Dynamic earthquake rupture modeling in fracture networks of geo reservoirs accounting for the effects of thermal pressurization

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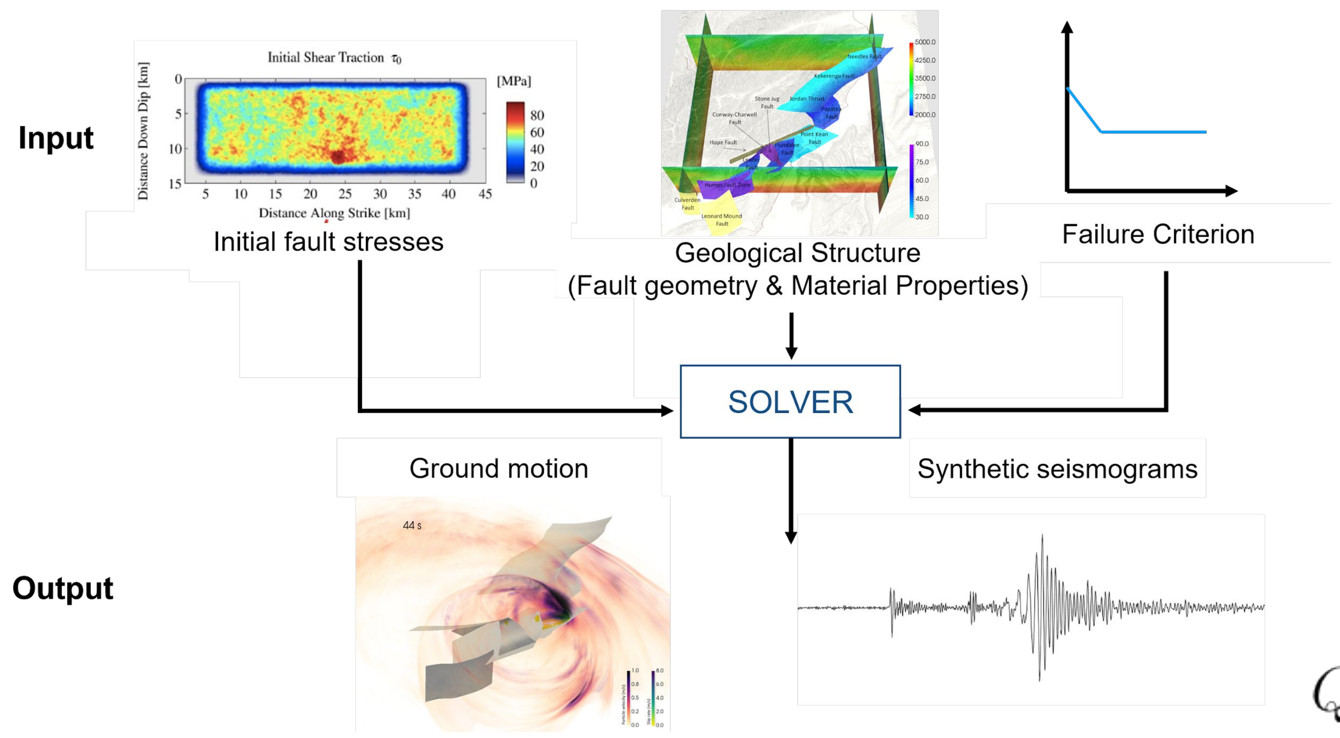
Introduction

The **presence of fractures** in geo-reservoirs, natural or man-made, is crucial to the economics of oil & gas production and geothermal-energy harvesting. Monitoring and controlling their properties and their growth is an important aspect of reservoir engineering. On the other hand, the related seismic hazard due to the (re-)**activation of these fractures,** and their ability to generate sizeable earthquakes, has received limited attention until recently. Earthquake faults **interact with fluids** in a variety of ways, through mechanisms that operate on **different space-time scales**. The relation between hydraulic properties of faults/fractures, dynamic changes of pore pressure, and the likelihood of inducing larger earthquakes, potentially through cascading failure of fractures, is largely unknown. The goal is to find the **likelihood of earthquake initiation** and the **maximum expected earthquake size** using physics based earthquake simulations



Modelling Framework

Recently developed realistic earthquake scenarios performed with **SeisSol** (www.seissol.org) shed new light on the fundamentals of earthquake physics and help to constrain source inversion and rupture imaging studies [1].

