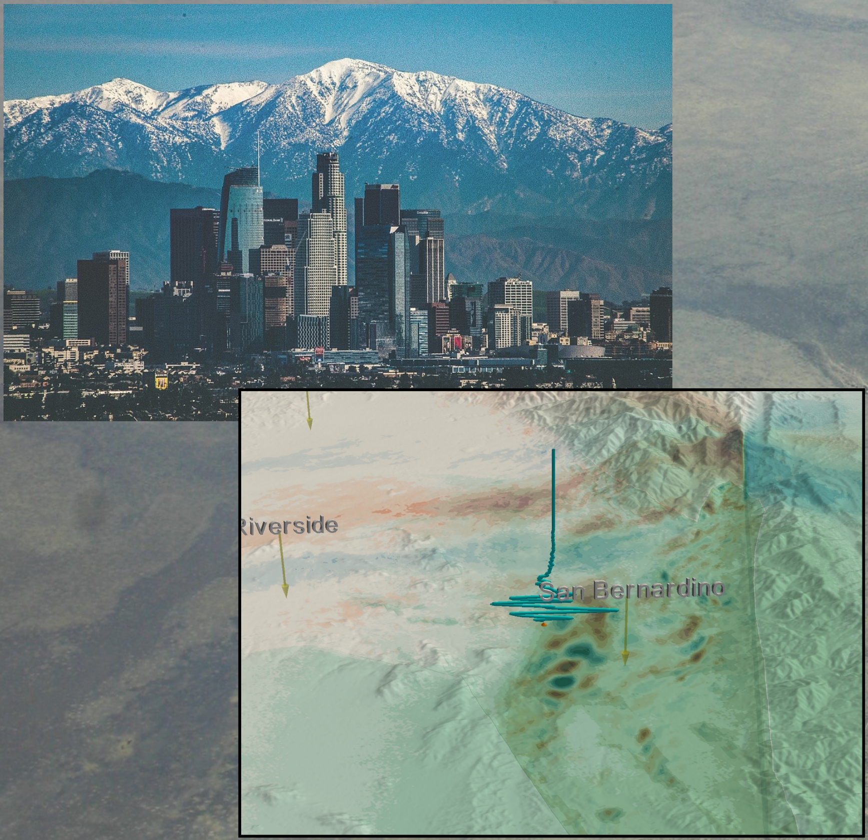
Nonlinear dynamic modeling for a M7.8 earthquake on the southern San Andreas fault



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Frontera User Meeting, Aug 3-4, 2023

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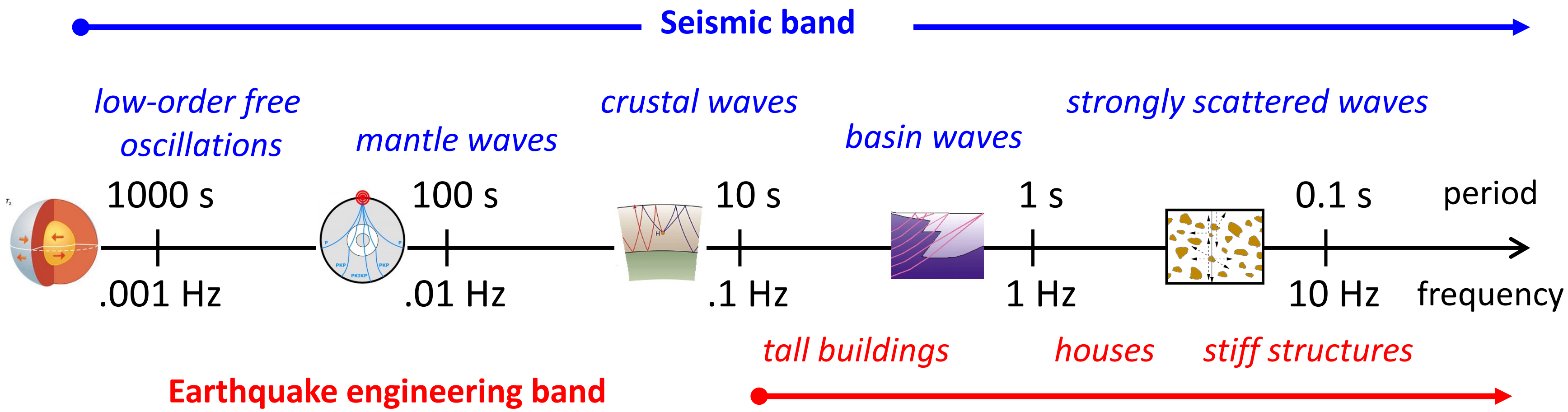
Computing Allocation

TACC LSCP Allocation: *SCEC Earthquake Modeling, Ground Motion and Hazard Simulations*

Funding

NSF/TACC LCCF CSA, NSF/USGS SCEC Core, NSF CSSI

High Frequency Earthquake Modeling



Seismic band

low-order free oscillations
mantle waves
crustal waves
basin waves
strongly scattered waves

1000 s | 100 s | 10 s | 1 s | 0.1 s | period

.001 Hz | .01 Hz | .1 Hz | 1 Hz | 10 Hz | frequency

tall buildings
houses
stiff structures

Earthquake engineering band

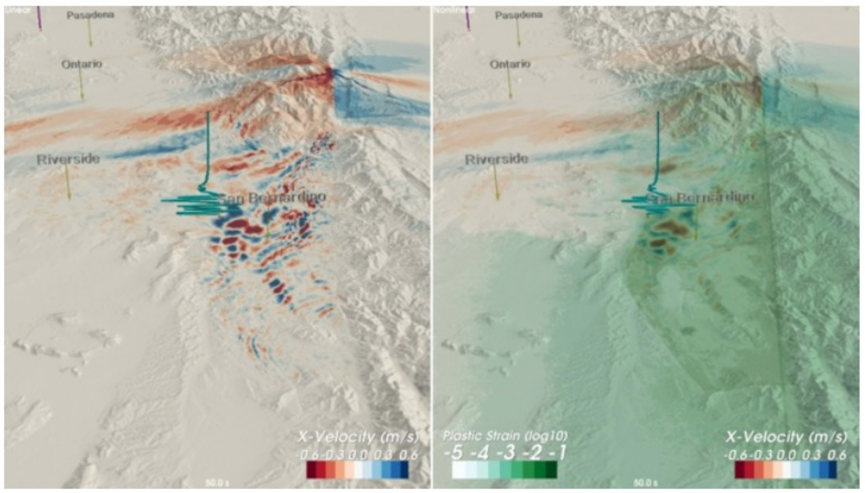
SAF simulation 2023

physics-based deterministic

4 Hz

CyberShake 1 Hz

empirical stochastic



(Snapshots from linear (left) and nonlinear (right) simulations using AWP-ODC showing wave propagation during a magnitude 7.7 SAF earthquake, Roten, SC'16)

Must validate new physics

- fault roughness
- near-fault plasticity
- frequency-dependent attenuation
- Topography
- small-scale near-surface heterogeneity
- multi-surface nonlinearity

8 Hz

SAF Simulation 2026

physics-based deterministic

physics-based stochastic

empirical stochastic

AWP-ODC

- **Started as personal research code (Olsen 1994)**
- **3D velocity-stress wave equations**

$$\partial_t v = \frac{1}{\rho}\nabla\cdot\sigma \qquad \partial_t\sigma = \lambda(\nabla\cdot v)\mathrm{I} + \mu(\nabla v + \nabla v^{\mathrm{T}})$$

solved by explicit staggered-grid 4th-order FD

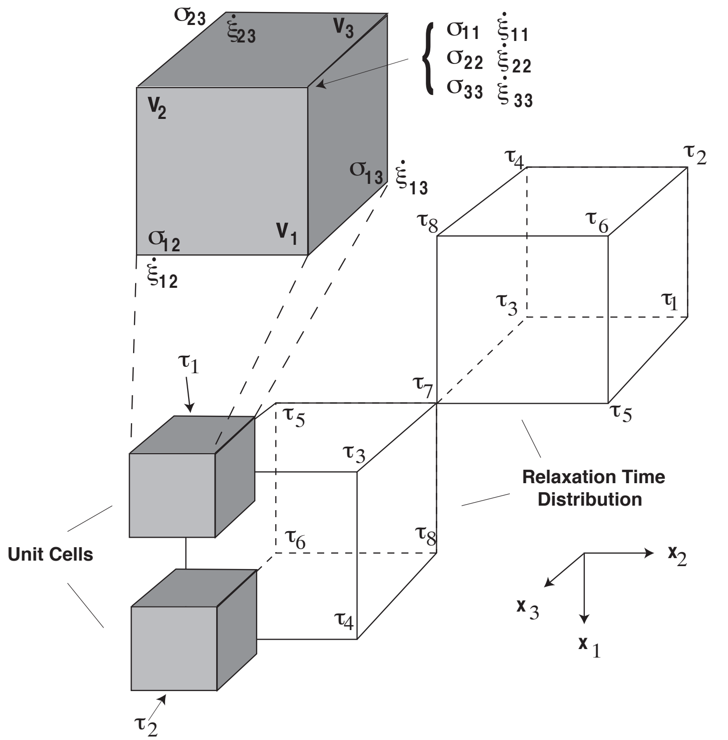
- **Memory variable formulation of inelastic relaxation**

$$\sigma(t) = M_u\left[\varepsilon(t) - \sum_{i=1}^{N}\varsigma_i(t)\right] \qquad \tau_i\frac{d\varsigma_i(t)}{dt} + \varsigma_i(t) = \lambda_i\frac{\delta M}{M_u}\varepsilon(t)$$

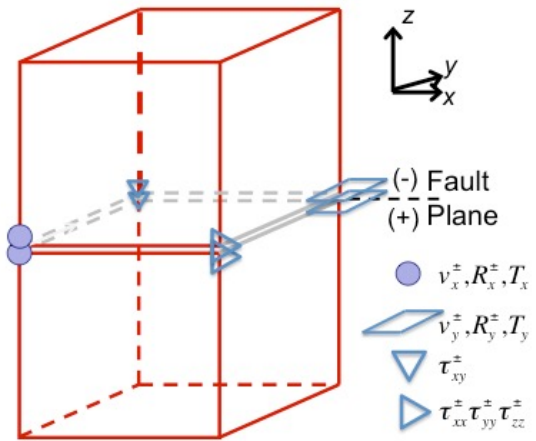
$$Q^{-1}(\omega) \approx \frac{\delta M}{M_u}\sum_{i=1}^{N}\frac{\lambda_i\omega\tau_i}{\omega^2\tau_i^2+1}$$

using coarse-grained representation (Day 1998)

- **Dynamic rupture by the staggered-grid split-node (SGSN) method (Dalguer and Day 2007)**
  - **Displacement nodes split at fault surface: explicitly discontinuous displacement & velocity**
  - **All interactions between sides occur through traction vector at displacement node**
- **Absorbing boundary conditions by perfectly matched layers (PML) (Marcinkovich and Olsen 2003) and Cerjan et al. (1985)**



