The Power of Oomph:

A loud story about earthquakes, tsunamis, sound, and HPC

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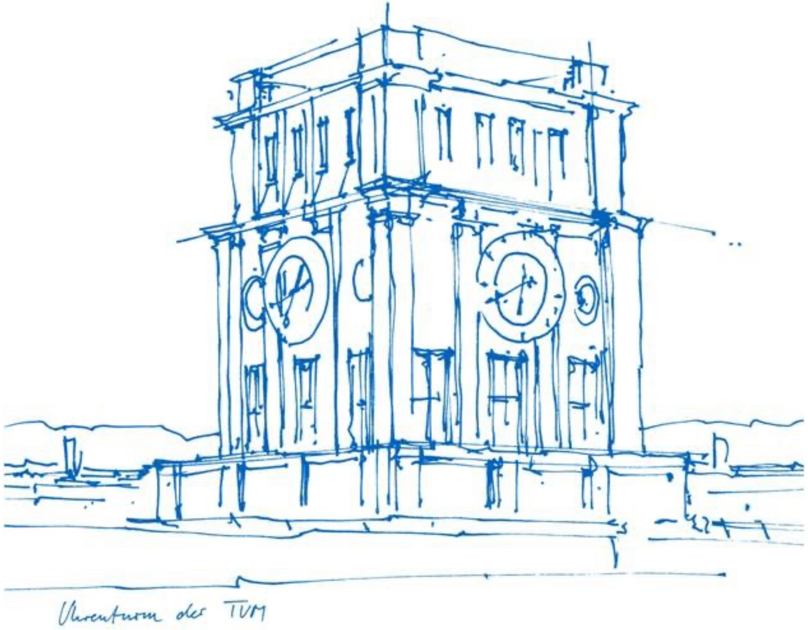

Collaborations & Funding

Technological University of Munich

Ravil Dorozhinksii, Lukas Krenz, Sebastian Wolf, David Schneller, Michael Bader

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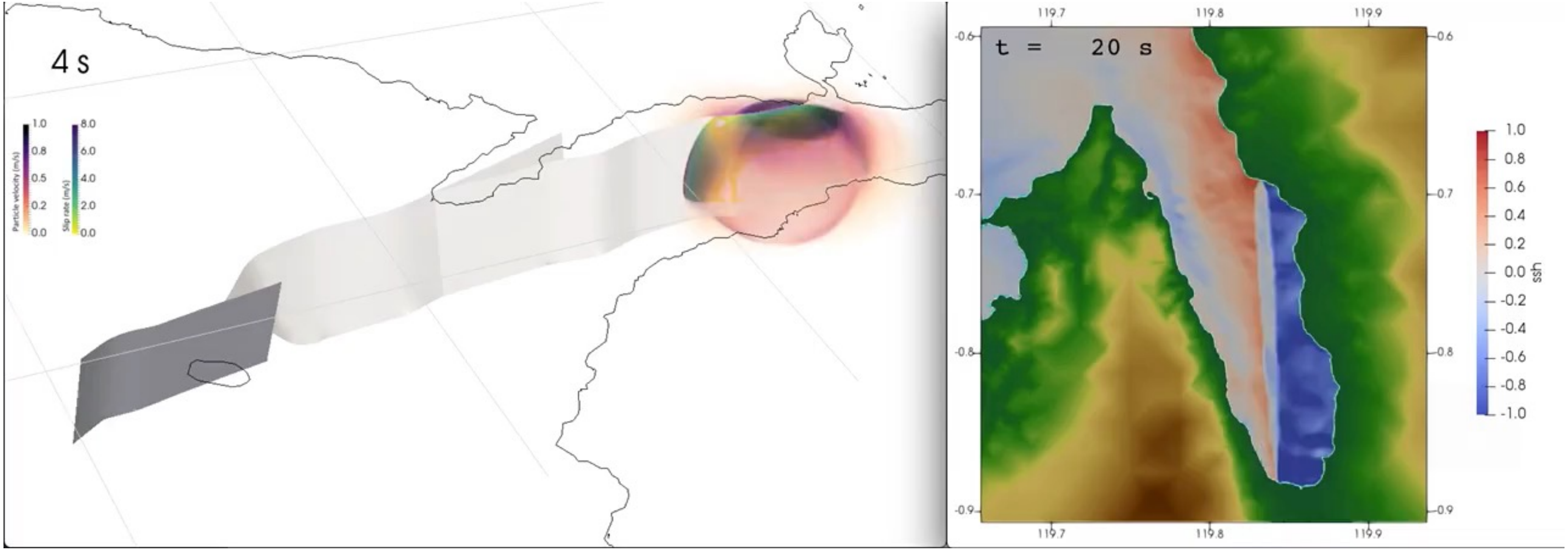
Part I: Fully-coupled Earthquake-Tsunami Simulations

Earthquake-Tsunami Coupling



Earthquake-Tsunami Coupling Workflows

One-way Linked

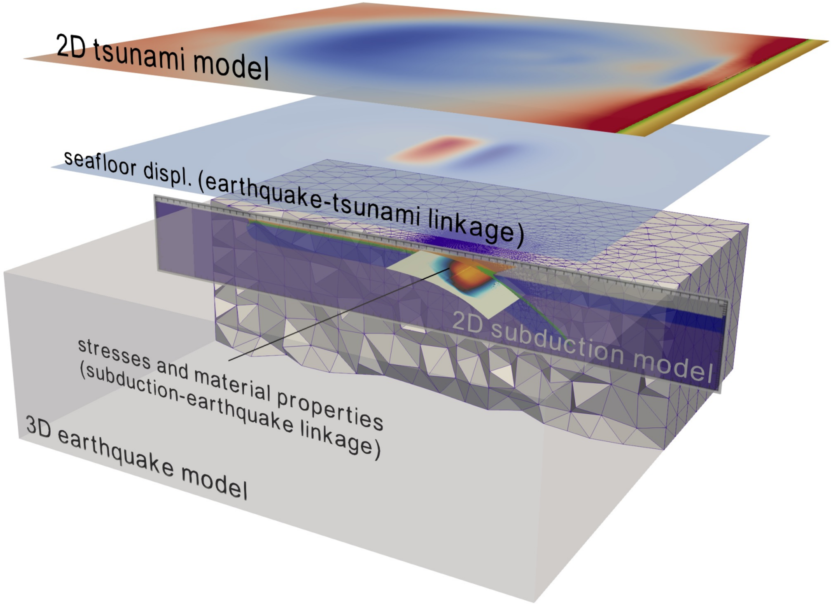
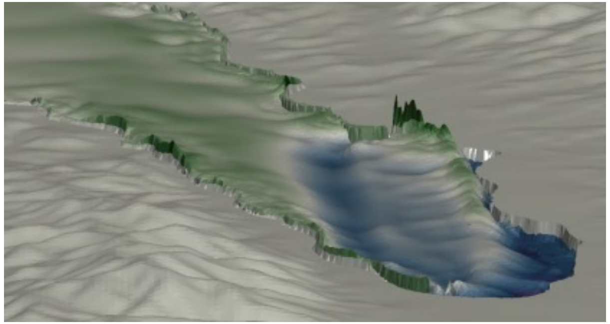


Figure from: H. Madden et al. “Linked 3-D modelling of megathrust earthquake-tsunami events: from subduction to tsunami run up (2021)

Fully Coupled

Earthquake

⇧



⇩

Tsunami

One-way linking vs 3D coupling

Using shallow water equations for tsunami has disadvantages:

• No **dispersion** (if not using Boussinesq approximation)
• No **acoustic waves** (i.e., assuming incompressible ocean) -> **Potentially dominant** in data recorded by offshore instruments
• Only works in **shallow water** limit

