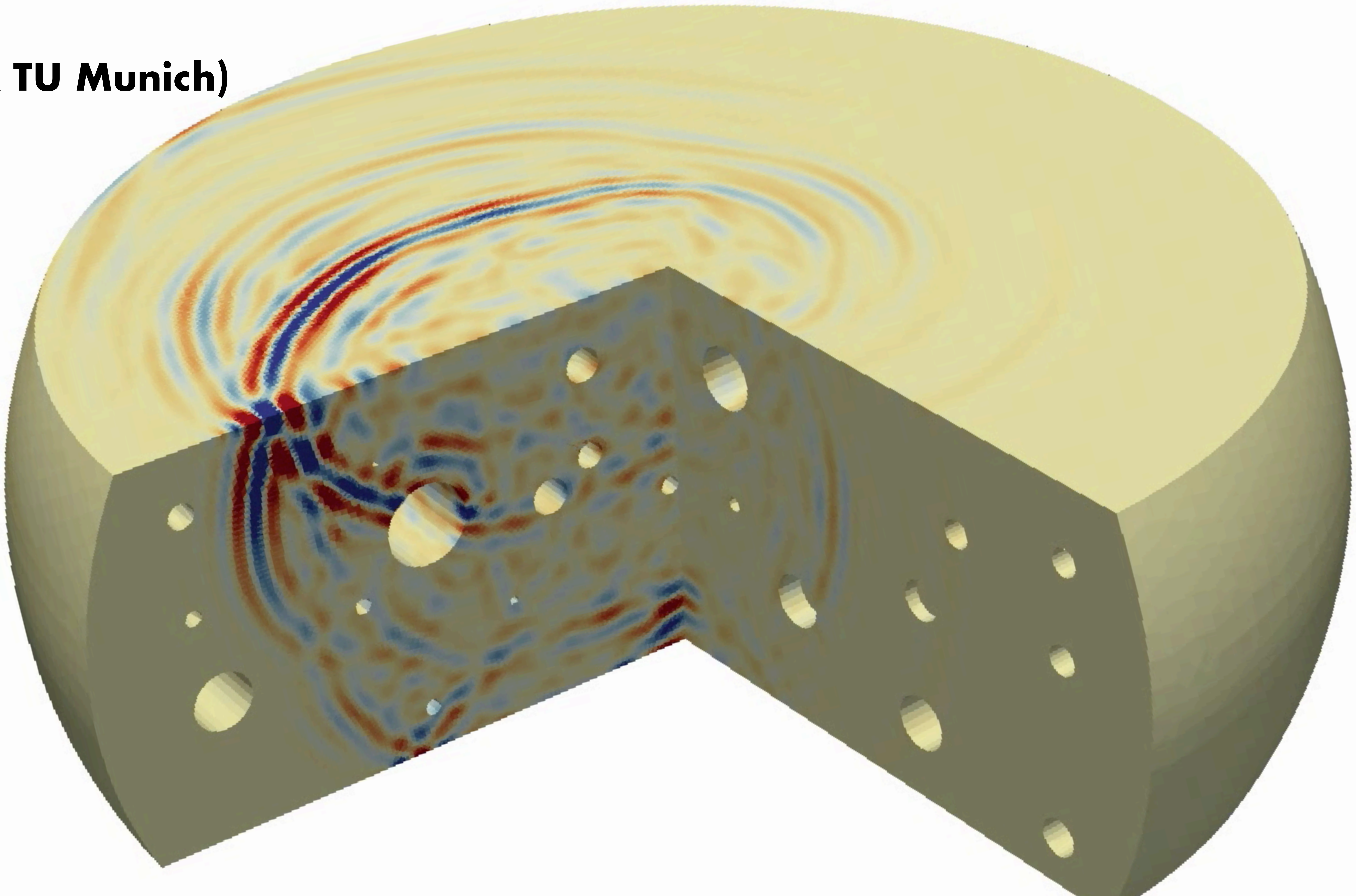
SeisSol - open-source software for multi-physics and multi-scale wave propagation and earthquake rupture dynamics using supercomputers

Alice-Agnes Gabriel
(and many others at LMU & TU Munich)

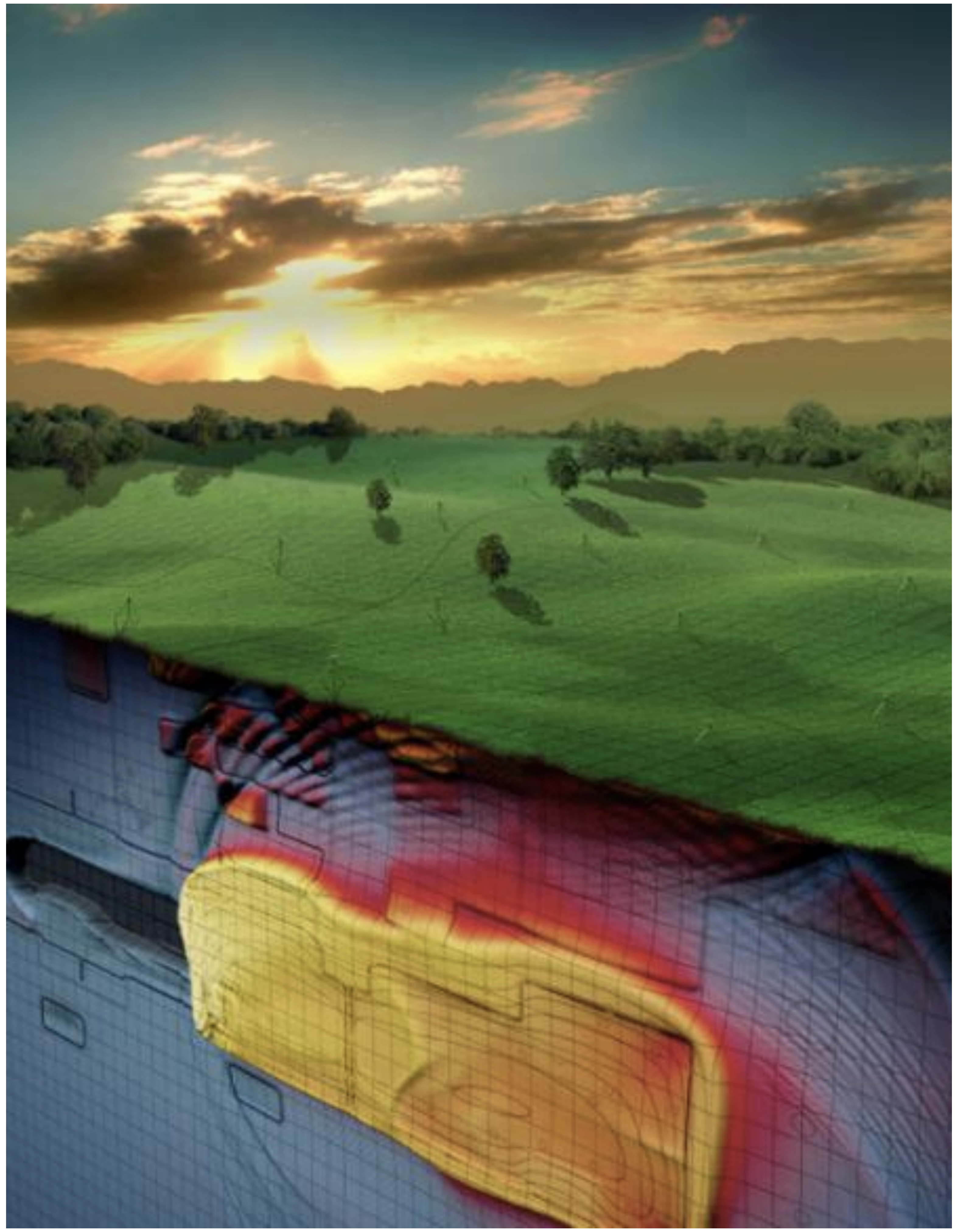


www.seissol.org

github.com/SeisSol

Physics-based Earthquake Seismology: The dynamic rupture problem

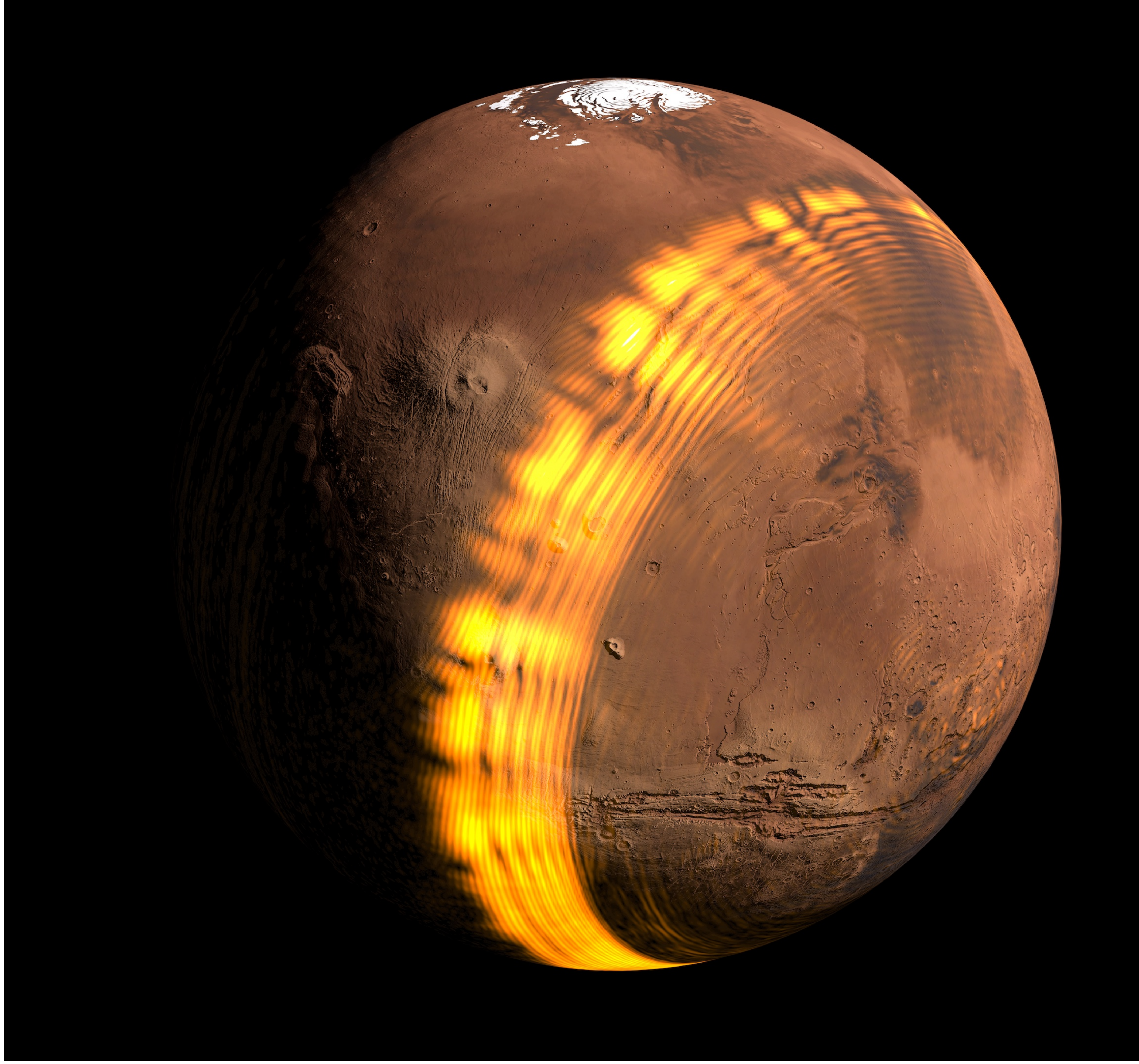
Global seismic wave simulations of the 2009 L'Aquila earthquake using SeisSol, Igel 2017, Wenk et al., 2009



Schematic view of on-going seismic rupture of the Parkfield segment of Sand Andreas Fault, Caltech/Tim Pyle

Computational seismology

- A pioneering field and has been pioneered by **HPC for** imaging Earth's interior, understanding the dynamics of the mantle, tracking down energy resources
- Seismology is **data-rich** and can often be treated as **linear system**
- **Key activities:** Calculation of synthetic seismograms in 3D Earth and solving seismic inverse problems
- **Common approach:** time-domain solutions of space-dependent seismic wavefield solved by domain decomposition
- **On-going challenges:** 3D (elastic, anisotropic, poroelastic, homogenised) Earth structure, computational efficiency (resolving high frequencies), meshing (irregular geometries), the need for community solutions (cf. SpecFEM)



On May 5th, the NASA "InSight"-lander set off to investigate the internal structure of Mars carrying a seismometer. Forward simulations of seismic waves travelling through Mars have been performed on "Piz Daint" at CSCS solving 10 billion degrees of freedom and 300,000 time steps (Bozdag et al., 2017). Salvus computation for InSight.

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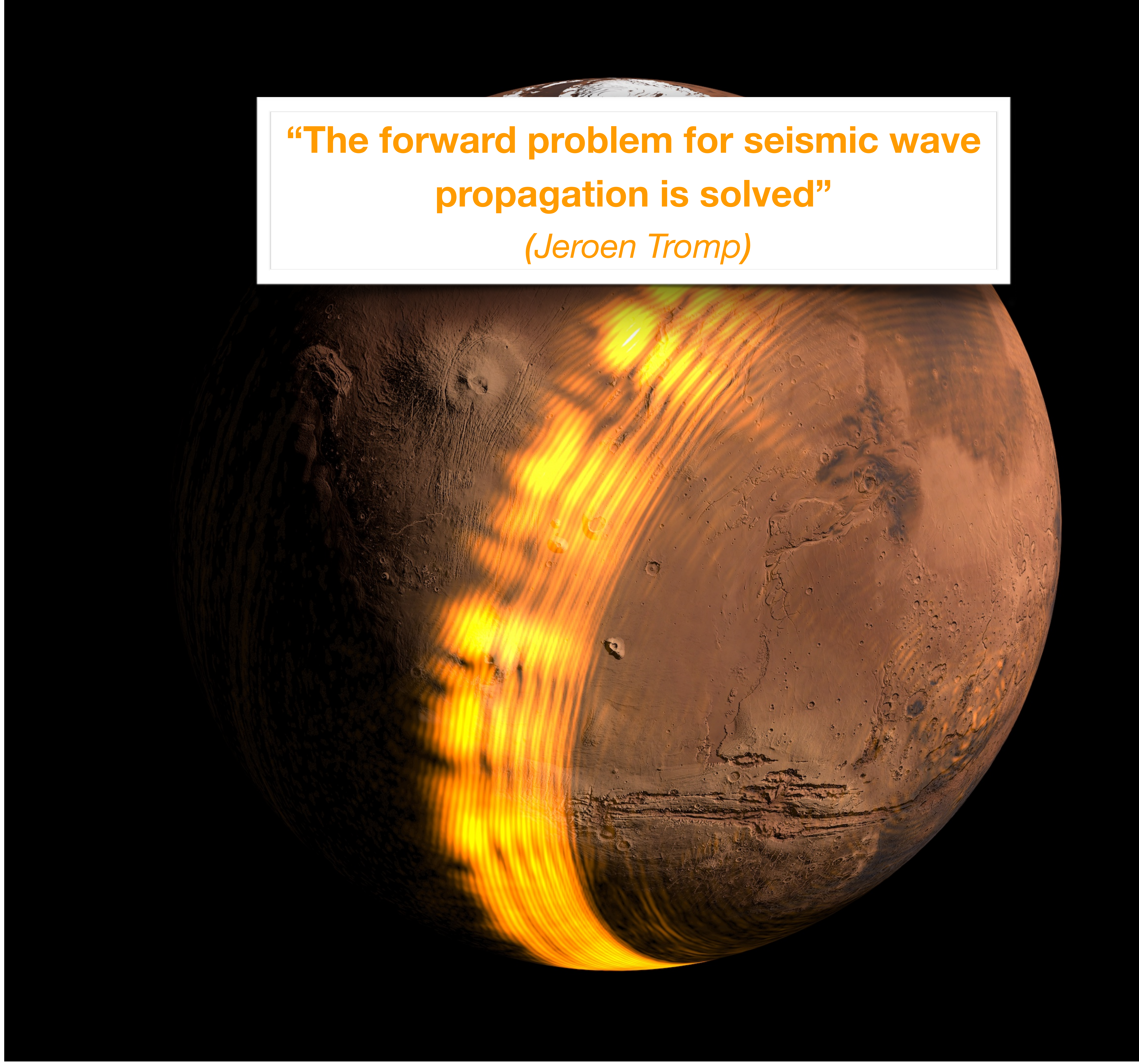

"The forward problem for seismic wave propagation is solved"

(Jeroen Tromp)

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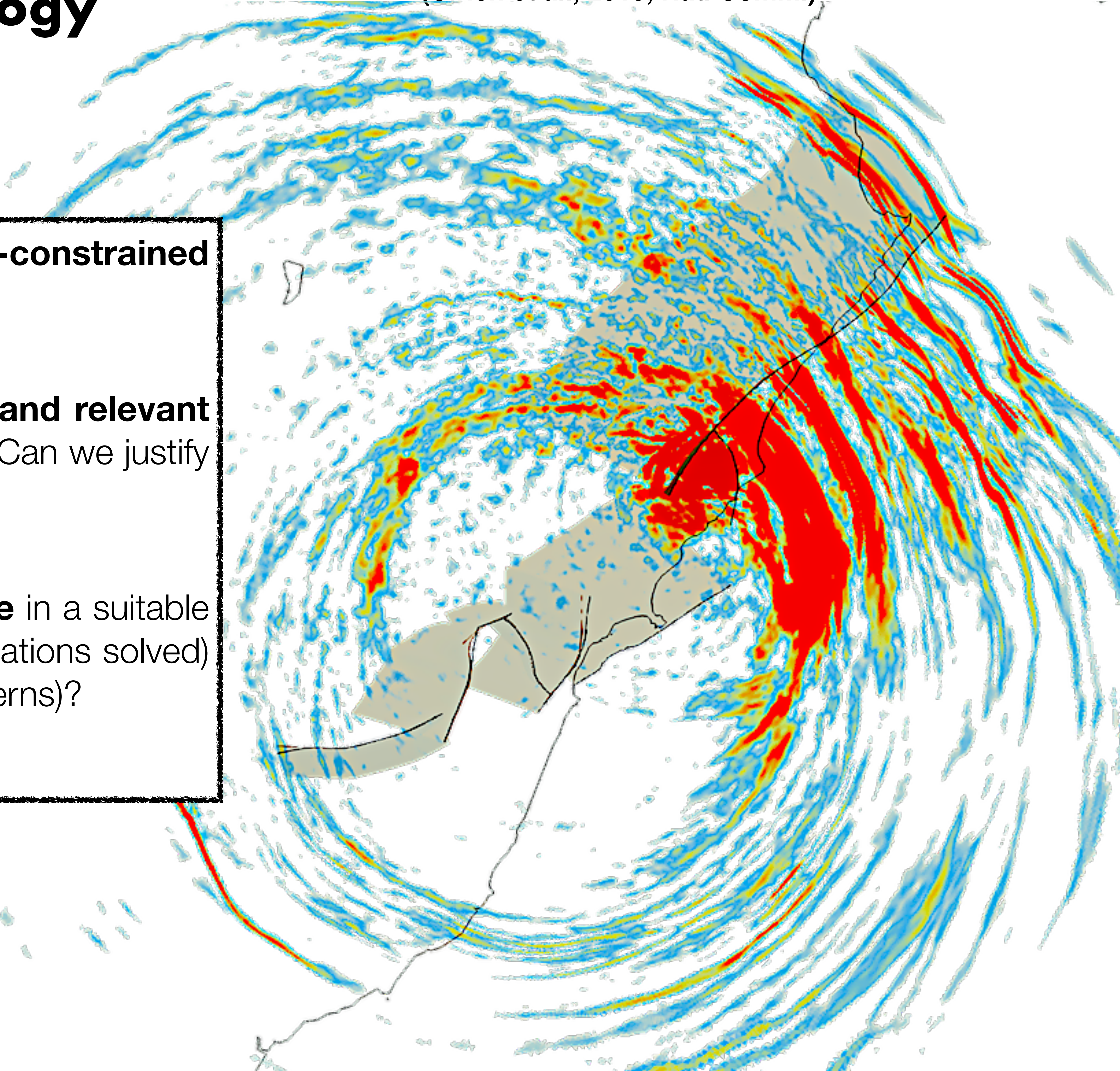
Computational earthquake seismology

Challenge 1: Earthquake source processes are (very) **ill-constrained** and **highly non-linear.**

Challenge 2: Which **physical processes** are **dominant and relevant** at a given spatio-temporal scale (and in real earthquakes)? Can we justify the "cost" of their inclusion?

Challenge 3: How to **assimilate all available knowledge** in a suitable manner for **software** (numerical discretisation, solvers, equations solved) and **hardware** (heterogeneous HPC systems, energy concerns)?

Observationally constrained 3D dynamic rupture scenario of the 2016, Kaikōura Earthquake (Ulrich et al., 2019, Nat. Comm.)

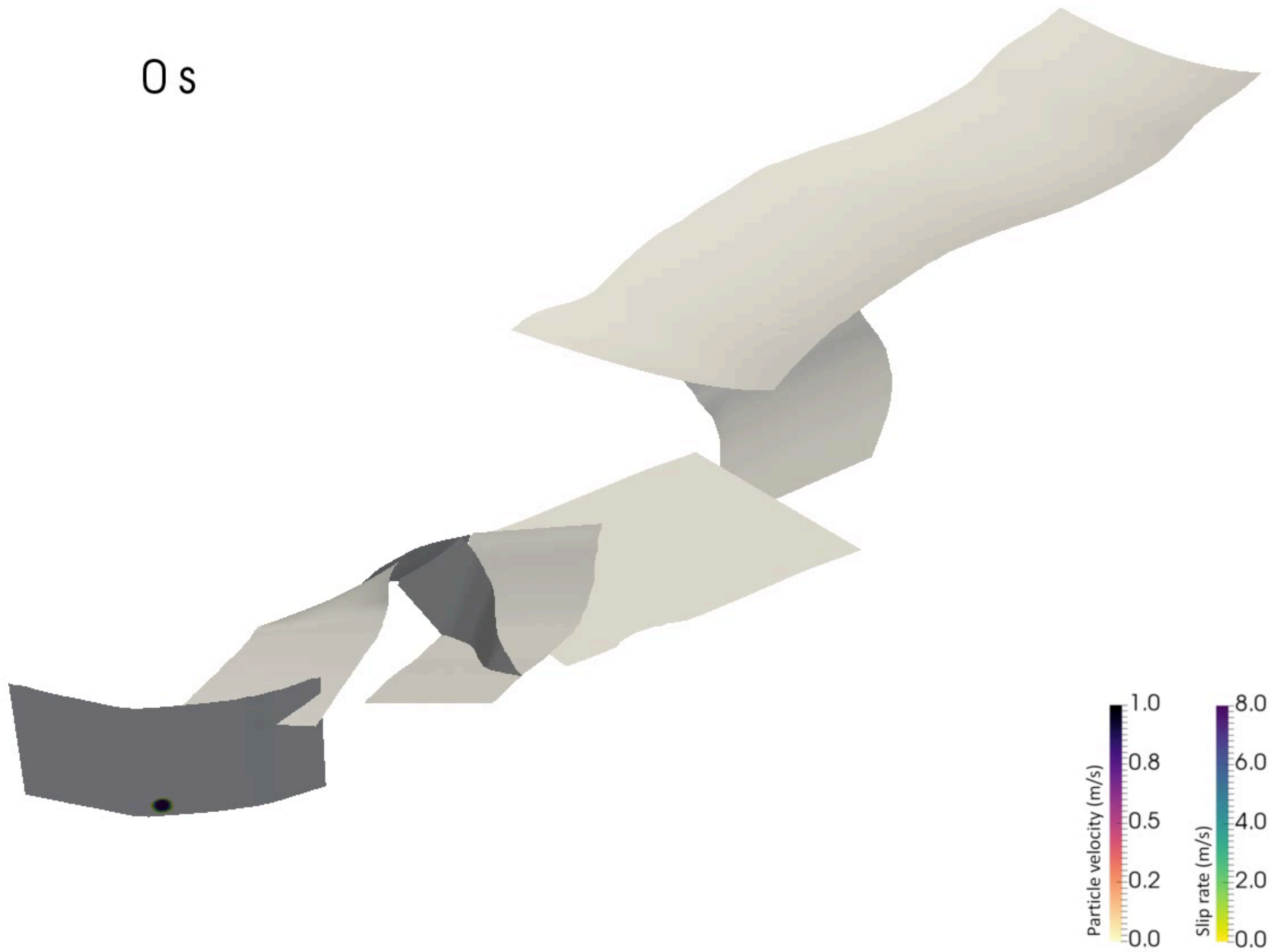


Computational earthquake seismology

Observationally constrained 3D dynamic rupture scenario of the 2016, Kaikōura Earthquake (Ulrich et al., 2019, Nat. Comm.)