Inelastic relaxation variables for memory-variable ODEs in AWP-ODC



Variables:

$V_i^\pm$	split-node particle velocities
τ_{ij}	stresses
$T_i^\pm$	split-node traction (no jump)
$R_i^\pm$	stress divergence terms

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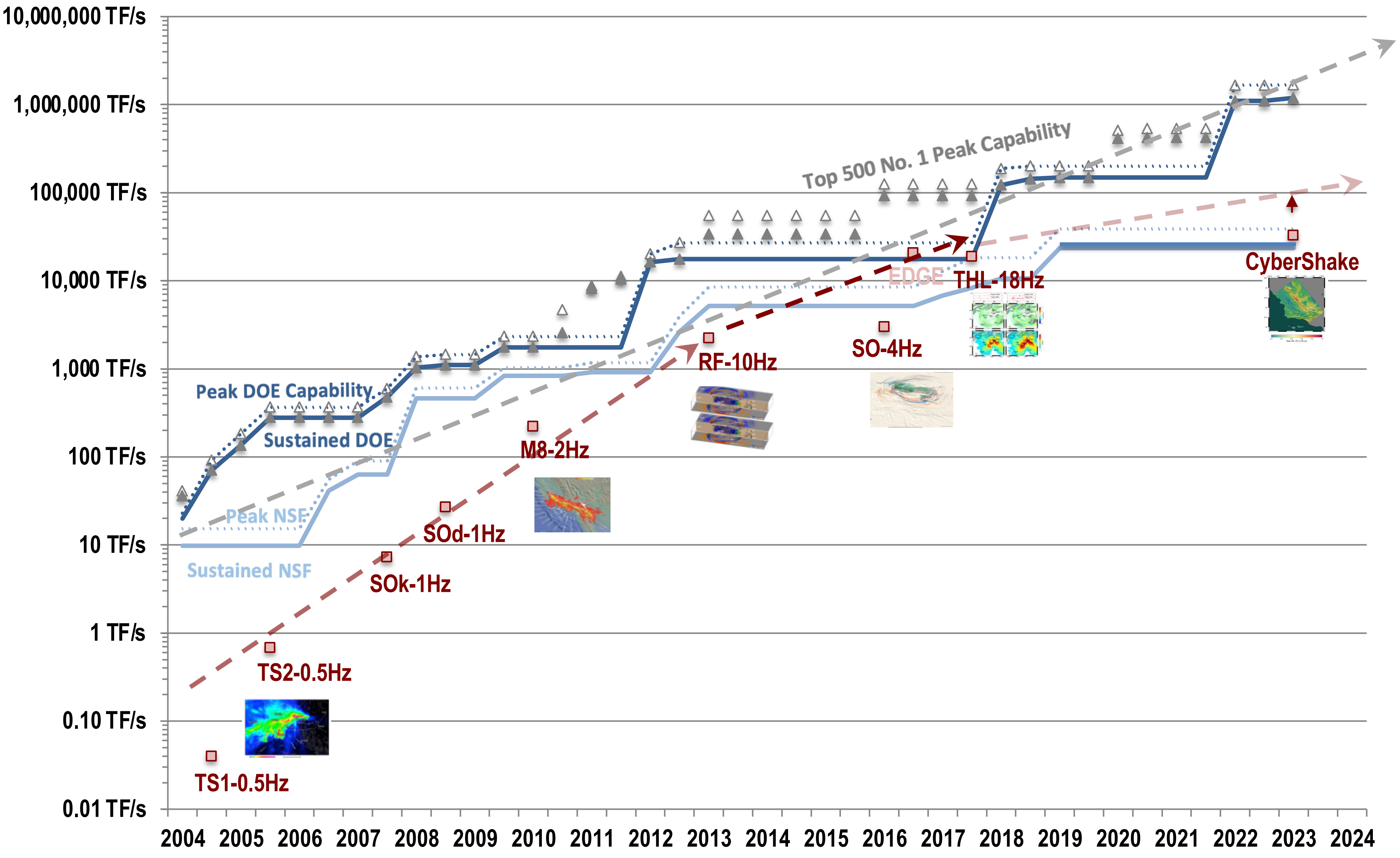
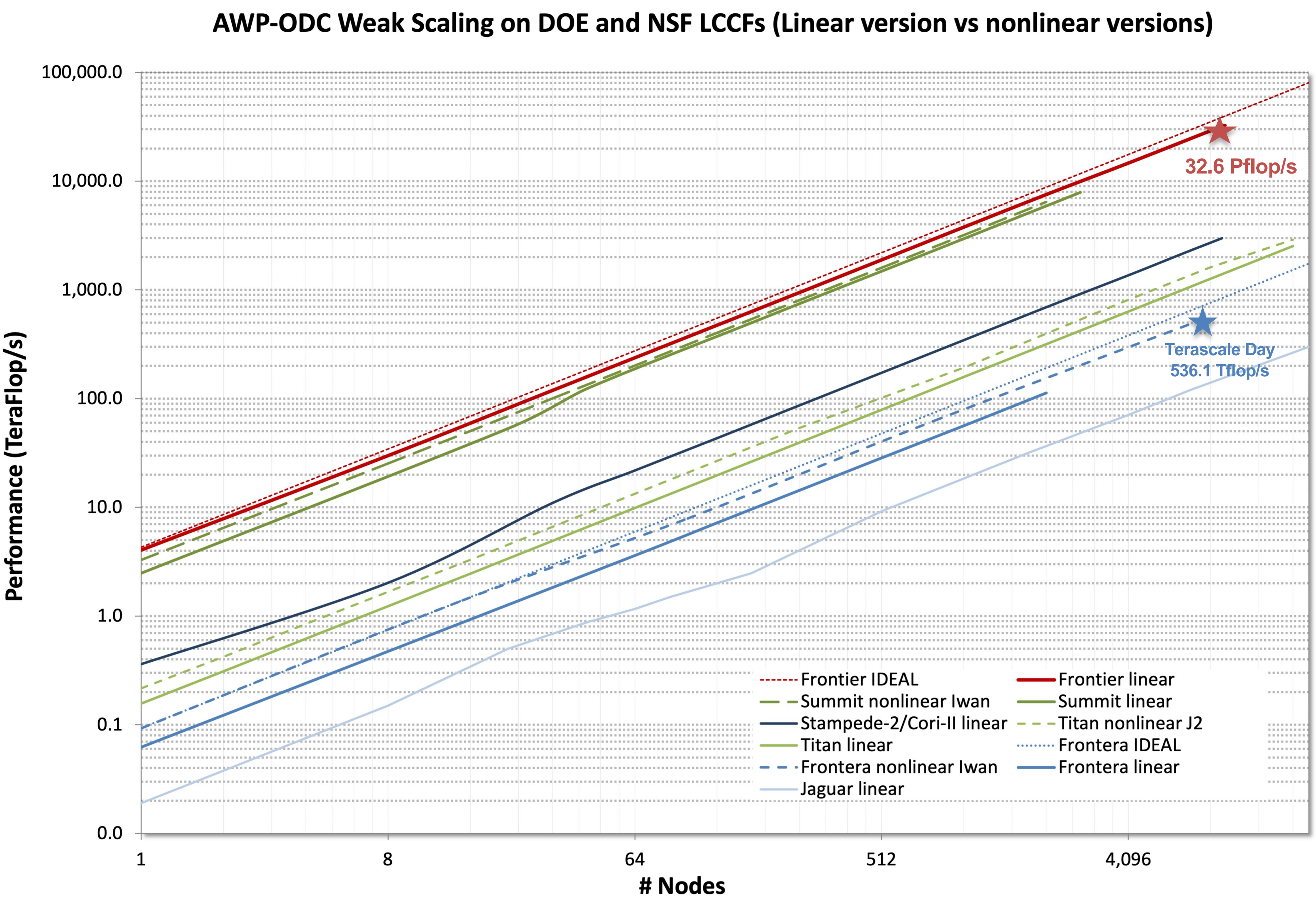
The Earthquake System Science Challenges at Extreme-Scale

