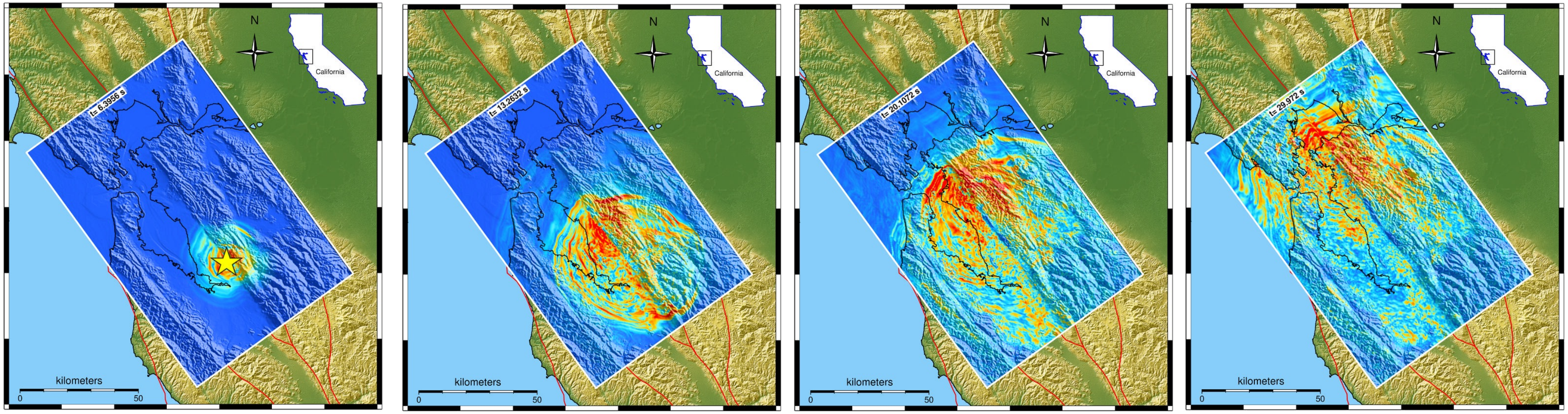

Hayward Fault Rupture Model Realizations

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PEER Workshop
Berkeley, Jan18-19,2024

BERKELEY LAB

U.S. DEPARTMENT OF ENERGY

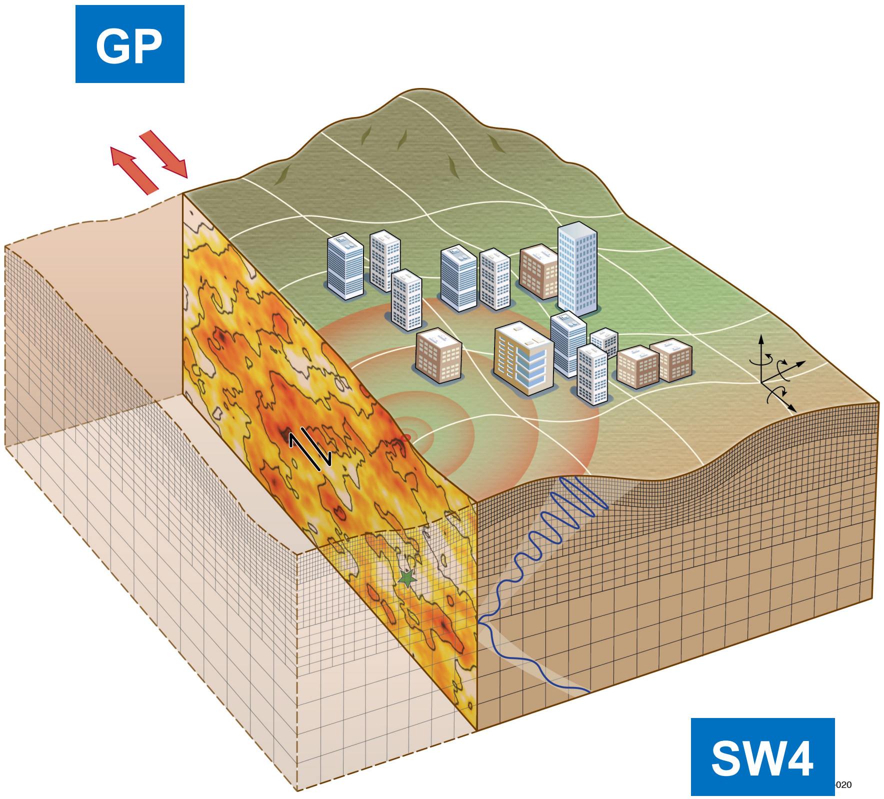
Office of Cybersecurity, Energy Security, and Emergency Response

ECP
EXASCALE COMPUTING PROJECT

Outline

1. General information on Hayward Fault
2. Previous 3D ground motion simulations of earthquakes on the Hayward fault
3. Hayward fault rupture realizations using the Graves&Pitarka method
4. Performance of the EQSIM in 5 Hz simulations of the Loma Prieta earthquake in the SFBA

EQSIM Platform
Source and Wave Propagation Module



GP – Graves and Pitarka Rupture Generator

(Grave&Pitarka, BSSA 2016; Pitarka et al BSSA 2021)

- Hybrid slip distribution
- Depth dependent kinematic rupture parametrization
- SRF HDF5-based format