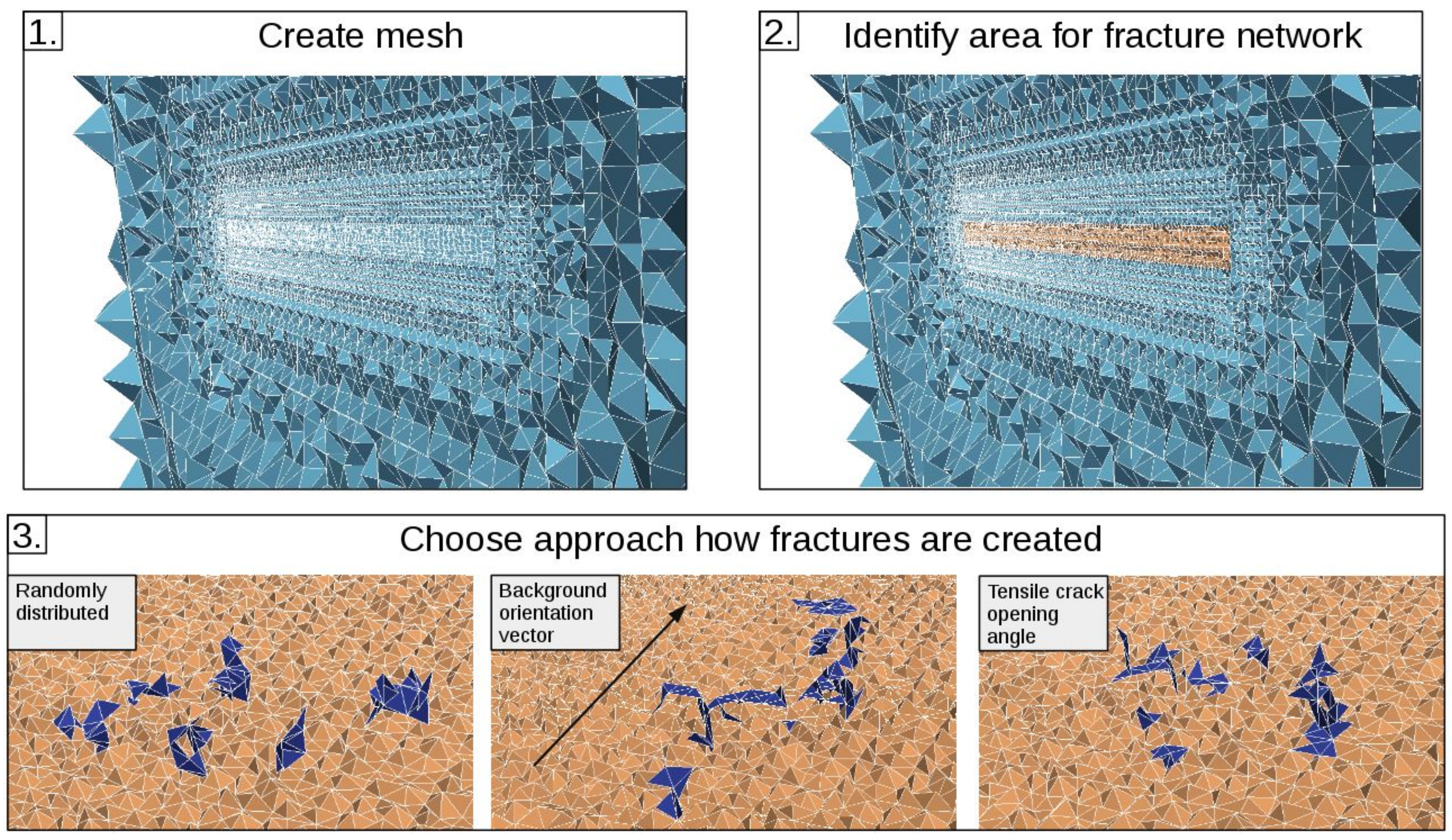
- open-source software package available at **https://github.com/SeisSol/SeisSol**
- arbitrary high-order derivative Discontinuous Galerkin method (**ADER-DG**), modal approach, elastic wave equation in velocity stress formulation (linear hyperbolic system):

