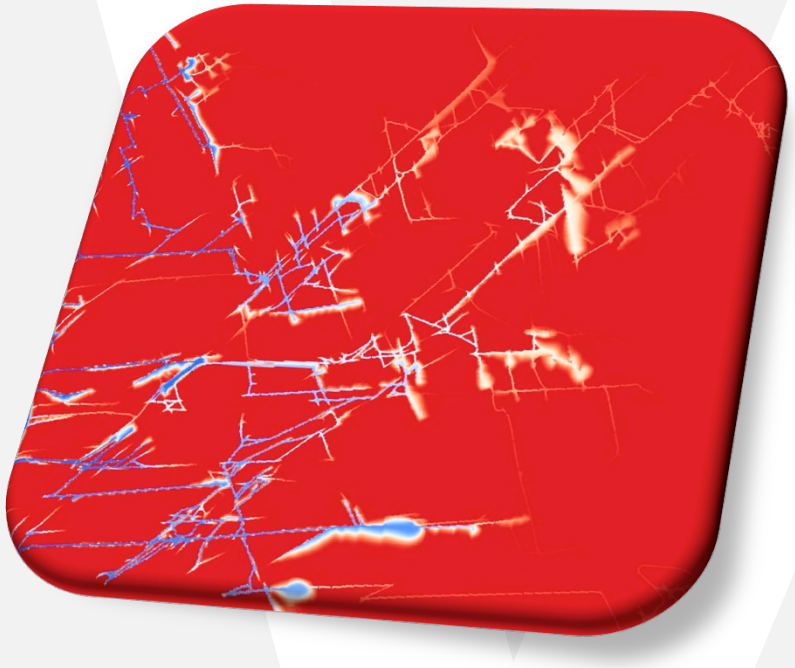
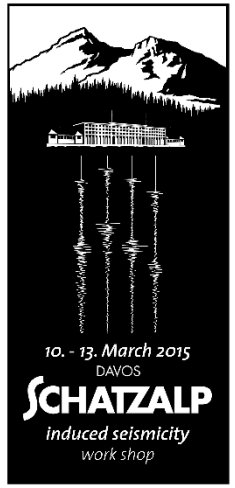
Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

ETH zürich

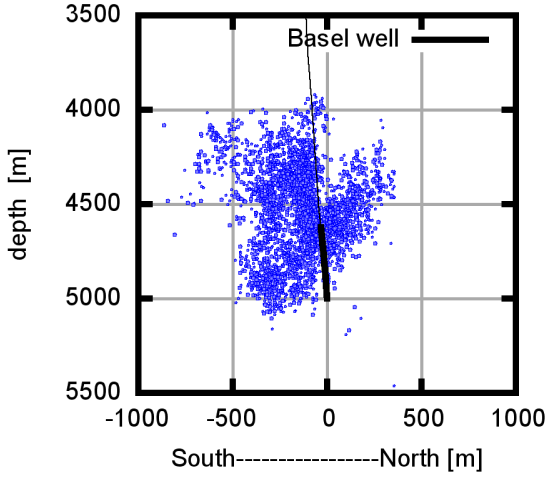
# Monte-Carlo Simulations of EGS Stimulation Phase with a 3-D Hybrid Model