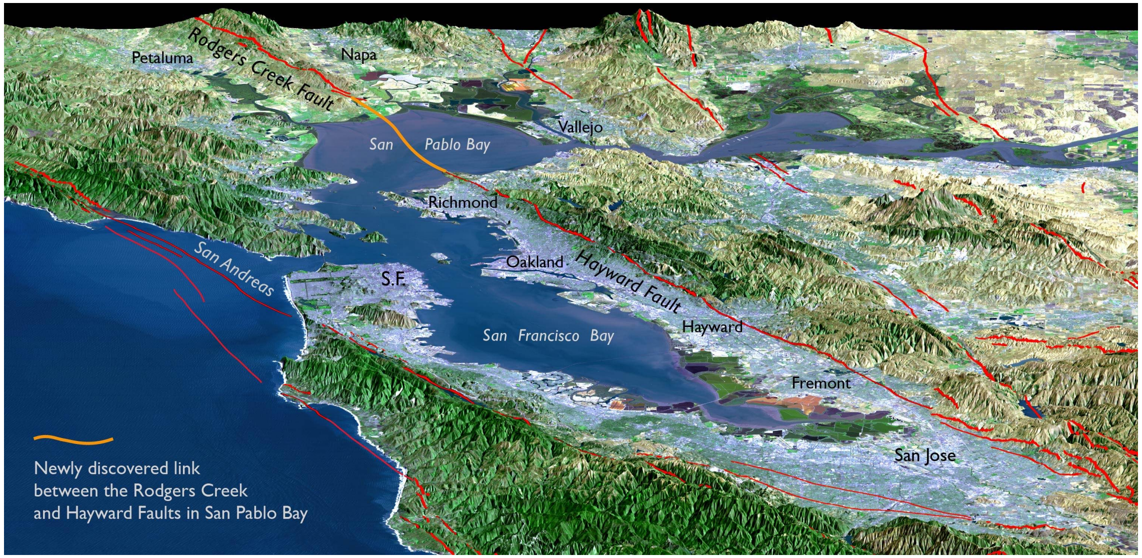
SW4 - GPU-based (LBNL and LLNL Computing Platforms)

(Peterson and Sjogreen, 2015)

- 4th order accuracy with curvilinear mesh refinement
- HDF5-based IO

Hayward Fault

Known Active Faults in the SFBA

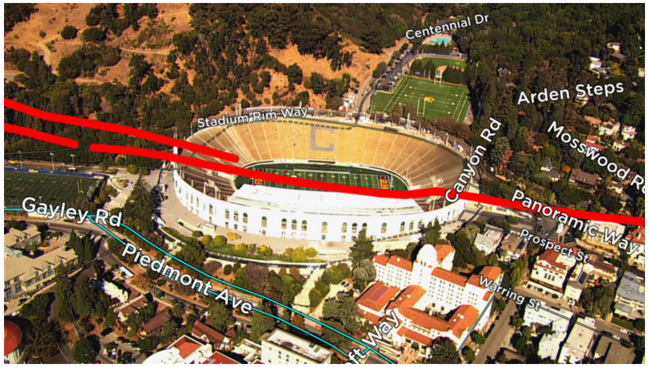


-There is a 72% probability that a magnitude M6.7 or greater earthquake will occur in the region by the year 2043.

-There is a 33% probability that a M6.7 or higher earthquake will occur on the Hayward fault in the next ~30 years

-The last large earthquake on the Hayward fault had a M6.8, occured in 1868 (155 years ago)

-There is geologic evidence of 11 comparable ruptures with average recurrence intervals of 140–160 yrs

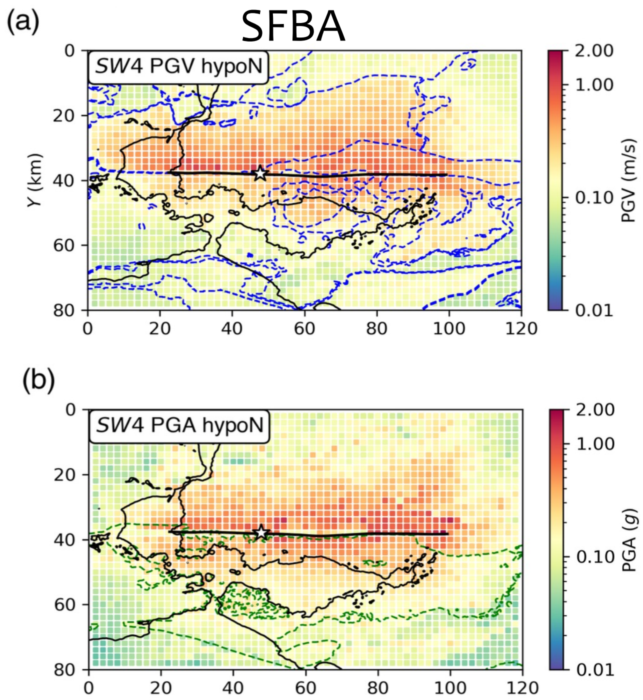


What have we learned from previous regional-scale 3D simulations of scenario earthquakes on the Hayward fault ?

