3D dynamic rupture modeling with thermal pressurization

Alice-Agnes Gabriel[1], Jagdish Vyas[2], Thomas Ulrich[1], Jean-Paul Ampuero[3], P. Martin Mai[2]

[1]Ludwig-Maximillians-Universität (LMU) Munich, Germany [2]King-Abdullah-University for Science and Technology (KAUST), Thuwal, Saudi Arabia, [3]Université Côte d'Azur, CNRS, Observatoire de la Côte d'Azur, IRD, Géoazur, Valbonne, France

Summary

Thermal pressurization of pore fluids (TP, Sibson 1973) is considered a dominant dynamic weakening mechanism affecting earthquake rupture nucleation, propagation and arrest (e.g., Noda et al., 2009, Viesca and Garagash, 2015, Badt et al., 2020). In the context of geo-reservoirs, pressure increase can drive fluid flow and in turn govern earthquake dynamics (e.g., Galis et al., 2017).

Several numerical implementations have been proposed to include TP **in dynamic earthquake rupture modeling** based on the theoretical foundations of conservation of fluid mass and energy, Fourier's law and Darcy's law. We here present 3D dynamic rupture simulations to account for the interaction of fluids and earthquake faults through thermal pressurization of pore fluids using **an accurate spectral implementation (Noda & Lapusta, 2010) combined with an efficient update scheme in the Discontinuous Galerkin software SeisSol.** We show superior accuracy of this implementation while the computational cost is equivalent to coupling SeisSol with a finite difference TP approach on supercomputing infrastructure.

We employ dynamic rupture modeling to examine **the effects of hydraulic diffusivity (α) and shear-zone half-width (w) on dynamic and kinematic properties such as mean slip, peak slip rate and rupture speed.** We statistically analyze a suite of 3D models under rate-and-state (strong velocity weakening) friction incorporating a shallow velocity-strengthening region in which also hydraulic diffusivity varies and smooth rupture arrests. We observe **highly sensitive trade-offs of rupture nucleation, rapid dynamic weakening effects, realistic heat production and fault stress and strength initial conditions**. Varying the **shear-zone half-width (w)** within observational uncertainties **impacts the resulting mean peak slip rate stronger** than other TP parameters, whereas the effects of hydraulic diffusivity and shear zone width on rupture speed are comparably. Additionally, **mean slip decreases with increasing hydraulic diffusivity (α), but remains nearly unaffected by variations of tshear-zone half-width (w)**.

SeisSol employs fully adaptive, unstructured tetrahedral meshes suitable to combine geometrically complex 3D geological structures, nonlinear rheologies, and high-order accurate propagation of seismic waves. **Hence, future work will analyze synthetic ground motions, combine TP with geometric 3D fault complexity and analyze trade-offs with off-fault plasticity** (Wollherr et al., 2019, Ulrich et al., 2019).

Fault strength governed by thermal pressurization and rapid velocity weakening friction

- pore pressure changes due to thermal expansion and confinement of fluids within matrix with lower thermal expansivity
- extreme reduction of friction coefficient, expected to prevent fault melting

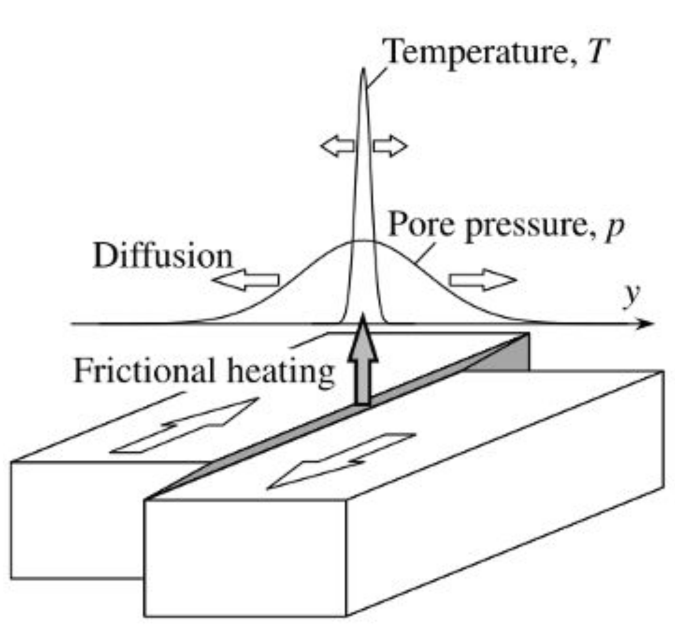


Figure 1: Sketch of the interplay of frictional heating and pore pressurization (Noda & Lapusta, 2010).