Evolution of AWP-ODC



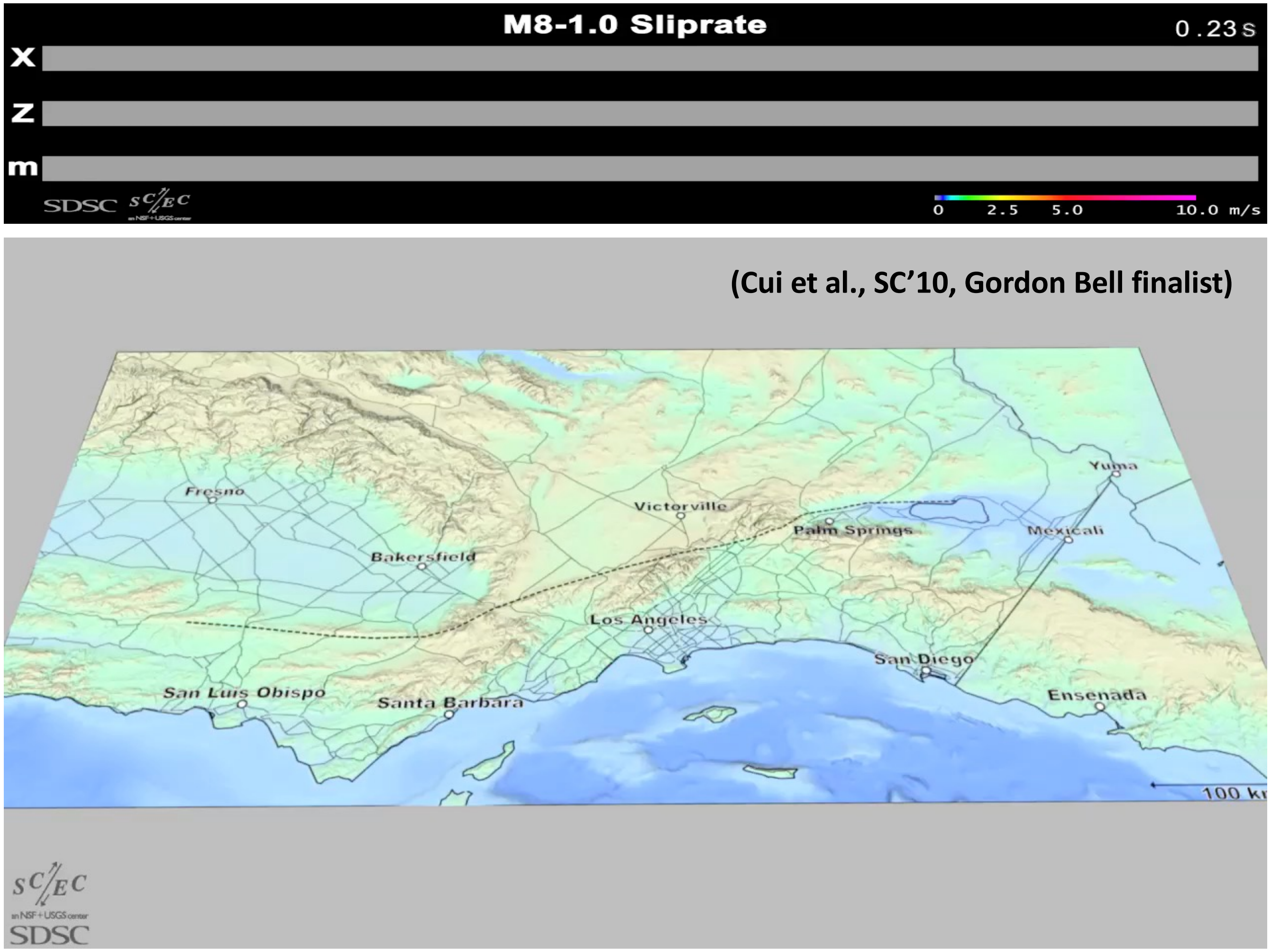
AWP-ODC Weak Scaling



0-2 Hz M8 Linear Earthquake Simulation, 2010

- **Magnitude 8.0 wall-to-wall scenario, worst-case for southern San Andreas Fault**
  - **Fault length: 545 km, minimum wavelength: 200 m, NW→SE rupture propagation**
- **Dynamic rupture simulation performed on Kraken, 7.5 hours using 2160 cores**
  - **881,475 subfaults, 250s of rupture**
- **Wave propagation simulation performed on Jaguar, 24 hours using 223,074 cores (220 Tflop/s sustained)**
  - **436 billion grid points representing SCEC Community Velocity Model V4 of dimension 810 x 405 x 85 km (spatial resolution of 40 m)**
  - **Minimum shear-wave velocity of 400 m/s**
  - **368 s of ground motions (160,000 time steps of 0.0023 s) representing seismic frequencies up to 2 Hz**

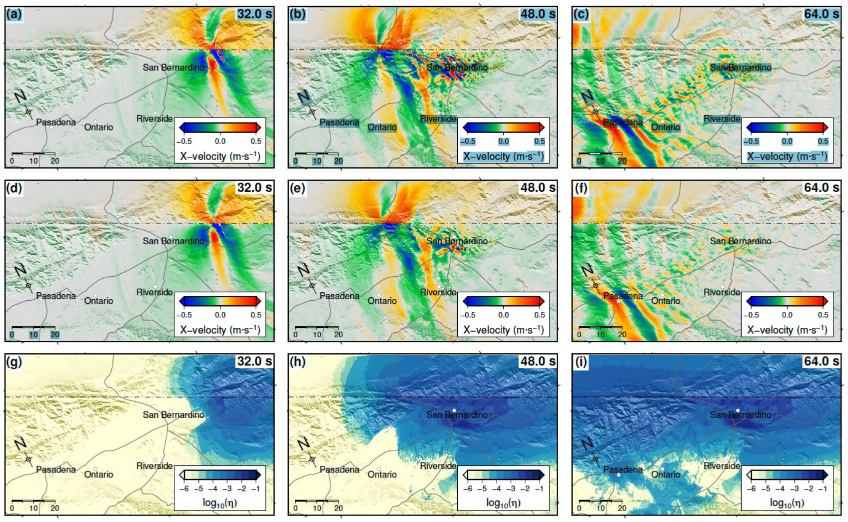
https://www.youtube.com/watch?v=V2Ow0Yuv5co



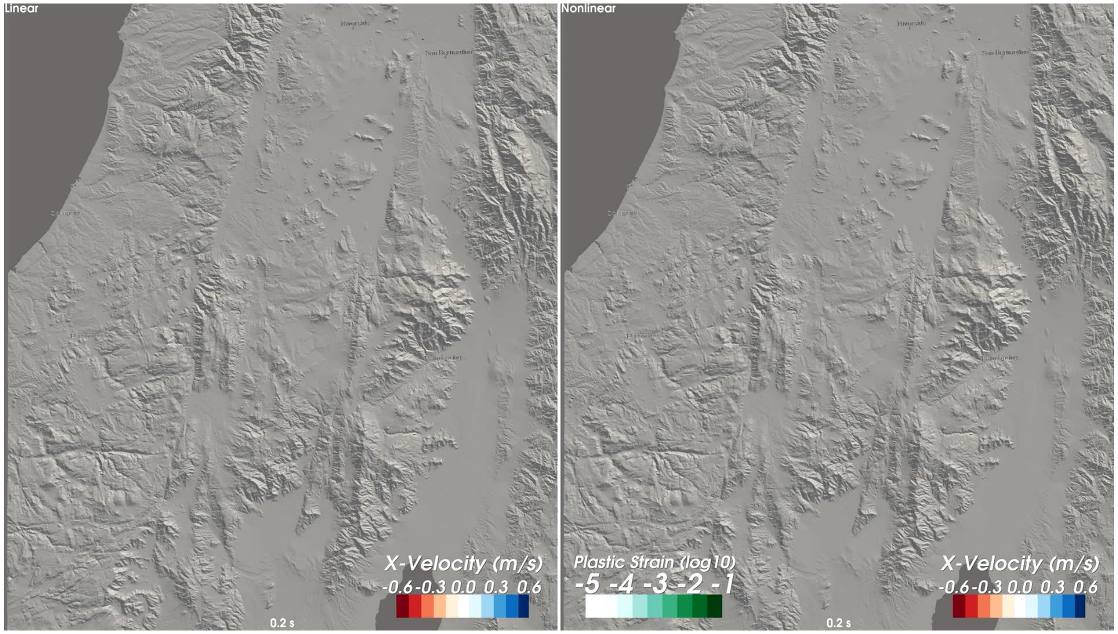
(Cui et al., SC'10, Gordon Bell finalist)

0-4 Hz Drucker-Prager (J2) nonlinear ShakeOut Simulation, 2016

- **A First 4-Hz nonlinear M7.7 earthquake simulation on the southern San Andreas Fault**
- **Nonlinear dynamic rupture simulation was conducted using 24,000 CPU-cores on Blue Waters, running 37 hrs**
- **Nonlinear wave propagation simulation was conducted using 4,200 GPUs on Titan, running 12 hours**
- **Initially 400% computing time required compared to linear code. With optimized yield factor interpolation, this reduces the computing time from 400% to 165% only**



(Roten, et al., SC'16)



(Roten et al., SC'16)

(Roten et al., 2016)

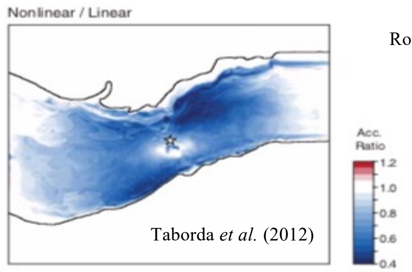
- **Inside the Whittier Narrows corridor, spectral accelerations at 3 seconds (3s-SAs) are reduced from 1g in the linear case to 0.3-0.6g in the nonlinear case, depending on the choice of reference strain.**
- **Plastic simulations obtained with a single von Mises yield surface predict 3s-SAs that are higher than those obtained with the multi-surface Iwan model, but lower than the linear values.**

https://www.youtube.com/watch?v=qOH0Oj3t6QM

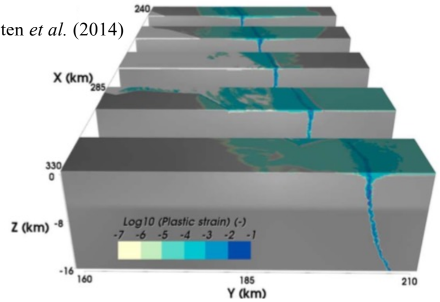
The Iwan Nonlinear Model

❖ Elasto-plastic Yield Criteria in 3D GMP

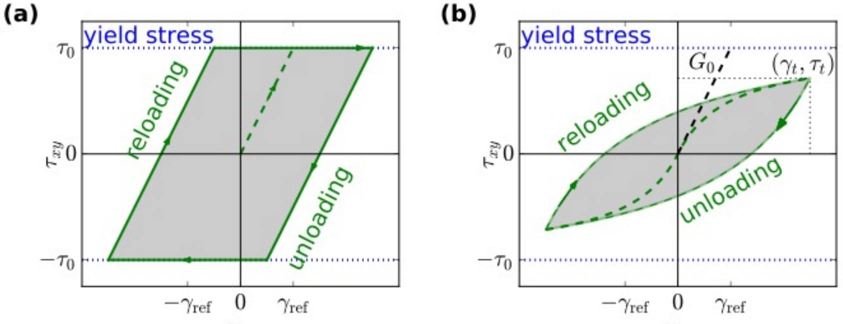
- **Extensive use of elasto-plastic (e.g., Drucker-Prager or von Mises) yield criteria for shallow (sediments, crustal rocks) nonlinearities in 3D simulations (e.g., Andrews et al., 2008; Taborda *et al.*, 2012; Roten *et al.*, 2014)**
- **These criteria do not accurately reproduce stress-strain behavior of most geomaterials:**
  - ○ **artificially large hysteresis loops (unwanted damping)**
  - ○ **delayed onset of nonlinearity**
- **Need for more advanced constitutive models in wave propagation codes**



Taborda *et al.* (2012)



Roten *et al.* (2014)



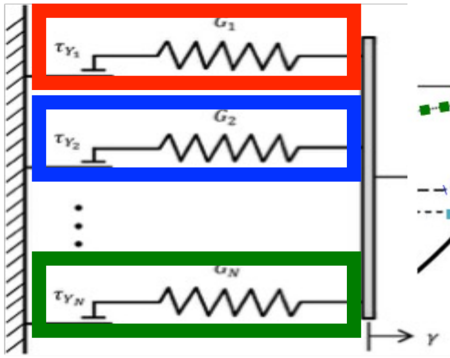
Mohr-Coulomb soil model

Hyperbolic soil model

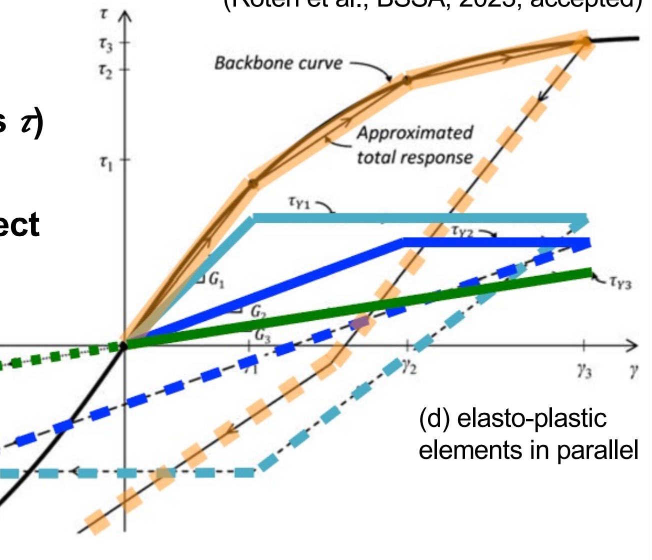
(Roten et al., BSSA, 2023, accepted)