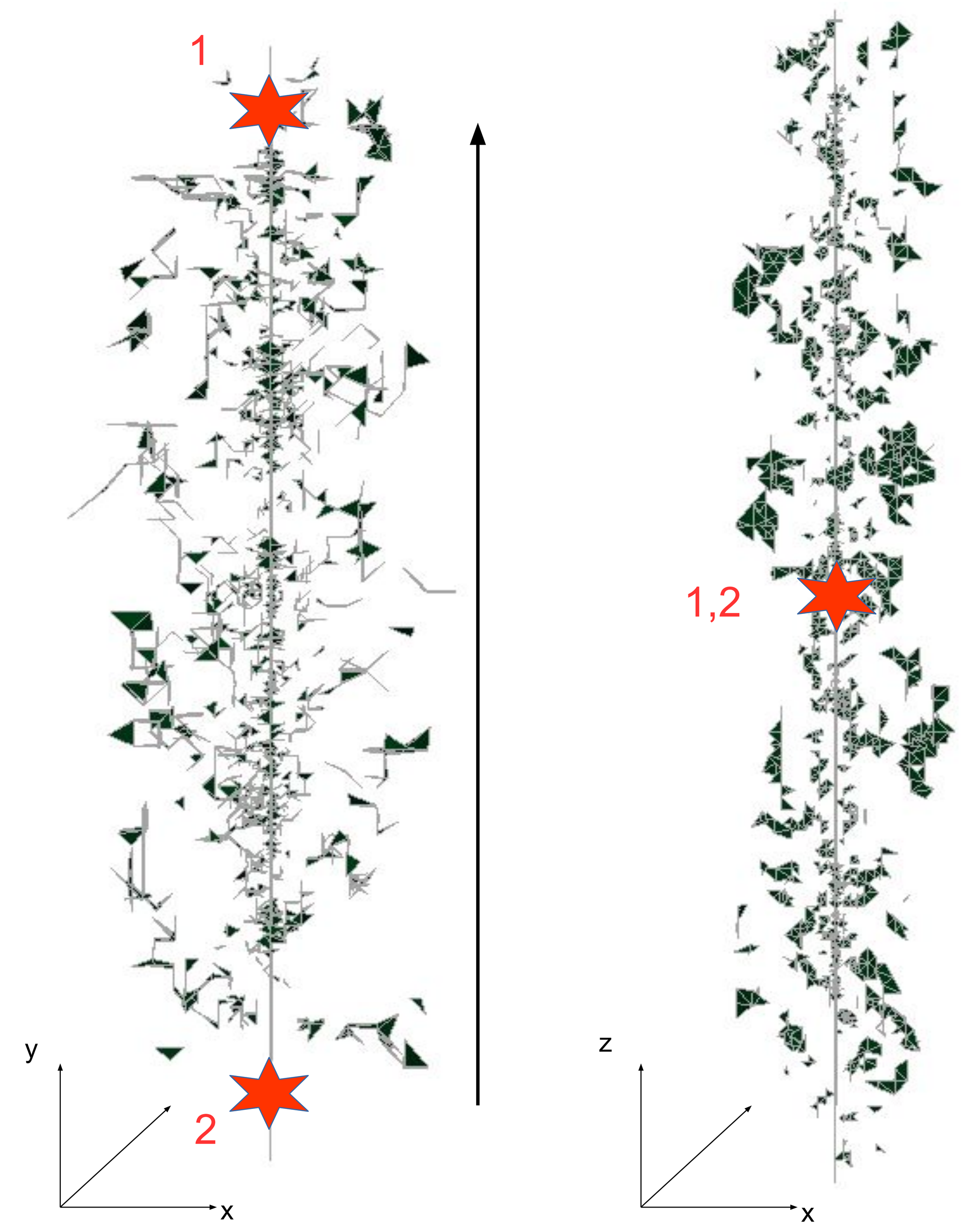
$$\frac{\partial Q_p}{\partial t} = \vec{\nabla} \cdot (A_{pq}\vec{i} + B_{pq}\vec{j} + C_{pq}\vec{k})Q_q = 0$$