TP equations: 2 diffusion equations for temperature and pore pressure with dilatancy normal to the fault

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

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

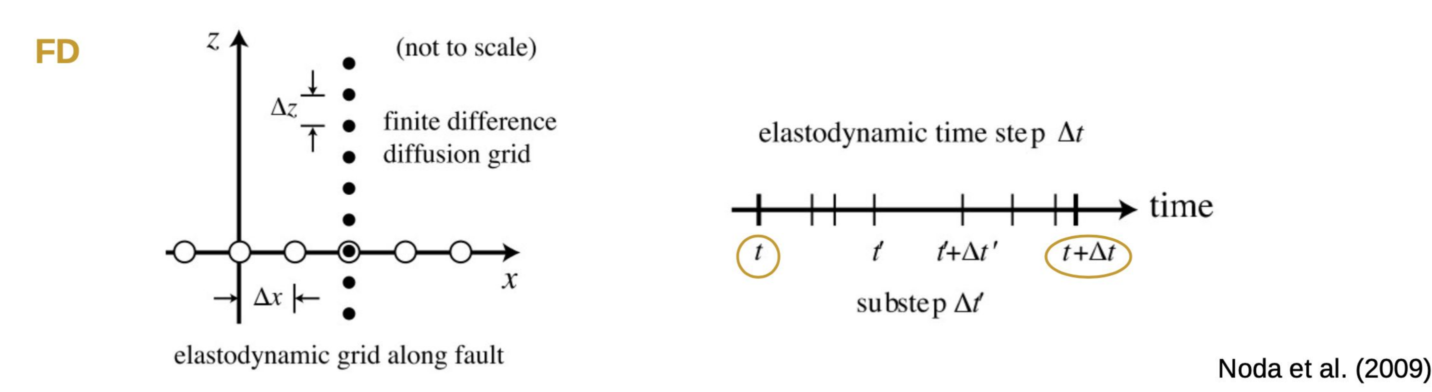
$$\omega = \tau V \frac{\exp(-y^2/2w^2)}{\sqrt{2\pi}w}$$

ρc: specific heat capacity
α: thermal / **hydraulic diffusivity**
Λ: pore pressure change per unit temperature
V: magnitude of slip rate
T: temperature
p: pore pressure
ω: shear heating source
τ: frictional strength
w: half width of shearing layer

A Spectral Thermal Pressurization Implementation for the 3D Discontinuous Galerkin Dynamic Rupture Software SeisSol

- TP solvers vary in efficiency and flexibility.
- We couple a semi-analytic, stable, precise and efficient spectral diffusion solver (Noda and Lapusta, 2010) with 3D elastodynamic dynamic rupture modeling in the HPC-empowered software SeisSol (www.seissol.org) using Fourier transformation for the spatial variables but not for the time domain. In contrast to finite-element methods, the basis functions here are non-zero over the whole domain leading to a global approach.
- We optimized the **update scheme** for this TP solver coupled to strong rate-dependent friction dynamic rupture following Kaneko et al. (2008)
- For SeisSol we observe excellent error properties, computationally lower cost than an FE approach, and comparable computational cost as a FD TP solver
- We conduct **numerical stability analysis** dependent of diffusivity and shear zone half-width (which can change in orders of magnitude)