Rodgers et al., 2019; 2020

1. 0-2.5 Hz M_w6.5 3D Ground motion simulations for a Vsmin=250m/s: effect of fault geometry and Vsmin

2. 0-10 Hz M_w7 3D Ground motion simulations for a Vsmin=500m/s



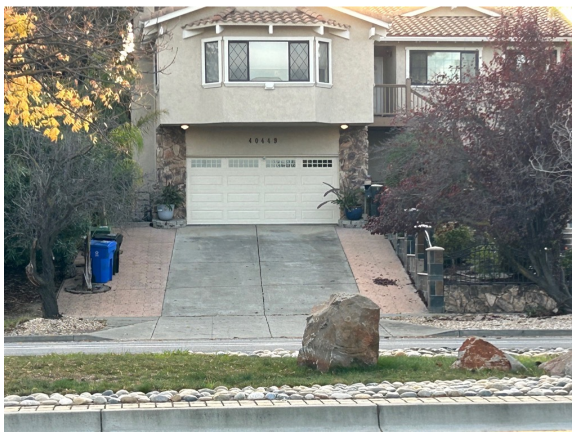
- Nonvertical fault geometries result in larger motions on the hanging wall relative to the vertical fault
- Assuming a VS min of 500 m/s underestimates intensities west of the HF for frequencies above 0.5 Hz
- Simulations suggest that limiting the V_{smin} to 500m/s may cause underestimation of the ground motion in SFBA
- demonstrated the need for region-specific GMMs using BB simulations and taking into consideration the non-linear soil response

What have we learned from previous regional-scale 3D simulations of scenario earthquakes on the Hayward fault ?

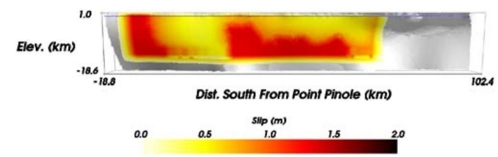
(Aagaard et al., BSSA 2010)

Simulation of long-period (>1s) and broad-band (0-10Hz) 39 scenario earthquakes involving the Hayward, Calaveras and Rodgers Creek faults.

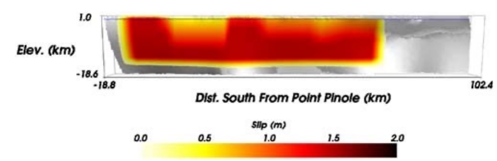
Effects of fault creep

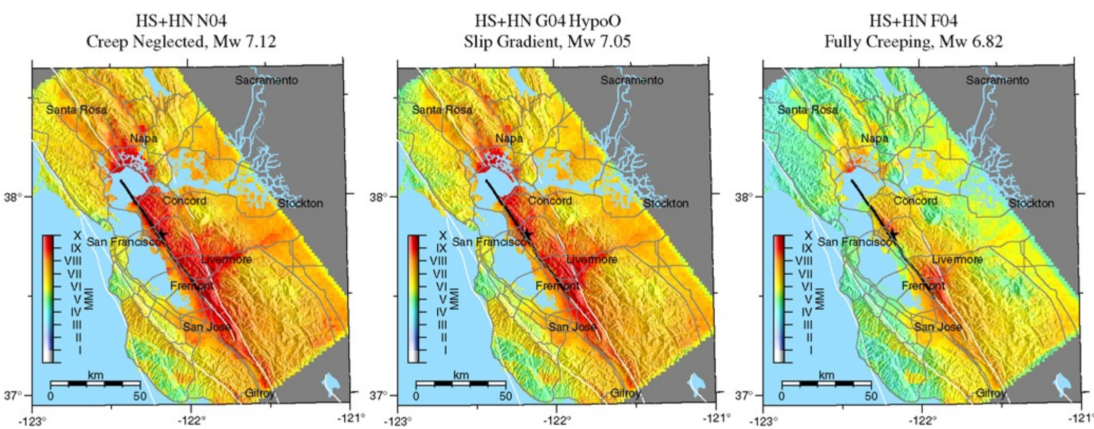


Slip predictable approach



Slip gradient approach





- strong sensitivity to the rupture length (magnitude), hypocenter (rupture directivity), and slip distribution.
- weaker sensitivity to the rise time and rupture speed.
- uncertainties in fault creep at depth

Ruth Harris (2016) on uncertainties in simulations of earthquakes on creeping faults

“Analysis of strong ground-shaking observations from magnitude <6.7 creeping-fault earthquakes shows that their range of recorded peak ground motions is similar to the range of recorded peak shaking produced by earthquakes of the same magnitude that have occurred on locked faults.
Similarly the fault-surface areas that rupture appear to be neither consistently bigger nor consistently smaller than those for equivalent magnitude earthquakes on locked faults”.

Recommendations for kinematic rupture models on faults with creeping segments

- Earthquakes may nucleate at the boundaries between creeping and locked parts of faults

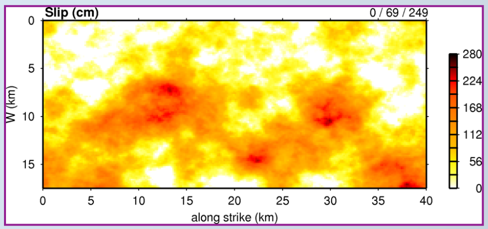
- Low probability of large shallow slip patches in the fault creeping areas. Small-scale slip variations with depth dependent slip rate may be expected in the entire fault rupture area, including the creeping parts