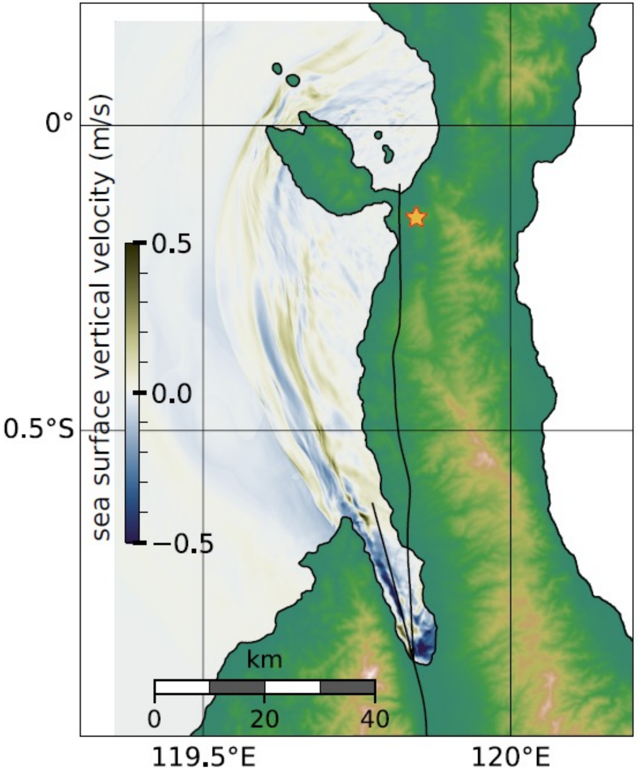
Fully-coupled elastic-acoustic model solves **entirely new class** of earthquake-tsunami problem

Compares well with one-way linking under certain conditions

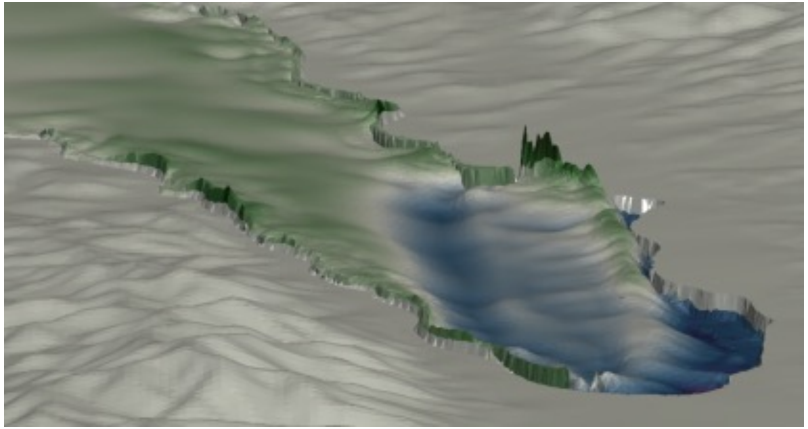
Detailed model comparison: Abrahams, Lauren S., et al. "Comparison of methods for coupled earthquake and tsunami modelling." *Geophysical Journal International* 234.1 (2023)

Example: Palu, Sulawesi September 2018

- Mw 7.5 **strike-slip** earthquake
  Propagation at **supershear** speed crossing narrow Palu Bay
- Followed by **unexpected** and **localized tsunami**
- Complicated geometry: bath-tub like bay, very shallow water (average 600 m)
- Details: L. Krenz et al. “3D Acoustic-Elastic Coupling with Gravity: The Dynamics of the 2018 Palu, Sulawesi Earthquake and Tsunami”. *Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis, 2021*



SeisSol

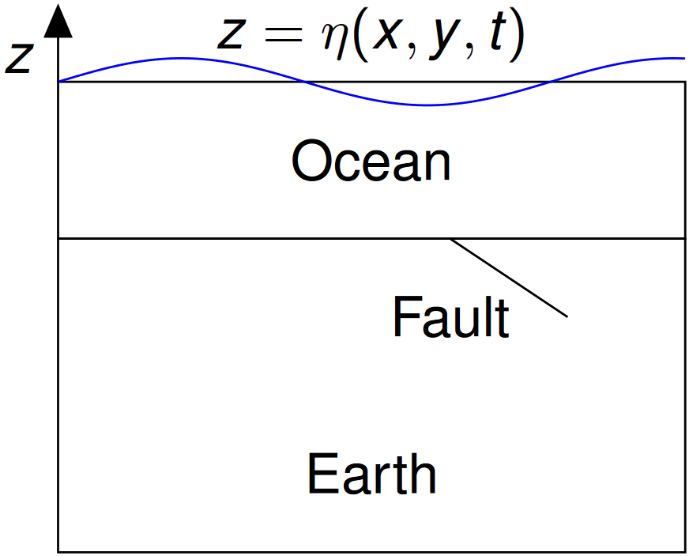


What
- (An)**Isotropic elastic** wave propagation
- **Acoustic** wave propagation
- Viscoelastic wave propagation
- Poroelasticity
- Off-fault **plasticity**
- **Dynamic earthquake rupture**

How
- Numerics: ADER-DG
- Unstructured tetrahedral meshes with local time-stepping
- Optimized Hybrid MPI + OpenMP Parallelization

Available (open-source) at `https://github.com/SeisSol/SeisSol/`

Two-Way Elastic-Acoustic Coupling



Based on 2D model of (Lotto and Dunham, 2015)

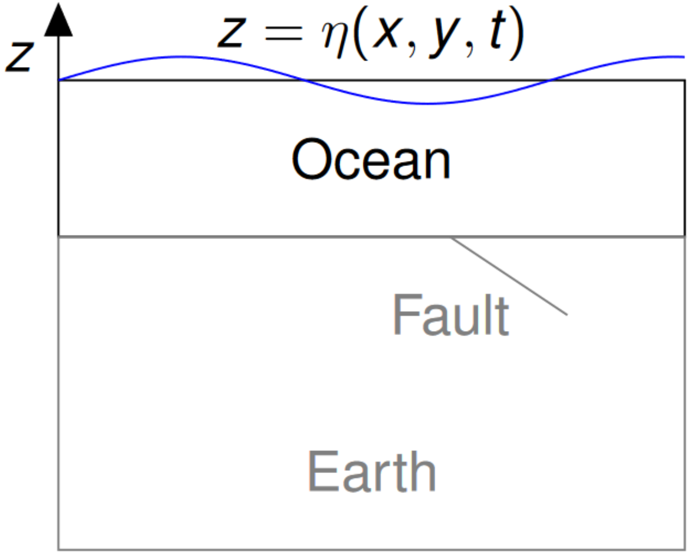
Here: First 3D implementation!

With:

- $\eta(x, y, t)$ sea surface height
- Ocean at rest at $z = 0$

Figures in 2D for illustration, all simulations are 3D

Ocean Model



Linear acoustic medium, q = (u, v , w, p)

Treated as special case of elastic wave equation with stress tensor $\sigma_{ij} = -p\ \delta_{ij}$,density ρ and $g = 9.81\frac{m}{s^2}$.

Free surface

$$p(x, y, \eta) = 0$$

Typically solved by moving mesh.

Following (Lotto, Dunham 2015),linearized to:

$$p(x, y, z = 0) = \rho g\ \eta(x, y)$$

$$\frac{\partial \eta}{\partial t} = v_z$$

The ADER-DG Approach

Solve linear hyperbolic equations of the form

$$\frac{\partial \boldsymbol{q}}{\partial t} + \boldsymbol{A}\frac{\partial \boldsymbol{q}}{\partial x} + \mathbf{B}\frac{\partial \boldsymbol{q}}{\partial y} + \mathbf{C}\frac{\partial \boldsymbol{q}}{\partial z} = 0$$

with q vector of variables, x = (x, y, z) position, t time, A(x), B(x), C(x) flux matrices.

Discontinuous Galerkin (DG) divides domain into disjoint elements, approximates solutions by piecewise-polynomials.

Elements are connected by solving the Riemann problem exactly.

ADER-Approach uses element-local Taylor expansion for time integration instead of Runge-Kutta procedures.