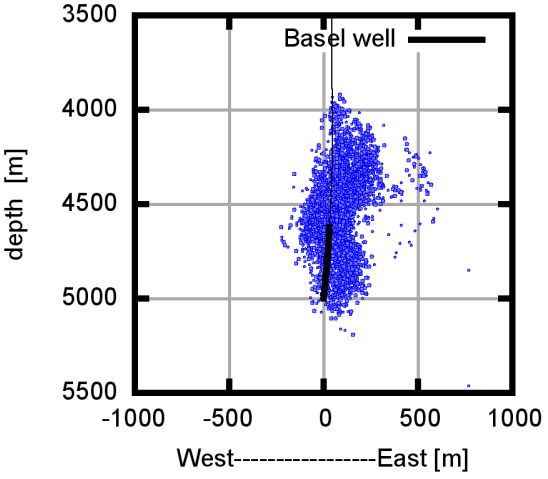
Dimitrios Karvounis and Stefan Wiemer

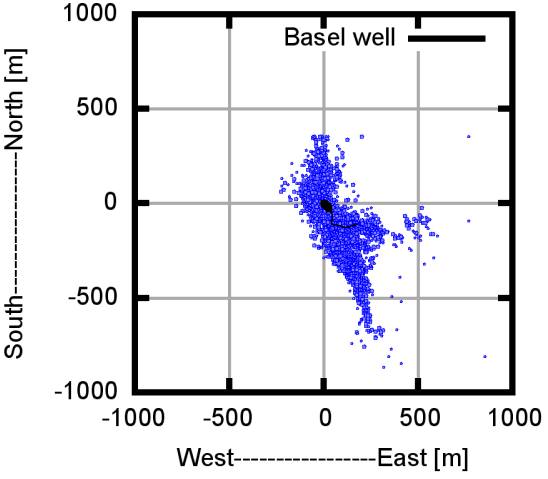




# Enhanced Geothermal System in Basel



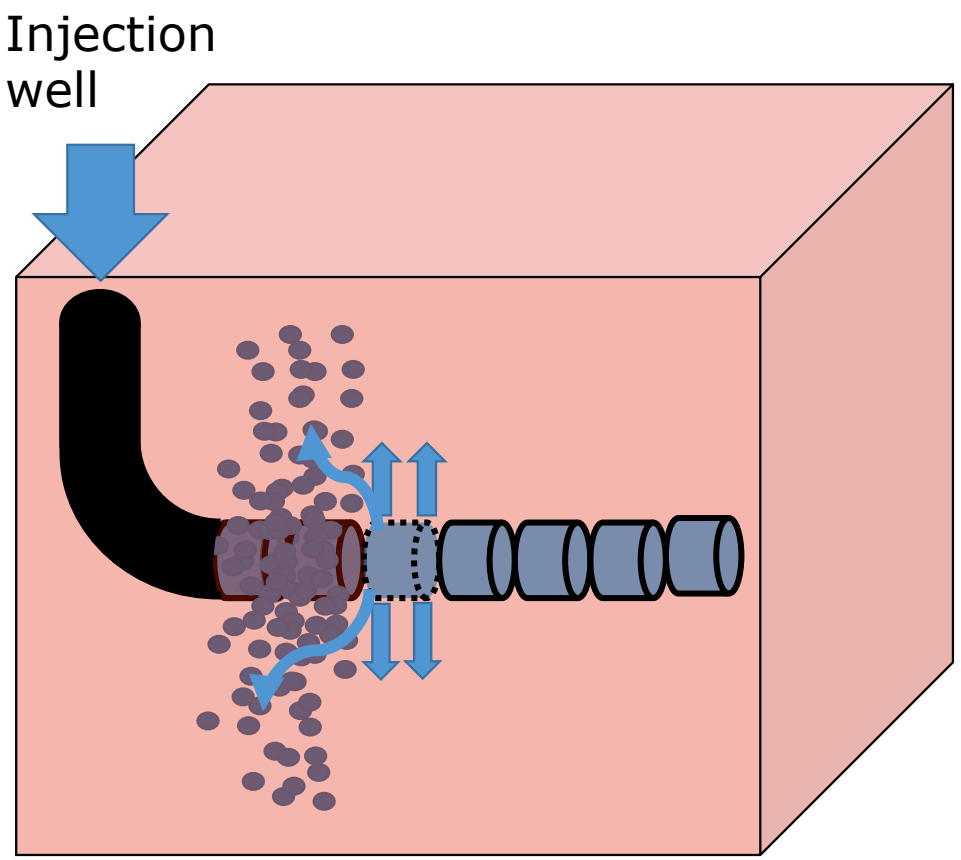




In Basel:

- A vertical well was drilled until 5 km in depth.
- The last 400 m was the only open case segment of the well.
- Temperature was high enough both for generating electrical power and providing heating, but only if the EGS reservoir was stimulated successfully.
- The stimulation of the EGS reservoir in Basel was not successful.
- Induced seismicity was observed during pre-tests experiments (artesian flow & injection of small flow rates).

# Future 'Multi-stage' EGS in Switzerland




(for more info: attend P. Meier's talk on Friday)

In a 'multi-stage' system:

- Wells are horizontal and reach similar depths and temperatures.
- There are many open case segments of the well.
- Stimulation principle: Inject water through only one well-segment at each time.

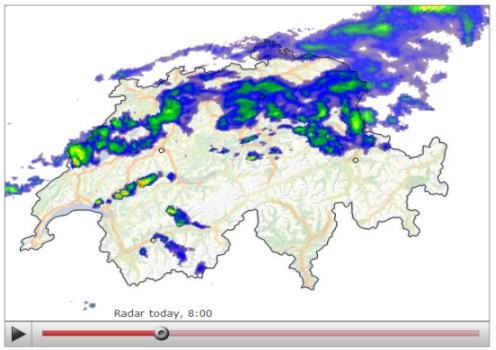
**Challenge**: Find optimal stimulation strategy.

**Goal**: Forecast both induced seismicity hazard & estimate expected electrical energy revenues.

"*In a coherent world, there should be no other types of forecasts except probabilistic*",

Roman Krzysztofowicz
(J. of Hydrology, 2001)

# Forecasts need to be sharp

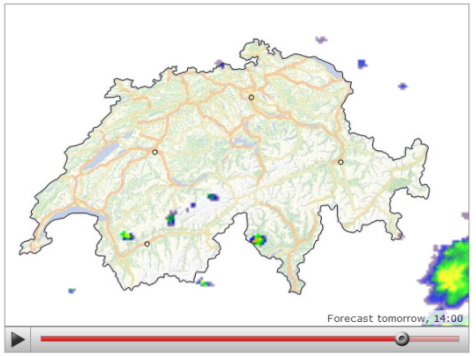



Satellite observation

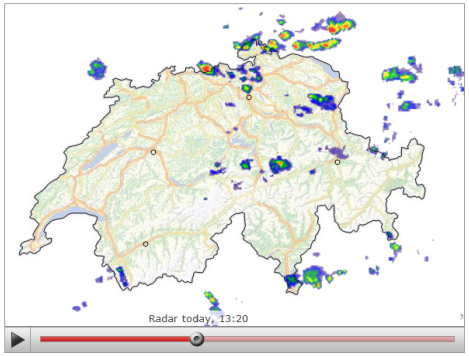
Statistical models

If it rains now, don't forget your umbrella tomorrow (2 out of 3 times is true)