Physics-based approach

- Solving for spontaneous dynamic earthquake rupture as non-linear interaction of frictional failure and seismic wave propagation
- Earthquake = frictional shear failure of brittle solids under compression along preexisting weak interfaces
- **We often "bootstrap" on methods originally not developed for earthquake source modelling**



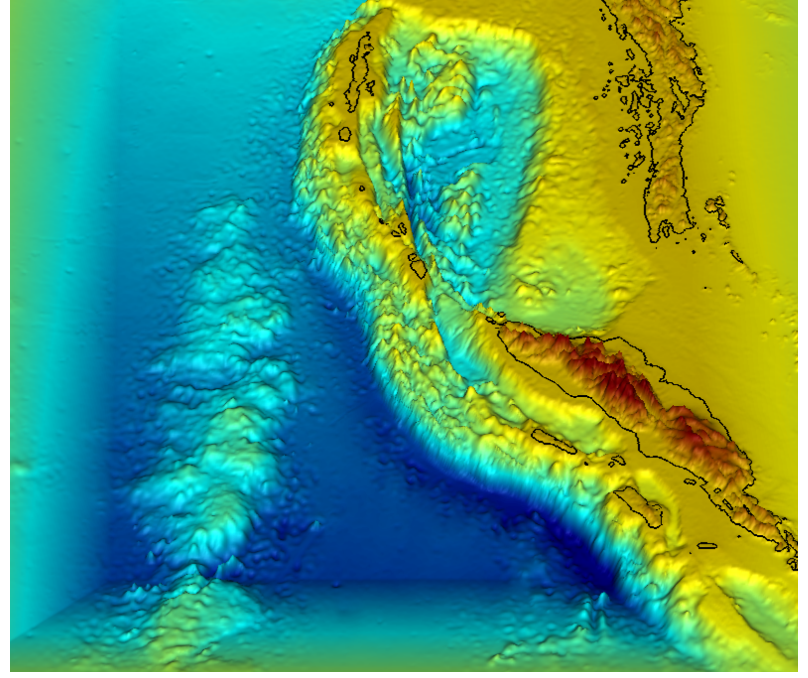
Computational earthquake seismology

Adapted from Harris et al., SRL 2011, 2018;

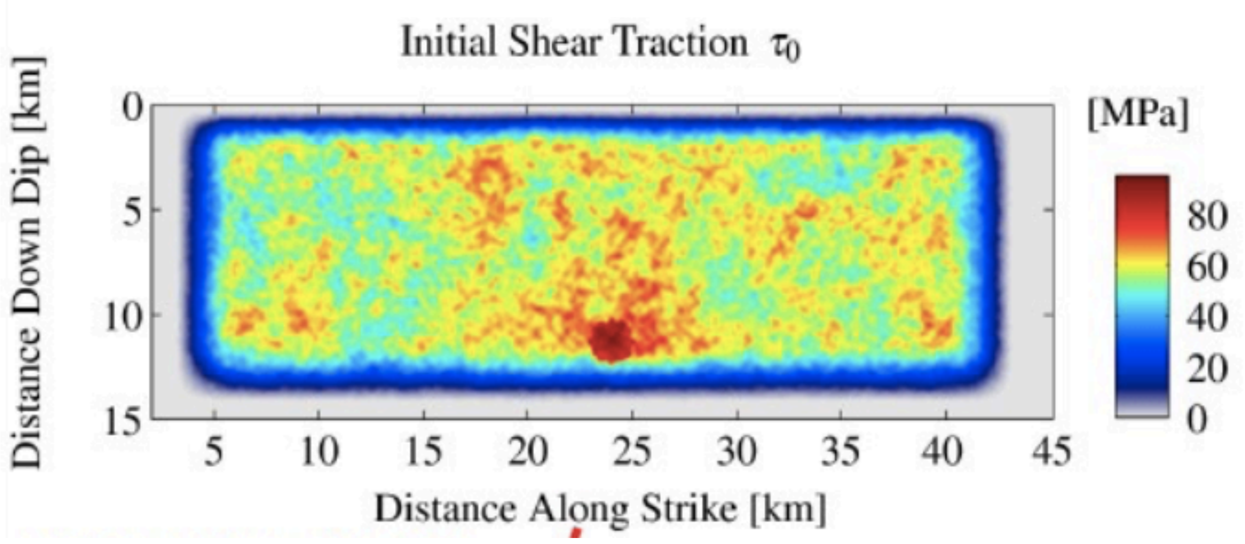
also see white Paper "Modeling earthquake source processes: from tectonics to dynamic rupture" led by Nadia Lapusta

Bridging scales and disciplines

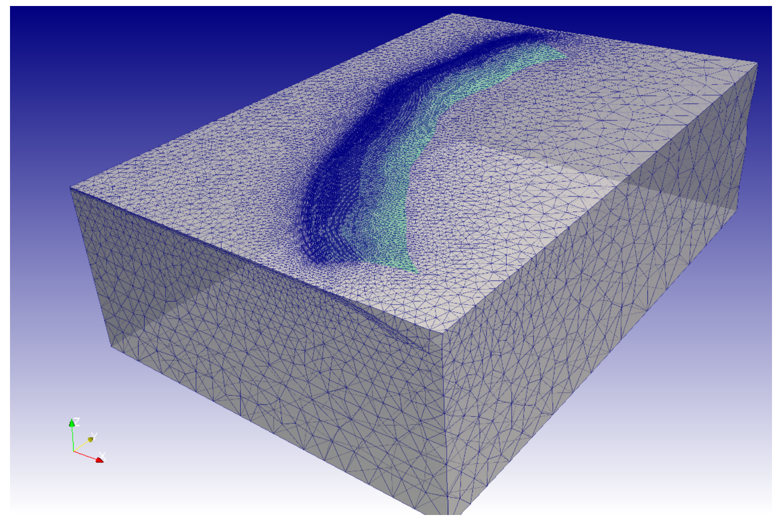
- **Integration** and **interpretation** of full range of observations
- **Tightly links** seismology, geodesy, geology, tectonophysics, hydrology with numerical computing, data science, machine learning, applied mathematics, continuum mechanics, tribology, rock mechanics, materials science, and engineering



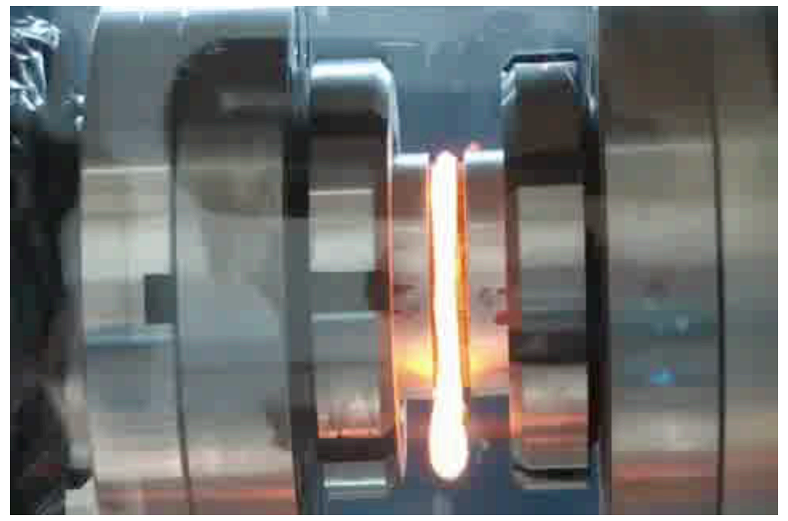
Geology



Initial fault stresses



Mesh generation



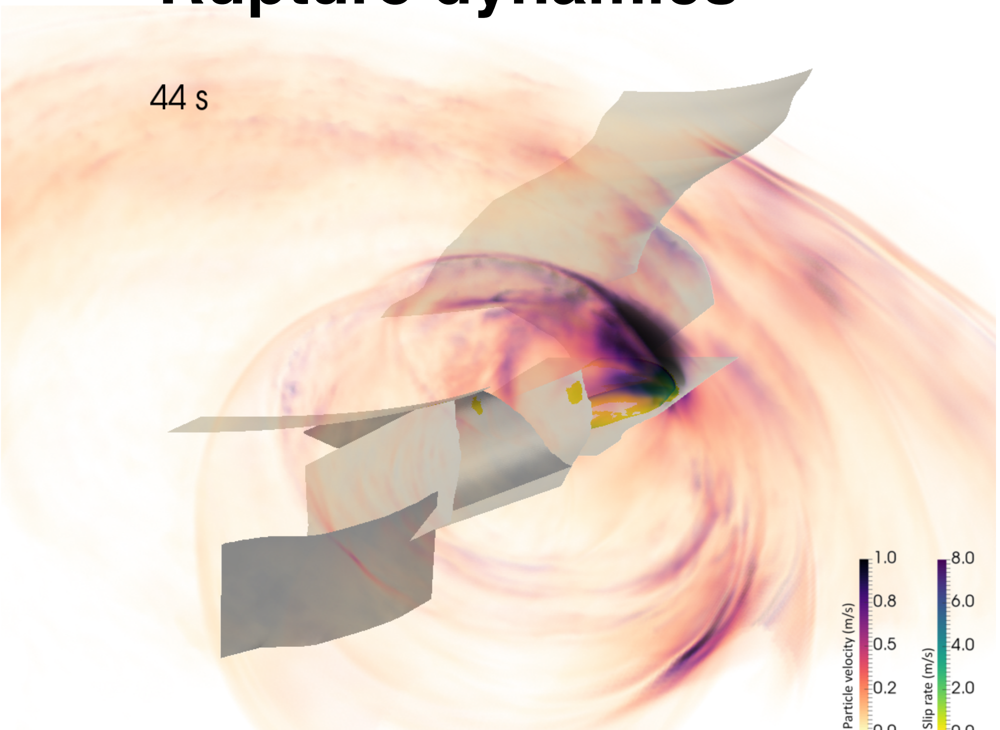
Friction experiments

"Input"

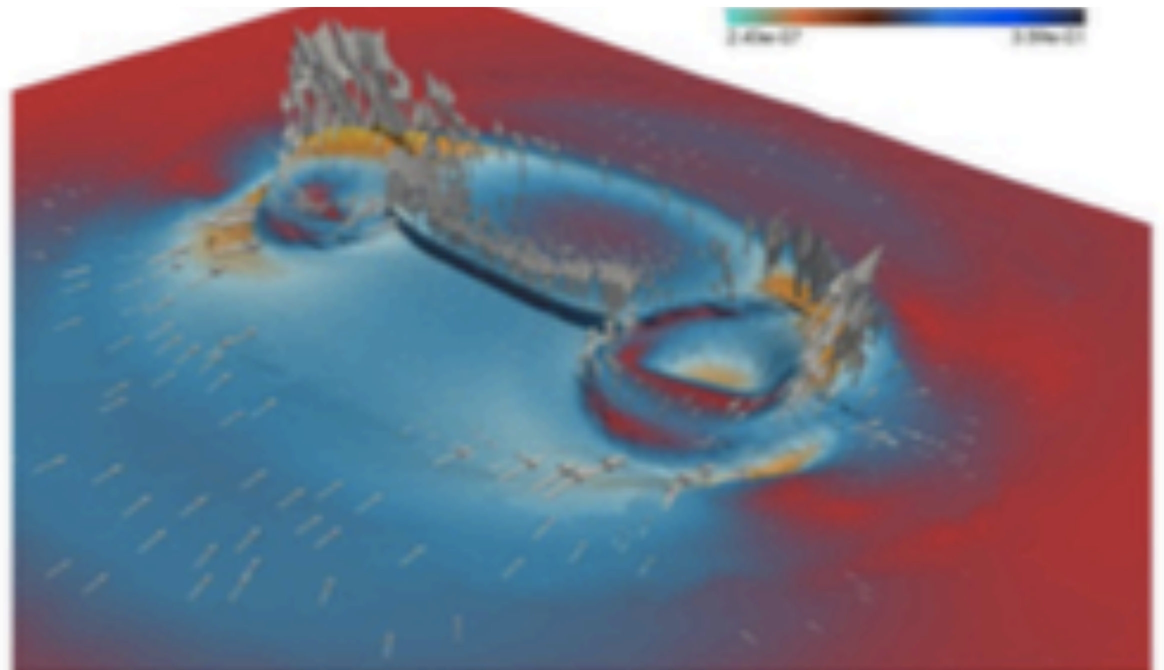
SOLVER

"Output"

Rupture dynamics



Ground deformation

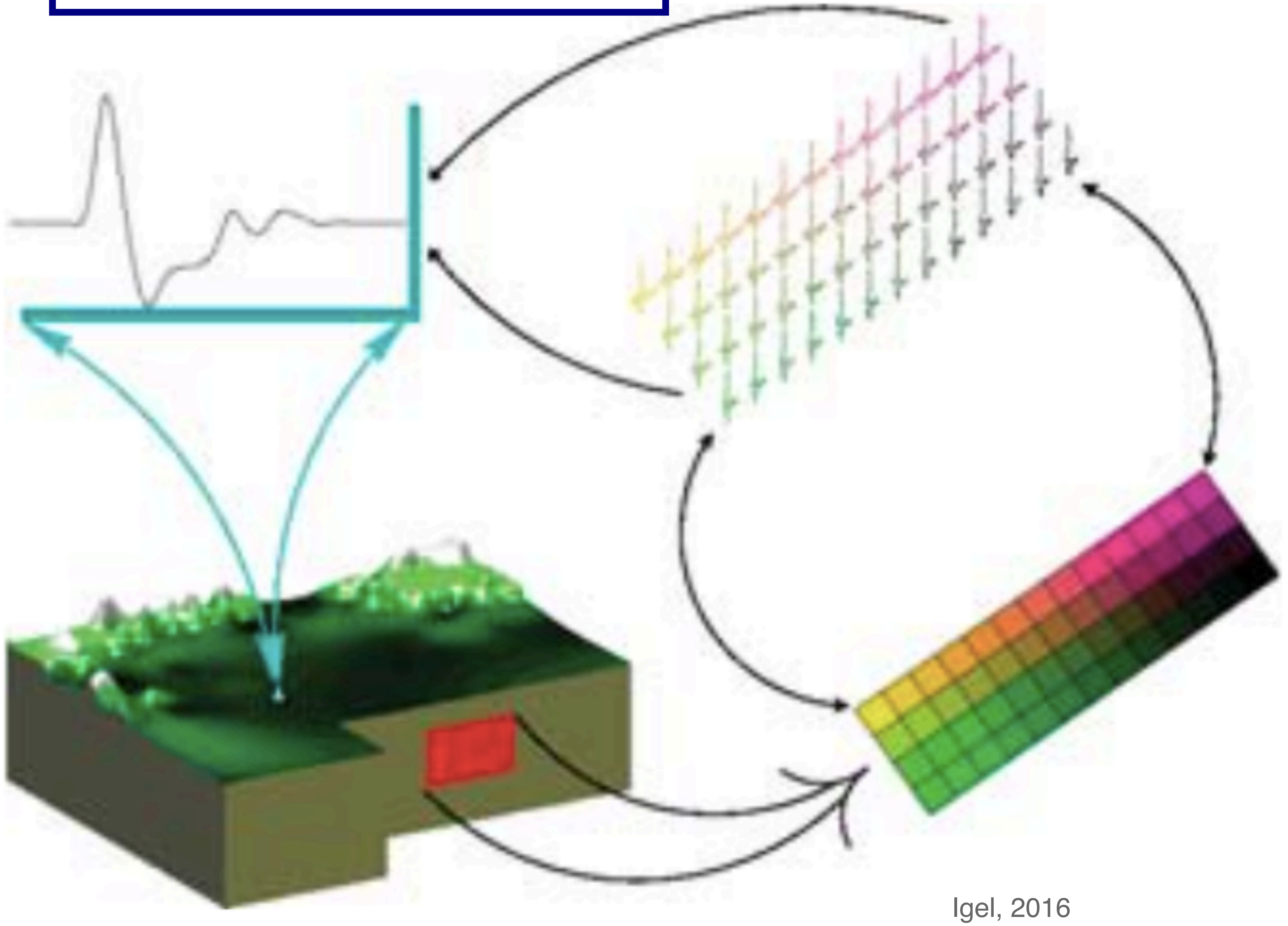


Synthetic observables

Kinematic earthquake source modeling

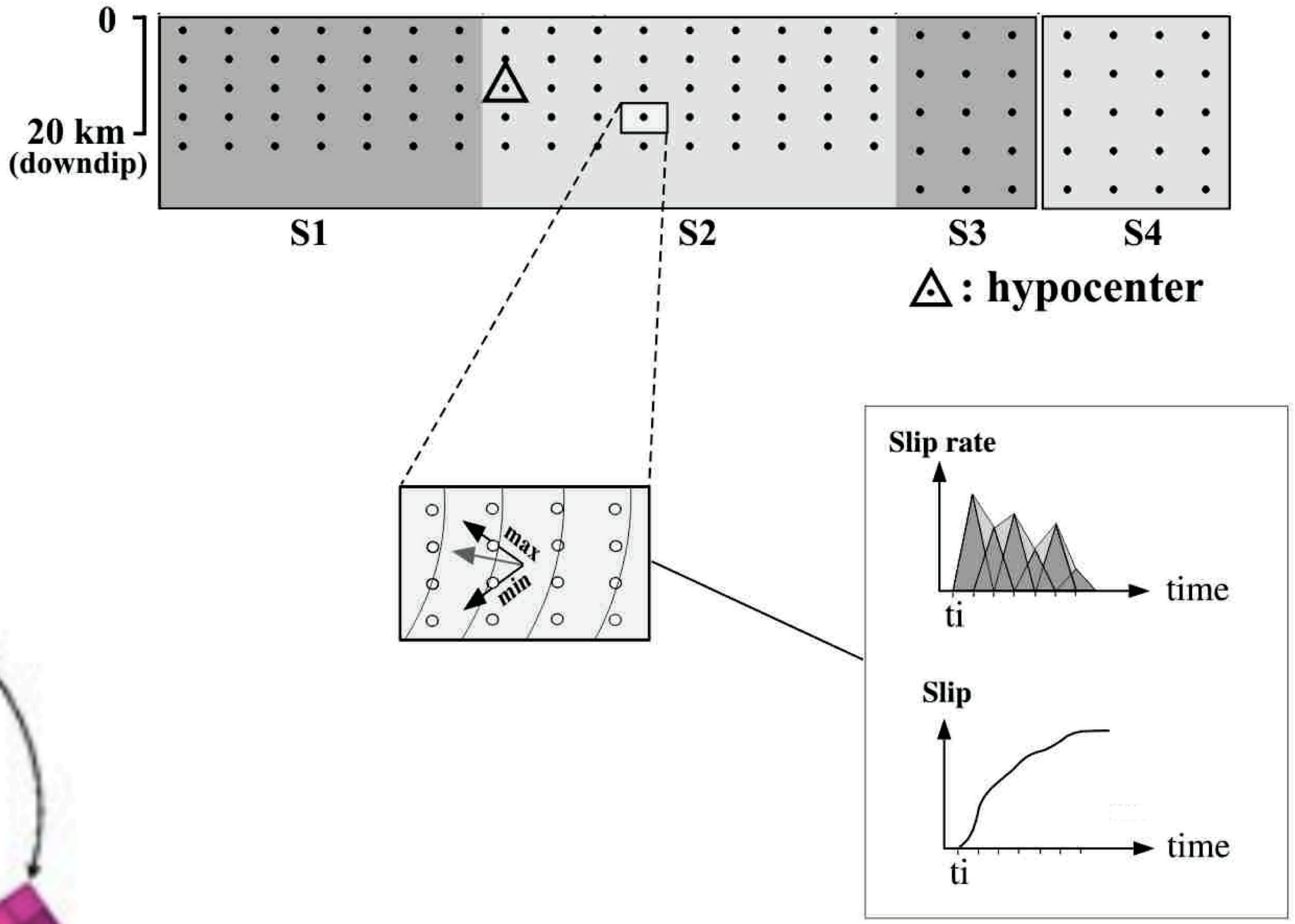
Standard inverse approach:
Linearisation of Volterra's formula

$$\boxed{\text{ground motion} \approx \sum \text{source} * \text{structure}}$$



Igel, 2016

Delouis et al, 2002

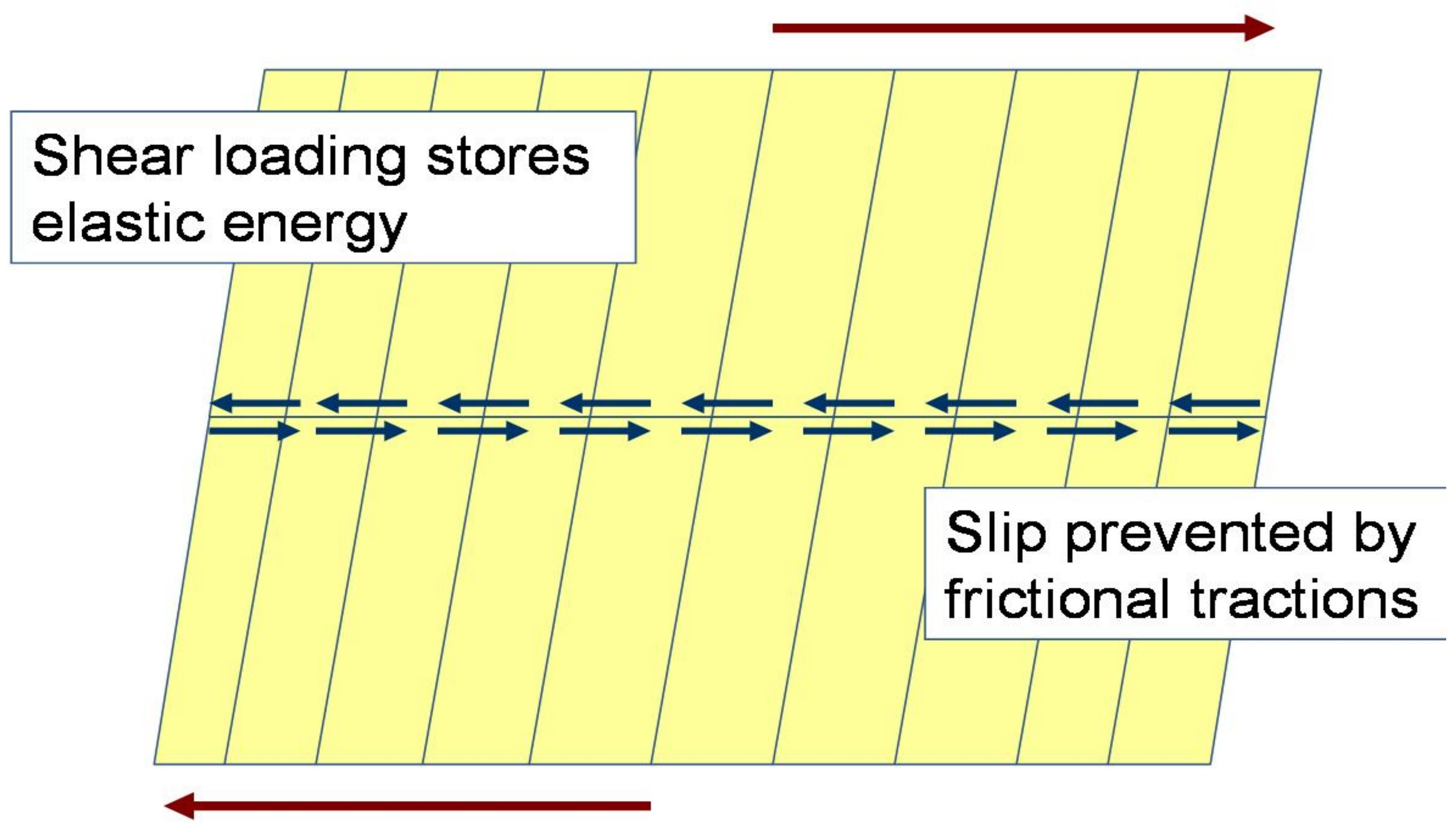


- seismograms for arbitrary finite sources are obtained by adding up seismograms (Green's functions) from a sufficient number of point sources appropriately timed and scaled to correctly reproduce the kinematic source

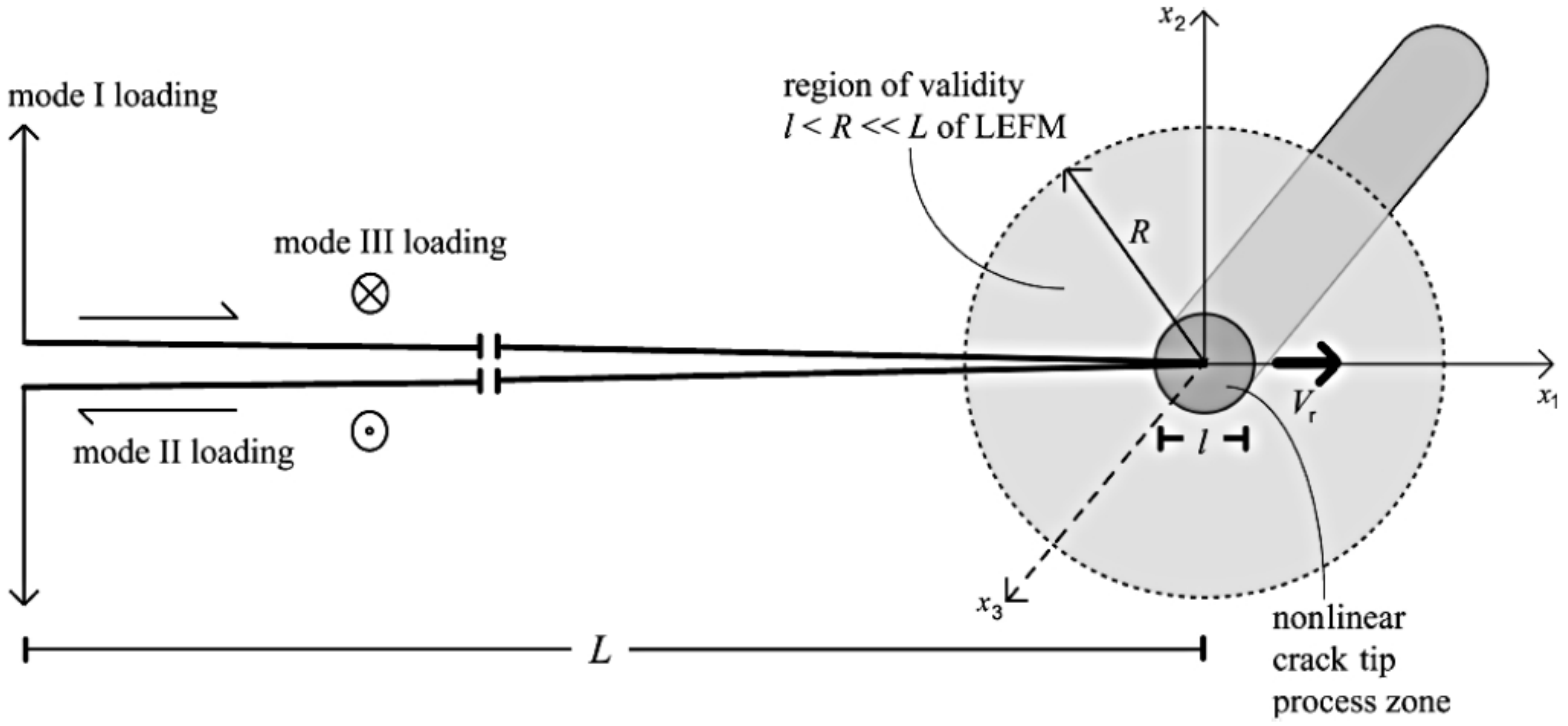
Courtesy of Eric Dunham

Modelling spontaneous earthquake rupture dynamics

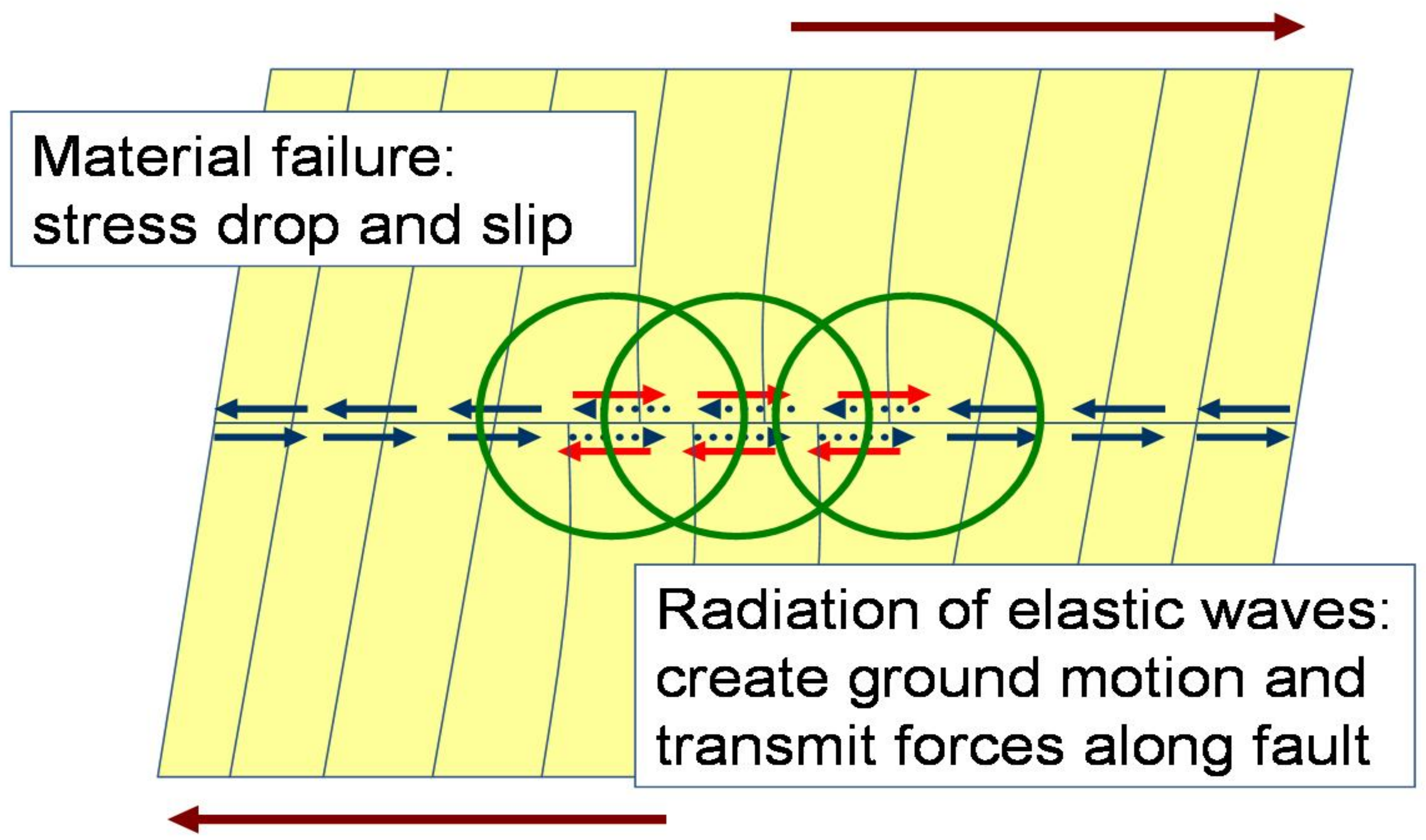
- <u>definition:</u> Earthquake = Frictional shear failure of brittle solids under compression along preexisting weak interfaces
- elastodynamics with embedded frictional interfaces
- inherent length scale: cohesive zone



The fault is the horizontal line through the center, with the blue arrows representing frictional forces that keep the sides of the fault locked. The slanted vertical lines indicate the shear displacements created by tectonic loading.