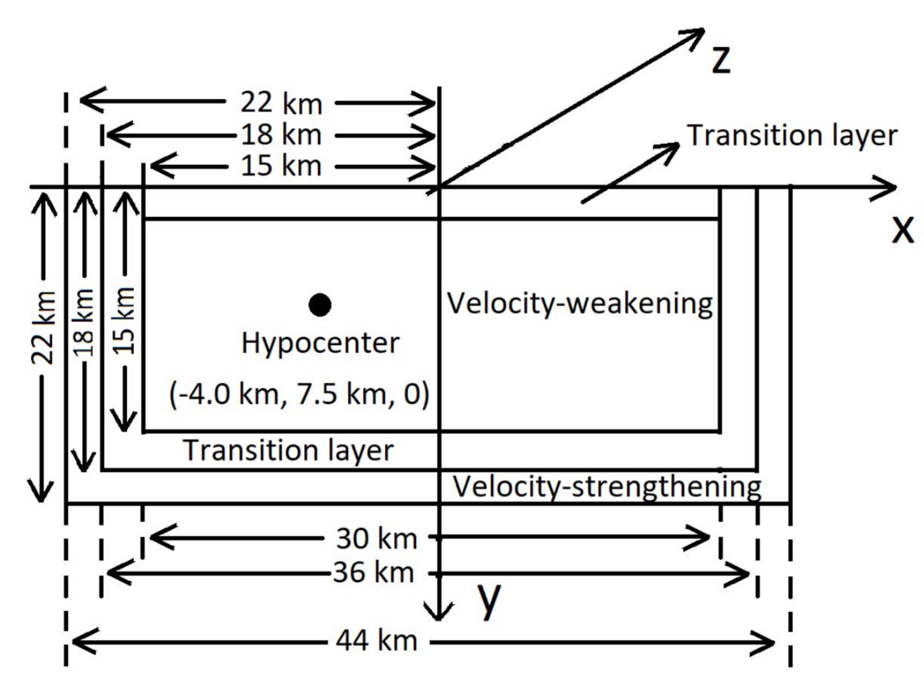
Numerical Method	pros	cons	used in
(explicit) Finite Difference	very simple, heterog. diffusivity parameters possible	very restrictive time step size; interpolation between major time steps (storage of the slip history at substeps)	Noda et al. (2009)
