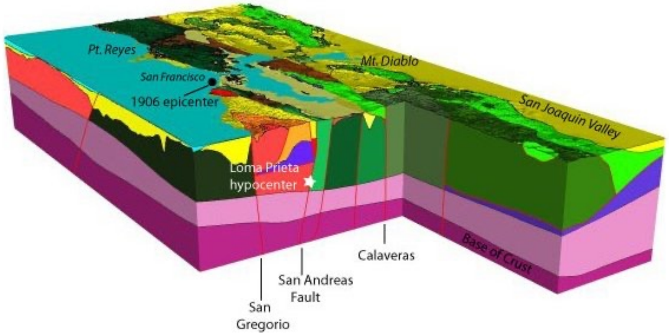
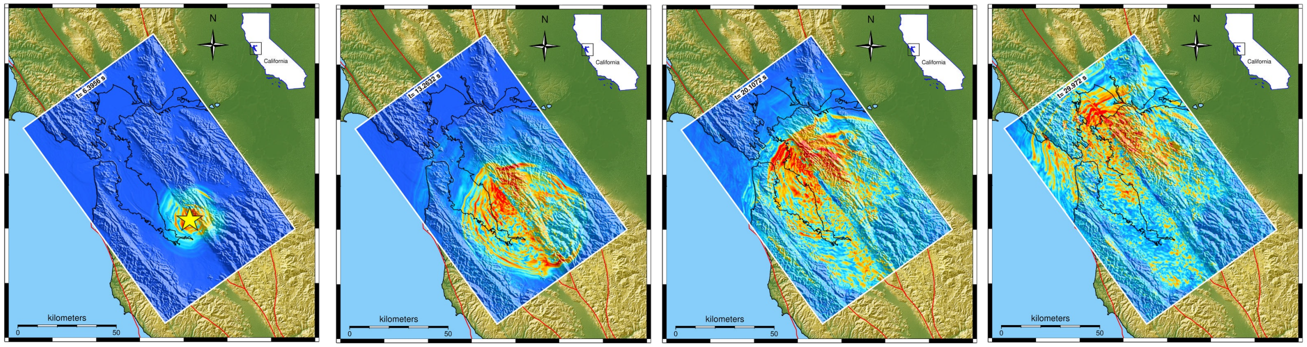




Earthquake Source Modeling for Engineering Risk Assessment

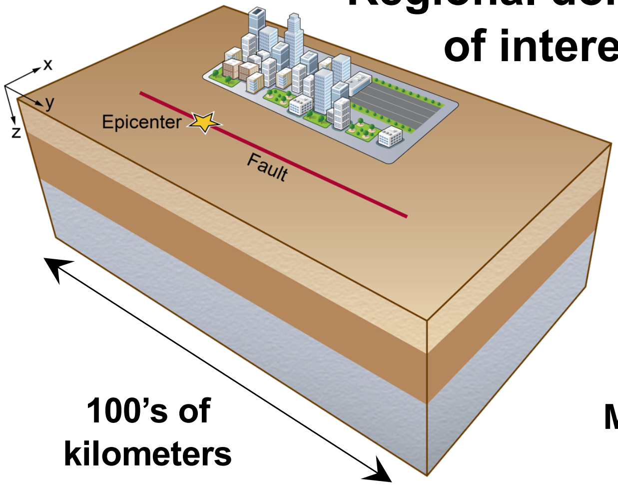
Arben Pitarka
Lawrence Livermore National Laboratory

David McCallen
Lawrence Berkeley National Laboratory

Workshop on the Regional-Scale Simulated Ground Motion
Database(SGMD) for the San Francisco Bay Area , March 24, 2025

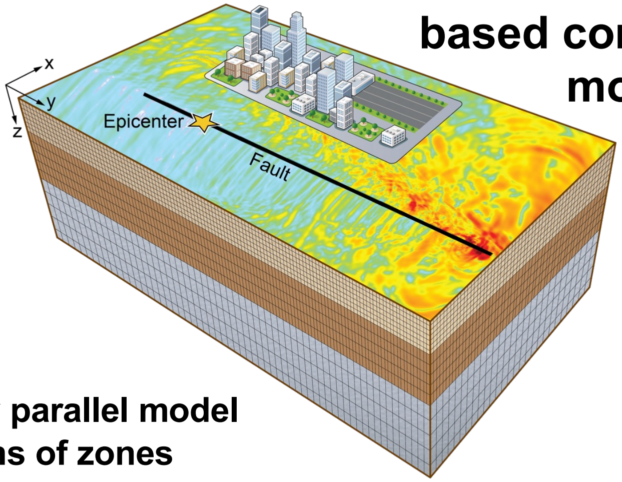
Regional-scale Simulations

Regional domain of interest



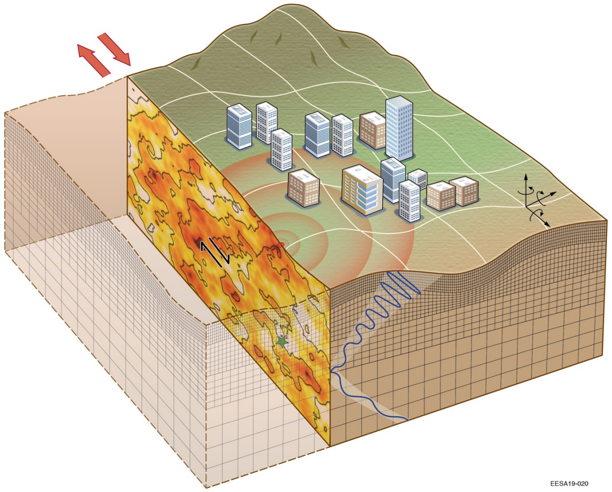
100’s of kilometers

Deterministic, physics-based computational models

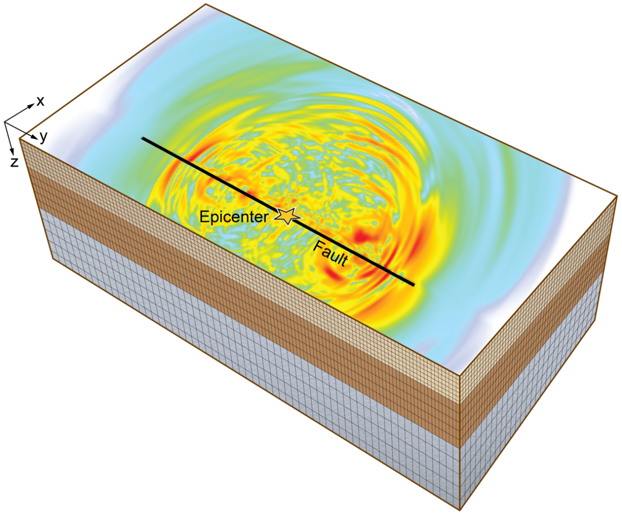


Massively parallel model billions of zones

Kinematic Rupture Model



SW4: Elastic Wave Propagation



Generation of Rupture Models for a M7 Strike-slip Earthquake on the Hayward Fault

Objective:

Generate kinematic rupture models that are suitable for 0-5 Hz deterministic strong motion simulations of M7 strike slip earthquakes

Requirements:

1: Constrained by physics-based rupture modeling and empirical data

2: Capable of reproducing recorded ground motion characteristics at both near-fault and long distances relevant to engineering applications in the target frequency range 0-5Hz

3: Characterized by a tractable and small number of model parameters

4: Rupture models used in generating the database should be available upon request

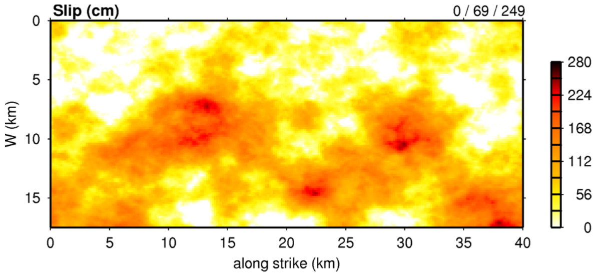
5: Validated against recorded waveforms and ground motion models

Graves&Pitarka (GP) Kinematic Rupture Generator

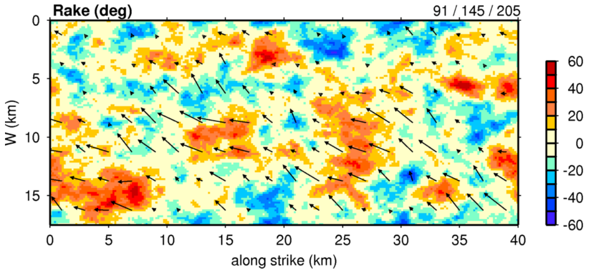
(Graves and Pitarka, BSSA 2010,2016; Pitarka et al., BSSA 2021)

Stochastic Slip

K^{-2} wavenumber spectrum (Mai and Beroza ,2002)



Rake Angle

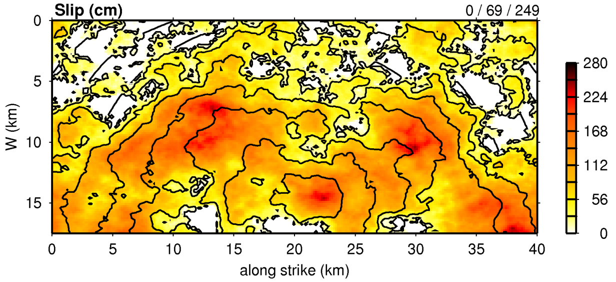


$\lambda = \lambda_o + \varepsilon \qquad \sigma_\varepsilon = 15^o$

$-60^o < \varepsilon < 60^o$

Random perturbations of rake follow spatial distribution given by K^{-2} falloff.