❖ We choose the parallel-series Iwan Model

- **Hysteretic yielding behavior of material represented by a collection of perfectly elasto-plastic spring-slider elements**
- **Each element has different constants (Lamé parameters λ, μ , yield stress τ)**
- **This overlay approach (Kaklamanos *et al.*, 2015) is capable of modeling Masing unloading and reloading behavior as well as the Bauschinger effect**
- **It is generalized to 3D using a collection of concentric von Mises or Drucker-Prager yield surfaces (c)**
- **Lamé parameters and yield stresses calibrated to a predefined backbone curve (d)**



(c) Schematic 1D parallel-series Iwan model (Kaklamanos et 2015)

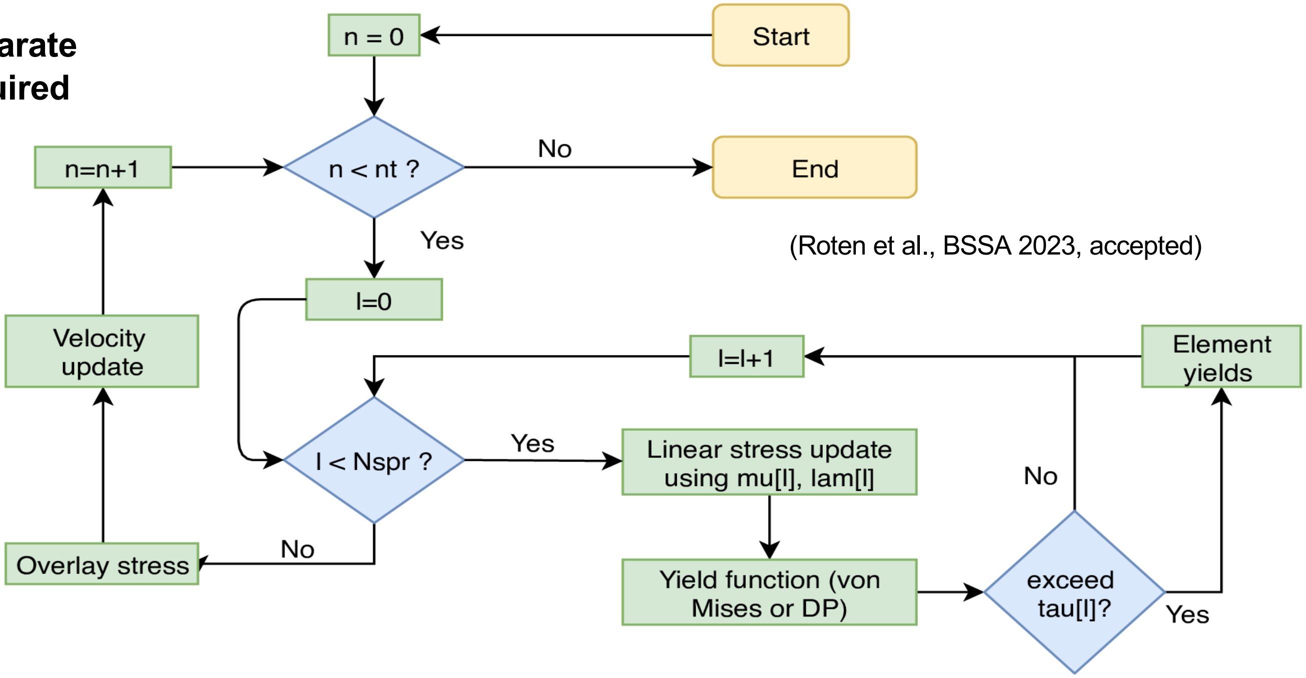


(d) elasto-plastic elements in parallel

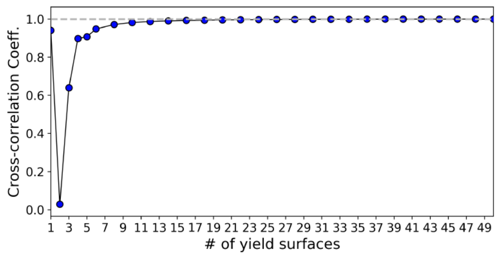
Implementation of Iwan Model in AWP-CPU

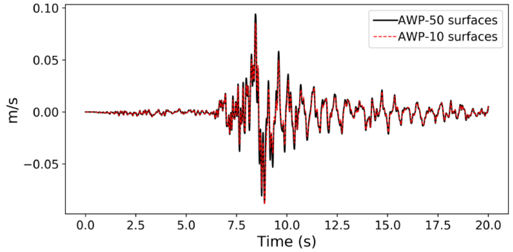
❖ Computational challenges:

- **Computationally expensive: separate stress and plasticity update required for each yield surface**
- **Memory requirements: each yield surface requires a separate copy of stress tensor τxx, τyy, , τzz, τxz, τyz, τxy, Lamé parameters μ, λ, and yield factor r.**
- **MPI communication overhead: stress tensor and yield factor of each yield surface needs to be swapped during each time step (reduced scalability)**
- **Shear modulus reduction reduces max. resolvable frequency**
- **10-20x more expensive compared to our 2016 nonlinear simulation which used a simple J2 nonlinear material model, or 20-30x compared to linear solution**
- **Memory increased by (1 + 0.4* Nspr) to linear simulation (*Nspr = nr of yield surfaces)***


Start
n = 0
n < nt ?
No
End
Yes
n=n+1
l=0
Velocity update
l=l+1
Element yields
l < Nspr ?
Yes
Linear stress update using mu[l], lam[l]
No
No
Overlay stress
Yield function (von Mises or DP)
exceed tau[l]?
Yes

(Roten et al., BSSA 2023, accepted)





❖ Solutions:

- **Iwan model in AWP-GPU**
- **Limit nonlinearity to shallow part and use discontinuous mesh (implemented in AWP-GPU)**

Verification of AWP-Iwan

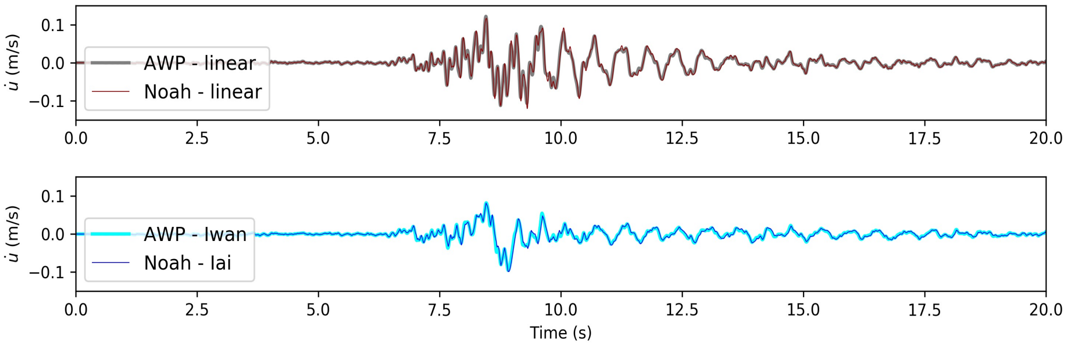
Verification using 1D and 2D benchmarks

- **Periodic boundary conditions at horizontal boundaries (disabling absorption, periodic MPI grid)**
- **User-specified input velocity (e.g., borehole record) inserted at bottom of domain**
- **Verify against 1D and 2D versions of Noah code (Bonilla *et al.*, 2005), which has been verified against ~20 other nonlinear codes in the framework of PRENOLIN (Regnier *et al.*, 2016, 2018)**

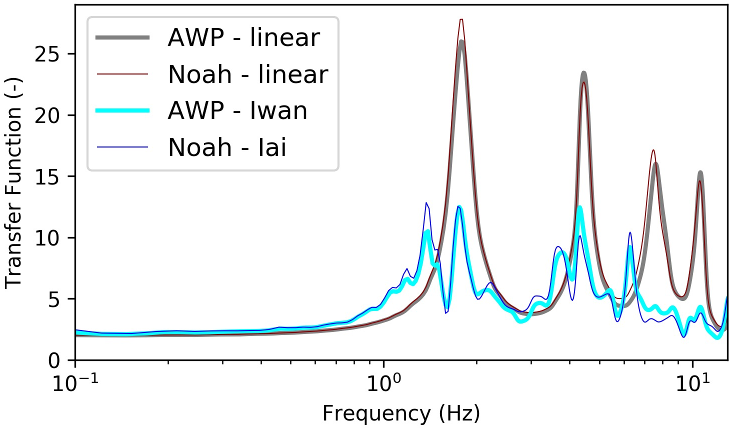
Verification for Horizontally layered SH Case

KiK-net site KSRH10

- ***γ_r computed from μ, φ and c provided by Regnier et al. (2015)***
- **Δh = 2 m, 20 yield surfaces in AWP**
- **Δh = 1 m in Noah1D, w/o damping control**
- **M6 EQ from Nov 29 2004**

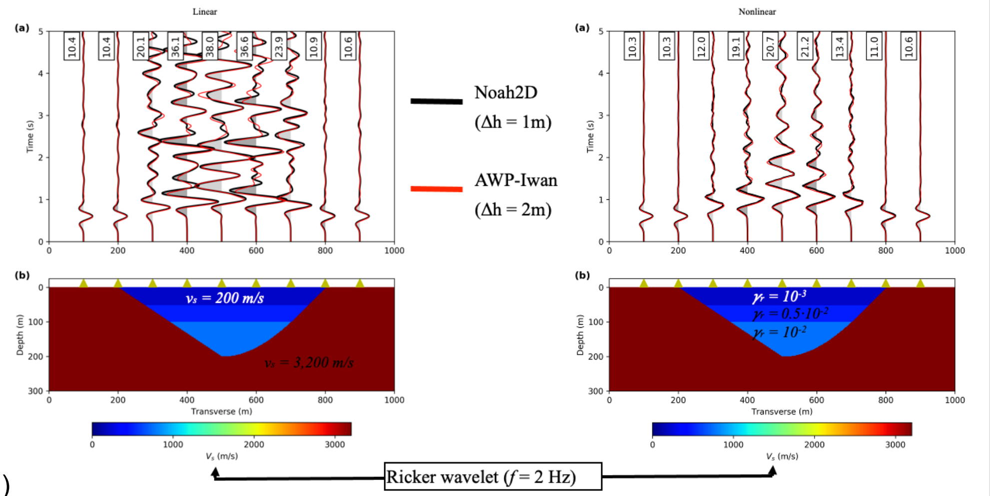


(Roten et al., BSSA, 2023, accepted)



(Roten et al., BSSA, 2023, accepted)