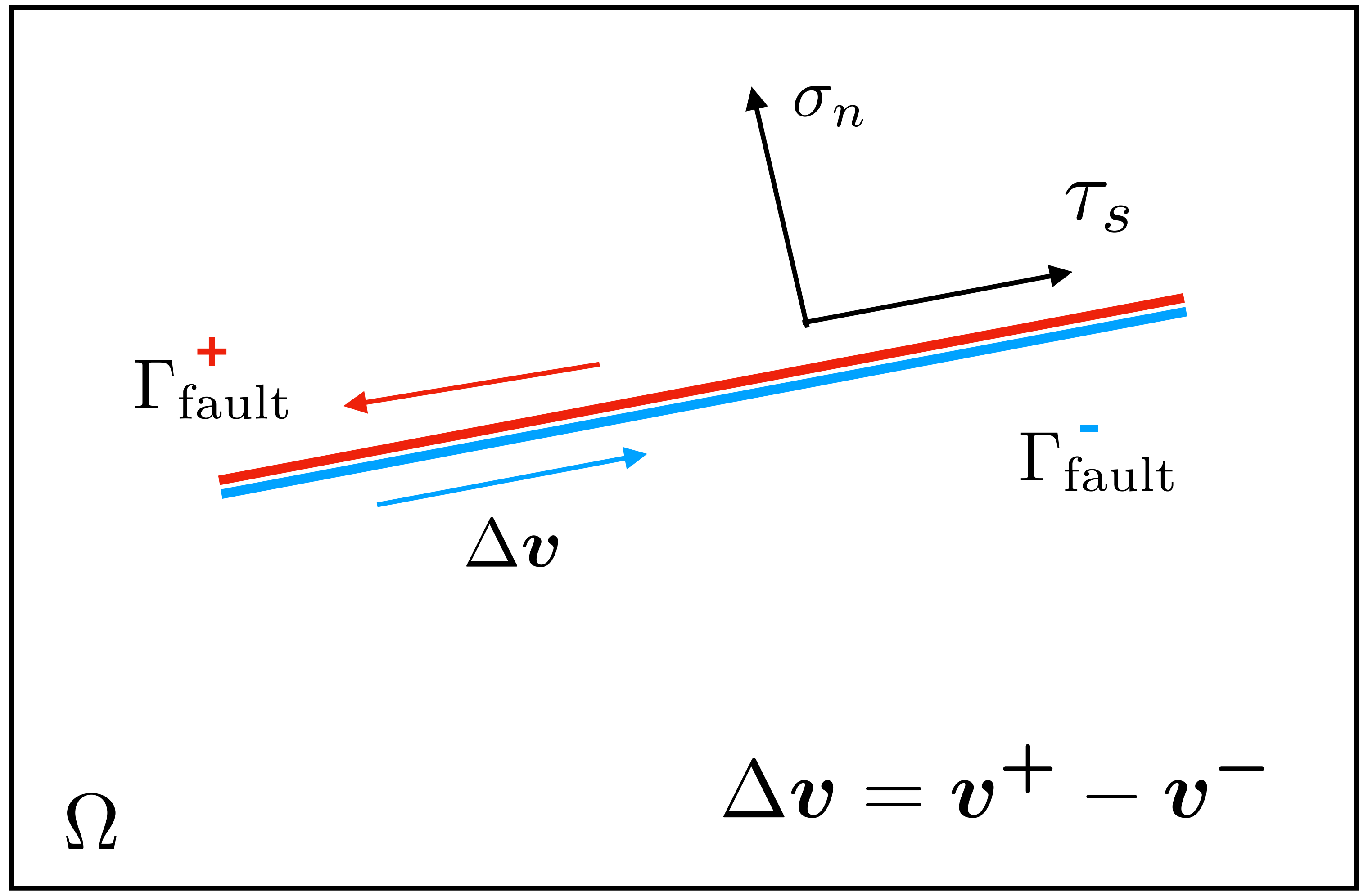
A schematic of a 2D crack illustrating the region of validity for linear elastic fracture mechanics and modes I, II and III of rupture extending along the x_1 axis with velocity v_r (Ben-Zion, 2003).



Material in the fault zone fails (or static friction is exceeded) and the fault begins to slip. Physically, we can view this process as the application of shear forces on the fault that negate the static friction, as represented by the red arrows. This releases elastic waves, indicated by the expanding green circles.

Modelling spontaneous earthquake rupture dynamics

- Earthquake dynamic rupture is treated as a boundary condition in terms of **contact and friction**
- **Thin fault without 'opening'** - two matching fault surfaces are in unilateral contact
- **Displacement discontinuity** across the fault = **slip**
- Much complexity lives in the definition of **friction** (shear traction is bounded by the fault strength), and **fault geometry** and **intersections**
- Can be implemented by **splitting the fault interface**



Earthquake dynamics are not predetermined: but evolve as a consequence of the model's initial conditions and the way the fault yields and slides controlled by an assigned friction law relating shear and normal traction on frictional interfaces

Modelling spontaneous earthquake rupture dynamics

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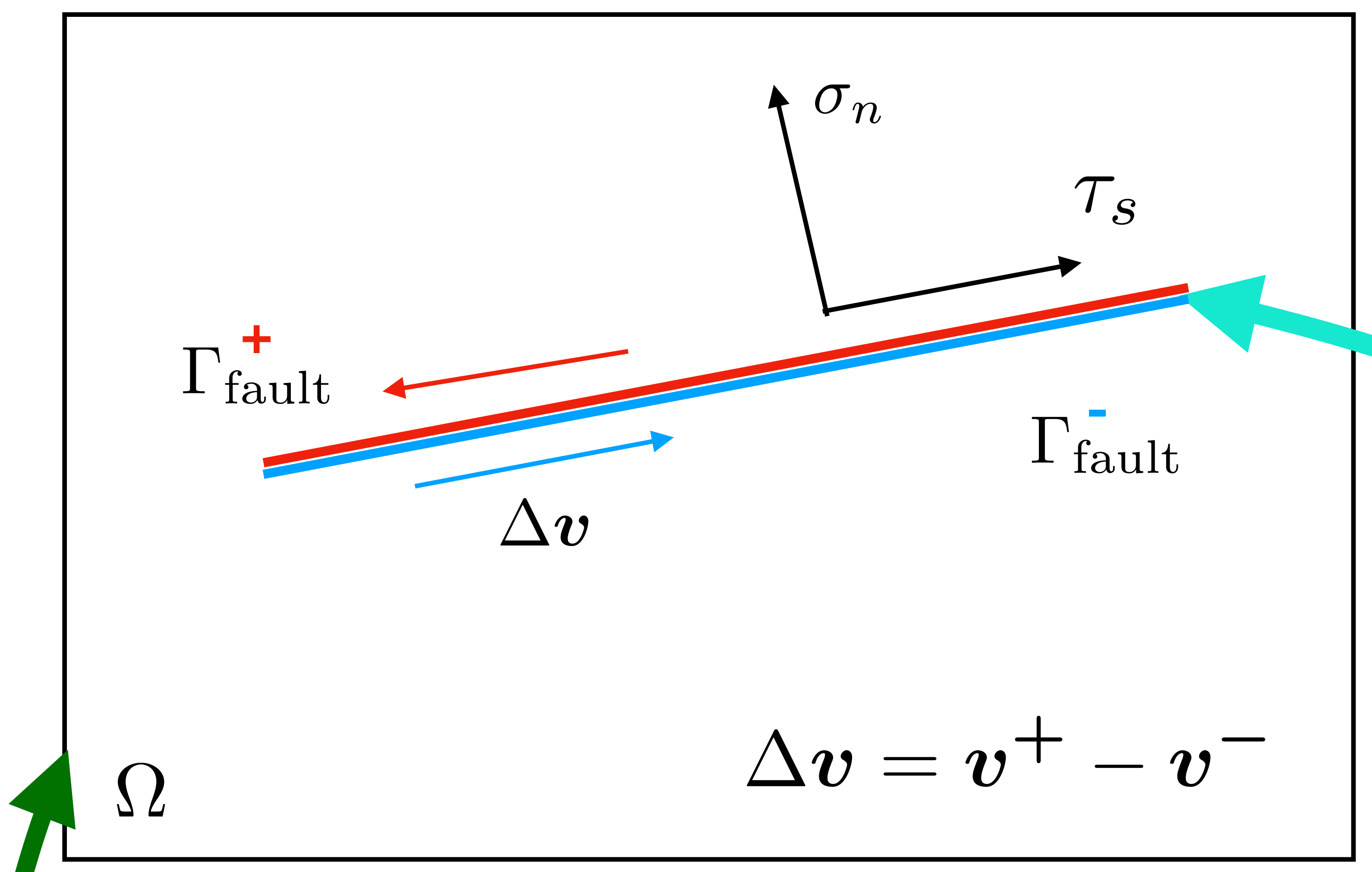


constitutive law (volume)

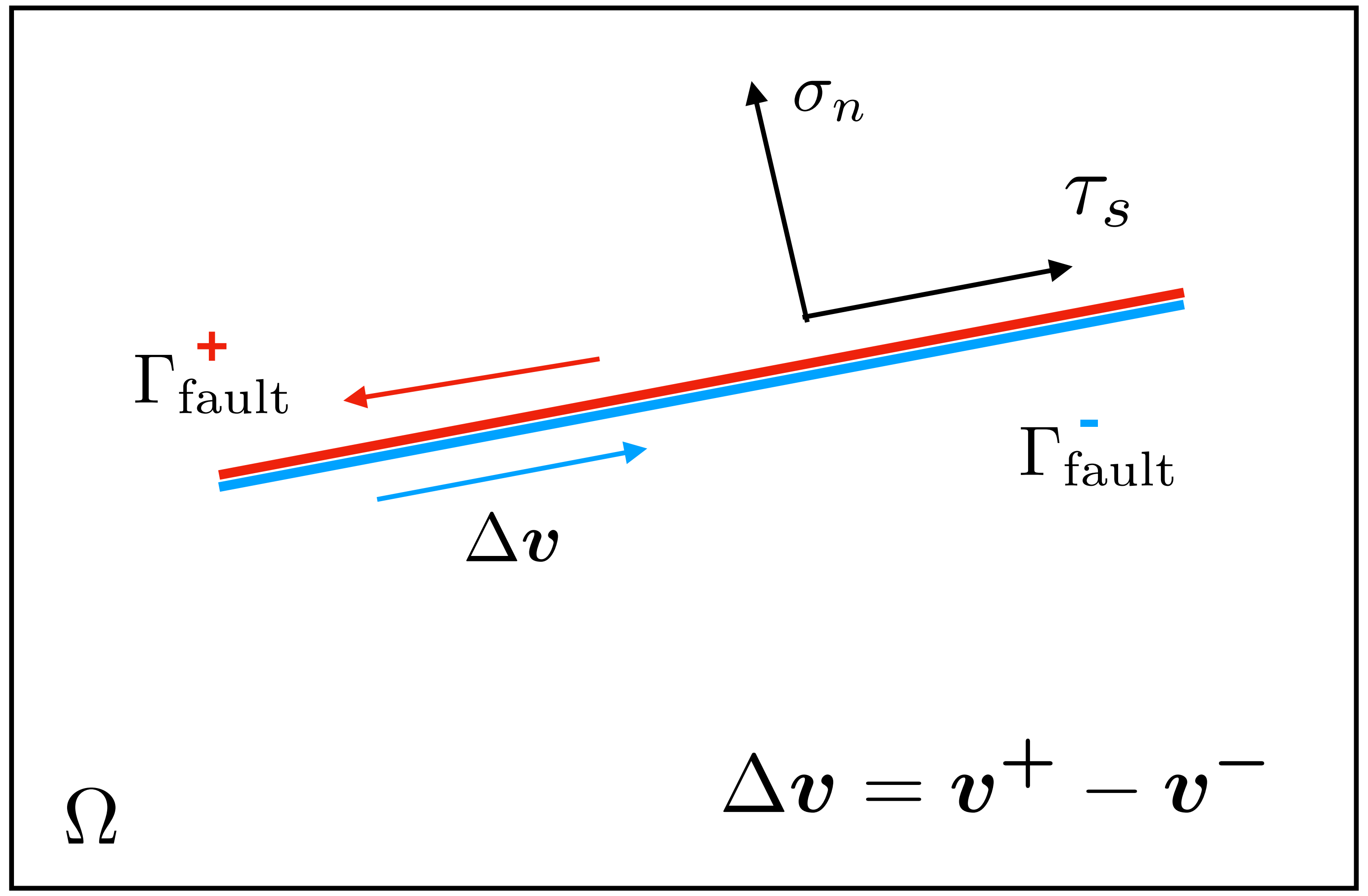
$$\frac{\partial}{\partial t}\sigma_{xx} - (\lambda + 2\mu)\frac{\partial}{\partial x}u - \lambda\frac{\partial}{\partial y}v - \lambda\frac{\partial}{\partial z}w = 0,$$
$$\frac{\partial}{\partial t}\sigma_{yy} - \lambda\frac{\partial}{\partial x}u - (\lambda + 2\mu)\frac{\partial}{\partial y}v - \lambda\frac{\partial}{\partial z}w = 0,$$
$$\frac{\partial}{\partial t}\sigma_{zz} - \lambda\frac{\partial}{\partial x}u - \lambda\frac{\partial}{\partial y}v - (\lambda + 2\mu)\frac{\partial}{\partial z}w = 0,$$

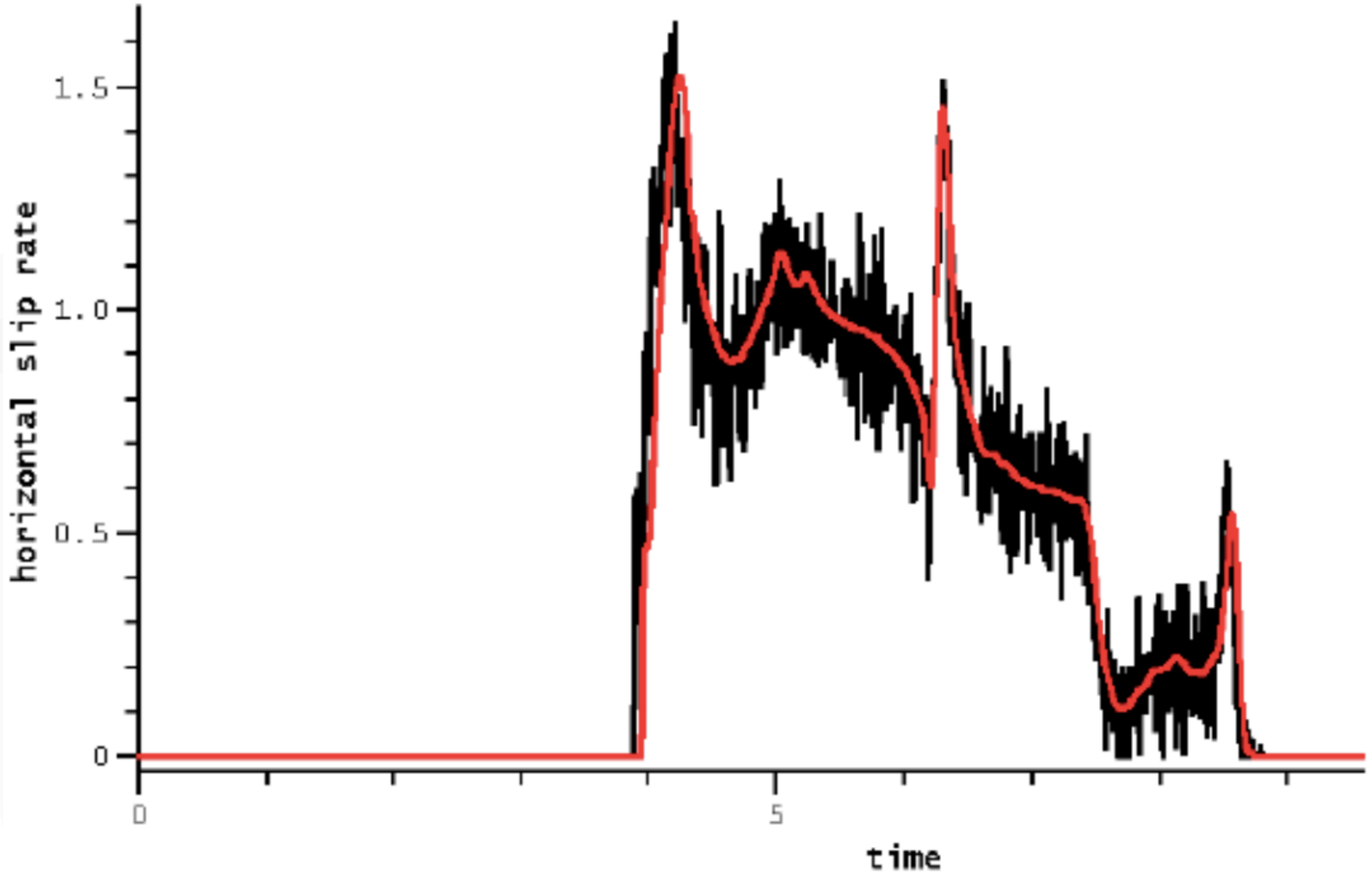
constitutive law (surfaces)

$$\tau_s = \mu_f \sigma_n.$$
$$|\boldsymbol{\tau}| \leq \tau_s,$$
$$\begin{aligned} (|\boldsymbol{\tau}| - \tau_s)|\Delta \mathbf{v}| &= 0, \\ \Delta \mathbf{v}|\boldsymbol{\tau}| + |\Delta \mathbf{v}|\boldsymbol{\tau} &= 0. \end{aligned}$$

Modelling spontaneous earthquake rupture dynamics

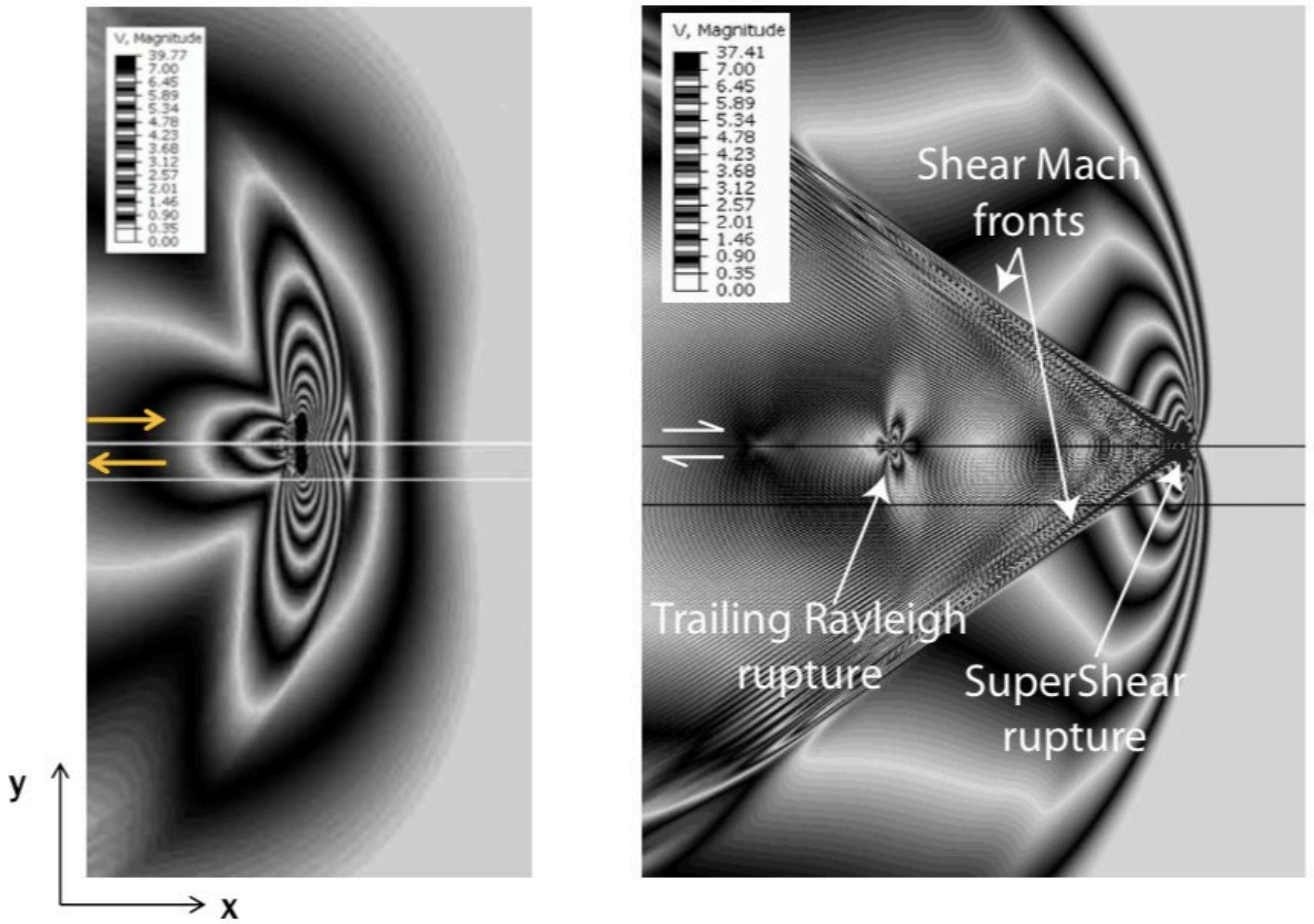
- Earthquake dynamic rupture is treated as a boundary condition in terms of **contact and friction**
- **Thin fault without 'opening'** - two matching fault surfaces are in unilateral contact
- **Displacement discontinuity** across the fault = **slip**
- Much complexity lives in the definition of **friction** (shear traction is bounded by the fault strength), and **fault geometry** and **intersections**
- Can be implemented by **splitting the fault interface**
- **FD, FEM, SEM methods suffer from spurious oscillations - which have to be damped (e.g., by a thin layer of Kelvin-Voigt-Damping cells, Day et al., 2005)**



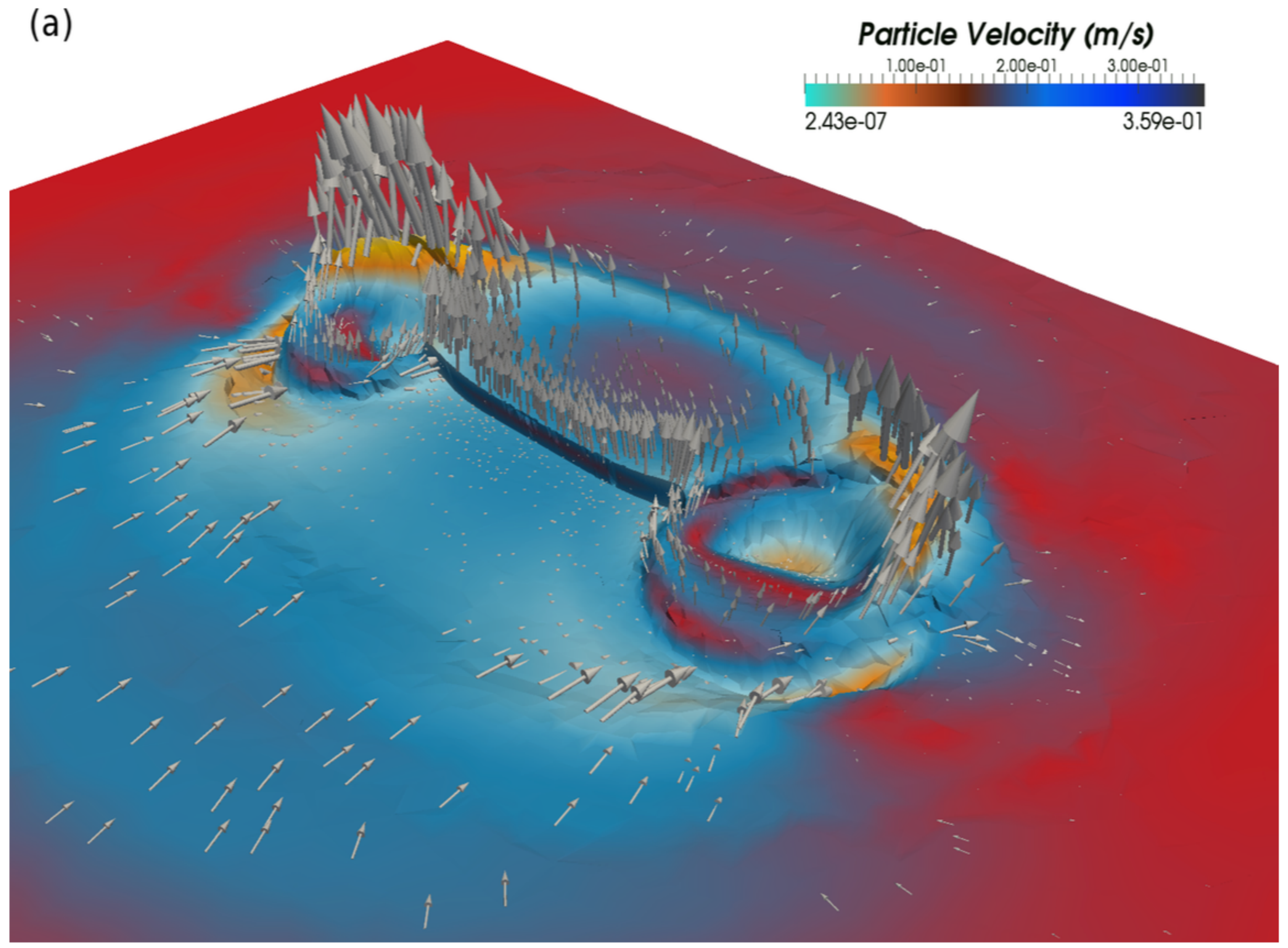


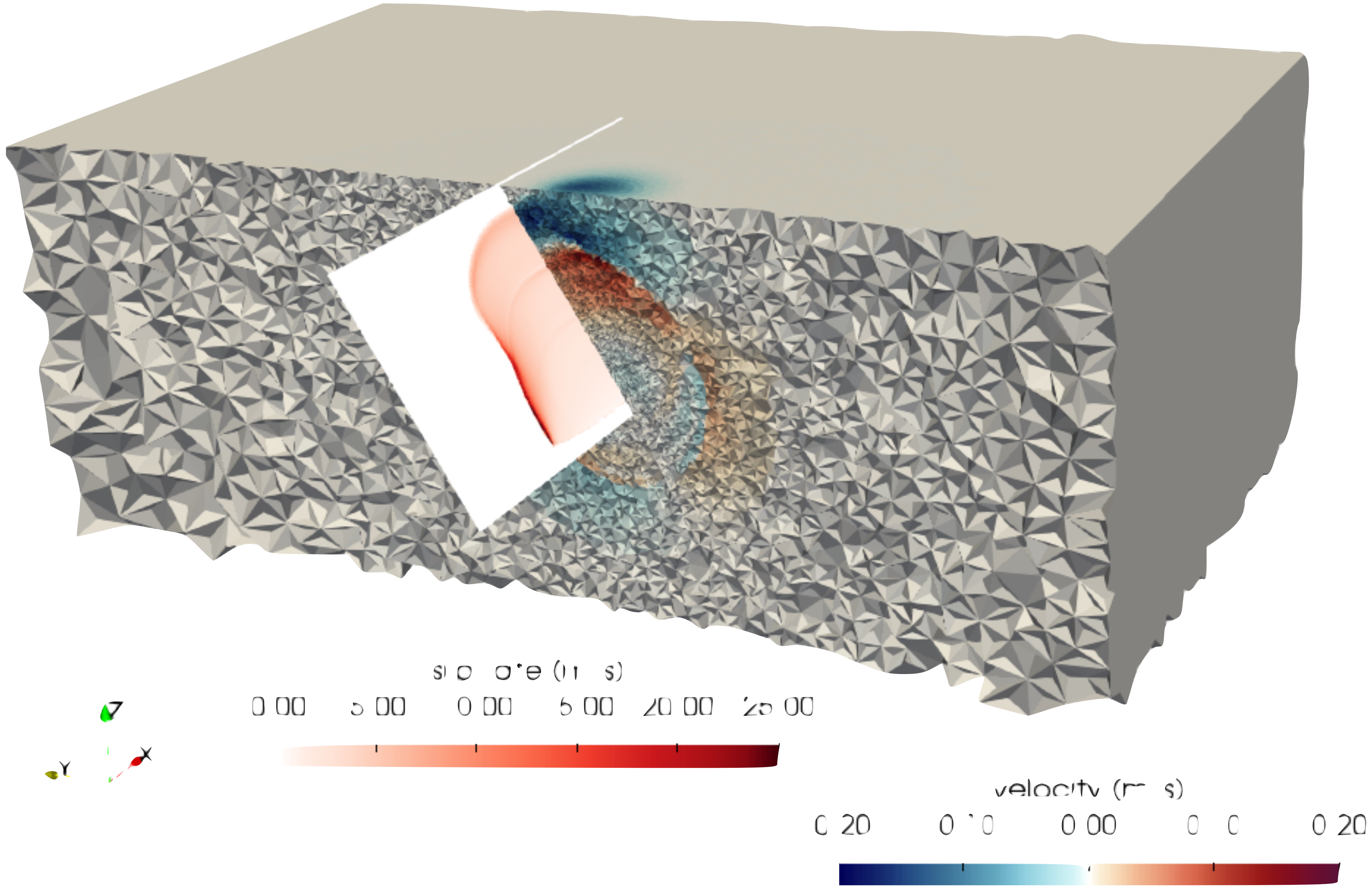
Modelling spontaneous earthquake rupture dynamics