Advantages: One-step scheme, **arbitrary order in time and space**

Modeling Goals & Resulting Challenges

Goals

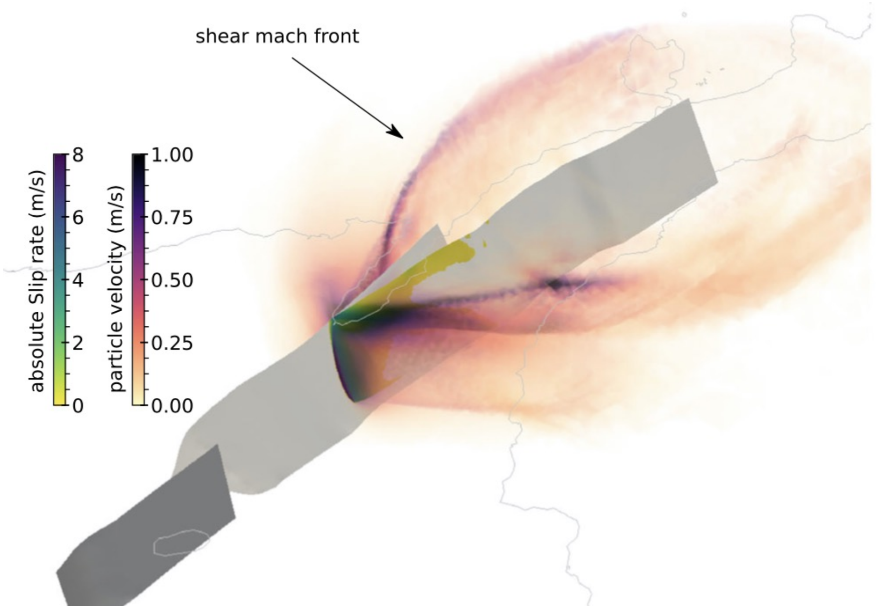
- Capture **entire process**: earthquake rupture, generation and propagation of seismic waves, ocean acoustic waves and tsunamis
- High resolution in 3D Earth (10 Hz) and ocean (15 Hz)
- Complex geometry, including bathymetry/topography
- 3D solid-fluid coupling

Challenges

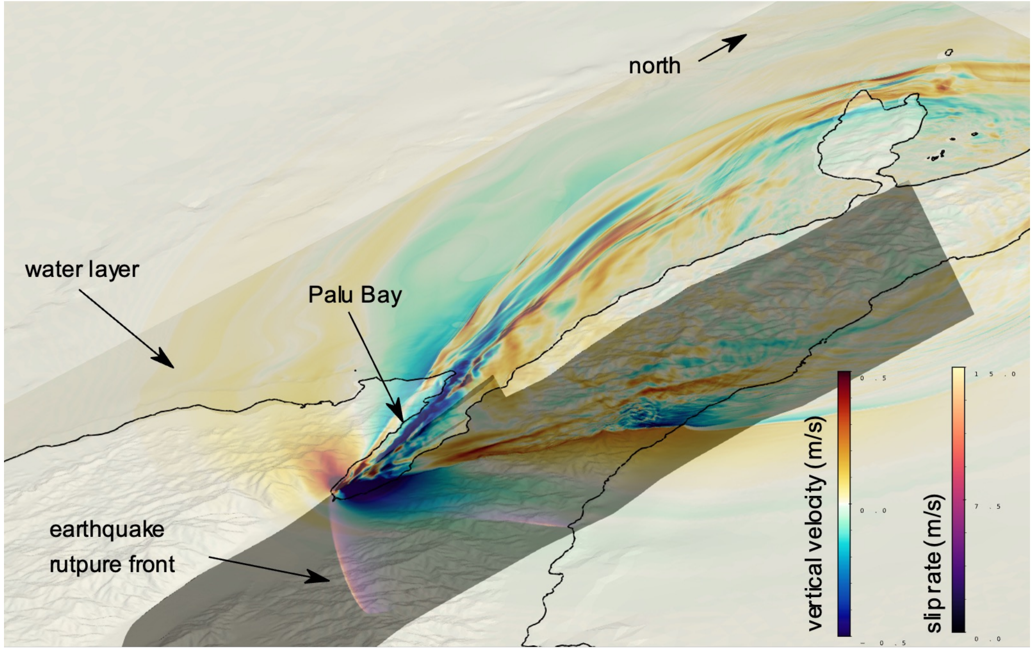
- Resolution leads to large setups: **≈ 250 billion degrees of freedom**
- Vastly different element sizes $\Longrightarrow$ **vastly different time step size**
- Geometry requires unstructured meshes

Palu: Our setup

- Added **water layer** to existing earthquake model (Ulrich et al., 2019).
- **Fully coupled** model (including plasticity,seismic and acoustic waves, dynamic,earthquake rupture)
- Two meshes: **M** (89 million elements), **L** (518 million elements)
- **Poly. Order 5**, 46 and 261 billion degrees of freedom
- M: 5.3 hours on **1000 nodes** of SuperMUC-NG for 100s simulated time
- L: 5.5 hours on **3072 nodes** of SuperMUC-NG for 30s simulated time



Palu: 3D View at 15s



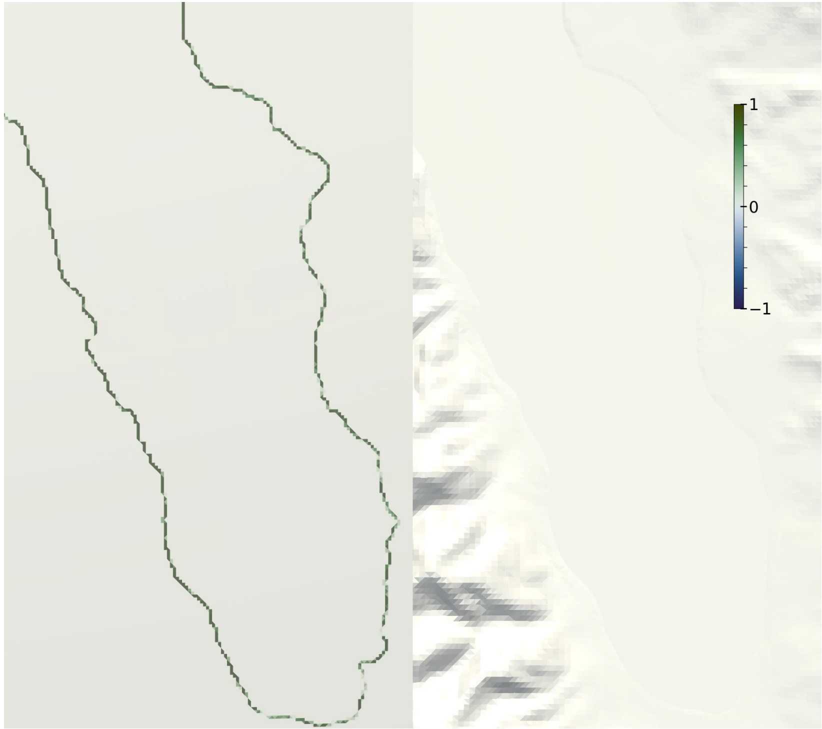
Comparison with One-Way Linking

Left: One-way linking, **right: fully-coupled**

Shows: Sea surface displacement for $t = 1s, \ldots, 100s$

Use identical earthquake model

Matches well overall, with some differences (e.g. at coast, “smoother” tsunami)



Part II: Fully-coupled Earthquake-Sound Simulations

“Big blast followed by a long 10-second echo.” Helsinki, 2018-07-08 20:37

Enhanced Geothermal System in Helsinki

- Otaniemi project
- Enhanced geothermal system (EGS), stimulated in June and July 2018 in the region of Helsinki
- Thousands of **induced, small earthquakes**
- Observations of **ground shaking** and **audible disturbances** collected by **Macroseismic questionnaire** of the Institute of Seismology, University of Helsinki
- More details:

  Lukas Krenz, Sebastian Wolf, Gregor Hillers, Alice-Agnes Gabriel, Michael Bader; Numerical Simulations of Seismoacoustic Nuisance Patterns from an Induced M 1.8 Earthquake in the Helsinki, Southern Finland, Metropolitan Area. Bulletin of the Seismological Society of America 2023;; 113 (4): 1596–1615. doi: https://doi.org/10.1785/0120220225

Enhanced Geothermal Systems (EGS)

1: Reservoir
2: Pump house
3: Heat exchanger
4: Turbine hall
5: Production well
6: Injection well
7: Hot water to district heating
8: Porous rock
9: Well
10: Solid bedrock