Monte Carlo Simulations




24 h forecast with 95% confidence




Eventually: forecast was indeed true in ~95% of Switzerland

# Outline

Hybrid model with HFR-Sim

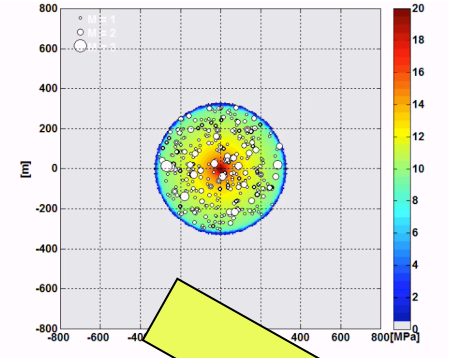
Examples of hybrid simulations

- Vertical well – Basel like stress conditions
- Multi-stage EGS – Basel like stress conditions

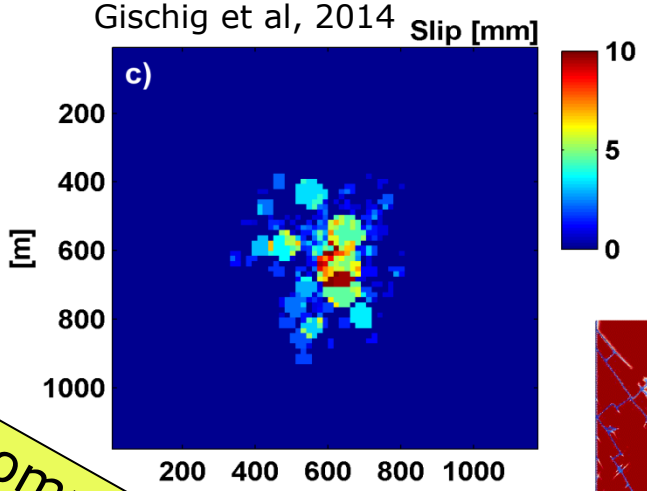
Conclusion

# Hybrid models: flow models & seed-model

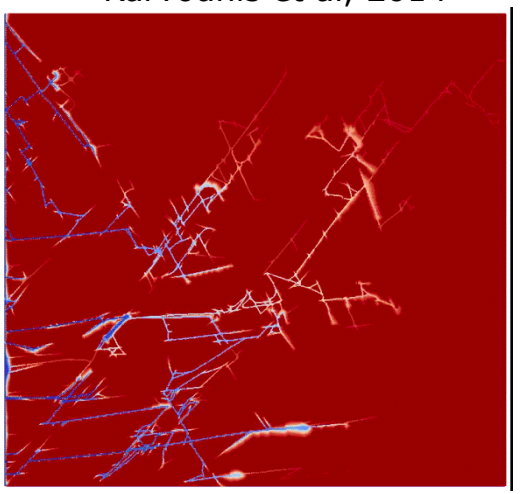
Gischig & Wiemer, 2013
Goertz-Allmann & Wiemer, 2013



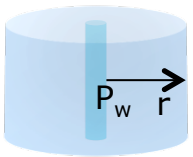

Gischig et al, 2014



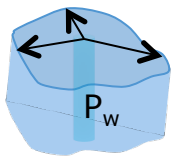

Karvounis et al, 2014



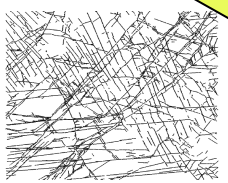
Model Complexity




1D with
COMSOL &
Seed model



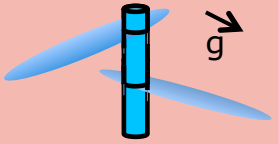

2D with
SUTRA &
Seed model



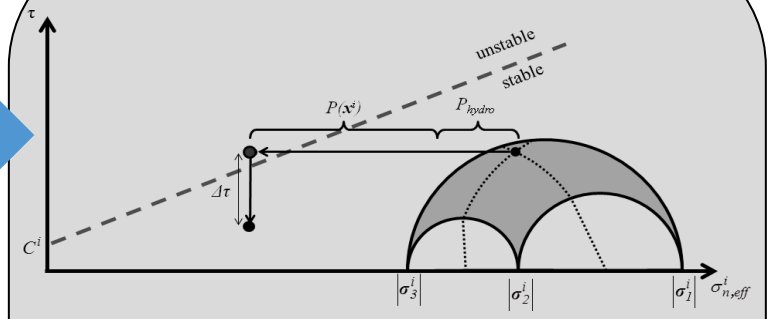
HFR-Sim: 3D Discrete
Fracture Modeling &
Seed model

# 3-D Discrete Fracture Hybrid Model with HFR-Sim

Start

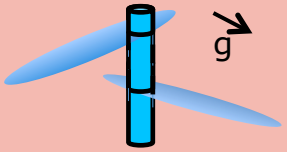



HFR-Sim approximates the pressure field inside the EGS reservoir at each time-step

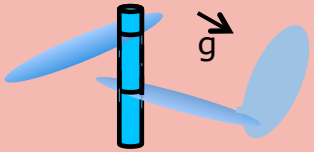



The Mohr-Coulomb failure criterion is applied on the seed points. We randomly choose the position, the orientation and the principal stresses of each seed in a three dimensional Cartesian system.