Rupture Initiation Time (Rupture Velocity)



$T_i = r / V_r - \delta t(D)$

V_r = 80% local V_s depth > 8 km

= 56% local V_s depth < 5 km

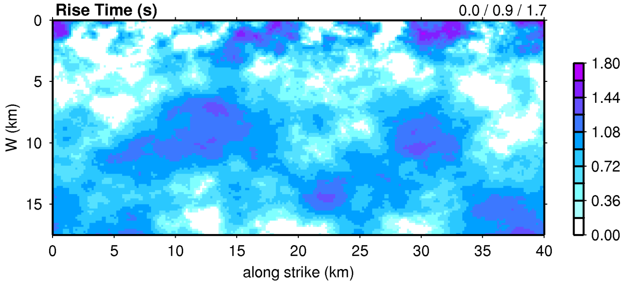
linear transition between 5-8 km

δt scales with local slip (D) to accelerate or decelerate rupture

$\delta t(D_{avg}) = 0$

Physical constrains used in the rupture model are derived from dynamic rupture modeling and are consistent with empirical observations during past earthquakes

Rise Time



$\tau = k \cdot D^{1/2}$ depth > 8 km

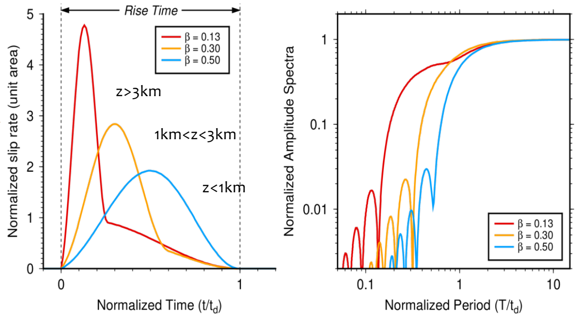
$= 2 \cdot k \cdot D^{1/2}$ depth < 5 km

linear transition between 5-8 km

Scales with square root of local slip (D) with constant (k) set so average rise time is given by the Somerville et al (1999) relation:

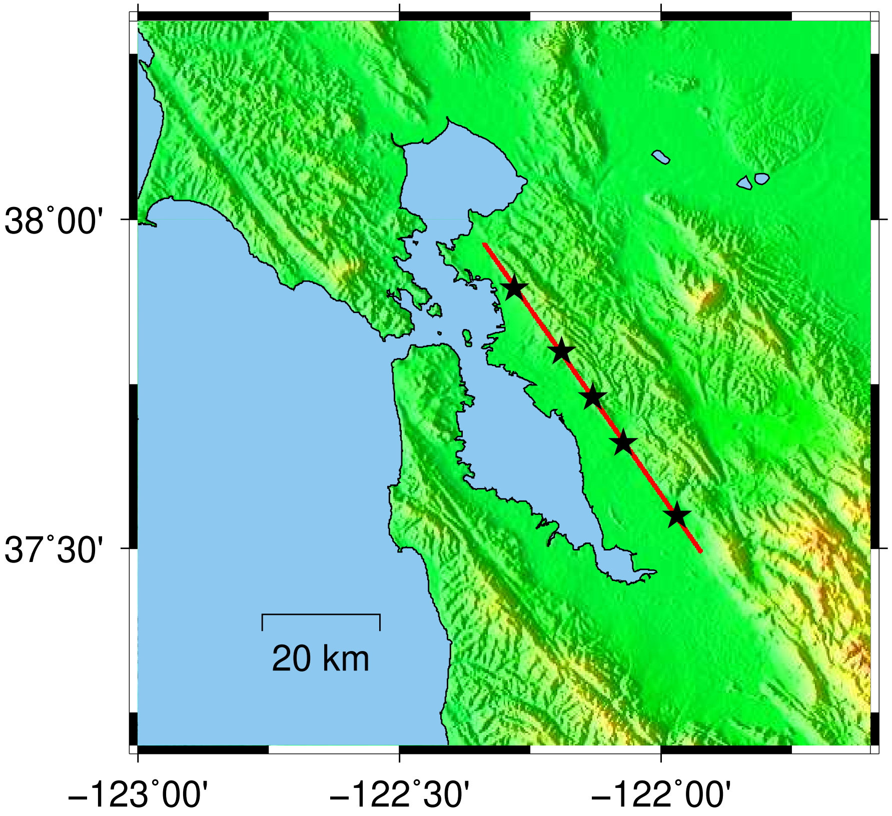
$\tau_A = 1.6e\text{-}09 \cdot M_o^{1/3}$

Slip Rate Function



25 Fault Rupture Scenarios
5 Rupture Initiation Locations

San Francisco Bay Area



Fixed Rupture Parameters

M_w : 7.0
Fault Depth: 200m
Fault Geometry : Planar
Dip Angle : 80°
Subfault dimensions dl: 40mx40m

Variable Rupture Parameters

- Fault Length : 58-**66**km
- Fault width : 14.5-**15**km
- Rupture initiation : 5 locations
- Slip : fully stochastic, hybrid with large slip patches
- Rupture velocity Vr : 0.65Vs, **0.72Vs**, 0.75Vs, 0.83Vs

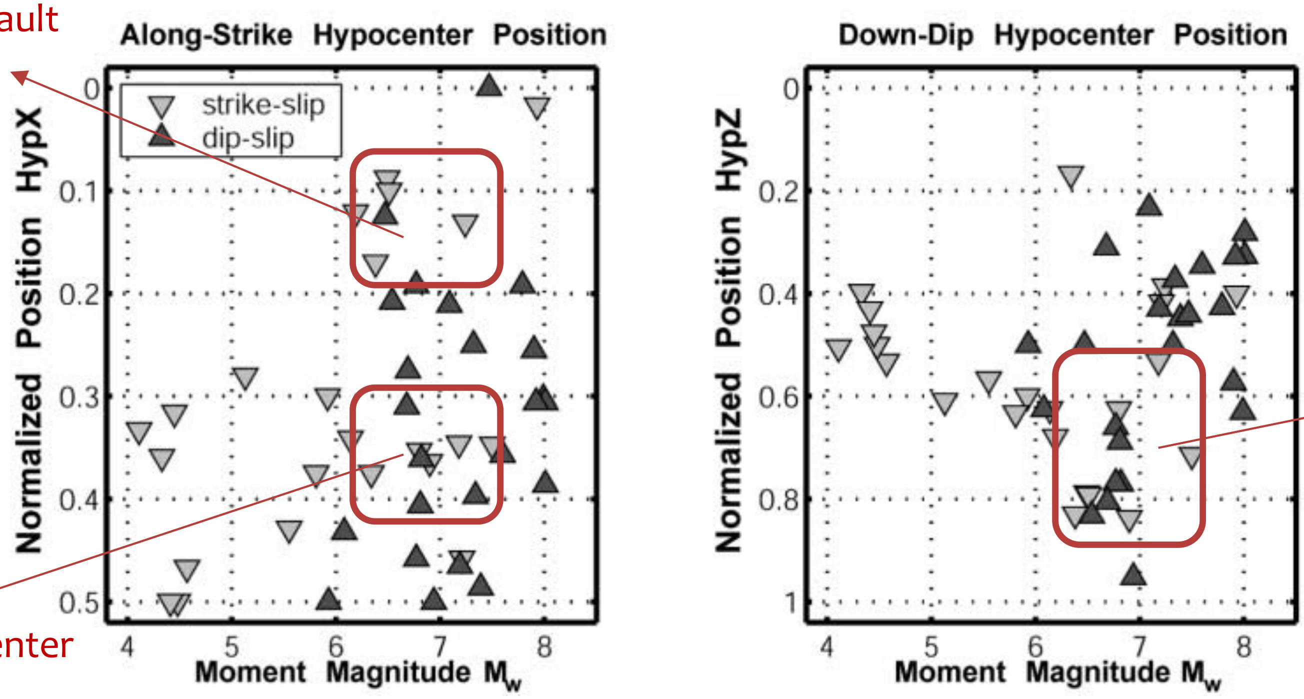
Parameter Space in Future Simulations

- Fault location
- Slip distribution
- Slip patch depth
- Hypocenter depth
- Rupture Velocity
- Peak slip rate roughness
- Fault surface roughness