Verification for 2D P-SV Case



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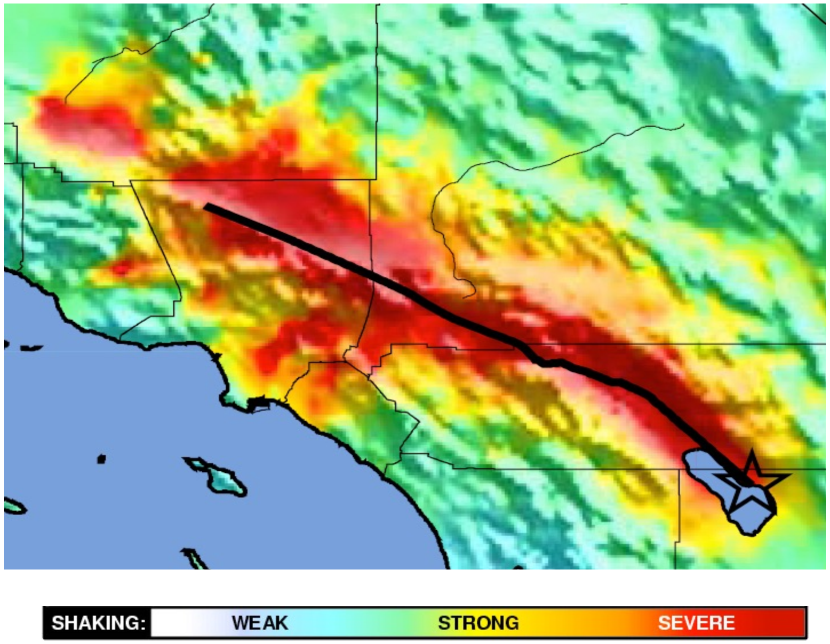
The ShakeOut Scenario

M7.8 Earthquake on Southern San Andreas Fault

Scenario Results

- **M7.8 mainshock**
  - **Broadband ground motion simulation (0-10 Hz)**
- **Large aftershocks**
  M7.2, M7.0, M6.0, M5.7…
- **10,000-100,000 landslides**
- **1,600 fire ignitions**
- **$213 billion in direct economic losses**
  - **300,000 buildings significantly damaged**
  - **Widespread infrastructure damage**
  - **270,000 displaced persons**
  - **50,000 injuries**
  - **1,800 deaths**
- **Long recovery time**



shaking intensity

Great Southern California ShakeOut

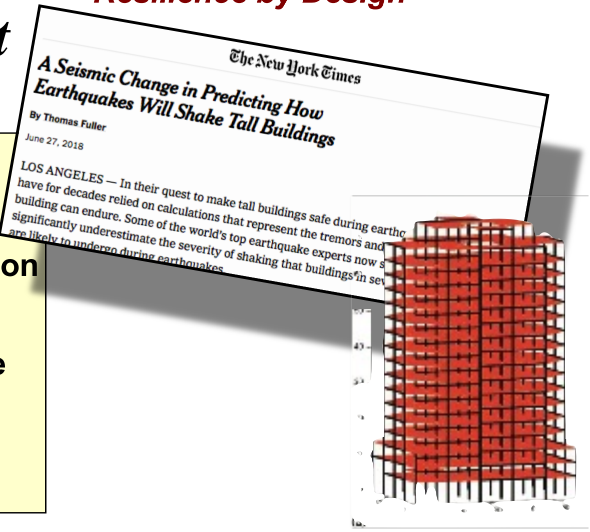
November 13, 2008

Exercise Results

- **Largest emergency response exercise in US history**
  - **Golden Guardian exercise**
  - **Public events involving multi-million registered participants**
- **Demonstrated that existing disaster plans are inadequate for an event of this scale**
  - **Motivated reformulation of system preparedness and emergency response**
  - **Scientific basis for the LA Seismic Safety Task Force report, *Resilience by Design***

Waveguide amplification in LA Basin

- **Caused by string of contiguous sedimentary basins (Olsen et al, 2006, 2009)**
- **ShakeOut scenario predict strong long-period ground motions in Los Angeles region**
- **Hazard to pre-Northridge high-rise buildings**
- **All these approaches assume a linear stress-strain relationship in the fault damage zone and shallow sediments**
- **Simulations with DP-plasticity predict 30-70% lower ground motions than linear solutions (Roten et al., 2014, 2017)**



The New York Times

A Seismic Change in Predicting How Earthquakes Will Shake Tall Buildings

By Thomas Fuller

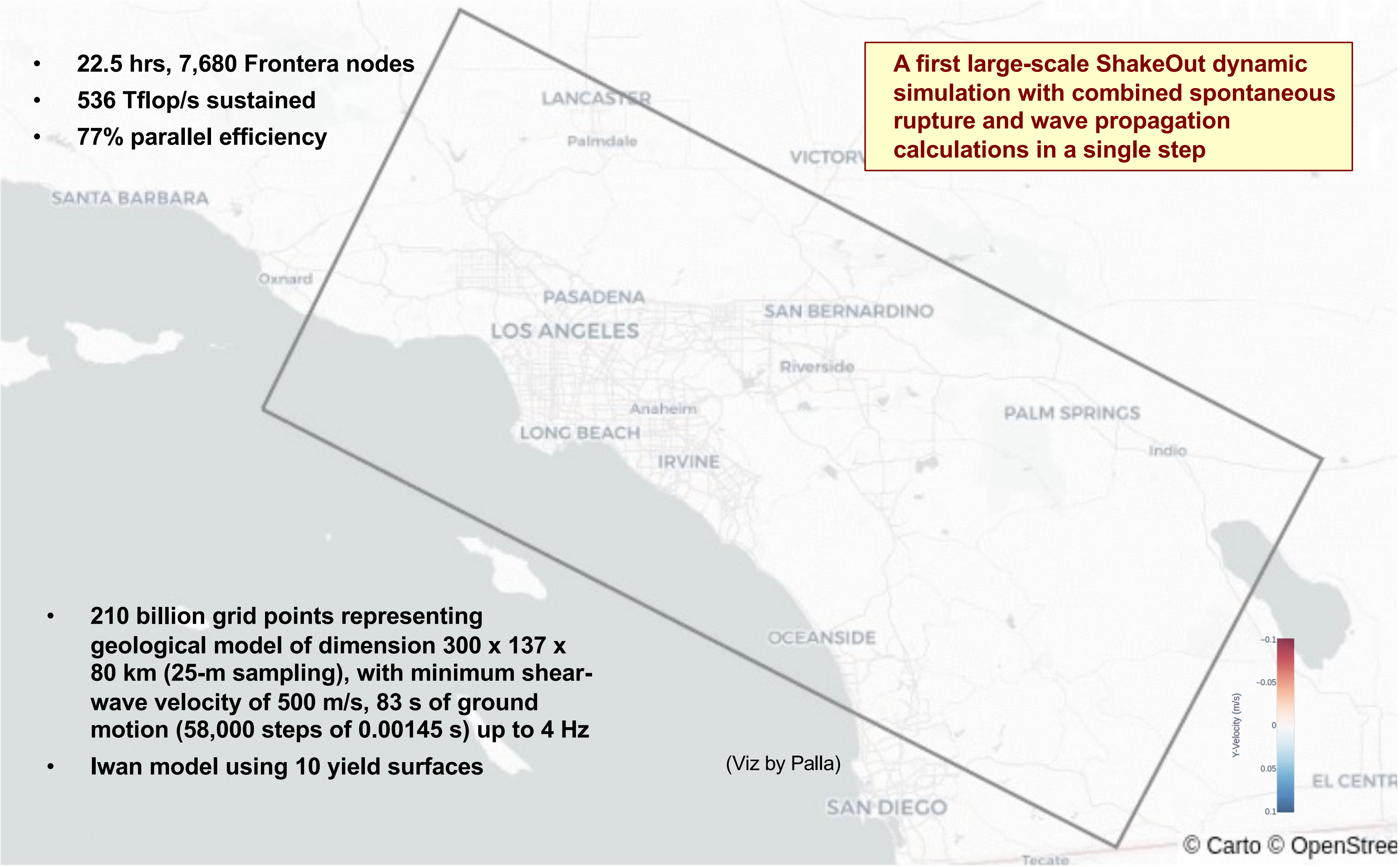
June 27, 2018

LOS ANGELES — In their quest to make tall buildings safe during eartho
have for decades relied on calculations that represent the tremors and
building can endure. Some of the world's top earthquake experts now s
significantly underestimate the severity of shaking that buildings in sev
are likely to undergo during earthquakes.

0-4 Hz Iwan Nonlinear Dynamic ShakeOut Simulation on Texascale Days

- **22.5 hrs, 7,680 Frontera nodes**
- **536 Tflop/s sustained**
- **77% parallel efficiency**

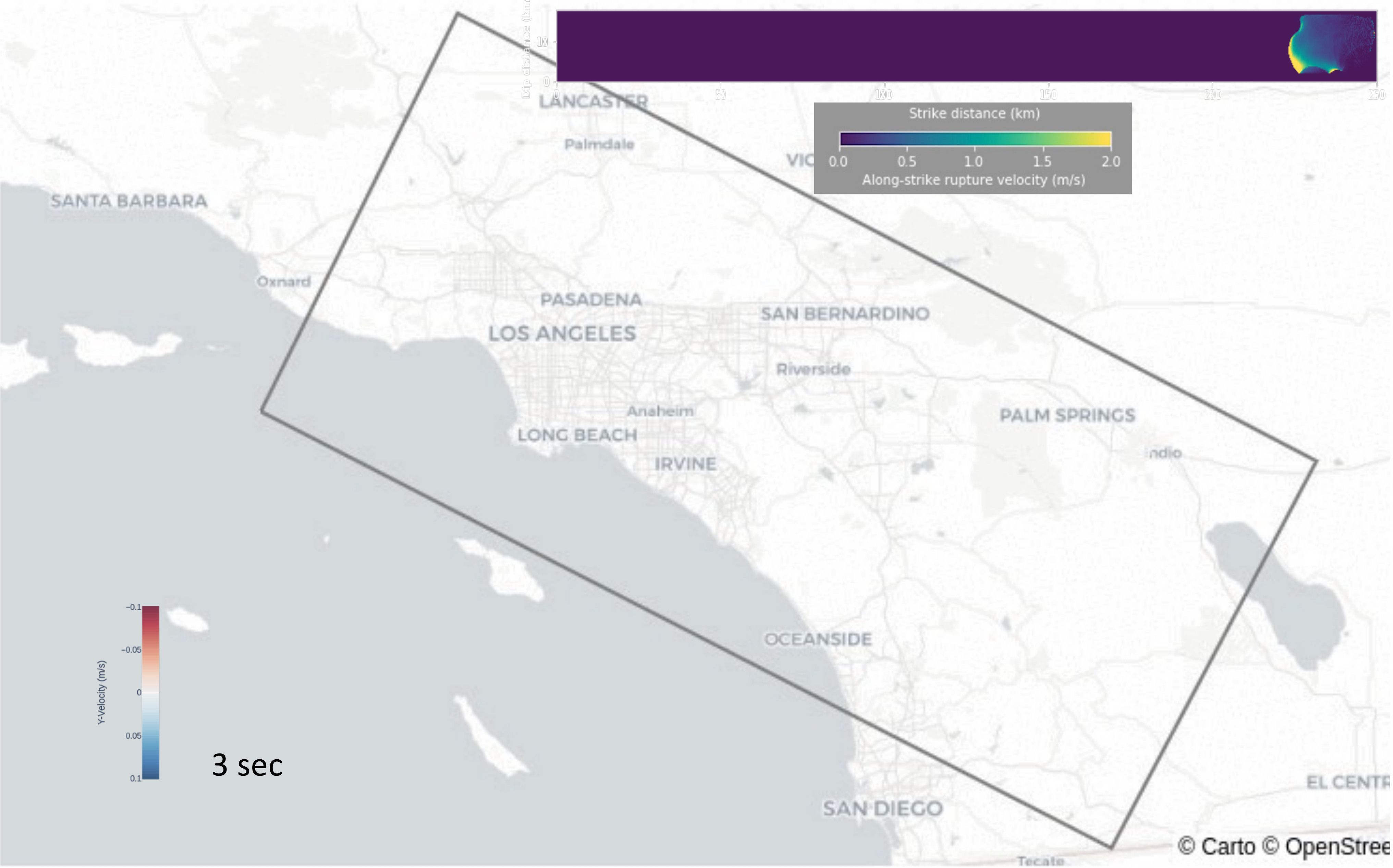
A first large-scale ShakeOut dynamic simulation with combined spontaneous rupture and wave propagation calculations in a single step



