Geothermal Energy and Reservoir Technology

Coupling of thermo-hydro-mechanical modeling with seismicity modeling in a faulted geothermal reservoir

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Motivation

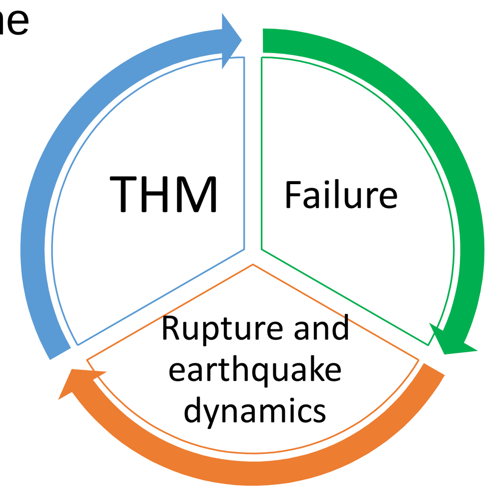
- Munich vision 2040 • 100% district heating from renewable energy (+17 plants)
- Induced seismicity • Seismicity and/or ground deformation (Monitoring/forecasting)
- Forecasting • An integrated tool that can guide the operator towards efficient exploitation
- Adaptive traffic light sytem • The operations can be adapted

Method

- A shell script to automate the work flow and the data format conversion
  - To call and execute MOOSE, SeisSol and the file conversion
  - To manage input and output files of both codes
- Reading and converting the outputs
  - Reading the data from the mesh is based on the element id
  - To convert the output format, Python scripts are used

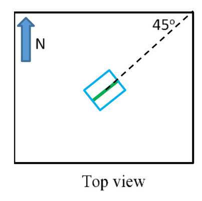
Concept

- Freeware
  - Open-source FE application based on **MOOSE** framework, fully coupled THM simulation in saturated porous and fractured geothermal reservoir
  - Open-source discontinuous Galerkin code for solving seismic wave equations (dynamic rupture): **SeisSol**
- Equations
  - Hydraulics: mass balance and Darcy's velocity (pore pressure)
  - Heat transport: advection-diffusion and Fourier's law (temperature)
  - Mechanics: force equilibrium in thermo-poroelastic medium (stress and strain). Strain as a function of porosity and permeability
  - Fault friction law: rate-and-state, linear slip weakening, linear slip strengthening
- Coupling
  - Compute stress change along fault and determine critical stress state with regards to failure criterion
  - Determine failure moment
  - Initiate seismic event and propagate rupture on the fault
  - Compute stress change (release) and update stress state

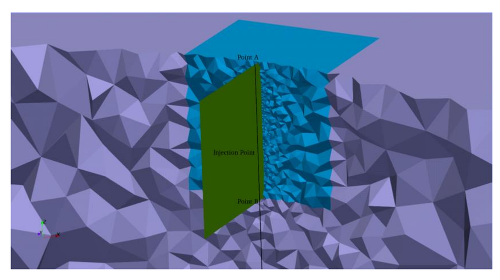


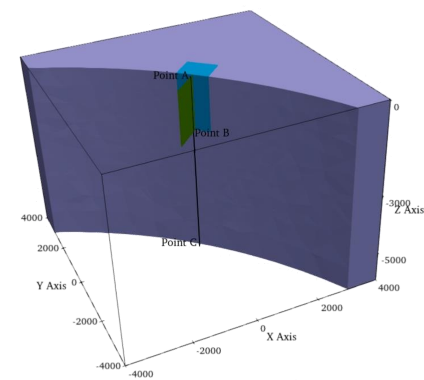
Synthetic case study

- Structural model
  - A simplified faulted reservoir (injection point at 1000 m depth)
  - A vertical reservoir (blue) crossed by a vertical fault (green) with 45°N azimuth (from top to the bottom of the reservoir)



- Boundary conditions
  - Reflective displacement boundaries (except on the top)
  - Zero normal displacement at the boundaries
  - Fixed bottom surface
  - No overburden force
- Initial conditions
  - Stress regime: strike slip
  - T(z): 3.5°C/km, P(z): hydrostatic
  - Stress state at reactivation

