siam 2021 | Conference on Mathematical & Computational Issues in the Geosciences

POLITECNICO MILANO 1863

MT2 - High-Performance Computing for Computational Seismology and Earthquake Physics

In cooperation with SIMAI SOCIETÀ ITALIANA DI MATEMATICA APPLICATA E INDUSTRIALE, InterPore

PATROCINIO Comune di Milano

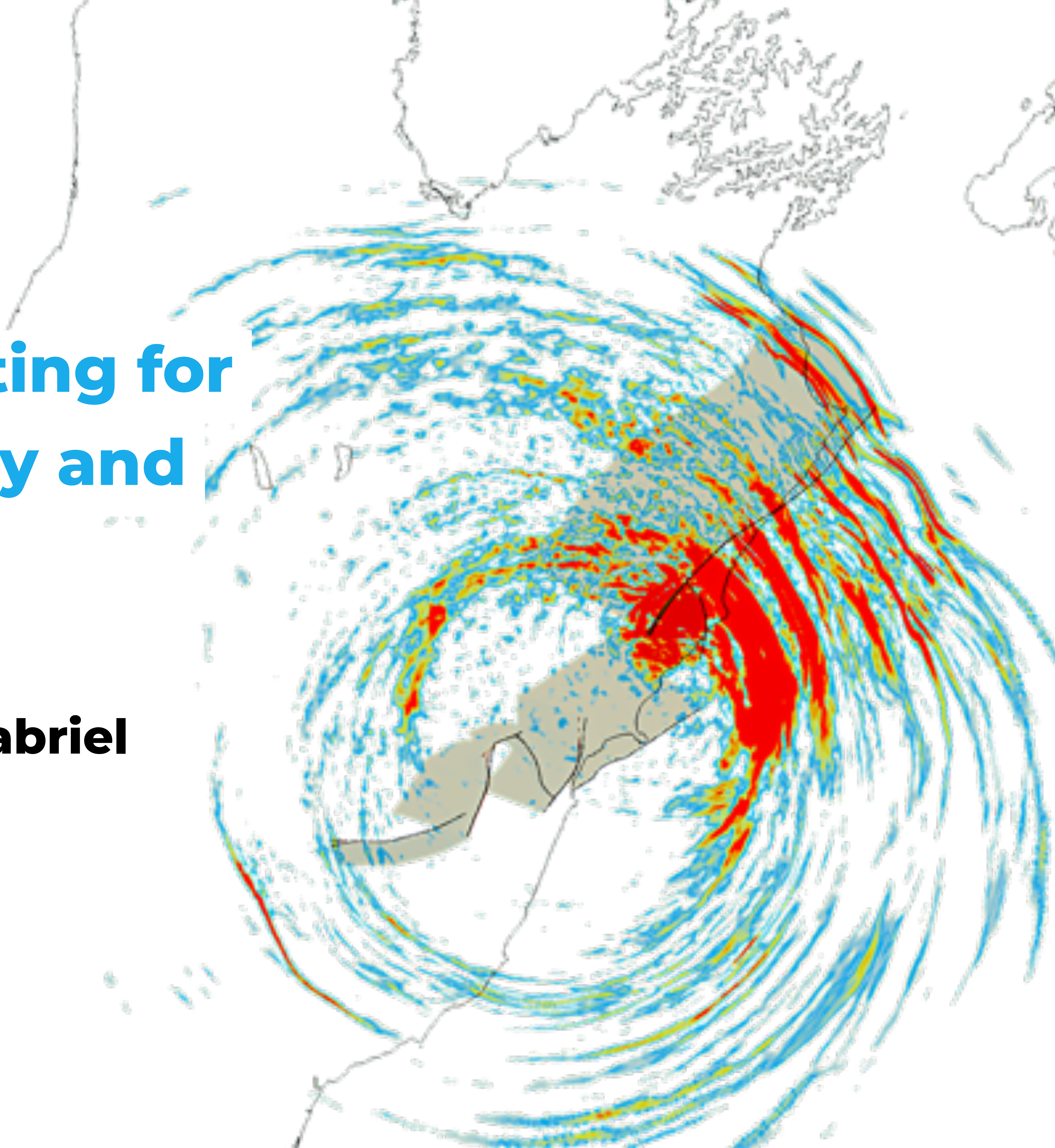
CONFERENCE SPONSORS

ENGINSOFT

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

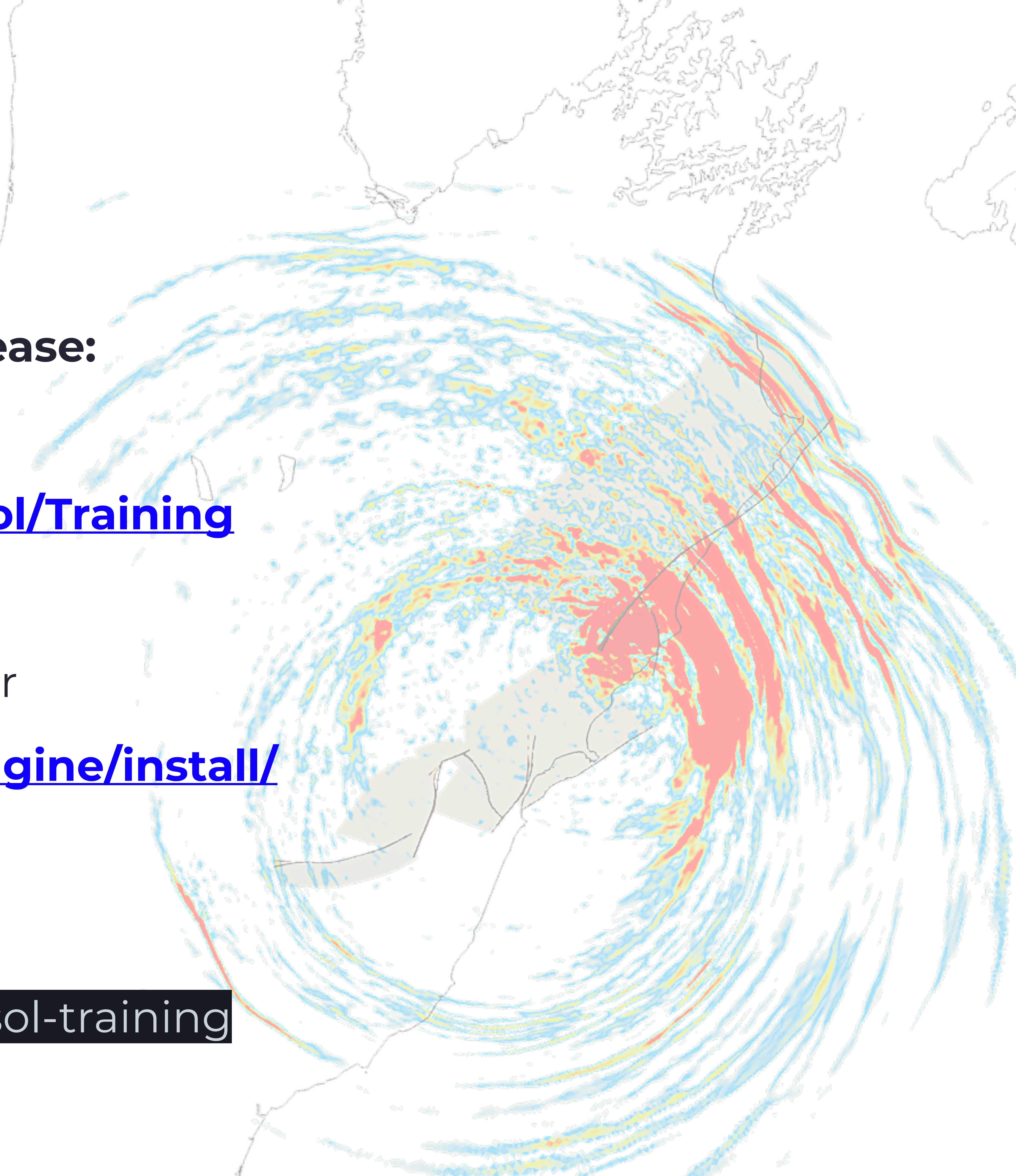
ifp Energies nouvelles

High-Performance Computing for Computational Seismology and Earthquake Physics



Carsten Uphoff & Alice-Agnes Gabriel

uphoff@geophysik.uni-muenchen.de
gabriel@geophysik.uni-muenchen.de
bit.ly/AAG8LMU
twitter @InSeismoland



Before we start, please:

—> visit

https://github.com/SeisSol/Training

—> install Docker

https://docs.docker.com/engine/install/

—> run

```
$ docker pull uphoffc/seissol-training
```

Acknowledgements

TECHNISCHE UNIVERSITÄT MÜNCHEN

Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

Michael Bader

Leonhard Rannabauer

Sebastian Wolf

Lukas Krenz

Ravil Dorozhinksii

SuperMUC-NG

www.tear-erc.eu

European Research Council

Established by the European Commission

King Abdullah University of Science and Technology

Carsten Uphoff

Duo Li

Taufiqurrahman

Nicolas Hayek

Thomas Ulrich

Bo Li

Aniko Wirp

Casper Pranger

ChEESE

www.cheese-coe.eu

siam 2021

Computational seismology

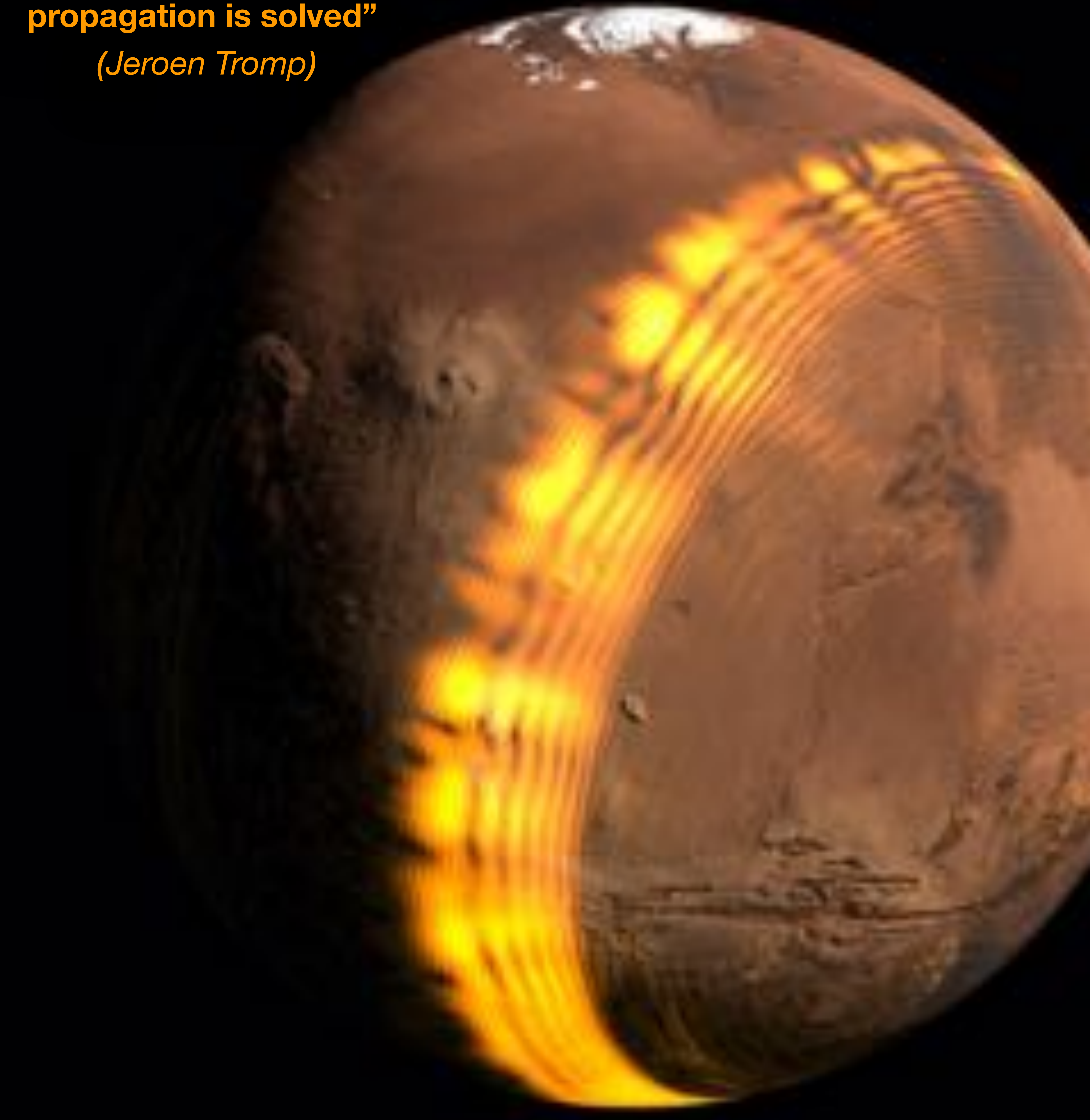
- A pioneering field for **HPC** to image Earth's interior, understand the dynamics of the mantle, track down energy resources
- Seismology is **data-rich** and can often be treated as a **linear** (hyperbolic PDE) system
- **Key activities:** Calculation of synthetic seismograms in 3D Earth and solving seismic inverse problems

Wave simulations of the 2009 L'Aquila earthquake using a DG method on unstructured tetrahedral meshes, Wenk et al., 2009

Computational seismology

- A pioneering field for **HPC** to image Earth's interior, understand the dynamics of the mantle, track down energy resources
- Seismology is **data-rich** and can often be treated as a **linear** (hyperbolic PDE) 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 Earth structure, computational efficiency, complex geological subsurface
- **Need** for open community solutions (cf. SpecFEM)

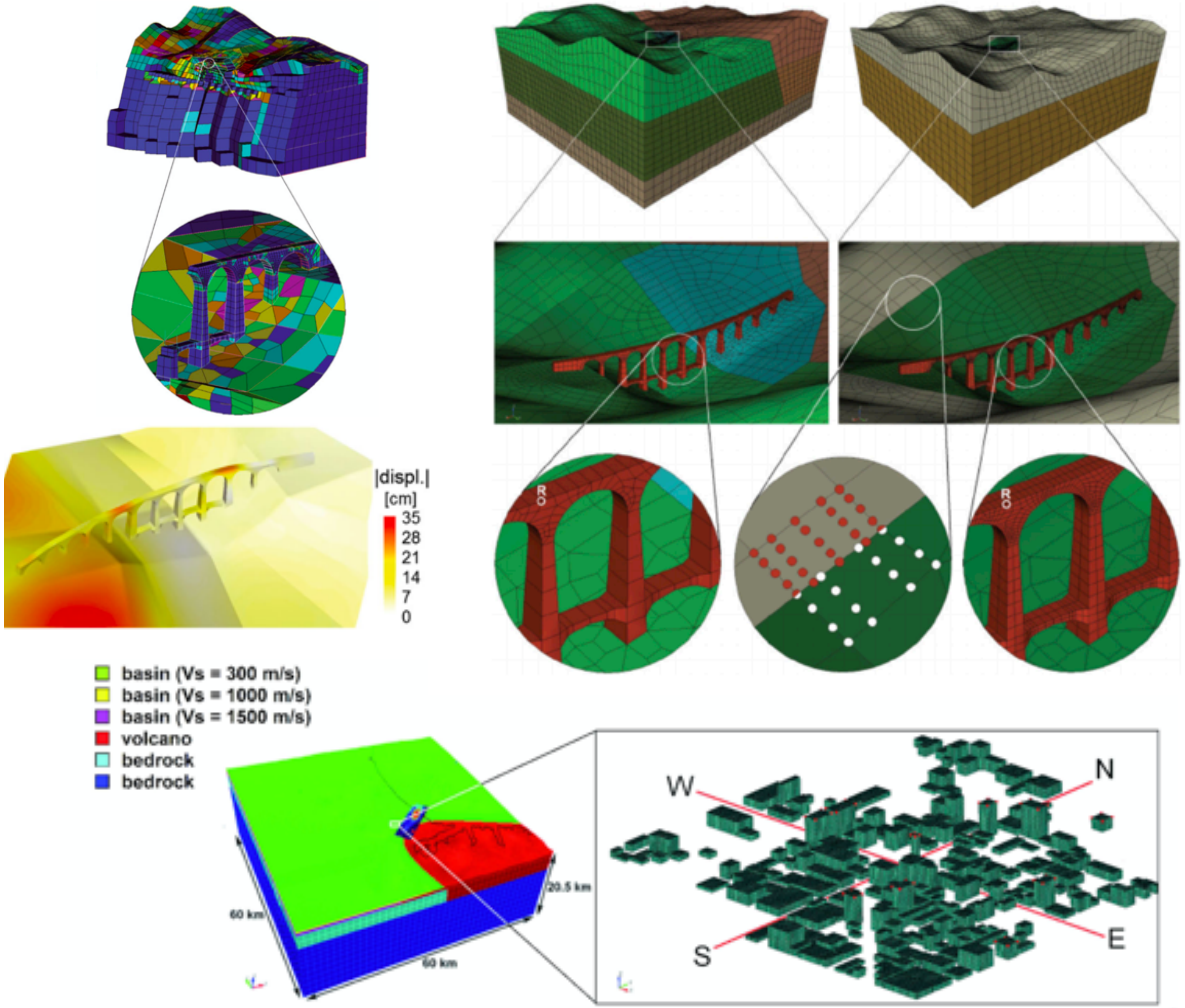
"The forward problem for seismic wave propagation is solved"
(Jeroen Tromp)



Forward simulations of seismic waves travelling through Mars on "Piz Daint" at CSCS solving 10 billion degrees of freedom and 300,000 time steps (Bozdag et al., 2017).

Computational seismology

- A pioneering field for **HPC** to image Earth's interior, understand the dynamics of the mantle, track down energy resources
- Seismology is **data-rich** and can often be treated as a **linear** (hyperbolic PDE) 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 Earth structure, computational efficiency, complex geological subsurface
- **Need** for open community solutions (cf. SpecFEM)
- Applications, e.g. from engineering, require **multi-scale and multi-physics** capabilities



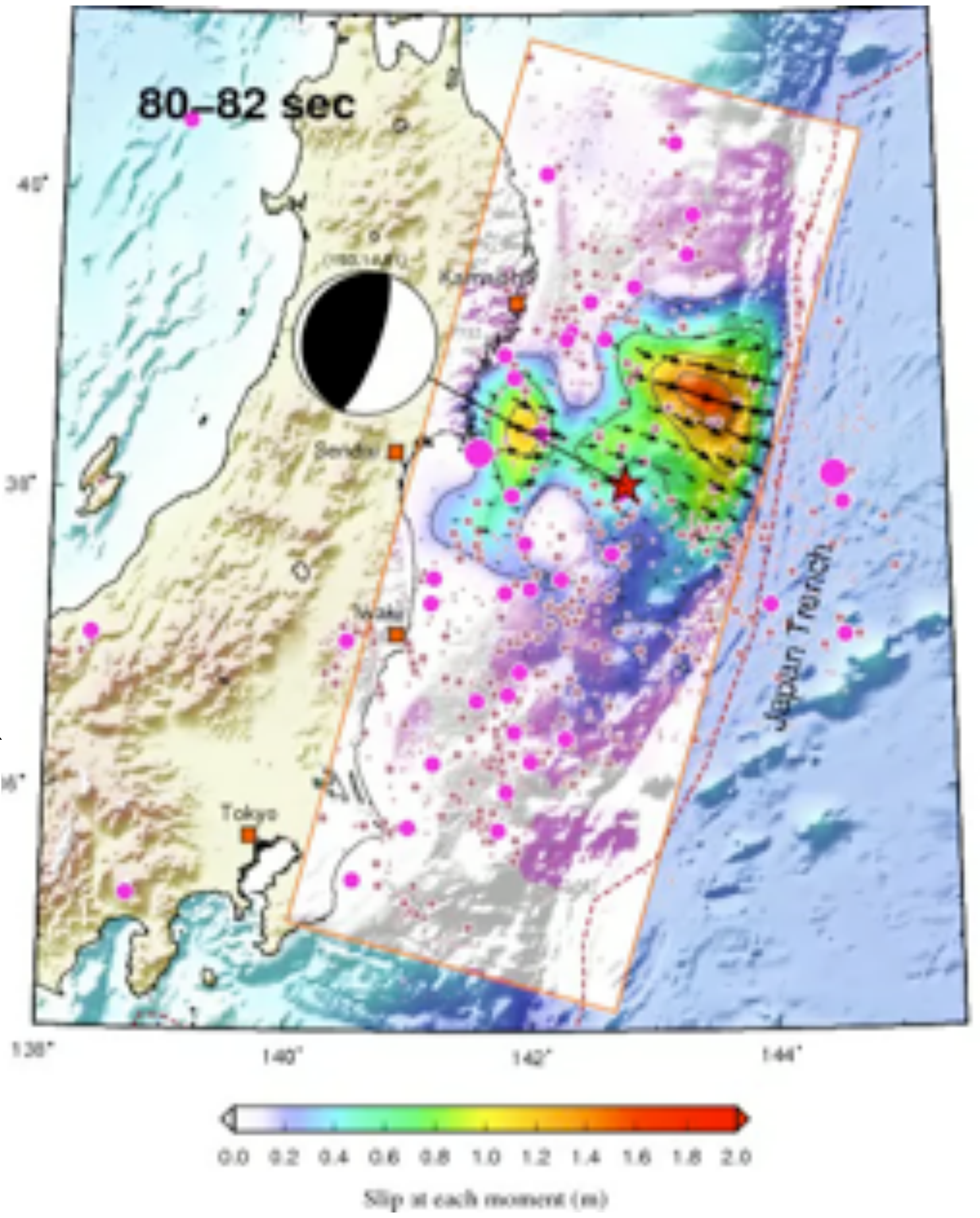
SPEED engineering seismology simulations of the seismic response of the Acquasanta bridge and the 2011 Canterbury, NZ earthquake strong ground motions and soil city interactions (Mazzieri et al., 2013).

Earthquake seismology

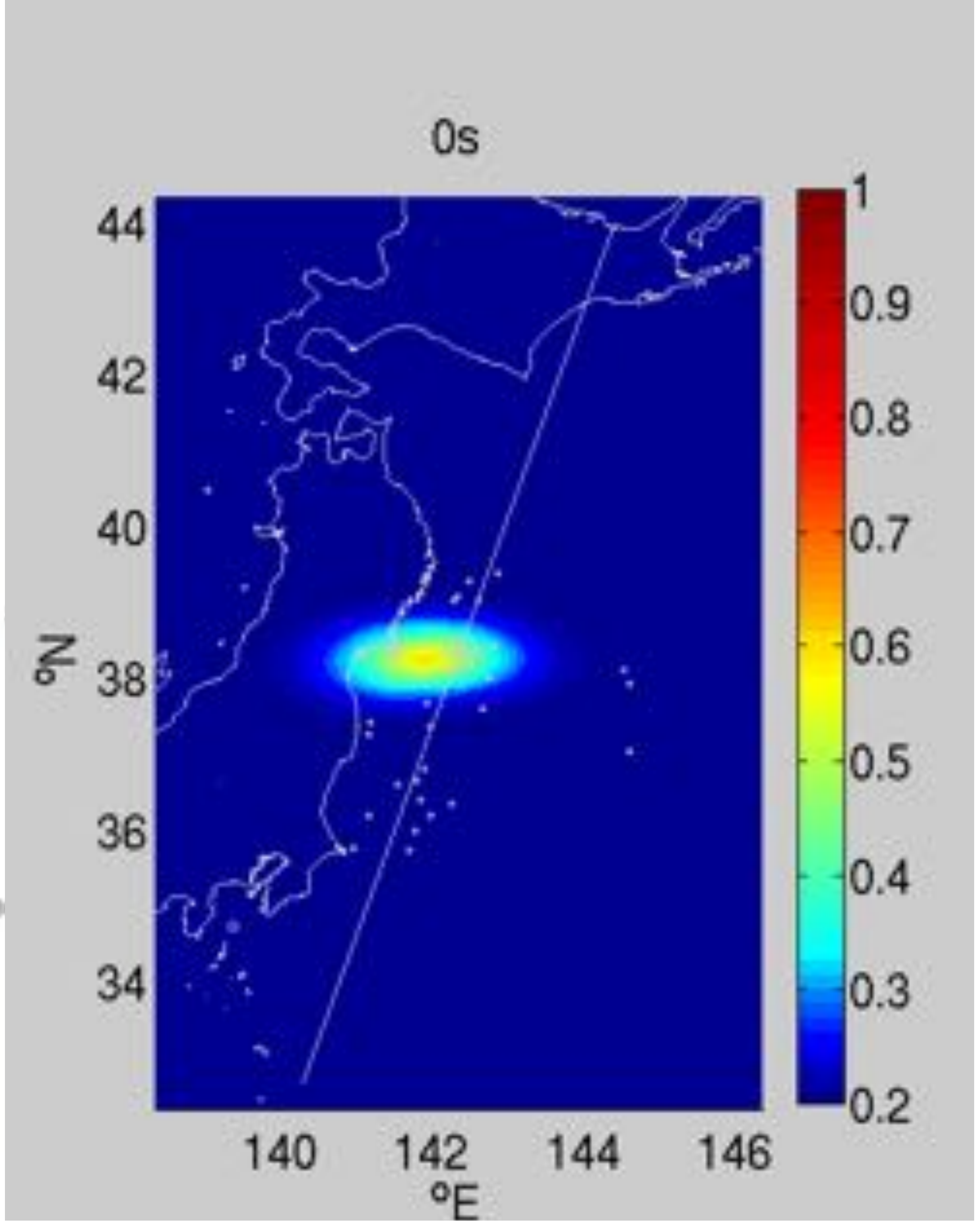
Recent well-recorded earthquakes and laboratory experiments reveal **striking variability**

- Slip reactivation
- Nucleation with/without slow-slip pre-cursors
- Variability of rupture style (pulses vs cracks)
- Rupture cascading and “jumping”
- Propagation along both locked and creeping fault sections during the same earthquake
- Super-shear propagation

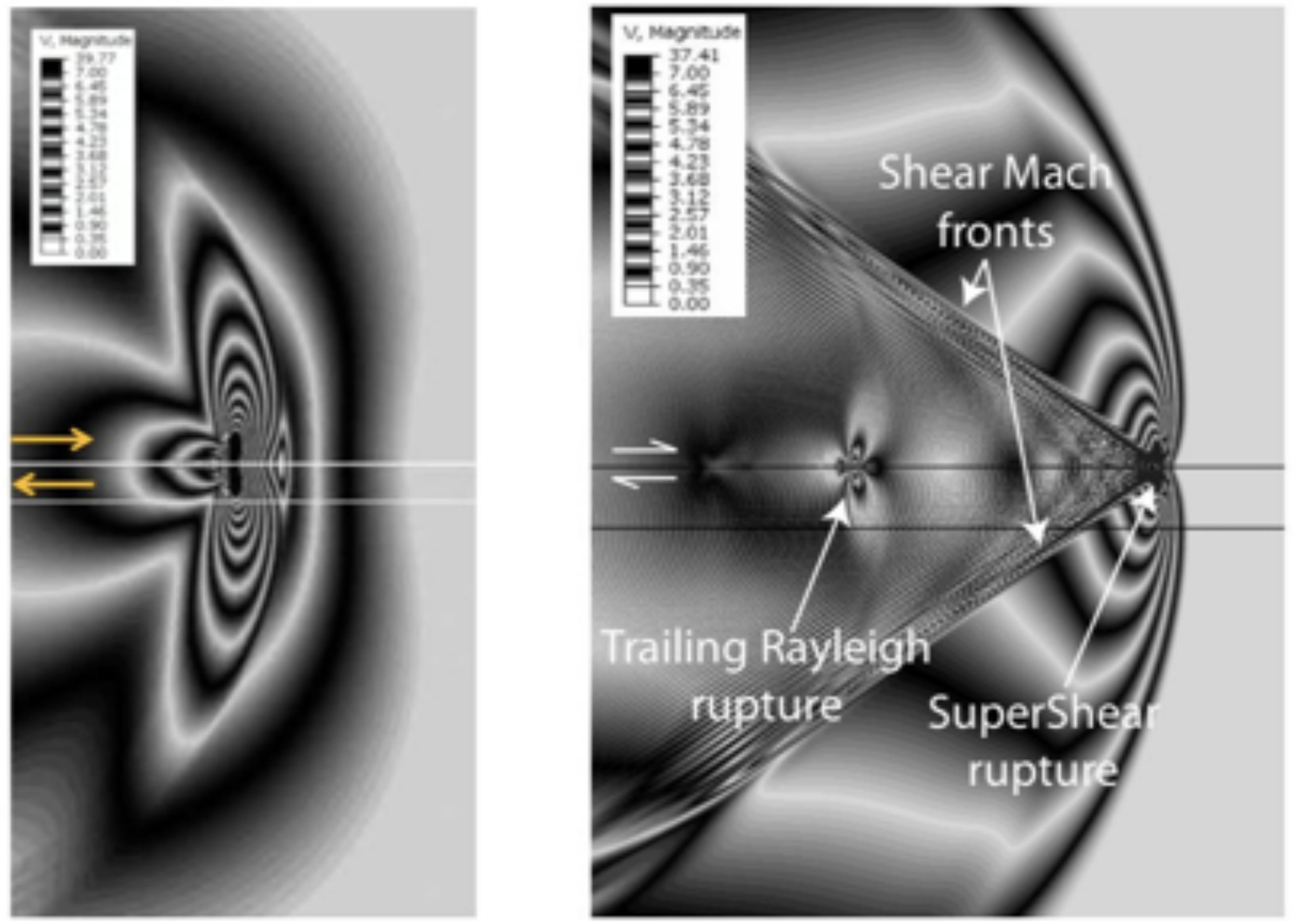
“The most useful thing seismologists could do – understand (predict) earthquakes - is what they are least able to”
(P. Shearer)



Source inversion model of Tohoku-Oki event (Japan) 2011, from combined local ground motion, teleseismics, GPS & multiple time window parametrization of slip rate. (Lee & Wang, 2011)



Back projection: Indicating major areas of high-frequency radiation on the fault (Meng et al., 2012)



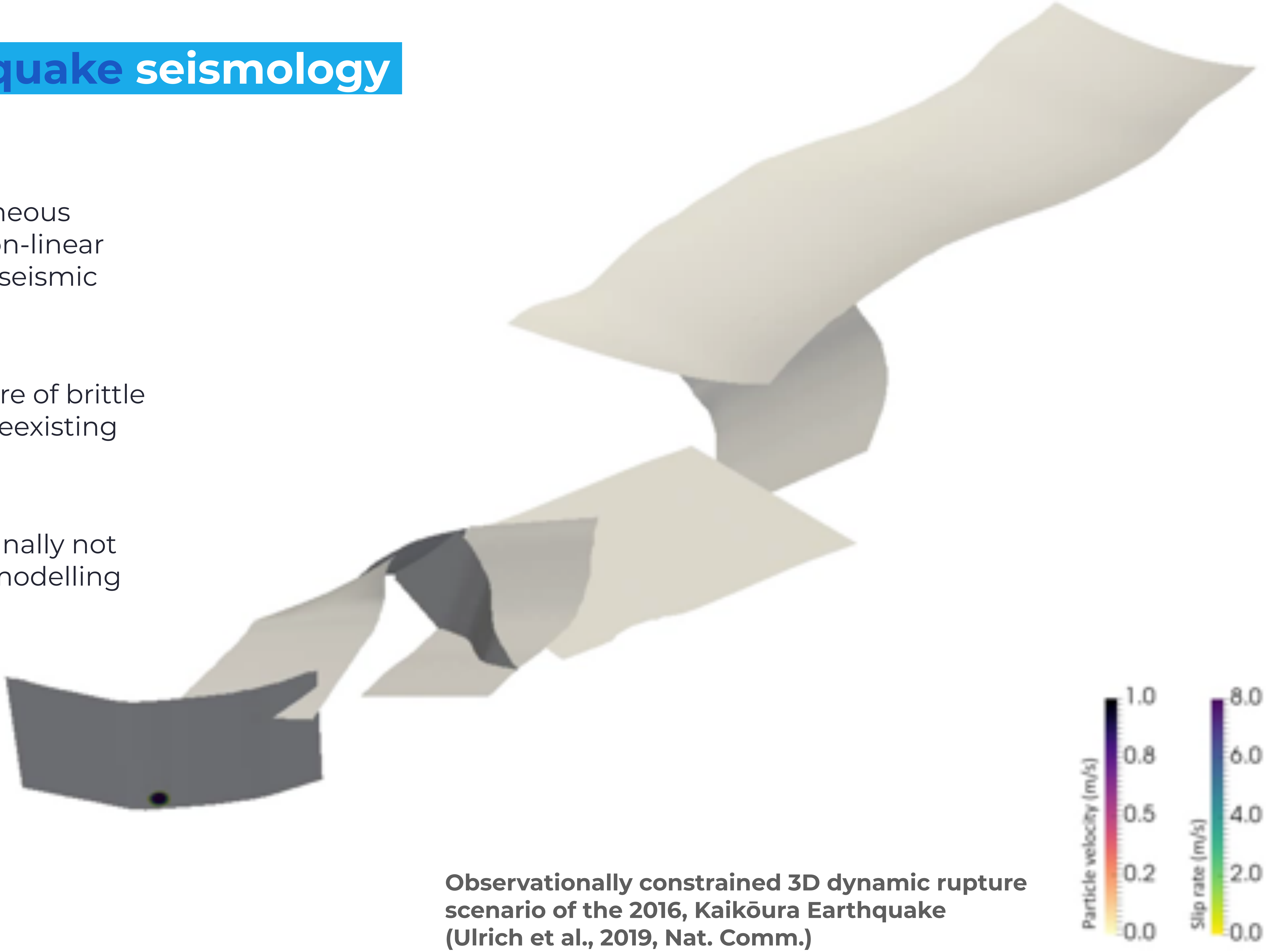
Sub-Rayleigh vs **supershear** rupture in the laboratory. Mach cone emanating from rupture tip (courtesy of L. Bruhat)