Observed Rupture Initiation Location for Strike-Slip and Dip-Slip Faulting

Mai et al., 2005

Rupture in ~M7 strike-slip and crustal dip-slip earthquakes tends to nucleate in the deeper sections of the fault

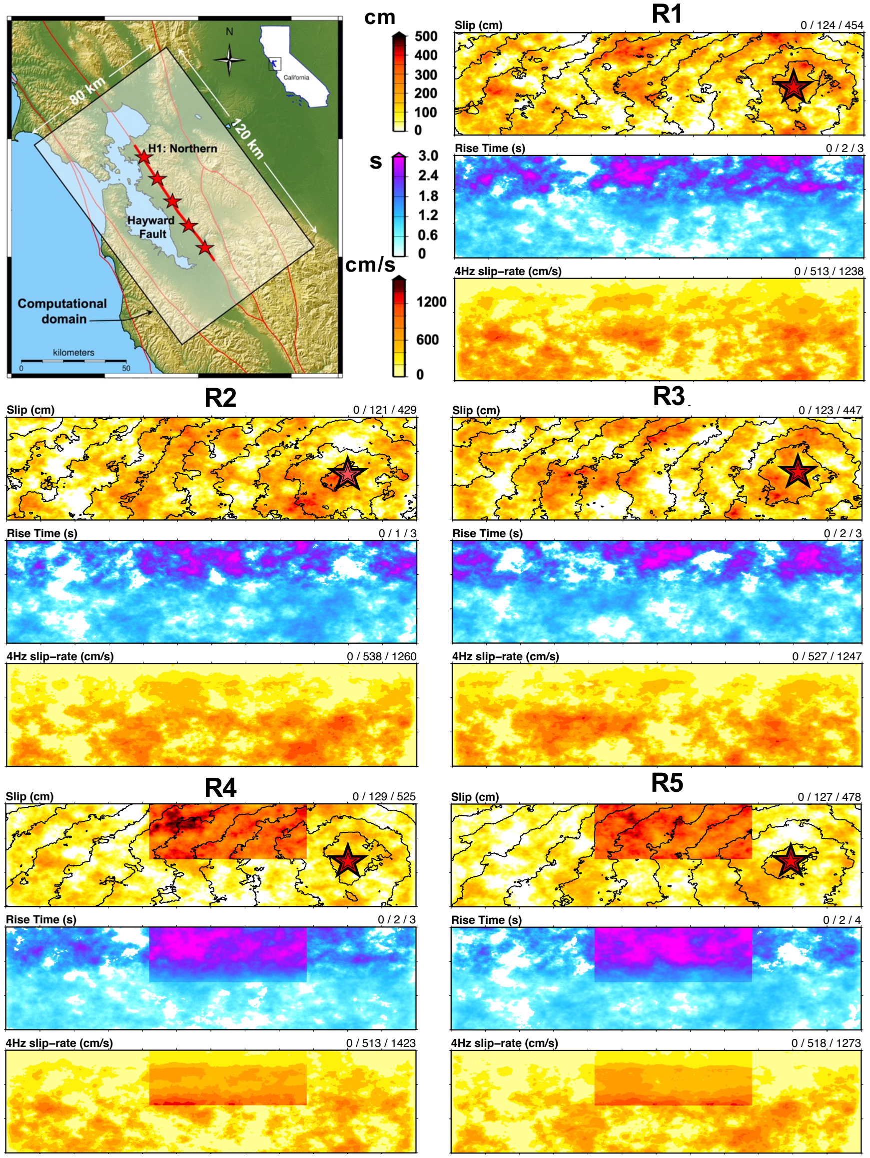


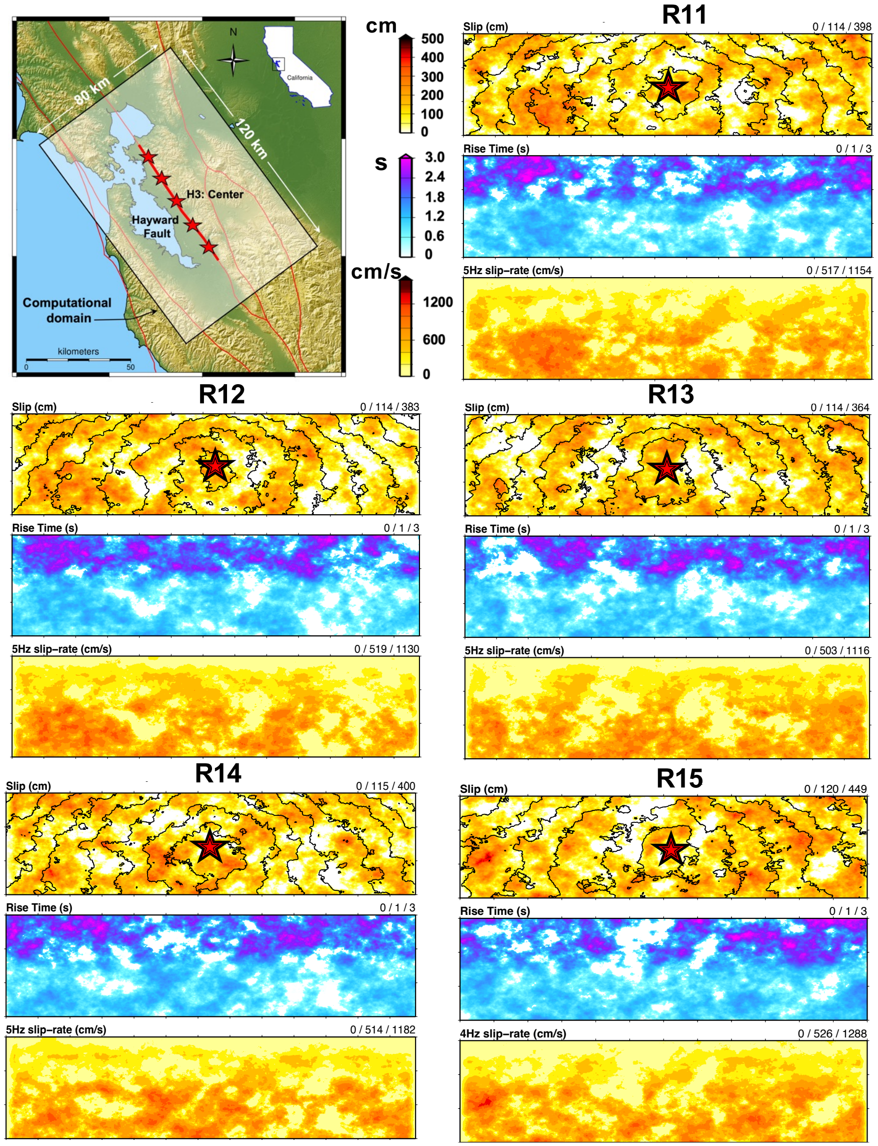
Near the fault edge

Near the center of the fault

Deep rupture initiation

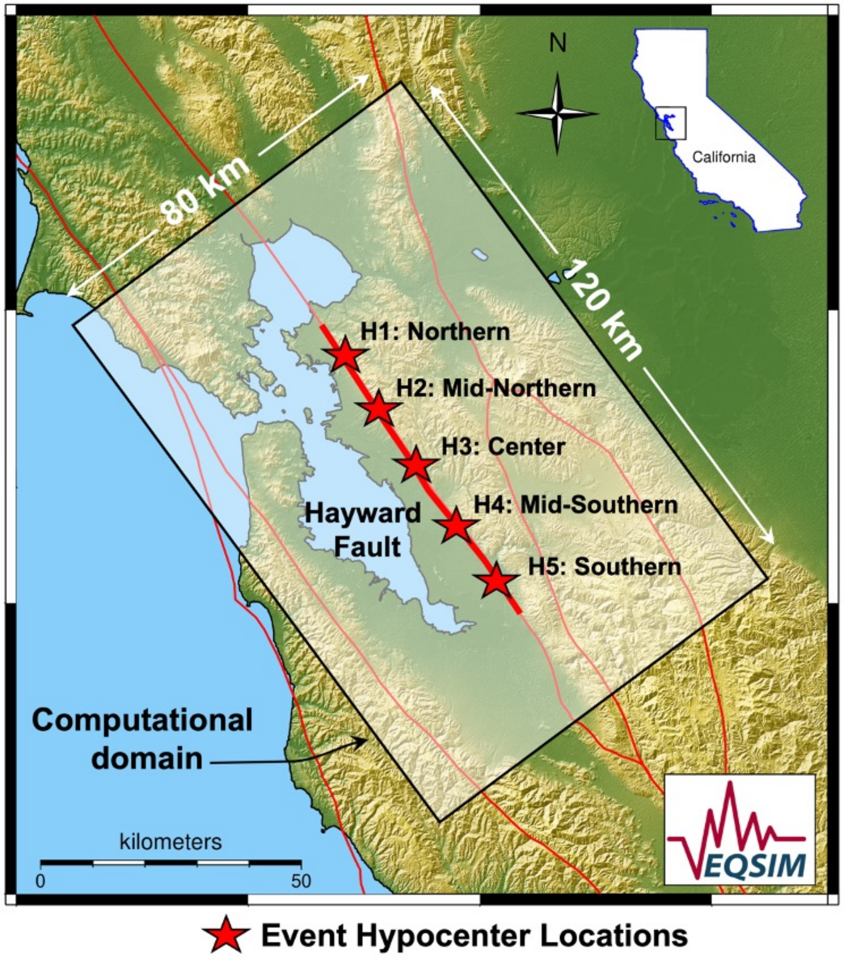
25 Fault Rupture Scenarios
5 Rupture Initiation Locations