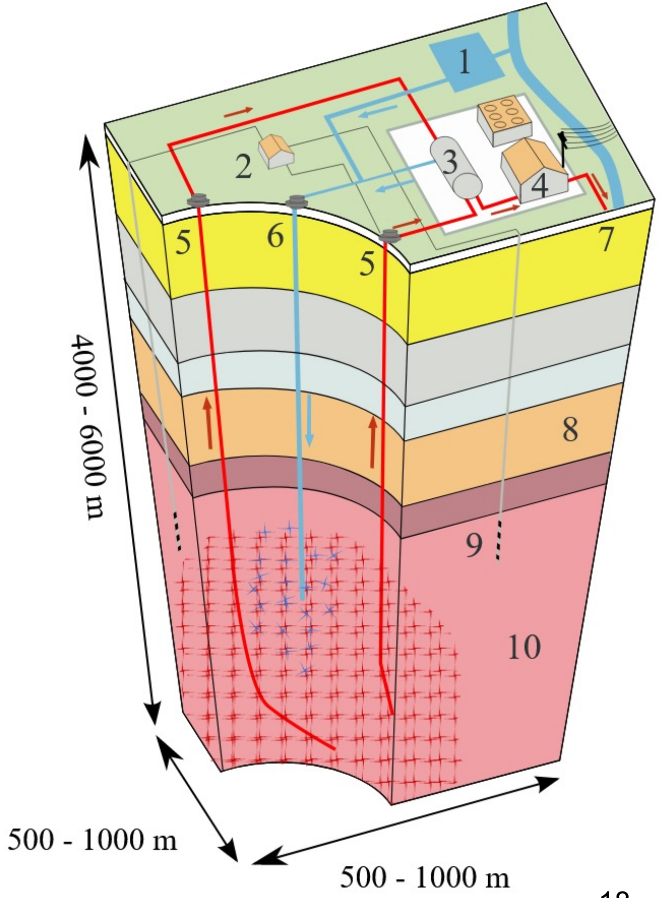


Image from:
*Geothermie_Prinzip.svg: *Geothermie_Prinzip01.jpg: "Siemens Pressebild" http://www.siemens.comderivative work: FischX (talk)Geothermie_Prinzip01.jpg: "Siemens Pressebild" http://www.siemens.comderivative work: Ytrottier, CC BY-SA 3.0*

Traffic Light System

Red: Stop; $M_L \geq 2.1$

Amber: Be Careful; PGV ≥ 1 mm/s detected and $M_L \geq 1.0$; $M_L \geq 1.2$

Green: Everything's fine

SCIENCE ADVANCES | RESEARCH ARTICLE

EARTH SCIENCES

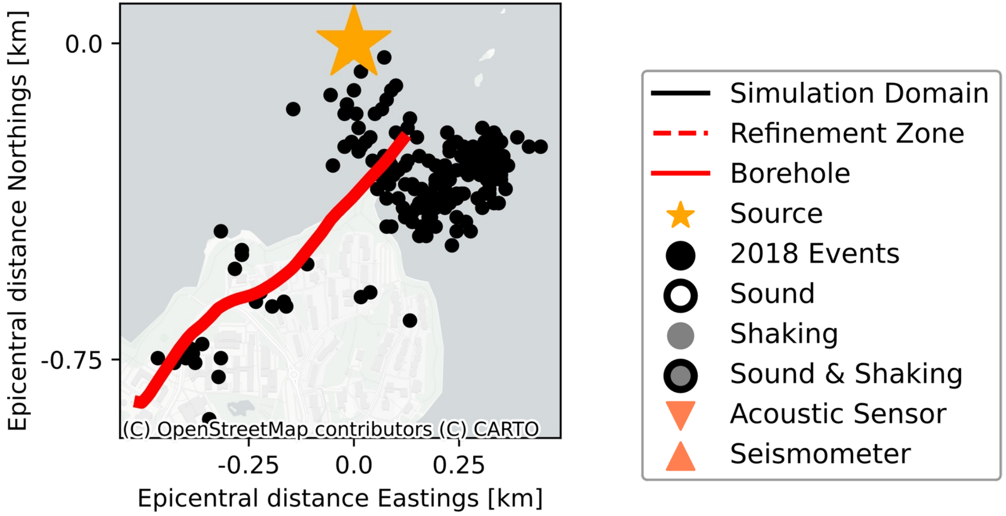
Controlling fluid-induced seismicity during a 6.1-km-deep geothermal stimulation in Finland

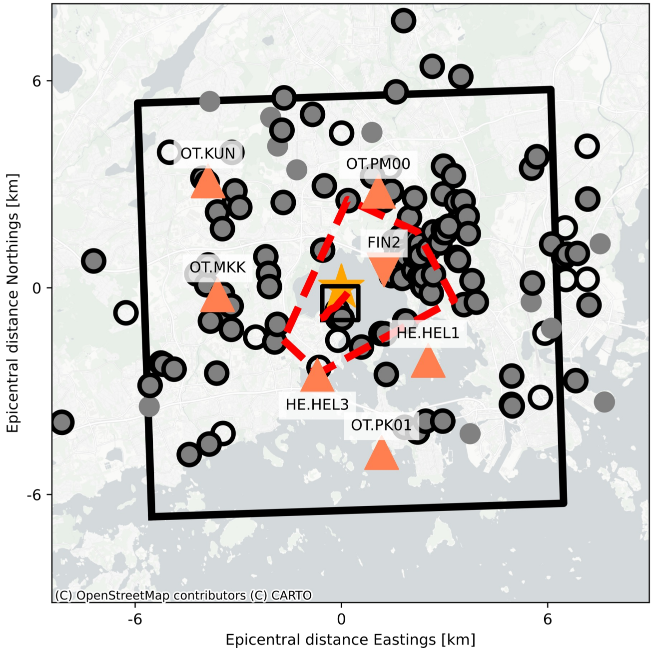
Grzegorz Kwiatek[1,2]*, Tero Saarno[3], Thomas Ader[4], Felix Bluemle[1], Marco Bohnhoff[1,2], Michael Chendorain[4], Georg Dresen[1,5], Pekka Heikkinen[3,6], Ilmo Kukkonen[6], Peter Leary[7], Maria Leonhardt[1], Peter Malin[1,7], Patricia Martínez-Garzón[1], Kevin Passmore[7], Paul Passmore[7], Sergio Valenzuela[7], Christopher Wollin[1]

Design and implementation of a traffic light system for deep geothermal well stimulation in Finland

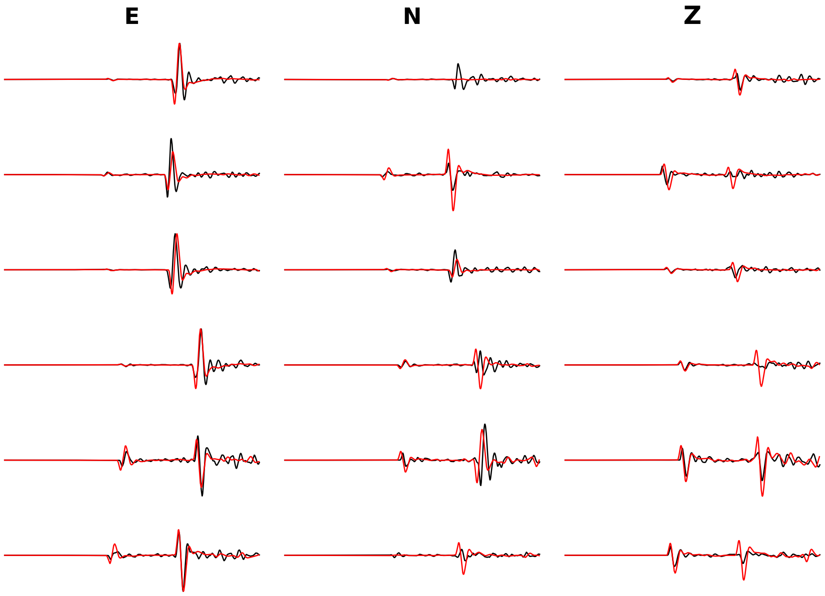
Thomas Ader · Michael Chendorain · Matthew Free · Tero Saarno · Pekka Heikkinen · Peter Eric Malin · Peter Leary · Grzegorz Kwiatek · Georg Dresen · Felix Bluemle · Tommi Vuorinen