Computational earthquake seismology

- **Physics-based:** solving for spontaneous dynamic earthquake rupture as non-linear interaction of frictional failure and seismic wave propagation

- **Earthquakes:** frictional shear failure of brittle solids under compression along preexisting weak interfaces

- "**Bootstrapping**": on methods originally not developed for earthquake source modelling

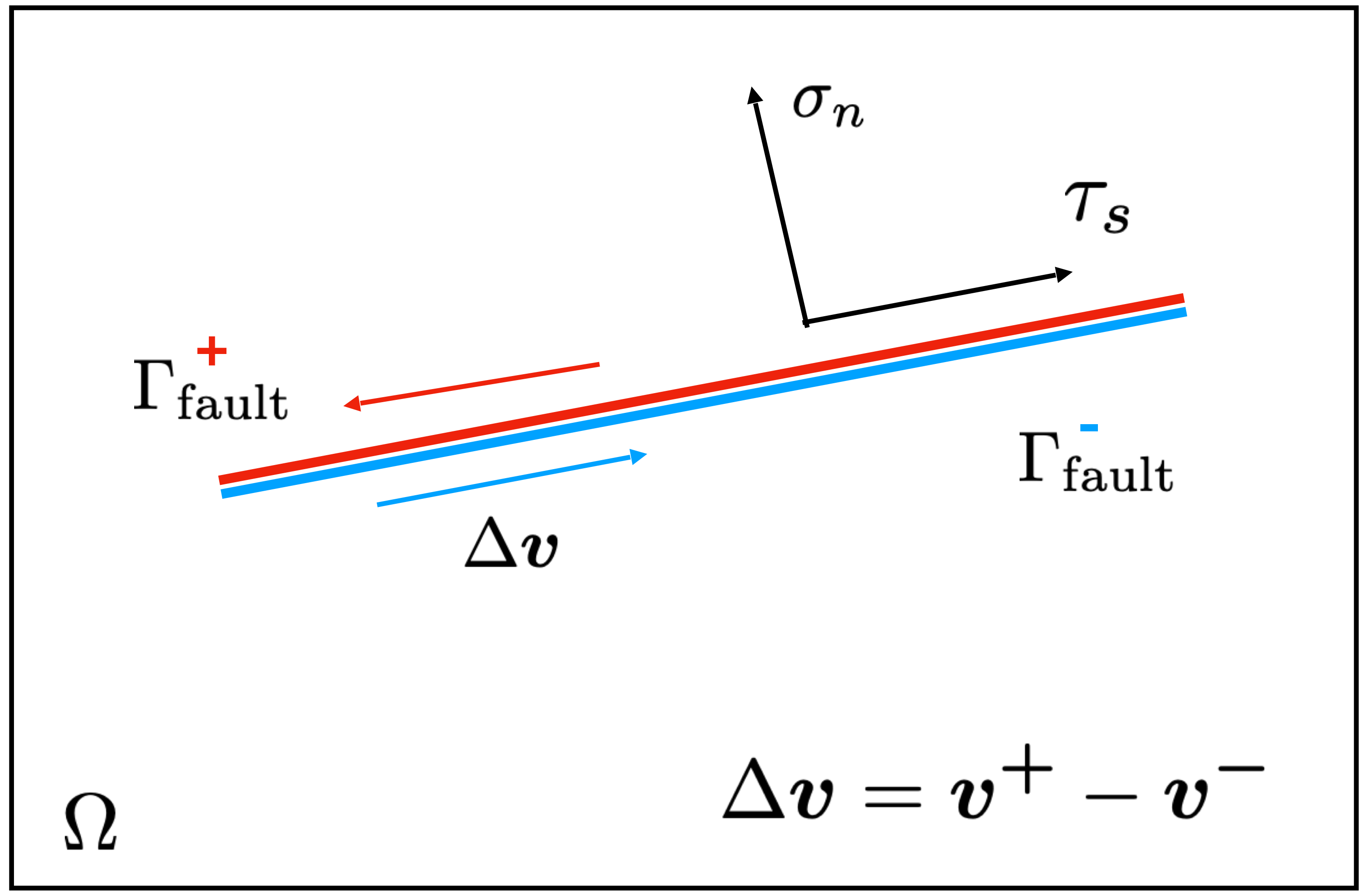


Observationally constrained 3D dynamic rupture scenario of the 2016, Kaikōura Earthquake (Ulrich et al., 2019, Nat. Comm.)

siam 2021

Computational earthquake seismology

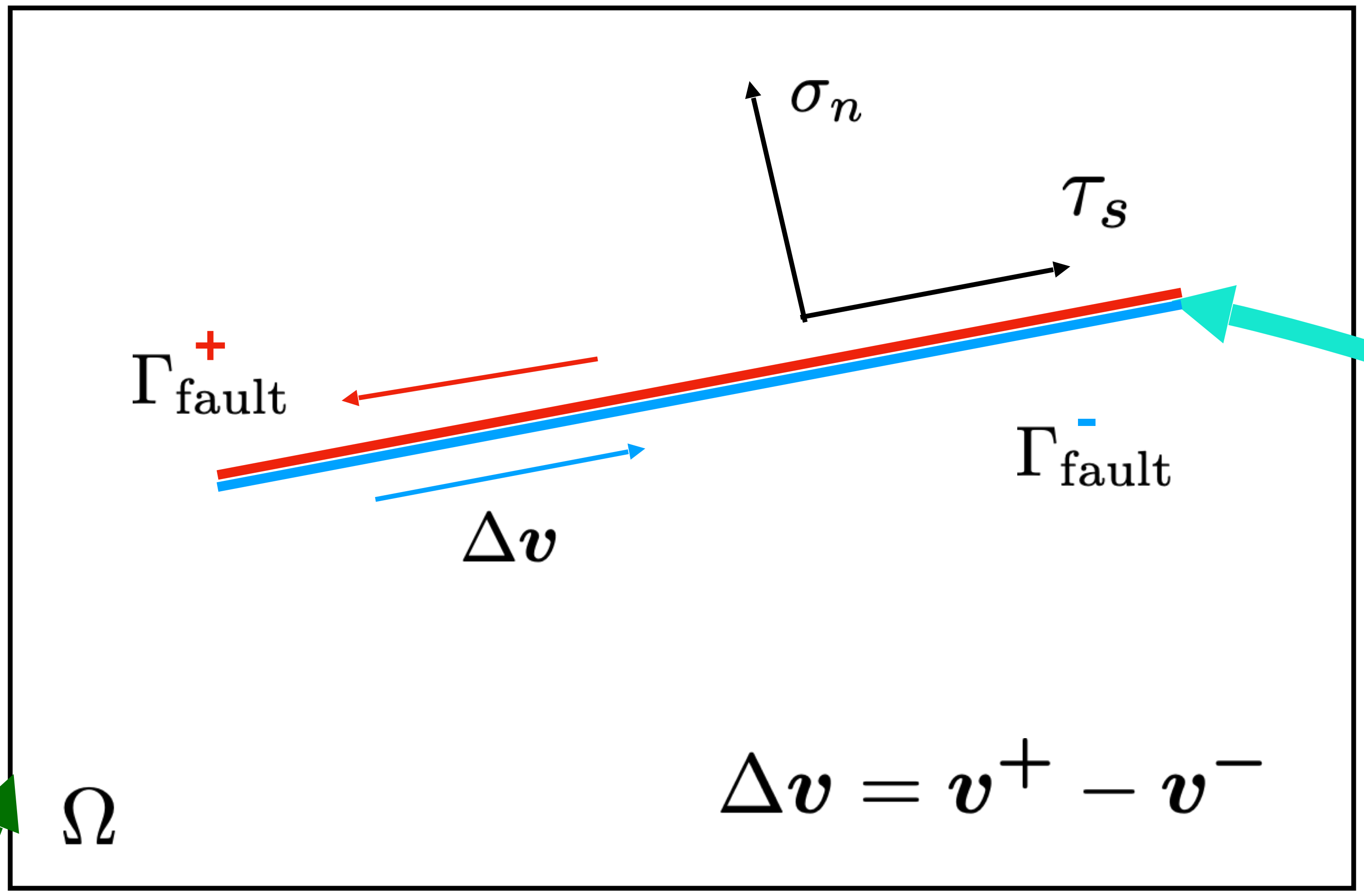
- Earthquake dynamic rupture is treated as a boundary condition in terms of **contact and friction**
- **Thin fault without 'opening'** - two matching fault surfaces are in unilateral contact
- **Displacement discontinuity** across the fault = **slip**
- Much complexity lives in the definition of **friction**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



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

Computational earthquake seismology

- 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)**



constitutive law (volume)

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

constitutive law (surfaces)

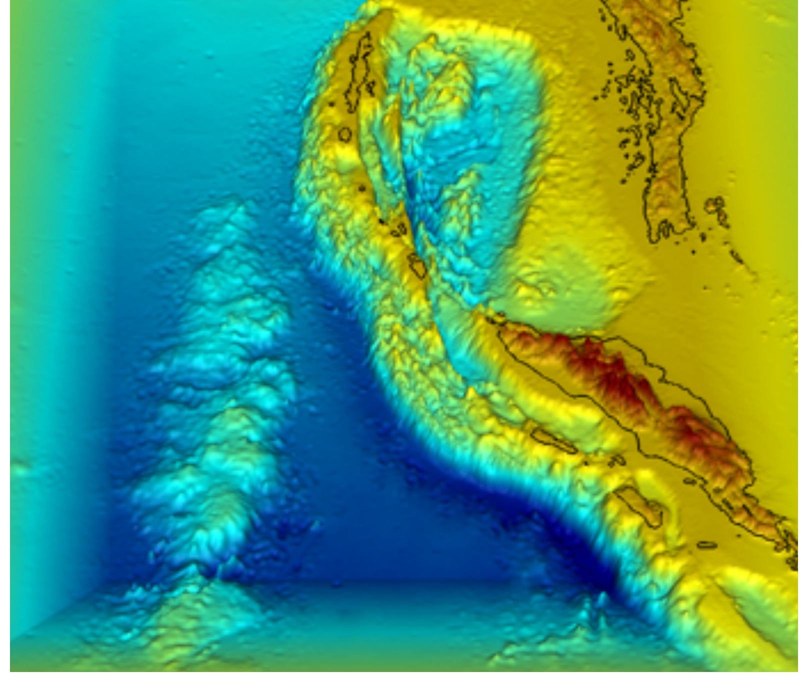
$$\tau_s = \mu_f \sigma_n.$$

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

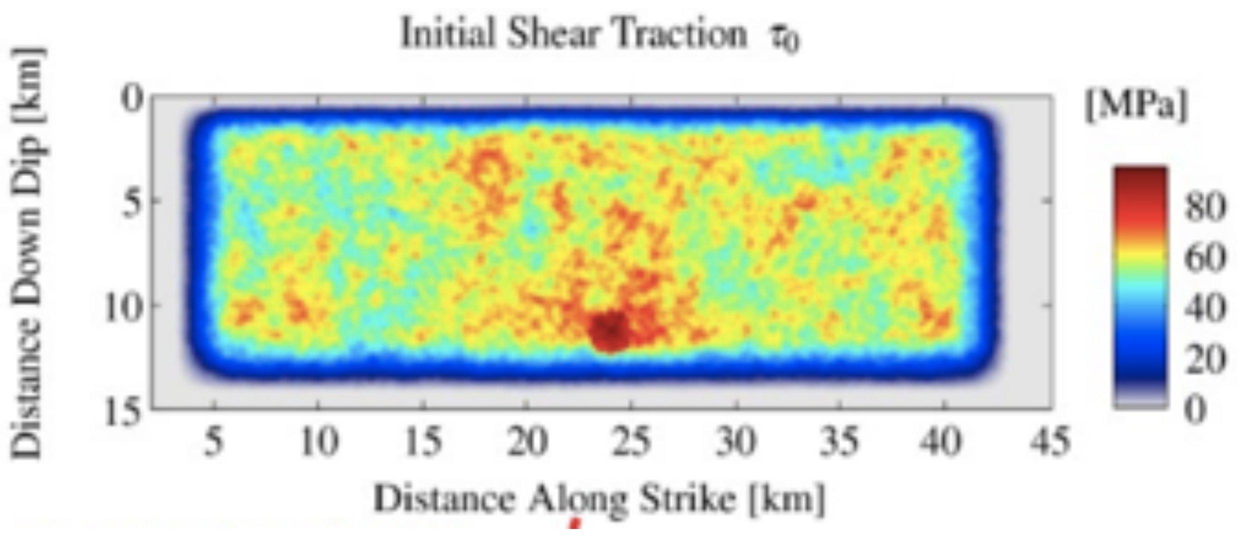
Adapted from Harris et al., SRL 2011, 2018

Computational earthquake seismology

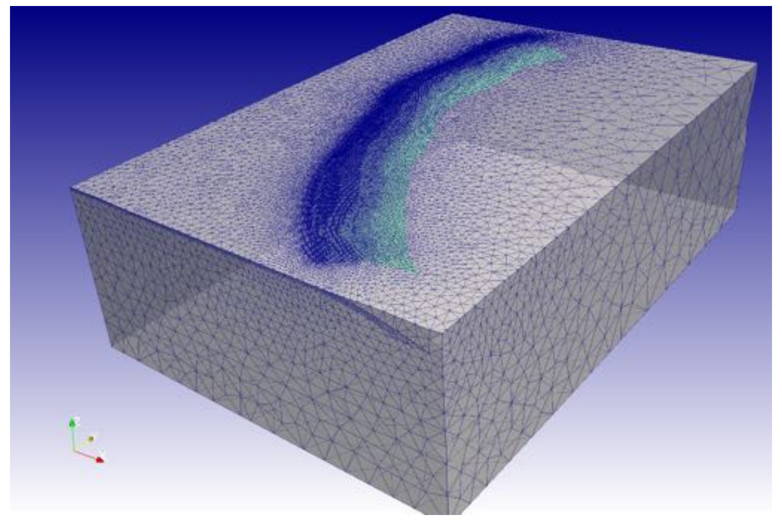
- **Integration** and **interpretation** of full range of observations
- **Tightly links** seismology, geodesy, geology, tectonophysics, hydrology with numerical computing, data science, machine learning, applied mathematics, continuum mechanics, tribology, rock mechanics, materials science, and engineering



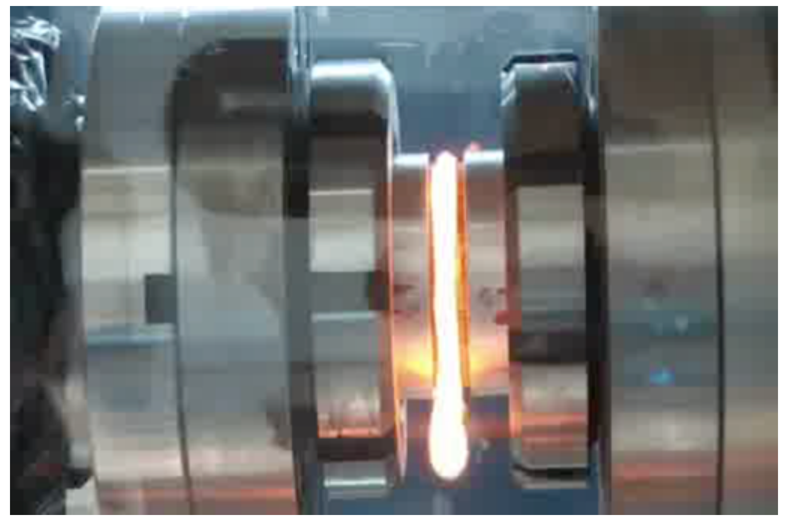
Geology



Initial fault stresses



Mesh generation



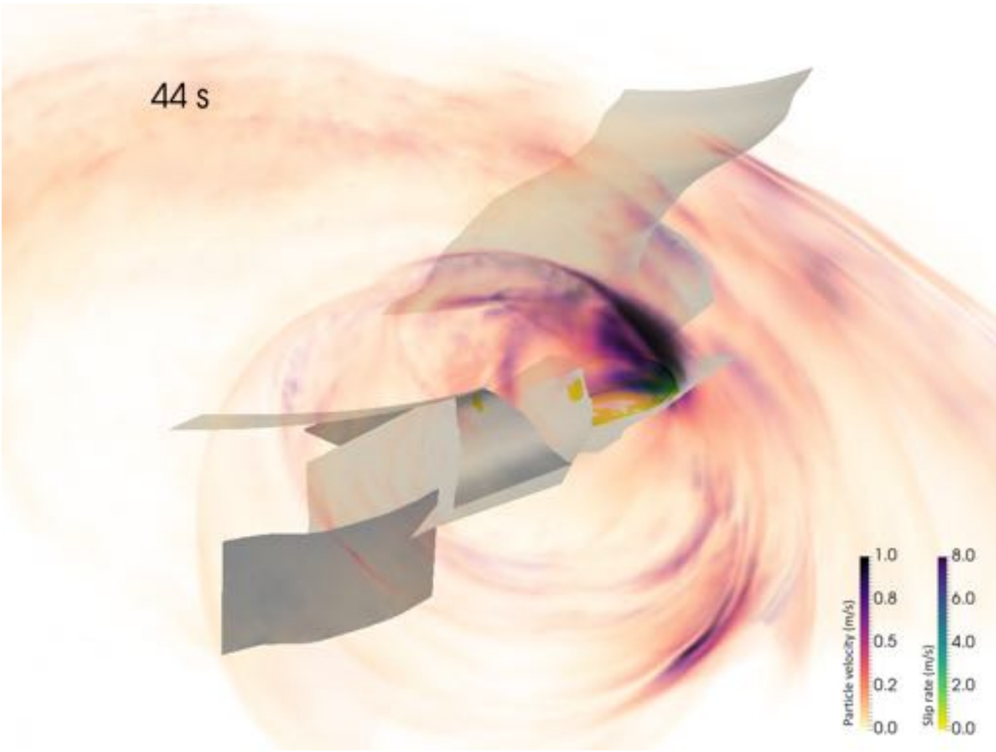
Friction experiments

"Input"

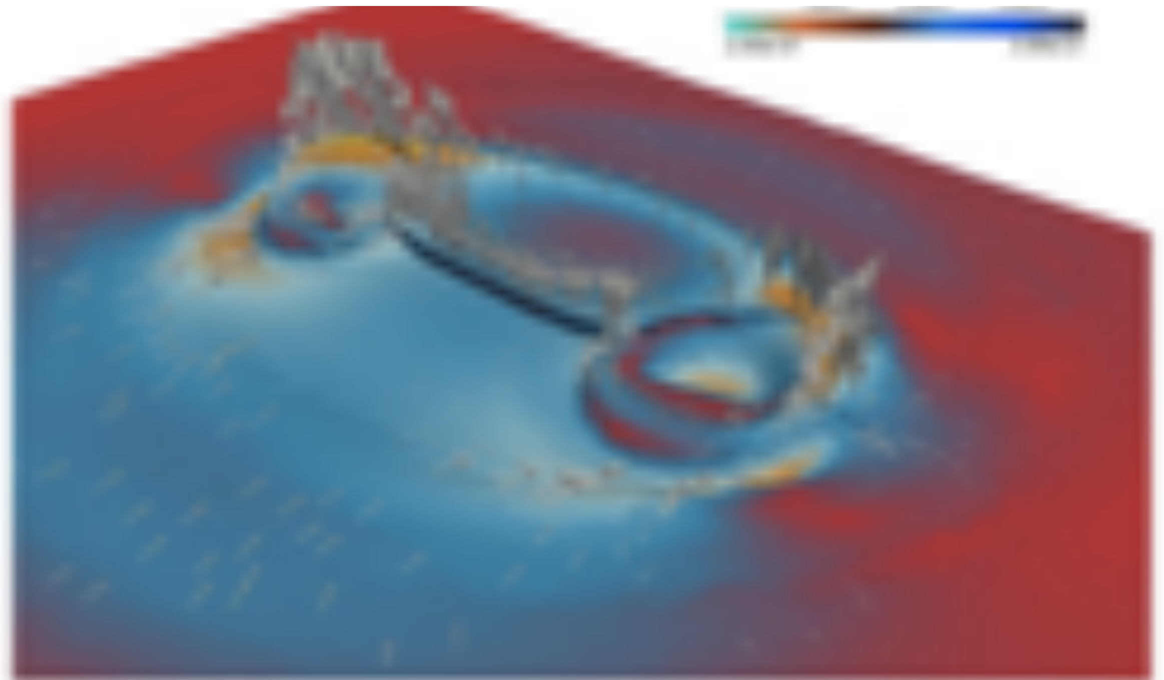
SOLVER

"Output"

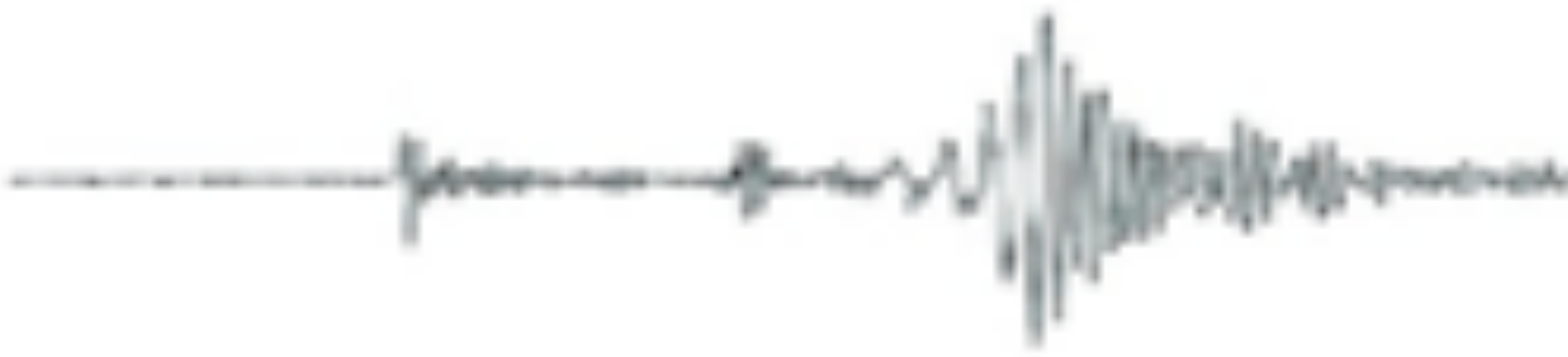
Rupture dynamics



Ground deformation

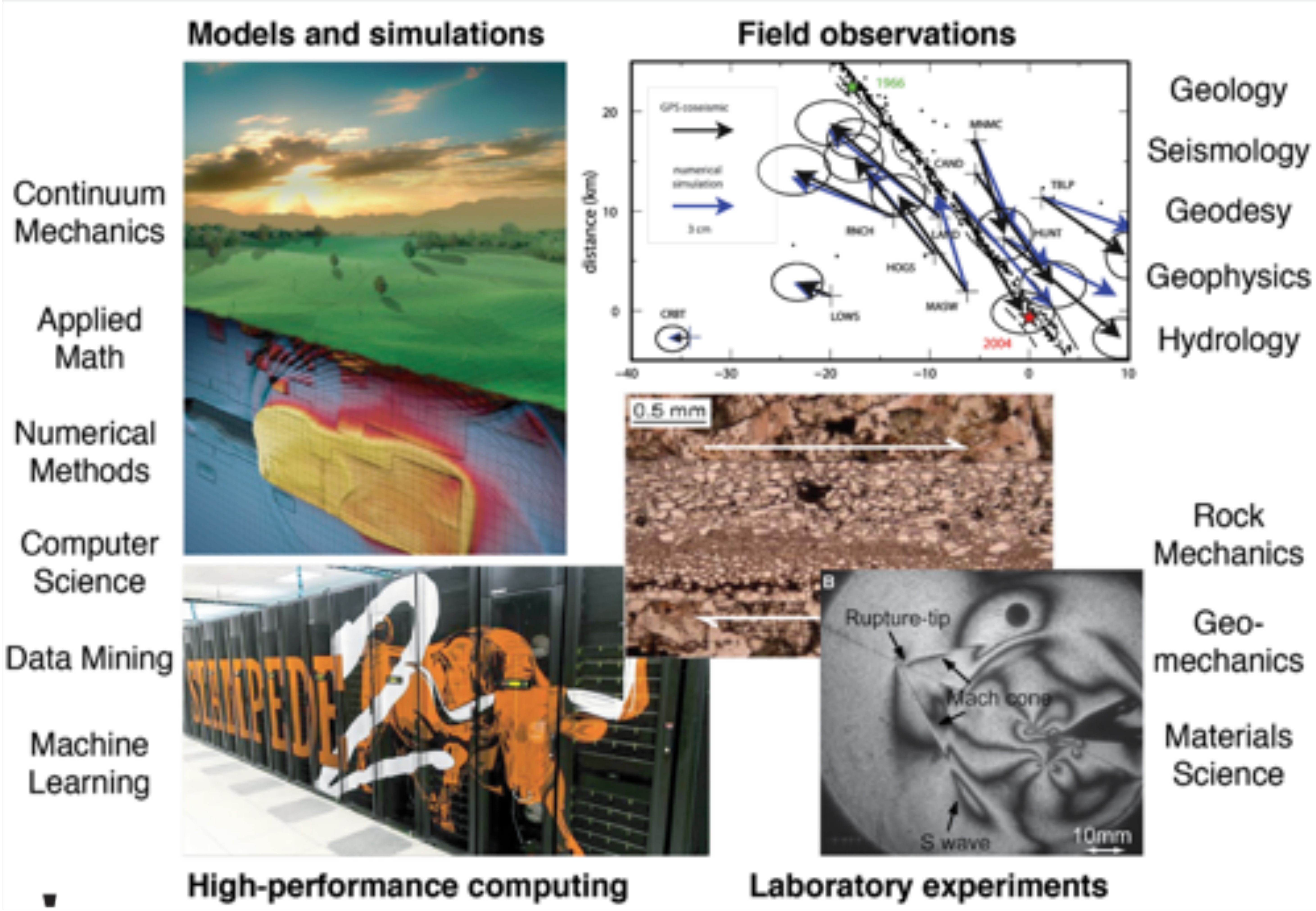


Synthetic observables



siam 2021

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)?

white paper "Modeling earthquake source processes: from tectonics to dynamic rupture", Lapusta et al., 2019

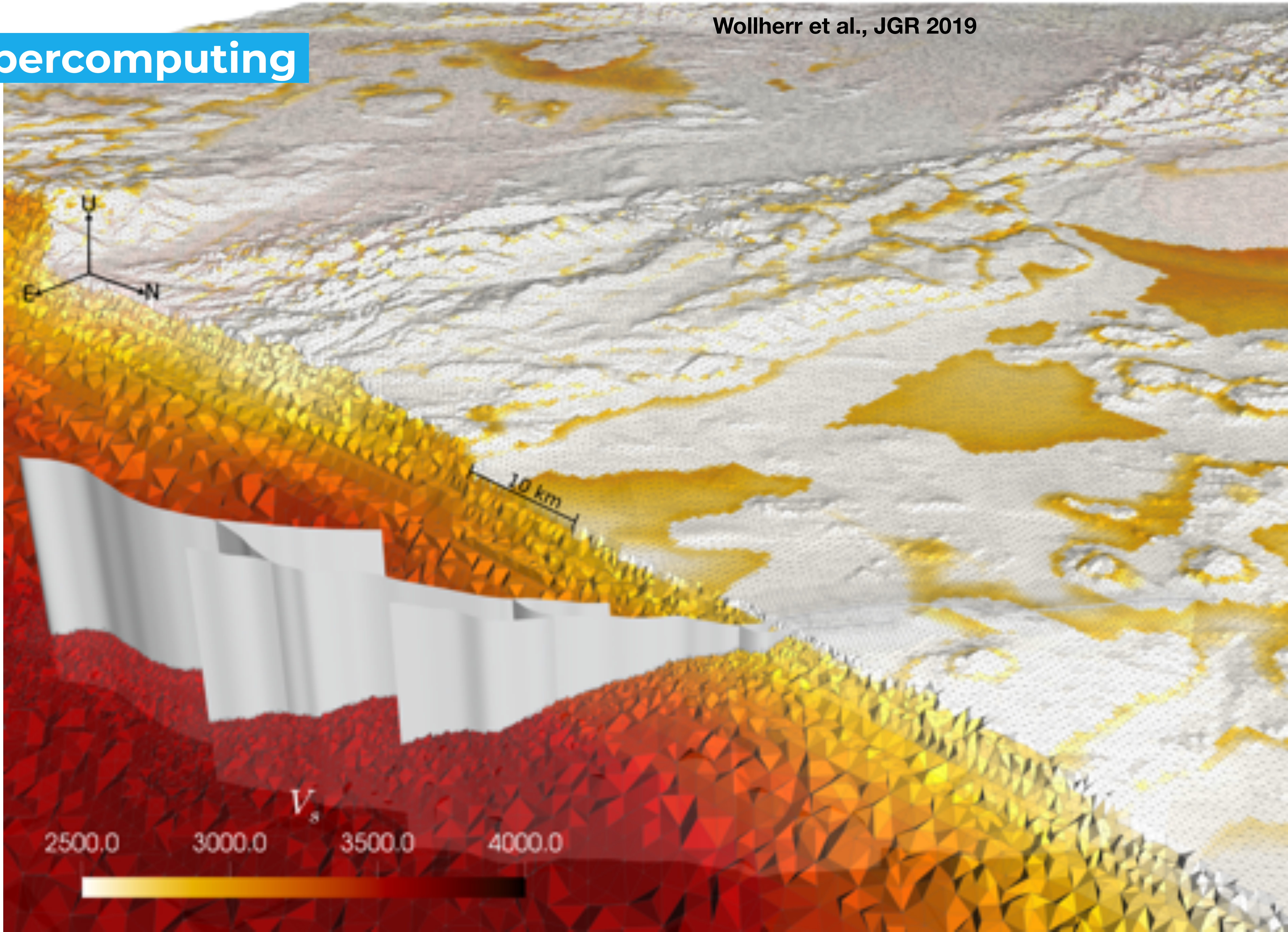
Empowered by supercomputing

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

Wollherr et al., JGR 2019

- We exploit 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 in open source software, e.g., SeisSol (www.seissol.org)**