$$Q = (\sigma_{xx}, \sigma_{yy}, \sigma_{zz}, \sigma_{xy}, \sigma_{yz}, \sigma_{xz}, u, v, w)^T$$

Statistical Fracture Network

Fault geometry has a strong influence on earthquake dynamics. Existing descriptions of **fracture network** characteristics are based on multi-well observations, outcrop mapping, seismic based fracture prediction and laboratory studies and reveal a vast degree of geometric complexity. Incorporating such structures with a sufficient degree of their complexity in computational models poses a major challenge for physics-based dynamic rupture simulations. We here use the **statistical nature** of fracture density in a novel, physics-based **Markov Chain** approach.





Fractures surrounding main fault up to 1km far away in unstructured media. Fracture length distribution according to [3]. The background orientation vector is along fault (y-axis).

Thermal Pressurization

We model the **interaction of fluids** and earthquake faults through thermal pressurization of pore fluids [5].

- We recently completed the first **2D-implementation** of thermal pressurization into a DG-based dynamic rupture solver using the spectral method [6, 7]

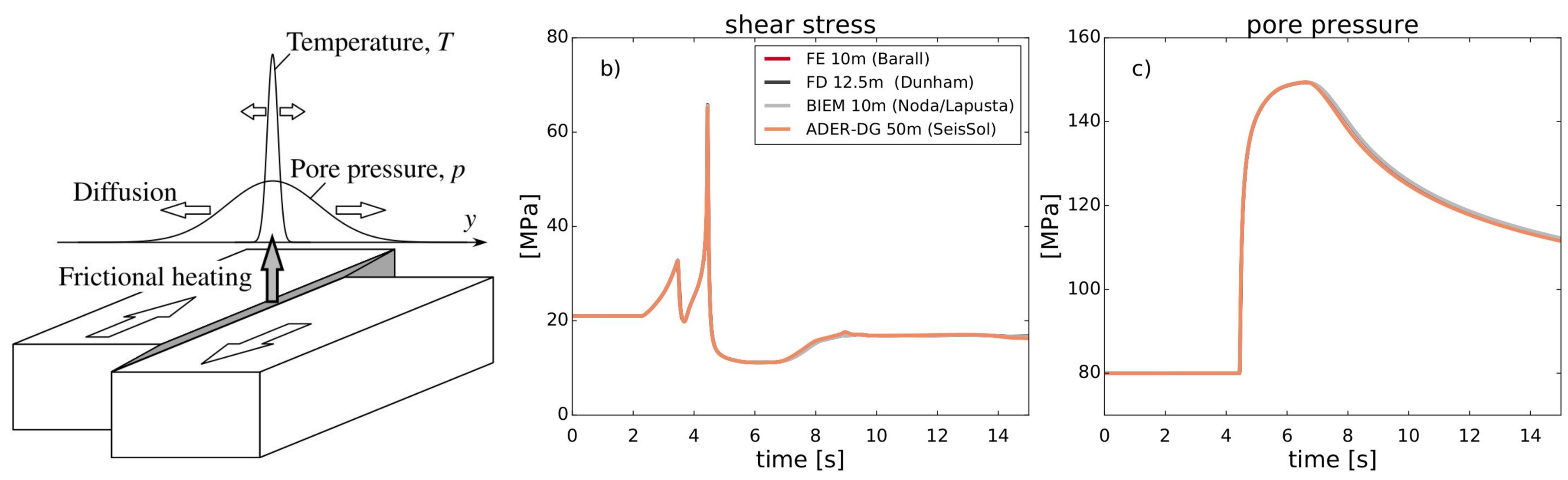
$$\frac{\partial T(x,y,z,t)}{\partial t} = \alpha_{th}\frac{\partial^2 T(x,y,z,t)}{\partial y^2} + \frac{\omega(x,y,z,t)}{\rho c}$$