Each triggered seed represents an earthquake due to hydro-shearing. The magnitude M of that earthquake is sampled according to the (also sampled) b-value of that seed point.



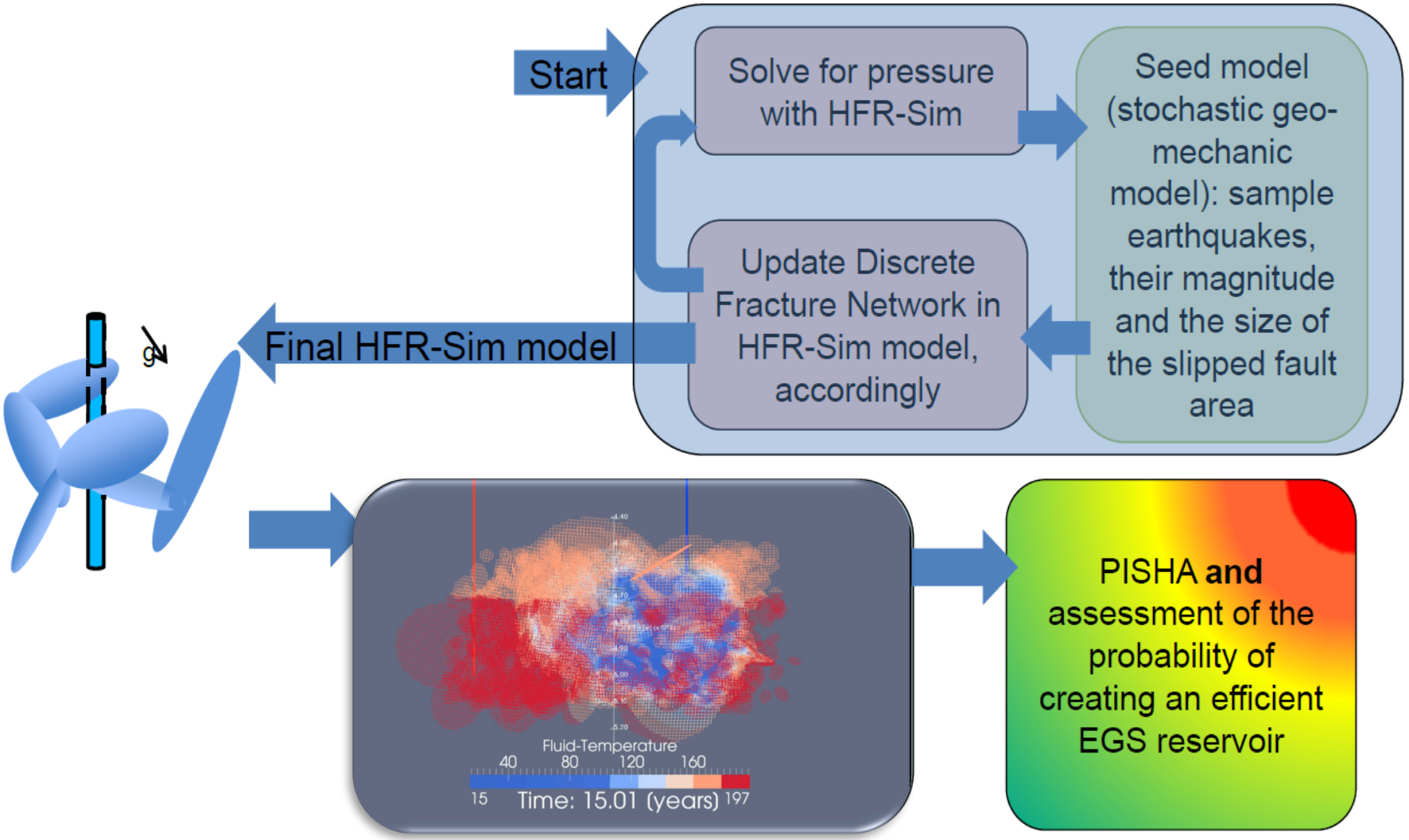

If M is smaller than a threshold value then the fault is not represented discretely but it is upscaled