Graves&Pitarka (GP) Kinematic Rupture Generator

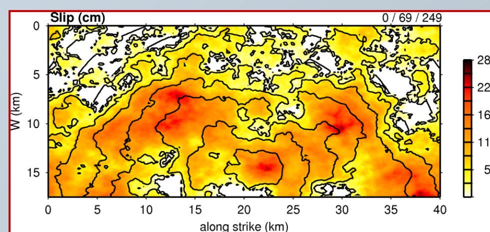
(Graves and Pitarka, BSSA 2016; Pitarka et al., BSSA 2021)

Semi-Deterministic Slip

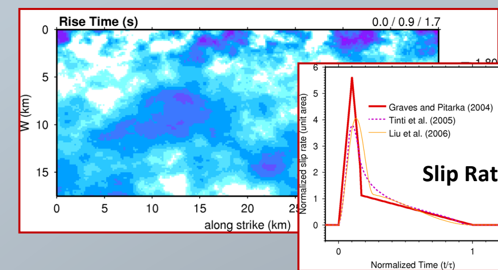
K^{-2} wavenumber spectrum
Mai and Beroza (2002)



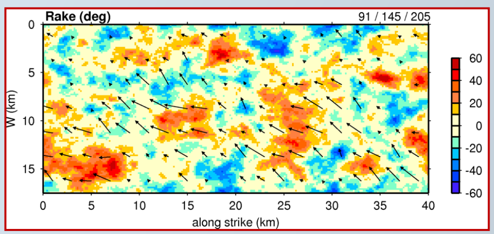
Rupture Initiation Time (Rupture Velocity)



Rise Time



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.

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

$V_r \quad = 80\%$ 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

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

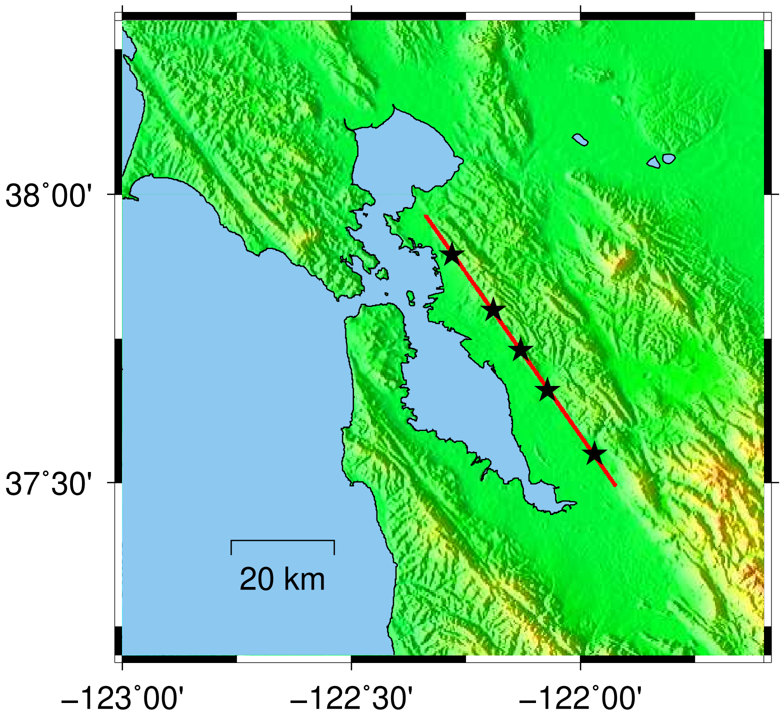
$\tau \quad = k \cdot D^{1/2}$ depth > 8 km
$= 2 \cdot k \cdot D^{1/2}$ depth < 5 km
linear transition between 5-8 km

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:

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

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

25 Fault Rupture Scenarios
5 Rupture Initiations



Fixed Rupture Parameters

M_w : 7.0
Fault Length : 60km
Fault width : 15km
Fault Depth: 200m
Fault Geometry : Planar
Dip Angle : 90^o
Subfault dimensions : 50x50m