Induced Earthquakes & Reports



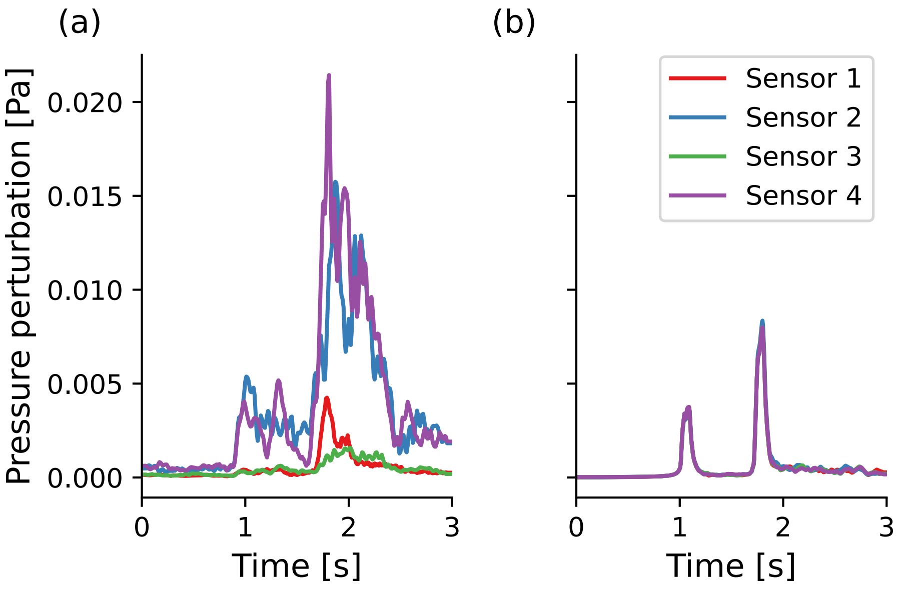


Comparisons with elastic measurements



Station	Measured mm/s	Simulated mm/s
HE HEL1	0.11	0.03
HE HEL3	0.06	0.02
OT PM00	0.08	0.04
OT PK01	0.05	0.02
OT KUN	0.03	0.01
OT MKK	0.06	0.01

Comparison with sound recordings



Approximating Sound Pressure

Fully-coupled simulations are **very** expensive

⇒ Use **two setups**: a fully refined **Earth-only** model & a **fully-coupled** model with refinement region

Common approximation for pressure perturbation Δp from vertical velocity v

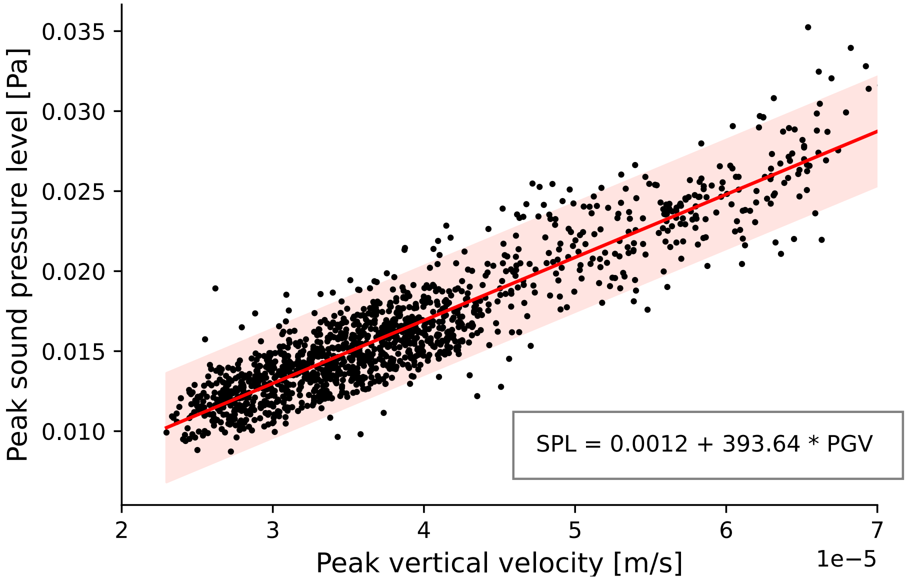
$$\Delta \mathrm{P} = \rho c v$$

Workflow:

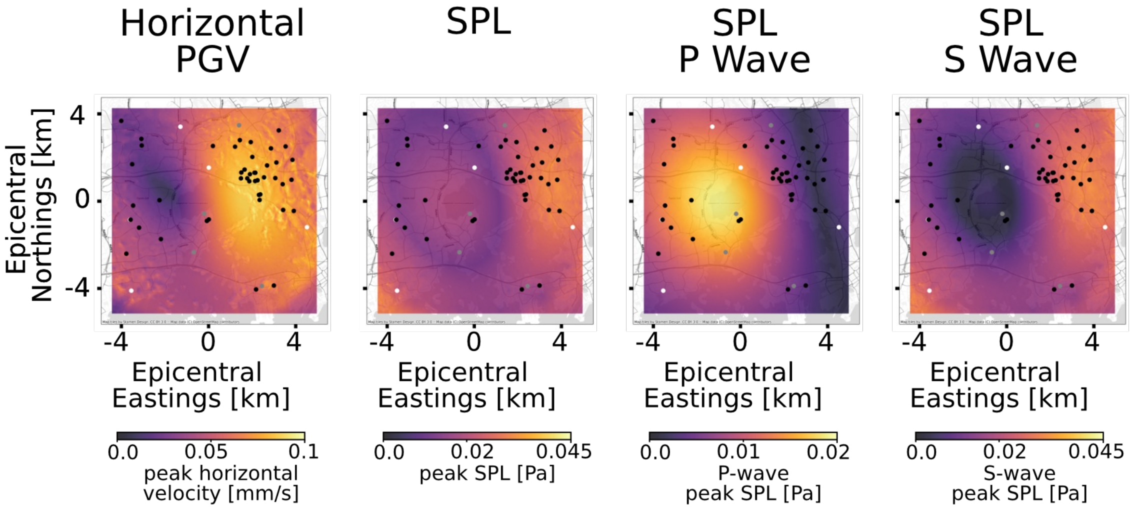
1. Compute acoustic receivers (0.5m above topography) and elastic (directly below)
2. For each pair, compute peak sound pressure level (SPL) and peak vertical velocity
3. Compute linear regression

$$\Delta P^{\mathrm{peak}} = \mathrm{c}_0 + \mathrm{c}_1 v^{\mathrm{peak}} + \epsilon$$

Predicting Sound Pressure Level from Vertical Velocity



PGV and SPL maps



PGV: Horizontal Peak Ground Velocity

SPL: Sound pressure level, reconstructed from peak vertical velocity

Part III: Local Time Stepping

Timestep restrictions of ADER-DG

$$\Delta t < \frac{1}{2N+1}\frac{l_{min}}{a_{max}}$$

With:

N order

l_{min} diameter of the insphere of tetrahedron

a_{max} largest signal speed inside tetrahedron

Huge variances in both values

Clustered Local Time Stepping

Idea:

Group elements into clusters with time step sizes

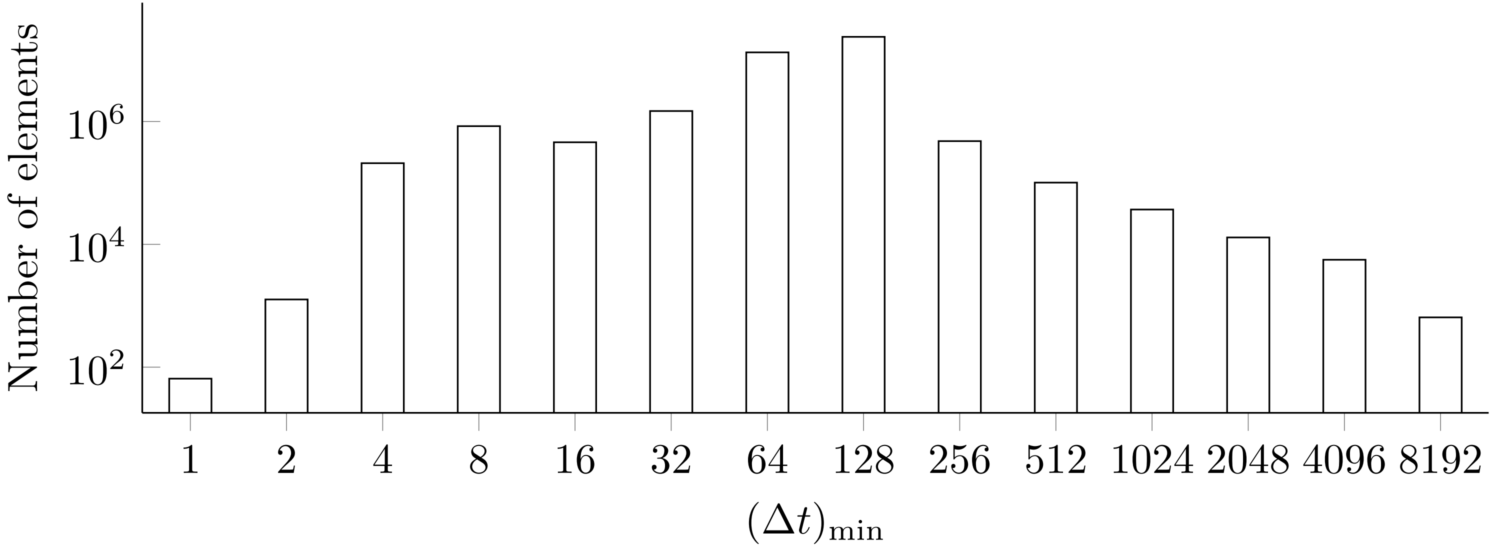
$$[\lambda \Delta t^{min}, \lambda 2 \Delta t^{min}], [\lambda 2 \Delta t^{min}, \lambda 4 \Delta t^{min}], \ldots$$

All elements from one cluster are updated at the same time

“Wiggle Factor“ λ can be optimized for better clustering

Breuer, Alexander, and Alexander Heinecke. "Next-Generation Local Time Stepping for the ADER-DG Finite Element Method." *2022 IEEE International Parallel and Distributed Processing Symposium (IPDPS)*. IEEE, 2022.

A Clustering Straight from HEL



simulation with large LTS speedup hangs after 80 to 100s #73

Closed **Thomas-Ulrich** opened this issue on Jun 21, 2019 · 11 comments

Thomas-Ulrich commented on Jun 21, 2019 • edited Member

Here is a setup with large LTS speed-up:

```
Fri Jun 21 11:45:45, Info:  Deriving clusters ids for min. time step width / multiRate: 8.87362e-05 / 2
Fri Jun 21 11:45:45, Info:  Number of elements in time clusters:
Fri Jun 21 11:45:45, Info:  0: 5
Fri Jun 21 11:45:45, Info:  1: 10
Fri Jun 21 11:45:45, Info:  2: 25
Fri Jun 21 11:45:45, Info:  3: 79
Fri Jun 21 11:45:45, Info:  4: 1082
Fri Jun 21 11:45:45, Info:  5: 10741
Fri Jun 21 11:45:45, Info:  6: 140838
Fri Jun 21 11:45:45, Info:  7: 1466102
Fri Jun 21 11:45:45, Info:  8: 375451
Fri Jun 21 11:45:45, Info:  9: 115857
Fri Jun 21 11:45:45, Info:  10: 37153
Fri Jun 21 11:45:45, Info:  11: 44016
Fri Jun 21 11:45:45, Info:  12: 62496
Fri Jun 21 11:45:45, Info:  maximum theoretical speedup (compared to GTS): 210.566 per cell LTS, 142.2 with th
Fri Jun 21 11:45:45, Info:  Number of elements in dynamic rupture time clusters:
Fri Jun 21 11:45:45, Info:  0 (dr): 0
Fri Jun 21 11:45:45, Info:  1 (dr): 0
Fri Jun 21 11:45:45, Info:  2 (dr): 0
Fri Jun 21 11:45:45, Info:  3 (dr): 2
Fri Jun 21 11:45:45, Info:  4 (dr): 16
Fri Jun 21 11:45:45, Info:  5 (dr): 287
Fri Jun 21 11:45:45, Info:  6 (dr): 2288
Fri Jun 21 11:45:45, Info:  7 (dr): 94102
Fri Jun 21 11:45:45, Info:  8 (dr): 305
Fri Jun 21 11:45:45, Info:  9 (dr): 0
Fri Jun 21 11:45:45, Info:  10 (dr): 0
Fri Jun 21 11:45:45, Info:  11 (dr): 0
Fri Jun 21 11:45:45, Info:  12 (dr): 0
```

That I run on 15 nodes of Supermuc 2 with seissol order 3, and which hangs after ~80s (no error message).

Actor LTS #512

Merged **krenzland** merged 90 commits into `master` from `actor` on May 3

Conversation 26 · Commits 90 · Checks 0 · Files changed 44

krenzland commented on Mar 15 • edited Member

This is a refactoring (or rather a rewrite) of our Time Cluster machinery. It includes:

- Step-based criteria instead of time-based scheduling: Avoids floating point comparisons
- New code structure for time cluster
- A refactoring of the communication thread

I've checked a lot of scenarios but I would appreciate if you would also check our applications. It's quite hard to thoroughly test every feature.
@ravil-mobile Could you please check whether the GPU version still works? I've ran some tests but it would be great if you'd double check.

PS: It's a slightly to get this to compile on SuperMUC-NG. Either use the GCC compiler or load module "intel-oneapi/2021.4". Older versions of the Intel compiler crash during compilation. With the new Intel compiler the compilation works but you have use the old versions of the modules to run it. Otherwise it crashes.

Old implementation

Algorithm 2 Generation of work items

procedure generateLocal($C_{l,p}$, t^{sync}, $t^{\text{dofs}}_{l-1,p}$, $t^{\text{pred}}_{l+1,p}$, $t^{\text{dofs}}_{l+1,p}$)
$e \leftarrow (\, C_{l,p} \notin \mathcal{L}^{\text{int}}_p) \wedge (C_{l,p} \notin \mathcal{L}^{\text{cop}}_p)$
$e \leftarrow (\, C_{l,p}.t^{\text{dofs}} < t^{\text{sync}}\,) \wedge e$
$e \leftarrow (\, C_{l,p}.t^{\text{pred}} \leq t^{\text{dofs}}_{l-1,p}\,) \wedge e$
$e \leftarrow (\, C_{l,p}.t^{\text{pred}} = C_{l,p}.t^{\text{dofs}}\,) \wedge e$
$e \leftarrow (\, (C_{l,p}.t^{\text{pred}} < t^{\text{pred}}_{l+1,p}) \vee (C_{l,p}.t^{\text{pred}} \leq t^{\text{dofs}}_{l+1,p})\,) \wedge e$
if e **then** ▷ Add local items if all conditions are met.
$\mathcal{L}^{\text{int}}_p \leftarrow C_{l,p} \cup \mathcal{L}^{\text{int}}_p$
$\mathcal{L}^{\text{cop}}_p \leftarrow C_{l,p} \cup \mathcal{L}^{\text{cop}}_p$
end if
end procedure

procedure generateNeighboring($C_{l,p}$, t^{sync}, $t^{\text{pred}}_{l-1,p}$, $t^{\text{pred}}_{l+1,p}$)
$e \leftarrow (\, C_{l,p} \notin \mathcal{N}^{\text{int}}_p) \wedge (C_{l,p} \notin \mathcal{N}^{\text{cop}}_p)$
$e \leftarrow (\, C_{l,p}.t^{\text{dofs}} < t^{\text{sync}}\,) \wedge e$
$e \leftarrow (\, C_{l,p}.t^{\text{pred}} \leq t^{\text{pred}}_{l-1,p}\,) \wedge e$
$e \leftarrow (\, C_{l,p}.t^{\text{pred}} > C_{l,p}.t^{\text{dofs}}\,) \wedge e$
$e \leftarrow (\, C_{l,p}.t^{\text{pred}} \leq t^{\text{pred}}_{l+1,p}\,) \wedge e$
if e **then** ▷ Add neighboring items if all conditions are met.
$\mathcal{N}^{\text{int}}_p \leftarrow C_{l,p} \cup \mathcal{N}^{\text{int}}_p$
$\mathcal{N}^{\text{cop}}_p \leftarrow C_{l,p} \cup \mathcal{N}^{\text{cop}}_p$
end if
end procedure