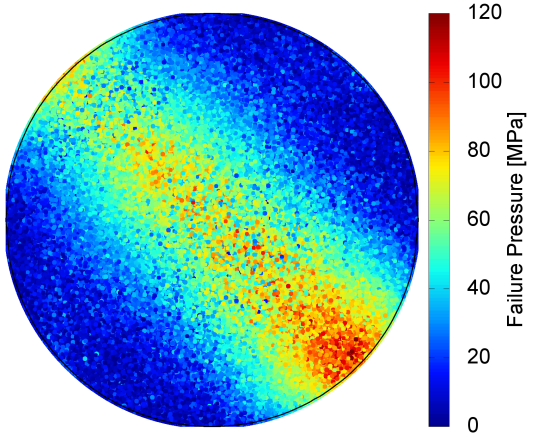

If M is larger than the threshold value, then a discrete fracture is added in the HFR-Sim flow model. The orientation and the size of this fracture is governed by the properties of the seed

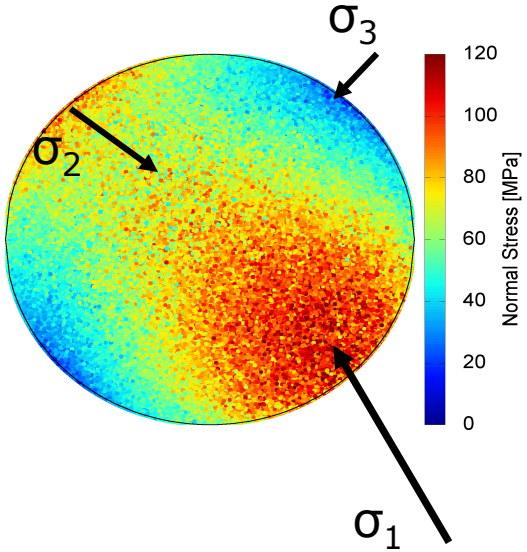
End

# 3-D Discrete Fracture Hybrid Model with HFR-Sim



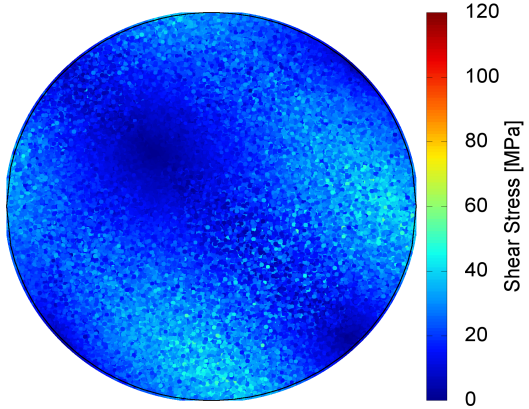
# Basel like stress conditions





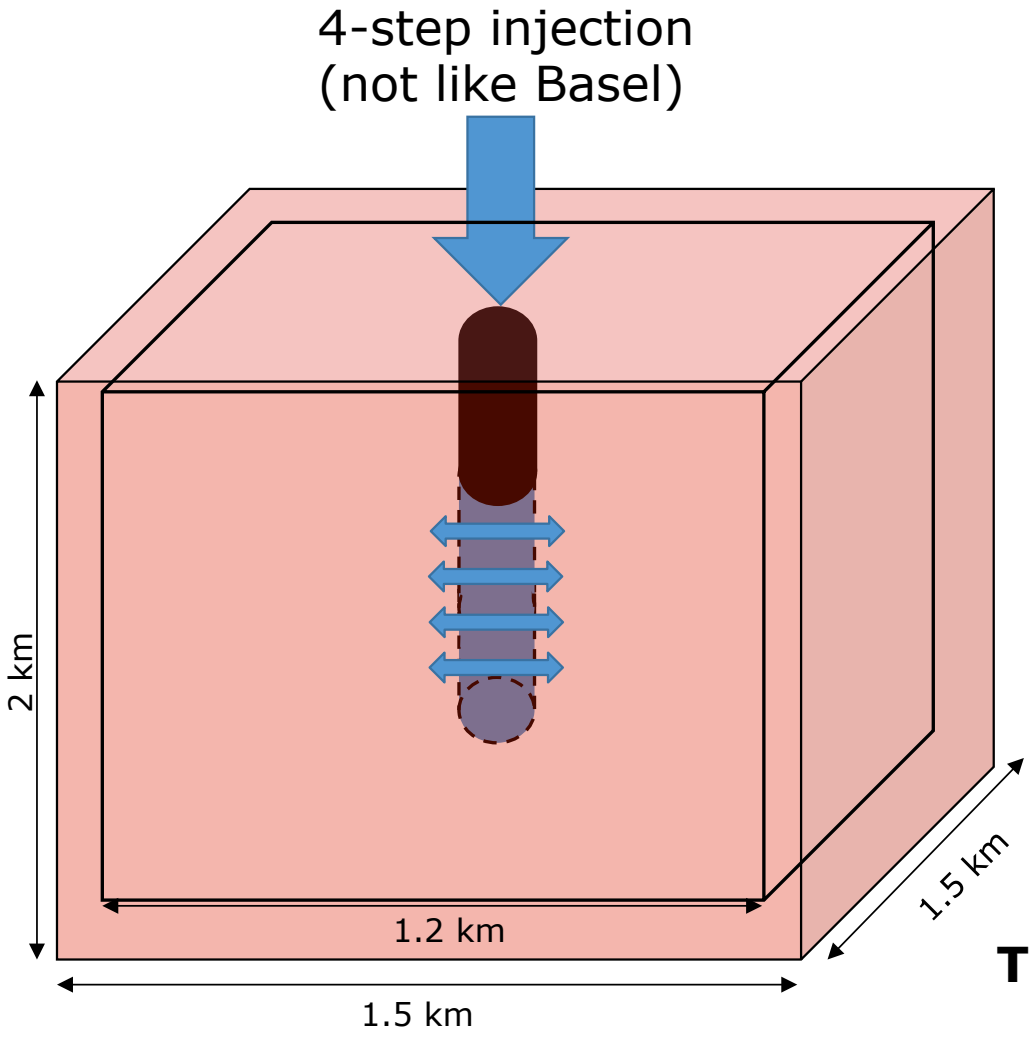





Seed model:

- Seeds are uniformly distributed with seed density *≈0.0004 seeds/m³*.
- Directions of principal stresses are similar to Basel and are *144.0Mpa*, *117.0Mpa* and *69.0MPa*.