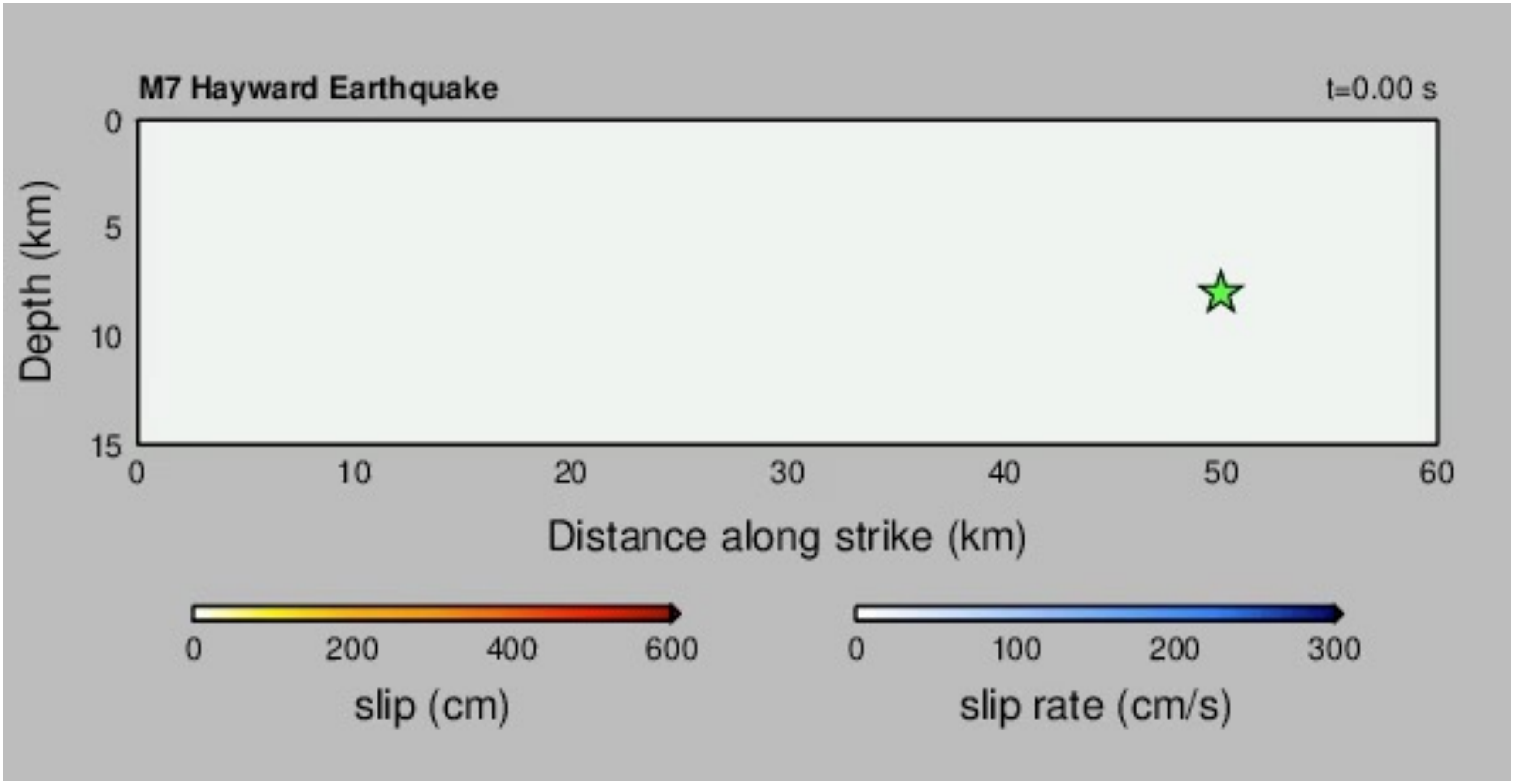
Variable Rupture Parameters

- 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

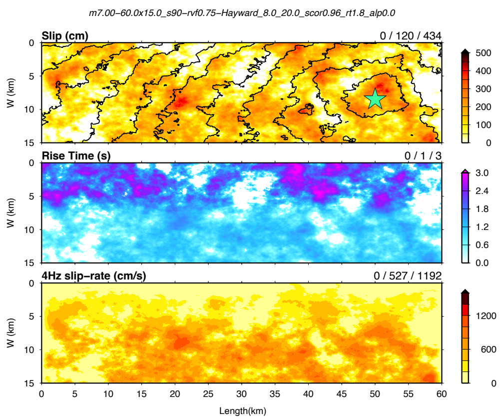
- Fault location
- Slip distribution
- Slip patch depth
- Hypocenter depth
- Rupture Velocity
- Peak slip rate roughness
- Fault surface roughness