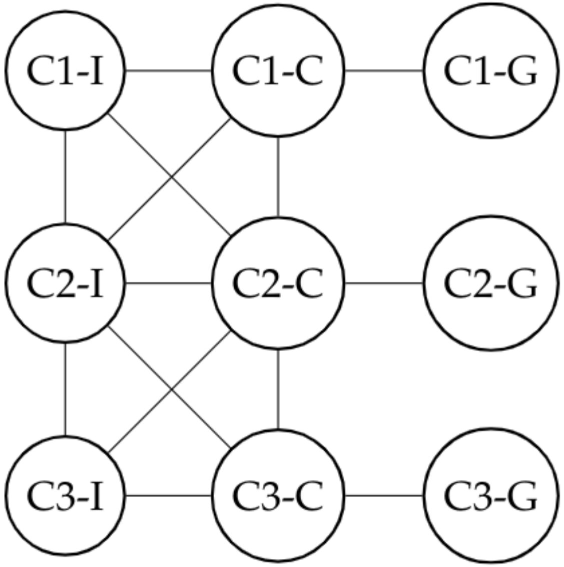
procedure generateWorkItems($C_{l,p}$, t^{sync})
$t^{\text{pred}}_{l-1,p} \leftarrow t^{\text{dofs}}_{l-1,p} \leftarrow$ limits::max()
$t^{\text{pred}}_{l+1,p} \leftarrow t^{\text{dofs}}_{l+1,p} \leftarrow$ limits::max()

if $\exists C_{l-1}, p$ **then** ▷ Get times of previous cluster if existent
$t^{\text{pred}}_{l-1,p} \leftarrow C_{l-1,p}.t^{\text{pred}}$
$t^{\text{dofs}}_{l-1,p} \leftarrow C_{l-1,p}.t^{\text{dofs}}$
end if
if $\exists C_{l+1}, p$ **then** ▷ Get times of next cluster if existent
$t^{\text{pred}}_{l+1,p} \leftarrow C_{l+1,p}.t^{\text{pred}}$
$t^{\text{dofs}}_{l+1,p} \leftarrow C_{l+1,p}.t^{\text{dofs}}$
end if

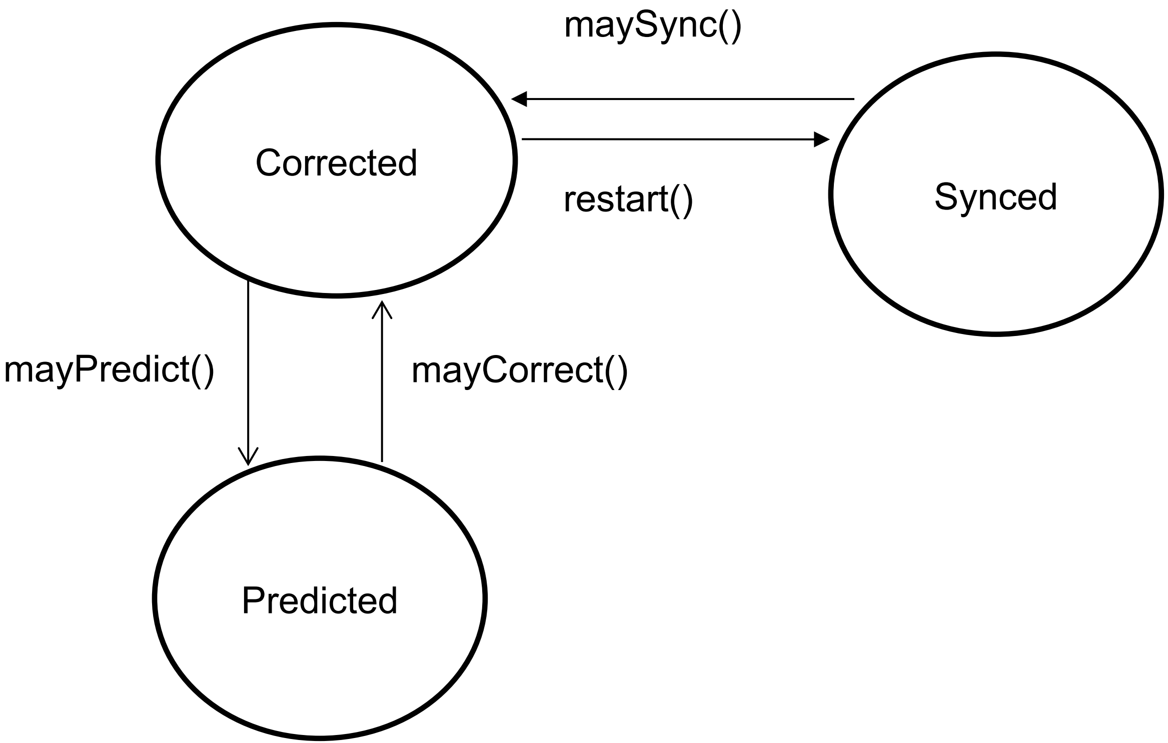
generateLocal($C_{l,p}$, t^{sync}, $t^{\text{dofs}}_{l-1,p}$, $t^{\text{pred}}_{l+1,p}$, $t^{\text{dofs}}_{l+1,p}$)
generateNeighboring($C_{l,p}$, t^{sync}, $t^{\text{pred}}_{l-1,p}$, $t^{\text{pred}}_{l+1,p}$)
end procedure

Image taken from:
Breuer, Alexander. "High Performance Earthquake Simulations." (2015).