- **210 billion grid points representing geological model of dimension 300 x 137 x 80 km (25-m sampling), with minimum shear-wave velocity of 500 m/s, 83 s of ground motion (58,000 steps of 0.00145 s) up to 4 Hz**
- **Iwan model using 10 yield surfaces**

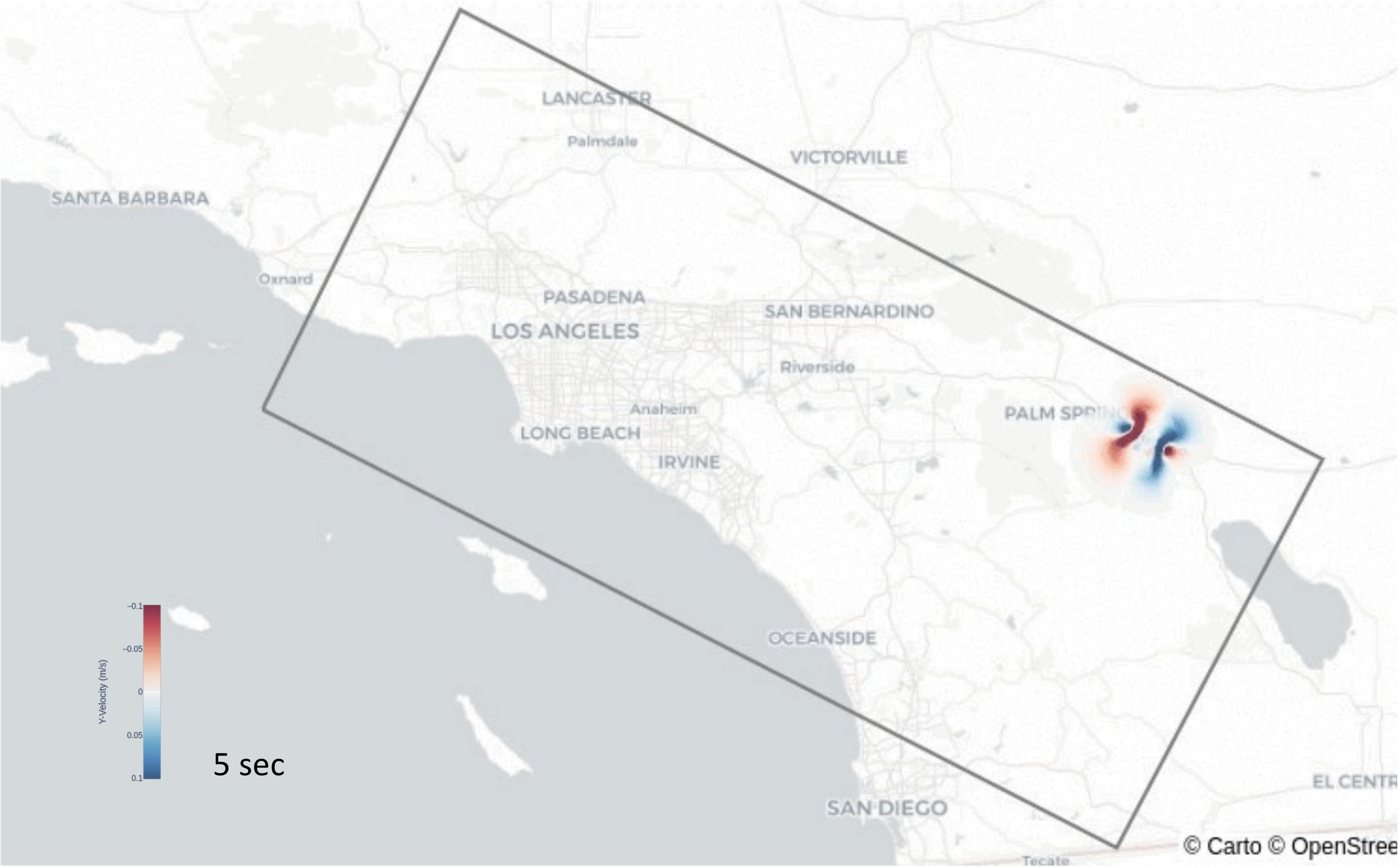
(Viz by Palla)