M_w7 Hayward Fault Earthquake Rupture Animation

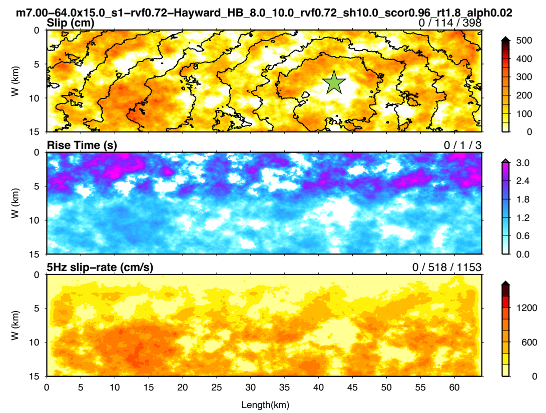


Rupture Parameter : Hypocenter Location

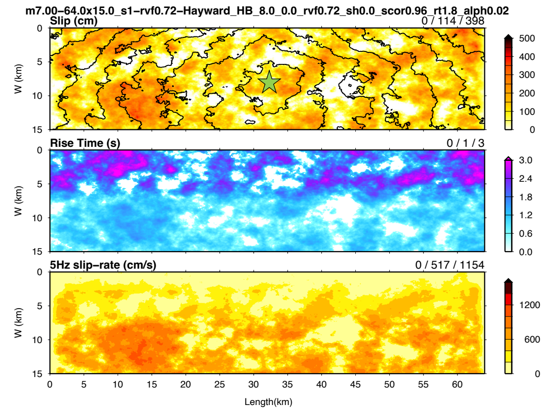
Hypocenter 1



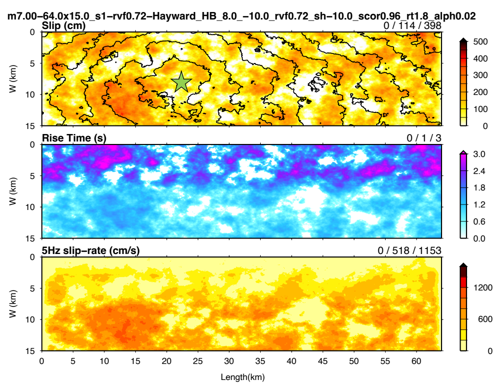
Hypocenter 2

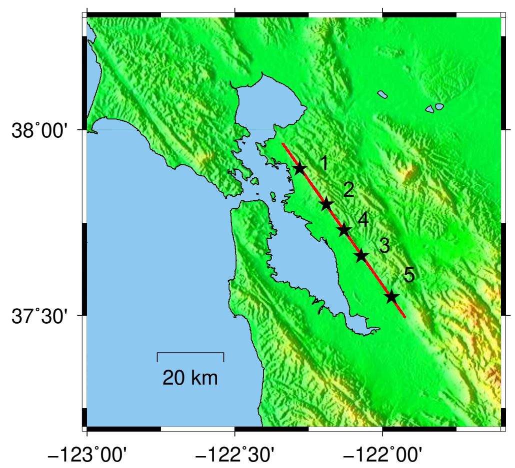


Hypocenter 3

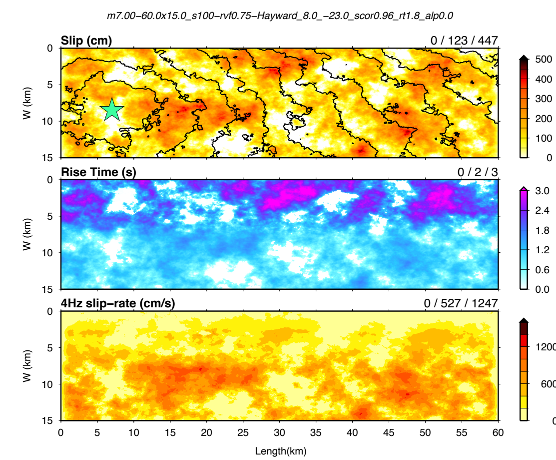


Hypocenter 4



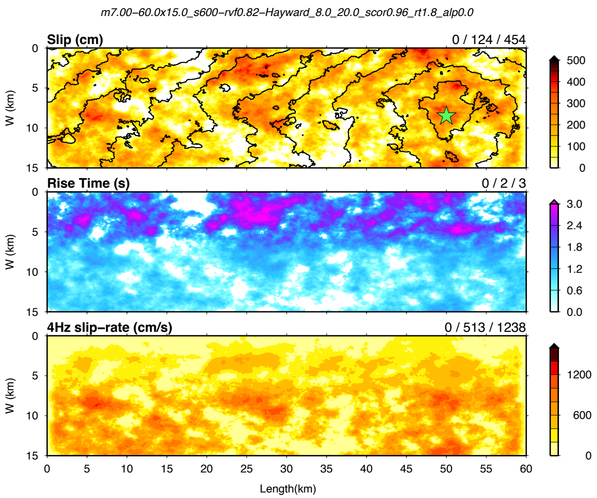


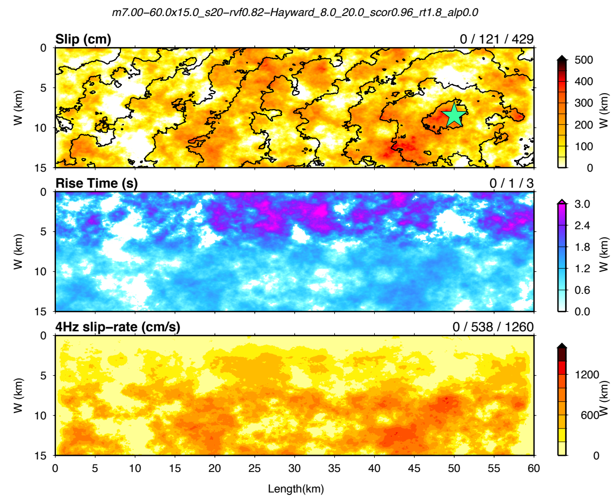
Hypocenter 5

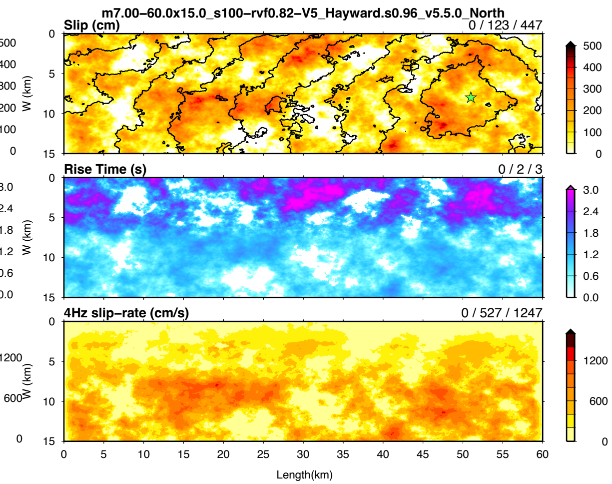