$$\frac{\partial (p + \Lambda' T)}{\partial t} = \alpha_{hy}\frac{\partial^2 (p+\Lambda' T)}{\partial y^2} + (\Lambda + \Lambda')\frac{\omega}{\rho c}$$

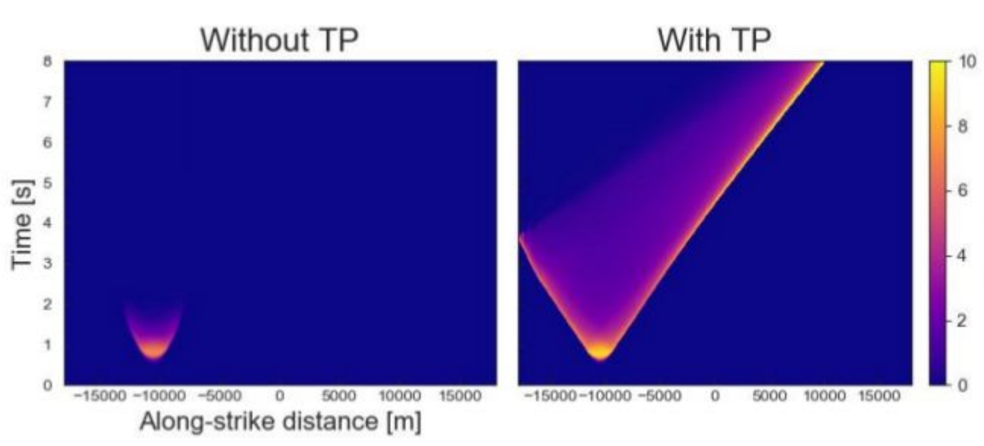
T: temperature
p: pore pressure
ω: shear heating source
Λ: undrained Δp/ΔT
ρc: specific heat

$\Lambda' = \Lambda\, \alpha_{th}/\alpha_{hy} - \alpha_{th})$

- Our results show a **sustained rupture** due to thermal weakening
- Our results show a **strong reduction of effective normal stress** due to increased pore pressure, in excellent agreement with alternative dynamic rupture solver
- We will extend our **implementation to 3D** to incorporate realistic 3D setups



a) Sketch of the interplay of frictional heating and pore pressurization [7] b) Shear stress and c) pore pressure on one point of a 1D fault in a 2D domain (benchmark by the Southern California Earthquake Center). Note the excellent agreement of SeisSol with established Finite Element [9], Finite Difference [8] and Boundary Integral Methods [7].



Effect of thermal weakening. Along-strike distance vs. Time with respect to slip rate along a 1D fault in a 2D domain (benchmark by the Southern California Earthquake Center).

Open questions:

- Interconnectivity between fractures?
- Densification vs. fracture length?
- 3D observations available?
- Aspect ratio for fractures in geo-reservoir setting?
- Possible model setups?
- Directivity effects?