the ideal world



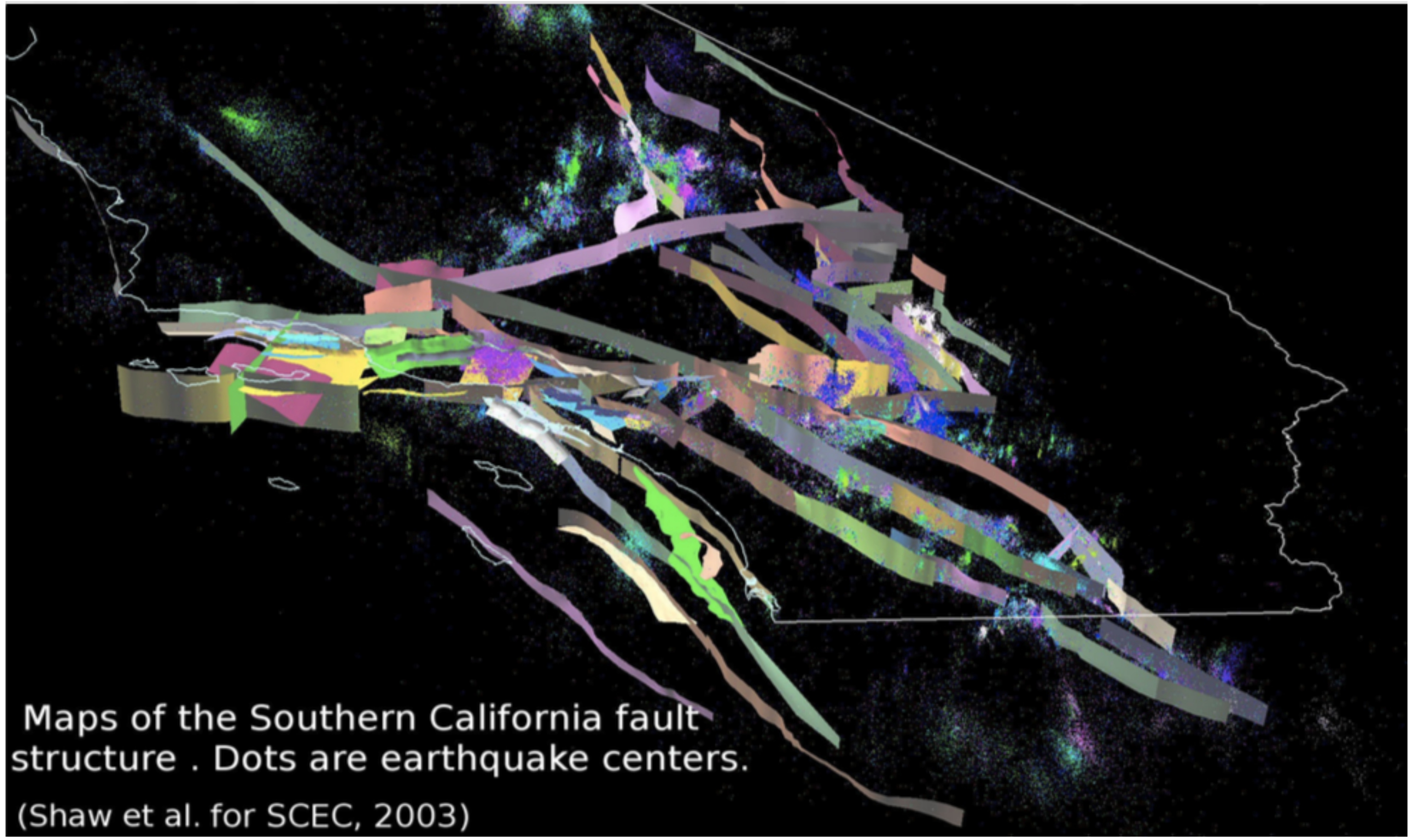
Sub-Rayleigh vs **supershear** rupture in the laboratory. Mach cone emanating from rupture tip (courtesy of L. Bruhat)





3D dynamic rupture
earthquake simulation

➡ Few methods support all modelling requirements



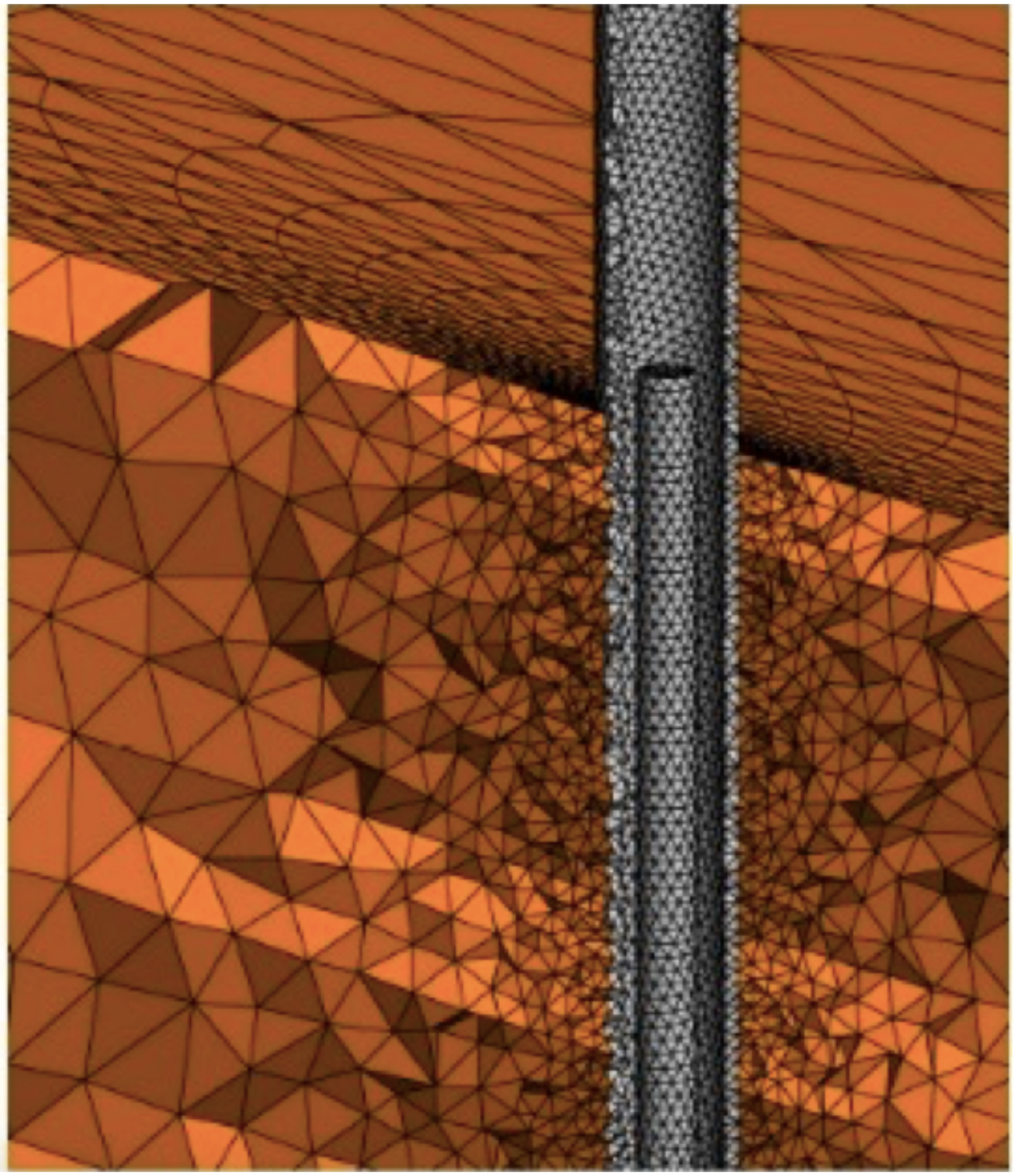
Multitude of spatio-temporal scales: fault geometry spans hundreds of km; frictional process zone size is m (or even cm) scale, tectonic loading (seismic cycle) 10-10000 years; rise time on second scale

the real world

- Non-planar, intersecting faults
- Non-linear friction
- Heterogeneities in stress and strength
- Dynamic damage around the fault
- Fault roughness and segmentation on all scales
- Bi-material effects
- Low velocity zones surrounding faults
- Thermal pressurization of fault zone fluids
- Thermal decomposition
- Dilatancy of the fault gouge
- Flash heating, melting, lubrication
- Feedback mechanisms across time scales

… this list grows continuously

SeisSol - A 3D dynamic rupture tool using the ADER-DG



SC17 BEST PAPER

www.seissol.org

github.com/SeisSol

AWARDS
Gordon Bell Prize

Extreme Scale Multi-Physics Simulations of the Tsunamigenic 2004 Sumatra Megathrust Earthquake

Carsten Uphoff
Sebastian Rettenberger
Michael Bader
uphoff@in.tum.de
rettenbs@in.tum.de
bader@in.tum.de
Technical University of Munich
Boltzmannstr. 3
85748 Garching, Germany

Elizabeth H. Madden
Thomas Ulrich
Stephanie Wollherr
Alice-Agnes Gabriel
madden@geophysik.uni-muenchen.de
ulrich@geophysik.uni-muenchen.de
wollherr@geophysik.uni-muenchen.de
gabriel@geophysik.uni-muenchen.de
Ludwig-Maximilians-Universität München
Theresienstr. 41
80333 Munich, Germany

SC'17

Petascale High Order Dynamic Rupture Earthquake Simulations on Heterogeneous Supercomputers

Alexander Heinecke[*‡], Alexander Breuer[*], Sebastian Rettenberger[*], Michael Bader[*], Alice-Agnes Gabriel[†], Christian Pelties[†], Arndt Bode[§*], William Barth[¶], Xiang-Ke Liao[‖], Karthikeyan Vaidyanathan[**], Mikhail Smelyanskiy[‡], Pradeep Dubey[‡]

SC'14

Discontinuous Galerkin methods for wave propagation in poroelastic media

Geophysics, 2008

Josep de la Puente[1], Michael Dumbser[2], Martin Käser[1], and Heiner Igel[1]

Verification of an ADER-DG method for complex dynamic rupture problems

C. Pelties[1], A.-A. Gabriel[1], and J.-P. Ampuero[2]

GMD, 2014

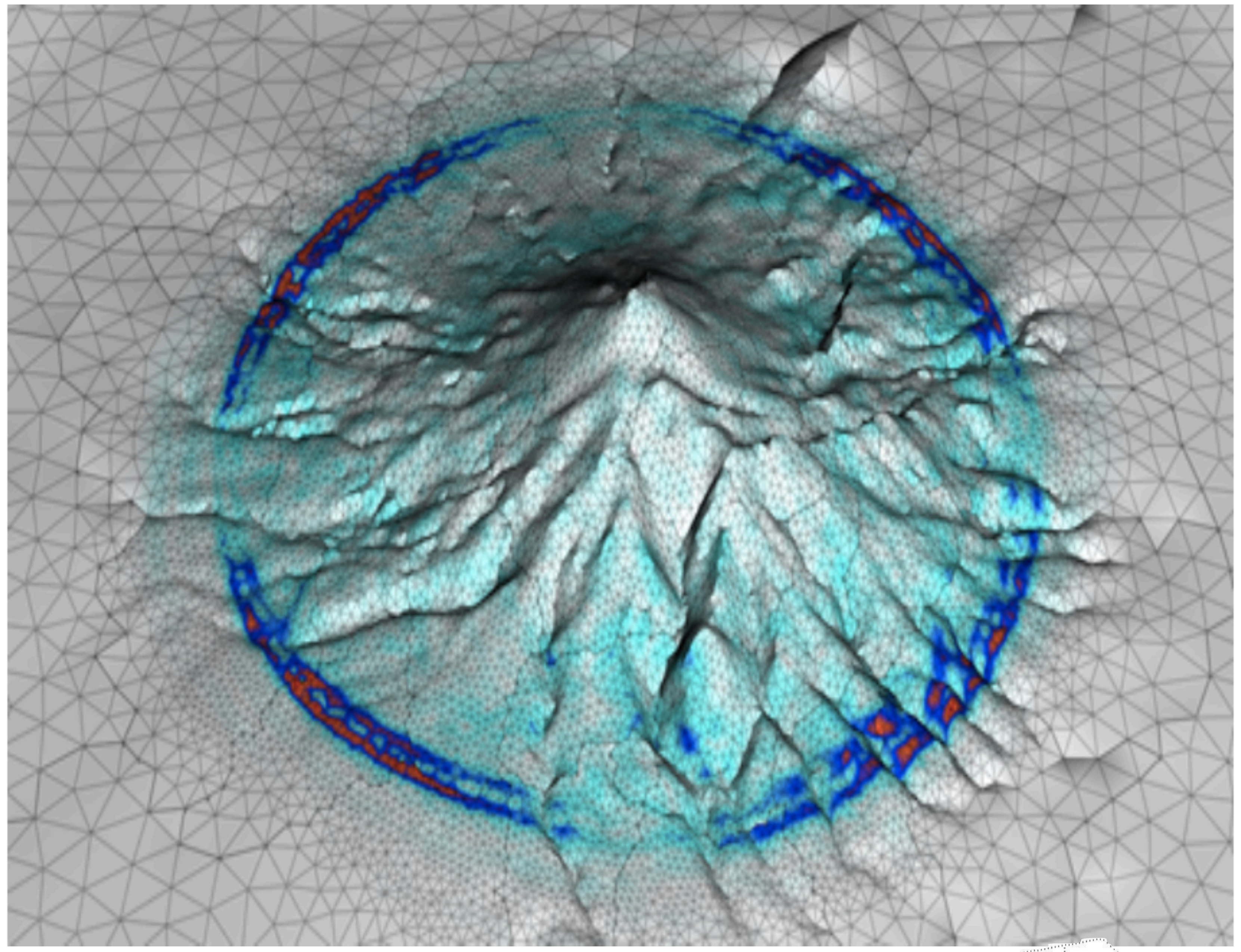
SeisSol - ADER-DG
A unique modelling framework

We develop and host an open-source Arbitrary high-order DERivative Discontinuous Galerkin (**ADER-DG**) software package. SeisSol solves the seismic wave equations in elastic, viscoelastic, and viscoplastic media on unstructured tetrahedral meshes.

The method, by design, permits:

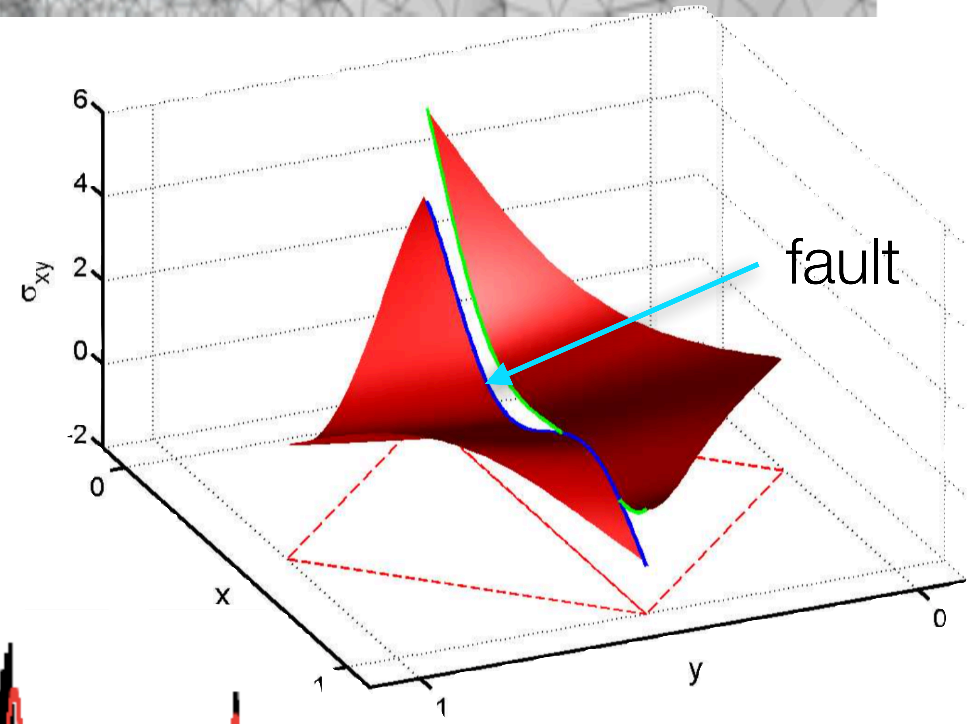
- representing **complex geometries** - by discretising the volume via a tetrahedral mesh
- modelling **heterogenous media** - elastic, viscoelastic, viscoplastic, anisotropic
- **multi-physics coupling** - flux based formulation is natural for representing physics defined on interfaces
- **high accuracy** - modal flux based formulation allows us to suppress spurious (unresolved) high frequencies
- **high resolution** - suitable for parallel computing environments

Käser and Dumbser, 2006; de la Puente et al., 2008; Pelties et al., 2014

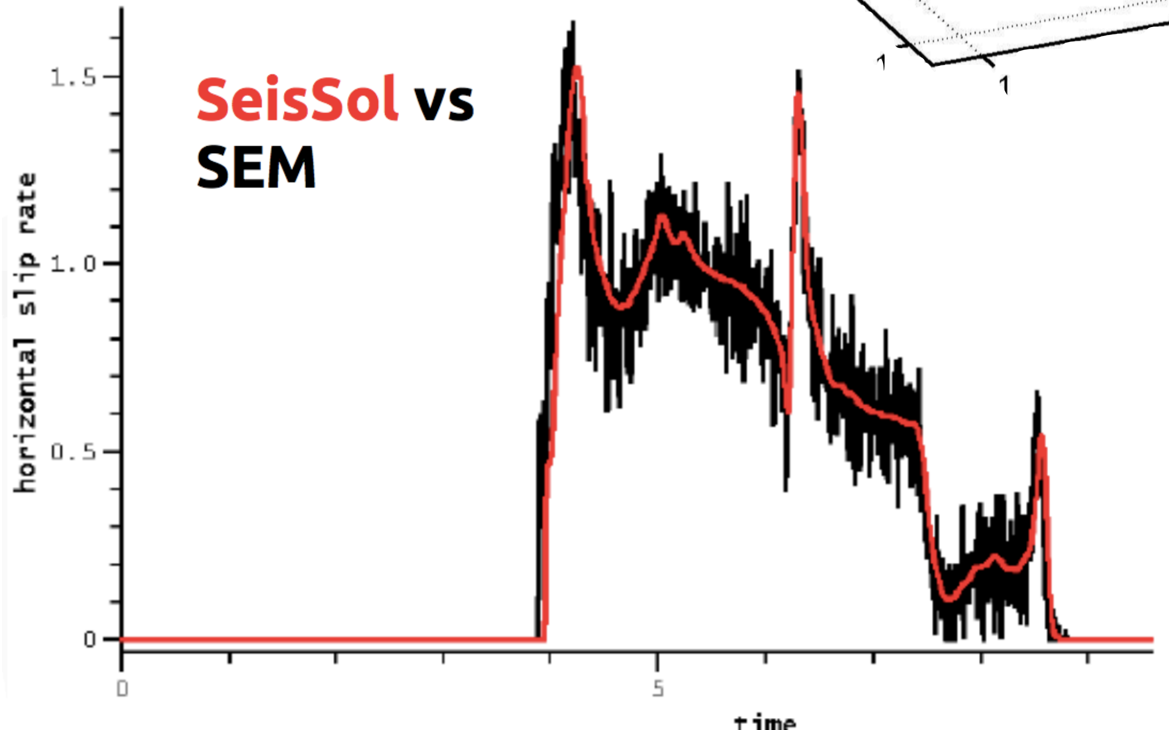


Wave field of a point source interacting with the topography of Mount Merapi Volcano.

PRACE ISC Award for producing the first simulations that obtained the “magical" performance milestone of 1 Peta-flop/s (10^{15} floating point operations per second) at the Munich Supercomputing Centre.



Representation of the shear stress discontinuity across the fault interface. Spontaneous rupture = internal boundary condition of flux term.



Due to the properties of the exact Riemann solver, solutions on the fault remain free of spurious oscillations

www.seissol.org github.com/SeisSol

SeisSol - ADER-DG
A unique modelling framework

Why DG? Low numerical dispersion, minor changes for dynamic rupture, suitable for intersecting and branching faults/structure, favourable numerical dissipation of the Godunov flux (Hu et al. 1999; Kaeser et al. 2008; Hesthaven & Warburton 2010)

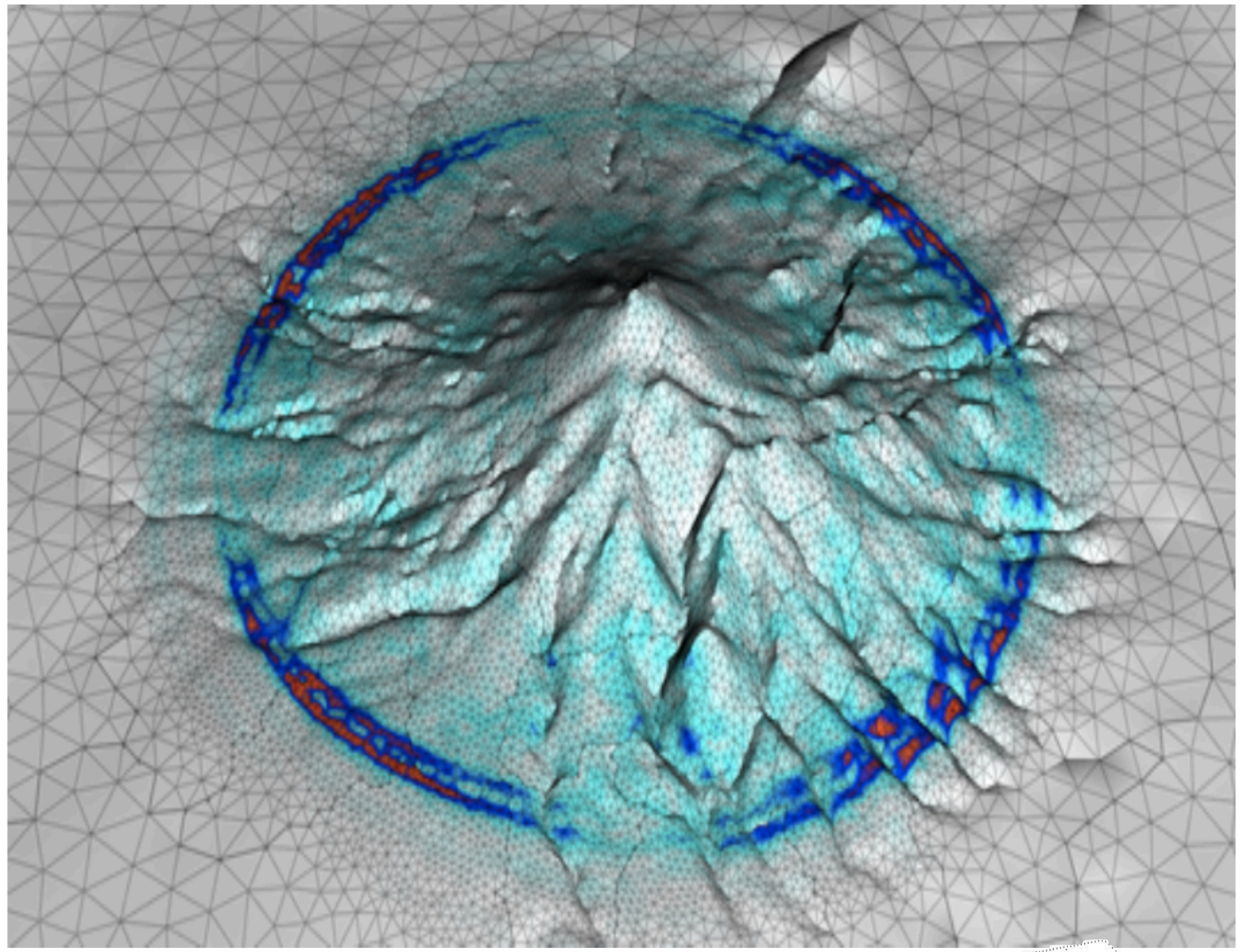
Why ADER? Equivalent high-order accuracy as in space using a single explicit time integration step. Increasing order of accuracy can be ‘cheap’ if hardware is exploited)

Why tets? Complex realities of geological subsurface, non-planar fault surfaces, intersecting undulating surfaces, static mesh refinement and coarsening

Why modal formulation? easy to build arbitrary high-order basis functions for tetrahedra, block-structured sparsity patterns with ADER

Why orthogonal basis functions? Dubiner’s basis functions (Cockburn et al. 2000), leads to well-conditioned diagonal mass matrix, all matrices can be pre-calculated analytically leading to a quadrature-free scheme (e.g., Atkins & Shu 1996)