- **Data-fused forward modeling using big geo-data-sets and community models**

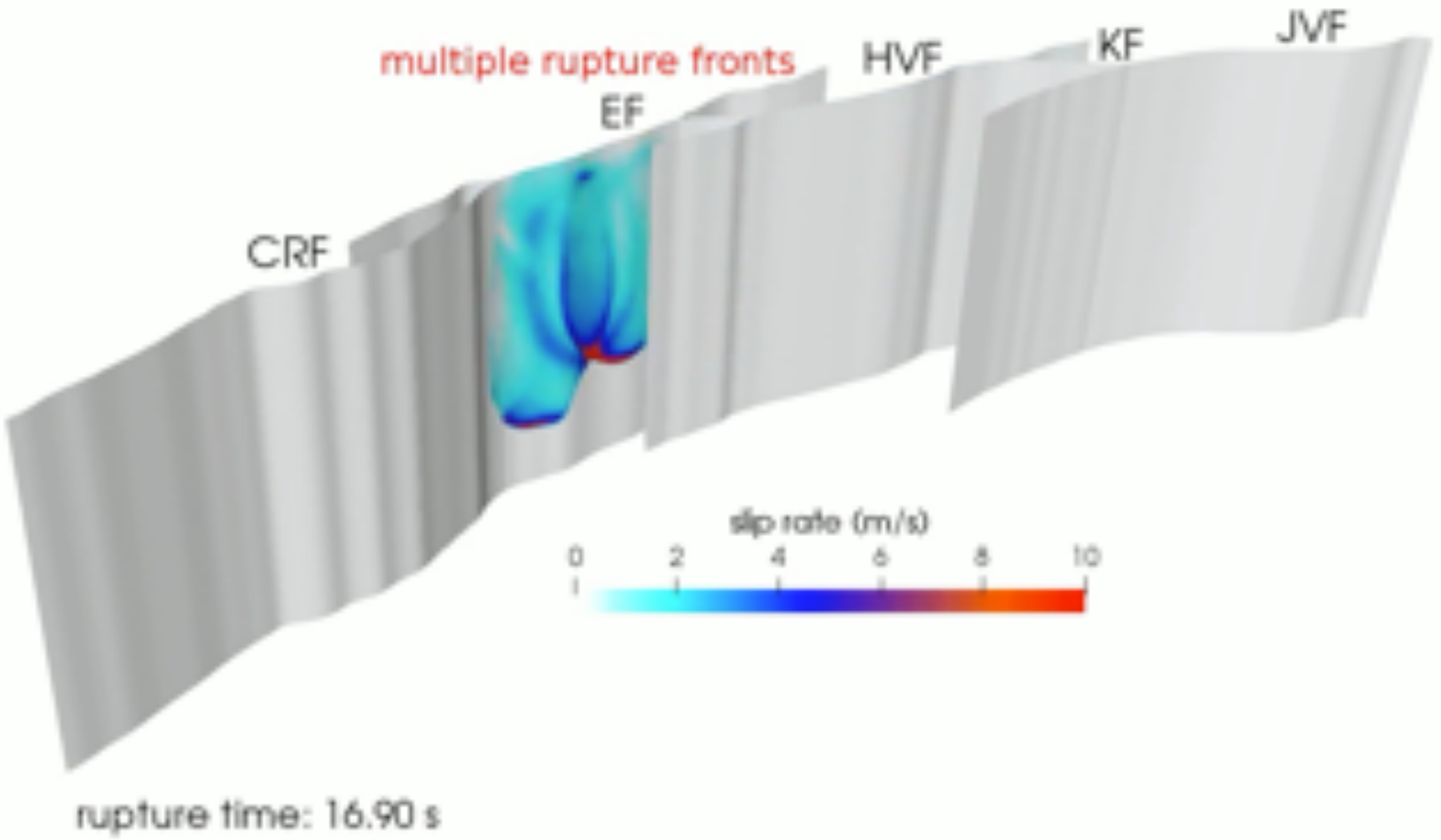


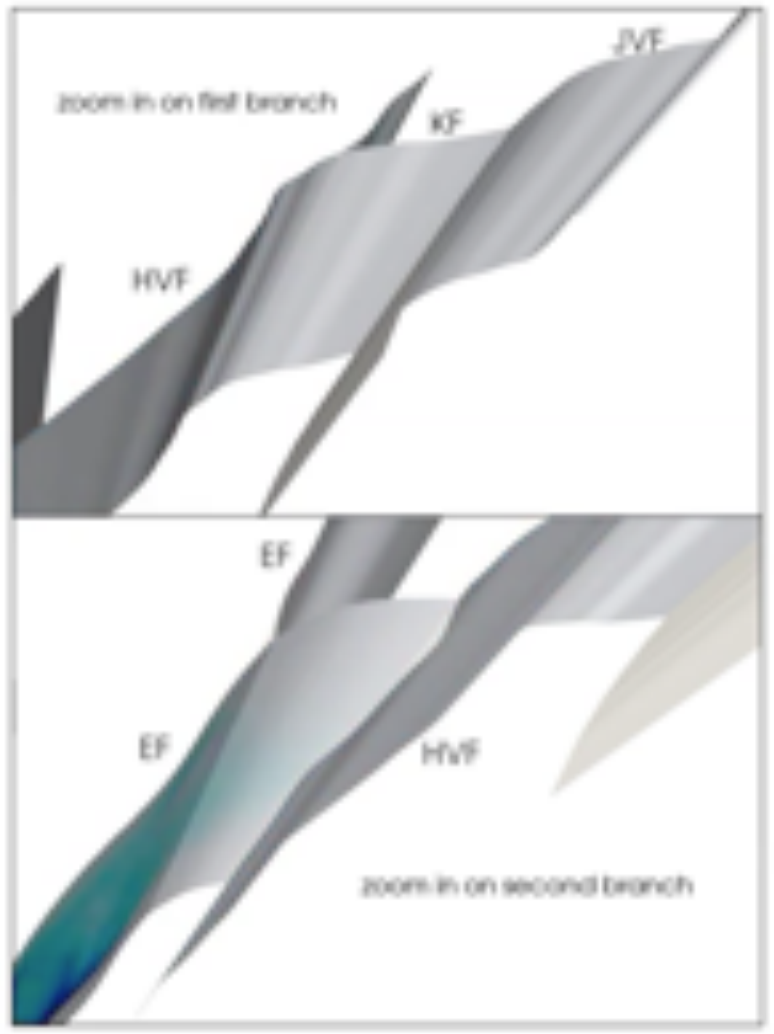
Heinecke et al., Gordon Bell Prize Finalist, SC’14

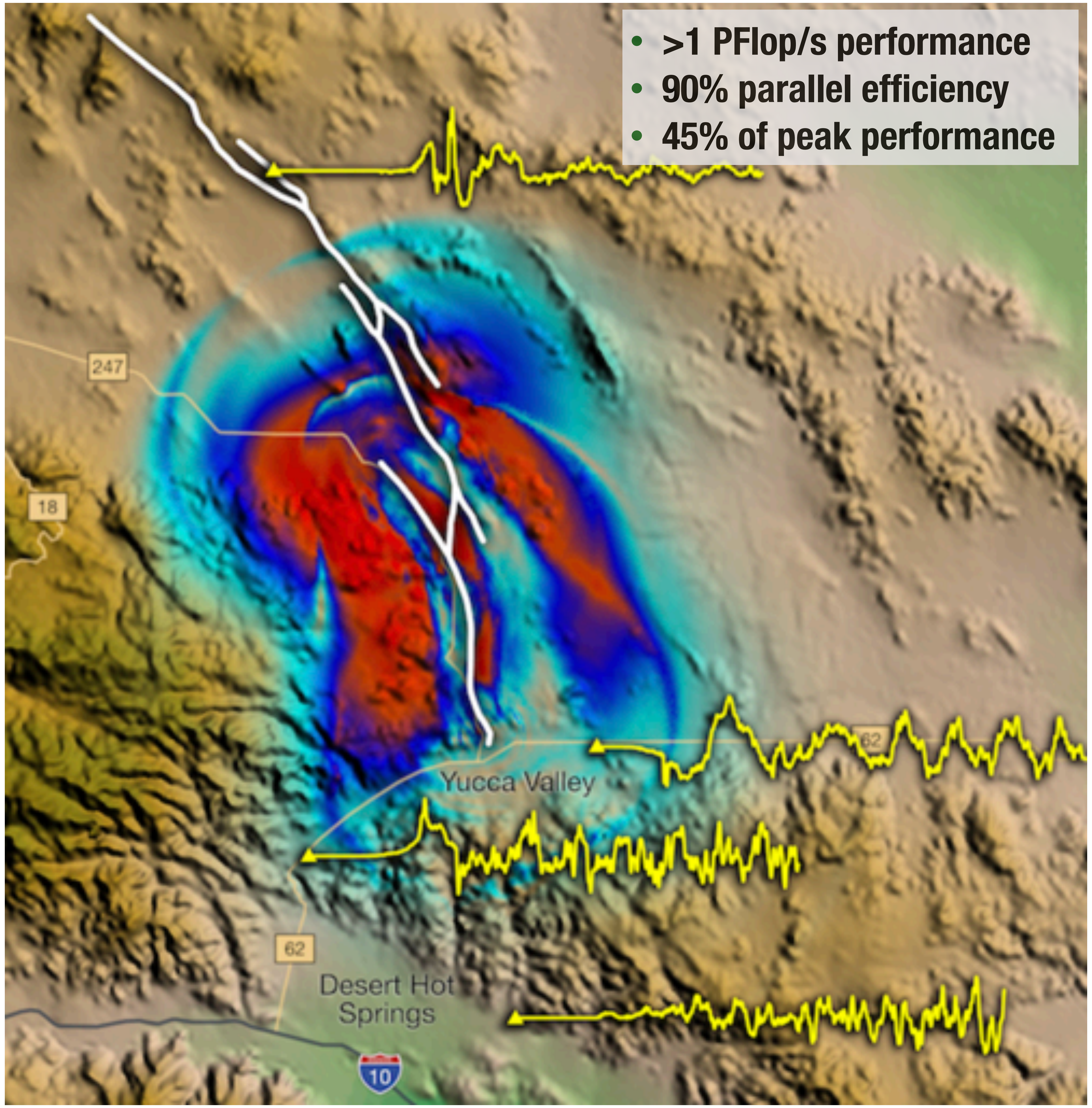
Wollherr et al., JGR 2019

Empowered by supercomputing

- **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





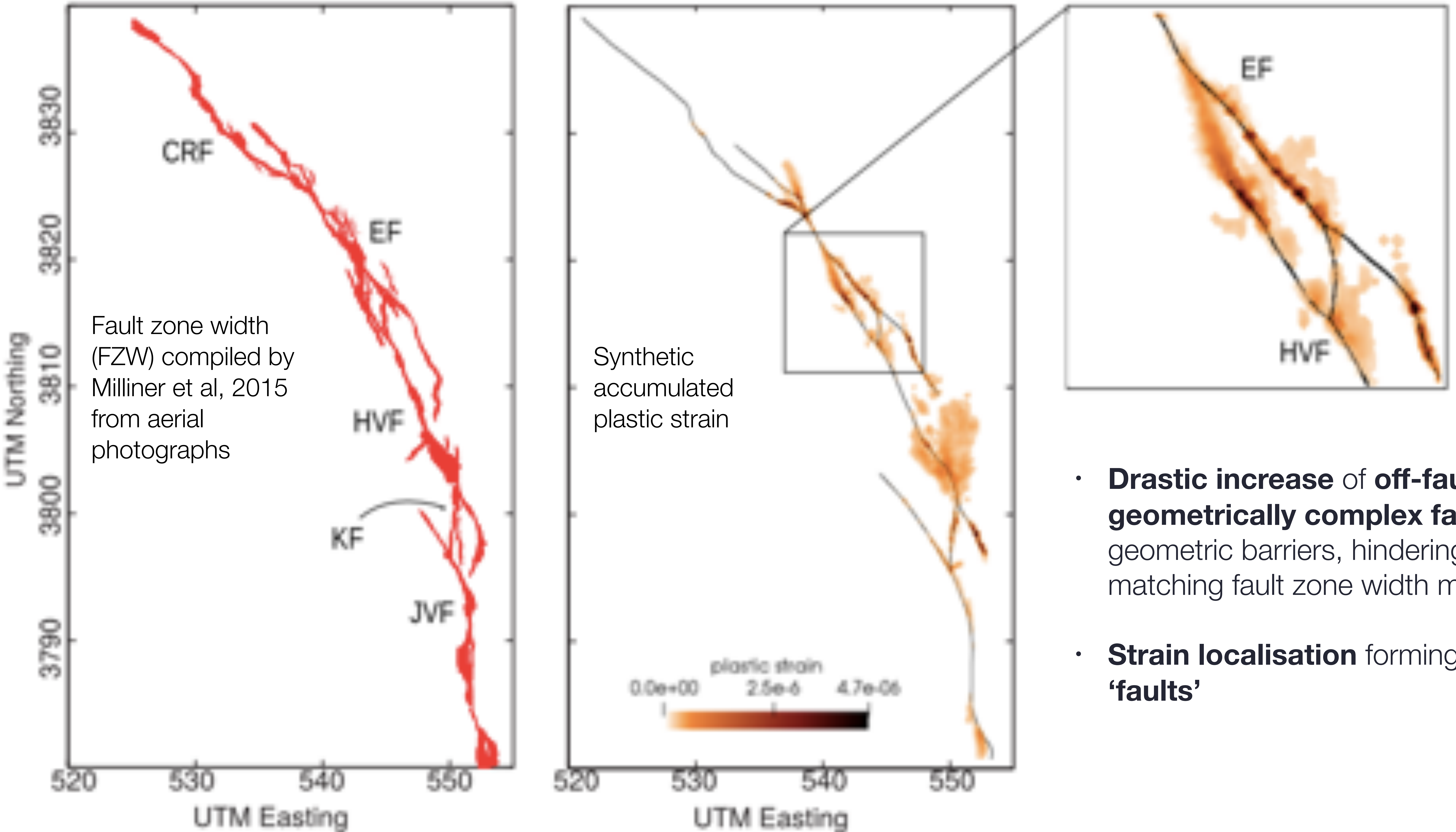


Landers earthquake dynamic rupture and 10 Hz wave propagation scenario (96 billion DoF, 200,000 time steps)

1992, Landers reloaded

➡ **Multi-scale and multi-physics matter - but which matter most?**

Wollherr, Gabriel, Mai, JGR, 2019



- **Drastic increase** of **off-fault deformation** in **geometrically complex fault regions** enhancing geometric barriers, hindering rupture transfers and matching fault zone width mapping
- **Strain localisation** forming **non-prescribed 'faults'**

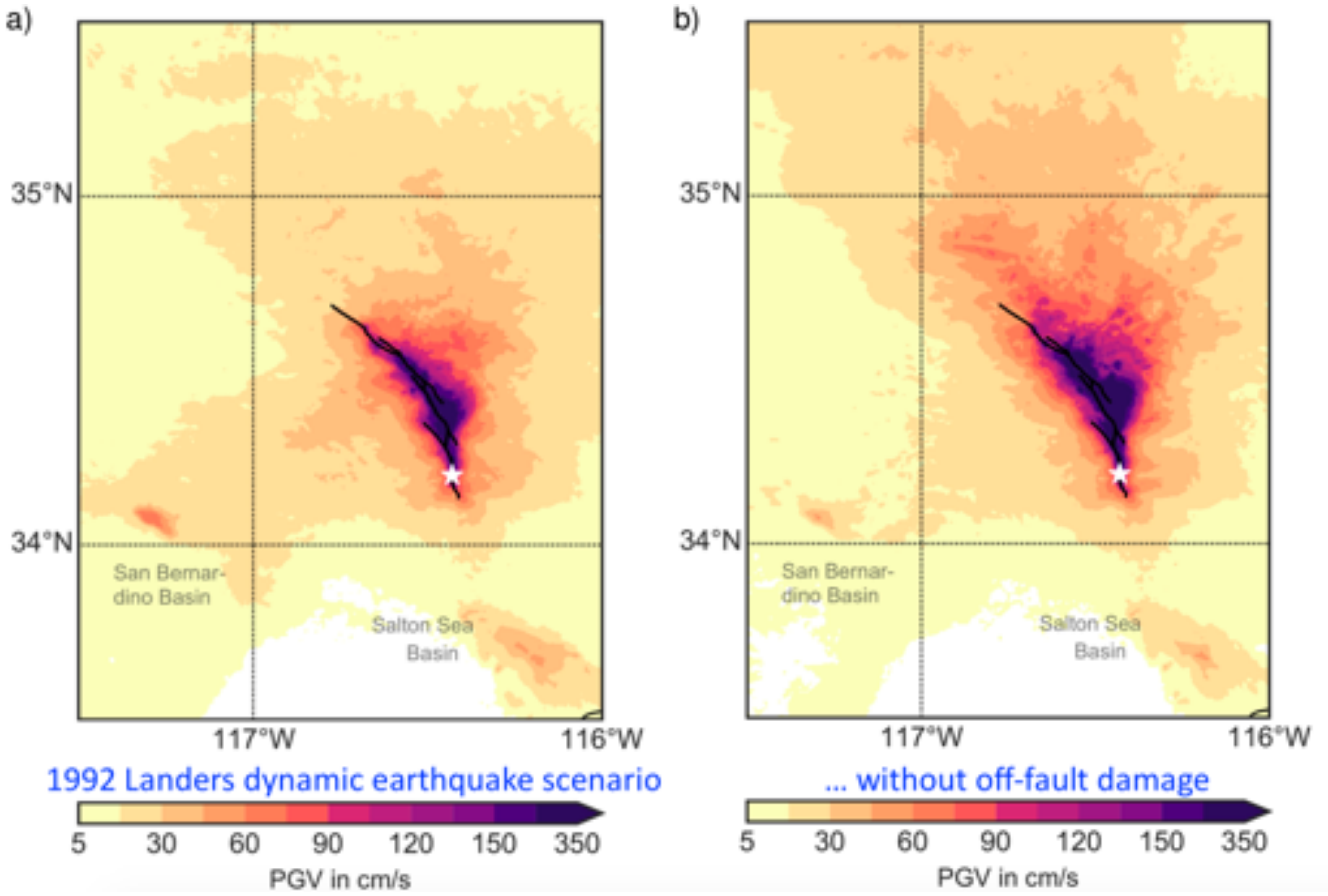
1992, Landers reloaded

Wollherr, Gabriel, Mai, JGR, 2019

➡ **Multi-scale and multi-physics matter - but which matter most?**

- Off-fault plasticity **reduces peak ground velocities (35% overall) as well as ground motion variability**

Simulated GMRotD50 PGVs for a purely elastic simulation cf. the visco-elasto-plastic simulation

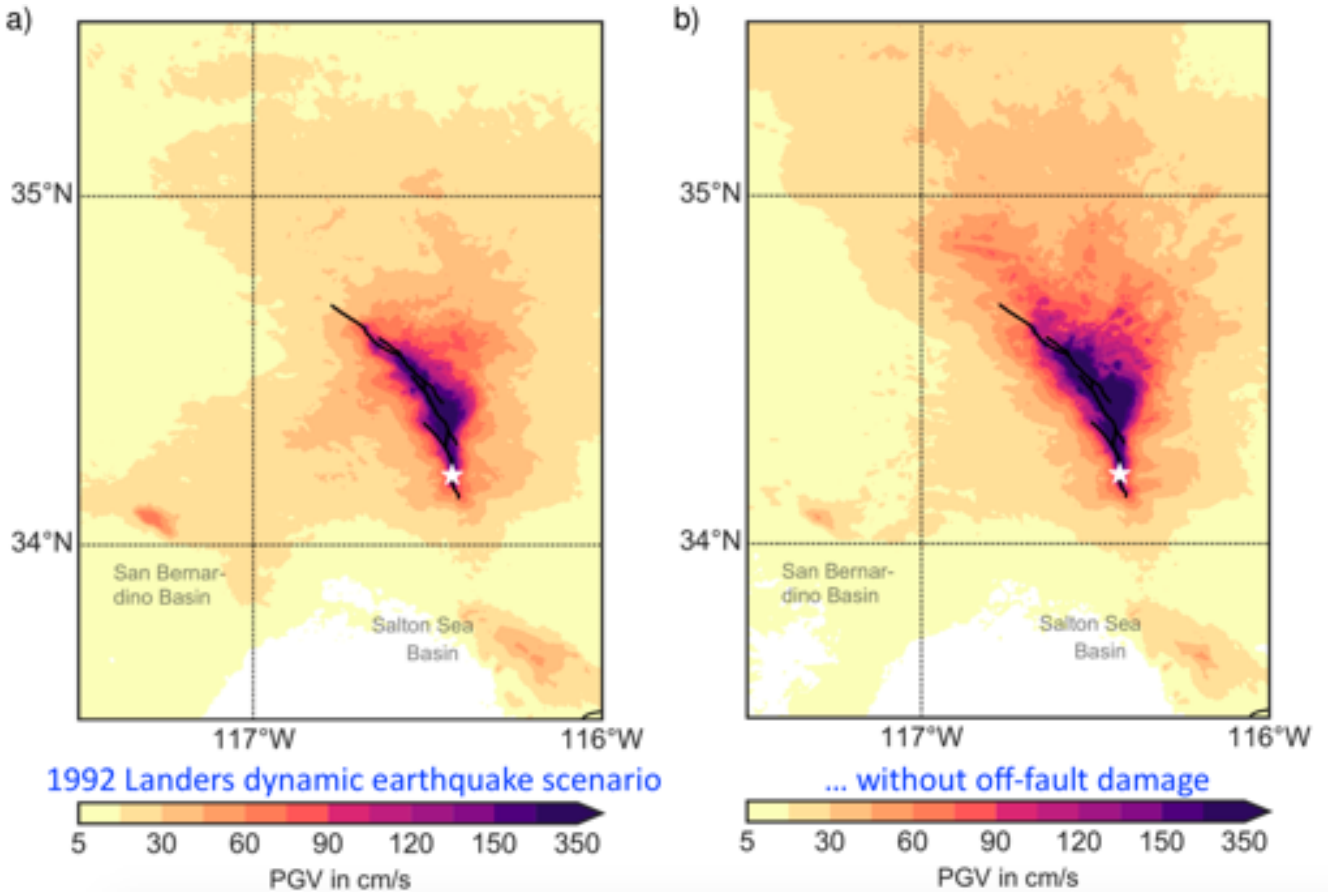


1992, Landers reloaded

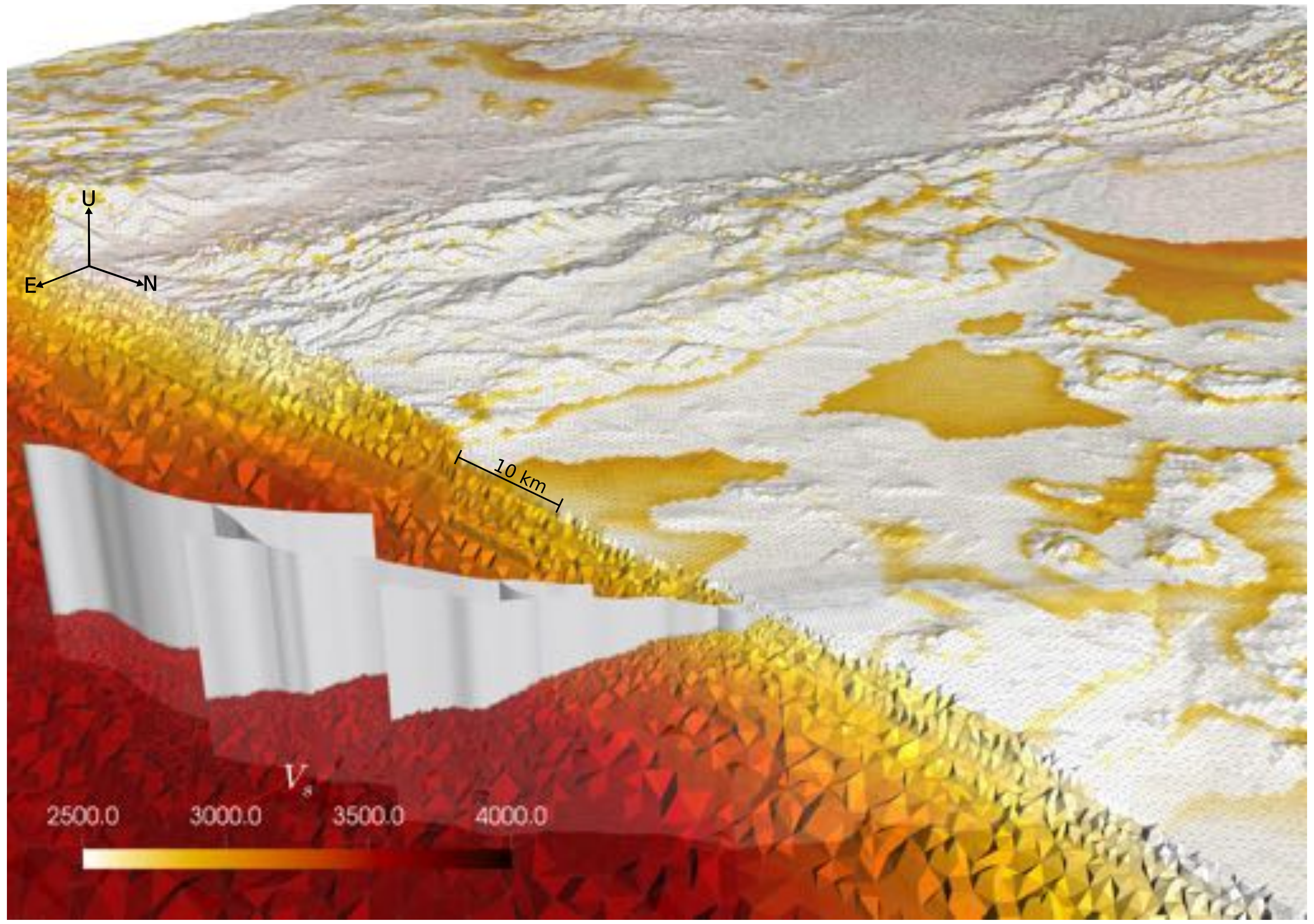
Wollherr, Gabriel, Mai, JGR, 2019

➡ **Multi-scale and multi-physics matter - but which matter most?**

Simulated GMRotD50 PGVs for a purely elastic simulation cf. the visco-elasto-plastic simulation



- Off-fault plasticity **reduces peak ground velocities (35% overall) as well as ground motion variability**
- **Utilizes high-performance computing** (here 7h on 525 nodes of SuperMuc1 for up to 4 Hz Wavefield and 150m cohesive zone size on-fault including off-fault plasticity +<10% and attenuation +80%)



The 2004 Sumatra-Andaman earthquake and tsunami - rise to a modelling challenge

Association for Computing Machinery

IEEE computer society

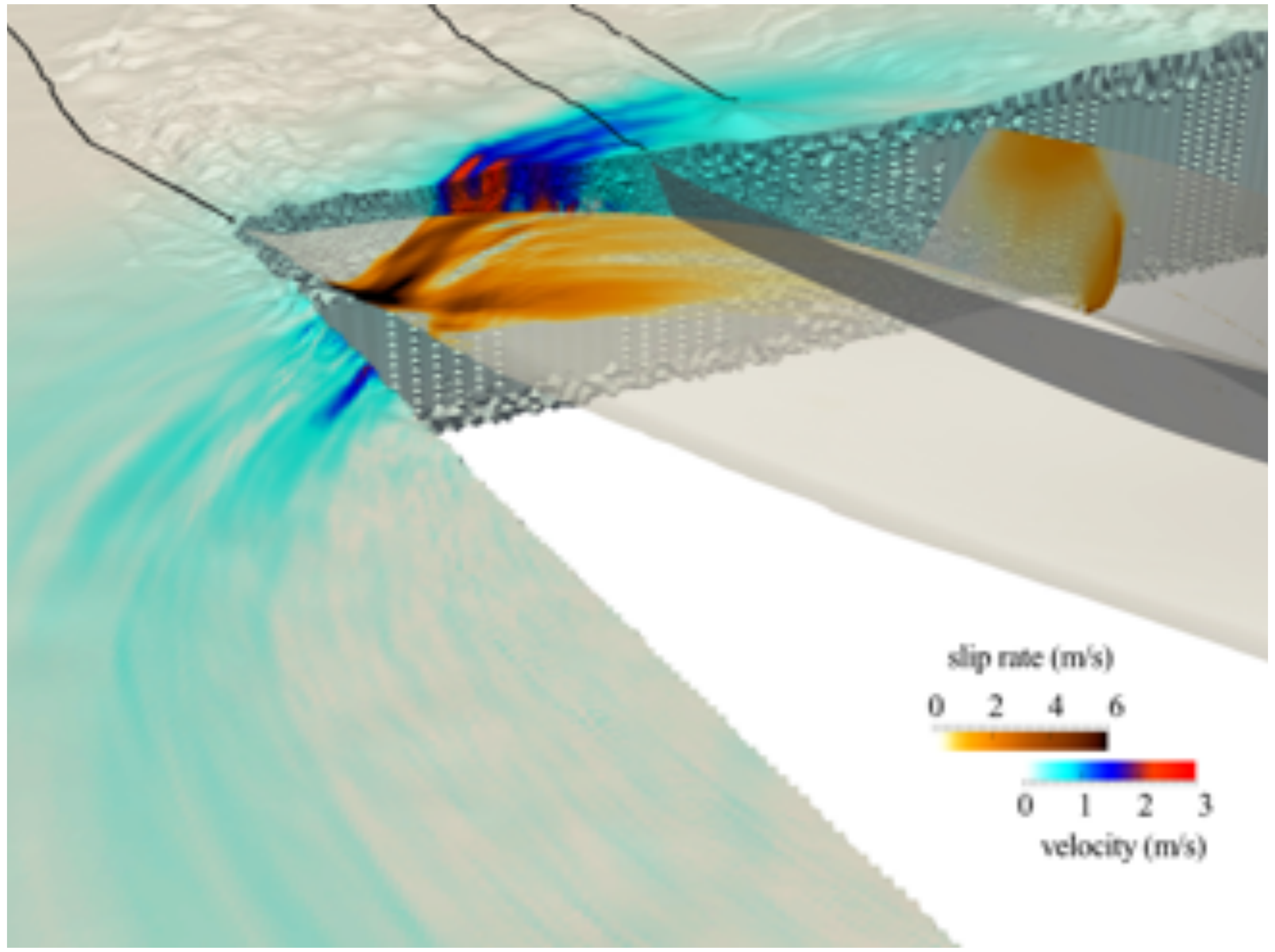
SC17

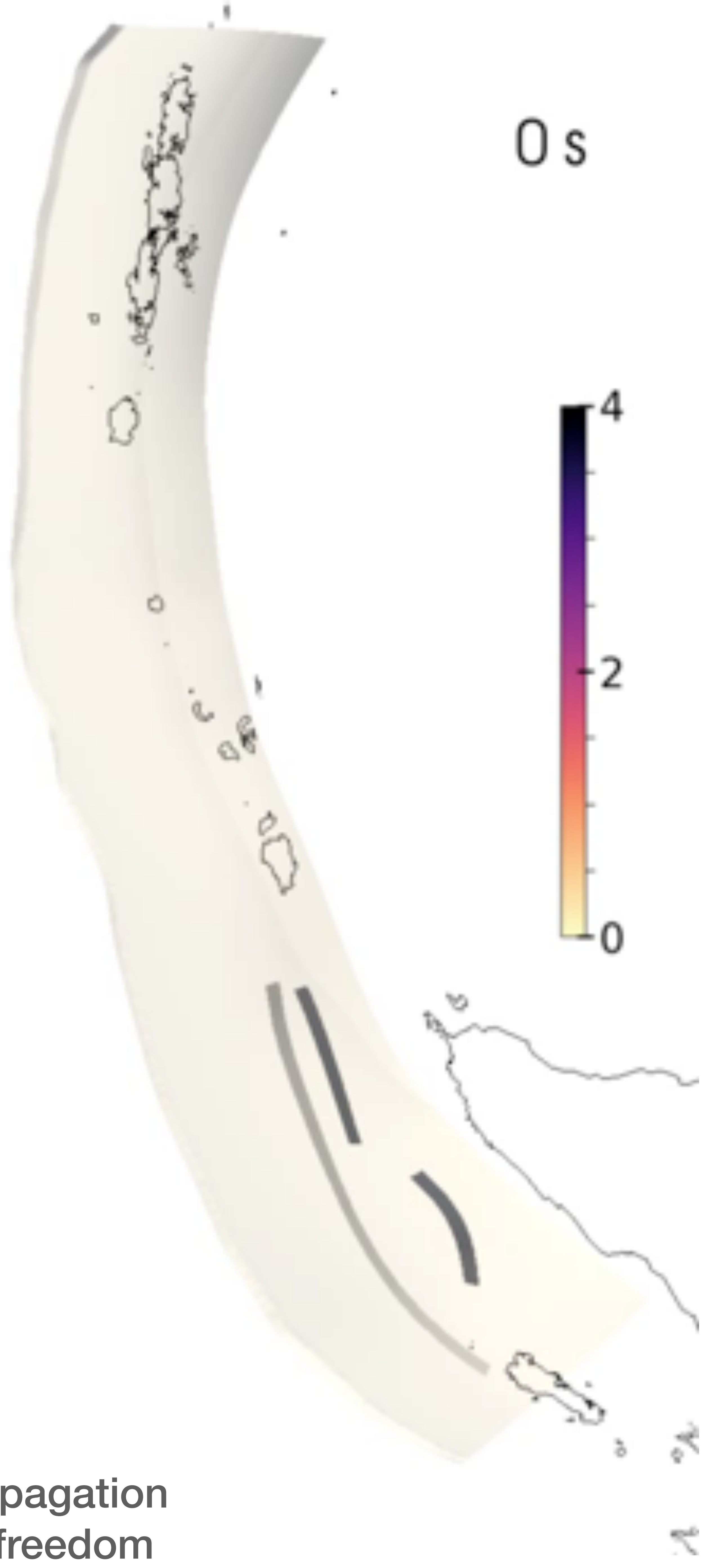
BEST PAPER

Uphoff et al., SC17

Ulrich et al., EarhArxiv'20
Madden et al., EarthArxiv'21

- Extreme-scale runs tackle the large space-time scales of **megathrust earthquakes and tsunami** modeling
- Requires numerical methods handling geometric complexity and **highly varying element sizes**
- parallel automatic mesh generation for tetrahedral meshes (tested up to **≈ 1 billion elements**)
- Local-time stepping mitigates e.g. 'sliver elements'





Sumatra earthquake dynamic rupture and tsunami propagation scenario with 220M elements ~111 x 10^9 degrees of freedom