Spectral Method	Larger time steps possible memory efficient	restricted to homog. diffusivity parameters	Noda & Lapusta (2010)



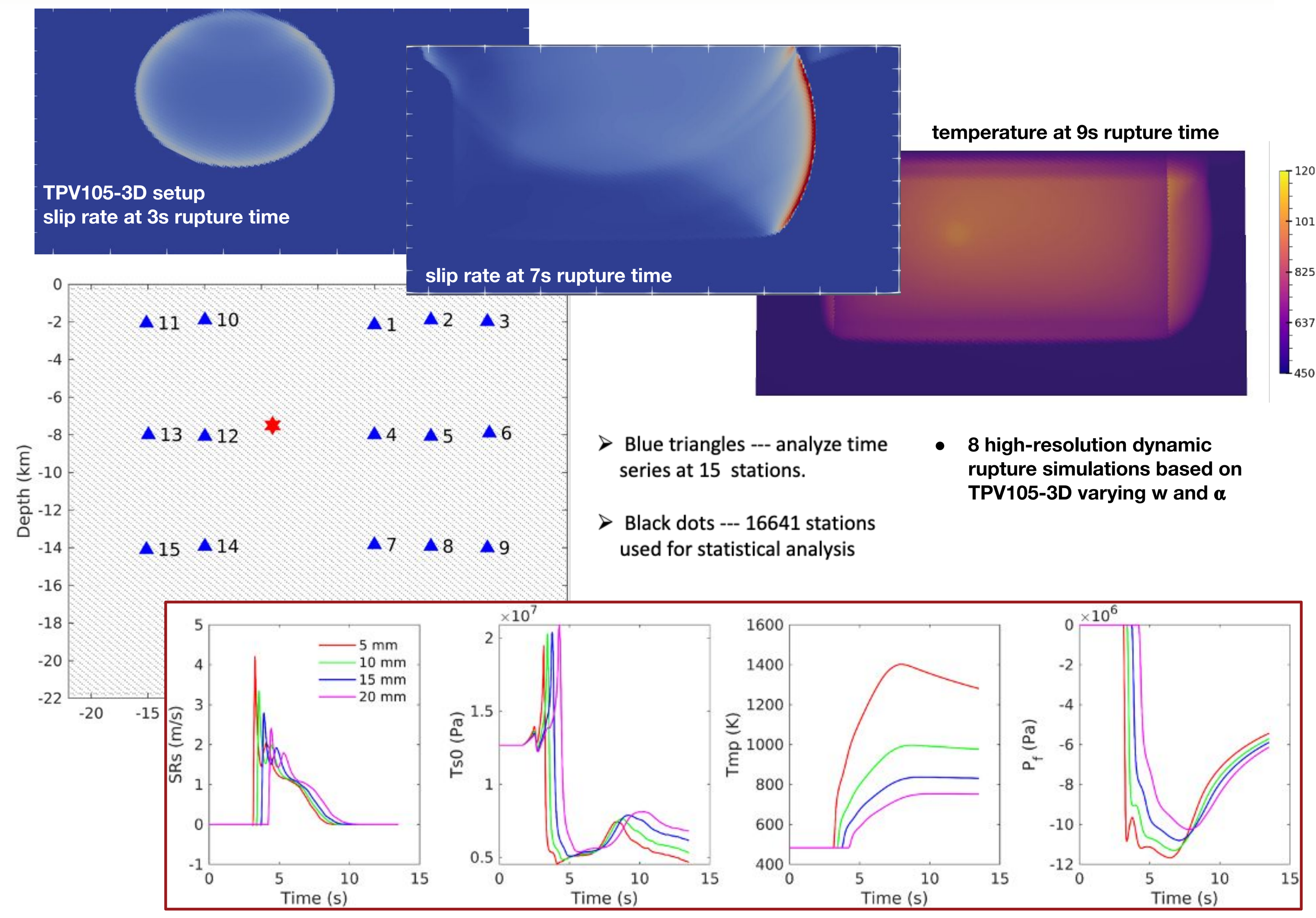
SCEC/USGS Spontaneous Rupture Code Verification