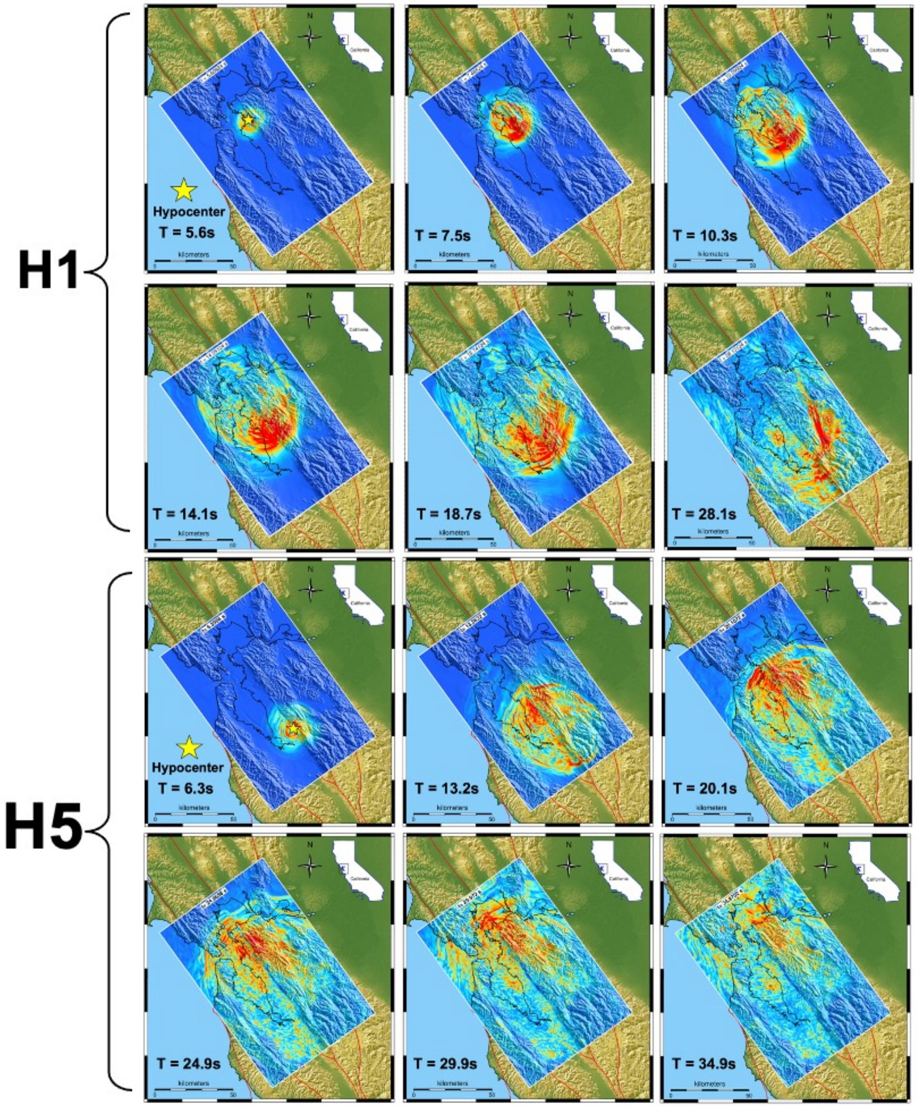




PEER Synthetic Ground Motion Database for Engineering Applications. Capture Source + Wave Propagation Effects

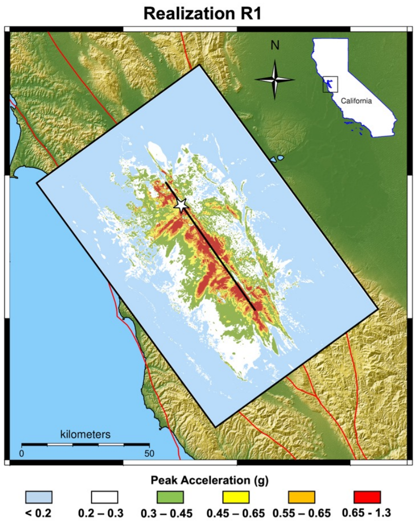
25 initial rupture realizations
Fmax 5Hz Vsmin 250m/s



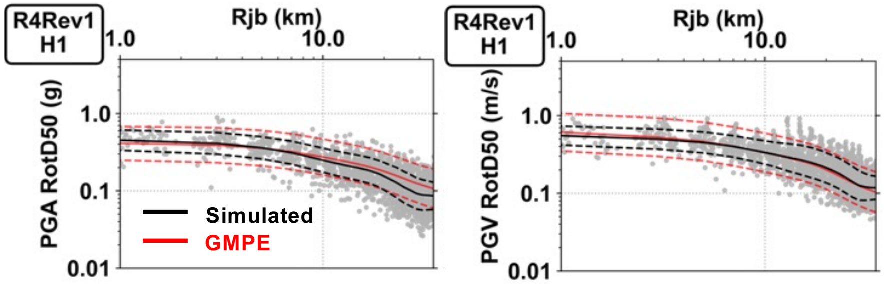


Validations Against M7 GMMs

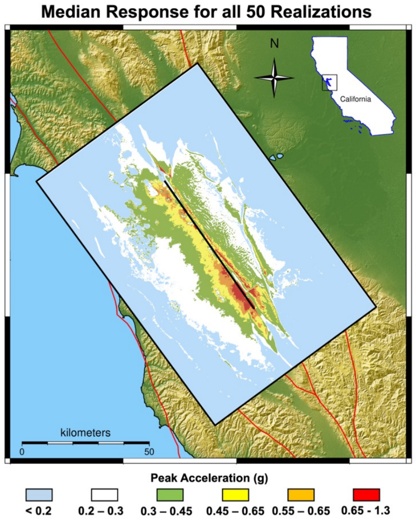
Single realization



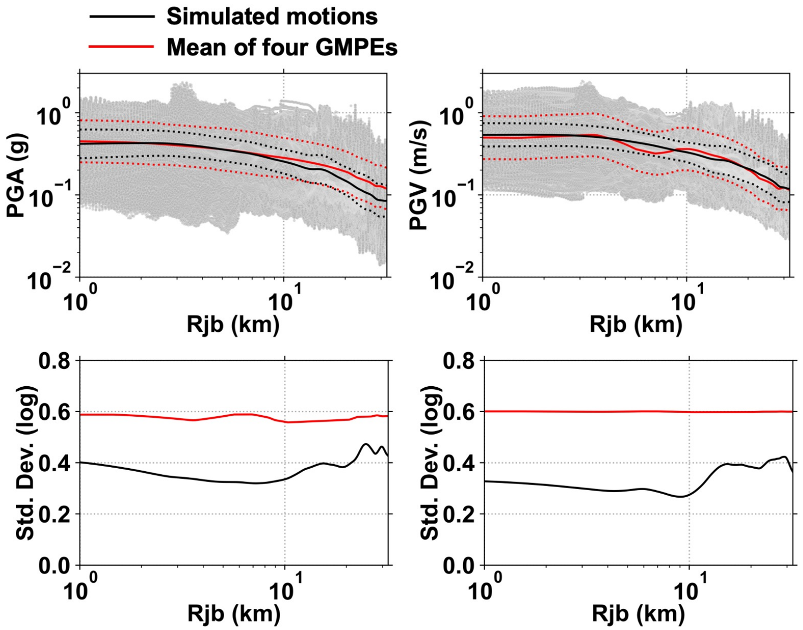
Hypocenter H1, Realization #4



Median 50 realization



All 50 Realizations



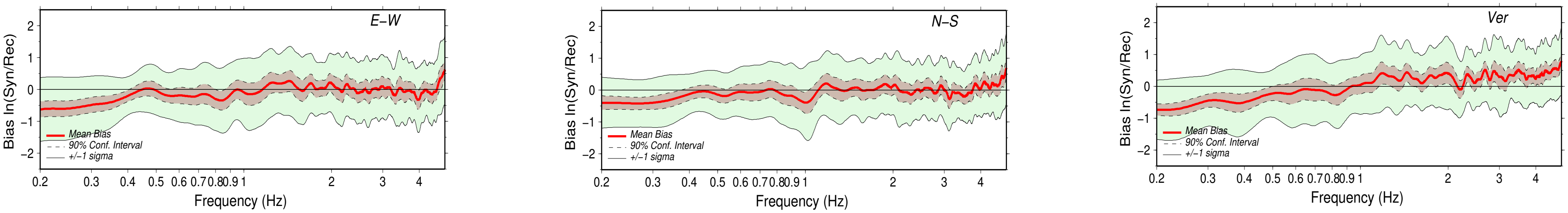
GMPEs

Simulated with one type of faulting mechanism!