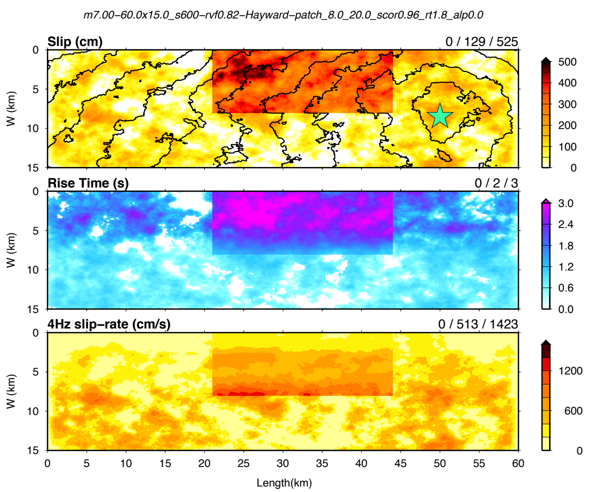
Rupture parameter: slip distribution

North Hypocenter; Vr=0.8Vs



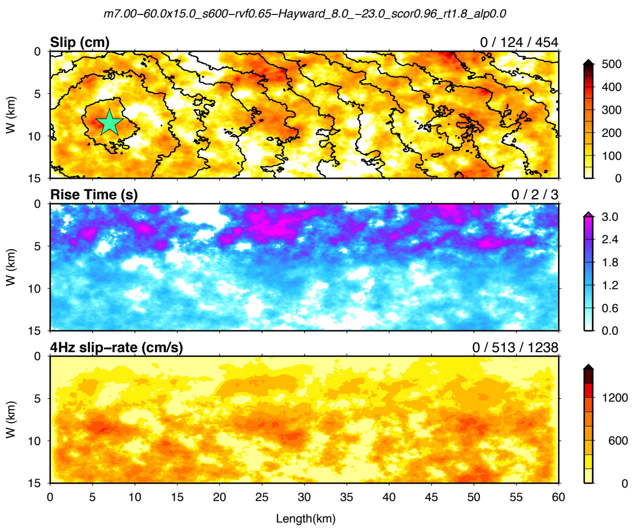




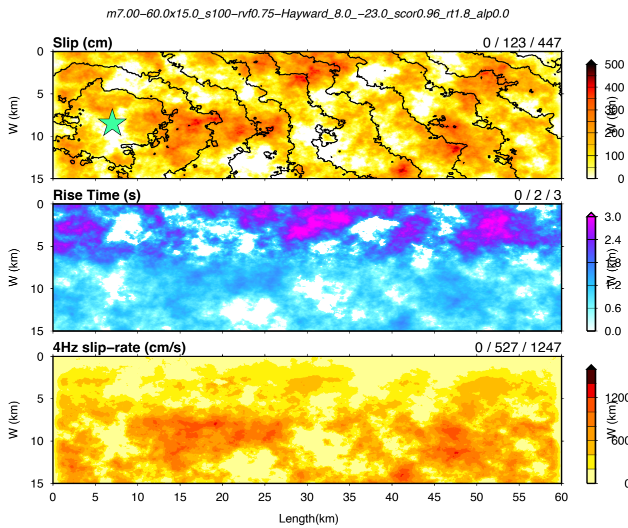


Rupture Parameter : Rupture Velocity

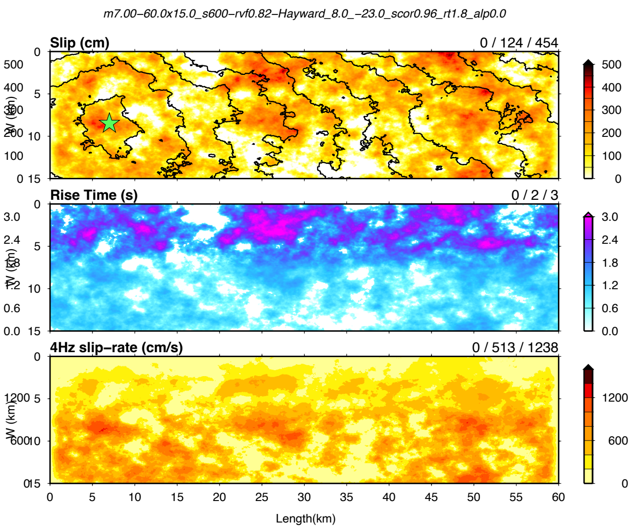
Vr=0.65Vr



Vr=0.75Vr



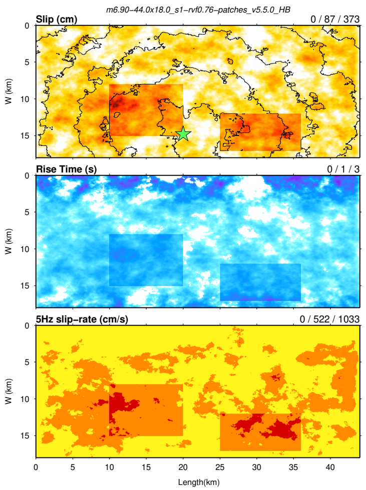
Vr=0.82Vr



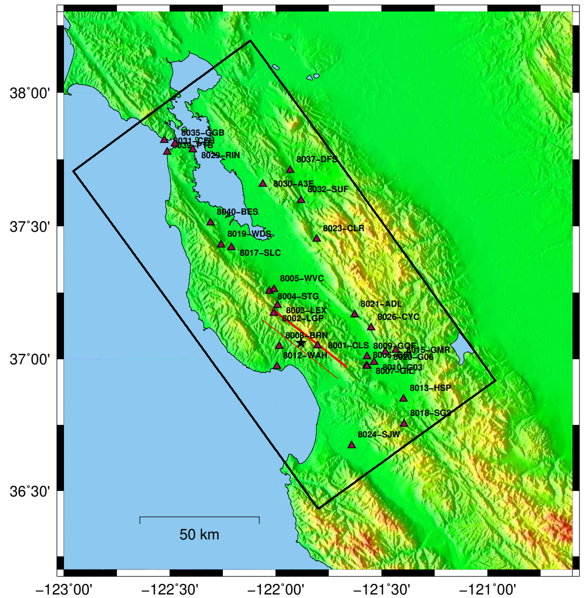
We have created a Data base of 25 kinematic rupture models in SRF format