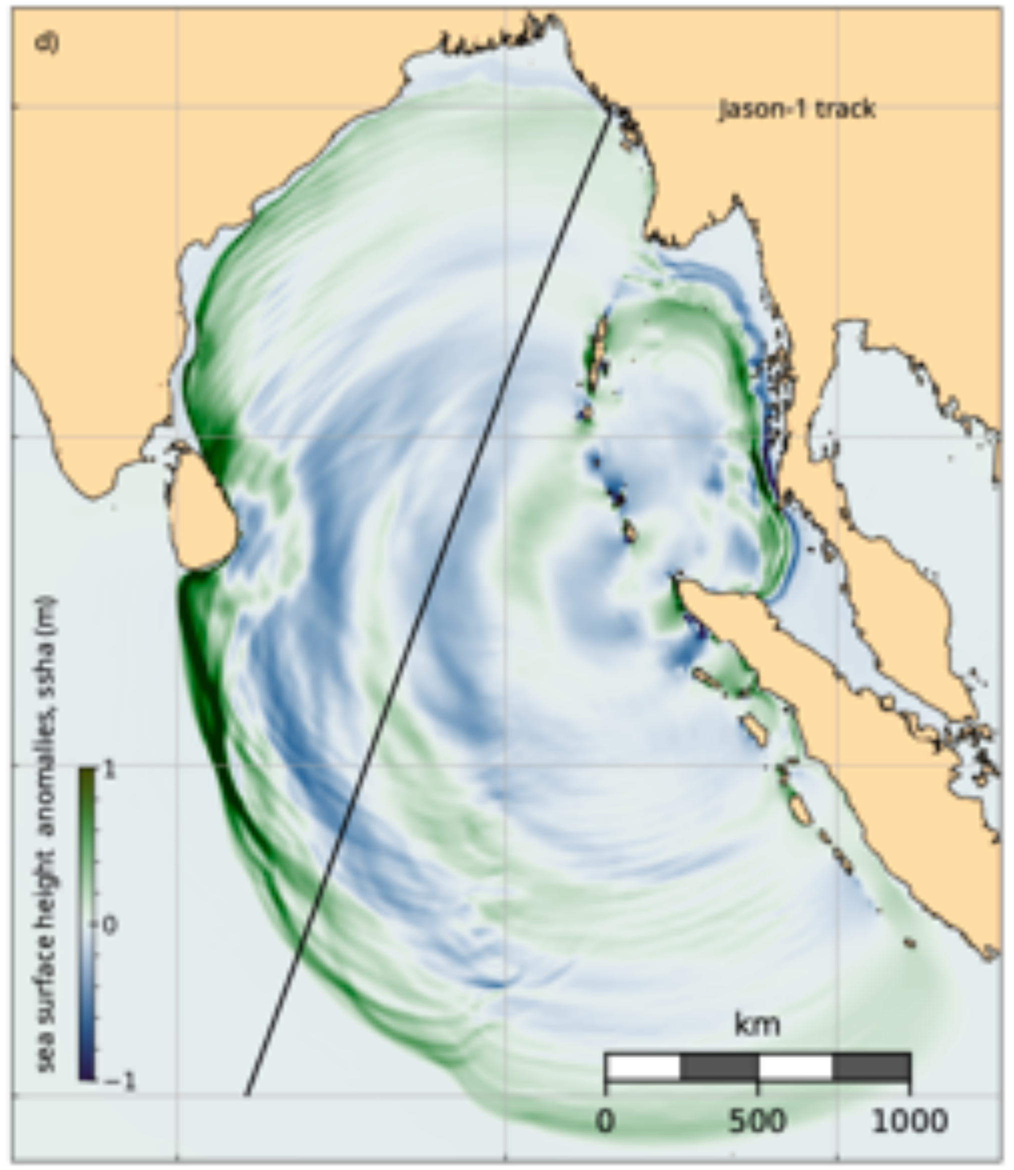
siam 2021

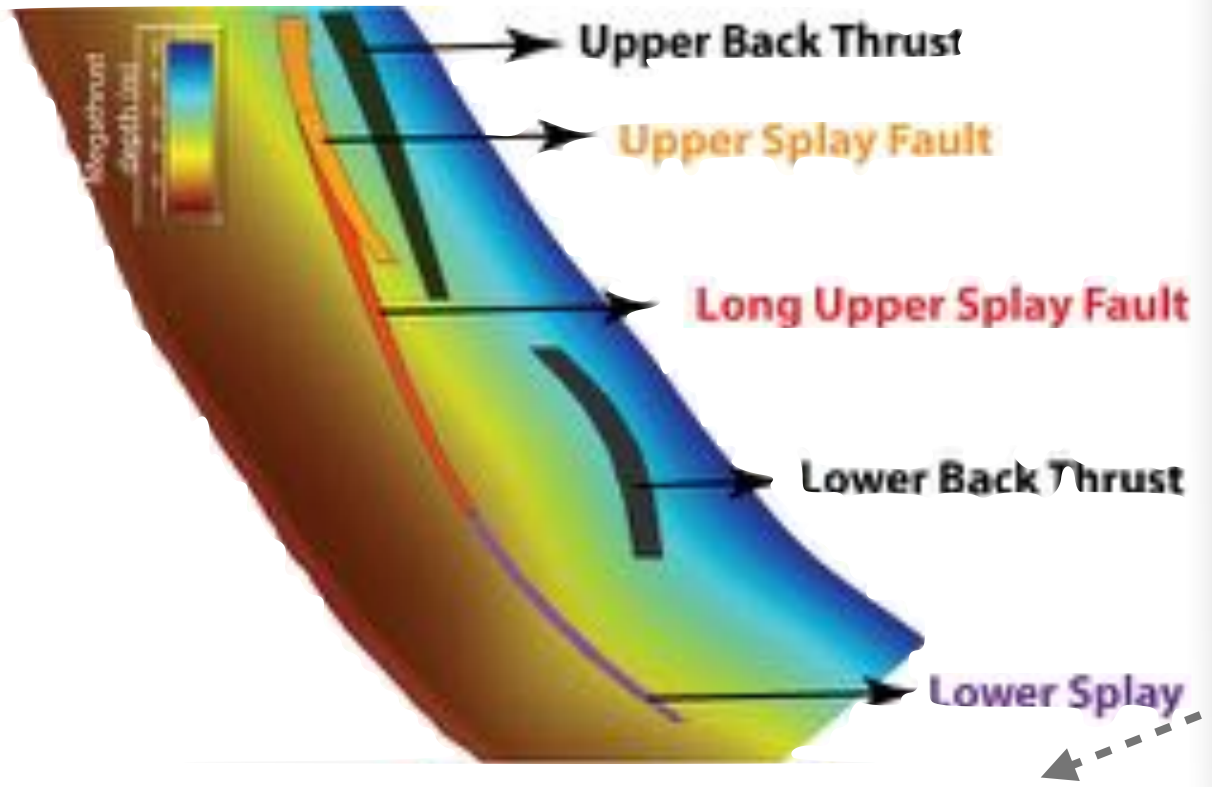
The 2004 Sumatra-Andaman earthquake and tsunami - rise to a modelling challenge

BEST PAPER

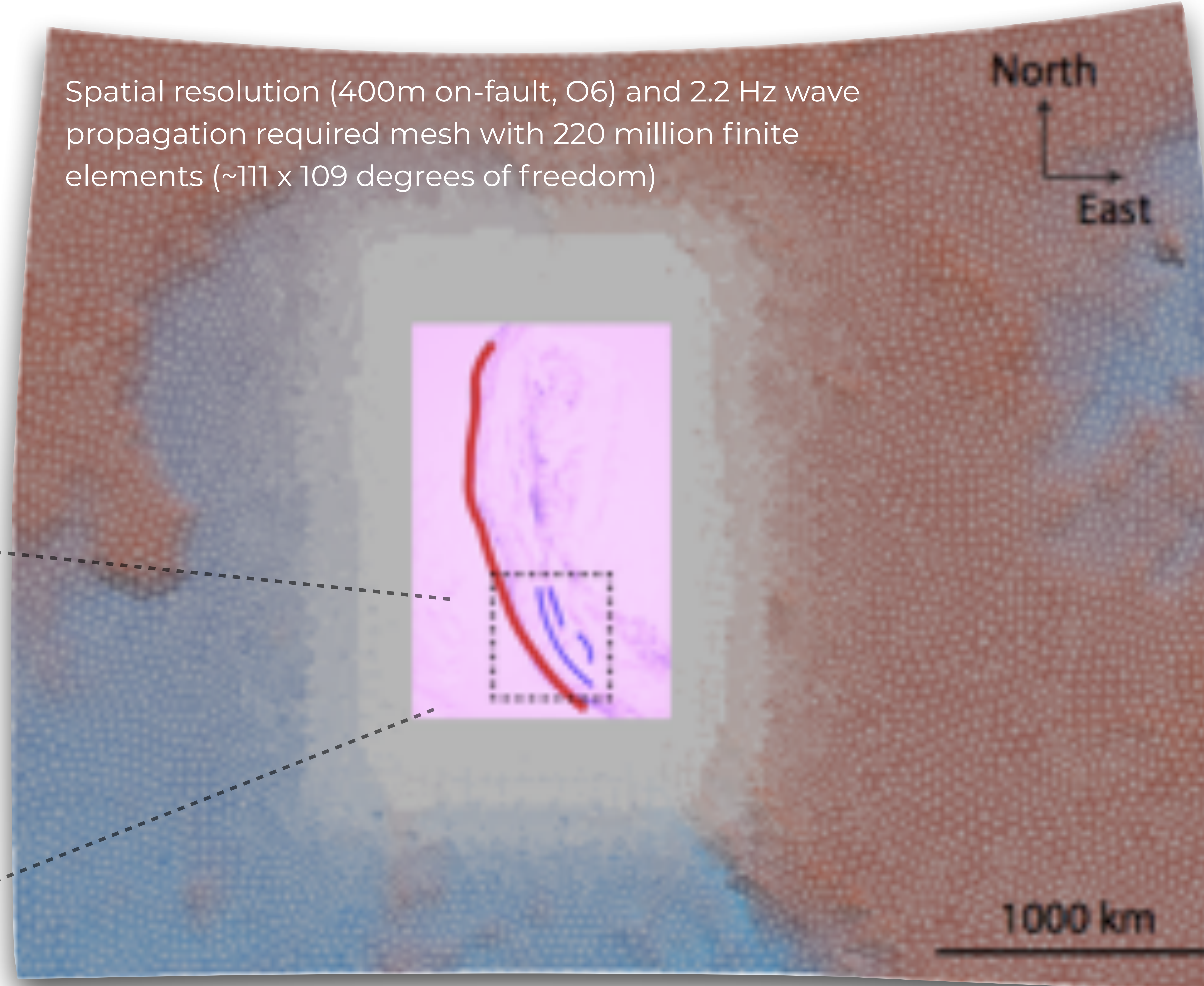
Uphoff et al., SC17

- While a **"hero run"** took 14h on full SuperMuc2; now typical high-order simulations: >10 Mio elements run 5h30 minutes on 16 nodes **(4k CPUh)**
- Enabled by end-to-end computational optimization including a **geoinformation server** for fast and asynchronous input/output, clustered local time stepping, off-line code generator, flexible boundary conditions (e.g. gravity), GPU optimisation (in progress)



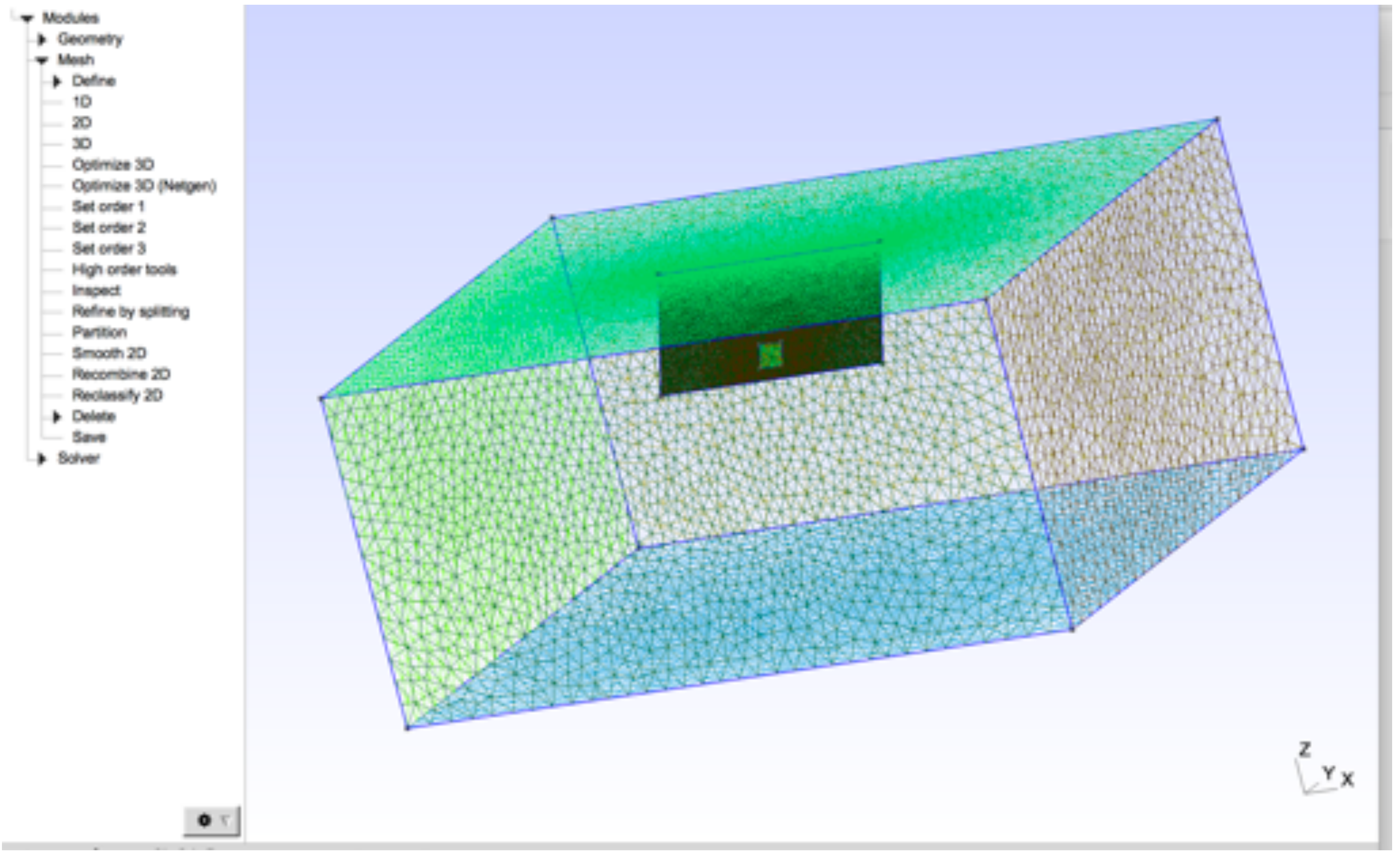


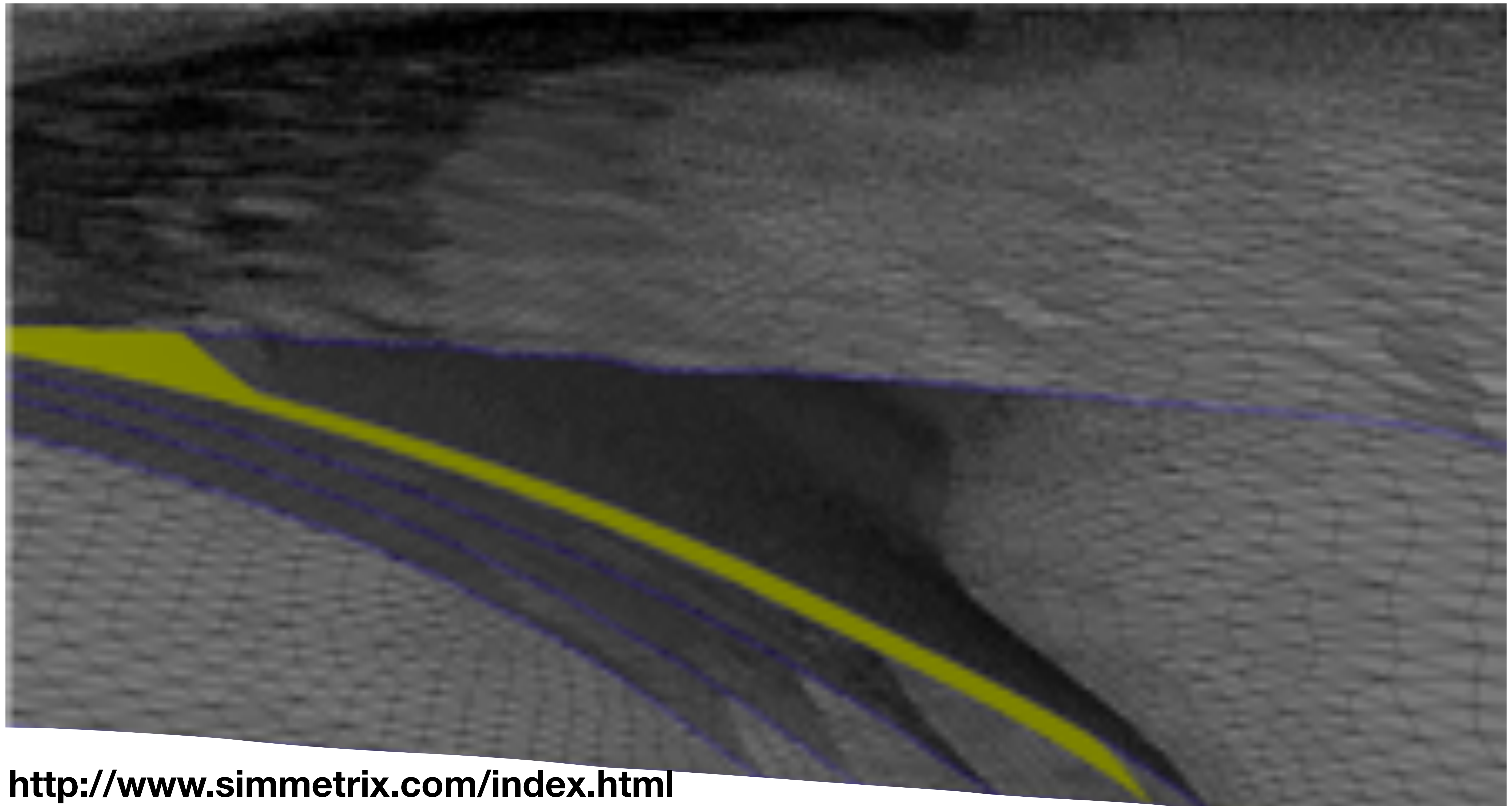
Ulrich et al., EarhArxiv'20
Madden et al., EarthArxiv'21



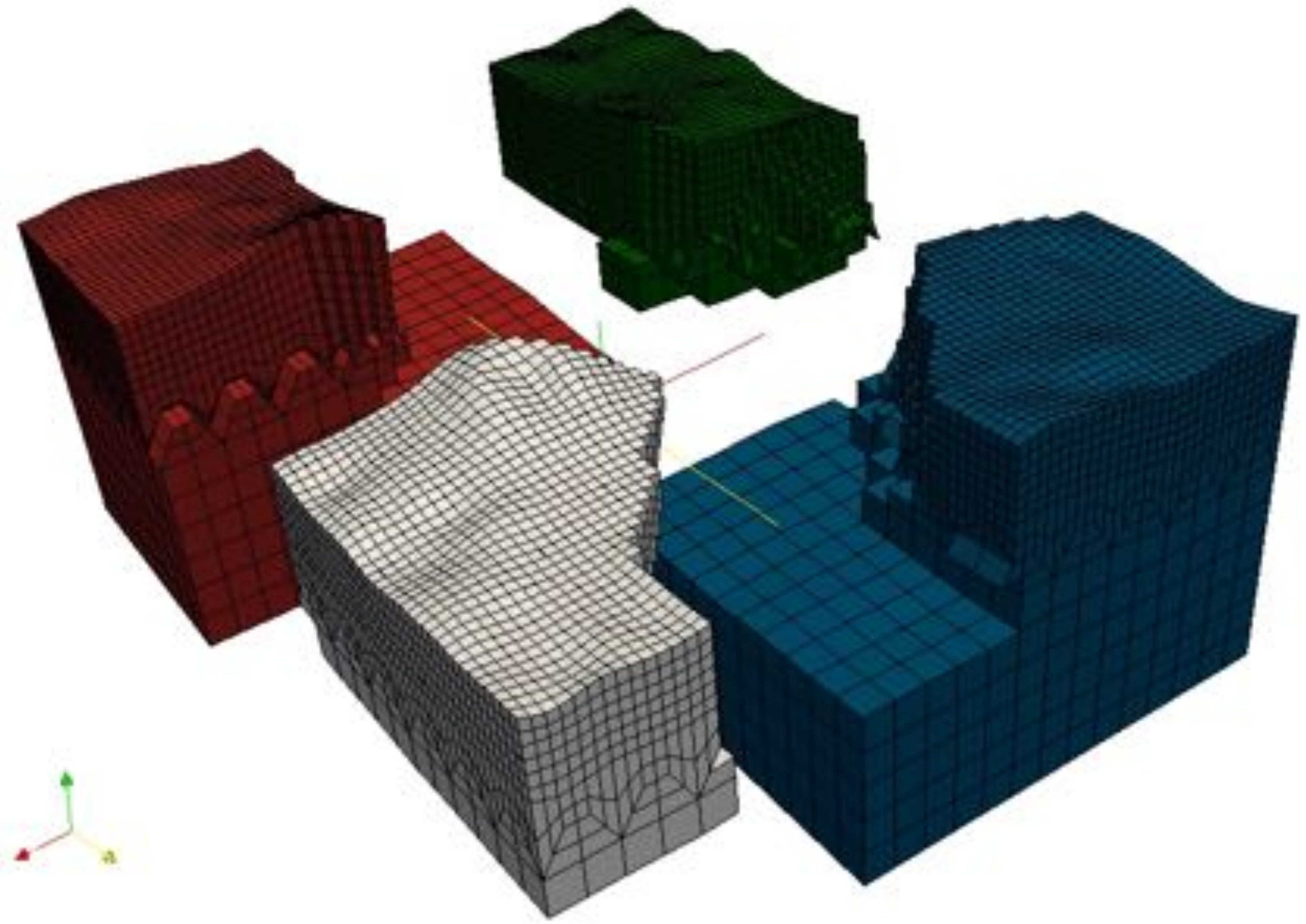
The “grand challenge” of meshing

- Community standard 1) **Hexahedral** meshes - may consume weeks in mesh generation , is **limited** for complex geometries (external / internal boundary conditions), common tool: TRELIS
- Community standard 2) **Unstructured tetrahedral** meshes - allows automatised meshing and complex internal/external boundary conditions, however are numerically challenging (sliver elements), common tools: GMSH, SIMMODELER

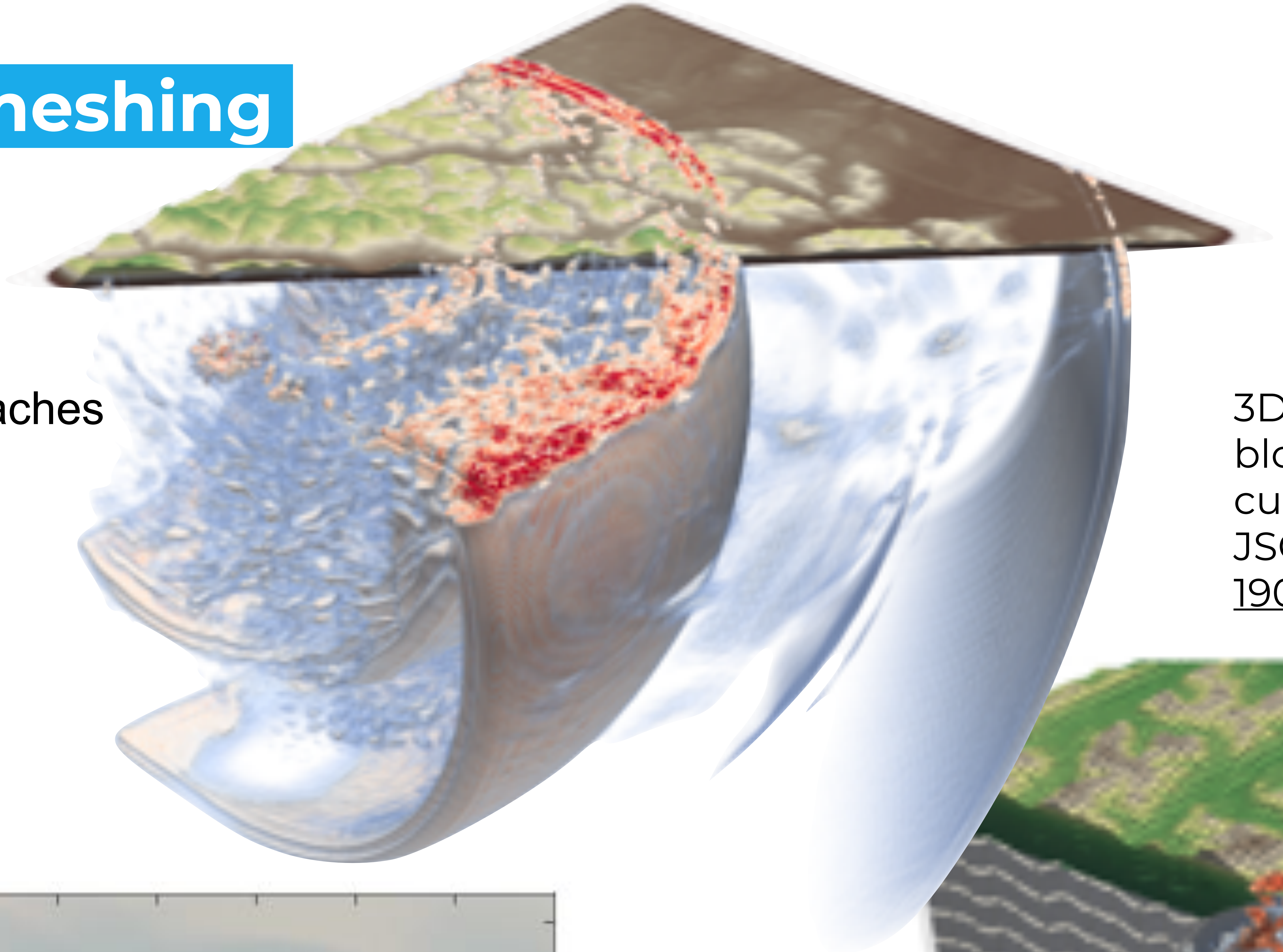




http://www.simmetrix.com/index.html



The “grand challenge” of meshing



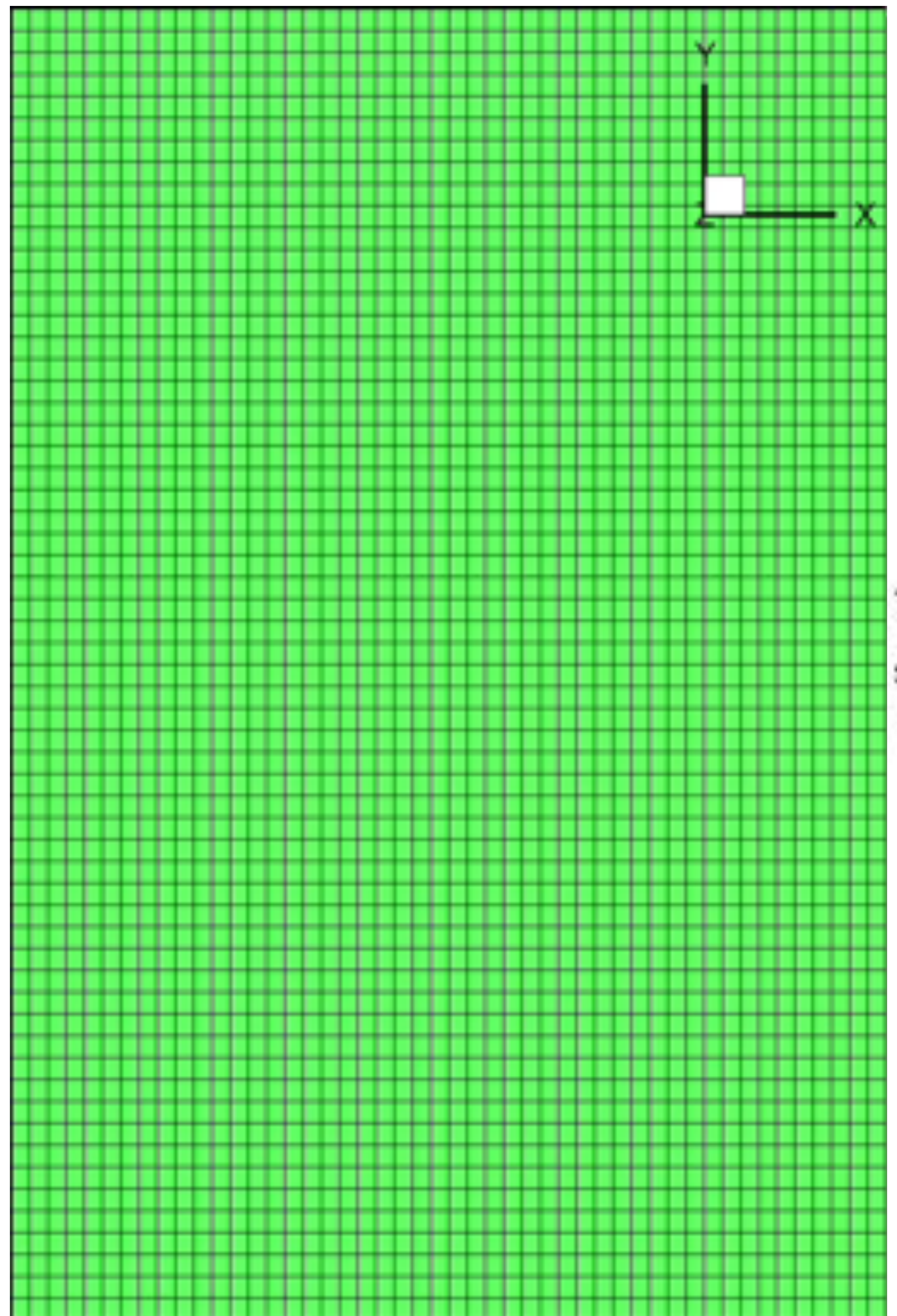
Reinarz et al., CPC, 2020

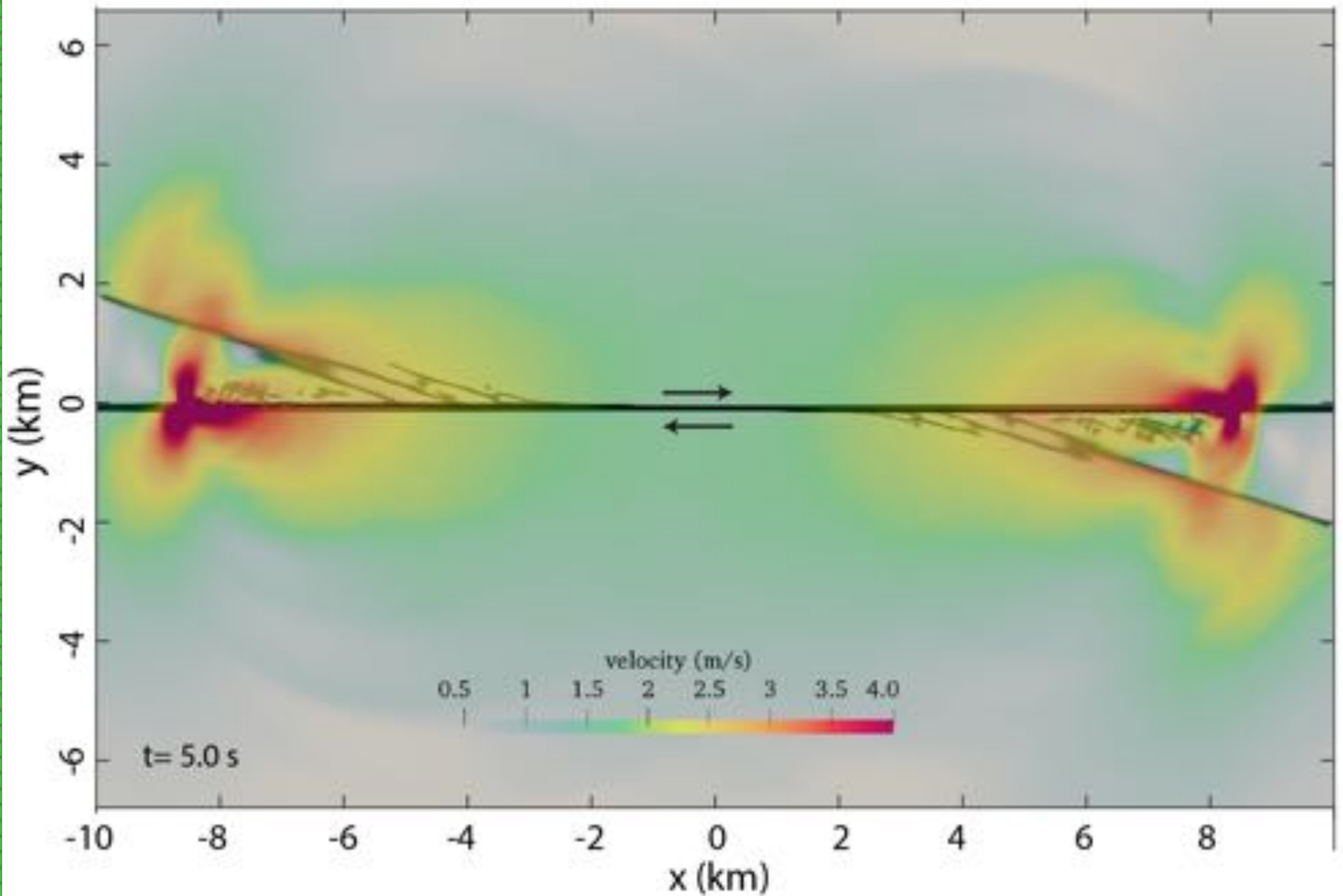
- Emerging:

Diffuse interface and **curvilinear mesh** approaches

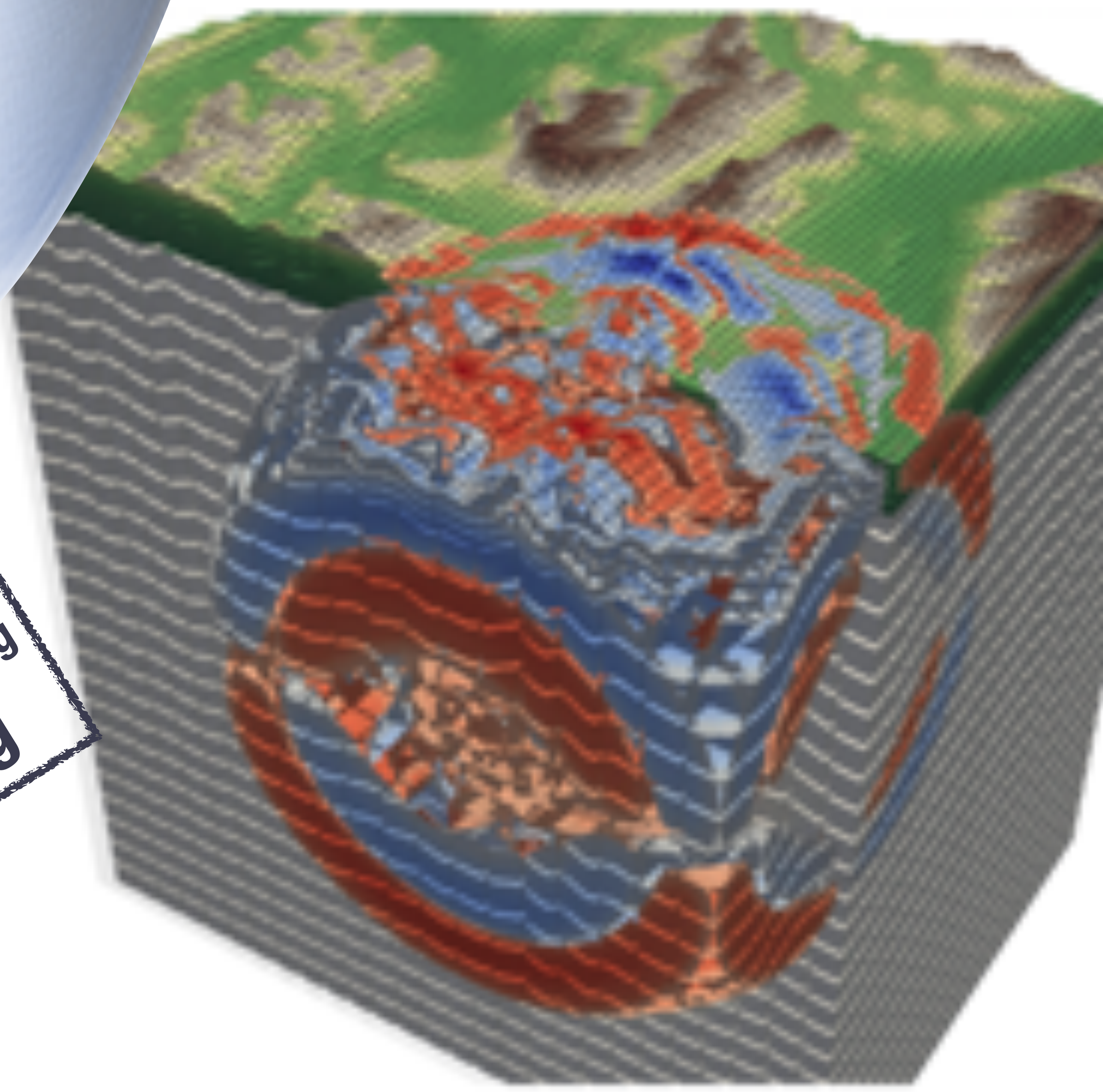
3D curvilinear meshes via multi-block boundary conforming curvilinear meshes (Duru et al., JSC’21 & https://arxiv.org/abs/1907.02658

Propagation of an out-of-plane brittle crack using the diffuse interface GPR model and ExaHyPE [Tavelli et al., JCP’20, Gabriel et al. Proc. R. Soc. A, 2021].





without feature-preserving meshing



www.seissol.org github.com/SeisSol

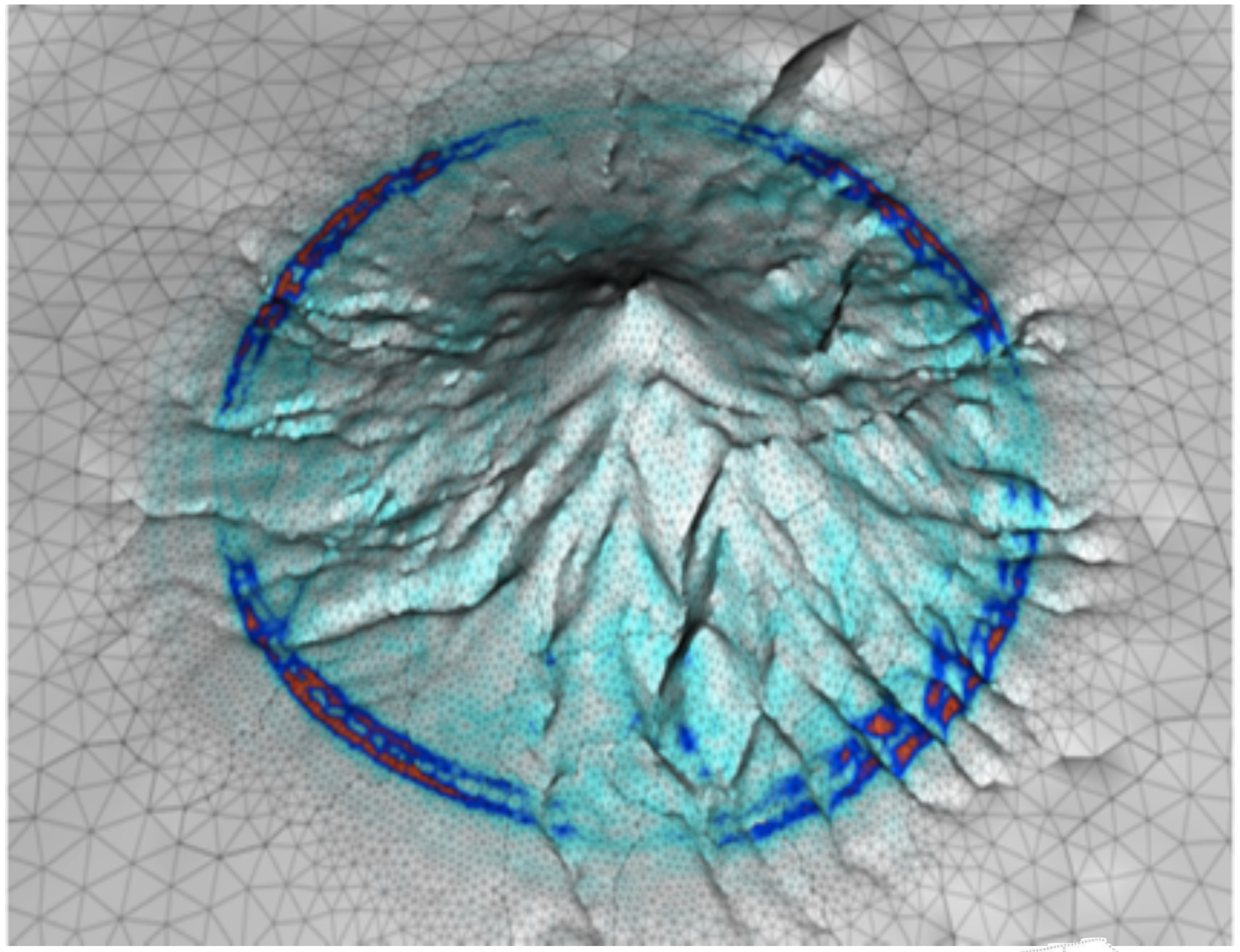
SeisSol - ADER-DG
A unique modelling framework

SeisSol solves the seismic wave equations using the ADER-DG method 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, poroelastic
- **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

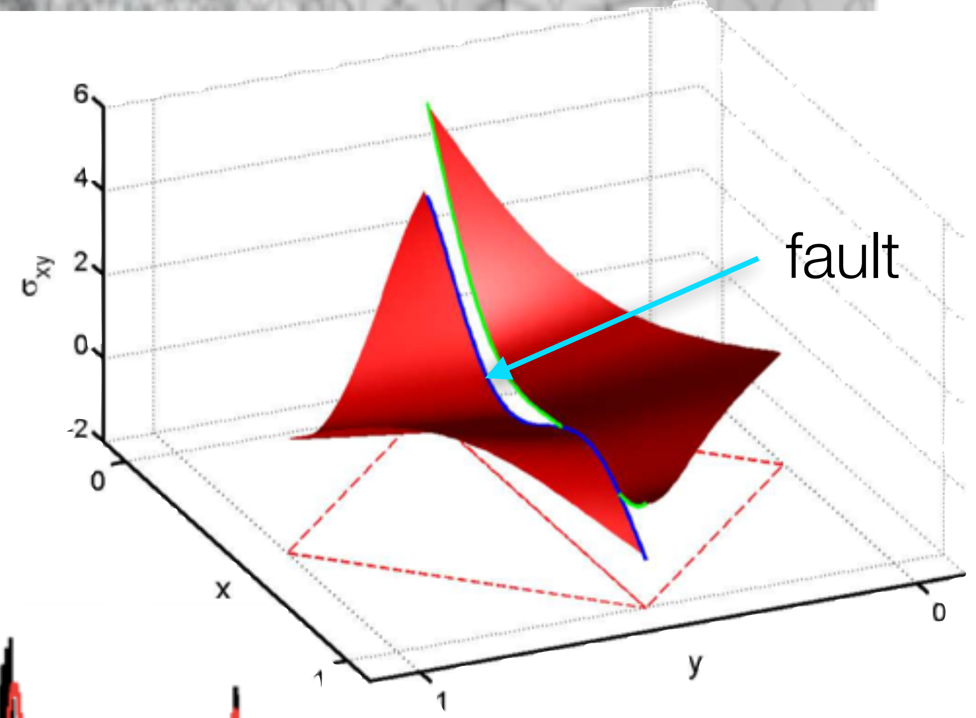
DG for elastodynamic wave propagation problems:
Duru et al., 2021; Reinarz et al., 2020; Peyrusse et al., 2014; Mazzieri et al., 2013; Antonietti et al., 2012; Etienne et al., 2010; Wilcox et al., 2010; Grote & Diaz, 2009; de Basabe et al., 2008; Riviere et al., 2007; Chung & Enquist, 2006



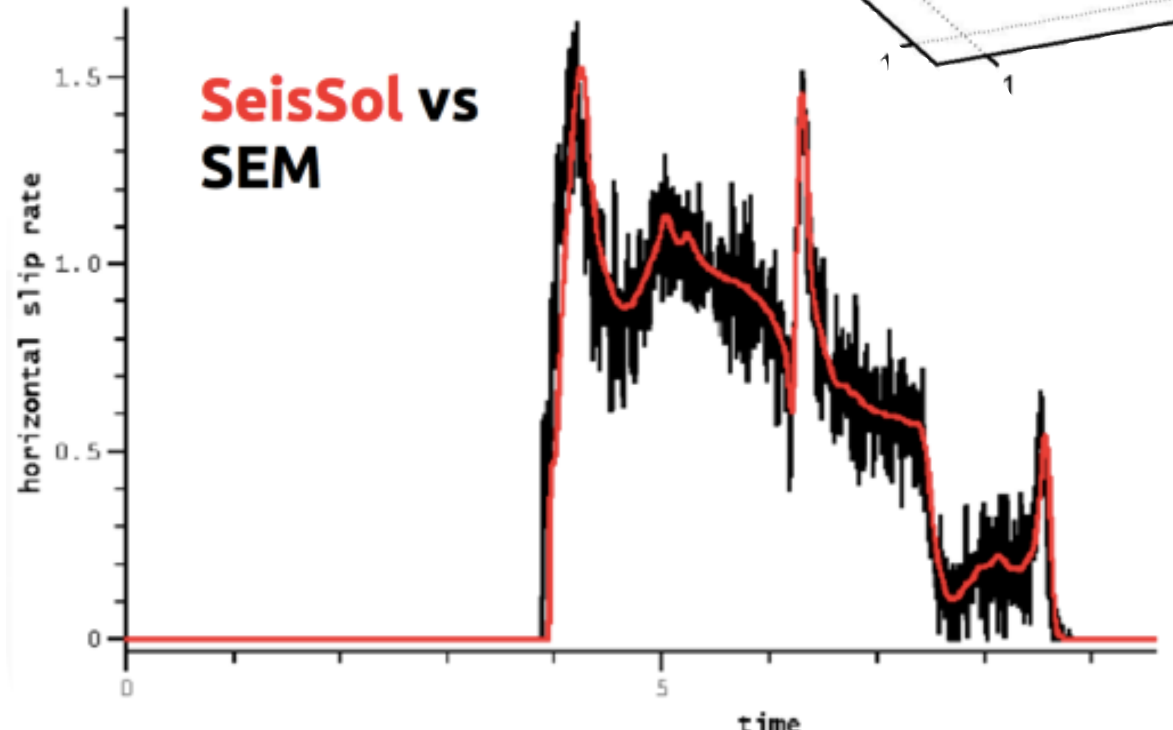
Wave field of a point source interacting with the topography of Mount Merapi Volcano.

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.

Käser and Dumbser, 2006; de la Puente et al., 2008; Pelties et al., 2014; Breuer et al., ISC'14



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

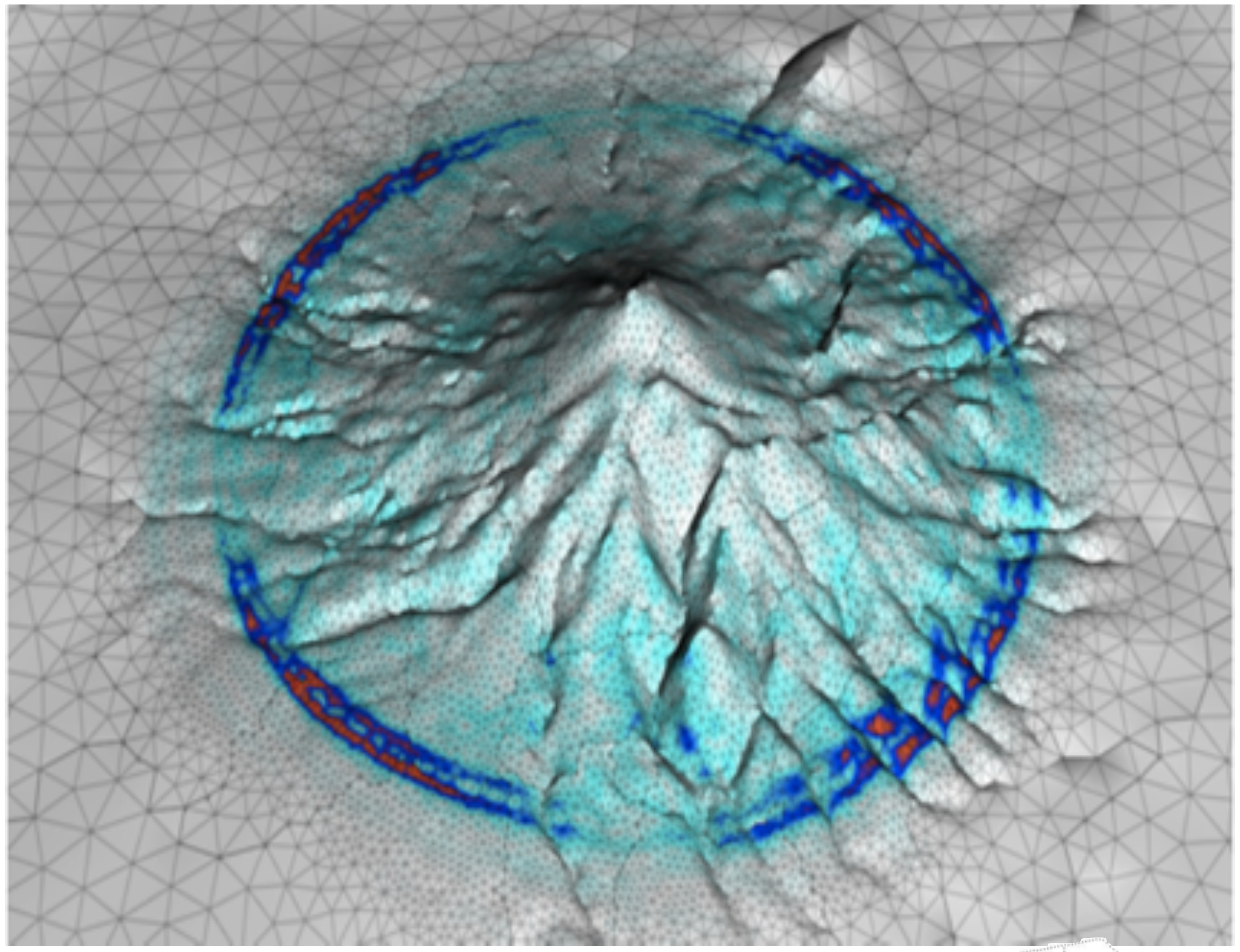
Why DG? Low numerical dispersion, minor changes for dynamic rupture, suitable for intersecting and branching faults/structure, favourable numerical dissipation of the Godunov flux (Hu et al. 1999; Kaeser et al. 2008; Hesthaven & Warburton 2010)

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

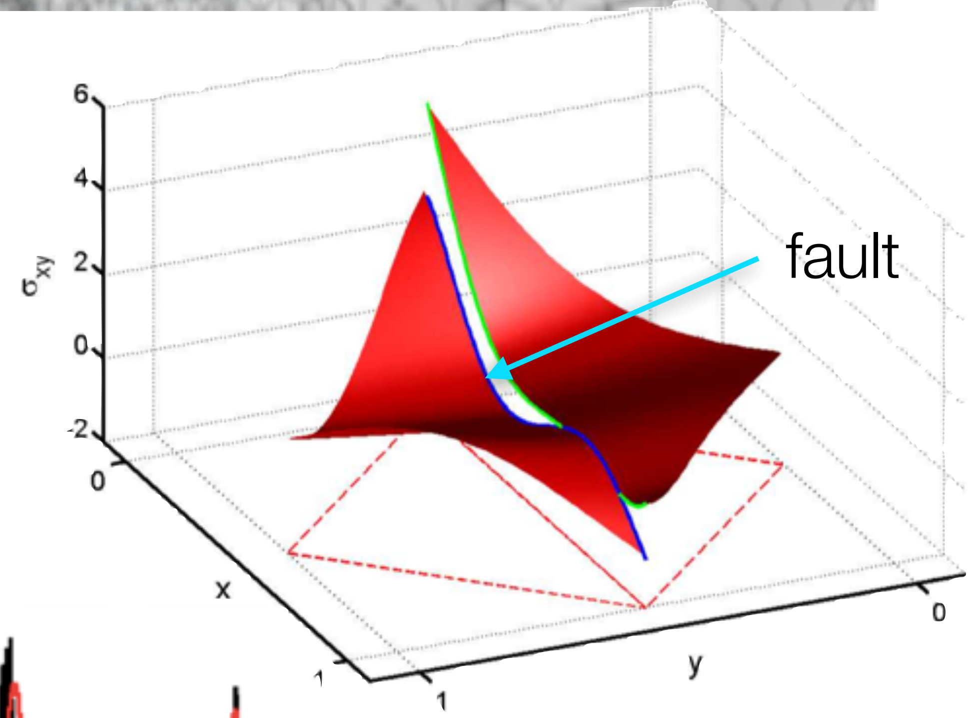
Why orthogonal basis functions? Dubiner's basis functions (Cockburn et al. 2000), leads to well-conditioned diagonal mass matrix, all matrices can be pre-calculated analytically leading to a quadrature-free scheme (e.g., Atkins & Shu 1996)



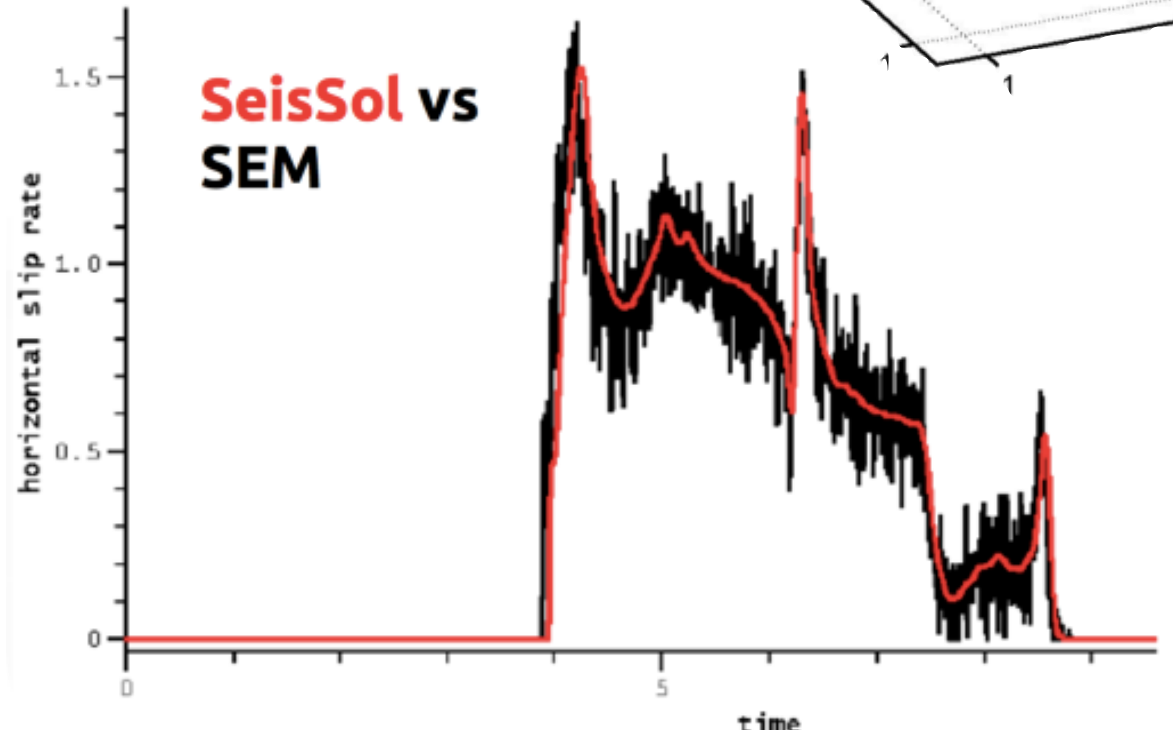
Wave field of a point source interacting with the topography of Mount Merapi Volcano.

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.

Käser and Dumbser, 2006; de la Puente et al., 2008; Pelties et al., 2014; Breuer et al., ISC'14



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)

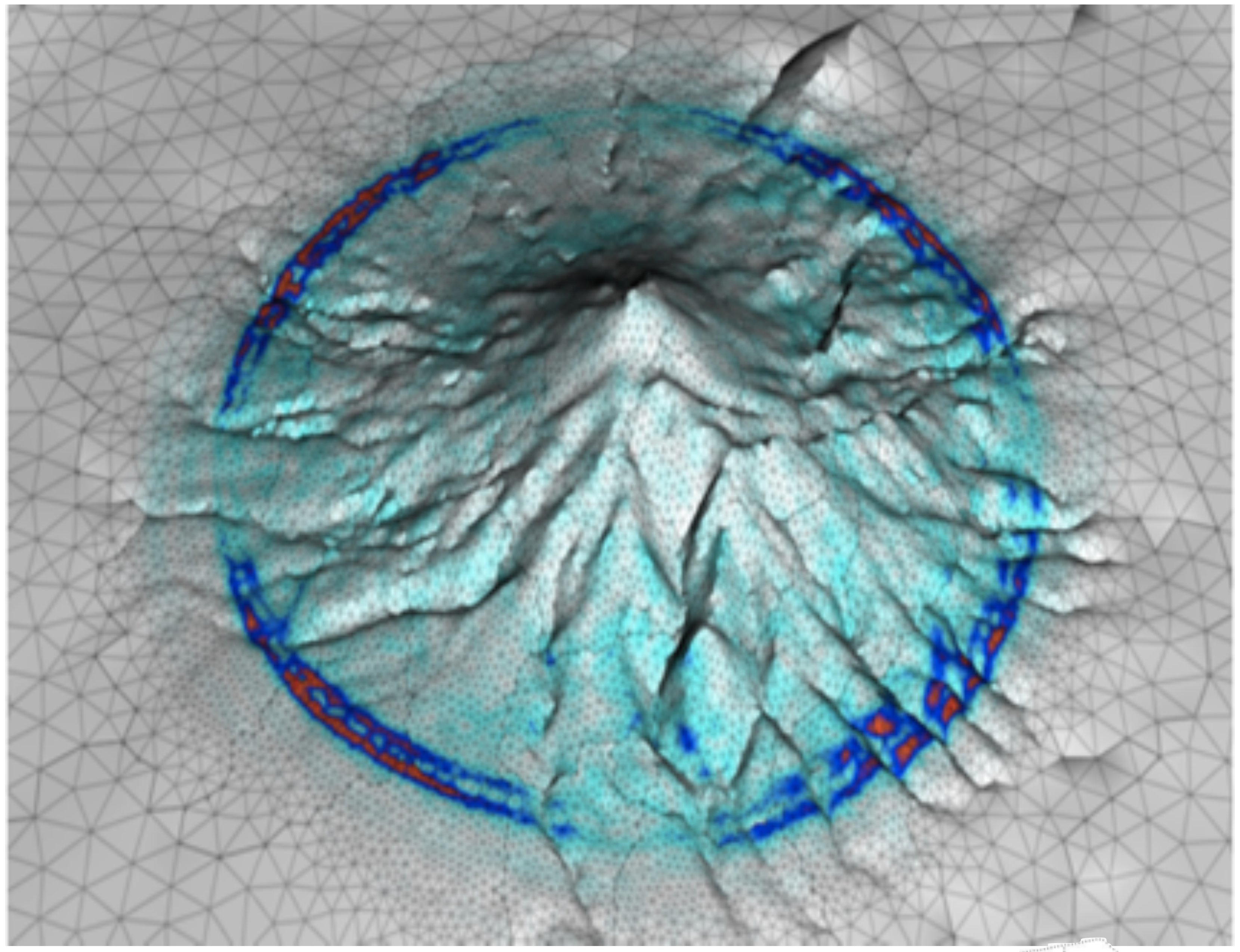
Why tets? Complex realities of geological subsurface, non-plana
mesh

Why
basis ... rns
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

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)

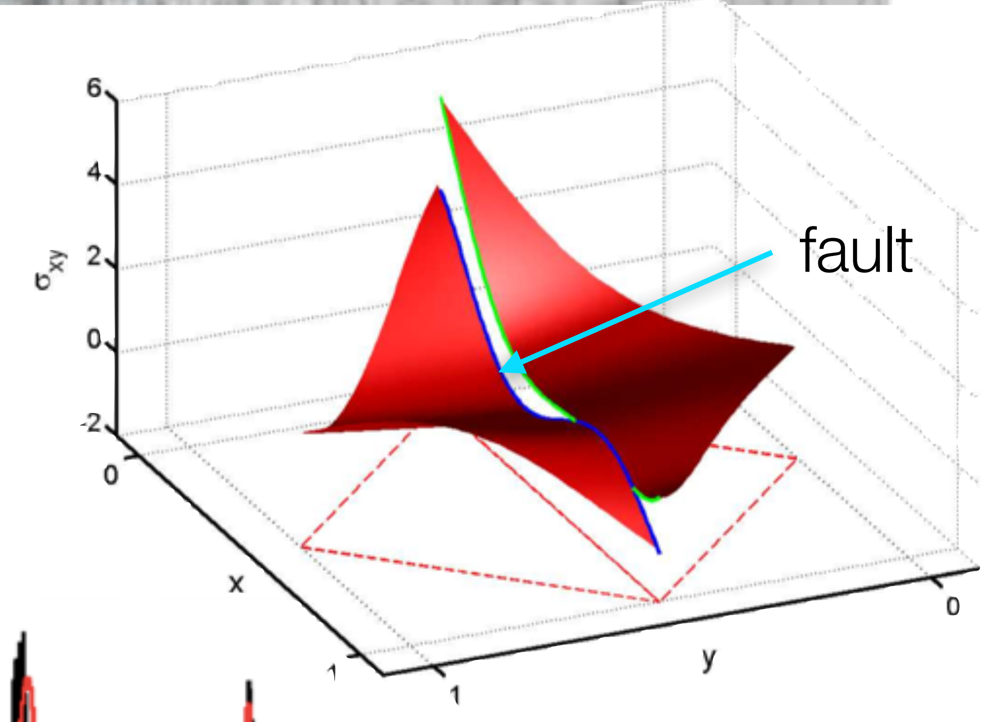
Good news: DG’s “extra” flops (storage, time to solution) compared to e.g. FEM can be performed fast using Computational Science



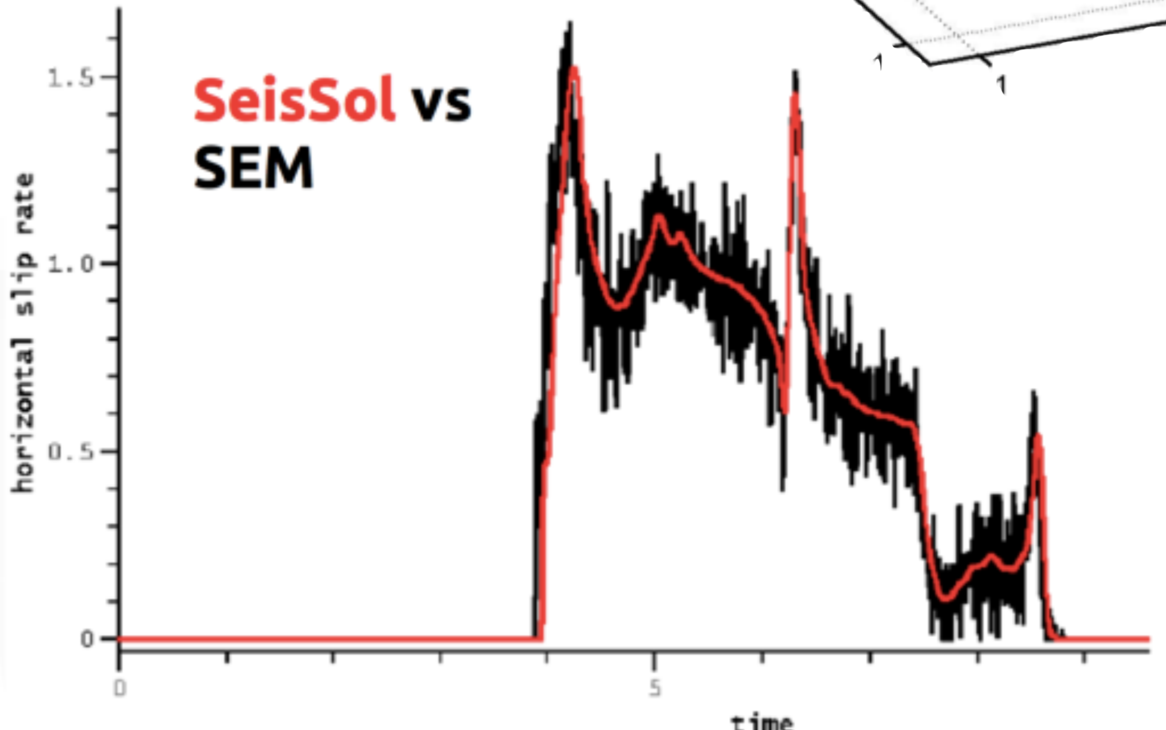
Wave field of a point source interacting with the topography of Mount Merapi Volcano.

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.