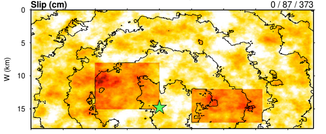
McCallen et al., 2025

Performance of EQSIM in 5Hz physics-based ground motion simulations of the Mw6.9 Loma Prieta earthquake
(see poster Pitarka et al.)

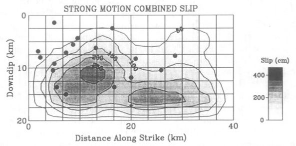
Fourier Amplitude Goodness-of-Fit

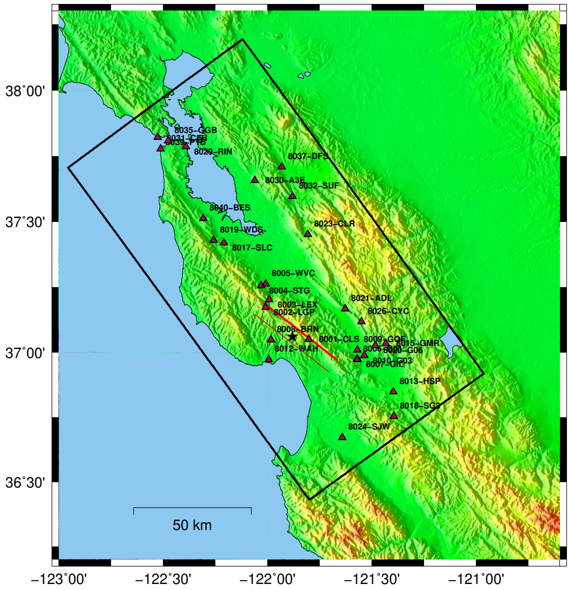


GP Rupture Model

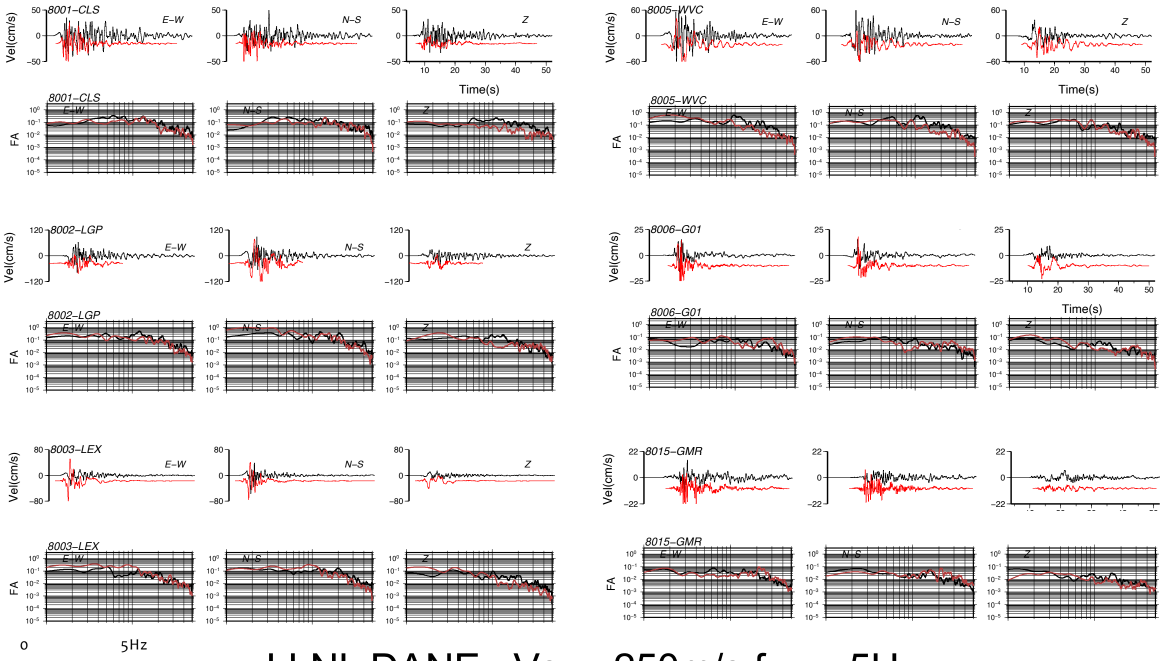


Target Slip Model





Velocity 0-5Hz 3D+Topo — synthetic — recorded



LLNL DANE: Vs_{min}:250m/s f_{max}= 5Hz
CPUs:20,000 WT: 24hrs

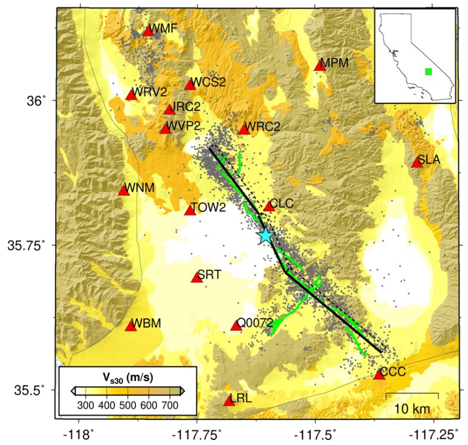
Building Confidence in Synthetic Ground Motion

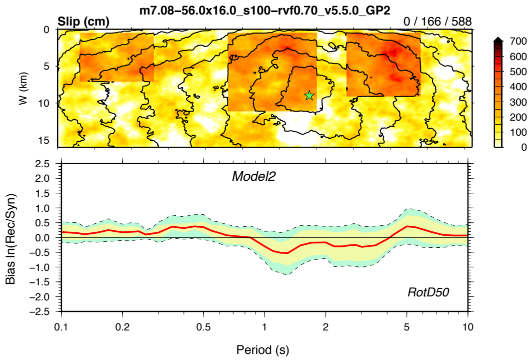
Validation of GP Rupture Model in Deterministic Simulations of Crustal Earthquakes