The Actor Model

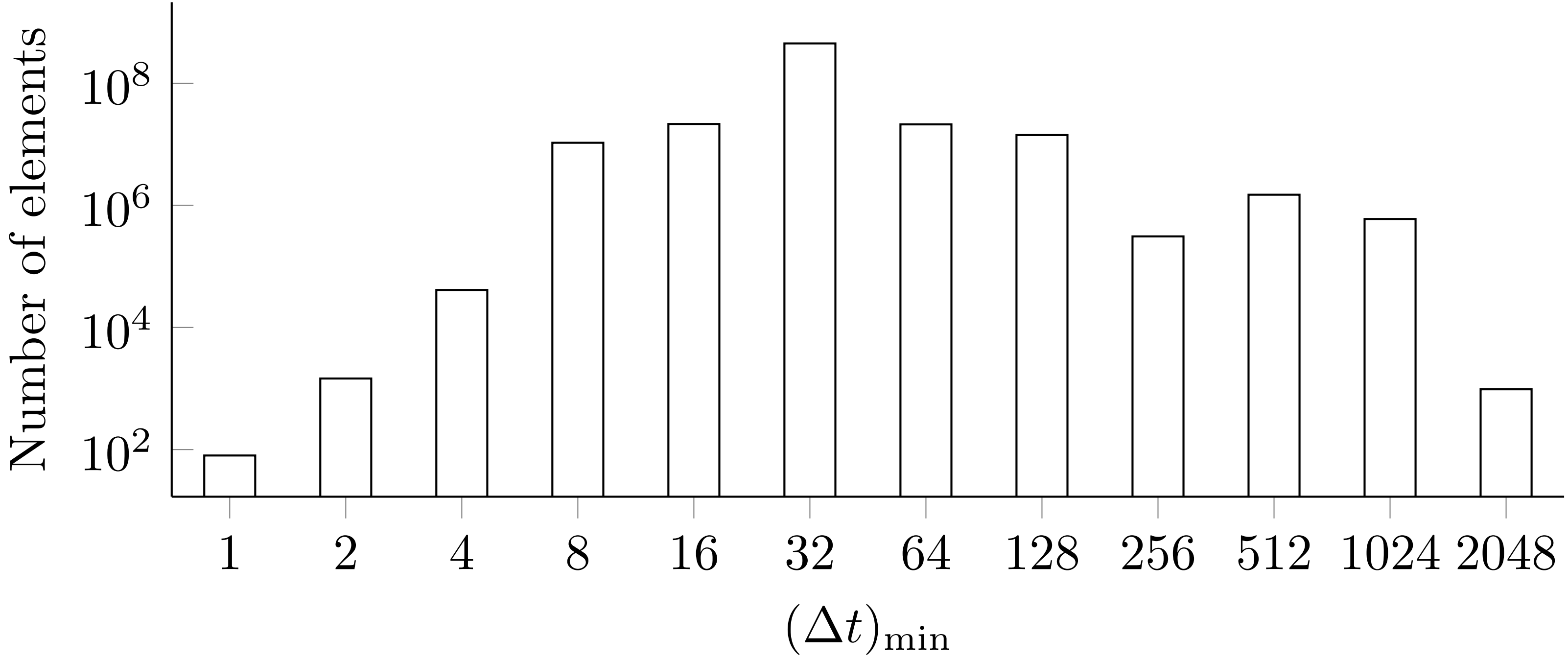


Cluster connectivity

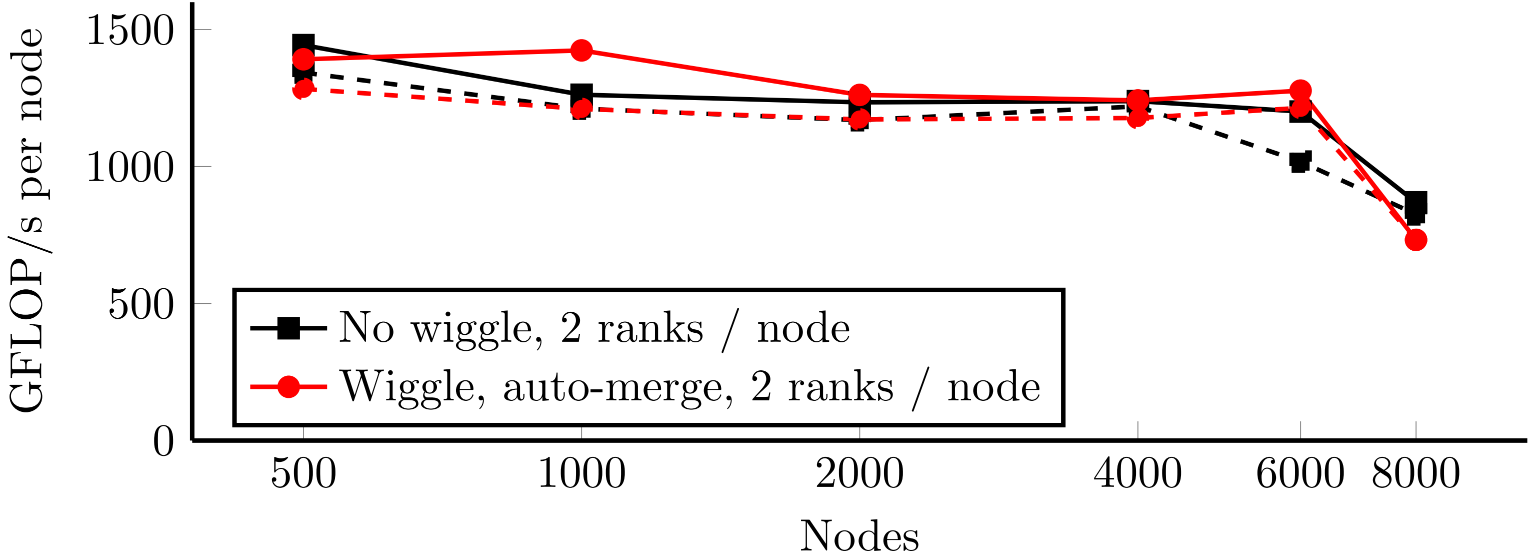


State machine for one time cluster

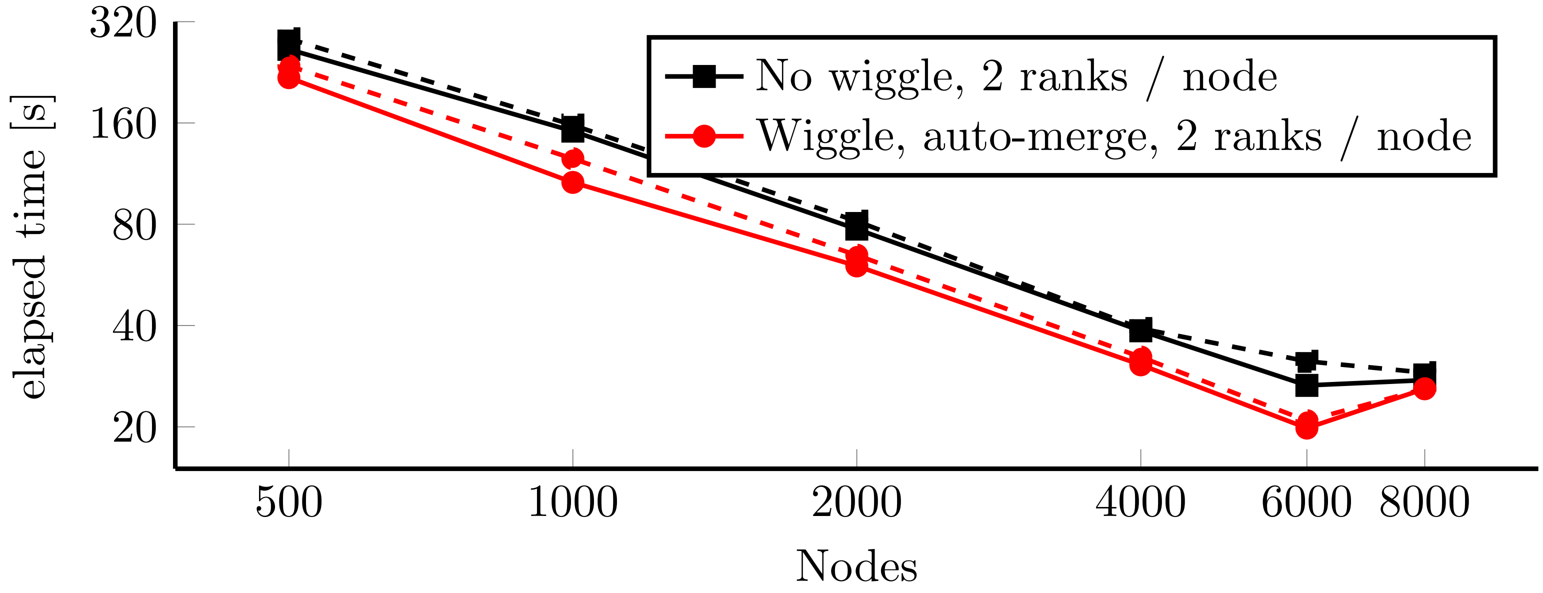
Clustering Palu (M)



Strong Scaling on Frontera (Palu L)



Strong Scaling on Frontera (Palu L): Time-to-solution



Conclusion

- **Fully coupled elastic-acoustic** simulations capture **more effects** than typical one-way linking strategies
- Linearization of free surface boundary conditions **efficient way of tracking sea surface height**
- Pronounced differences in Palu scenario: “smoother” tsunami
- Differences will be important when connecting to tsunami observations
- Further application: Modeling **sound** generated by **induced earthquakes** (due to geothermal energy)
- **Local Time-Stepping** useful for elastic-acoustic coupling
- New **state-machine** based model elegant & contains fewer (or different?) bugs
- Outlook: Fully-coupled models for Mediterranean tsunami (Hellenic arc); Húsavík-Flatey Fault Zone, North Iceland