Käser and Dumbser, 2006; de la Puente et al., 2008; Pelties et al., 2014; Breuer et al., ISC’14



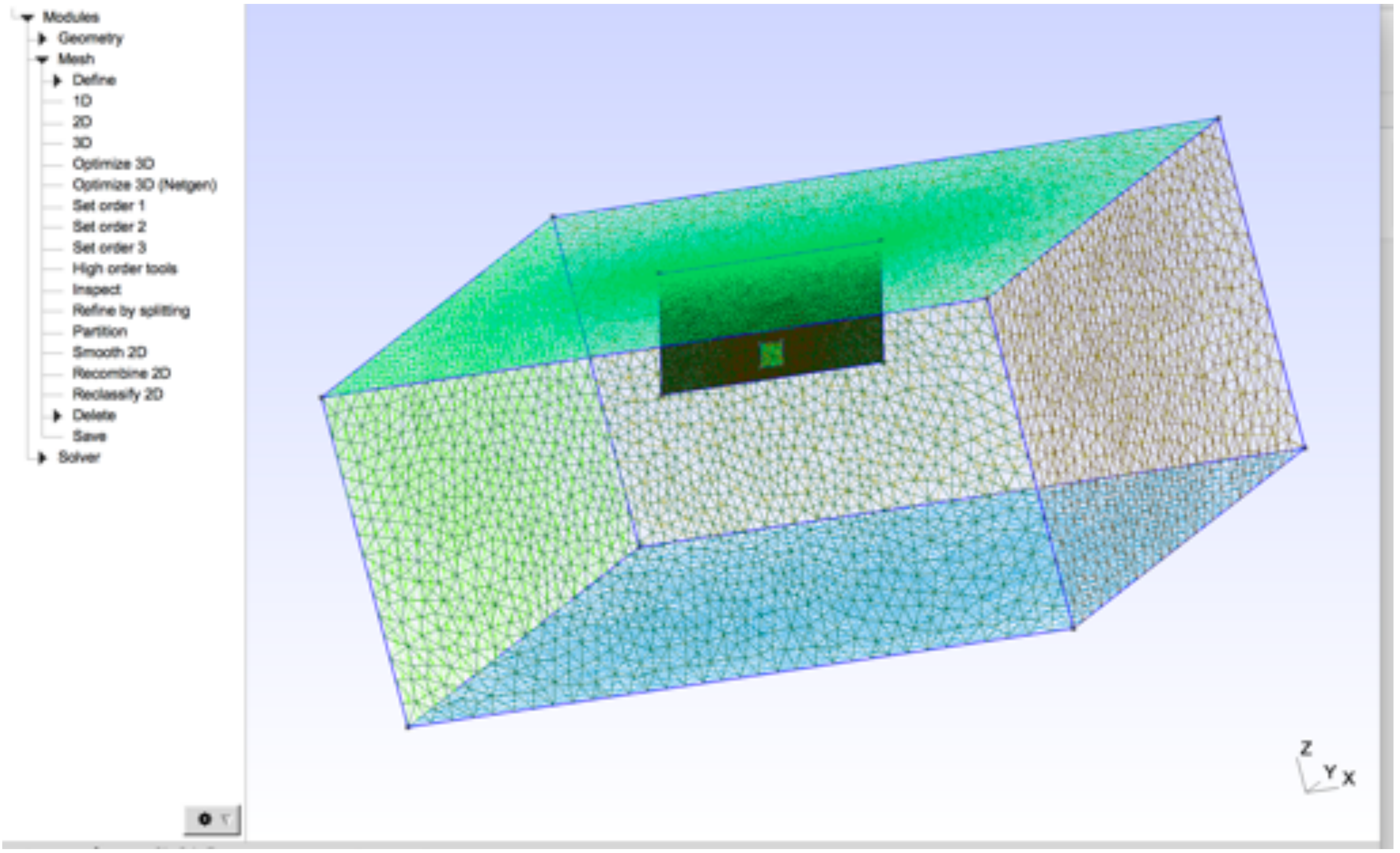
Representation of the shear stress discontinuity across the fault interface. Spontaneous rupture = internal boundary condition of flux term.



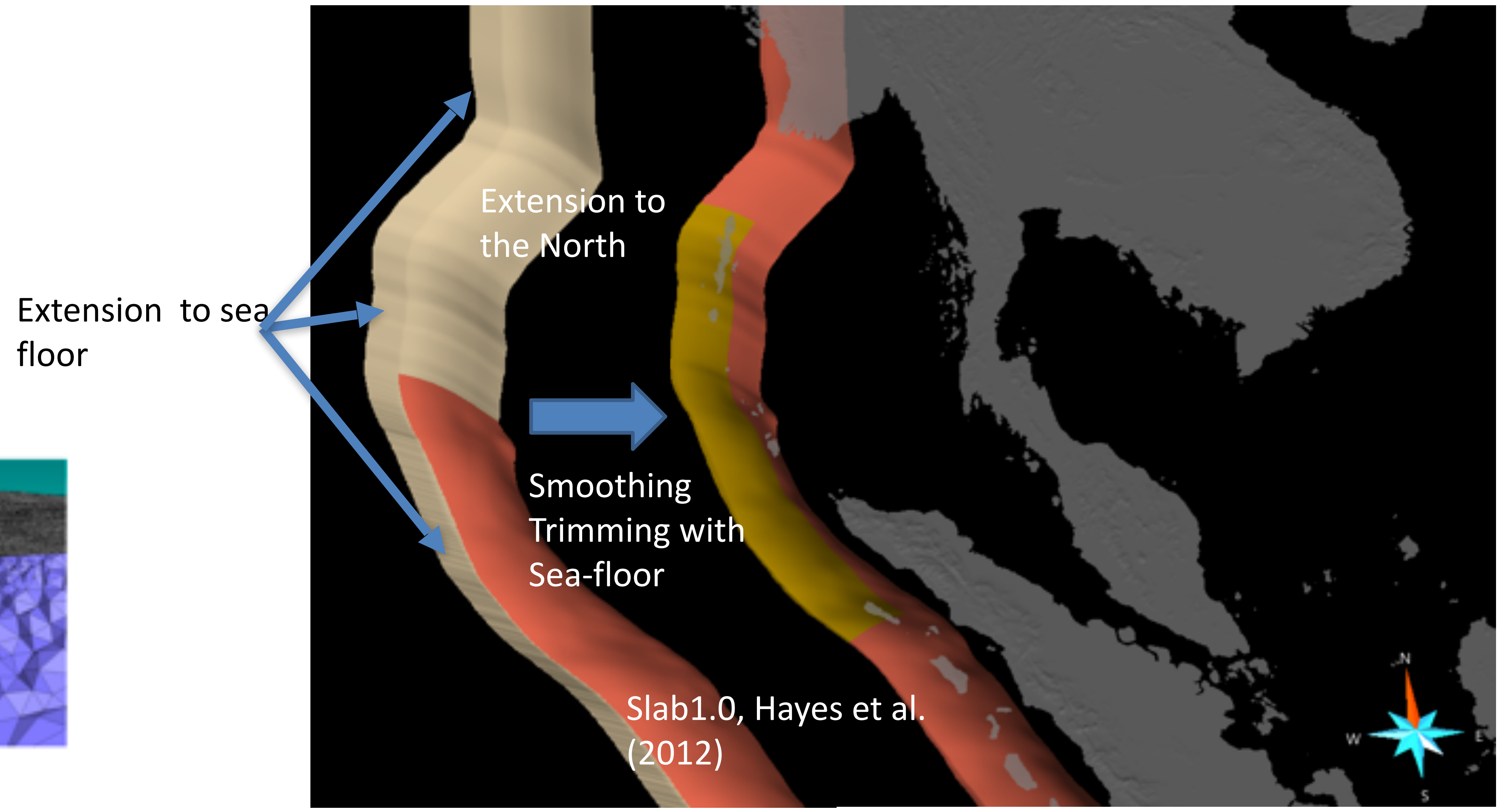
Due to the properties of the exact Riemann solver, solutions on the fault remain free of spurious oscillations

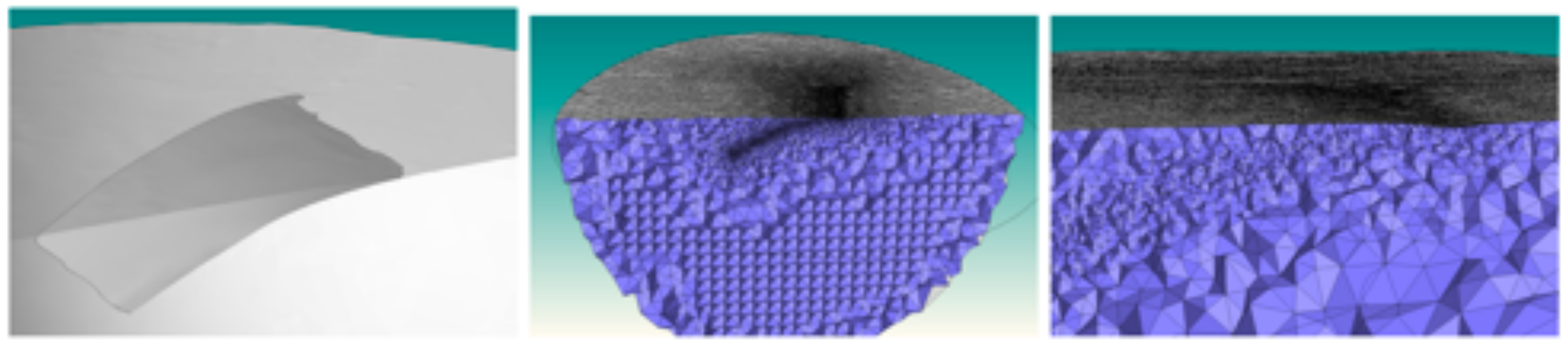
SeisSol: Geometry and meshing

- **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

siam 2021

Balancing HPC and geophysics

Breuer et al.,ISC14, Heinecke et al.,SC14
Breuer et al.,IEEE16, Heinecke et al.,SC16
Rettenberger et al., EASC16
Uphoff & Bader, HPCS'16
Uphoff et al., SC17
Wolf et al., ICCS'20
Uphoff & Bader, TOMS'20
Dorozhinskii & Bader, HPC Asia'21

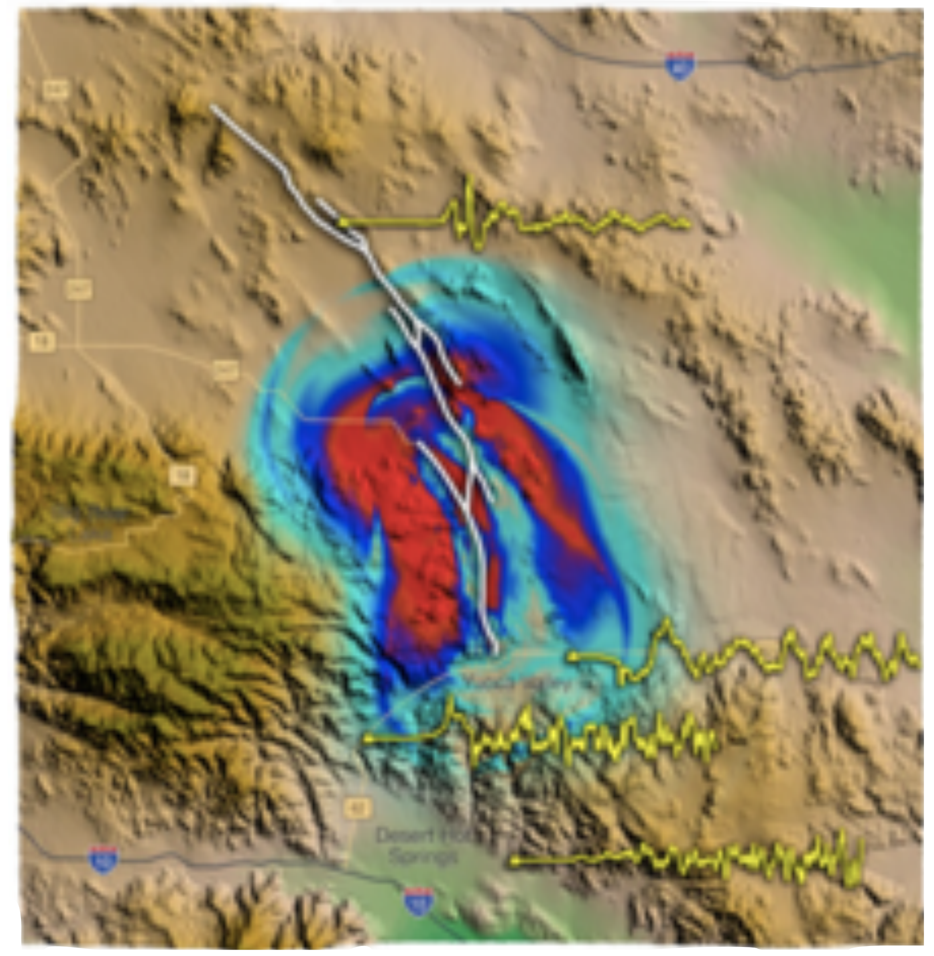
"Geophysics" Version

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

Balancing HPC and geophysics

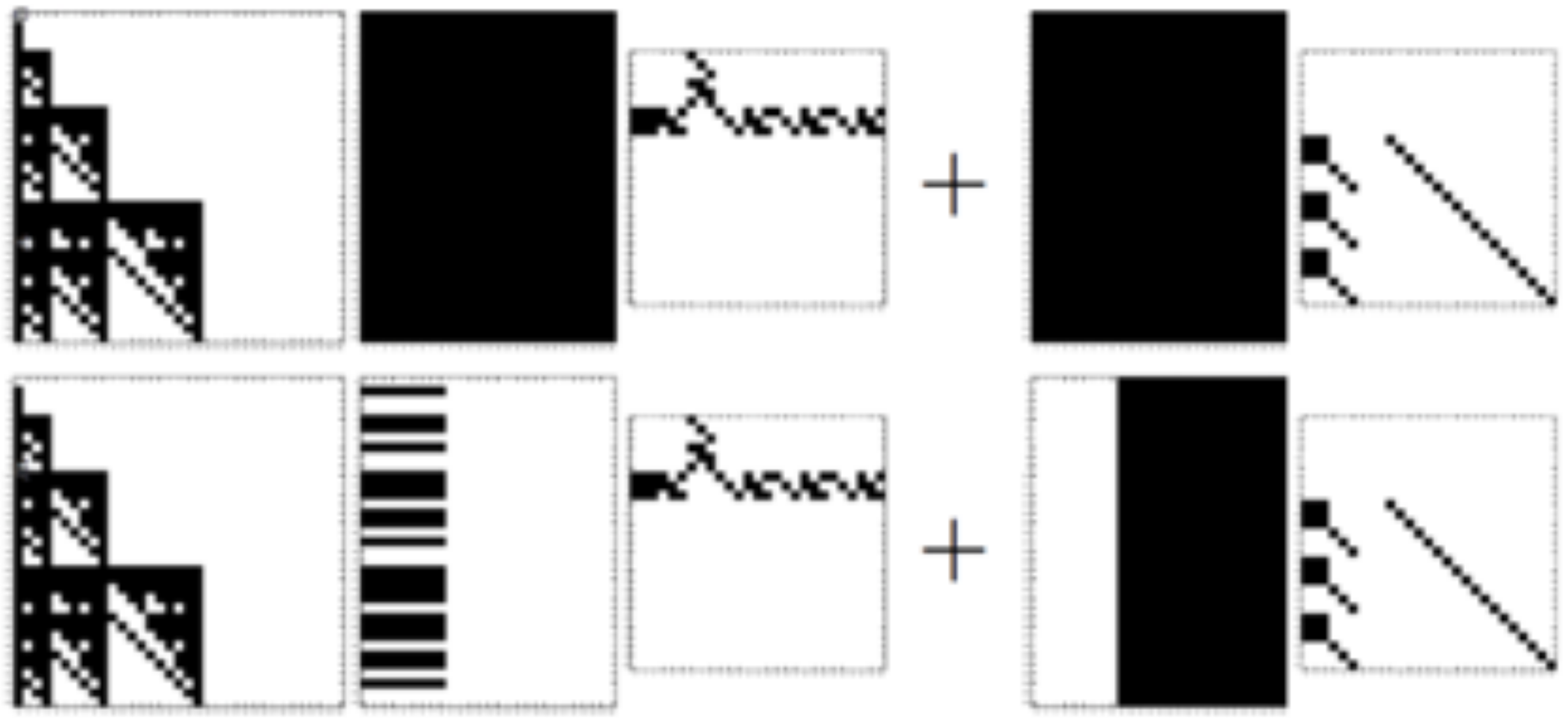
Breuer et al.,ISC14, Heinecke et al.,SC14
Breuer et al.,IEEE16, Heinecke et al.,SC16
Rettenberger et al., EASC16
Uphoff & Bader, HPCS'16
Uphoff et al., SC17
Wolf et al., ICCS'20
Uphoff & Bader, TOMS'20
Dorozhinskii & Bader, HPC Asia'21

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

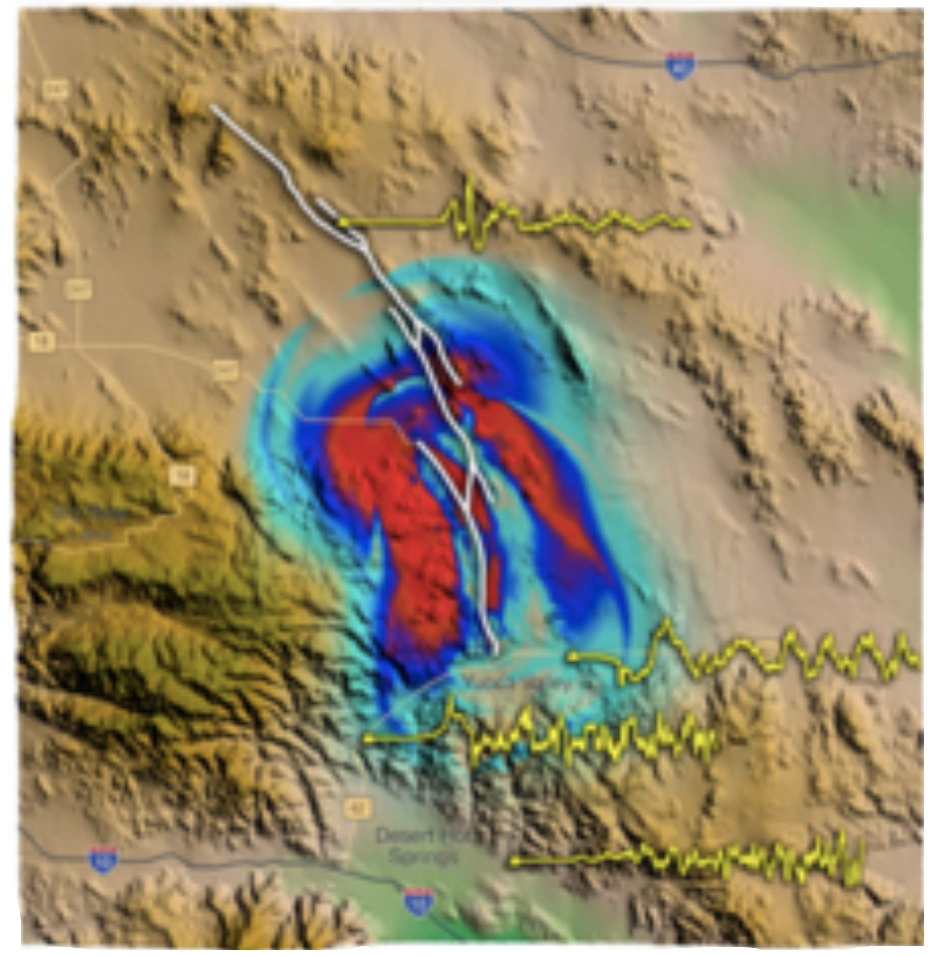
➡ **A code generator automatically detects and exploits sparse block patterns**
➡ **Hardware specific full "unrolling" and vectorization of all element operations**
➡ **Customised code for each matrix-matrix multiplication via the libxsmm back-end**

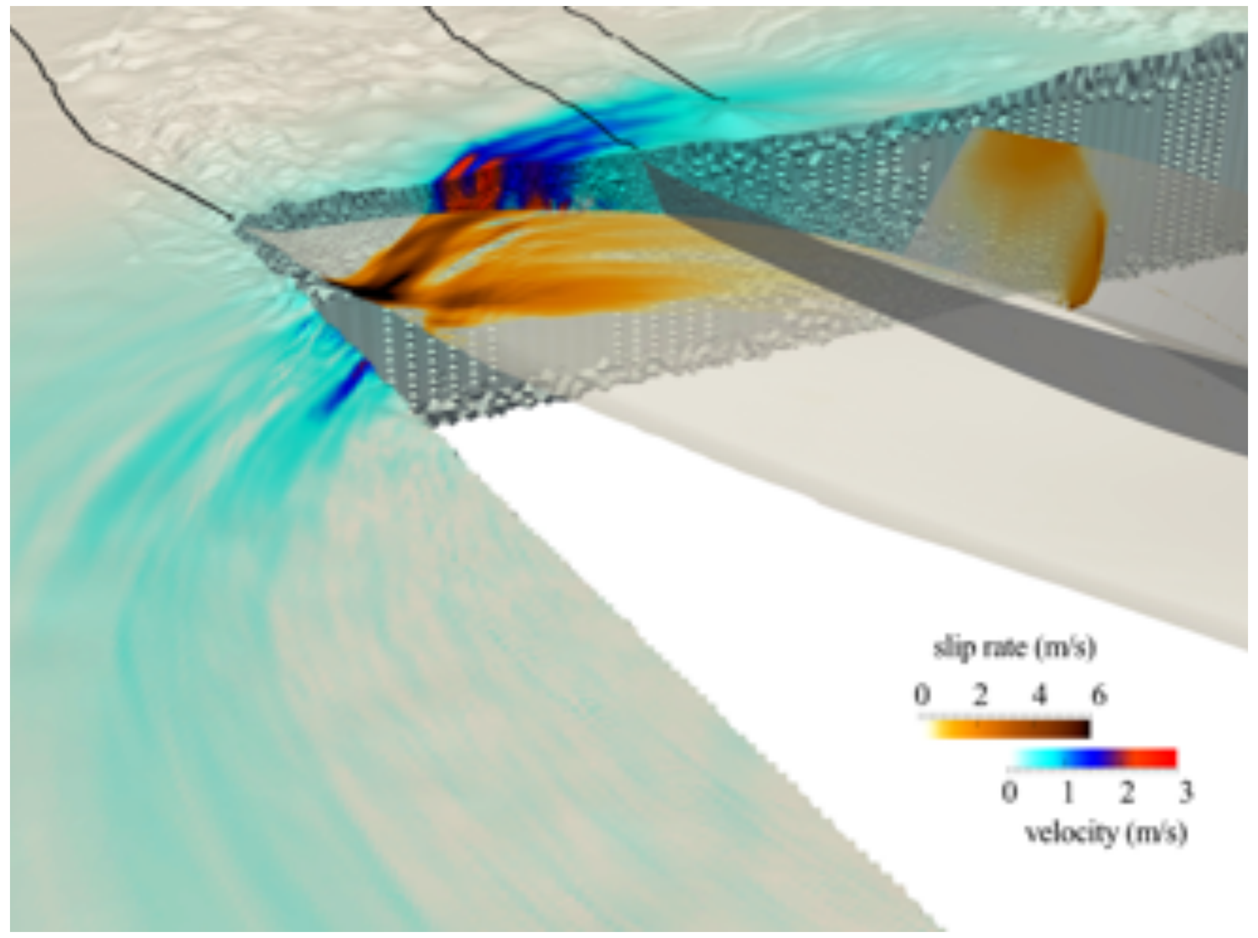
➡ **Efficiently exploits as of 2014 available hardware (AVX, MIC), reaching unto 8.6 PFLOPS on Tianhe-2 supercomputer**

Balancing HPC and geophysics

Breuer et al.,ISC14, Heinecke et al.,SC14
Breuer et al.,IEEE16, Heinecke et al.,SC16
Rettenberger et al., EASC16
Uphoff & Bader, HPCS'16
Uphoff et al., SC17
Wolf et al., ICCS'20
Uphoff & Bader, TOMS'20
Dorozhinskii & Bader, HPC Asia'21

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

- Hybrid MPI+OpenMP parallelisation
- Parallel I/O (HDF5, inc. mesh init.)
- G kernels
- oad scheme for
- ctures
- l time stepping
- Code generator also for advanced PDE's as viscoelastic attunation
- Asagi (XDMF)-geoinformation server
- Asynchronous input/output
- Overlaping computation and communication

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

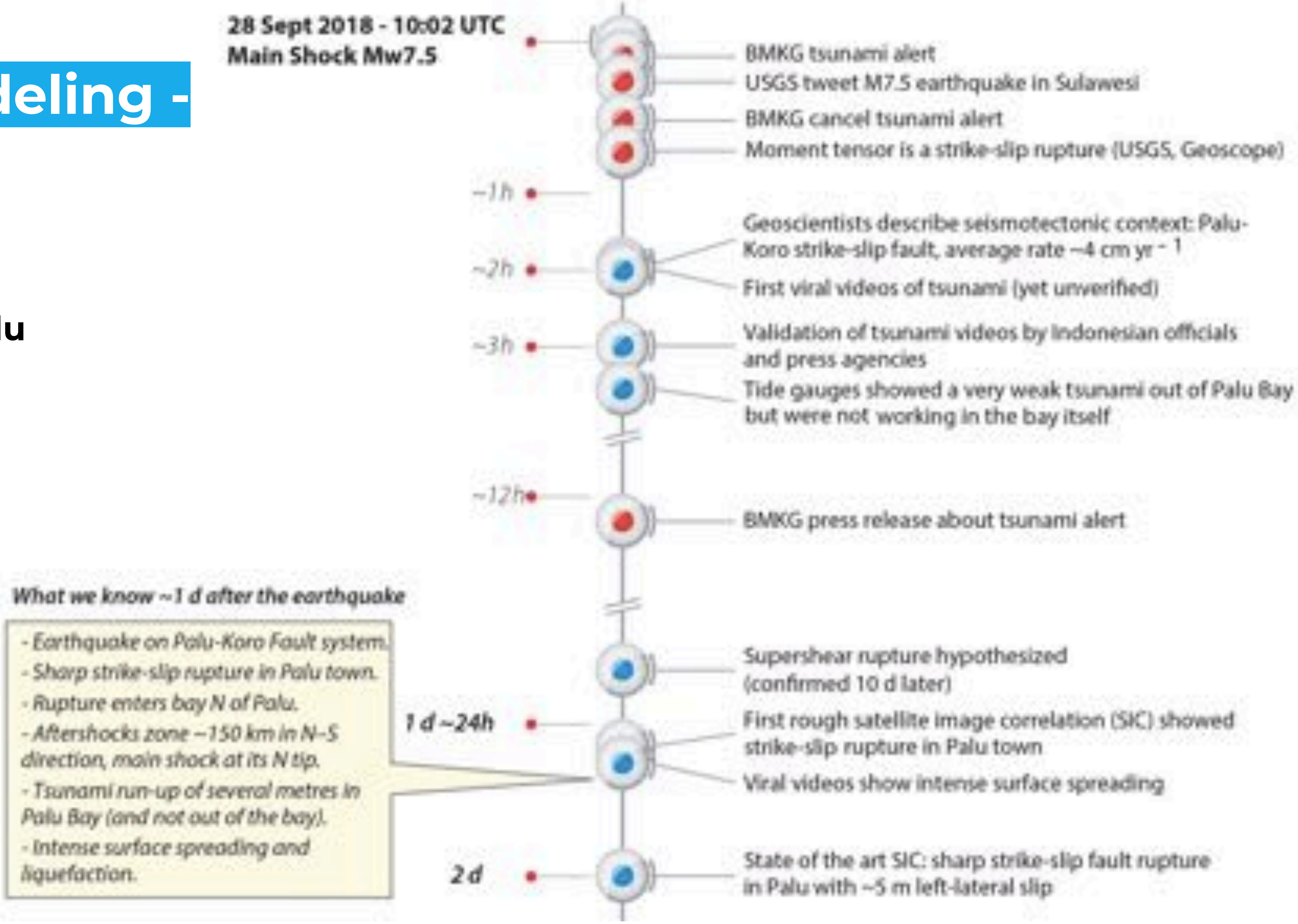
➡ **Multi-scale and multi-physics modelling is routinely feasible**
(few kCPUh per high resolution forward simulation)

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

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

Rapid earthquake/tsunami modeling - 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**

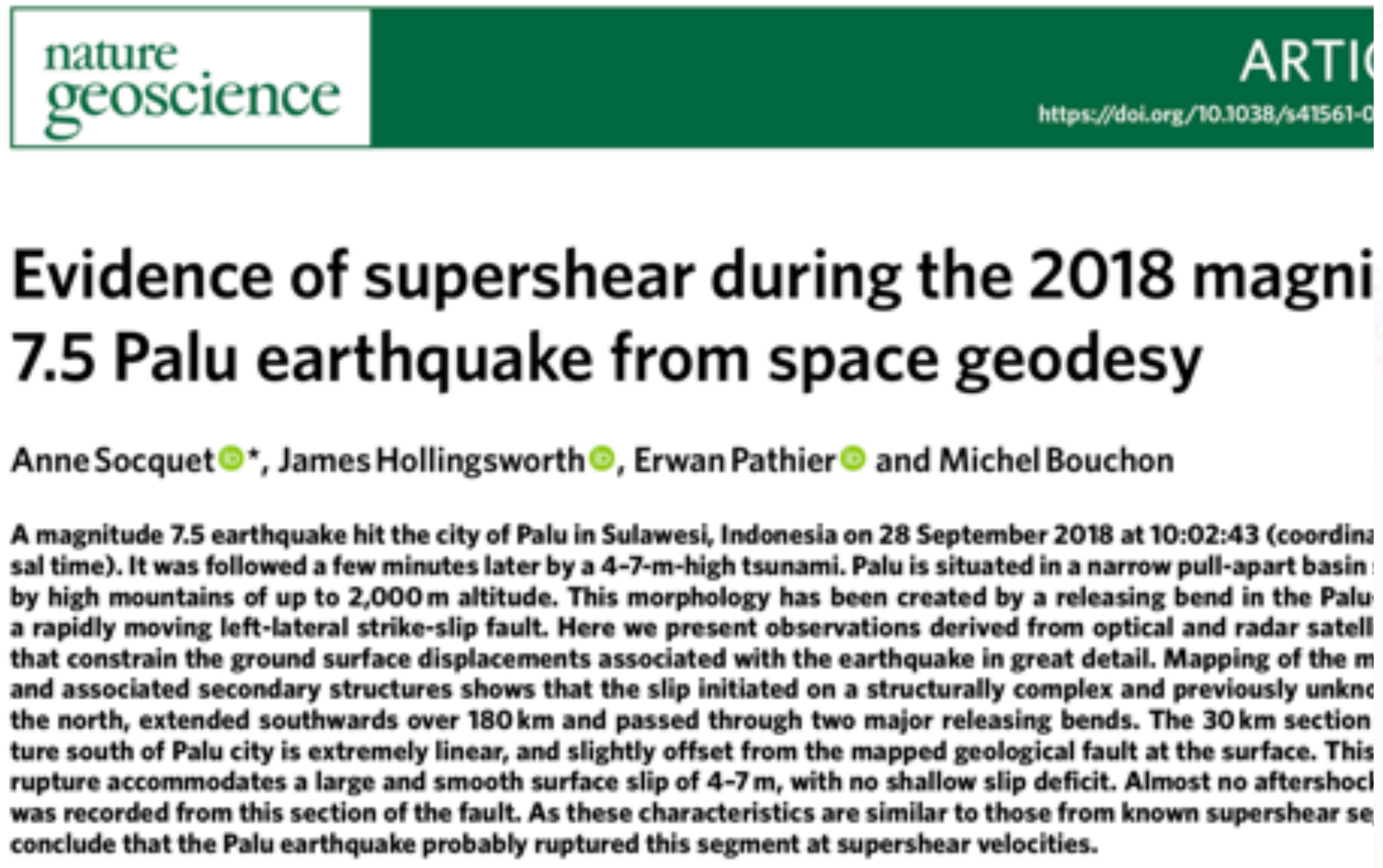


Lacassin et al., GC 2020

Lacassin et al., GC 2020

Rapid earthquake/tsunami modeling - 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**



nature geoscience

ARTI

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

Evidence of supershear during the 2018 magni
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 (coordina
sal time). It was followed a few minutes later by a 4–7-m-high tsunami. Palu is situated in a narrow pull-apart basin
by high mountains of up to 2,000 m altitude. This morphology has been created by a releasing bend in the Palu
a rapidly moving left-lateral strike-slip fault. Here we present observations derived from optical and radar satell
that constrain the ground surface displacements associated with the earthquake in great detail. Mapping of the m
and associated secondary structures shows that the slip initiated on a structurally complex and previously unkno
the north, extended southwards over 180 km and passed through two major releasing bends. The 30 km section
ture south of Palu city is extremely linear, and slightly offset from the mapped geological fault at the surface. This
rupture accommodates a large and smooth surface slip of 4–7 m, with no shallow slip deficit. Almost no aftershocl
was recorded from this section of the fault. As these characteristics are similar to those from known supershear se
conclude that the Palu earthquake probably ruptured this segment at supershear velocities.