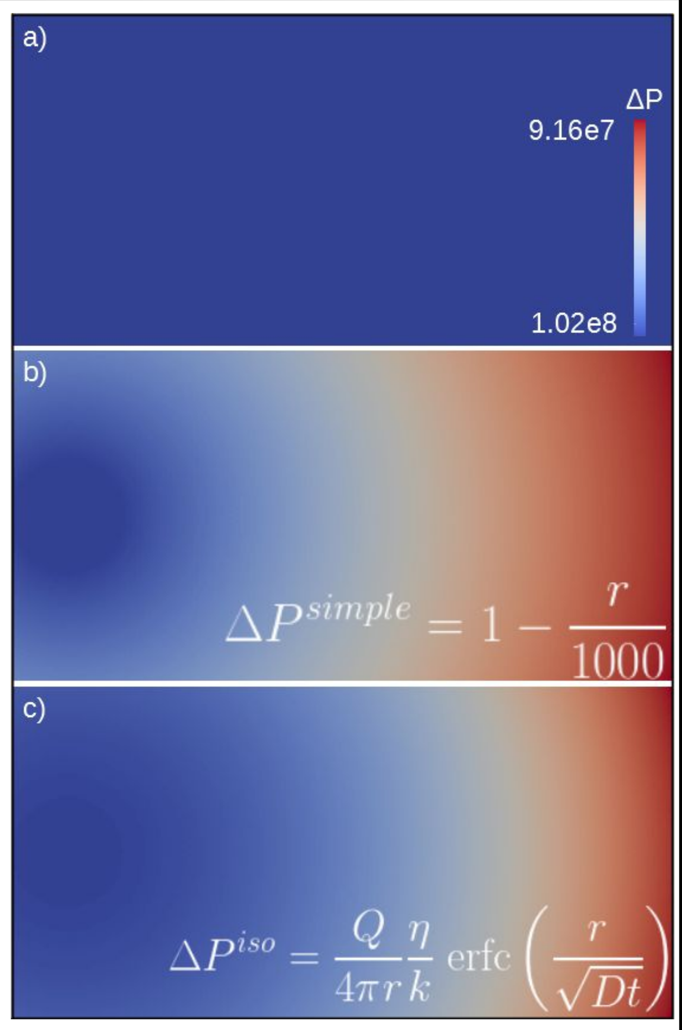
Model Setup

We model the influence of pore pressure gradients on the fault due to injection. The **injection** of water takes place **at the nucleation point 1**.

- Main fault dimensions: 12km x 6km
- Nucleation at red points (left or right)
- Fractures are **not** yet included
- **Pore pressure gradient ΔP^{iso}** used [2]

Q	Fluid injection rate	80 kPa
η	Viscosity	10^{18} Pas
κ	Permeability	10^{-12} m²
r	Distance from injection point	0 -12 km
D	Diffusivity	1 m²/s