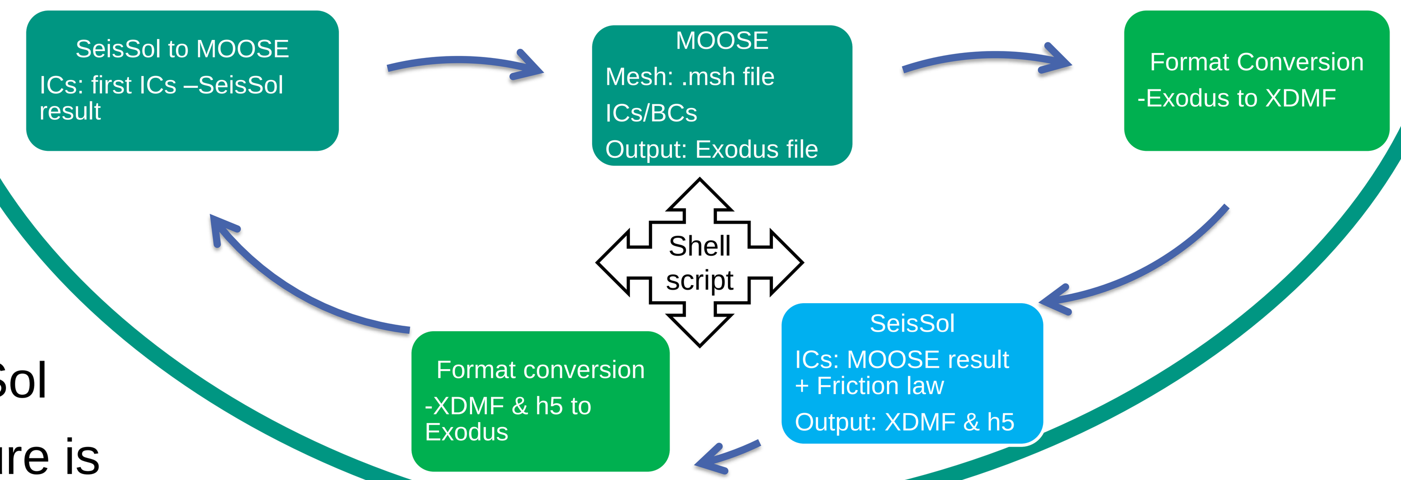




8 x 8 x 6 km³
0.5- 300 m mesh size

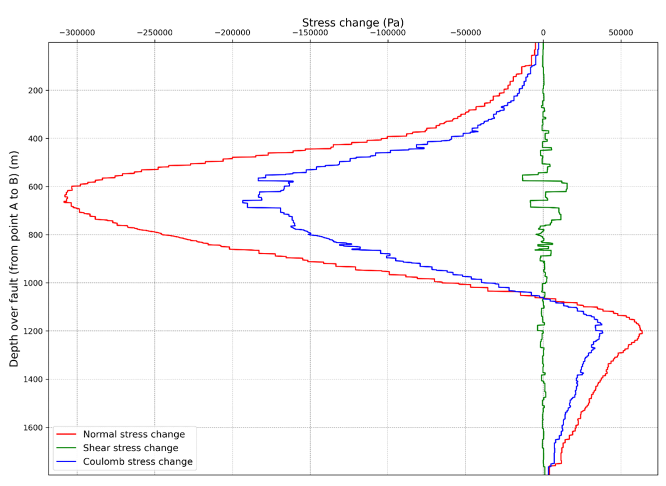
- Material properties

	Non-reservoir	Reservoir	Fault(s)
Thermal expansion[9] [10^{-6} K^{-1}]	1.0	1.0	1.0
Initial permeability[10] [m^2]	$3*10^{-17}$	$1.5*10^{-14}$	$4*10^{-10}$
Initial porosity[10] [%]	0.01	0.15	0.15
Compressibility [GPa^{-1}]	0.5	0.5	0.5
Thermal capacity[10] [$J.kg^{-1}.K^{-1}$]	800	800	800
Thermal conductivity[10] [$W.m^{-1}.K^{-1}$]	3.0	3.0	3.0
Density [$kg.m^{-3}$]	2500	2500	2500
Young´s modulus [GPa]	15	15	15
Poisson´s ratio	0.2	0.2	0.2

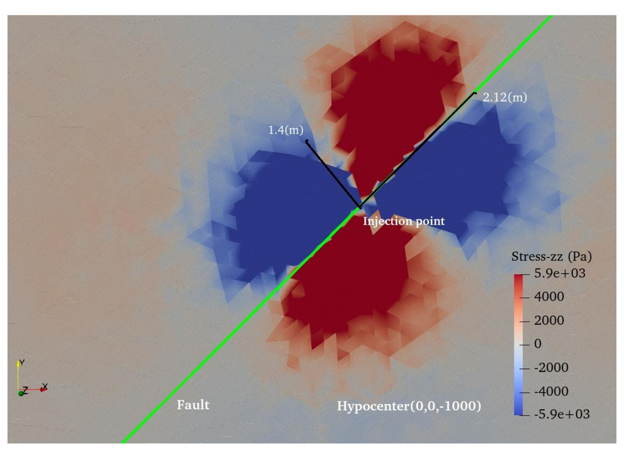


Results (during and after rupture)

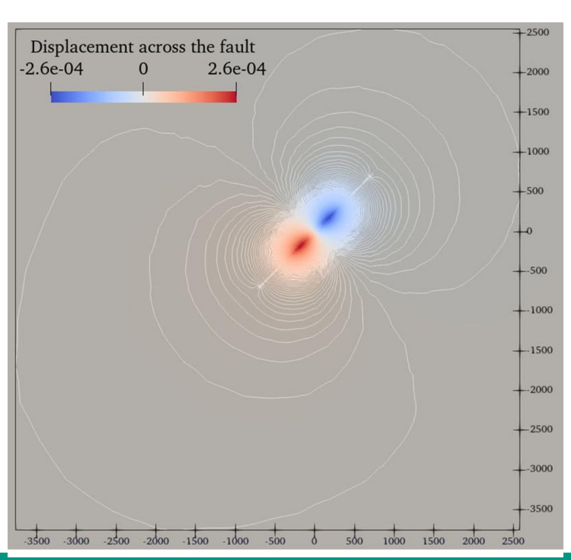
- The dynamic rupture model is initialized by stress field from the reservoir modeling at the failure time and linear slip weakening friction model is applied by SeisSol
- Stress changes due to the dynamic rupture is imported back into MOOSE
- Then reservoir simulation can proceed with the updated stress field until next failure and continue over the reservoir lifespan