M_w7.1 Ridgecrest, California

0-5Hz

Pitarka et al., BSSA 2021

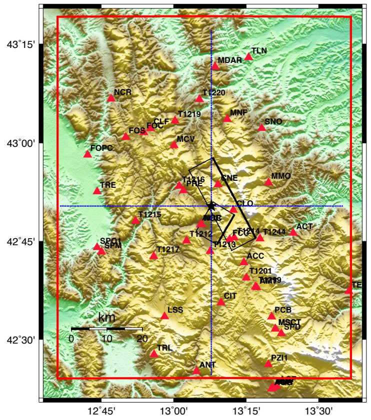


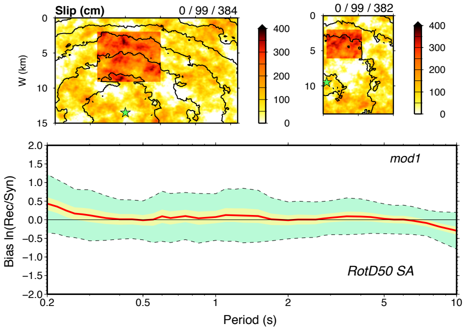


M_w6.5 Norcia, Italy

0-5Hz

Pitarka et al., BSSA 2021

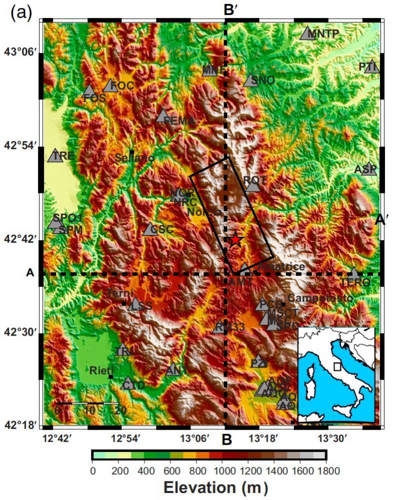


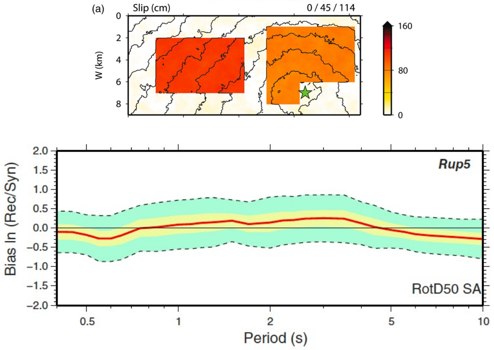


M_w6.2 Amatrice, Italy

0-3Hz

Akinci et al., BSSA 2024



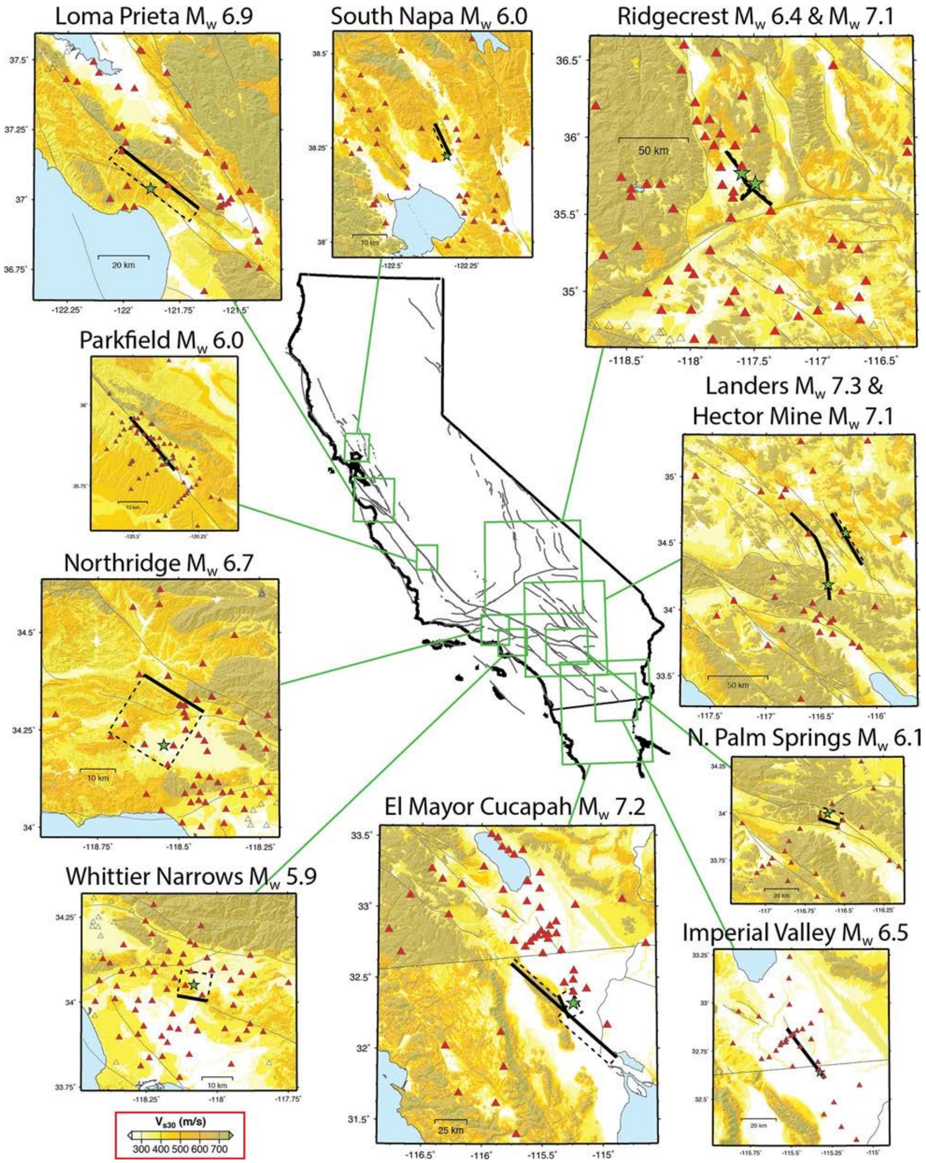


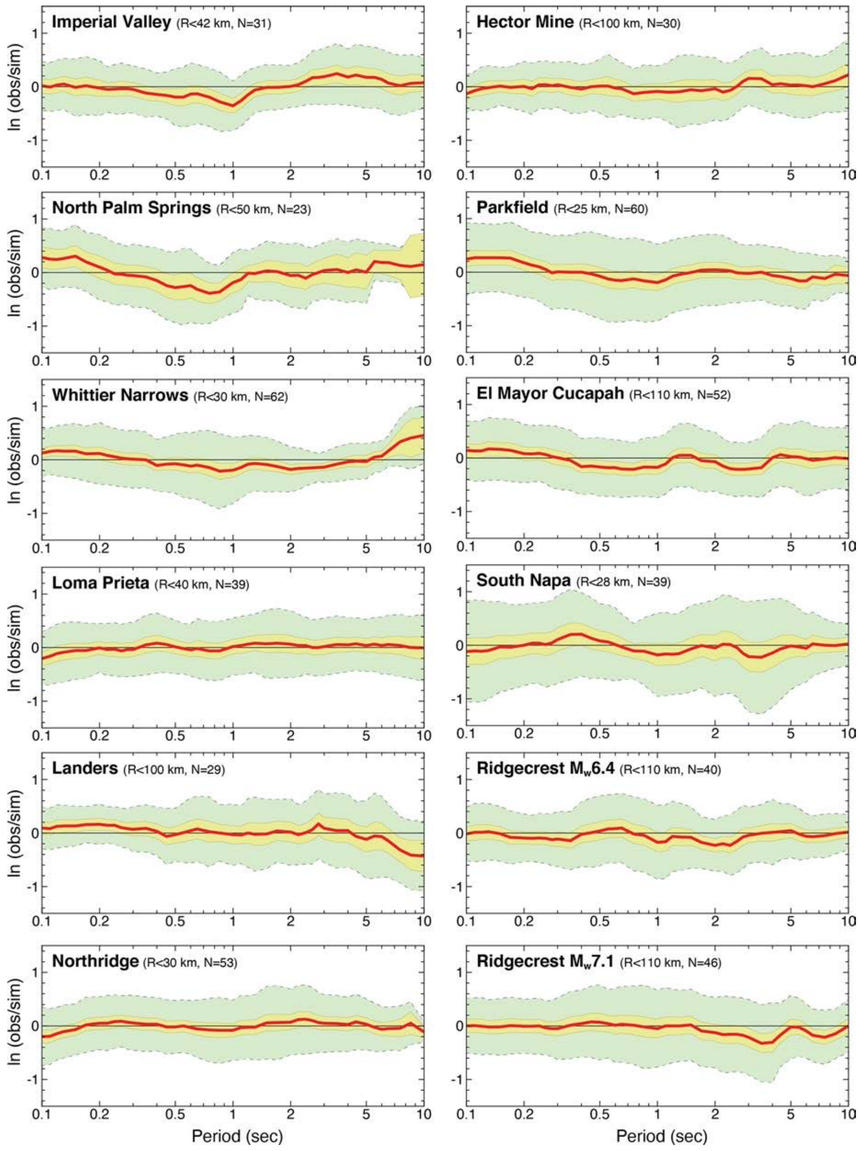
Ratio Between Recorded and Synthetic SA RotD50

Performance of the GP Rupture Model in BB Hybrid Simulations of California Earthquakes (0-1 Hz Deterministic and 1-10Hz stochastic)

10 California Earthquake M_w5.9-7.2

from: Graves, 2022

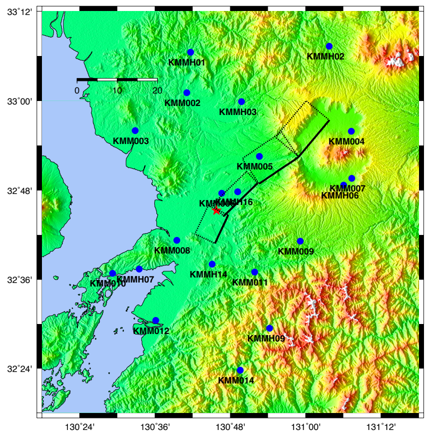




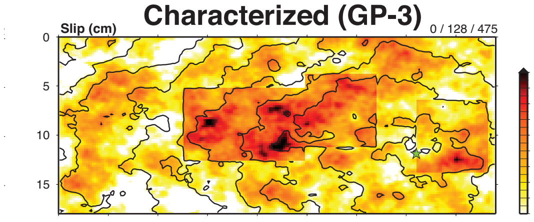
Performance of the GP Rupture Model in BB Hybrid Simulations of Japan and New Zealand Earthquakes (0-1 Hz Deterministic and 1-10Hz stochastic)

