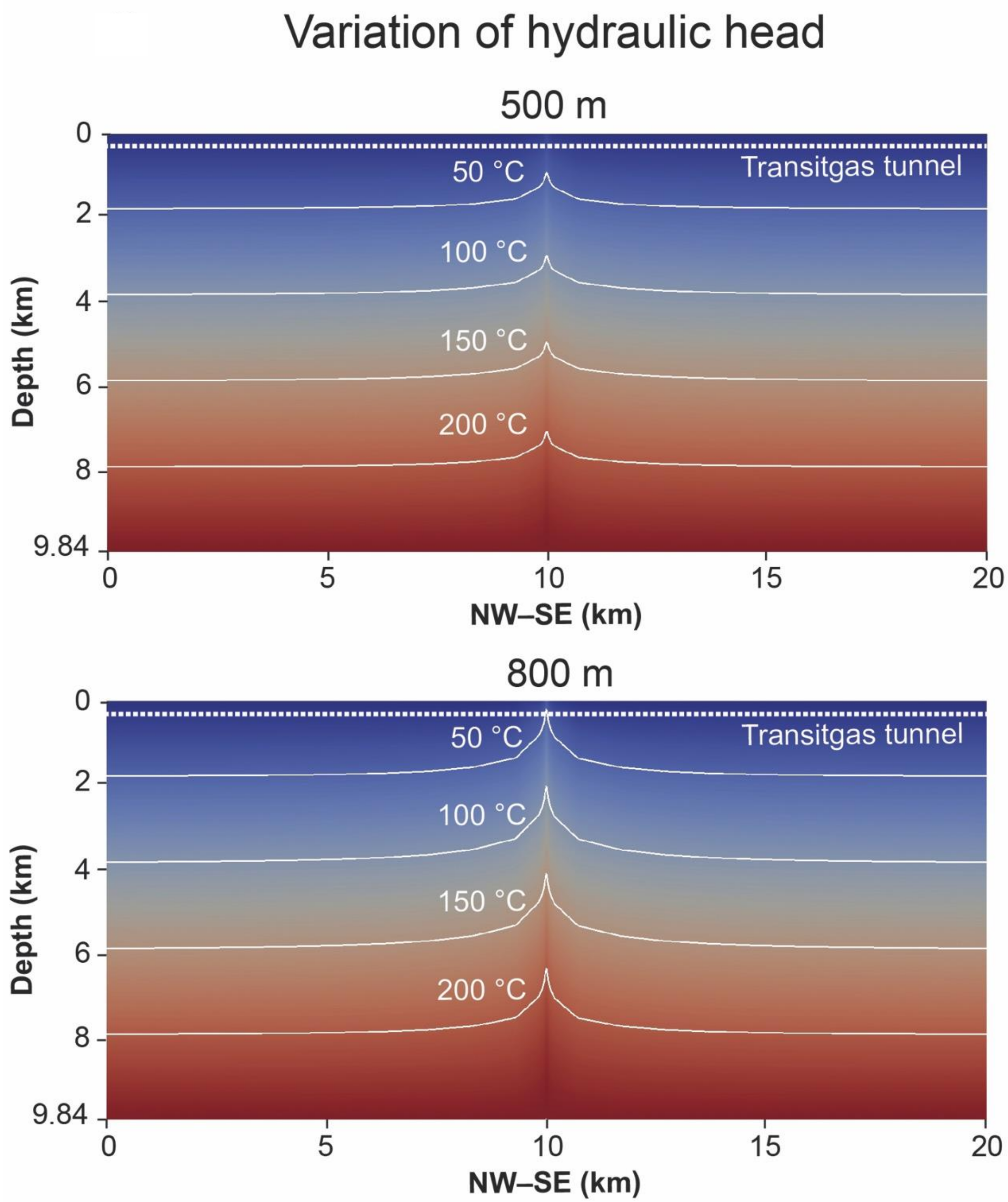
Hot springs occurring in the Rhone Valley



THANK YOU!

Model results: sensitivity analysis

- Steady-state temperature distribution is approached in less than 5000 a
- The extent of the temperature anomaly is mainly controlled by
  - ➢ The upflow velocity (permeability + hydraulic head)



Model results: sensitivity analysis

- Steady-state temperature distribution is approached in less than 5000 a
- The extent of the temperature anomaly is mainly controlled by
  - ➢ The upflow velocity (permeability + hydraulic head)
  - ➢ The 3D extent of the fault system