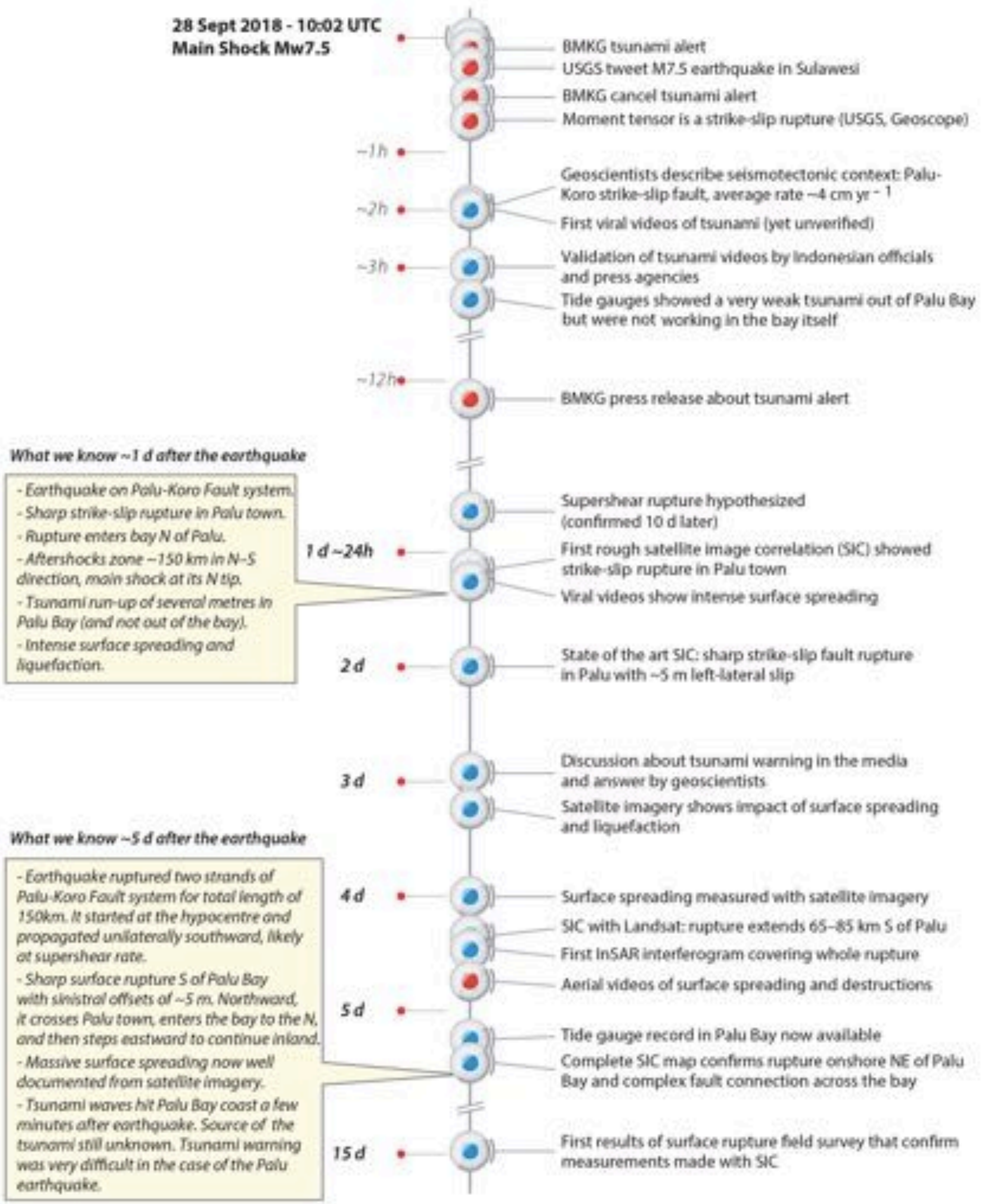
nature geoscience

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 velo
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.

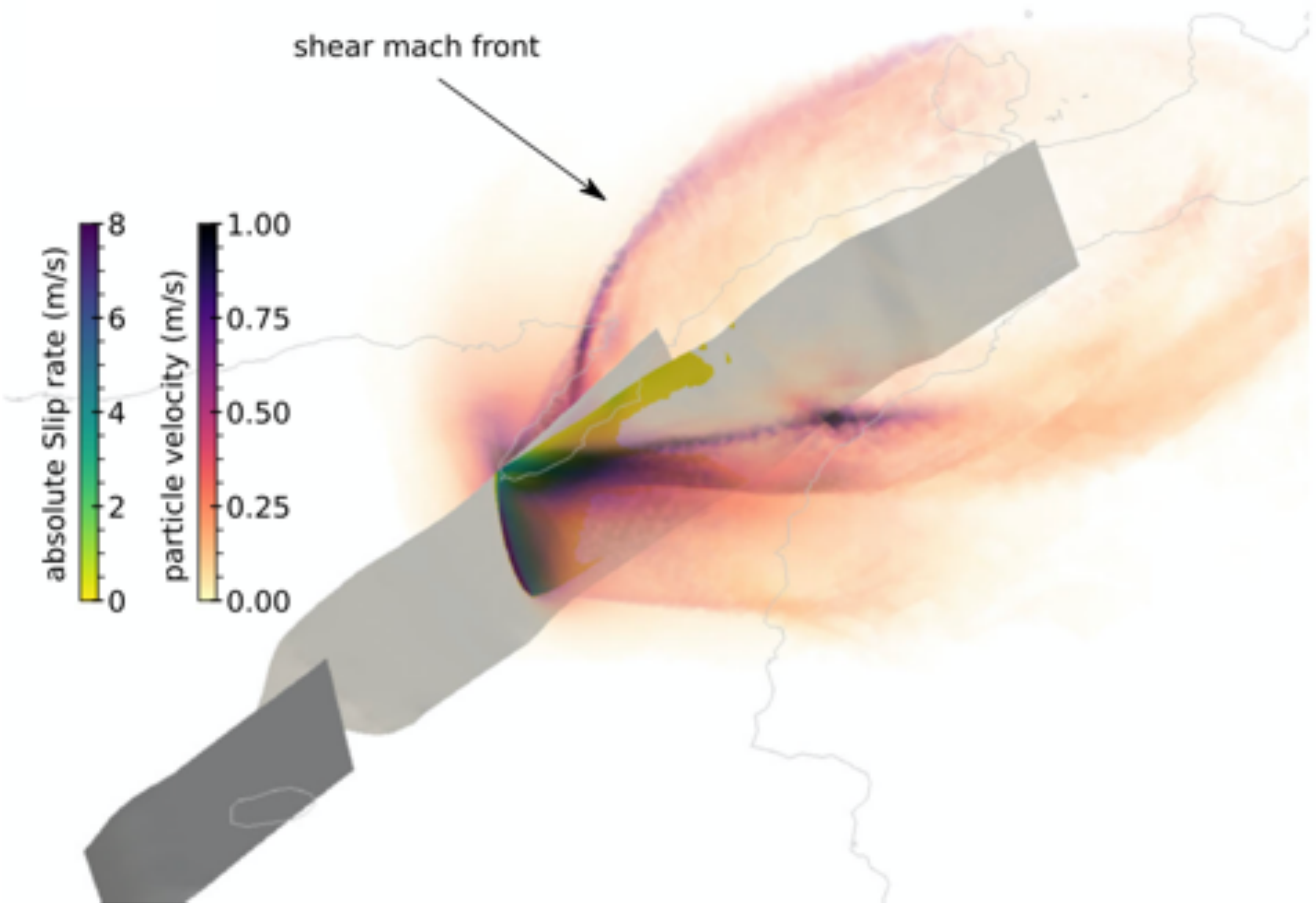


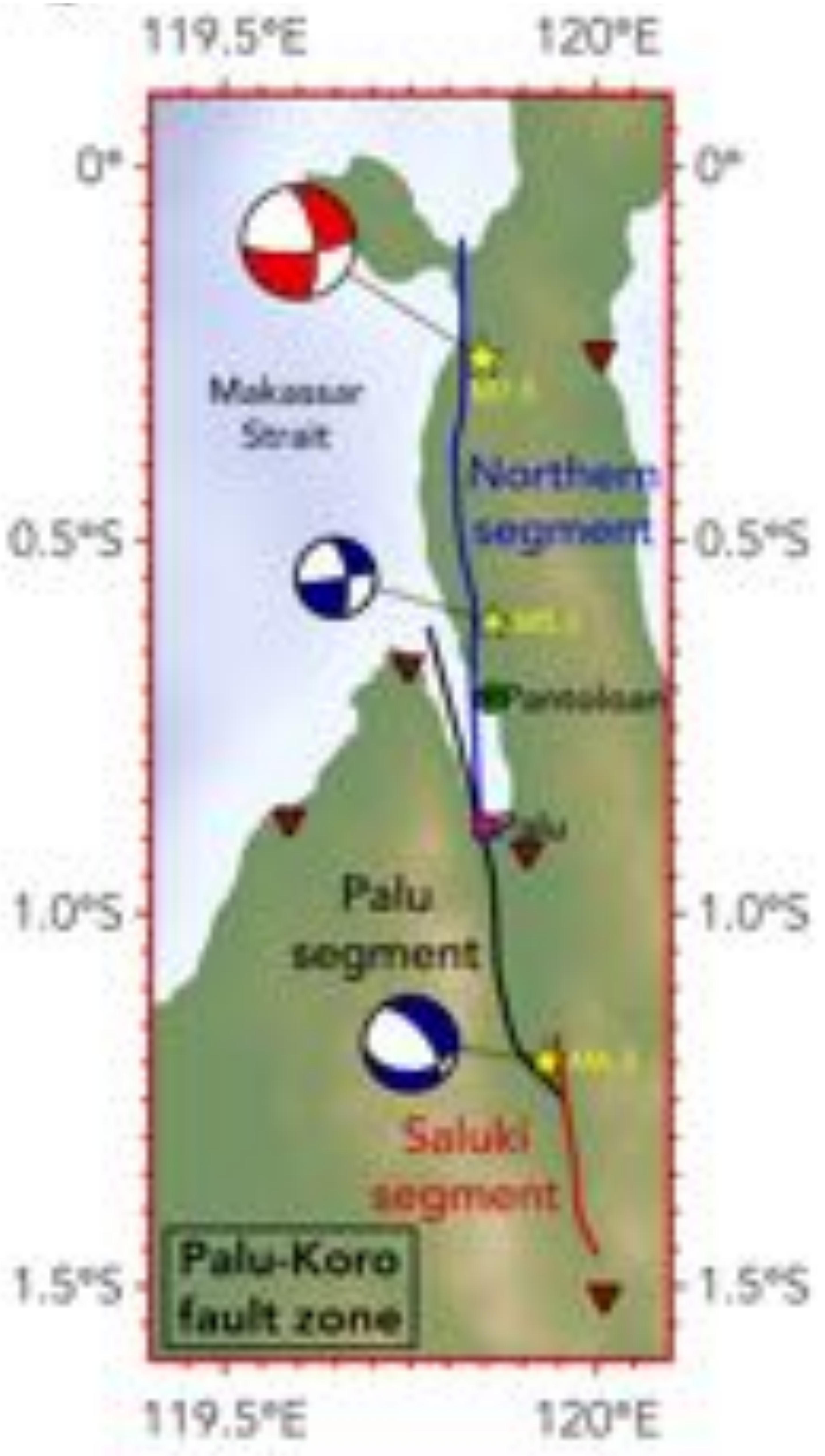
Ulrich et al., PAGEOPH 2019

Rapid earthquake/tsunami modelling - the 2018, Palu-Sulawesi Event

3D dynamic rupture setup from **sparse data**

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



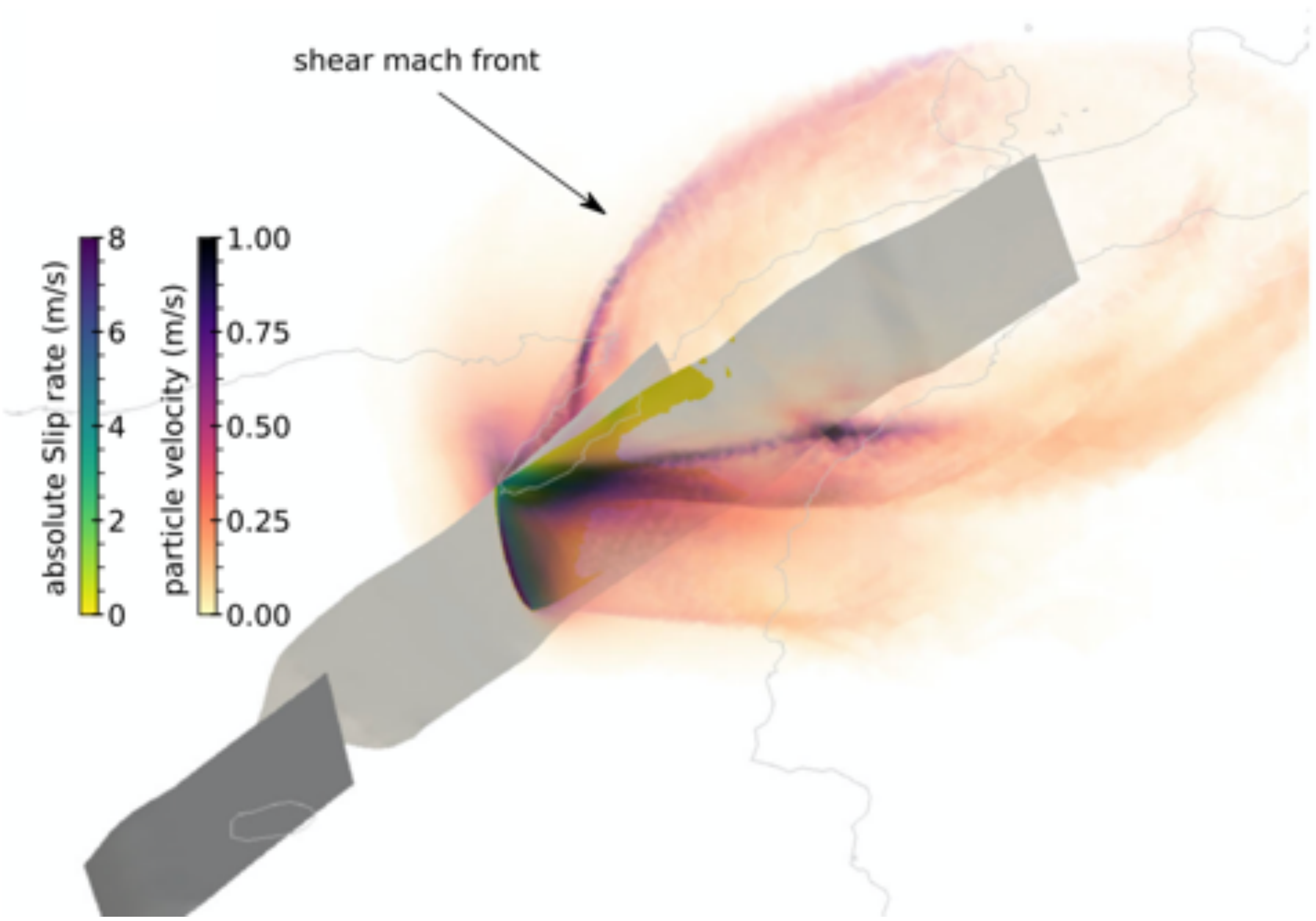


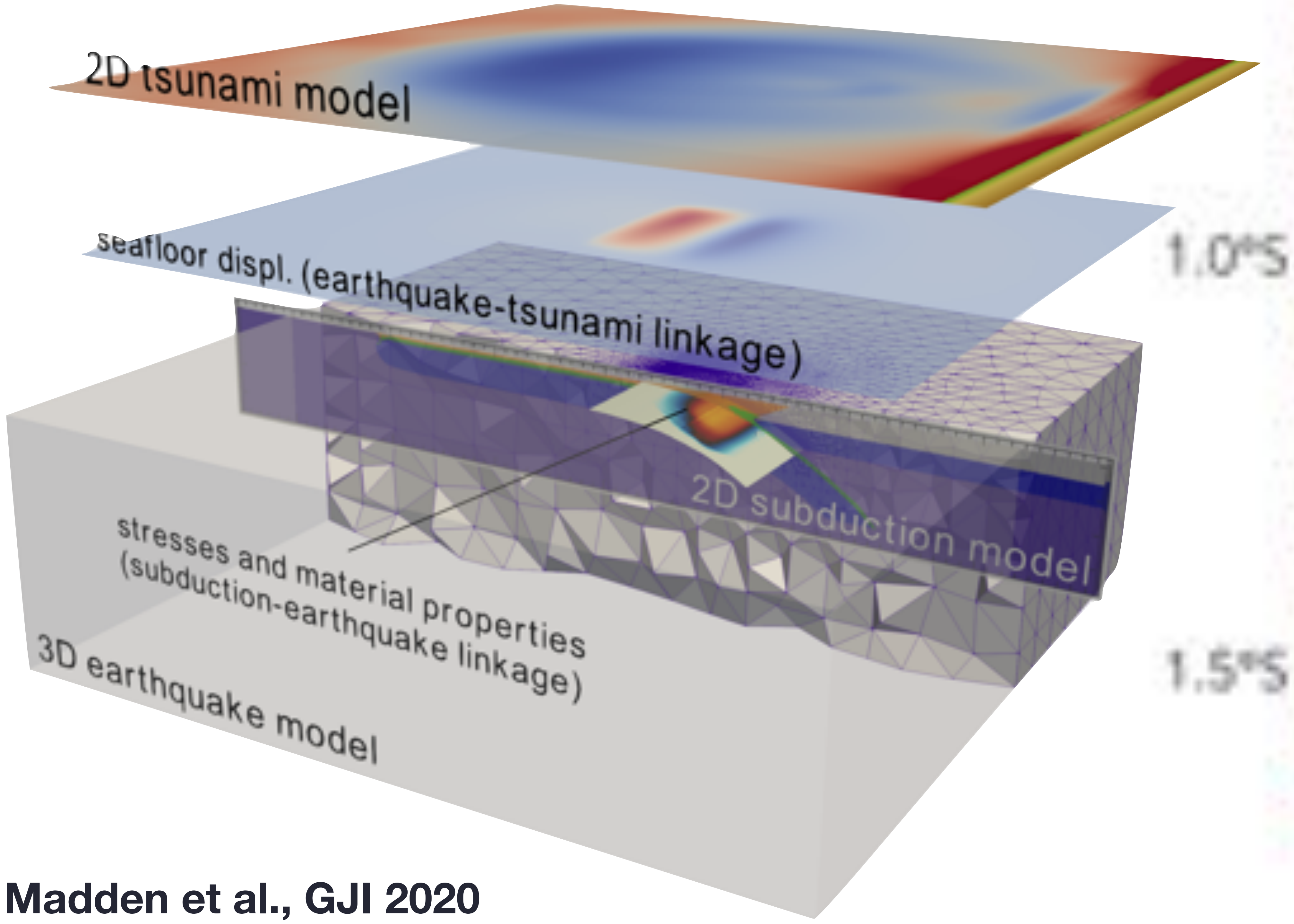
Ulrich et al., PAGEOPH 2019

Rapid earthquake/tsunami modelling - the 2018, Palu-Sulawesi Event

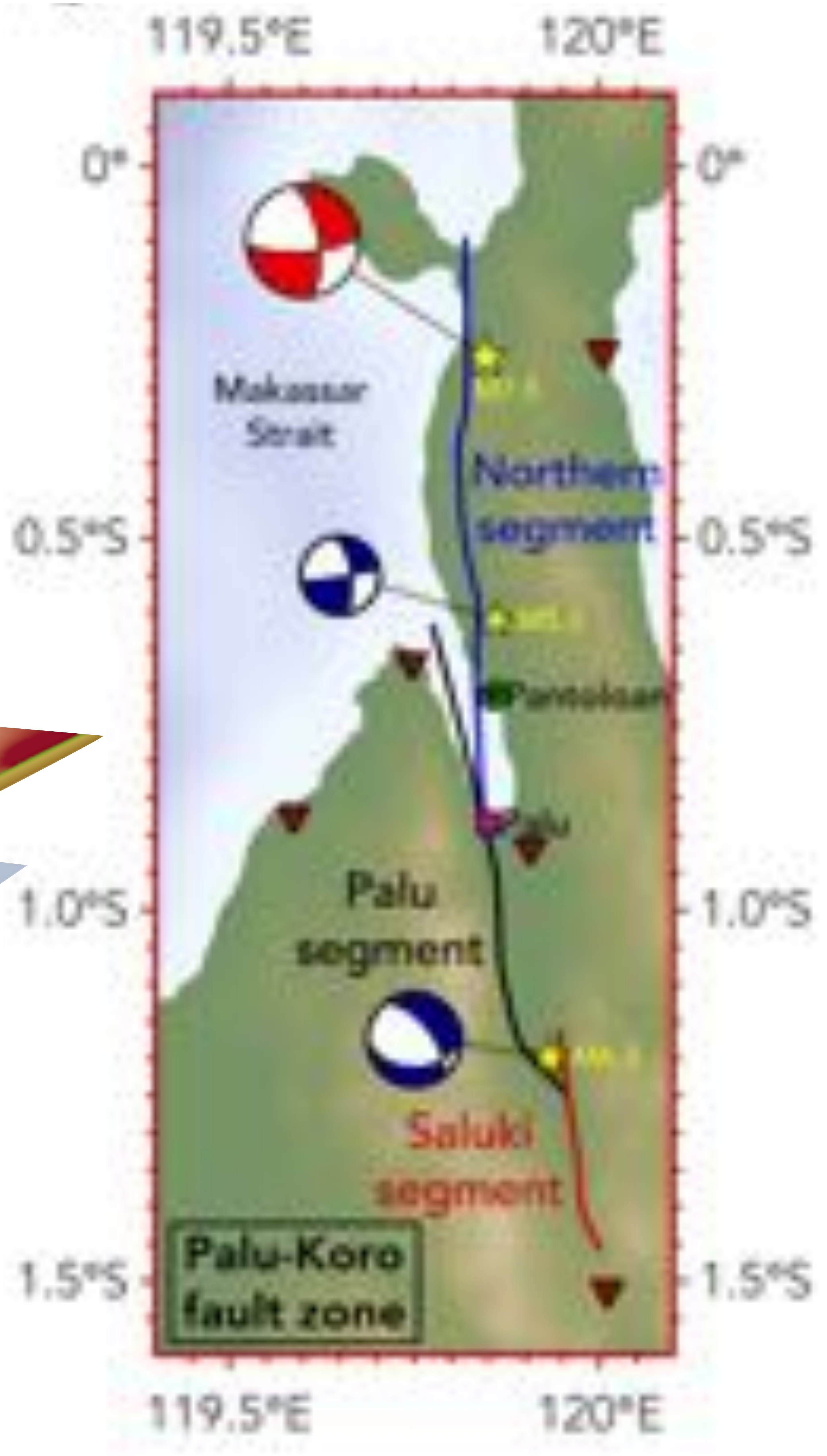
3D dynamic rupture setup from **sparse data**

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



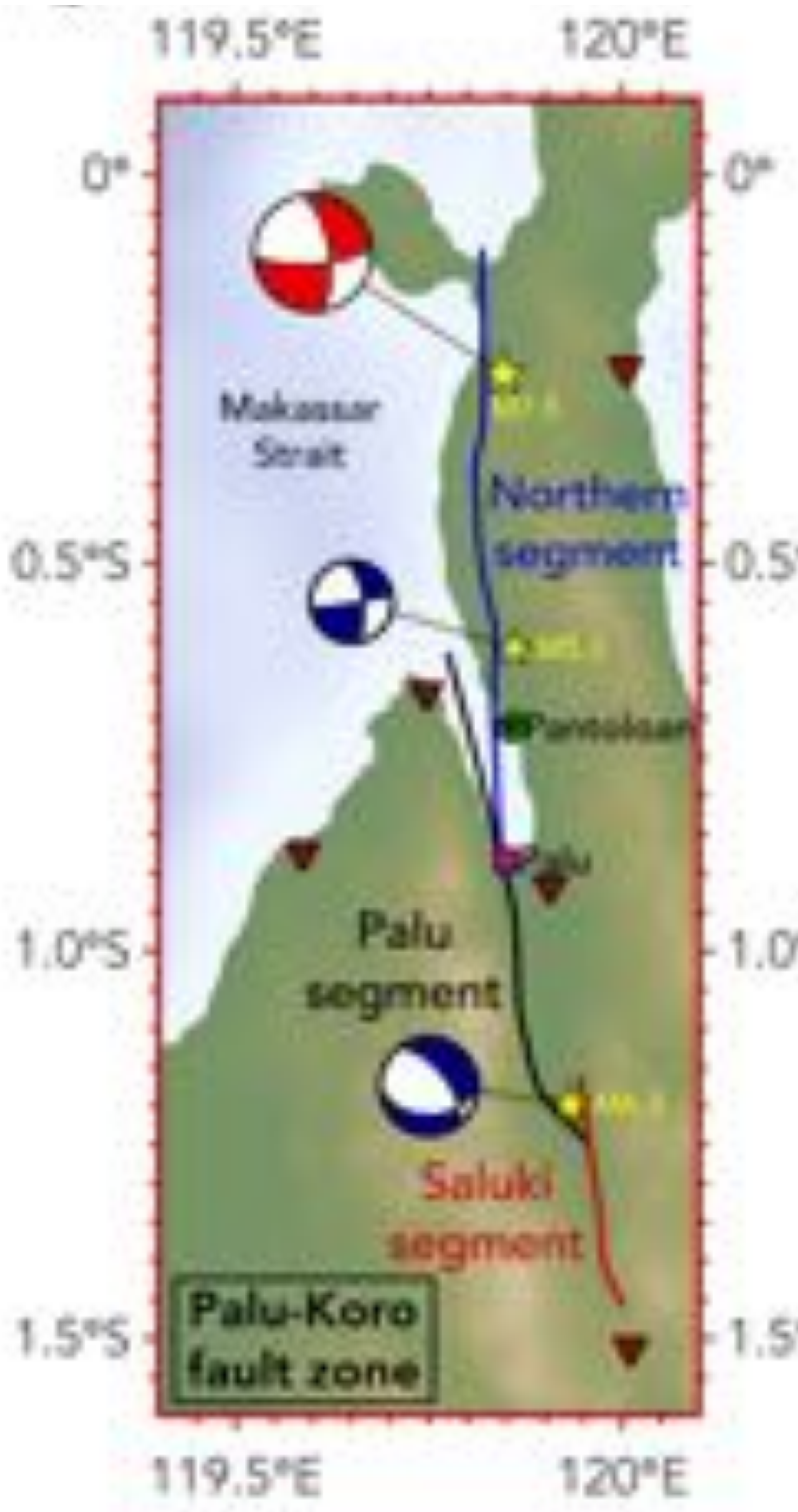


Madden et al., GJI 2020

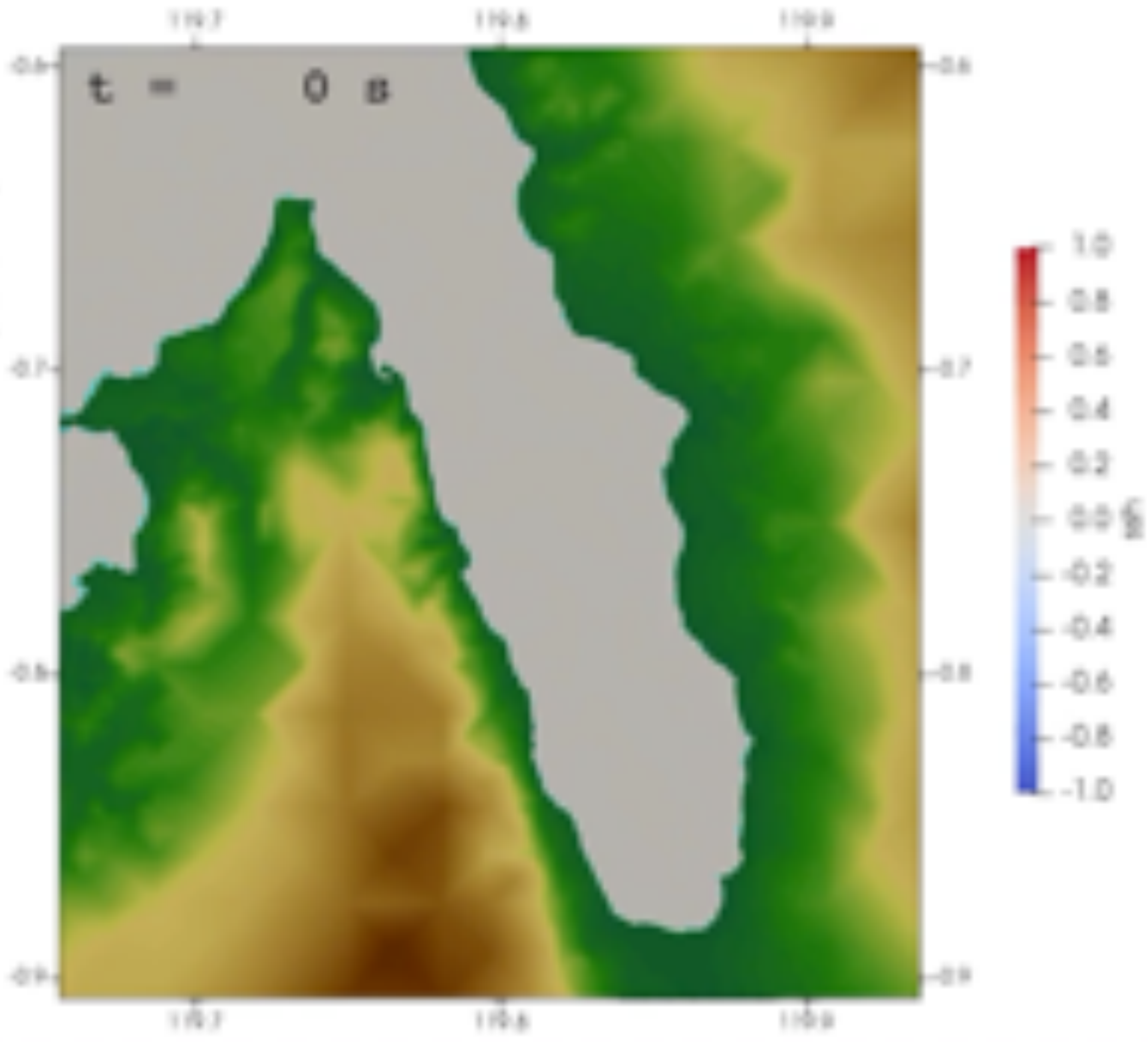


Ulrich et al., PAGEOPH 2019

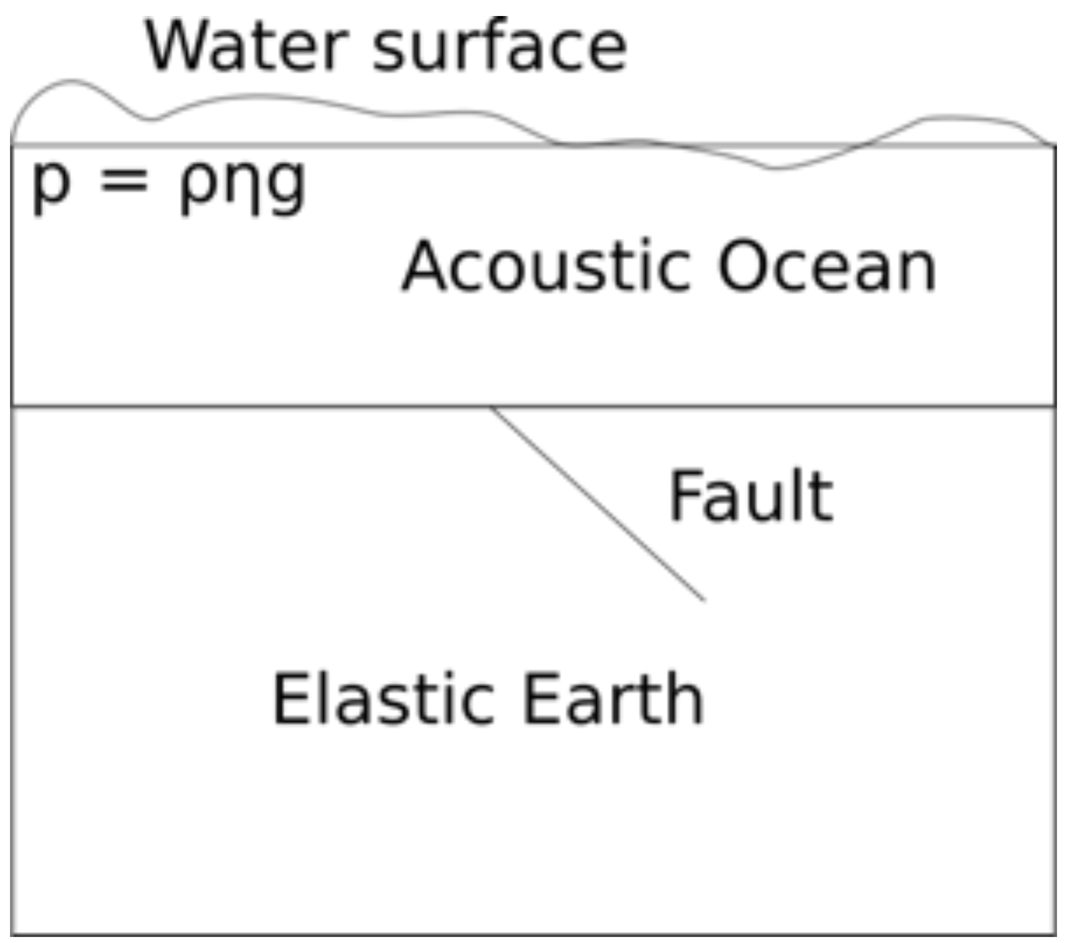
Rapid earthquake/tsunami modelling - the 2018, Palu-Sulawesi Event