0-4 Hz Iwan Nonlinear Dynamic ShakeOut Simulation on Texascale Days

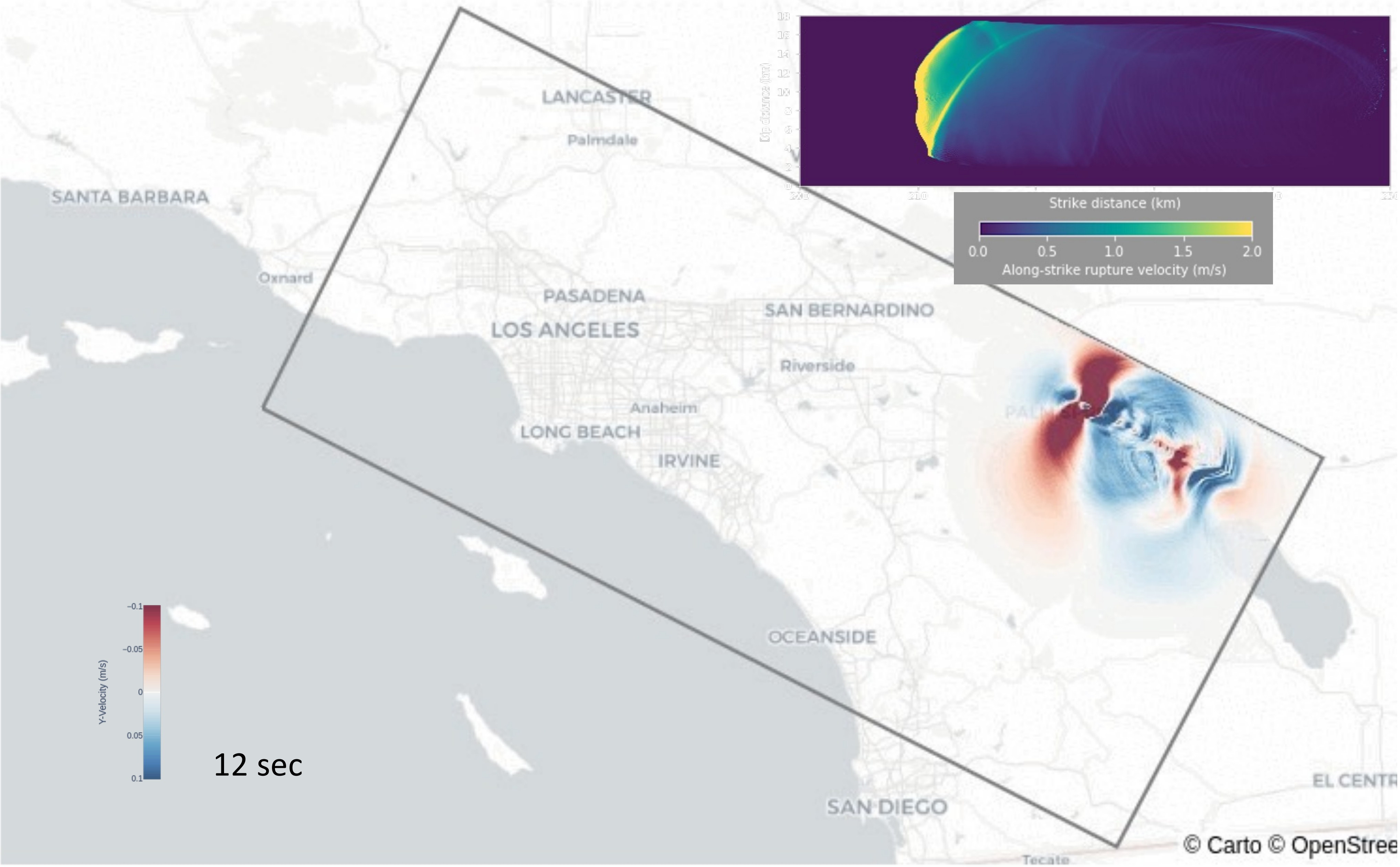


3 sec

0-4 Hz Iwan Nonlinear Dynamic ShakeOut Simulation on Texascale Days



0-4 Hz Iwan Nonlinear Dynamic ShakeOut Simulation on Texascale Days



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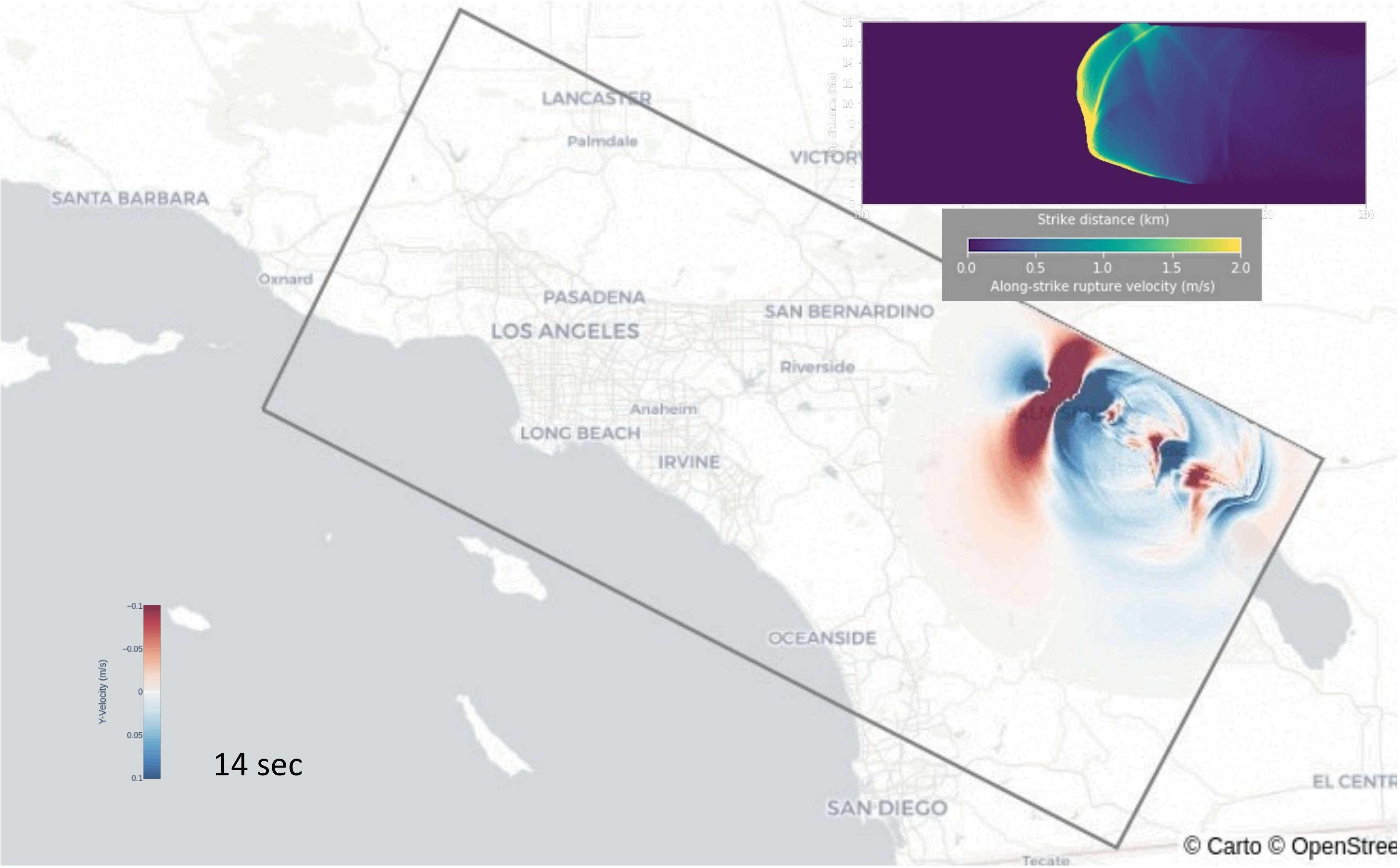
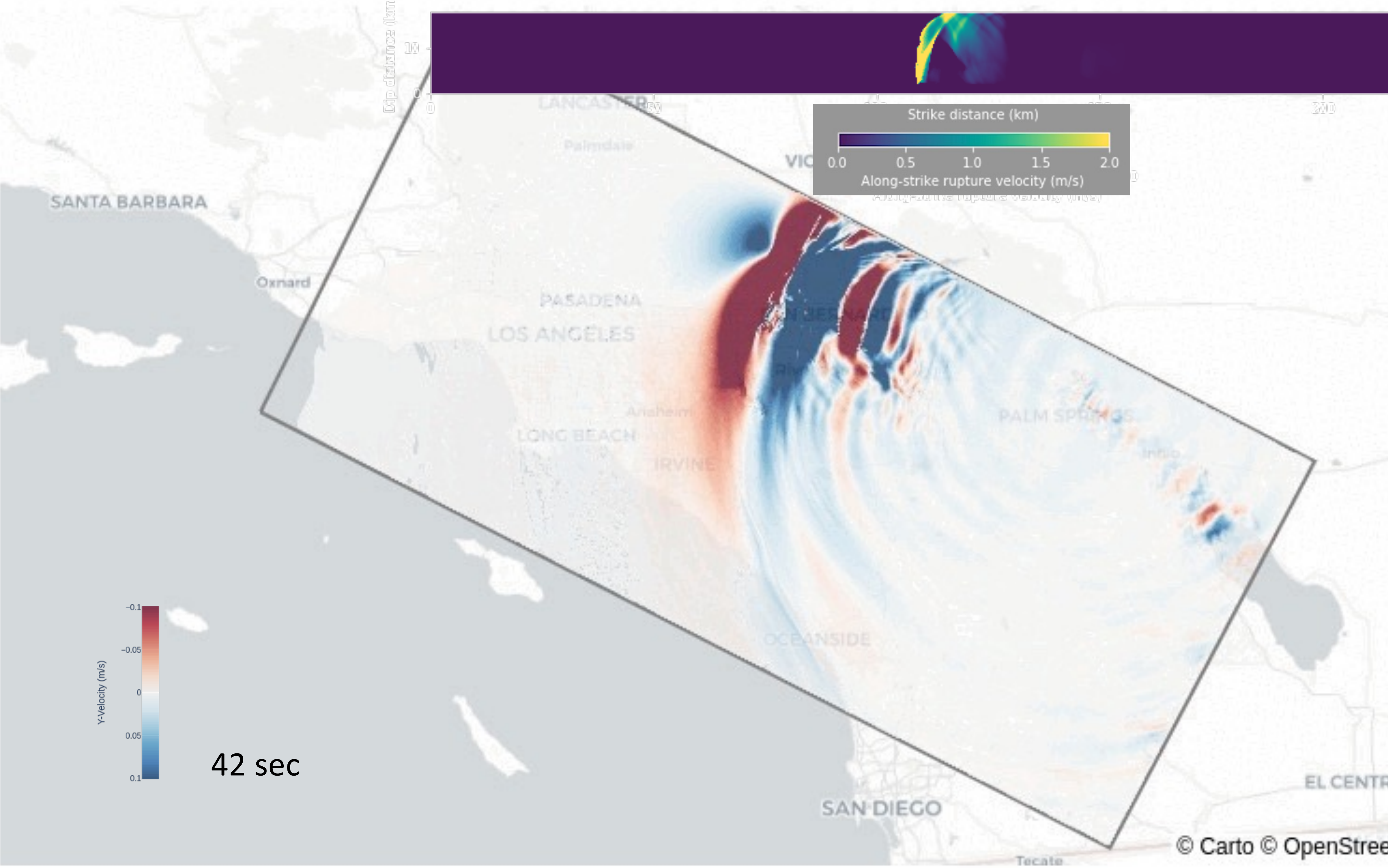
0-4 Hz Iwan Nonlinear Dynamic ShakeOut Simulation on Texascale Days