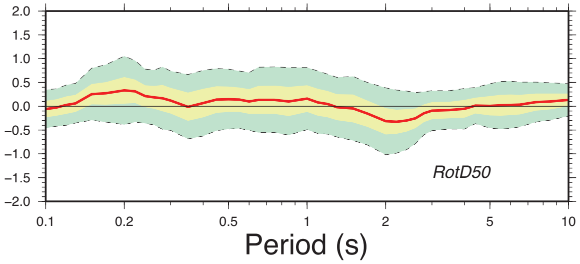
M_w7 2016 Kumamoto, Japan

Pitarka et al., PAGEOPH 2019



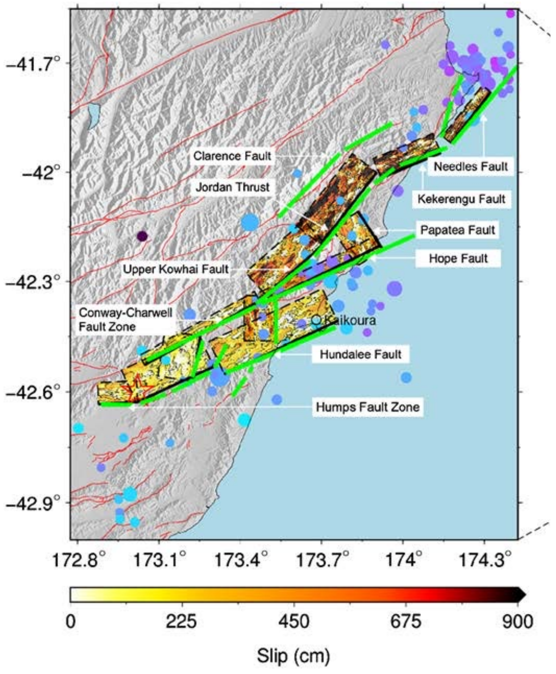
Characterized (GP-3)

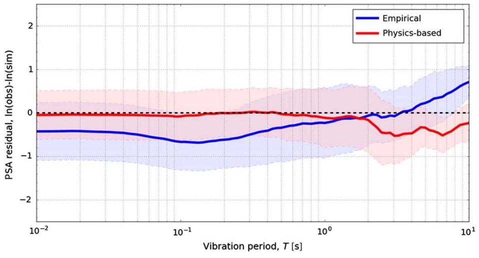




2016 Mw7.8 Kaikoura

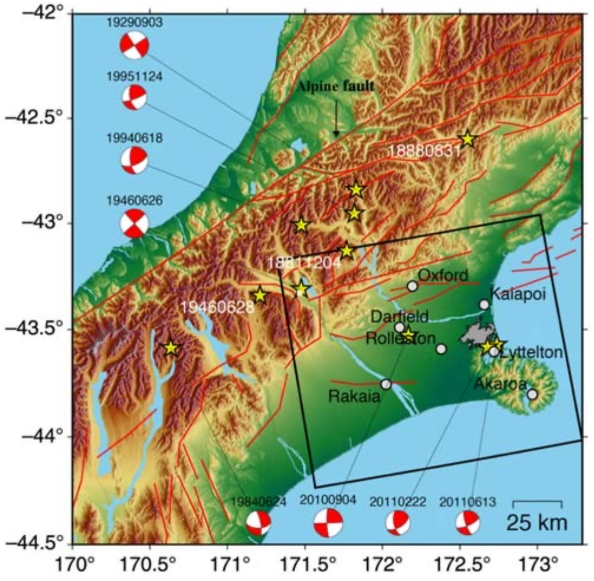
Bradley et al., 2017

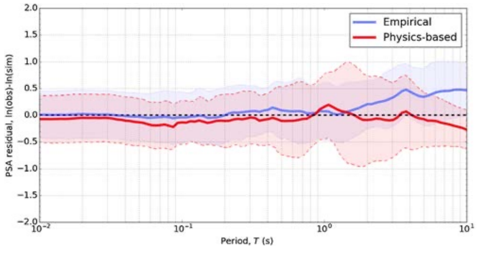




2011 Mw6.2 Christchurch

Razafindrakoto et al., 2018

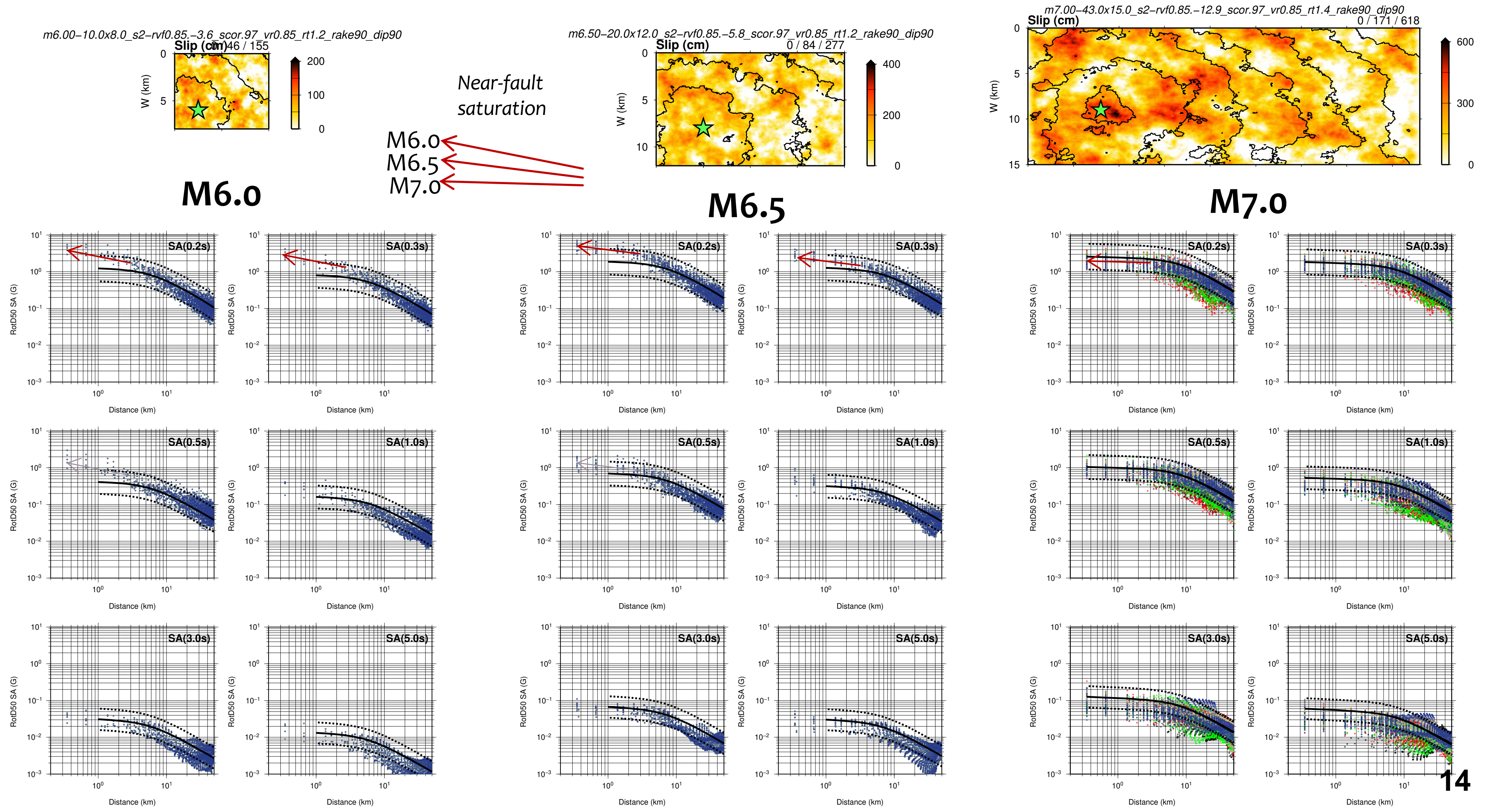




NRC Project on Use of Simulations to Improve Emprical Ground Motion Models for CEUS