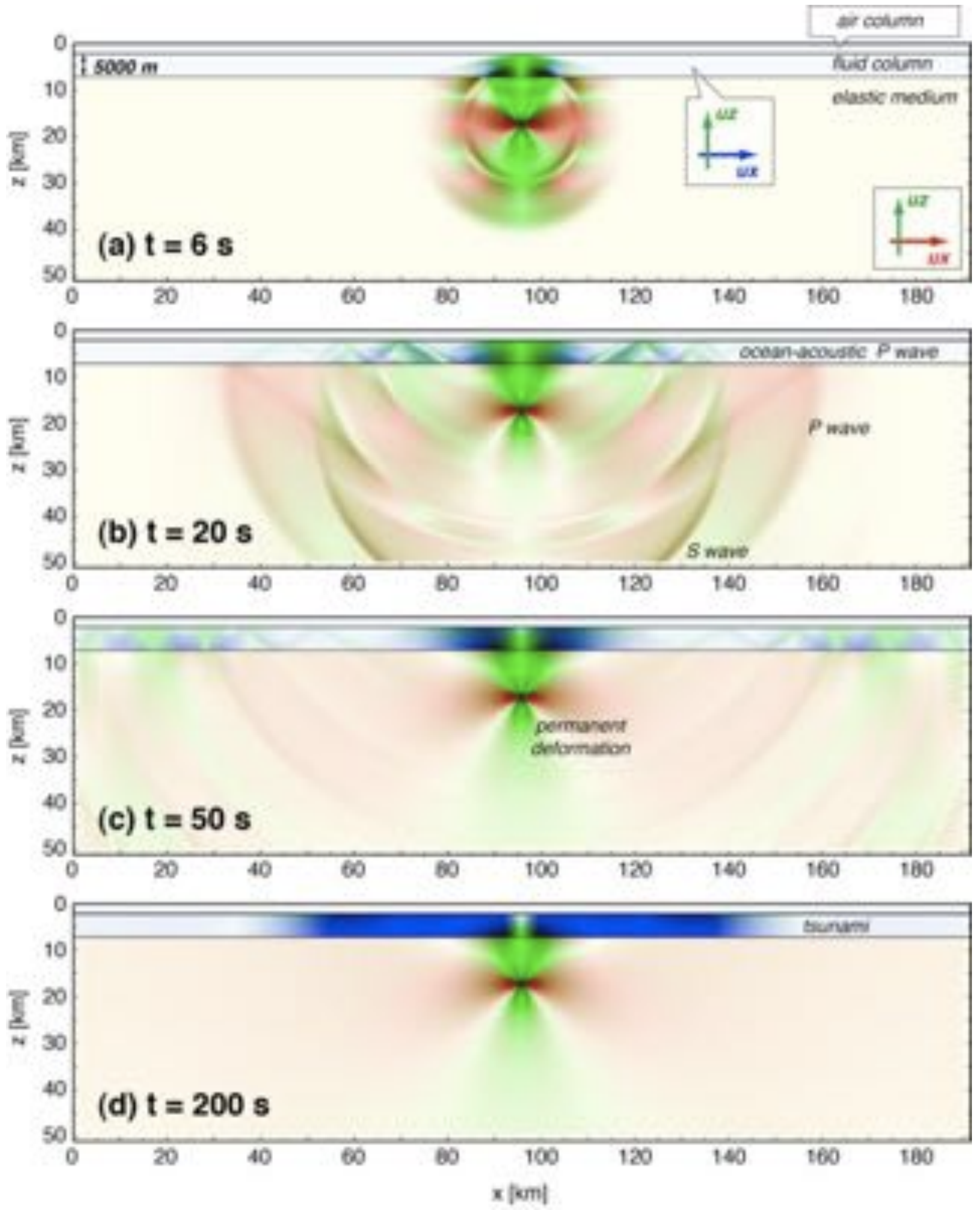


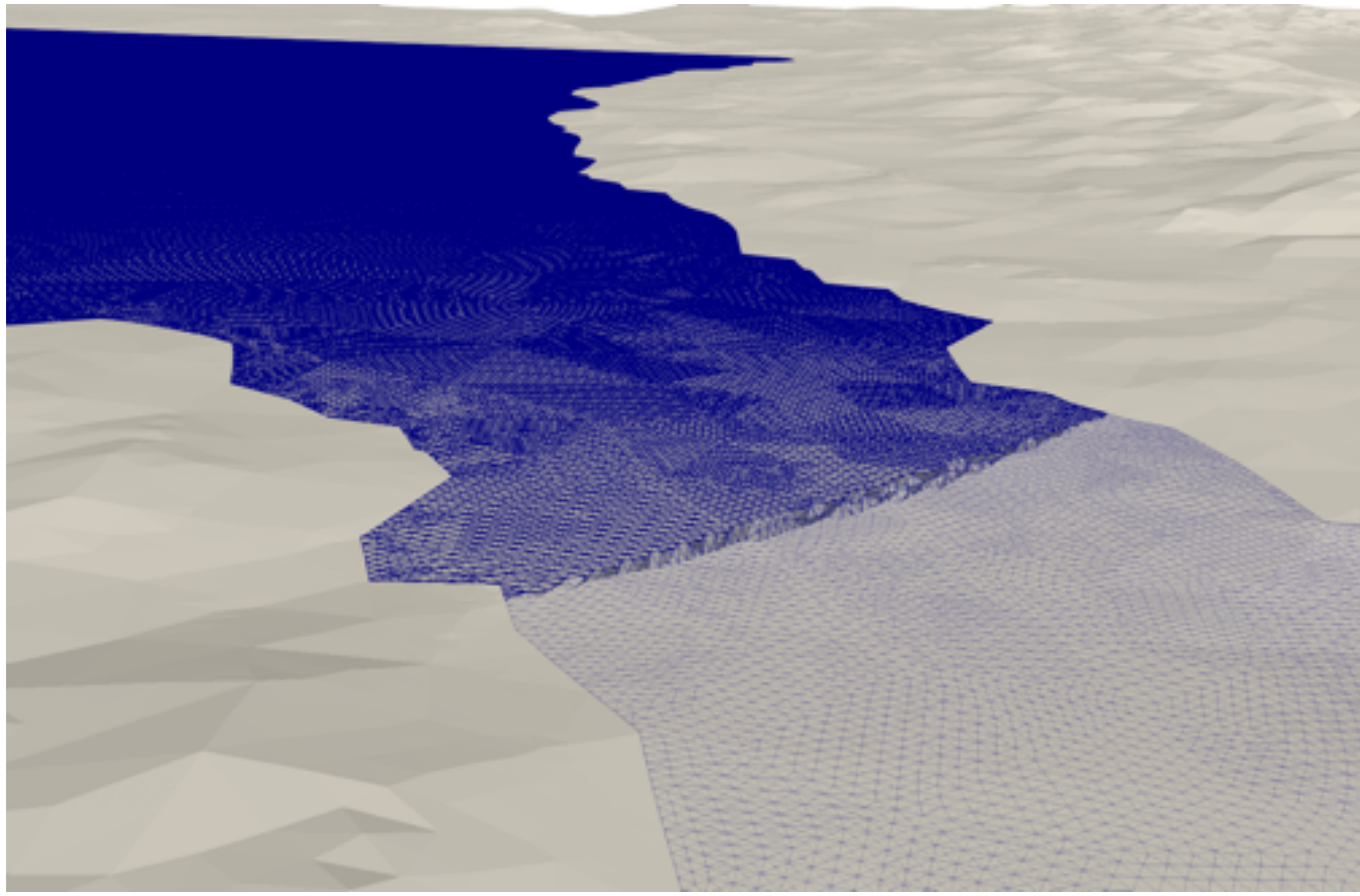
- Open source one-way linking workflow including proper treatment of time-dependent displacements, Fourier filtering of reverberating seismic waves, and also translating between geodynamic large deformation models to elastodynamics
- **Earthquake-induced movement of seafloor** beneath Palu Bay itself may played a critical role generating the tsunami

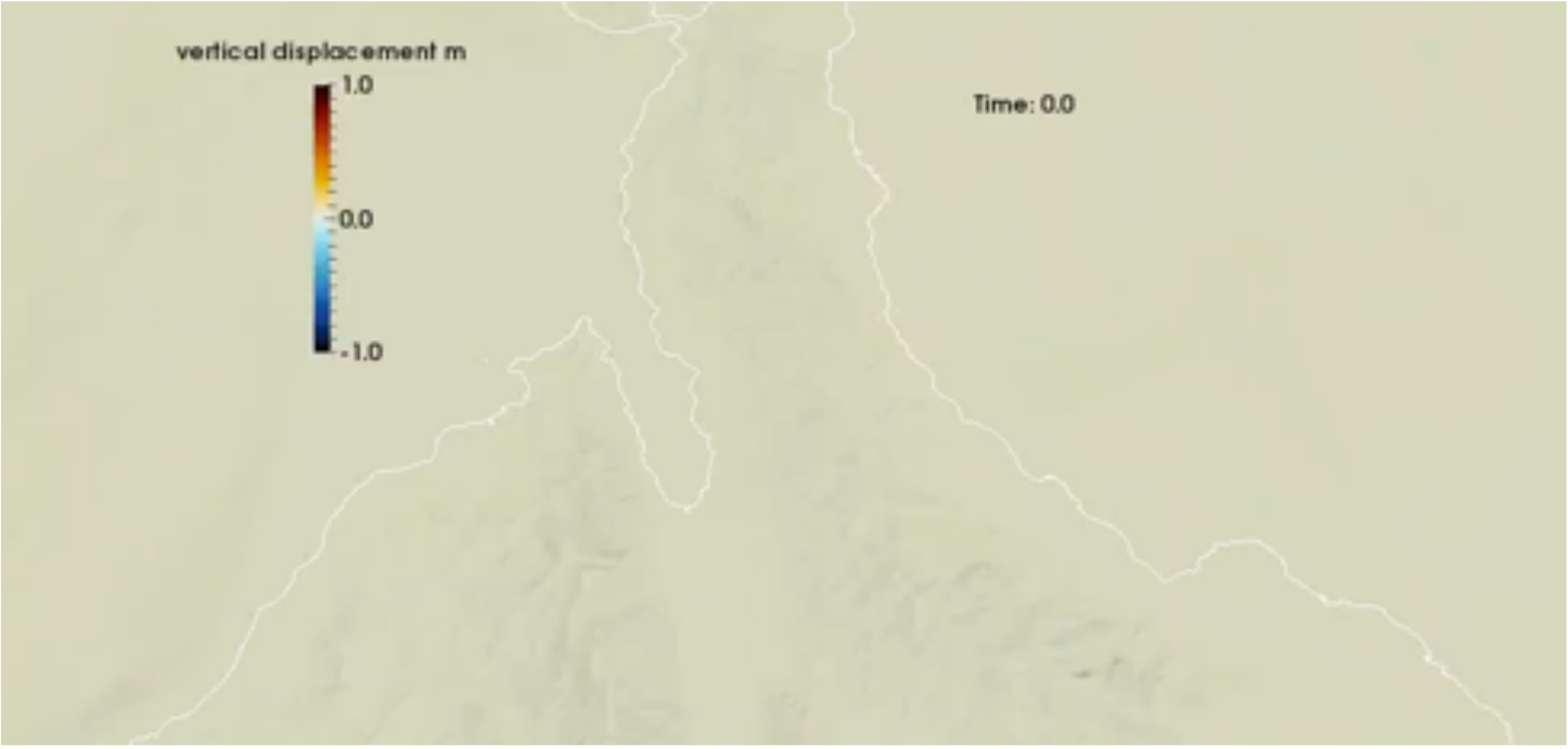


Fully coupled earthquake-tsunami modeling







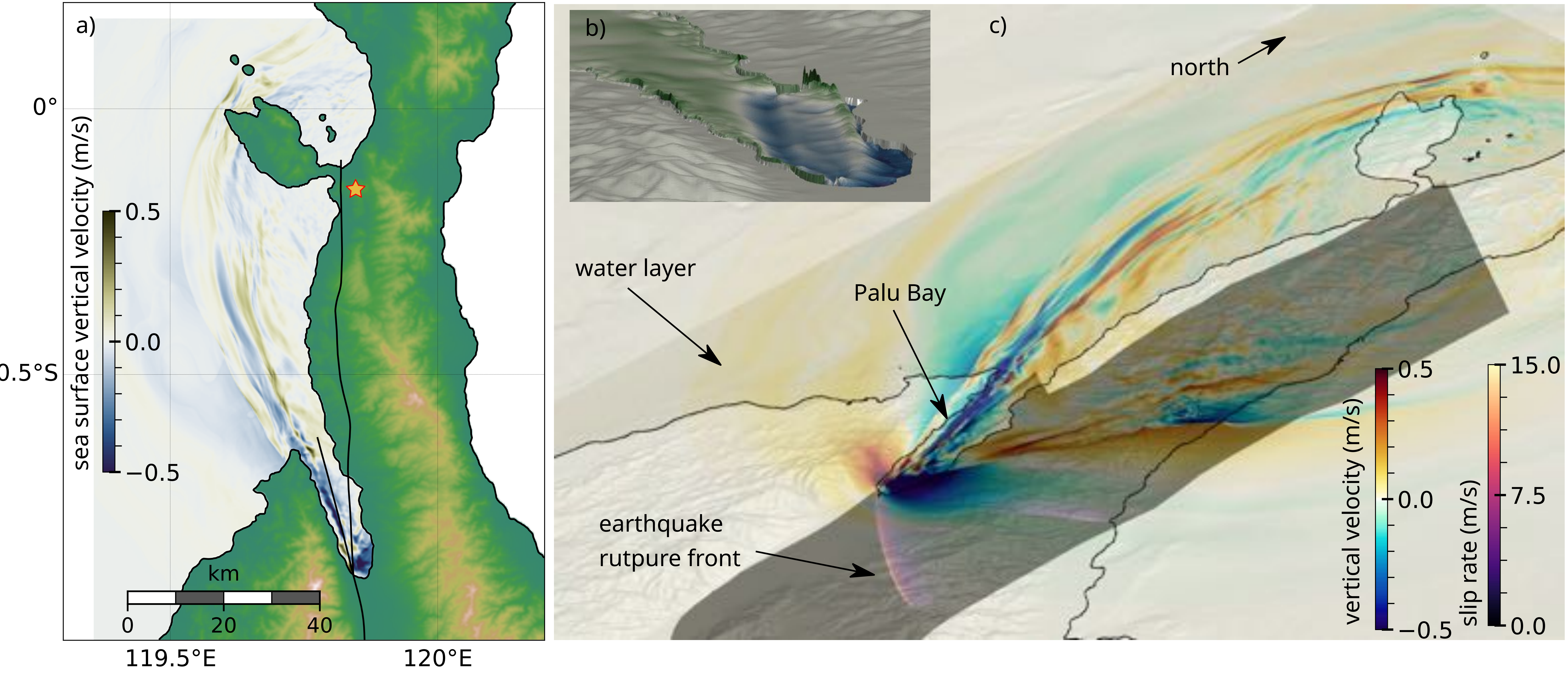


- **One-way linking to shallow water equations** may omit shallow water solvers may omit tsunami dispersion, acoustic waves and tsunami generation complexity

- **Fully coupled acoustic-elastic coupling with gravity,** via free surface tracking (gravitational effects) by linearised free surface boundary condition (2D: Maeda & Furumara, 2013, Lotto et al., 2015, 2017)

Fully coupled earthquake-tsunami modeling

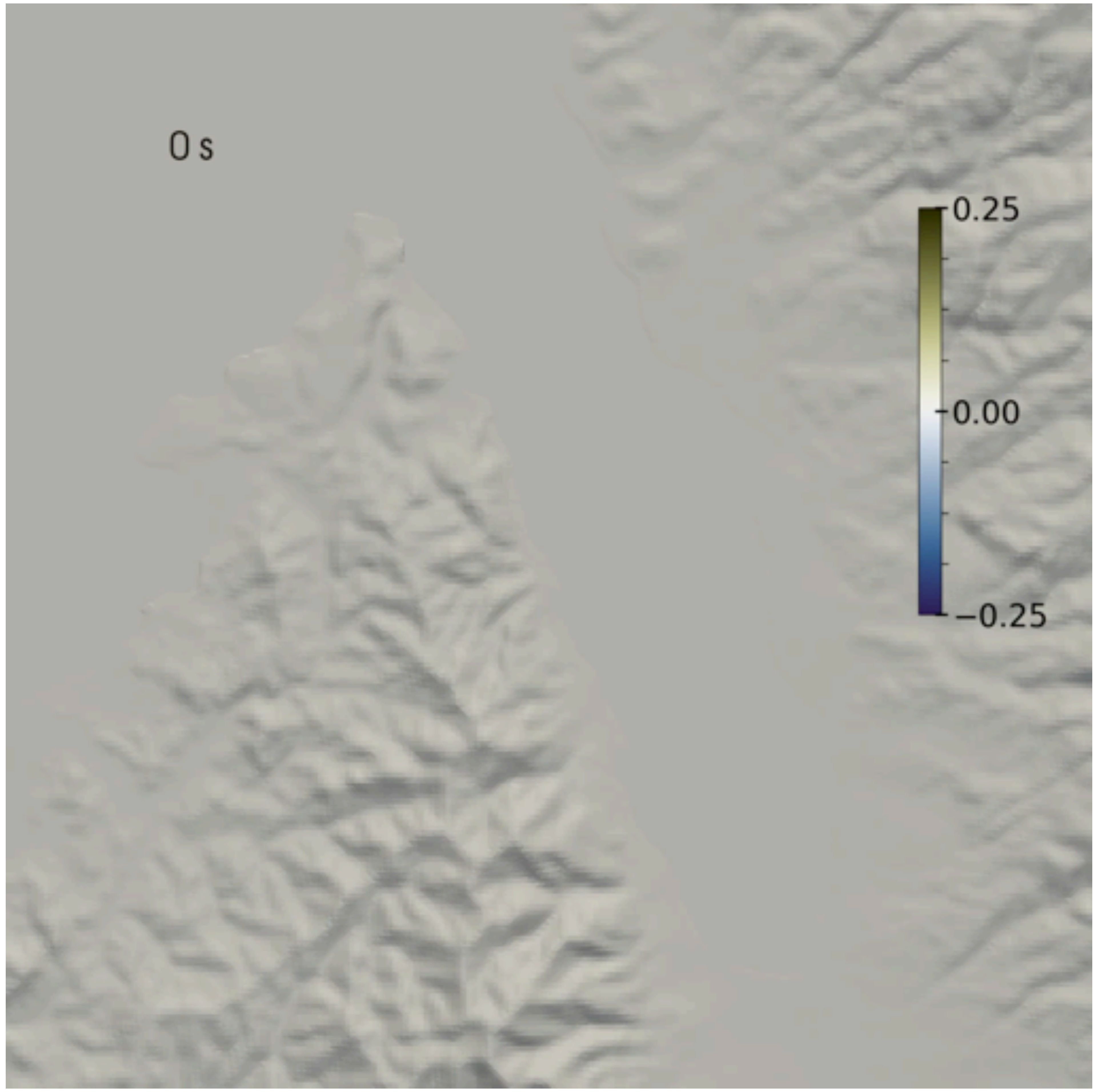
Krenz et al. 2021, submitted

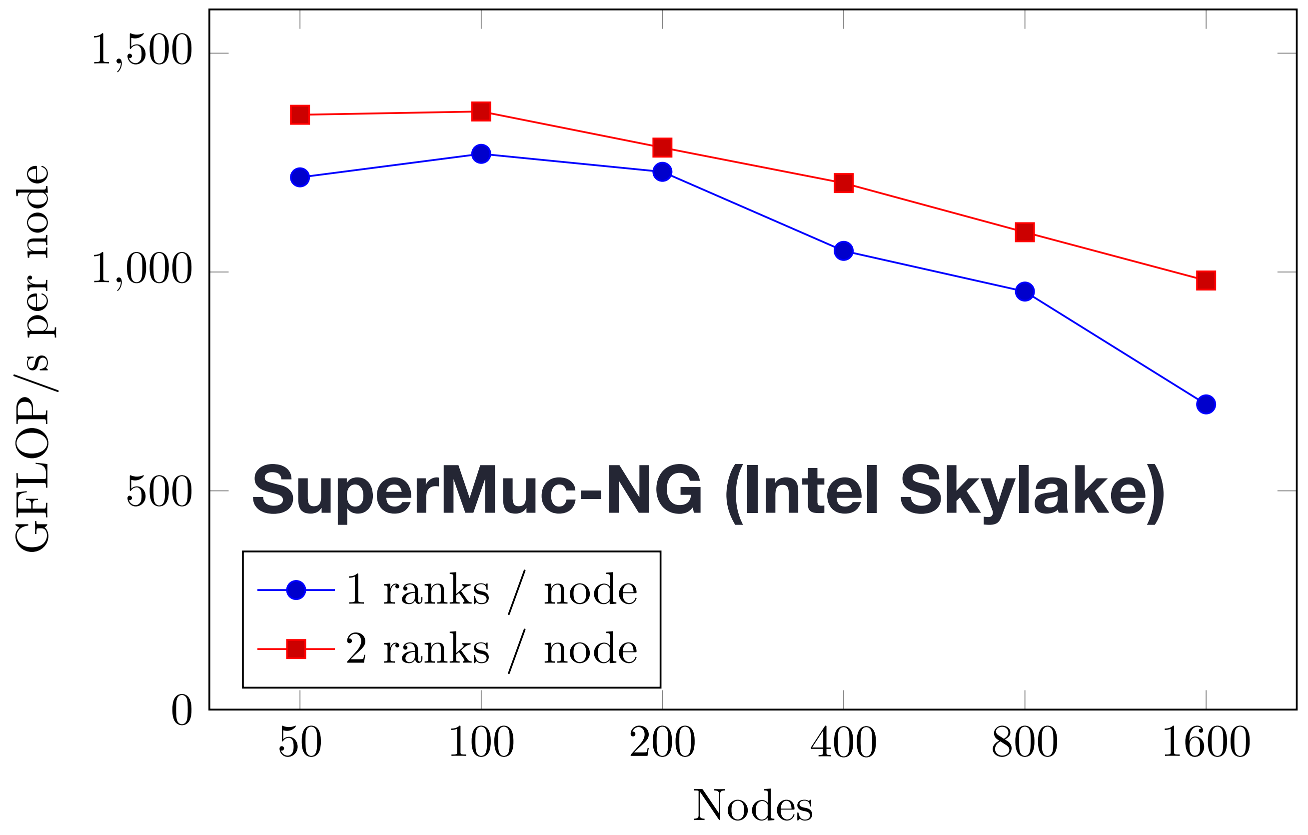


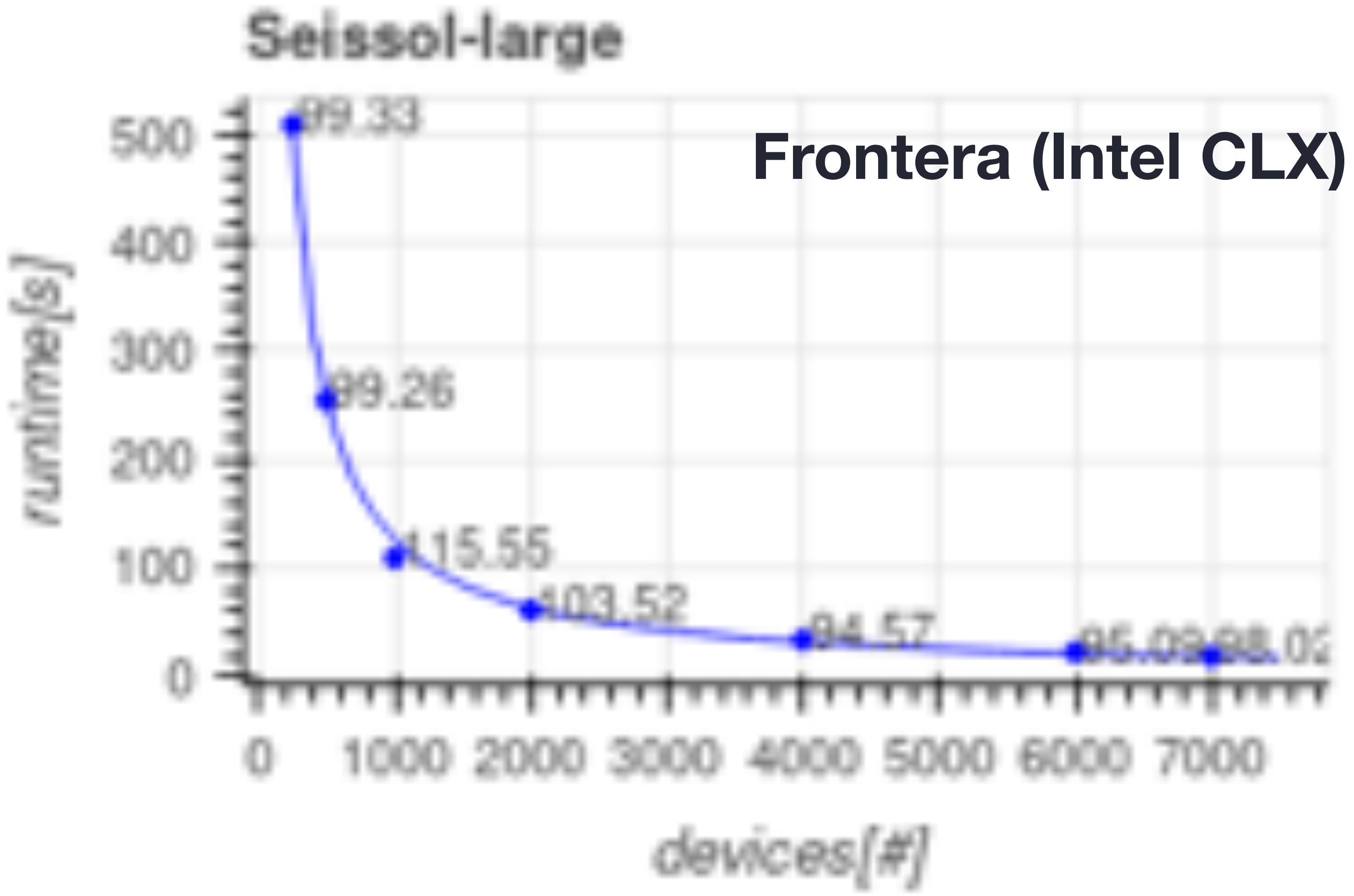
- 3D implementation in SeisSol of fully coupled acoustic-elastic coupling with gravity, applied to resolve the dynamics of the 2018, Palu Sulawesi earthquake and tsunami
- We solve the elastic wave equation coupled to non-linear frictional sliding in a complex fault network + the acoustic wave equation, describing perturbations about an equilibrium hydrostatic state in a compressible, inviscid ocean of variable depth + the effects of gravitational restoring forces through a modification of the standard free surface boundary condition

Fully coupled earthquake-tsunami modeling

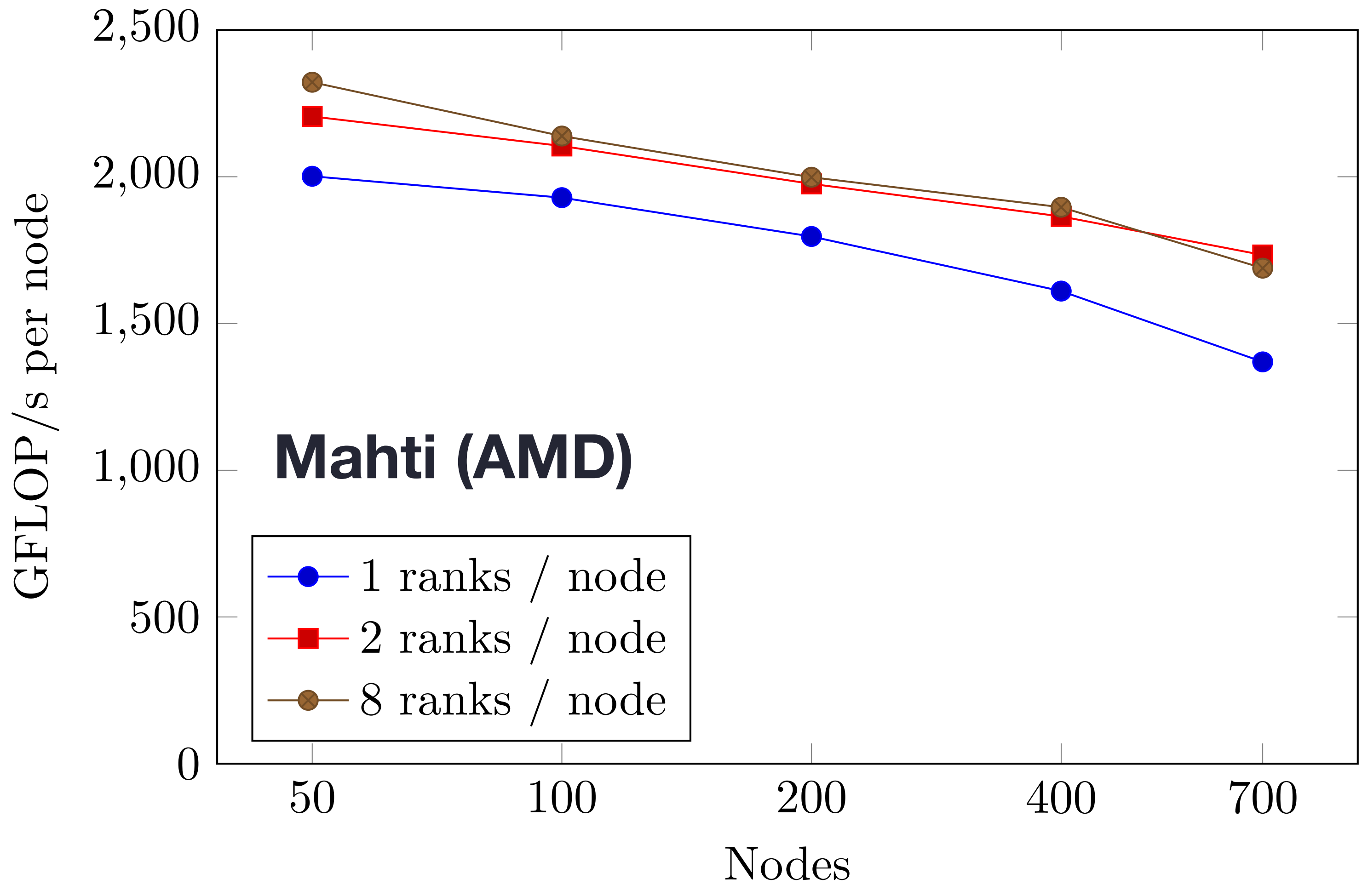
Krenz et al. 2021, submitted







strong scaling of a 518 mio. element mesh production run, reaching > 70% parallel efficiency



- We demonstrate scalability and performance of the MPI+OpenMP parallelisation on various peta-scale machines including SuperMuc-NG, Shaheen II, Mahti and Frontera

Summary - Part 1

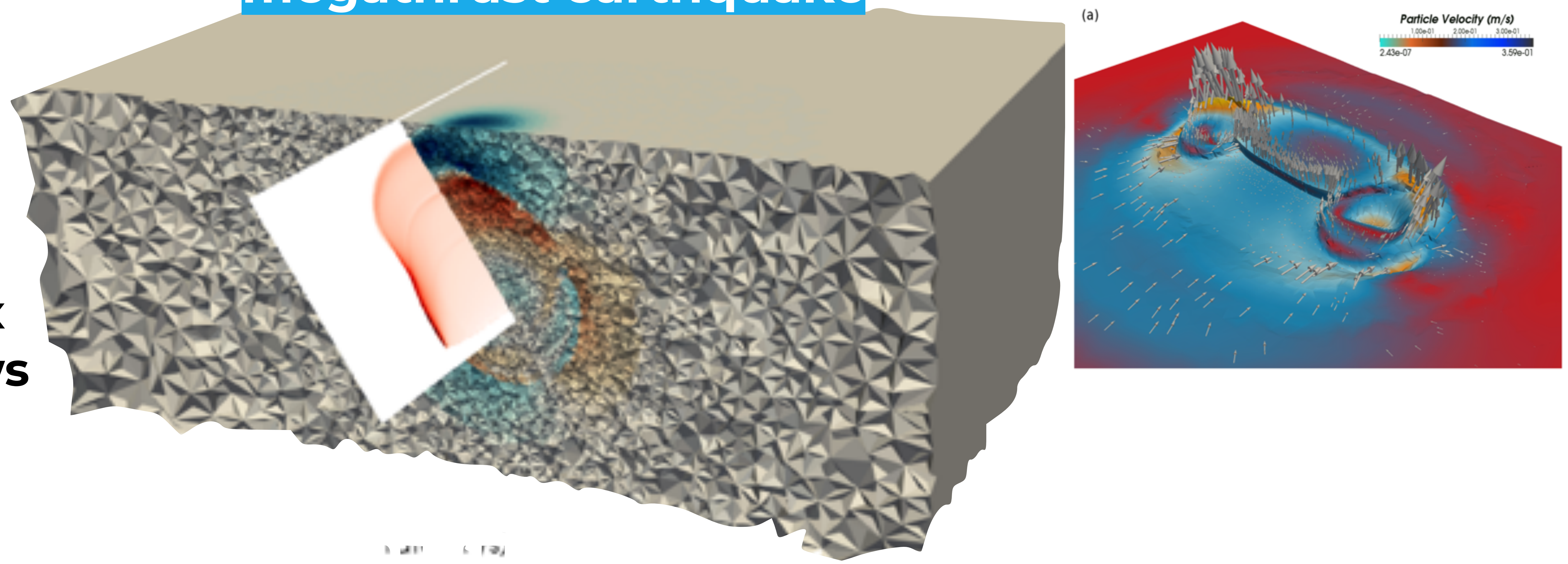
- Computational earthquake seismology provides mechanically viable insight into the physical conditions that allow earthquake rupture on complex fault systems and helps constraining competing views on earthquake behaviour

- Geo-data, specifically community models, can be routinely included; Observational methods can themselves be constrained

- Bridging scales by coupling to tsunami, global seismic wave propagation, engineering, intermediate and long-term geodynamic modelling

- The interplay of advances in high-performance computing and dense observations will allow us to go beyond scenario-based analysis, aiming for, e.g., fully non-linear source-path-site effects, urgent response, data-driven dynamic source inversion, (Bayesian) uncertainty quantification, ...

Training example 1 - Community benchmark megathrust earthquake



Training example 2 - Palu, Sulawesi strike-slip supershear earthquake