https://strike.scec.org/cvws/new_benchmarks.html

- Current 2020 group verification benchmark **TPV105-3D** is a 3D version of the earlier 2D thermal pressurization benchmark setup (tpv105-2D from 2011)
- 2D version revealed: **physics challenges** (e.g. **melting** occurred), **numerical challenges** (accuracy, time integration, ..)
- Current 2020 group verification benchmark is a 3D version of the earlier 2D thermal pressurization benchmark setup (tpv105-2D, 2011)
- Our 3D parametrization **prevents melting**, resembles realistic weakening effects, features smooth rupture stopping and **spatially heterogeneous TP characteristics**.
- We prevent high friction energy at shallow depth and prescribe shear traction at 42% of normal traction
- M_w 7.24; rupture duration 10s; p_{max}=19 MPa
- **strong trade-offs** of rupture nucleation, termination, rapid dynamic weakening effects, realistic heat production, and fault stress and strength initial conditions

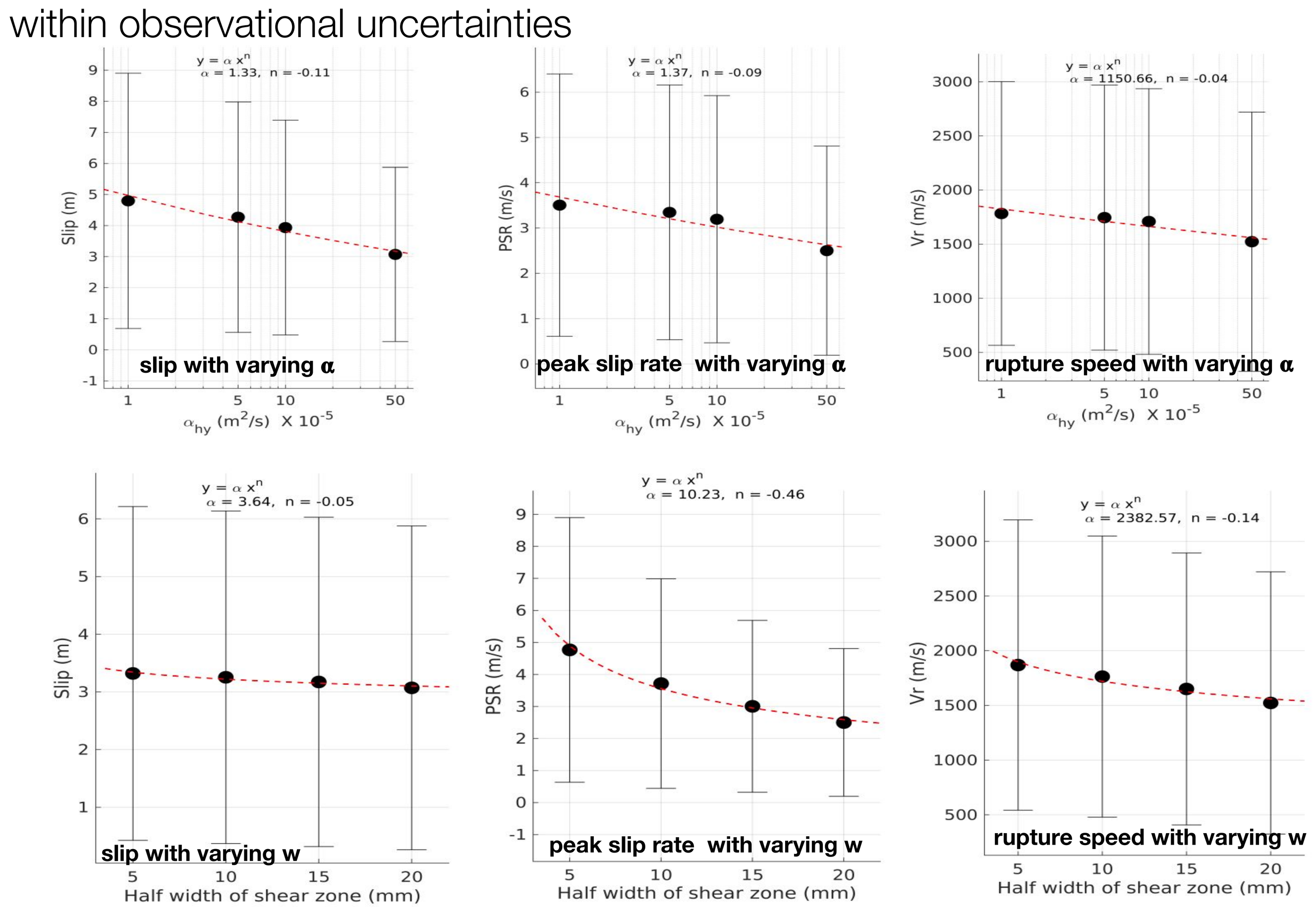


Strongly rate-dependent dynamic rupture under varying hydraulic diffusivity and shear zone width



on-fault station 10: effect of variation in w on along-strike slip rate, shear traction, temperature and pore pressure

- Variation of hydraulic diffusivity (**α**, top), and shear-zone half-width (**w**, bottom and above) within observational uncertainties



- We identify a relatively **narrow** (cf. observational uncertainties) **parameter range** to parametrize realistic earthquake rupture on a single, planar fault segment

  → requires a velocity-strengthening transition layer also at shallow depth to limit localised supershear rupture

  → and **spatially varying hydraulic diffusivity aligned with the rate-and-state parameters**

  → smooth rupture stopping for ground motion analysis
- Varying the shear-zone half-width (**w**) impacts mean peak slip rate stronger than other TP parameters
- Effects of hydraulic diffusivity (**α**) and shear-zone half-width (**w**) on rupture speed are comparable
- Average slip (magnitude) decreases with increasing hydraulic diffusivity (**α**), but remains nearly unaffected by variations in shear-zone half-width (**w**)

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Acknowledgements

This work is supported by **KAUST Competitive Research Grants** (**CRG project FRAGEN,** grant no. ORS-2017-CRG6 3389.02) and the **Dynamic Rupture TAG SCEC awards** 19121 and 20188. We also thank the **Caltech Seismolab** for supporting the 2D TP implementation in SeisSol by hosting a research visit of Stephanie Wollherr.