# Vertical well – Basel like stress conditions

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- Seeds are uniformly distributed with seed density *≈0.0004 seeds/m³*.
- Directions of principal stresses are similar to Basel and are *144.0Mpa*, *117.0Mpa* and *69.0MPa*.

Initial HFR-Sim model:

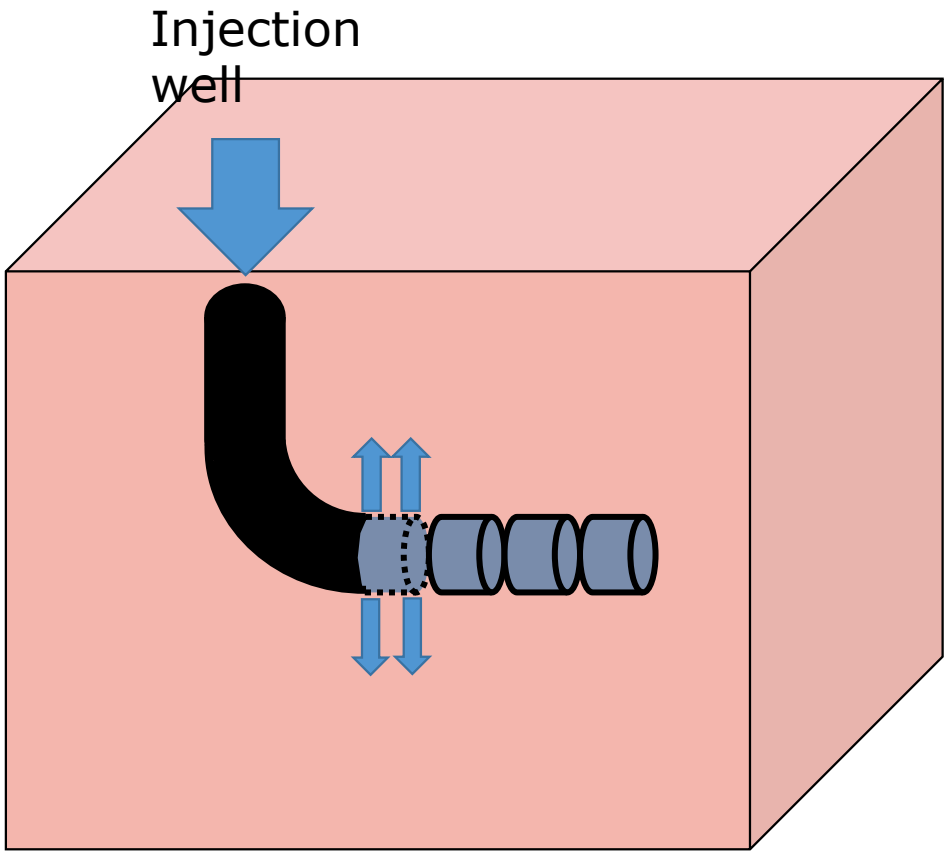
- Considers no discrete fractures, and
- Reproduces the pre-stimulation logs

Hybrid model:

- All fractures are disk-shaped fractures with aperture b=100µm.

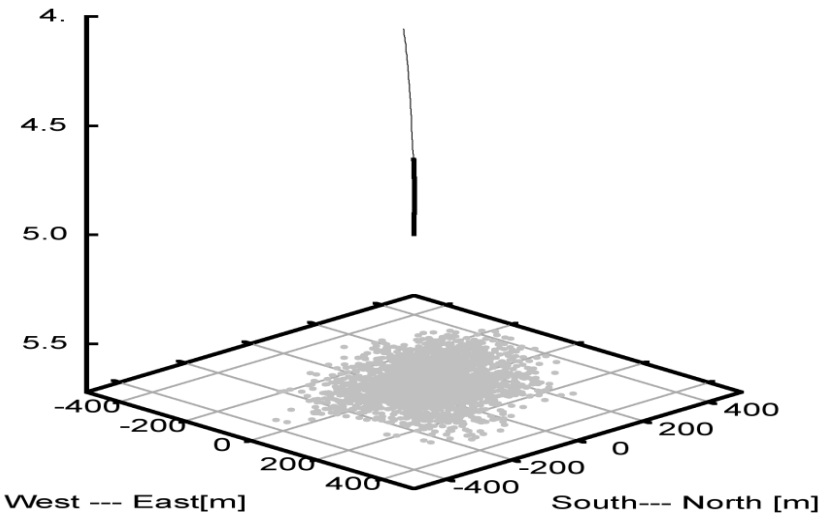
**This hybrid model has not been calibrated**