Performance of EQSIM and GP Rupture Generator in Ground Motion Simulations of the Mw6.9 Loma Prieta Earthquake

GP Rupture Model

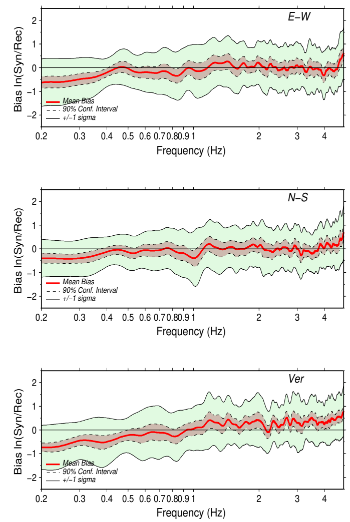


3D USGS Model

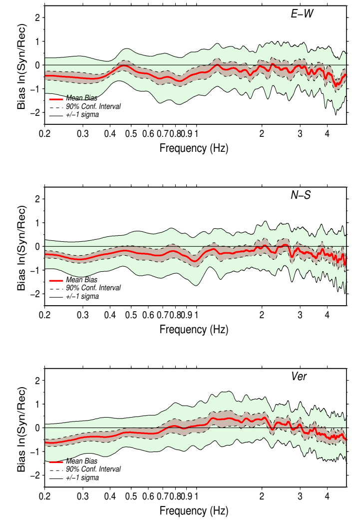


0-5Hz Velocity Fourier Amplitude GOF Averaged over 30 Stations

3D +TOPO



3D FLAT



CPU Platform: DANE

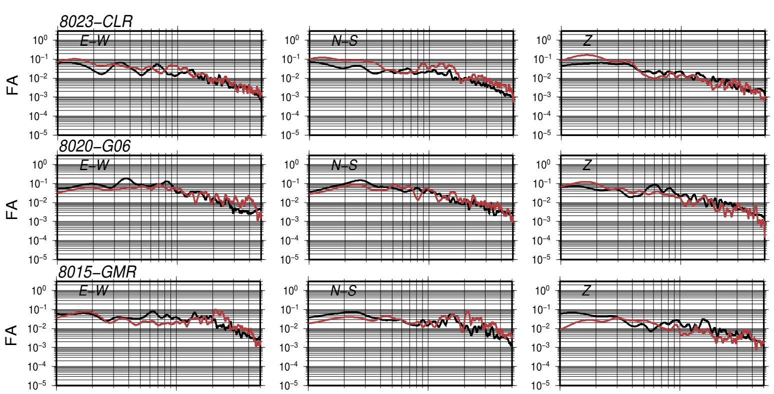
Vs_{min}:250m/s

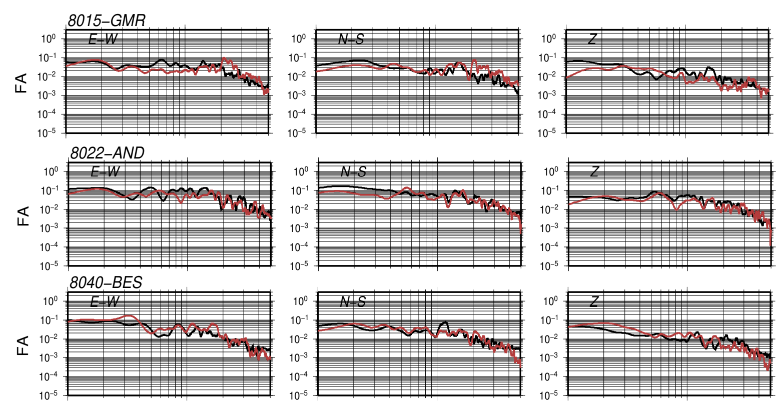
f_{max}= 5hz.

dh_{min}=6.5m

CPUs:40,000

WT: 32hrs





Future expansion of the M7 Hayward fault earthquake rupture scenarios database

1. Expand the rupture parameters space using plausible distributions for each of them within a probabilistic framework
2. Estimate the minimum number of rupture scenarios to fully capture source effects in BB simulations in the SFBA
3. Work in progress for improving SW4 to perform non-linear wave propagation modeling on a broad frequency range

Thank you !

This research was supported by the Exascale Computing Project (ECP), Project Number: 17-SC-20-SC, a collaborative effort of two DOE organizations -- the Office of Science and the National Nuclear Security Administration -- responsible for the planning and preparation of a capable Exascale ecosystem -- including software, applications, hardware, advanced system engineering, and early testbed platforms -- in order to support the nation's Exascale computing imperative. Parts of this work were also performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Ground motion simulations were performed on Dane (LLNL) and Perlmutter (LBNL) platforms