Käser and Dumbser, 2006; de la Puente et al., 2008; Pelties et al., 2014



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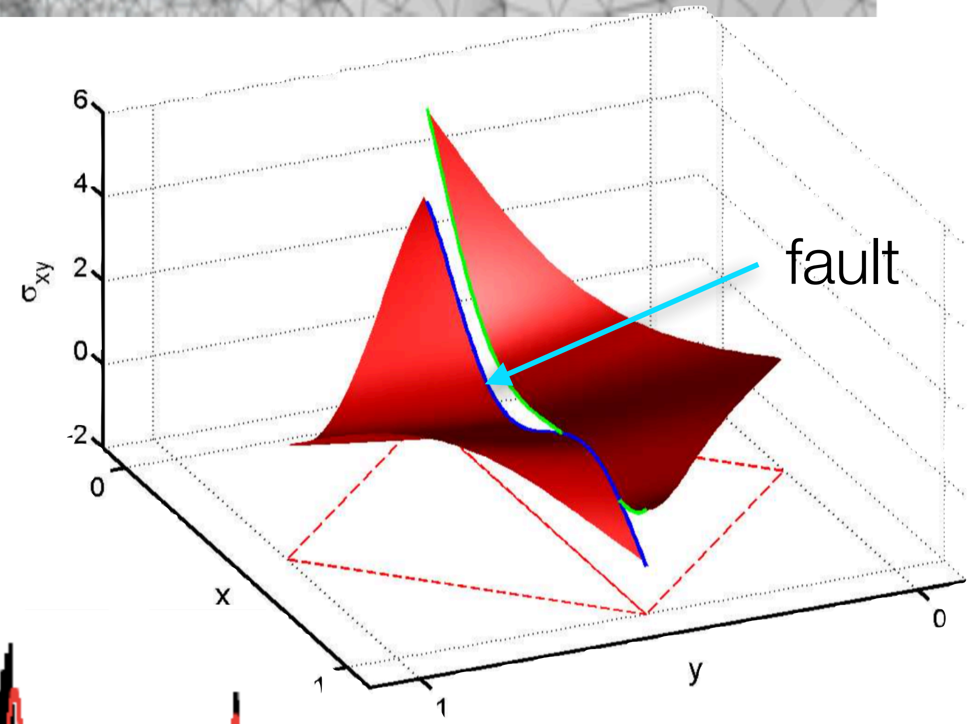

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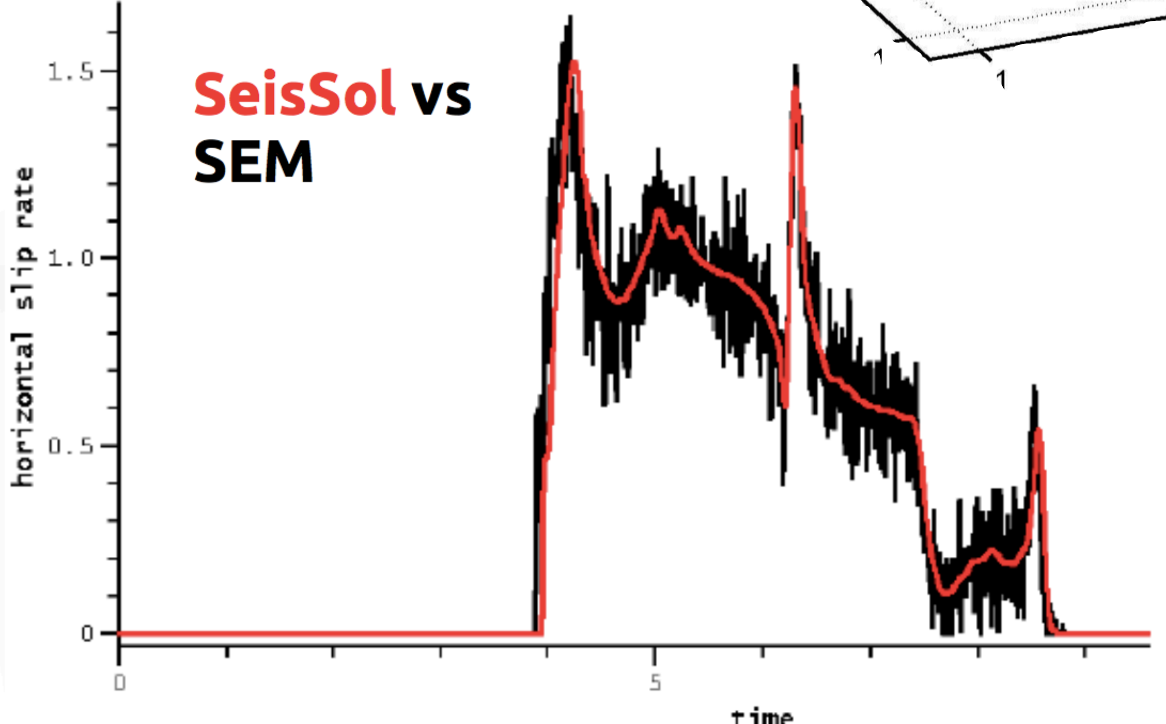

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Why
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with

A software that allows for rapid setup of models with realistic non-planar and intersecting fault systems while exploiting the accuracy of a high-order numerical method

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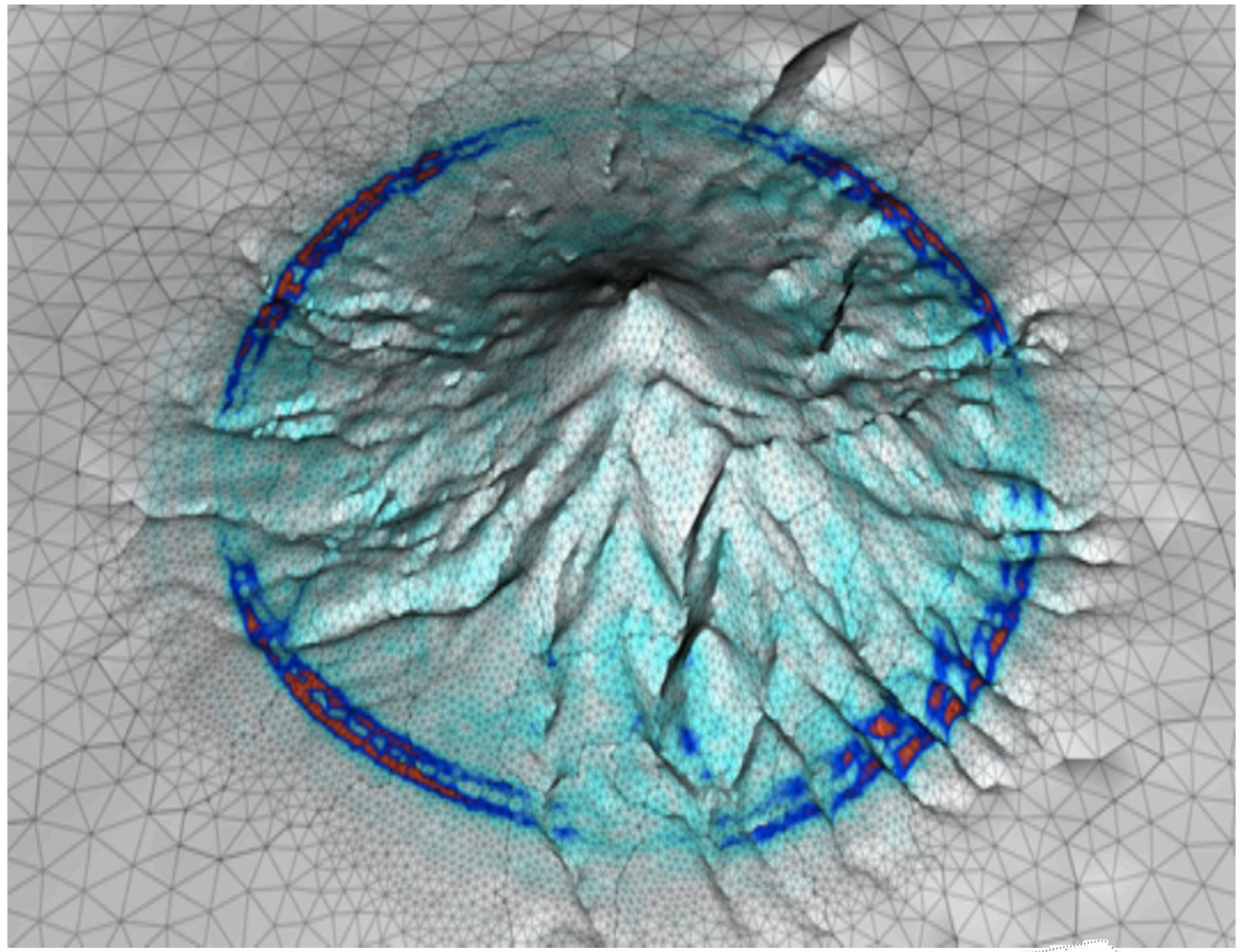

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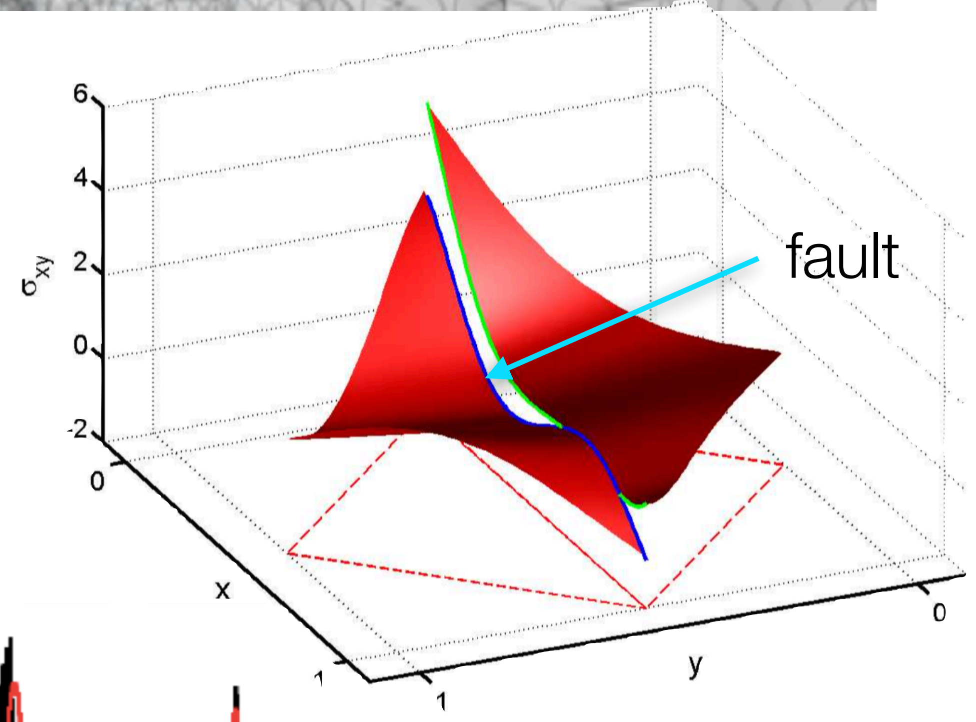

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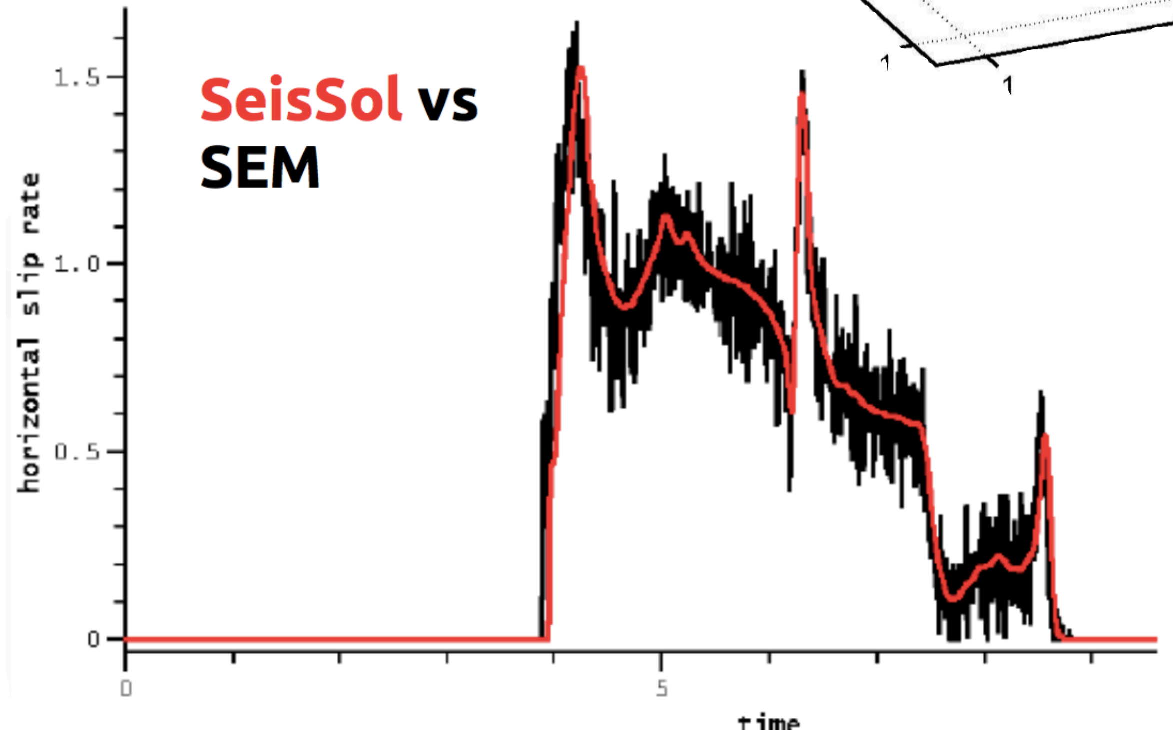

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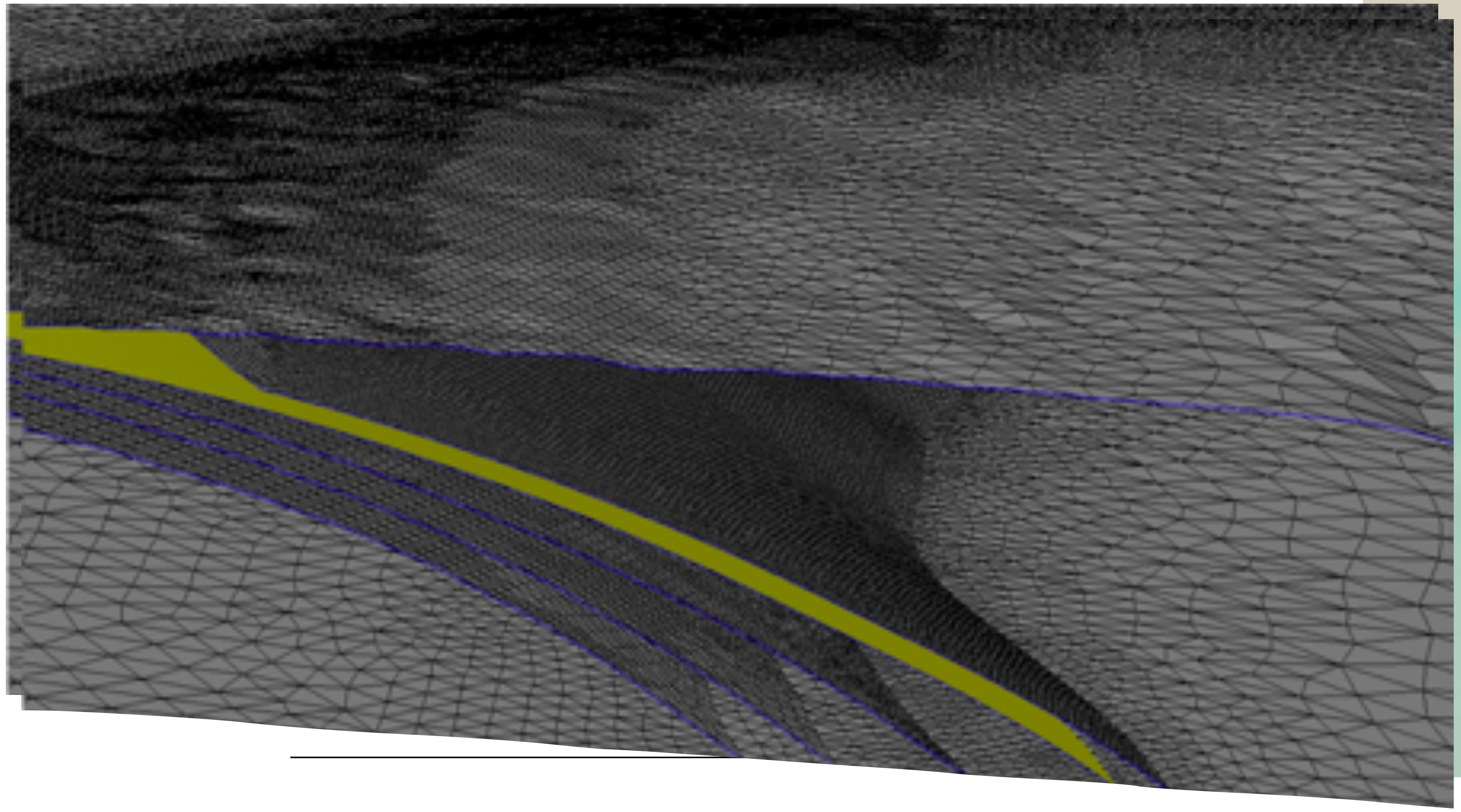
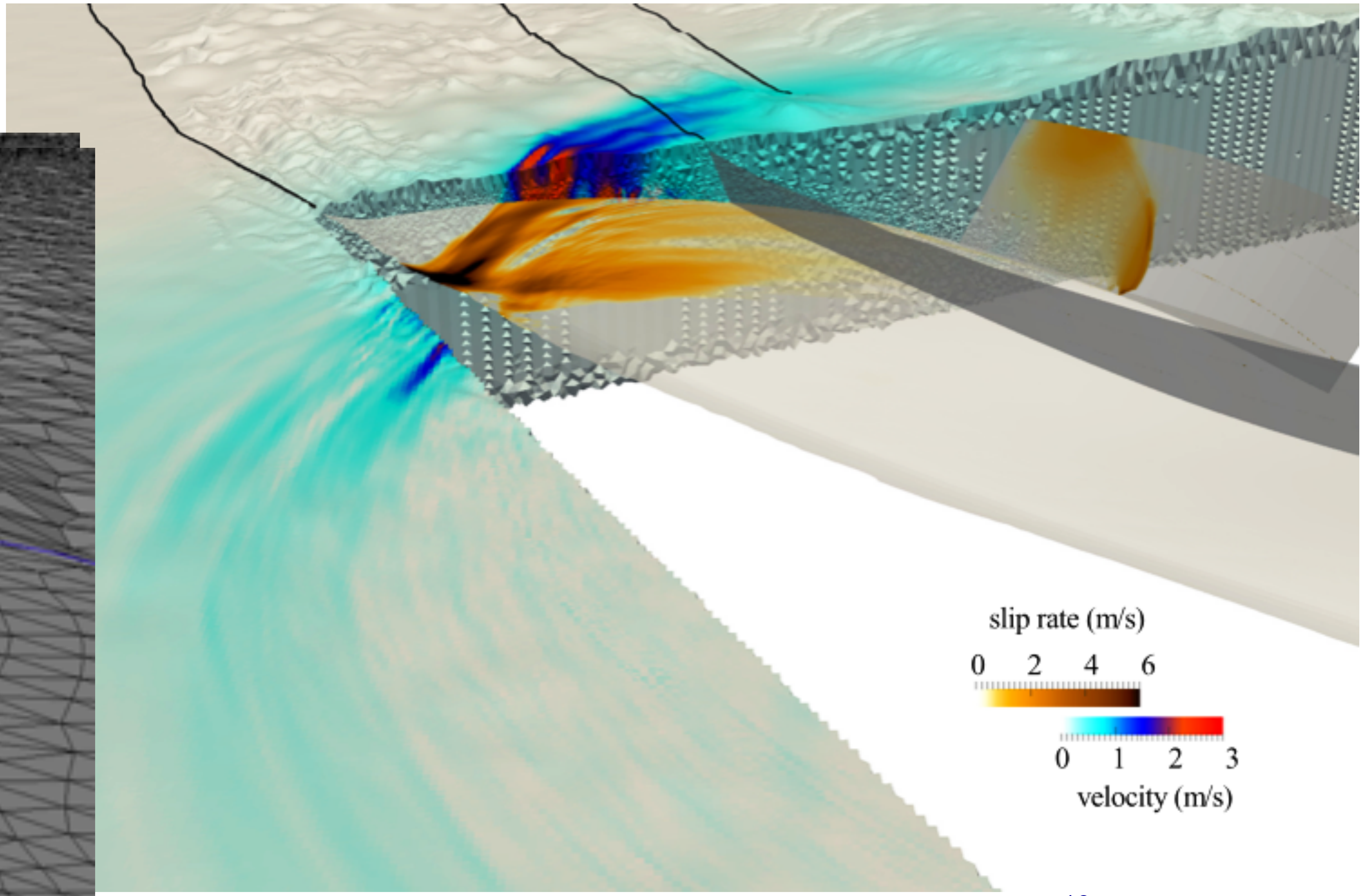
The “grand challenge” of meshing

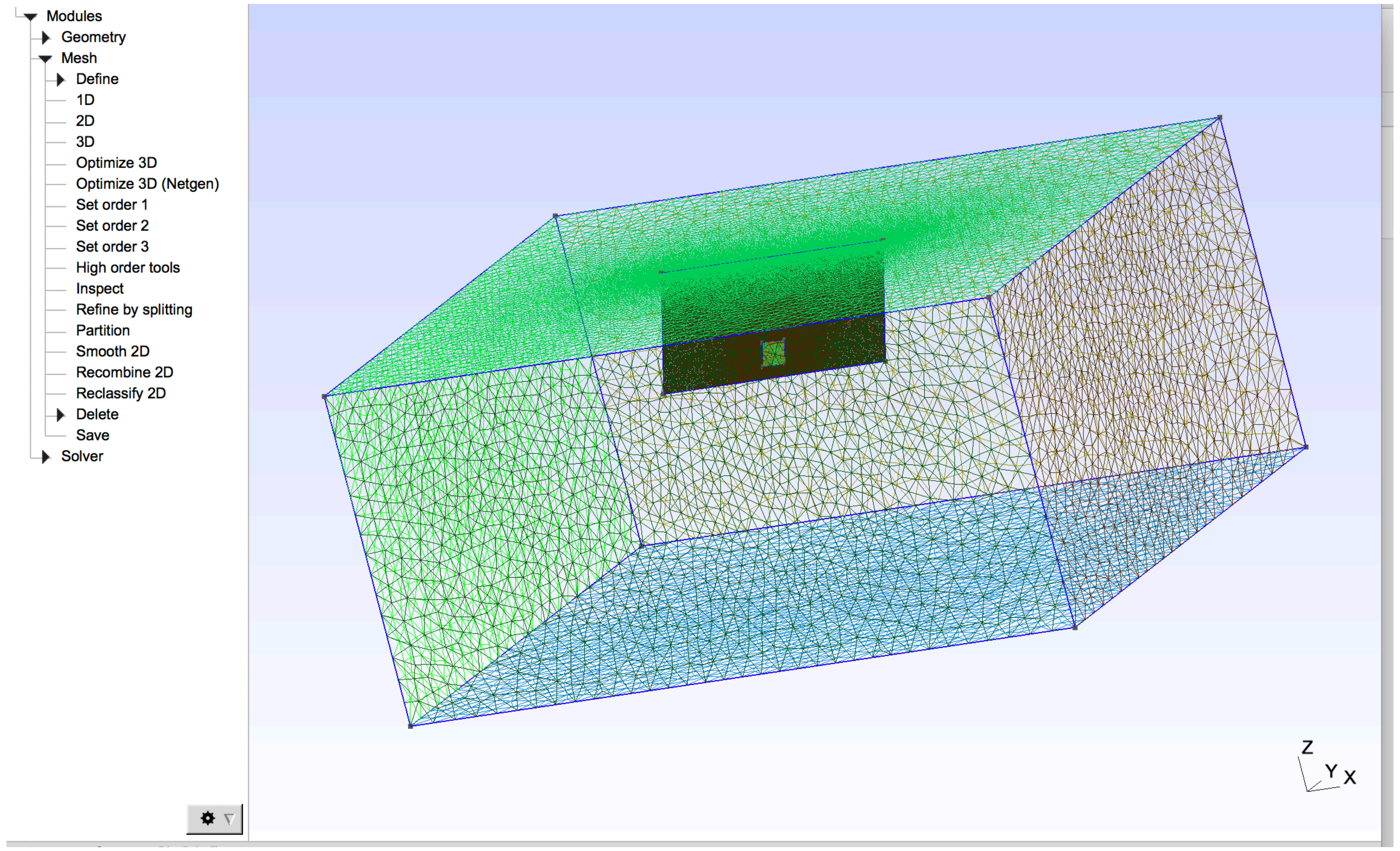
- Community standard 1) **Hexahedral** meshes - can easily consume **weeks to months,** is **limited** for complex geometries (external / internal boundary conditions)
- Community standard 2) **Unstructured tetrahedral** meshes - allows automatised meshing and complex internal/ external boundary conditions - however are numerically challenging (sliver elements)



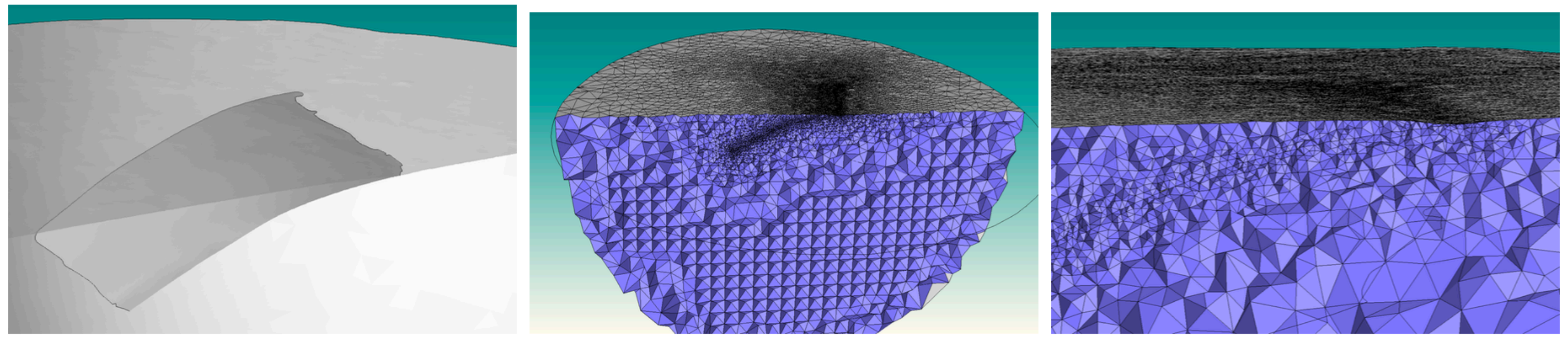


Geometry and meshing

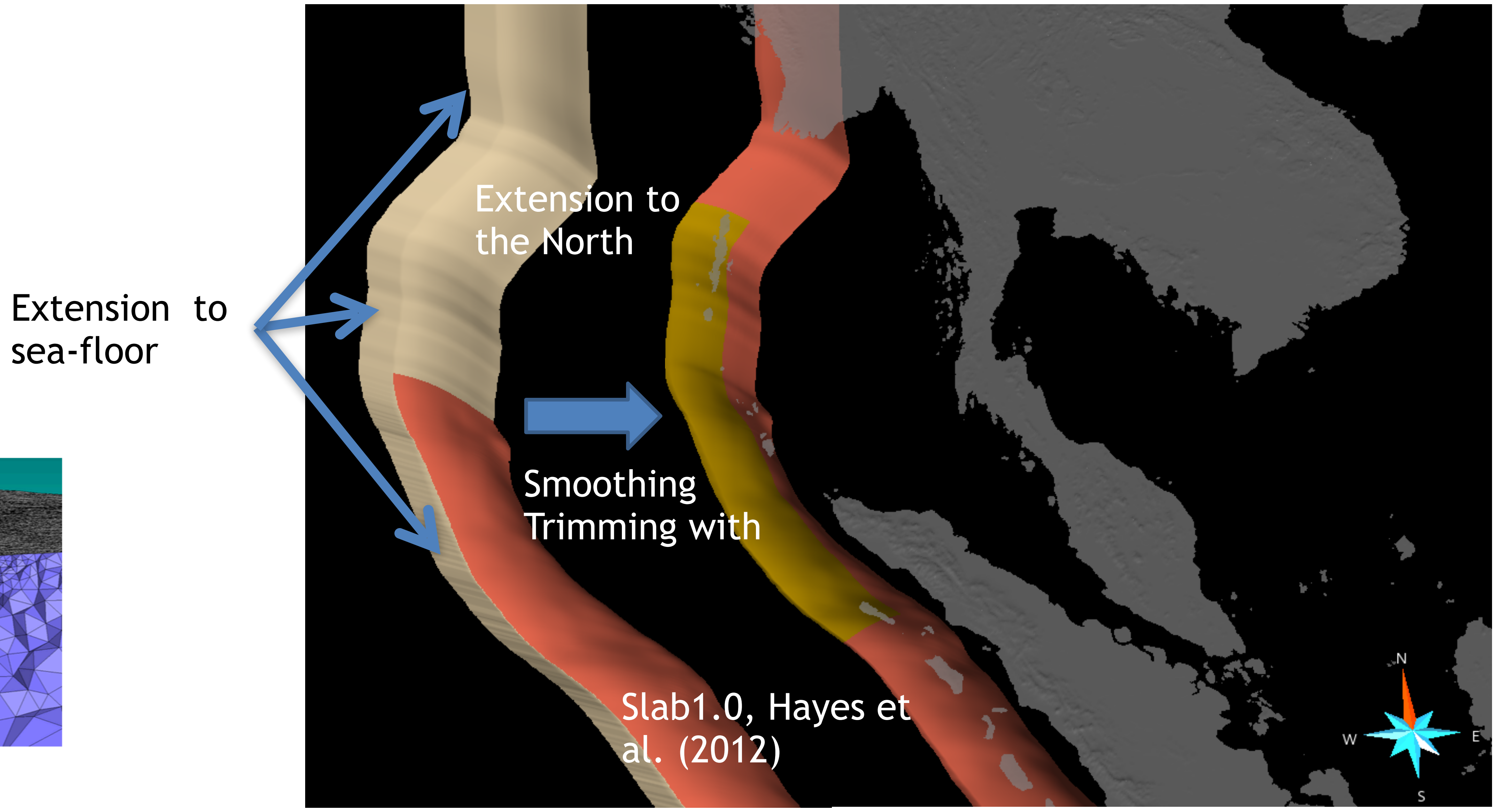
- **Gmsh** (http://gmsh.info, open source) for most simple geometries and every-day mesh sizes, many tutorials, limited in terms of geometry
- **Simmodeler** (Simmetrix, **free for academics**) for large meshes / complex geometries: customised GUI for SeisSol, pumgen library for parallel meshing on Clusters
- Mesh is provided in parallel data format - code does internal **partitioning**