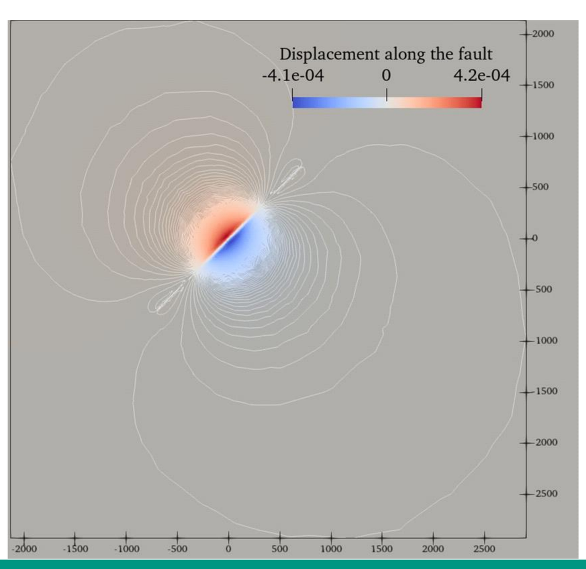
Effective normal/shear/Coulomb stresses change along fault over depth due to seismic event



Change of stress$_{zz}$ magnitude induced by seismic event



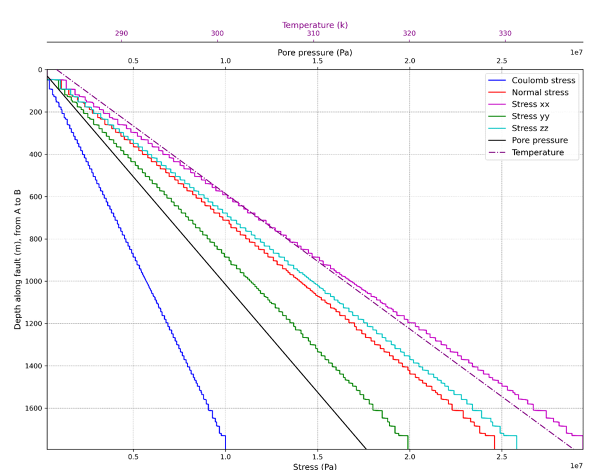
Displacement along/ across the fault due to seismic event

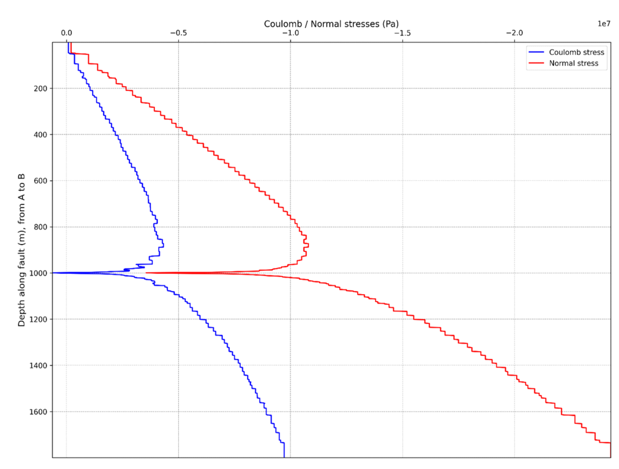


Results (prior to rupture)

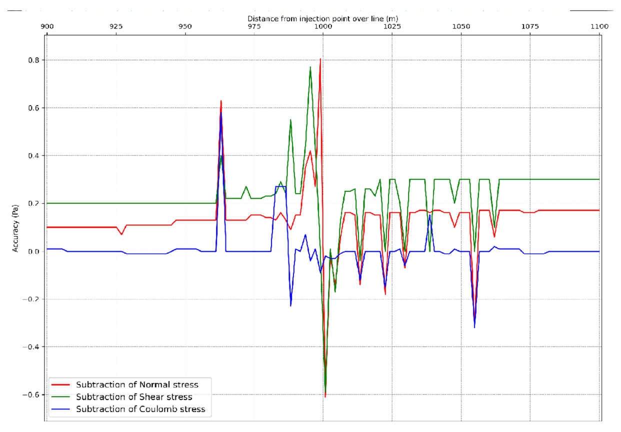
- Model is simulated and after about ~1222 days, the failure criterion is met.

Initialization of the model





Effective normal and Coulomb stresse changes along fault over depth at the reactivation moment



Accuracy of effective normal/shear/Coulomb stresses in conversion

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