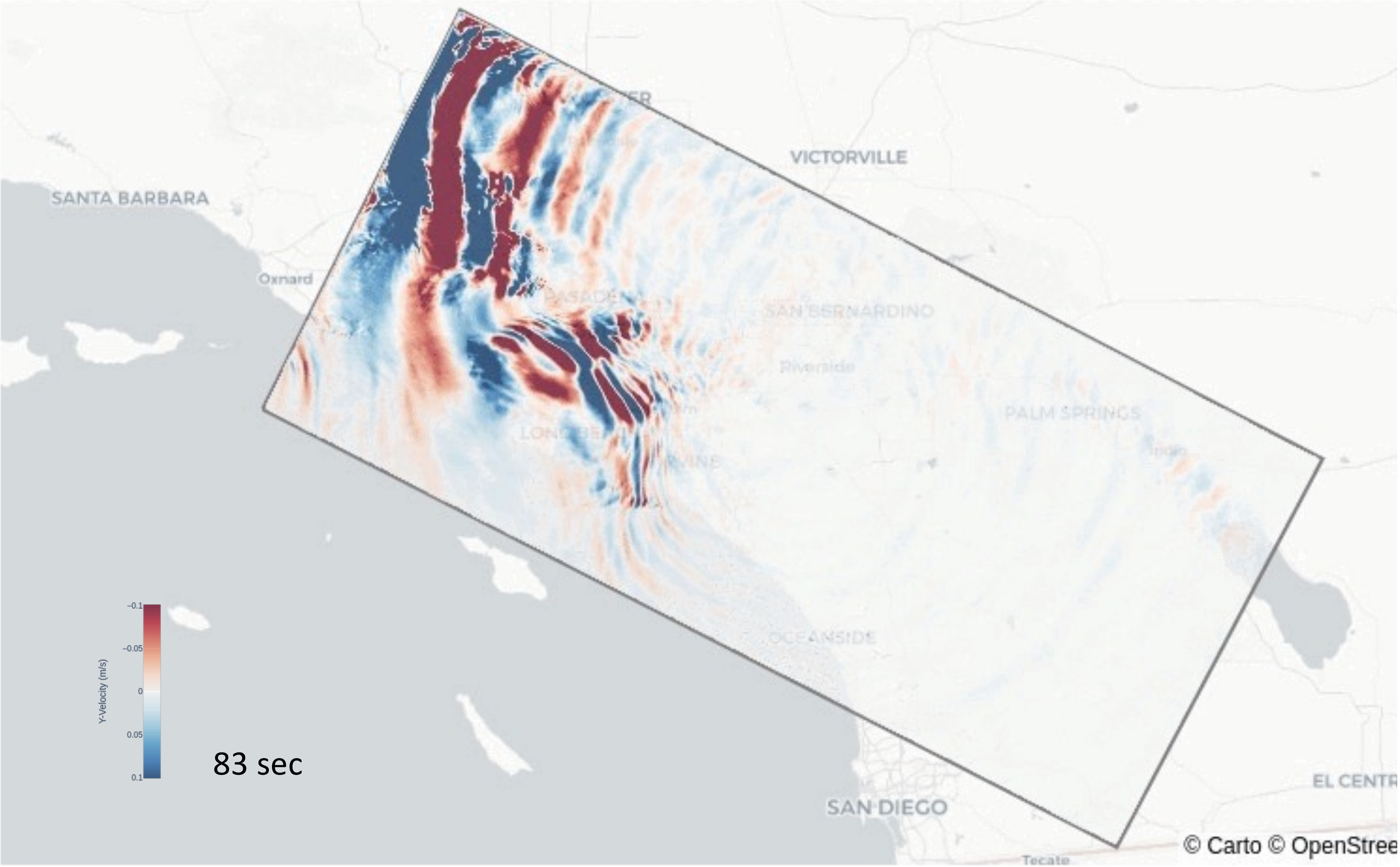
14 sec

© Carto © OpenStree

0-4 Hz Iwan Nonlinear Dynamic ShakeOut Simulation on Texascale Days



0-4 Hz Iwan Nonlinear Dynamic ShakeOut Simulation on Texascale Days



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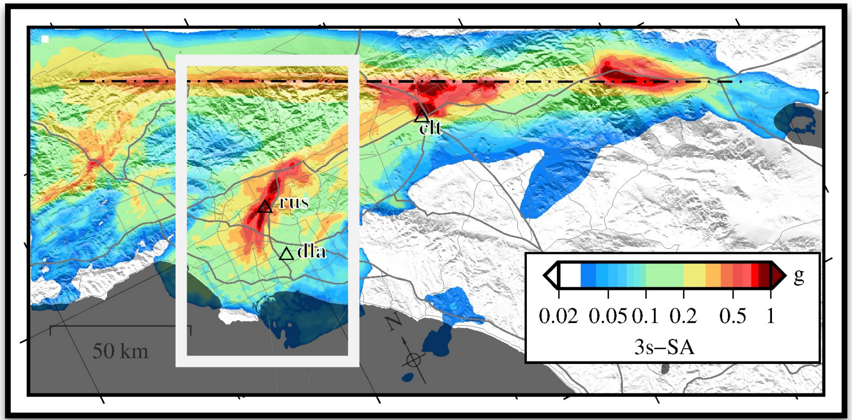
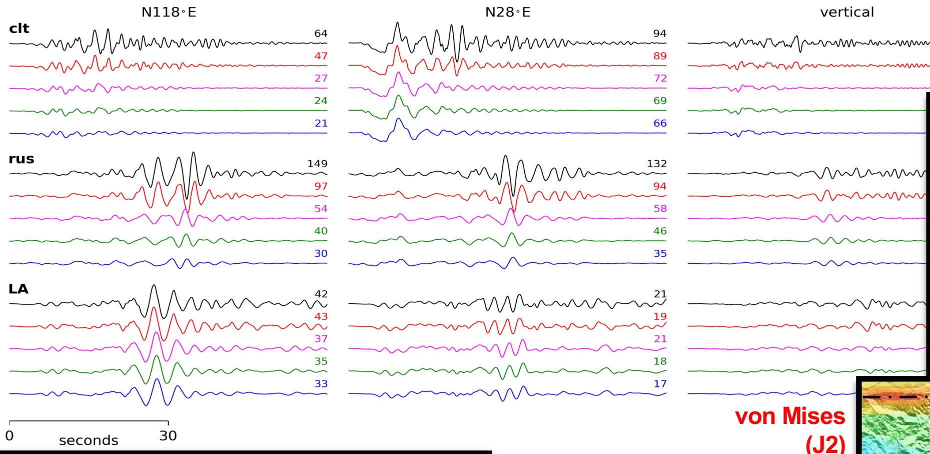
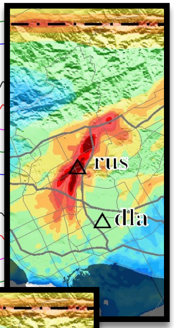
Iwan Nonlinearity Compared to linear and J2 nonlinearity

Linear

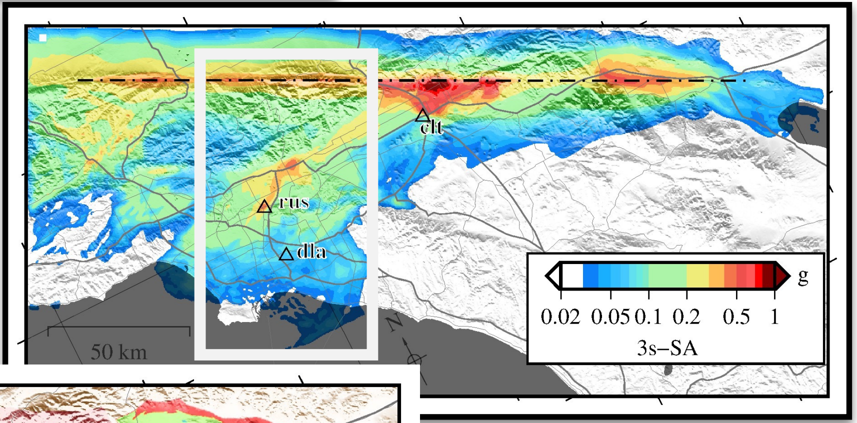




Linear



Iwan (*Darendeli*)

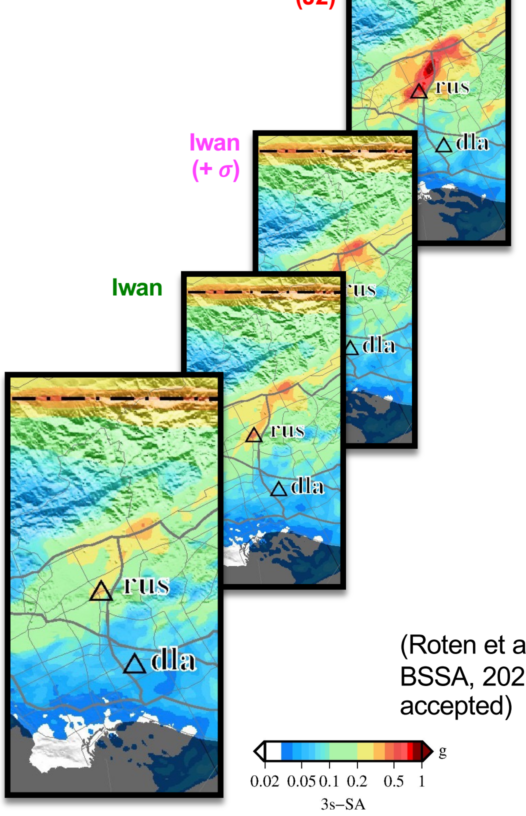


von Mises (J2)

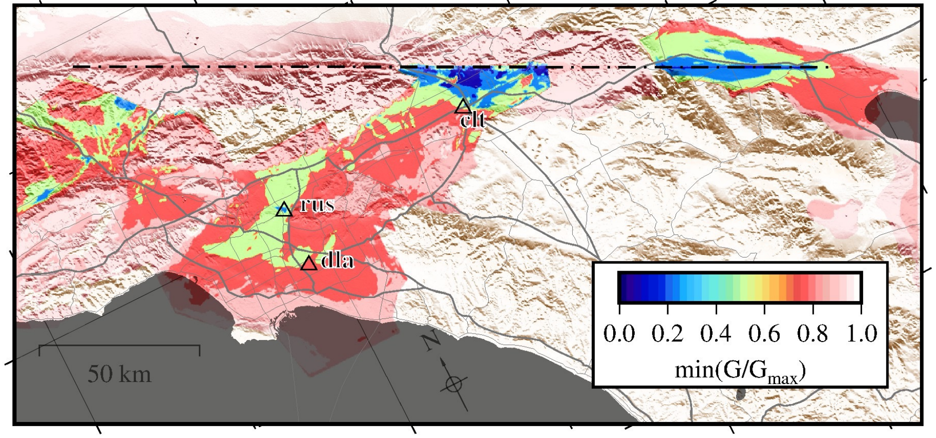
Iwan (+ σ)

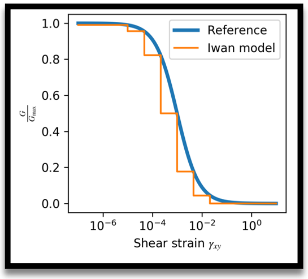
Iwan

Iwan (- σ)



Maximum shear modulus reduction encountered at the surface

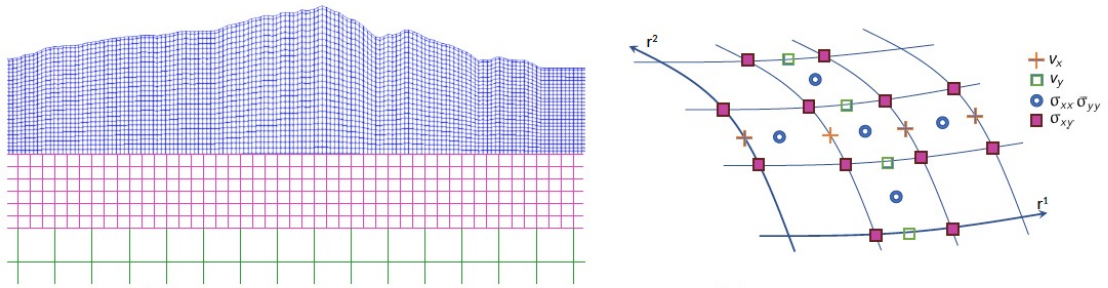




(Roten et al., BSSA, 2023, accepted)

Summary and Outlook

- A multi-surface Iwan type plasticity model in AWP-CPU, verified against the established codes for 1D and 2D SH-wave benchmarks, has been applied to predict the impact of realistic soil nonlinearity on long-period surface waves during large earthquakes on the southern San Andres fault
- While ShakeOut simulations with a single yield surface reduces long period ground motion amplitudes by ~25% inside a wave guide in greater LA, Iwan nonlinearity further reduces the values by a factor of two
- Computational requirements with Iwan model is 20-30x more expensive, and memory use 5-13x more compared to linear solution
- These challenges have been addressed by Iwan nonlinearity in the more efficient discontinuous mesh (DM), GPU-based version of AWP (10x speedup compared to equi-spaced grid), which runs on Summit/Lonestar-6 and is being ported to Frontier
- Topography has been added in GPU AWP code, a separate version using curvilinear grid
- Future plan is to model 3D ground motion above 8 Hz to realistically capture the full dynamics of a potential Big One at SAF on the coming hybrid *Horizon – using* CPUs for dynamic rupture simulation, and GPUs for Iwan-DM wave propagation simulation.

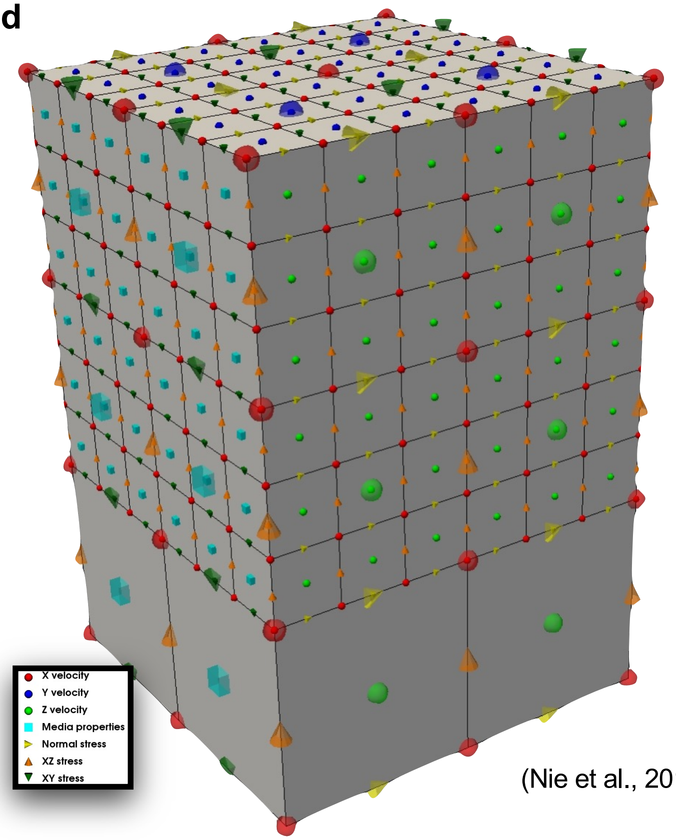


(a) Nonconforming multiblock grid

(b) Curvilinear staggered grid

Figure 1: (a) Curvilinear grid, used for discretizing topography, overlaying cartesian grids with decreasing grid resolution with depth. (b) Arrangement of velocity and stresses in a curvilinear staggered grid

(O'Reilly et al., 2022)



(Nie et al., 2017)