Gmsh interface for example geometry and 2D mesh



http://www.simmetrix.com/index.html



GoCAD interface for complex geometries

SeisSol - ADER-DG
Numerics in a nutshell

- **Elastic wave equation** in velocity stress formulation

linear hyperbolic system

$$\frac{\partial Q_p}{\partial t} + A_{pq}\frac{\partial Q_q}{\partial x} + B_{pq}\frac{\partial Q_q}{\partial y} + C_{pq}\frac{\partial Q_q}{\partial z} = S_p$$

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

$$\left.\begin{aligned}
\frac{\partial}{\partial t}\sigma_{xx} - (\lambda + 2\mu)\frac{\partial}{\partial x}u - \lambda\frac{\partial}{\partial y}v - \lambda\frac{\partial}{\partial z}w &= 0,\\
\frac{\partial}{\partial t}\sigma_{yy} - \lambda\frac{\partial}{\partial x}u - (\lambda + 2\mu)\frac{\partial}{\partial y}v - \lambda\frac{\partial}{\partial z}w &= 0,\\
\frac{\partial}{\partial t}\sigma_{zz} - \lambda\frac{\partial}{\partial x}u - \lambda\frac{\partial}{\partial y}v - (\lambda + 2\mu)\frac{\partial}{\partial z}w &= 0,\\
\frac{\partial}{\partial t}\sigma_{xy} - \mu\left(\frac{\partial}{\partial x}v + \frac{\partial}{\partial y}u\right) &= 0,\\
\frac{\partial}{\partial t}\sigma_{yz} - \mu\left(\frac{\partial}{\partial z}v + \frac{\partial}{\partial y}w\right) &= 0,\\
\frac{\partial}{\partial t}\sigma_{xz} - \mu\left(\frac{\partial}{\partial z}u + \frac{\partial}{\partial x}w\right) &= 0,
\end{aligned}\right\}\ \text{constitutive relationships in terms of velocity}$$

$$\left.\begin{aligned}
\rho\frac{\partial}{\partial t}u - \frac{\partial}{\partial x}\sigma_{xx} - \frac{\partial}{\partial y}\sigma_{xy} - \frac{\partial}{\partial z}\sigma_{xz} &= 0,\\
\rho\frac{\partial}{\partial t}v - \frac{\partial}{\partial x}\sigma_{xy} - \frac{\partial}{\partial y}\sigma_{yy} - \frac{\partial}{\partial z}\sigma_{yz} &= 0,\\
\rho\frac{\partial}{\partial t}w - \frac{\partial}{\partial x}\sigma_{xz} - \frac{\partial}{\partial y}\sigma_{yz} - \frac{\partial}{\partial z}\sigma_{zz} &= 0,
\end{aligned}\right\}\ \text{conservation of momentum}$$

SeisSol - ADER-DG
Numerics in a nutshell

$$\frac{\partial Q_p}{\partial t} + A_{pq}\frac{\partial Q_q}{\partial x} + B_{pq}\frac{\partial Q_q}{\partial y} + C_{pq}\frac{\partial Q_q}{\partial z} = S_p$$

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- **Elastic wave equation** in velocity stress formulation

- **ADER:** high-order time integration + **DG:** high-order space discretisation

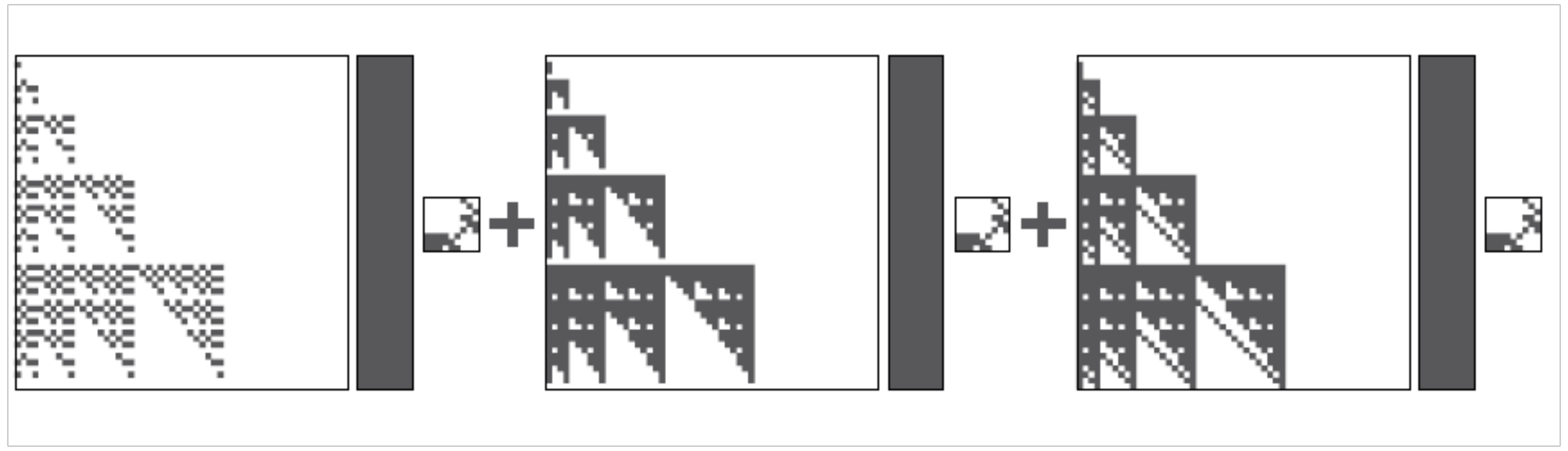
- DG with orthogonal basis functions **(modal)**

- **Exact Riemann-Solver** computes the upwind flux = state at the element interfaces

DG discrete form

$$\tilde{K}^{\xi}\left(\mathcal{J}_k^{n,n+1}\right) A_k^{\star} + \tilde{K}^{\eta}\left(\mathcal{J}_k^{n,n+1}\right) B_k^{\star} + \tilde{K}^{\zeta}\left(\mathcal{J}_k^{n,n+1}\right) C_k^{\star}$$

DG operators



SeisSol - ADER-DG
Numerics in a nutshell

- **Elastic wave equation** in velocity stress formulation

- **ADER:** high-order time integration + **DG:** high-order space discretisation
- DG with orthogonal basis functions **(modal)**
- **Exact Riemann-Solver** computes the upwind flux = state at the element interfaces

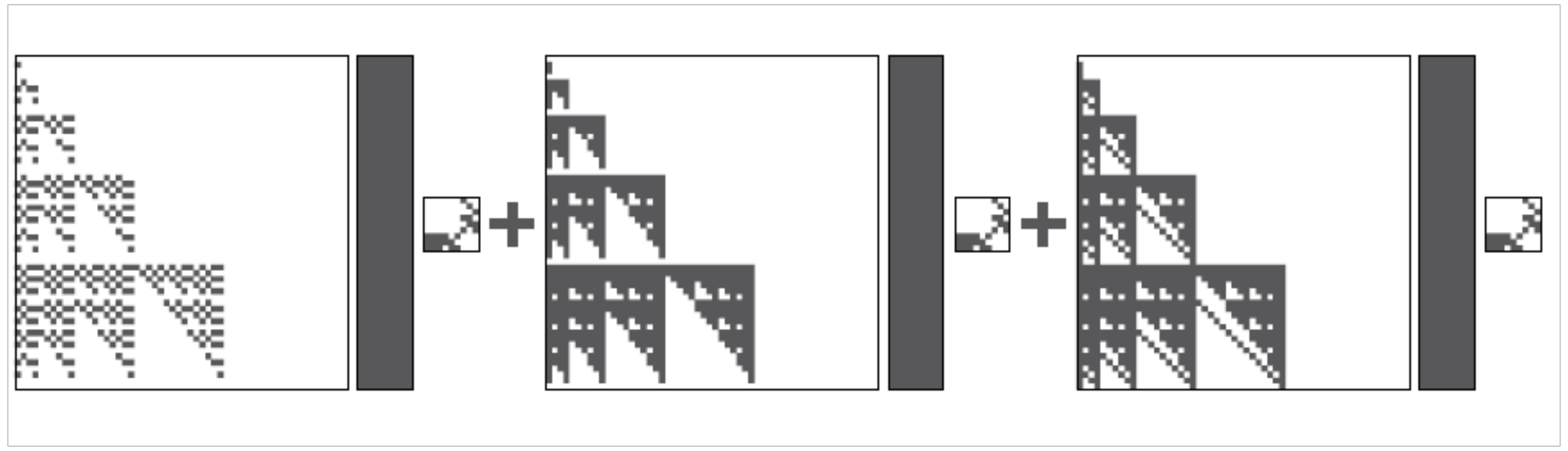
- **Locality of the computations:** only neighbouring elements exchange data

➡ **ADER-DG boils down to small matrix-matrix multiplications, where the dimension of the matrices depends on the order of the scheme (75 % of runtime consumption).**

$$\frac{\partial Q_p}{\partial t} + A_{pq}\frac{\partial Q_q}{\partial x} + B_{pq}\frac{\partial Q_q}{\partial y} + C_{pq}\frac{\partial Q_q}{\partial z} = S_p$$

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

$$\tilde{K}^{\xi}\left(J_k^{n,n+1}\right)A_k^{\star} + \tilde{K}^{\eta}\left(J_k^{n,n+1}\right)B_k^{\star} + \tilde{K}^{\zeta}\left(J_k^{n,n+1}\right)C_k^{\star}$$



Update scheme

$$\begin{aligned} Q_k^{n+1} = Q_k - \frac{|S_k|}{|J_k|}M^{-1}\Bigg(&\sum_{i=1}^{4} F^{-,i} I(t^n, t^{n+1}, Q_k^n) N_{k,i} A_k^{+} N_{k,i}^{-1} \\ &+ \sum_{i=1}^{4} F^{+,i,j,h} I(t^n, t^{n+1}, Q_{k(i)}^n) N_{k,i} A_{k(i)}^{-} N_{k,i}^{-1}\Bigg) \\ &+ M^{-1} K^{\xi} I(t^n, t^{n+1}, Q_k^n) A_k^{*} \\ &+ M^{-1} K^{\eta} I(t^n, t^{n+1}, Q_k^n) B_k^{*} \\ &+ M^{-1} K^{\zeta} I(t^n, t^{n+1}, Q_k^n) C_k^{*} \end{aligned}$$

Cauchy Kovalewski

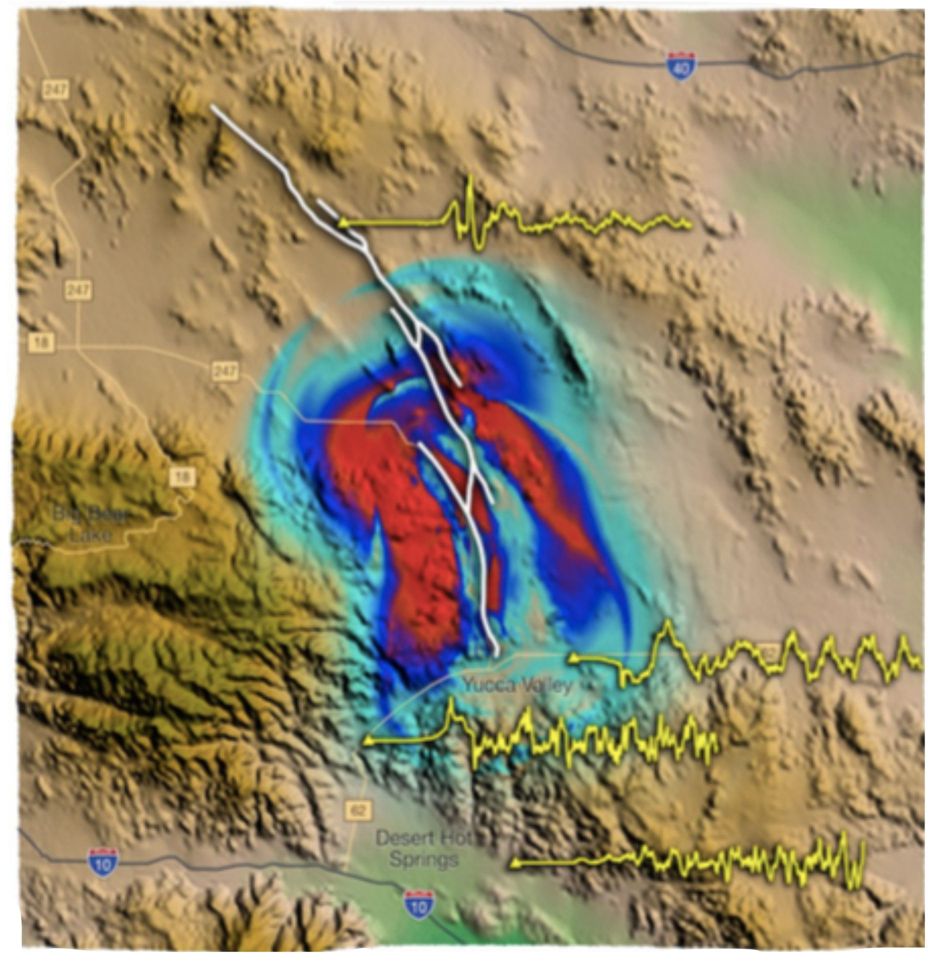
$$I(t^n, t^{n+1}, Q_k^n) = \sum_{j=0}^{J} \frac{(t^{n+1} - t^n)^{j+1}}{(j+1)!} \frac{\partial^j}{\partial t^j} Q_k(t^n)$$

$$(Q_k)_t = -M^{-1}\left((K^{\xi})^T Q_k A_k^{*} + (K^{\eta})^T Q_k B_k^{*} + (K^{\zeta})^T Q_k C_k^{*}\right)$$

Balancing HPC and geophysics - SeisSol

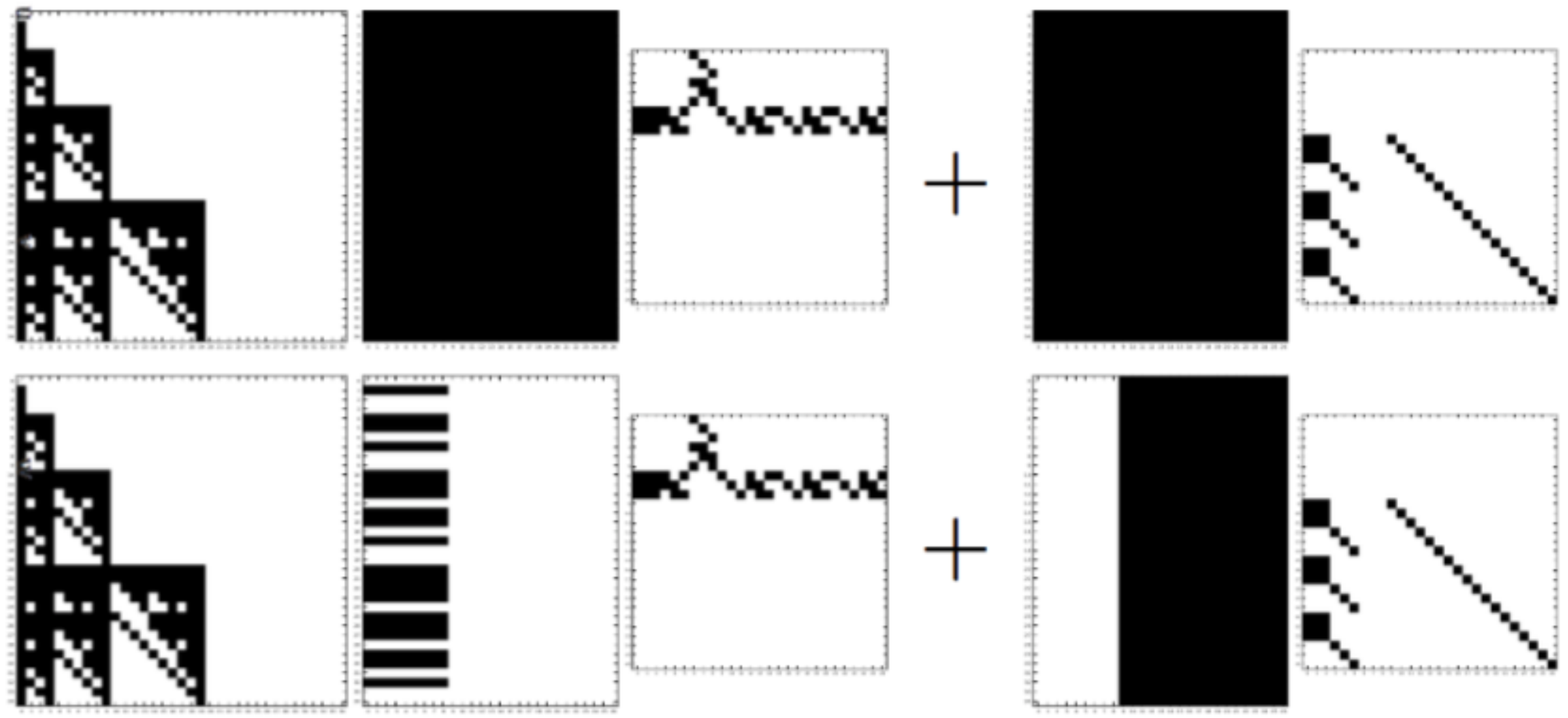
Breuer et al.,ISC14, Heinecke et al.,SC14
Breuer et al.,IEEE16, Heinecke et al.,SC16
Rettenberger et al., EASC16
Upphoff & Bader, HPCS'16
Uphoff et al., SC17
Wolf et al., ICCS'20
Uphoff & Bader, TOMS'20

Gordon Bell Prize Finalist, SC14



"Geophysics" Version	• Fortran 90 • MPI parallelised • Ascii based, serial I/O
Landers scenario (96 billion DoF, 200,000 time steps)	• Hybrid MPI+OpenMP parallelisation • Parallel I/O (HDF5, inc. mesh init.) • **Assembler-level DG kernels** • multi-physics off-load scheme for many-core architectures

- **> 1 PFlop/s performance**
- **90% parallel efficiency**
- **45% of peak performance**
- **5x-10x faster time-to-solution**
- **10x-100x bigger problems**



Partial kernel before (top) and after (bottom) removing irrelevant entries in matrix chain products

➡ **A code generator automatically detects and exploits sparse block patterns**

➡ **Hardware specific full "unrolling" and vectorization of all element operations**

➡ **Customised code for each matrix-matrix multiplication via the libxsmm back-end**

➡ **Efficiently exploits as of 2014 available hardware (AVX, MIC), reaching unto 8.6 PFLOPS on Tianhe-2**

Balancing HPC and geophysics - SeisSol

Breuer et al.,ISC14, Heinecke et al.,SC14
Breuer et al.,IEEE16, Heinecke et al.,SC16
Rettenberger et al., EASC16
Upphoff & Bader, HPCS'16
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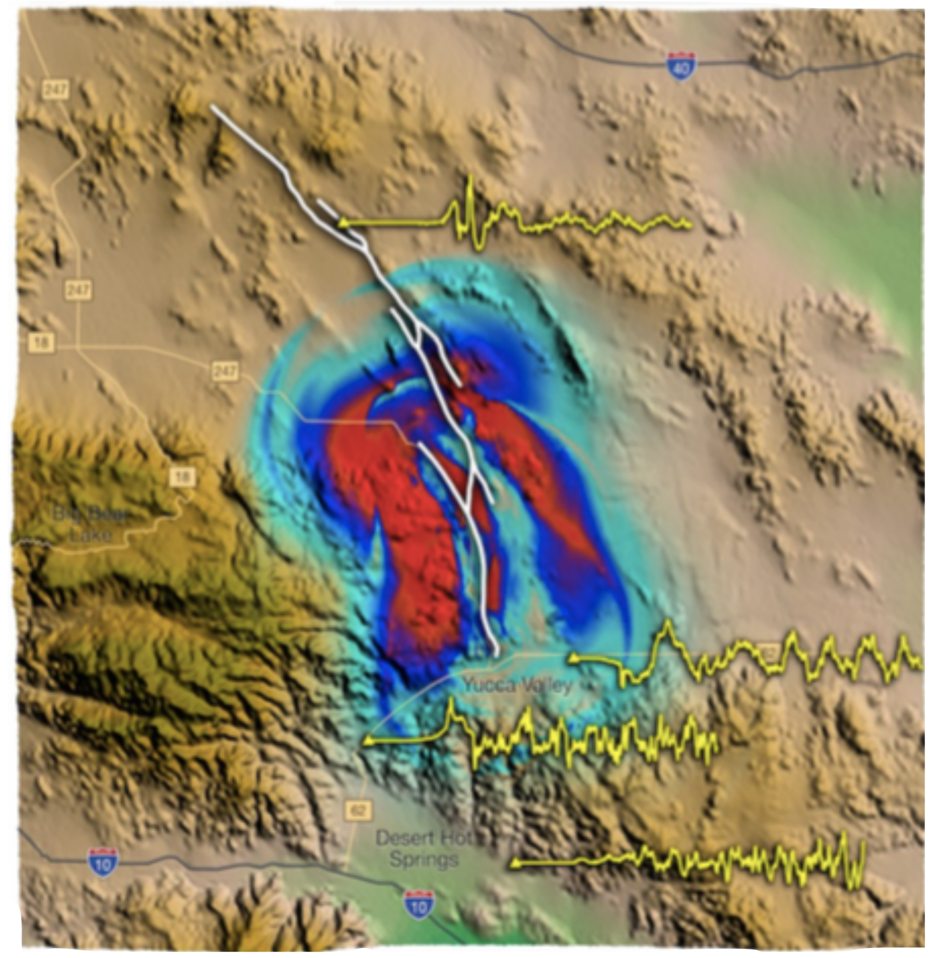
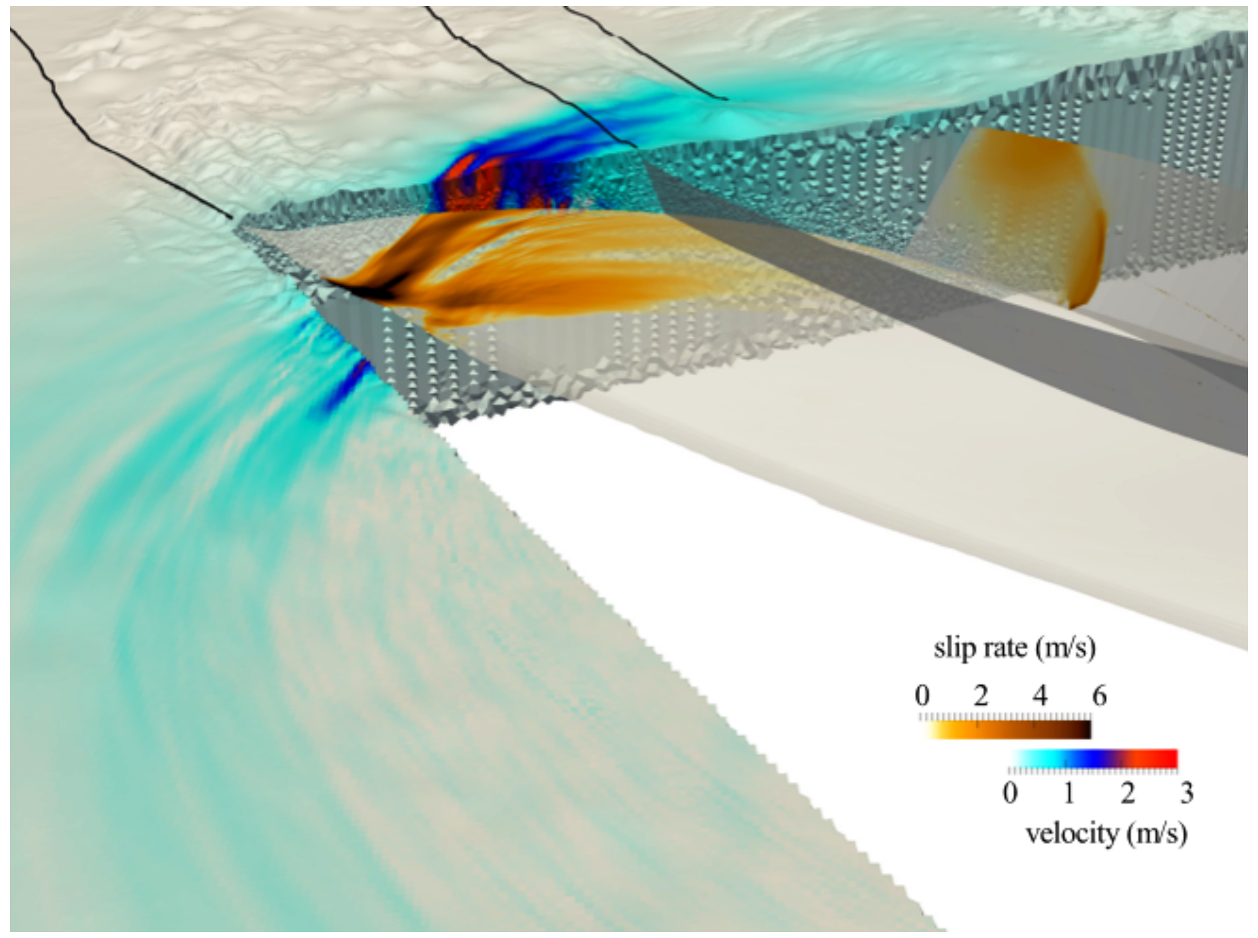
Gordon Bell Prize Finalist, SC14





Best Paper Award, SC17

"Geophysics" Version

- Fortran 90
- MPI parallelised
- Ascii based, serial I/O

Landers scenario
(96 billion DoF,
200,000 time steps)

- Hybrid MPI+OpenMP parallelisation
- Parallel I/O (HDF5, inc. mesh init.)
- Assembler-level DG kernels
- multi-physics off-load scheme for many-core architectures

- > 1 PFlop/s performance
- 90% parallel efficiency
- 45% of peak performance
- 5x-10x faster time-to-solution
- 10x-100x bigger problems