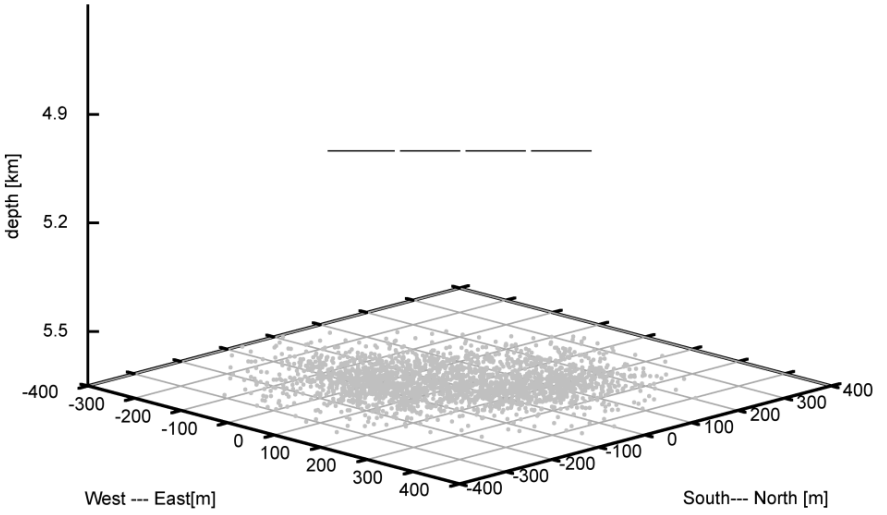
# Horizontal well – Basel like stress conditions

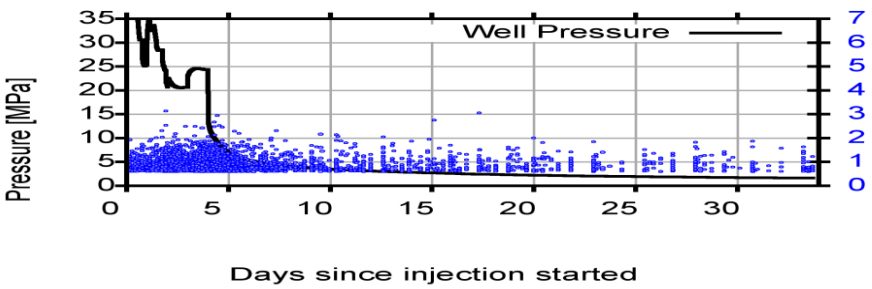



- Same seed settings and initial HFR-Sim model.
- The well has 4 segments and segment is stimulated separately with a 2 step injection.
- The well is along $\boldsymbol{\sigma_3}$.
- Total volume of water injected is same as before, but 2-step injection per stage.
- Fractures are again disk-shaped fractures with aperture b=100µm.

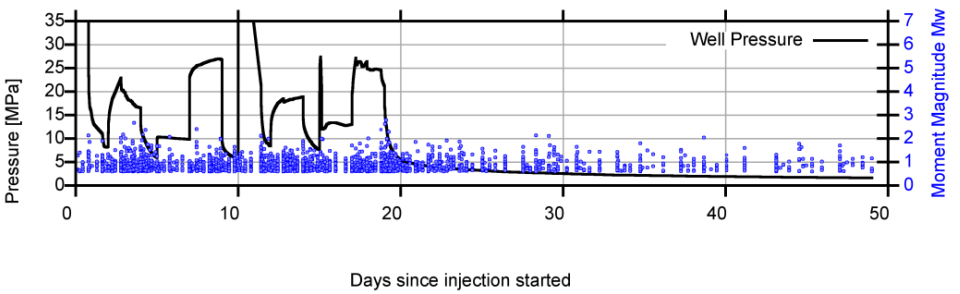
# Vertical well – Basel like stress conditions