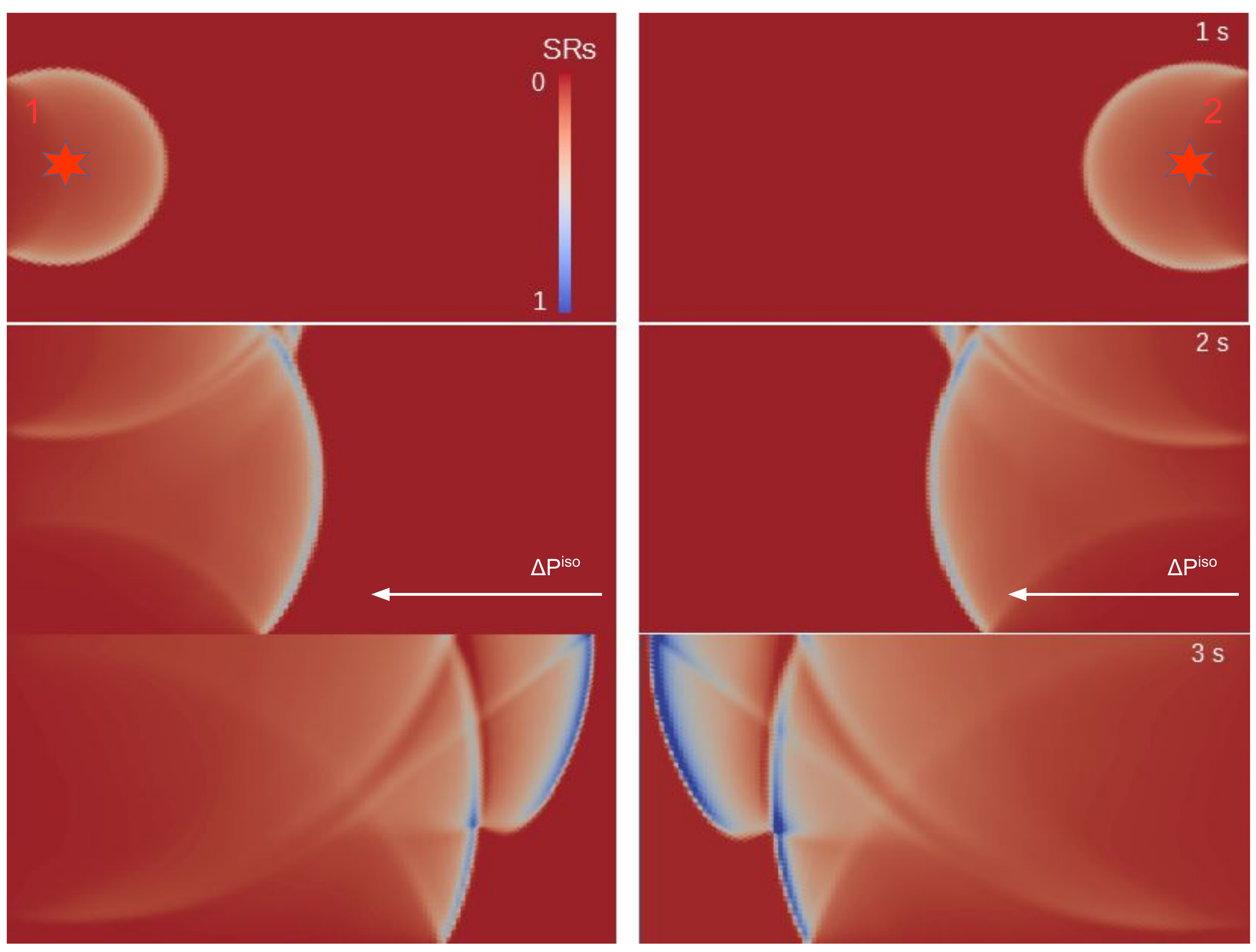
- Our results show a **higher slip rate** towards injection point and the **rupture is accelerating** with increasing pore fluid pressure.
- The next step is to include fractures and the interaction of fluids (Thermal Pressurization). We want further extend this to different fault geometries (i.e. branching)



$$\Delta P^{simple} = 1 - \frac{r}{1000}$$

$$\Delta P^{iso} = \frac{Q}{4\pi r}\frac{\eta}{k}\,\mathrm{erfc}\left(\frac{r}{\sqrt{Dt}}\right)$$

Different formulas to calculate pore pressure gradients. a) constant pore pressure, b) simple pore pressure gradient depending on nucleation size, and c) pore pressure solution in response to injection at a point source in an isotropic, 3D reservoir [3,4].



References

[1] Wollherr et al. (2018): Off-fault plasticity in three-dimensional dynamic rupture simulations using a modal Discontinuous Galerkin method on unstructured meshes: implementation, verification and application, GJI **[2]** Chen et al. (2018): Temporal correlation between seismic moment and injection volume for an induced earthquake sequence in central Oklahoma. JGR **[3]** Rice & Cleary (1976): Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents. Rev. Geophys. Space Phys **[4]** Rudnicki (1986): Fluid mass sources and point forces in linear elastic diffusive solids. Mech. Mater **[5]** Sibson (1973): Interaction between temperature and pore fluid pressure during earthquake faulting: A mechanism for partial or total stress relief, Nature **[6]** Wollherr et al. (2016): Realistic Physics for Dynamic Rupture Scenarios: The Example of the 1992 Landers Earthquake, AGU Abstract. **[7]** Noda & Lapusta (2010): Three-dimensional earthquake sequence simulations with evolving temperature and pore pressure due to shear heating: Effect of heterogeneous hydraulic diffusivity, JGR. **[8]** Dunham et al. (2011): Earthquake ruptures with strongly rate- weakening friction and off—fault plasticity, 2: Nonplanar faults, BSS. **[9]** Barall (2009): A grid-doubling finite-element technique for calculating dynamic three-dimensional spontaneous rupture on an earthquake fault, GJI.