Sumatra scenario
(111 billion DoF,
3,300,000 time steps)

- **Cluster-based local time stepping**
- Code generator also for advanced PDE's as viscoelastic attunation
- Asagi (XDMF)-geoinformation server
- Asynchronous input/output
- Overlaping computation and communication

- Optimized for Intel KNL
- Speed up of 14x
- 14 hours compared to almost 8 days for Sumatra scenario on SuperMuc2

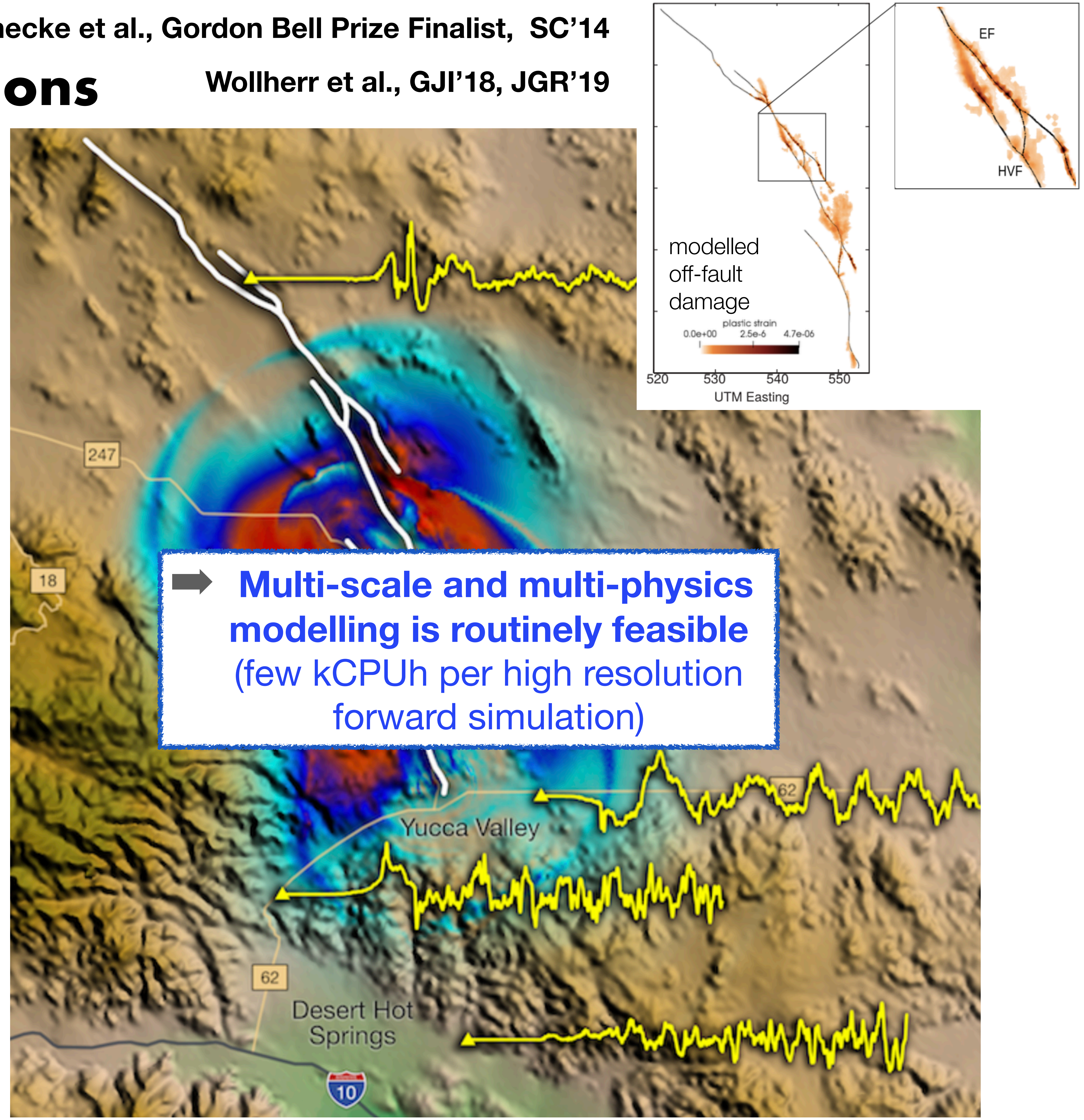
Heinecke et al., Gordon Bell Prize Finalist, SC’14

Wollherr et al., GJI’18, JGR’19

Integrating interdisciplinary observations in high-resolution forward models

The open source software **SeisSol** (www.seissol.org) exploits **unstructured tetrahedral meshes and high-order accuracy** in space and time based on an ADER-DG method handling **geometric complexity** and **highly varying element sizes**

- “**Hero runs**” use full supercomputers, e.g. a petaflop scale simulation revisiting the 1992 Landers earthquake linking 3D spontaneous dynamic rupture simulations with the interplay of fault geometry, topography, rheology, off-fault plasticity, and viscoelastic attenuation
- **Recent in-house developments:** a **geoinformation server** for fast and **asynchronous input/output**, clustered **local time stepping**, flexible boundary conditions (e.g. **gravity,** with Eric Dunham's group), **GPU optimisation**, code generator (YATeTo, Uphoff & Bader, TOMS 2020) generating > 80% of core routines



Landers earthquake dynamic rupture and 10 Hz wave propagation scenario (96 billion DoF, 200,000 time steps)

Breuer et al.,ISC14, Heinecke et al.,SC14
Breuer et al.,IEEE16, Heinecke et al.,SC16
Rettenberger et al., EASC16
Uphoff & Bader, HPCS’16

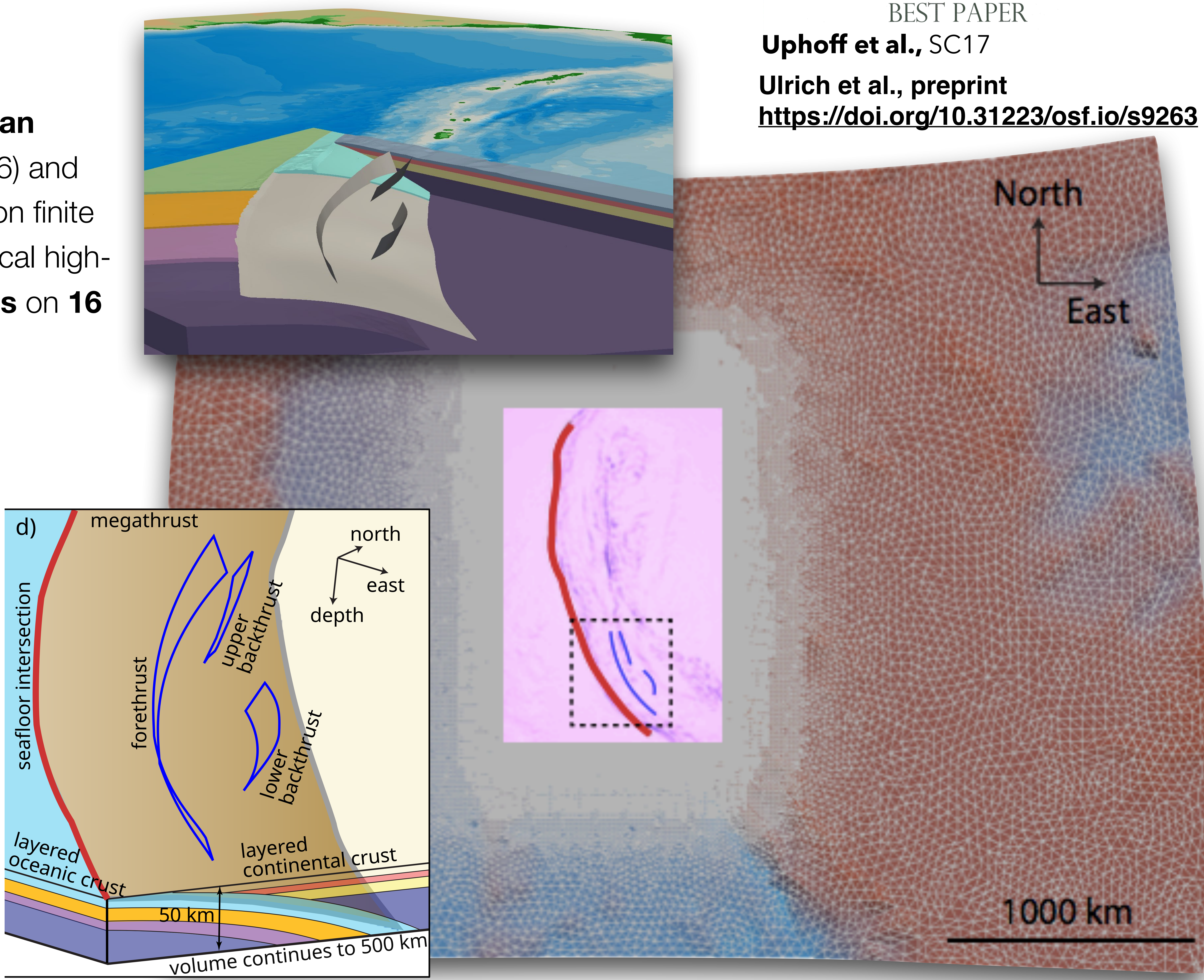
Linking geodynamic, earthquake and tsunami modeling tools

BEST PAPER

Uphoff et al., SC17

Ulrich et al., preprint
https://doi.org/10.31223/osf.io/s9263

- **The 2004 Sumatra-Andaman earthquake and Indian Ocean tsunami :** Spatial resolution (400m on-fault, O6) and 2.2 Hz wave propagation required mesh with 220 million finite elements (**~111 x 10^9 degrees of freedom**), now typical high-order simulations: >10 Mio elements run **5h30 minutes** on **16 nodes** (4k CPUh)

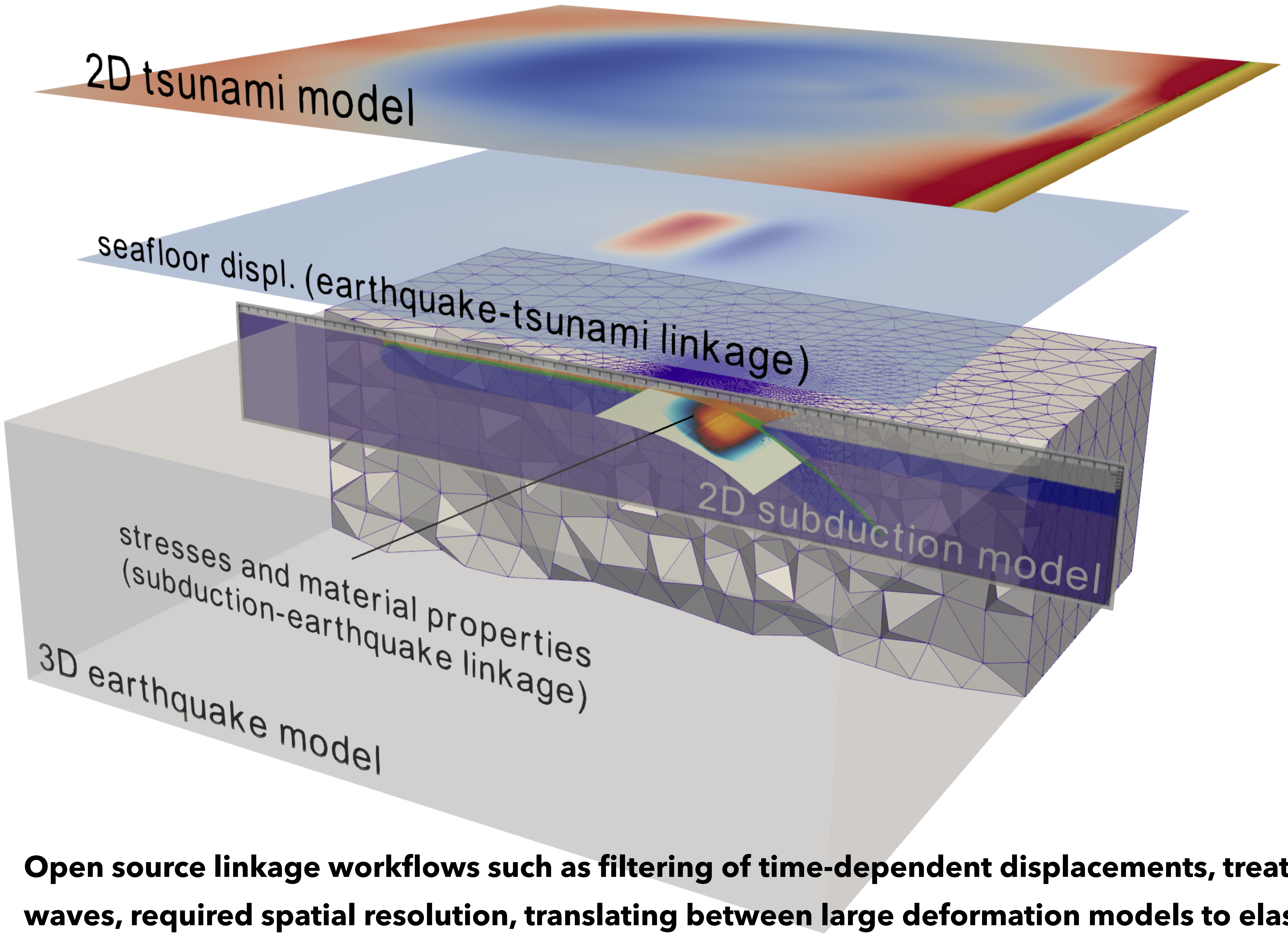


- **Reproducibility:** A setup including a mesh with over 3 million elements for the 2004 Sumatra-Andaman earthquake can be obtained from Zenodo https://dx.doi.org/10.5281/zenodo.439946.

- 16 teams of undergraduate students reproduced our paper in a real-time, non-stop, 48-hour challenge during the SC'18 conference.

Linking geodynamic, earthquake and tsunami modeling tools

Madden et al., GJI 2020



Ulrich et al., preprint
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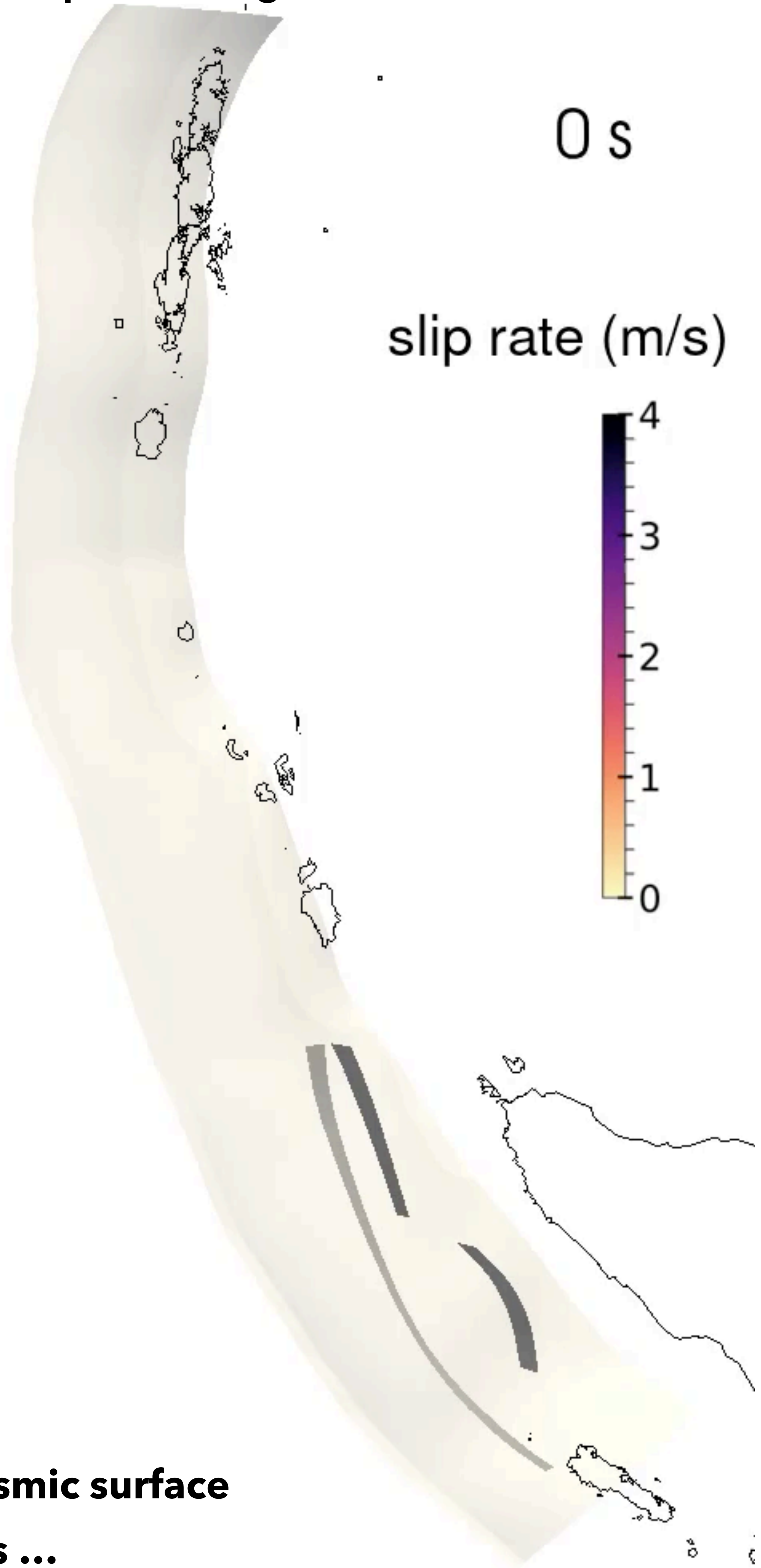


Open source linkage workflows such as filtering of time-dependent displacements, treatment of seismic surface waves, required spatial resolution, translating between large deformation models to elastodynamics …

Rapid earthquake/tsunami response - The 2018, Palu-Sulawesi Event

- A devastating 'surprise' tsunami related to a Mw7.8 strike-slip earthquake propagating at supershear speed crossing the narrow Bay of Palu

1

World Health Organization

Indonesia

Situation Report # 09
Date of issue: 19 October 2018
Location: Central Sulawesi, Indonesia
Emergency type: **Earthquake and Tsunami**
Date of onset: 28 September 2018

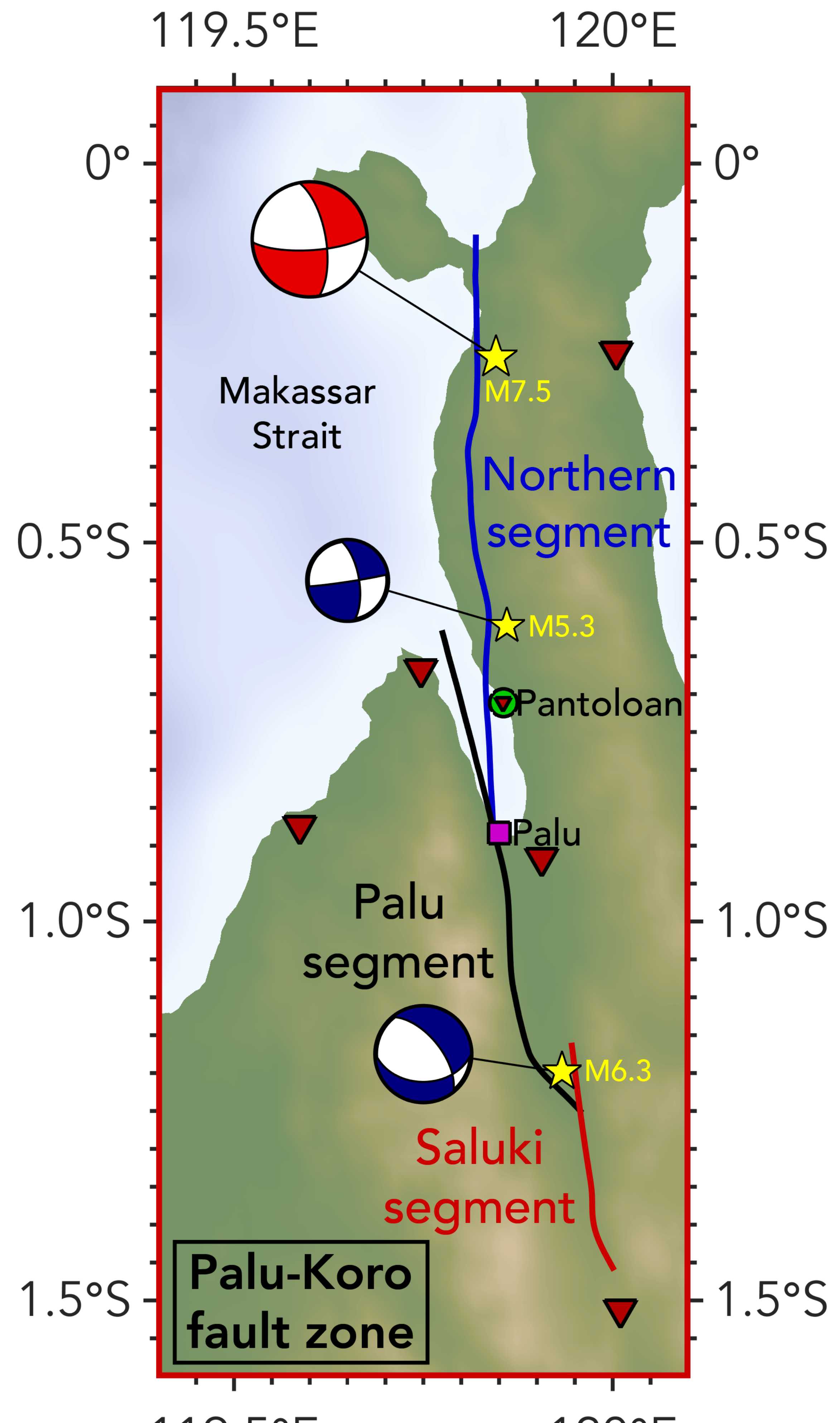
616 684 Affected

87752 displaced population in 147 sites

4 612 severely injured

2100 fatalities

45 health facilities affected



nature geoscience

https://doi.org/1

Early and persistent supershear rupture 2018 magnitude 7.5 Palu earthquake

Han Bao[1], Jean-Paul Ampuero[2,3*], Lingsen Meng[1], Eric J. Fielding[4], Cunren Lia
Christopher W. D. Milliner[4], Tian Feng[1] and Hui Huang[1]

The speed at which an earthquake rupture propagates affects its energy balance and ground shakin els of supershear earthquakes, which are faster than the speed of shear waves, often start at subs faster than Eshelby's speed. Here we present robust evidence of an early and persistent supershear ru speed of the 2018 magnitude 7.5 Palu, Indonesia, earthquake. Slowness-enhanced back-projection of t a sharp image of the rupture process, along a path consistent with the surface rupture trace inferre of synthetic-aperture radar and satellite optical images. The rupture propagated at a sustained velc initiation to its end, despite large fault bends. The persistent supershear speed is further validated by seismological evidence of far-field Rayleigh Mach waves. The unusual features of this earthquake probe the connections between the rupture dynamics and fault structure. An early supershear transition could be promoted by fault roughness near the hypocentre. Steady rupture propagation at a speed unexpected in homogeneous media could result from the presence of a low-velocity damaged fault zone.

nature geoscience

ARTICLES

https://doi.org/10.1038/s41561-018-0296-0

Evidence of supershear during the 2018 magnitude 7.5 Palu earthquake from space geodesy

Anne Socquet*, James Hollingsworth, Erwan Pathier and Michel Bouchon

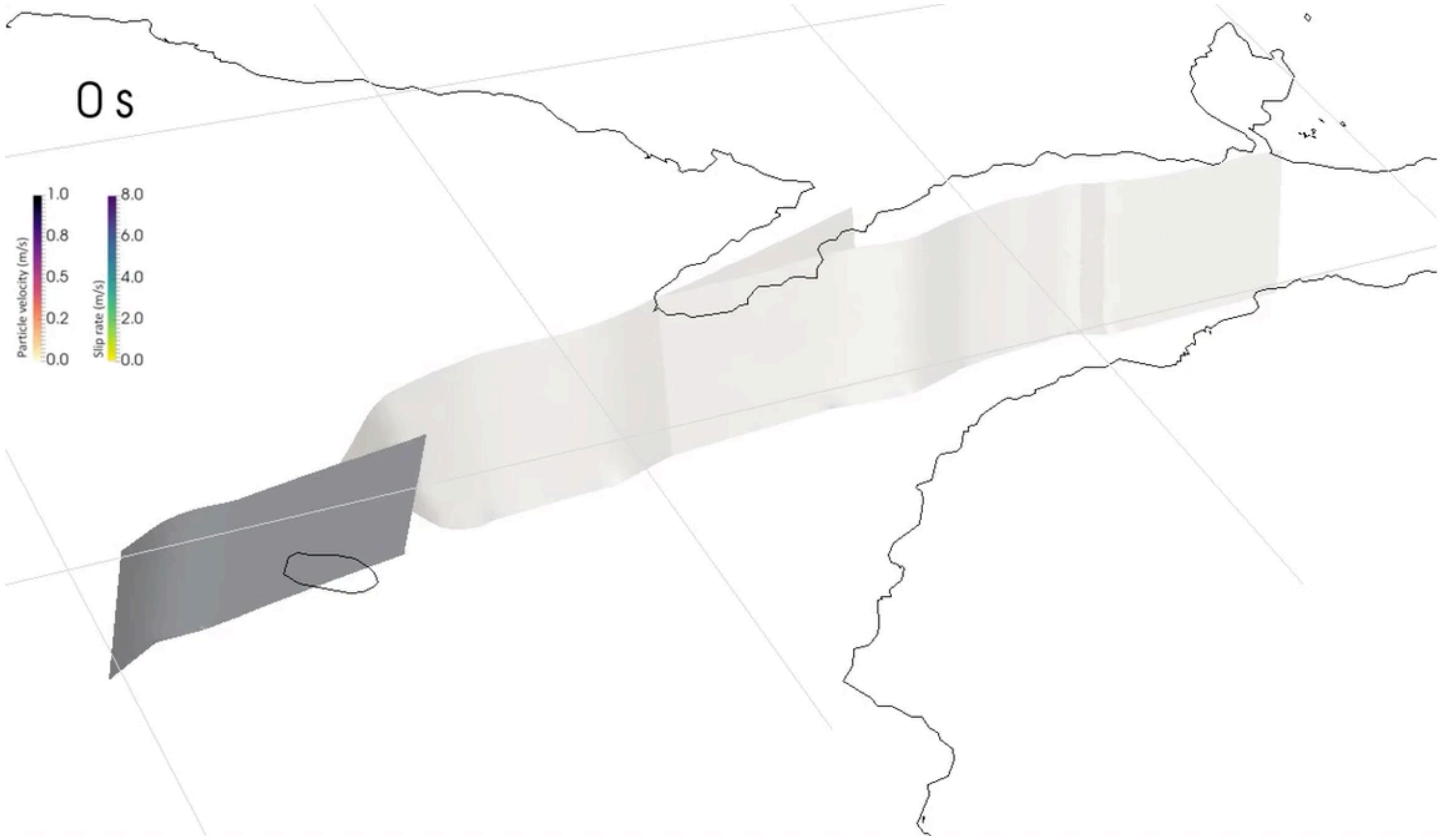
A magnitude 7.5 earthquake hit the city of Palu in Sulawesi, Indonesia on 28 September 2018 at 10:02:43 (coordinated universal time). It was followed a few minutes later by a 4–7-m-high tsunami. Palu is situated in a narrow pull-apart basin surrounded by high mountains of up to 2,000 m altitude. This morphology has been created by a releasing bend in the Palu-Koro fault, a rapidly moving left-lateral strike-slip fault. Here we present observations derived from optical and radar satellite imagery that constrain the ground surface displacements associated with the earthquake in great detail. Mapping of the main rupture and associated secondary structures shows that the slip initiated on a structurally complex and previously unknown fault to the north, extended southwards over 180 km and passed through two major releasing bends. The 30 km section of the rupture south of Palu city is extremely linear, and slightly offset from the mapped geological fault at the surface. This part of the rupture accommodates a large and smooth surface slip of 4–7 m, with no shallow slip deficit. Almost no aftershock seismicity was recorded from this section of the fault. As these characteristics are similar to those from known supershear segments, we conclude that the Palu earthquake probably ruptured this segment at supershear velocities.