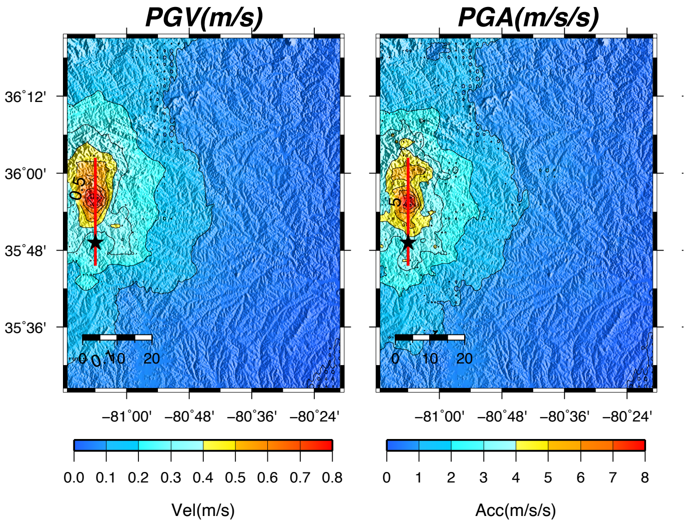
Pitarka and Graizer, 2024

Near-fault saturation: comparison with Graizer's GMM G12v2.M7,Vs1000



NRC Project for CEUS:
Dependency of Near-fault Saturation to Type of Faulting

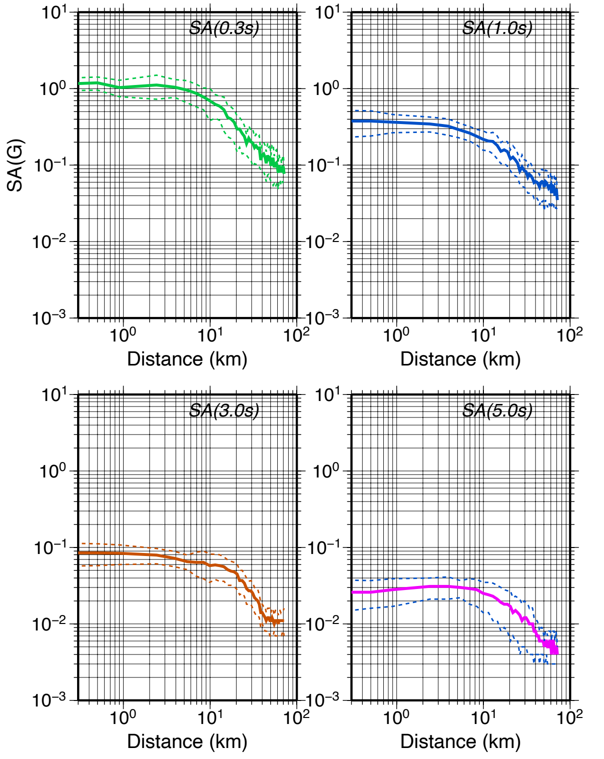
3D Simulation 0-10Hz
for Central Eastern US



Simulations performed on DANE
at Livermore Computing Center

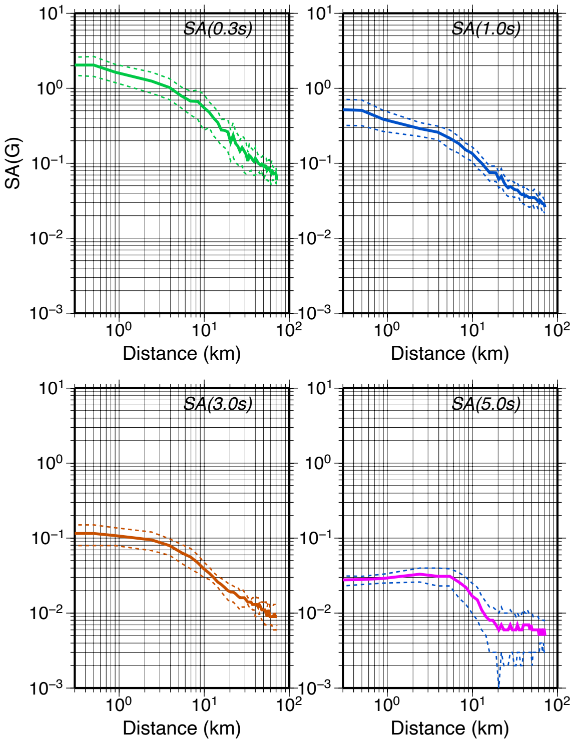
M7 Strike-Slip Faulting

(saturation)



M7 Thrust Faulting

(under saturation)



Published Engineering Applications of the Synthetic Ground Motion (2021-2024)

Kenawy, M. and A. Pitarka (2024), Performance Assessment of Near-Fault Buildings Subjected to Physics-Based Simulated Earthquake Ground Motions with Fling Step (2024), Earthquake Spectra, 1-31, DOI: 10.1177/87552930241285022.

McCallen, D., A. Pitarka,H. Tang, R. Pankajakshan, N. A. Petersson, M. Miah, J. Huang (2024).Regional-scale fault-to-structure earthquake simulations with EQSIM framework: workflow maturation and computational performance on GPU-accelerated exascale platforms, Earthquake Spectra,DOI: 10.1177/87552930241246235

McCallen, D., A. Pitarka,H. Tang, R. Pankajakshan, N. A. Petersson, M. Miah (2024). Transformal regional-Scale Earthquake Simulations with the DOE EarthQuake SIMulation (EQSIM) Exascale Framework, Computing in Science and Engineering, Volume 26, Issue 2, Pages 16-24, DOI: 10.1109/MCSE.2024.3397768

Petrone, F., A. Taslimi, M. Nia, D. Mccallen, and A. Pitarka (2024). Ground Motions Site and Event Specificity: Insights from Assessing a Suite of Simulated Ground Motions in The San Francisco Bay Area, Earthquake Spectra

Ramos, P.C., A. Pitarka, McCallen, and R. Nakata (2024) Performance evaluation of the USGS velocity model for the San Francisco Bay Area, submitted to Earthquake Spectra, (published September 2024)(DOI: 10.1177/87552930241270575)

Taslimi, Arsam, F. Petrone, and A. Pitarka (2023). Characteristics of Vertical Ground Motions and Their Effect on the Seismic Response of Bridges in the Near-Field: A State-of-the-Art Review, Journal of Bridge Engineering, 2024, DOI: 10.1061/JBENF2.BEENG-6507

Akinci, A., A. Pitarka, P.A. Harris, P. De Gori, and M. Buttinelli (2024) Impact of the Earthquake Rupture on Ground Motion Variability of the August 24, 2016 Mw6.2 Amatrice, Italy Earthquake, Bulletin of the Seismological Society of America, 114, 2823–2845, doi: 10.1785/0120240002 (published August, 2024

Kenawy, M., D. McCallen, and A. Pitarka (2023) Selection of Near-Fault Simulated Earthquake Ground Motions for Nonlinear Analysis of buildings, Earthquake Spectra 2023, DOI: 10.1177/87552930231182164.

Miah,M., D. Mccallen, A. Pitarka, F. Petrone (2023). Simulation-Based Characterization of the Variability of Earthquake Risk to Buildings in the Near-Field, *Earthquake Engineering & Structural Dynamics*, https://doi.org/10.1002/eqe.4007.

Kenawy, M., D. McCallen, A. Pitarka,(2021) Variability of near-fault seismic risk to reinforced concrete buildings based on high-resolution physics-based ground motion simulations,Earthquake Engng Sruct Dyn, 2021;1–21. https://doi.org/10.1002/eqe.3413

Petrone, F.,N. Abrahamson,D. McCallen, A. Pitarka, and A. Rodgers (2021) Engineering Evaluation of the EQSIM Simulated Ground-Motion Database: The San Francisco Bay Area Region. Earthquake Engineering and Structural Dynamics (published 10/01/21; https://doi.org/10.1002/eqe.3540

Pitarka, A., A. Akinci, P. De Gori, and M. Buttinelli (2021). Deterministic 3D Ground Motion Simulations (0-5Hz) and Surface Topography Effects of the 30 October 2016 Mw 6.5 Norcia, Italy Earthquake, Bull. Seism. Soc. Am., 1-25, doi:10.1785/0120210133 (published 10/07/21)

Rodgers, A., A. Pitarka, D. B. McCallen, The Effect of Fault Geometry and Minimum Shear Wavespeed on Three-Dimensional Ground Motion Simulations for an MW 6.5 Hayward Fault Scenario Earthquake, San Francisco Bay Area, Northern California, (2019 Bulletin of the Seismological Society of America,, https://doi.org/10.1785/0120180290

- Fling step effects on building response

- Seismic response of bridges

- Non-linear analysis of buildings

- Near-fault building response

- Engineering evaluation of synthetic ground motion

- Within and between events variability

- Source, wave path effects for use in GMMs

- Rupture directivity effects

- Source, wave path and topographic effects

Thank You !

This work was funded by the DOE Office of Cybersecurity, Energy Security and Emergency Response in support of ensuring resilience of U.S. energy infrastructure. This research used resources of the National Energy Research Scientific Computing Center (NERSC), a Department of Energy Office of Science User Facility using NERSC award DDR-ERCAPand resources of the Oak Ridge Leadership Computing Facility, which is a DOE Office of Science User Facility supported under Contract DE-AC05-00OR22725. Arben Pitarka's work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344