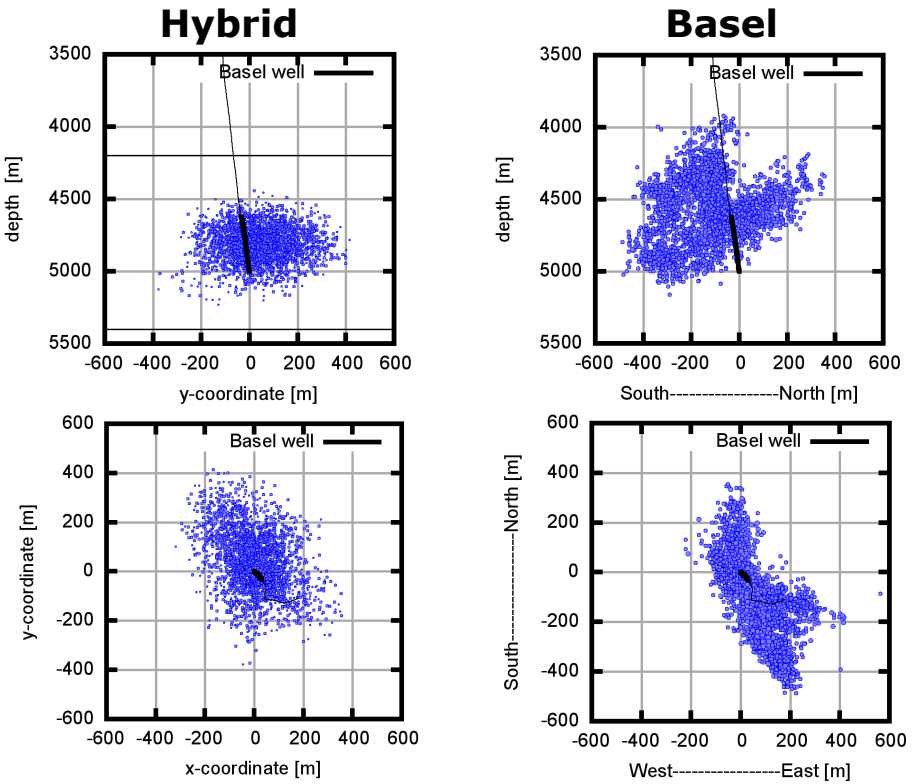




Basel Like EGS ≈1500 events




Multi-Stage EGS ≈1200 events

# Comparison between the Hybrid model and Basel




- Gravitational effects , induced seismicity from pre-stimulation tests, variations in the radius of the well and well image logs have not been included.
- Is the uniform distribution of seeds appropriate?
- Stress-interaction between seeds has been de-activated.
- Seeds are triggered only once.

# Conclusions

- A 3-D hybrid model has been developed that simulates
  1. induced seismicity due to increase of pore pressure, and
  2. the subsequent long term production phase of the EGS.
- It can be used for Monte Carlo simulations and to provide more sharp forecasts.
- Next steps:
  1. Probabilistically study the efficacy of risk mitigation strategies.
  2. Find optimal injection strategies and optimal well positions.
  3. Develop inversion algorithms that will calibrate the hybrid model and will improve forecasting abilities.

# Thank you

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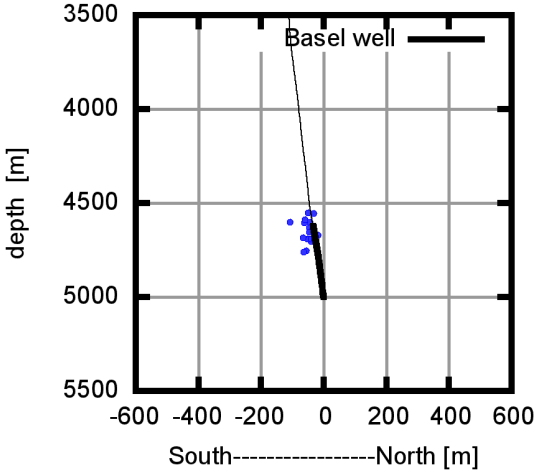
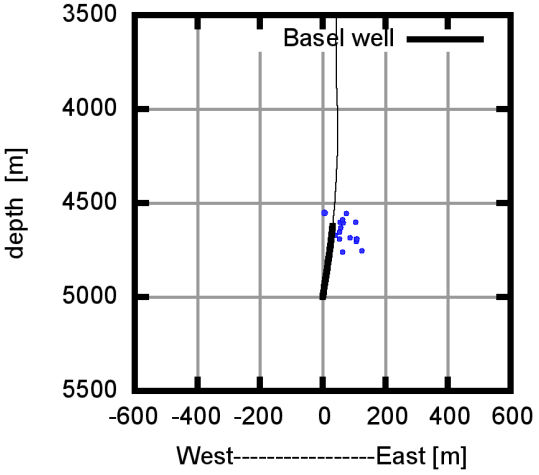
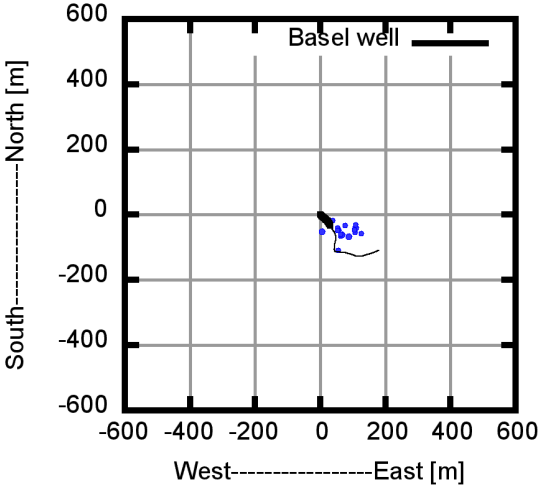
site: http://www.seismo.ethz.ch/index

# Enhanced Geothermal System in Basel

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