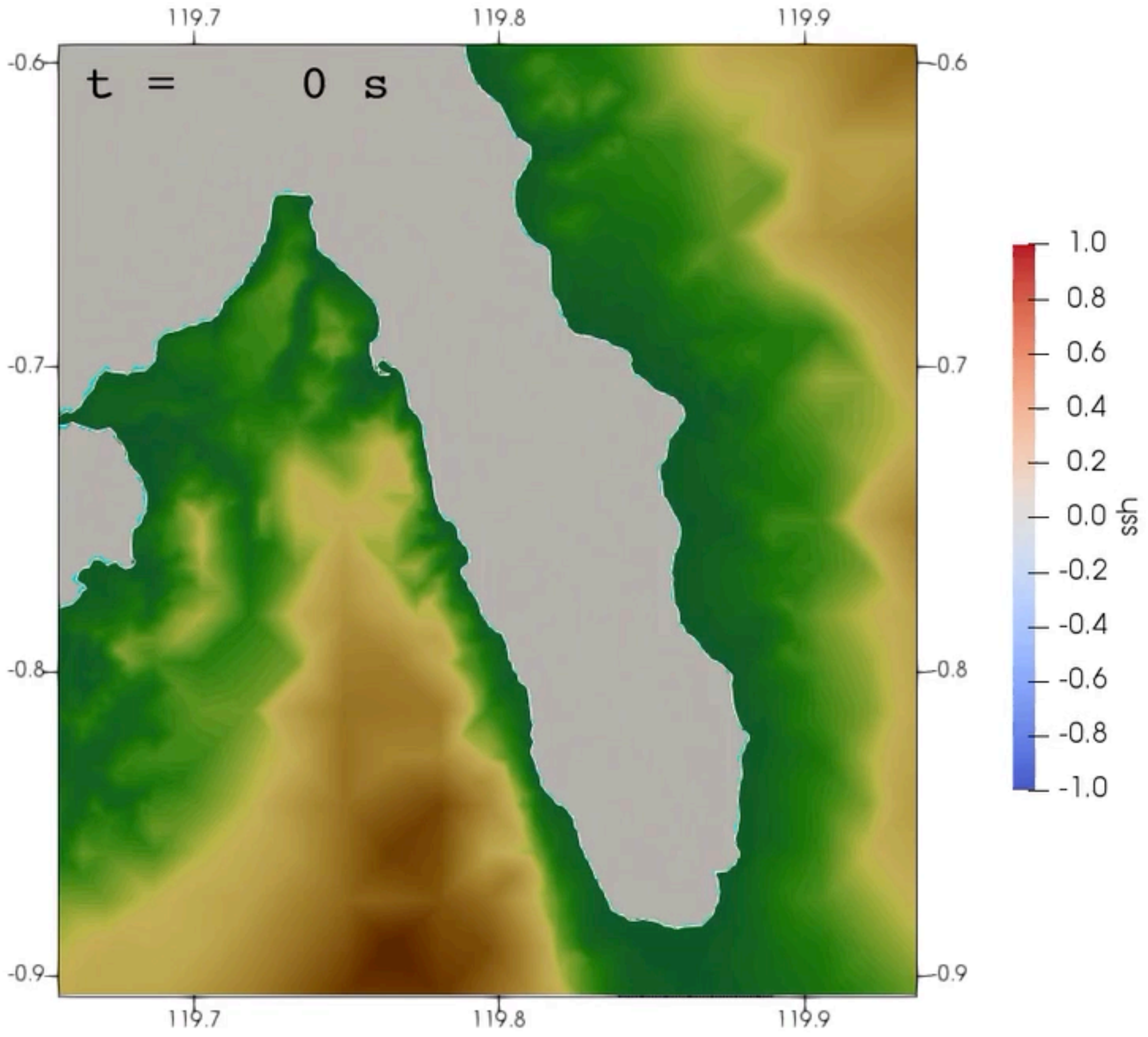
Rapid earthquake/tsunami response - The 2018, Palu-Sulawesi Event

Ulrich, Vater, Madden, Behrens, van Dinther, van Zelst, Fielding, Liang, Gabriel, PAGEOPH 2019

3D dynamic rupture setup from **sparse data: co-seismic (strike-slip) displacement**

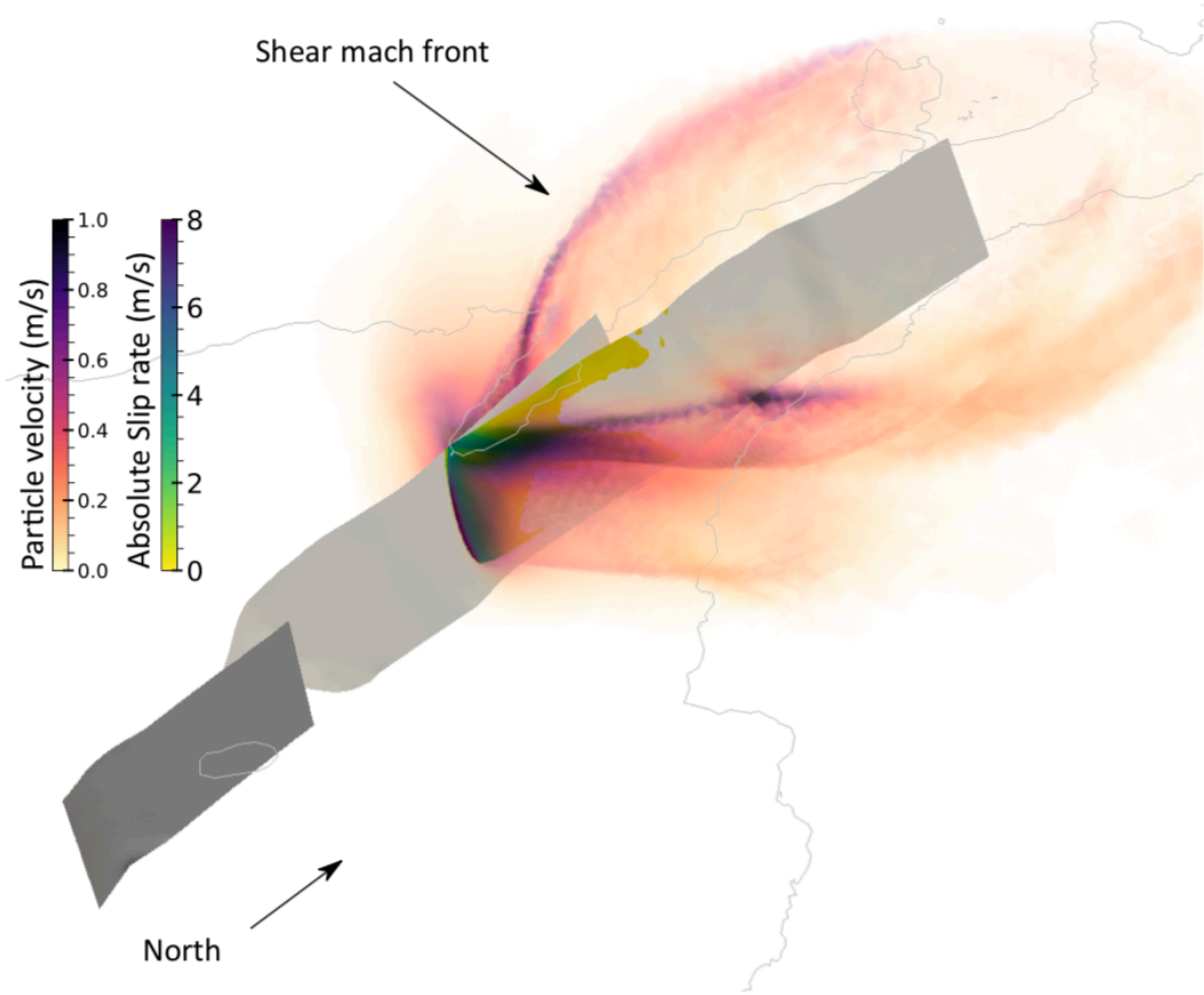
- **Fault system** from Sentinel-2, SAR data, regional seismicity; **Stress and strength** based on World stress map; and assuming a **transtensional** regime; high fluid pressure, mechanic viability across the fault system's geometric complexities, dynamics constrained by teleseismics and moment rate release
- **Earthquake-induced movement of seafloor beneath Palu Bay itself played a critical role generating the tsunami**



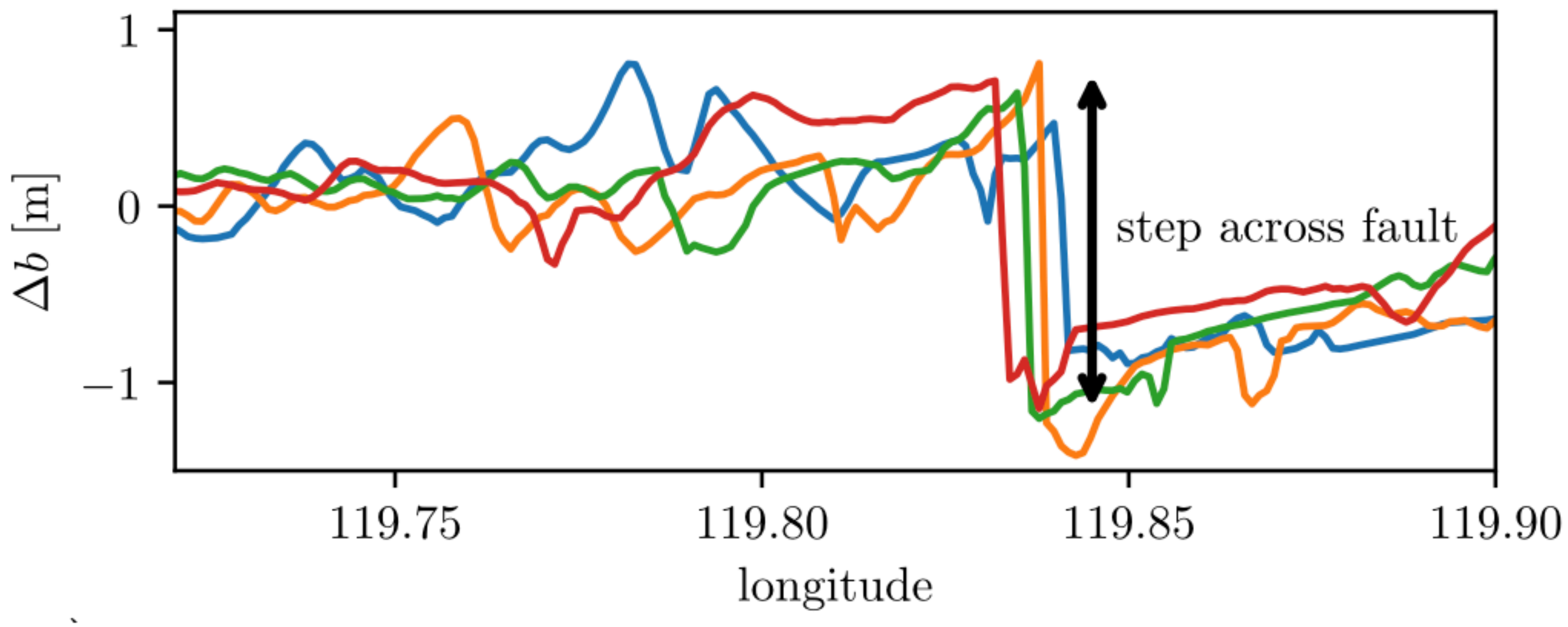


Rapid earthquake/tsunami response - The 2018, Palu-Sulawesi Event

Ulrich, Vater, Madden, Behrens, van Dinther, van Zelst, Fielding, Liang, Gabriel, PAGEOPH 2019



Step of ~1.5m across fault due to normal faulting component and horizontal movements beneath bathtub-like bathymetry



Fully coupled acoustic-elastic earthquake / tsunami modeling

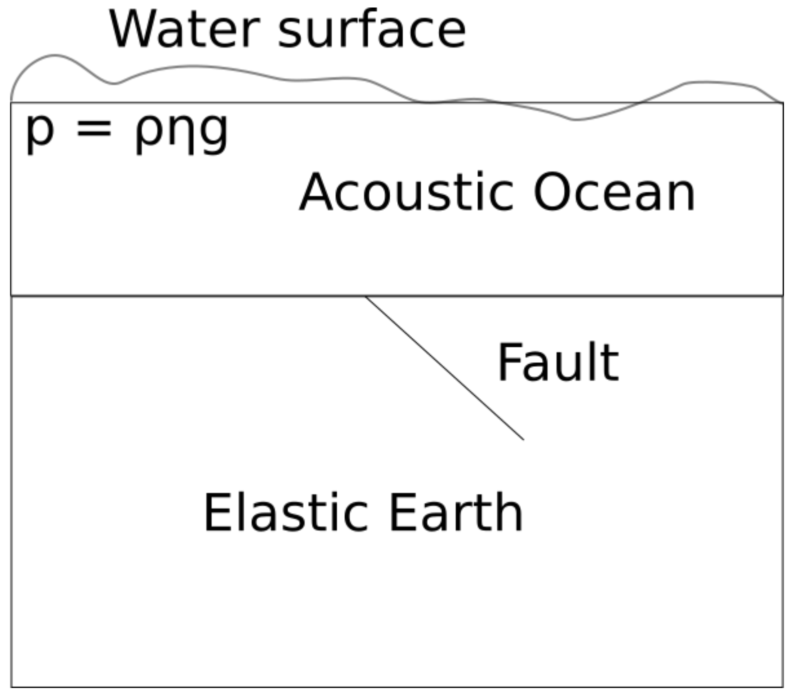
Lotto & Dunham, 2015; Lotto et al., 2017;
Krenz et al. & Abrahams et al. AGU'19

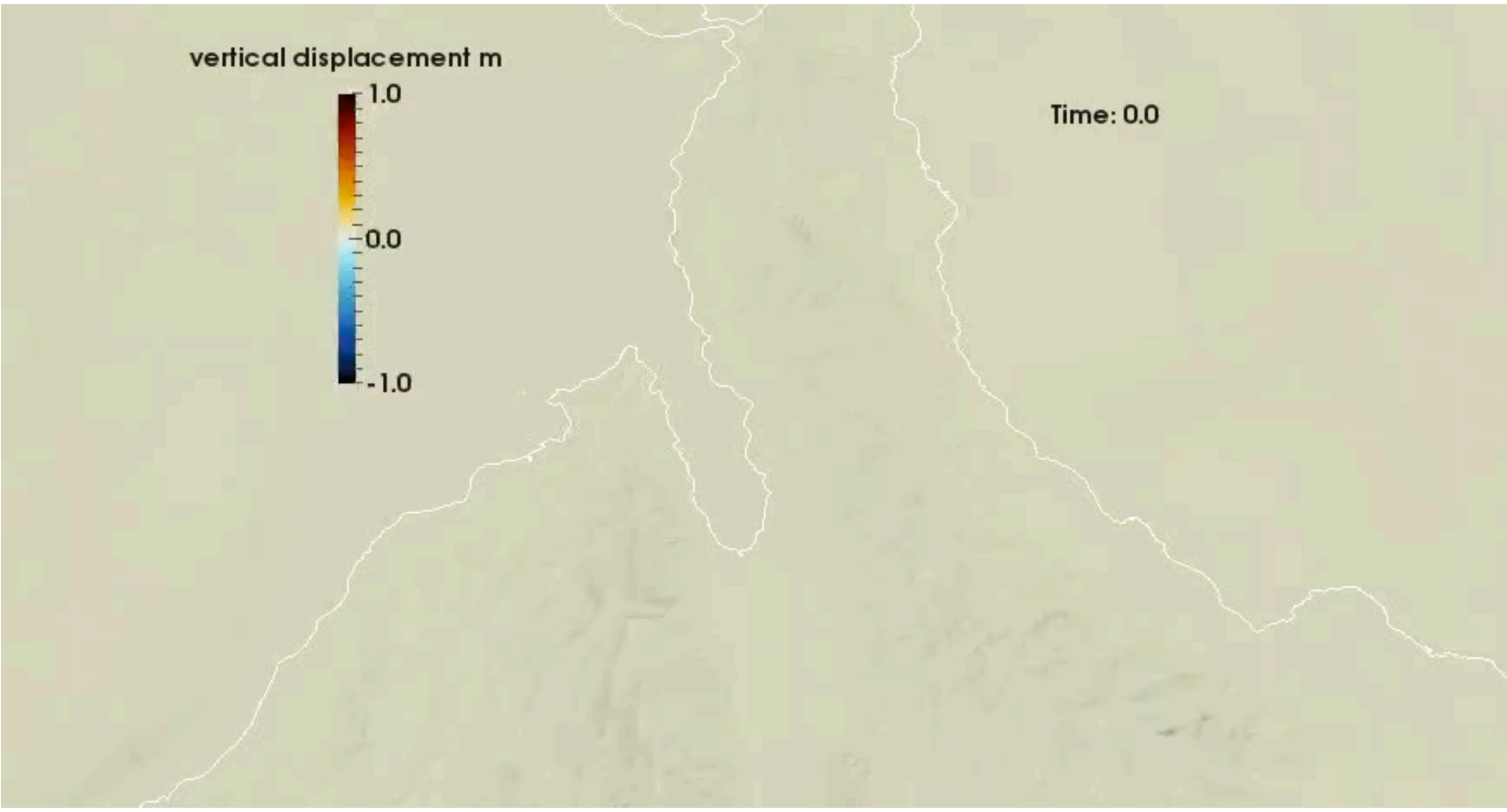
- **3D implementation of free surface tracking (gravitational effects)** by linearised free surface boundary condition (Lotto & Dunham, 2015)

- Accuracy of implementation investigated in convergence analysis of Scholte wave / Snell's Law (Abrahams et al., AGU 2019)

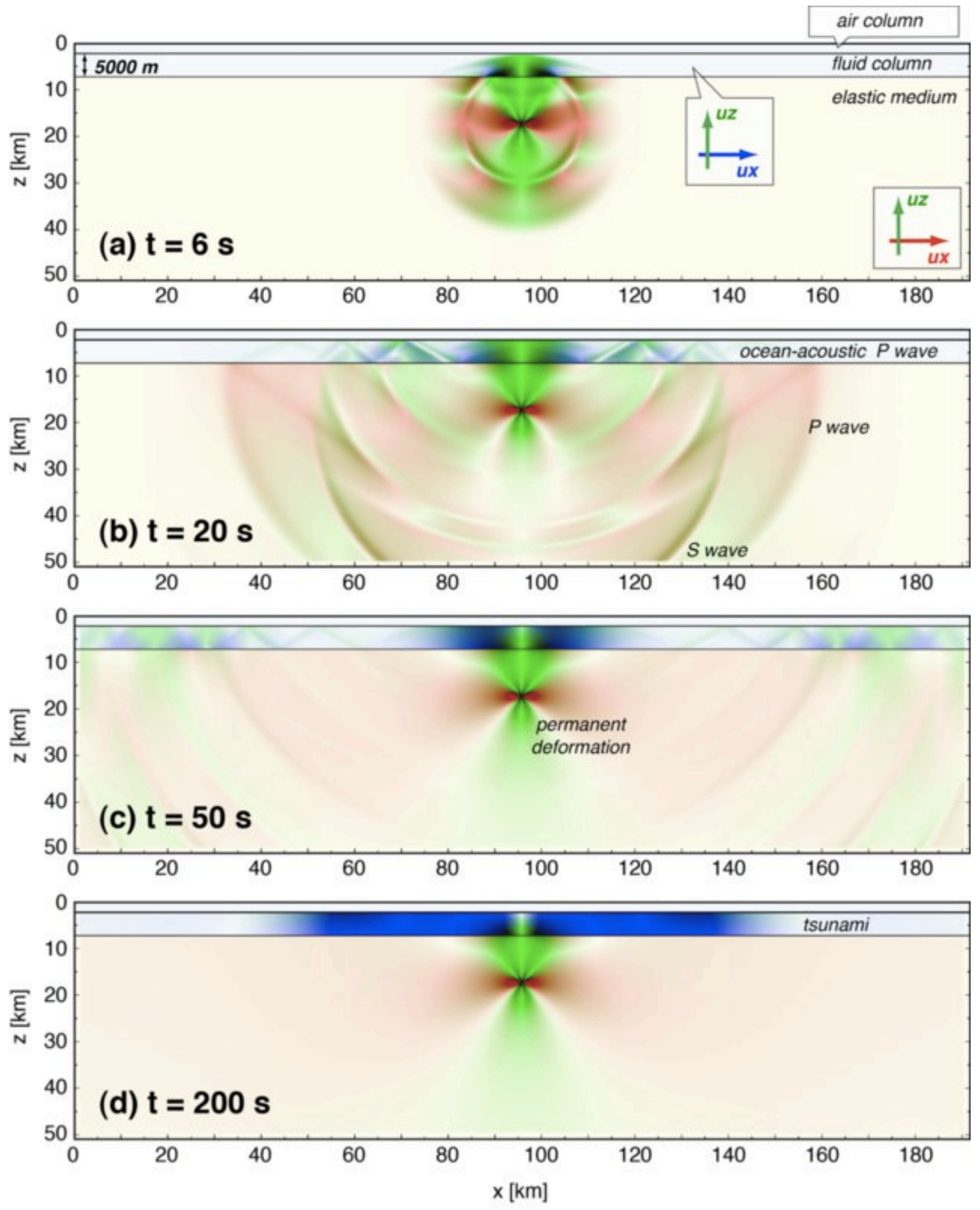
- **Local time stepping** is crucial to resolve the different wave speeds of acoustic and elastic media with both sufficient accuracy in an efficient manner.

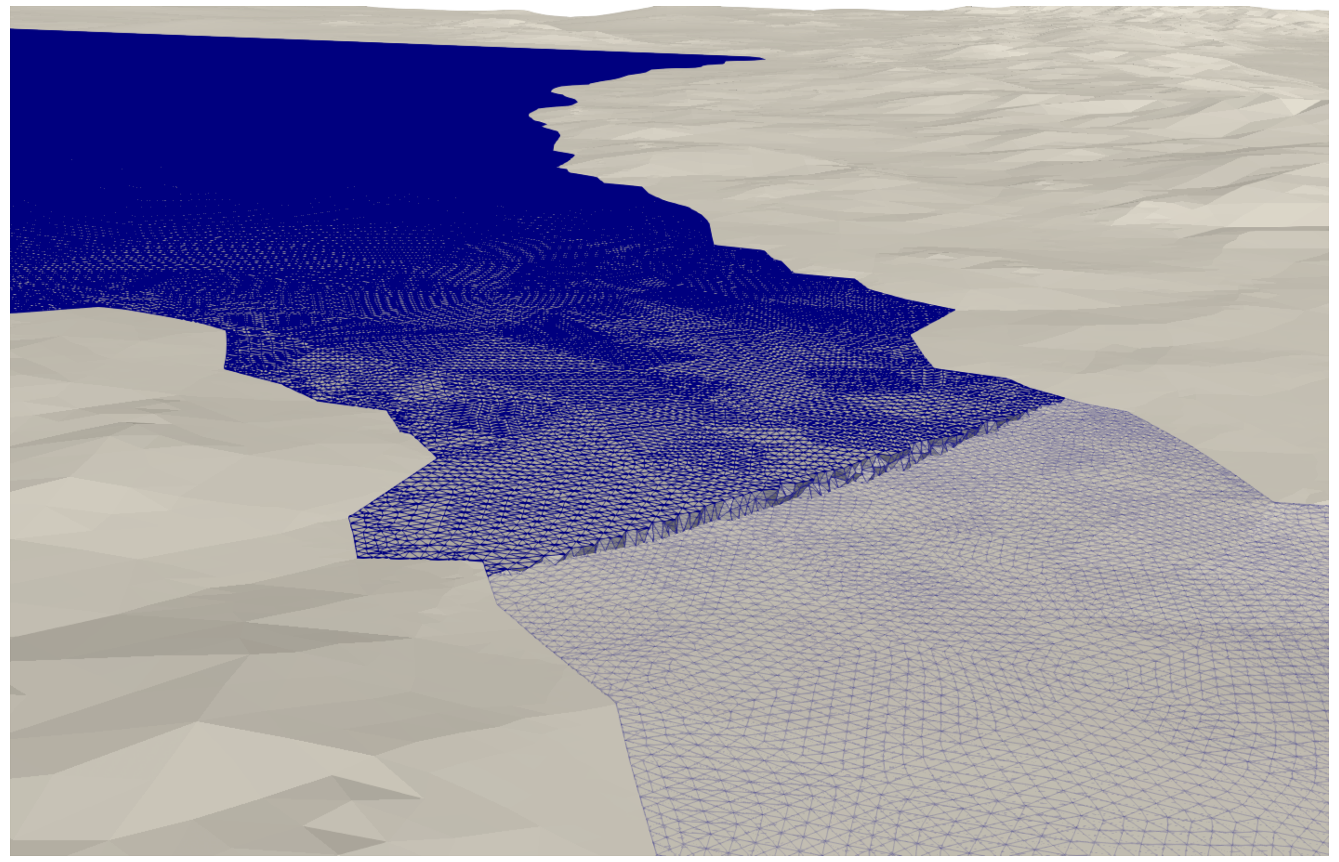
- Application to subduction Earthquake-Tsunami scenarios will require several hundred billion degrees of freedom and will need to exploit the entire computing power of the upcoming exascale supercomputers





Maeda & Furumara, 2013





Your SeisSol team for the next days

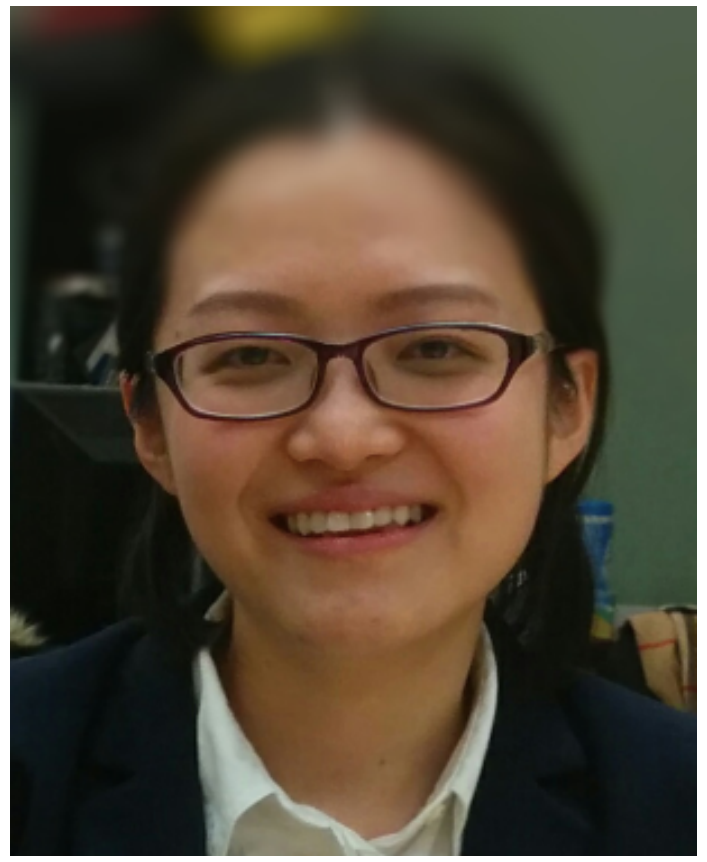
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

www.geophysik.uni-muenchen.de/Members/gabriel

Carsten Uphoff

Bo Li

Thomas Ulrich



Duo Li

Taufiqurrahman

Aniko Wirp

.. and members of the TUM team!

ChEESE

www.cheese-coe.eu