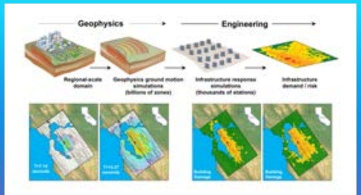

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Physics-Based Constraints on Kinematic Rupture Models Used in Broadband Ground Motion Simulations

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PEER

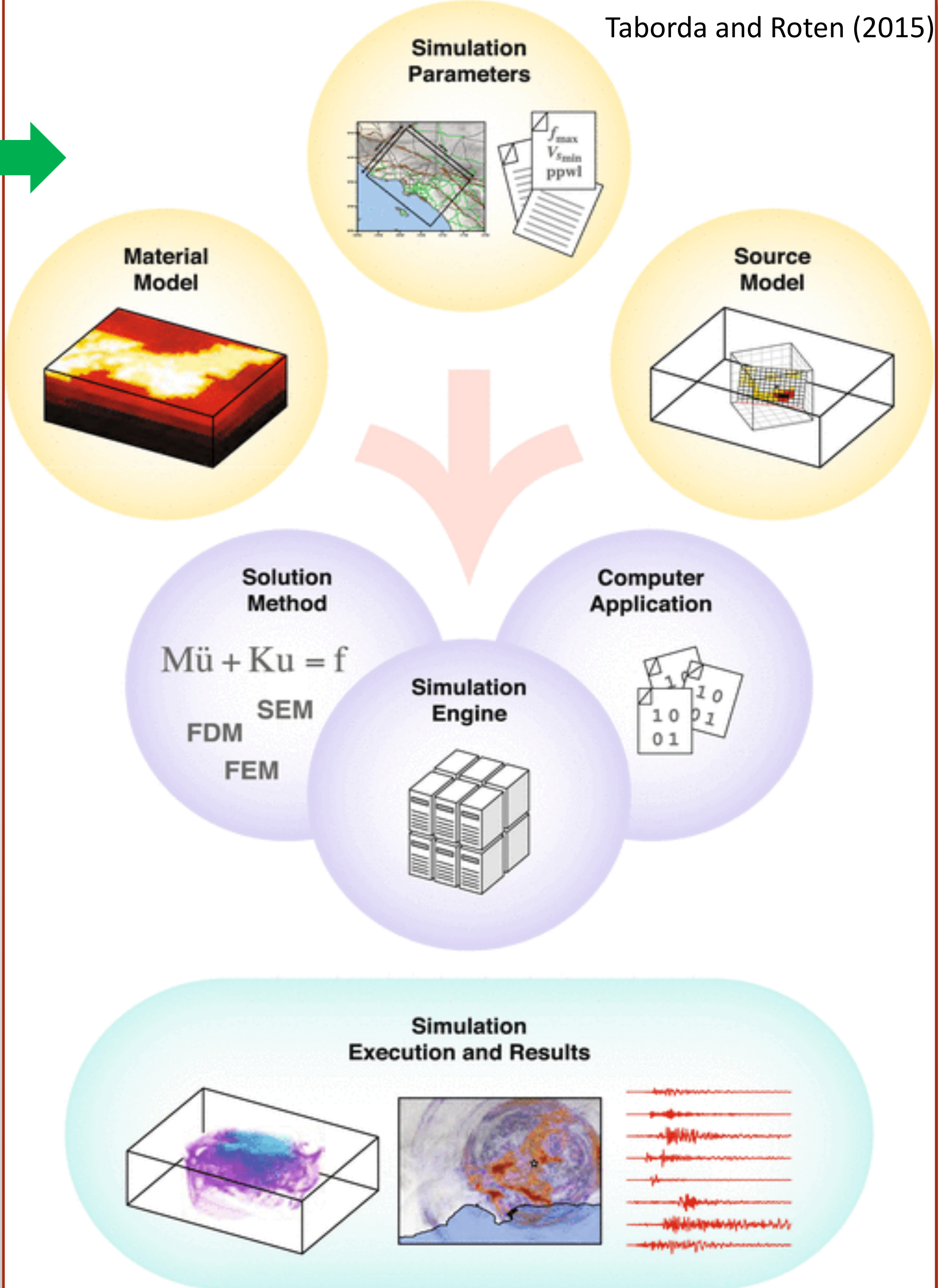
Outline

- Kinematic source modeling used in physics-based (deterministic) ground motion simulation techniques
- Dynamic rupture modeling to constrain and refine kinematic rupture parameters: Ridgecrest earthquake case
- Application to 0-5Hz ground motion simulations for scenario earthquakes on a splay fault in the Yucca Flat basin
- Challenges and needs for improvements

Earthquake Ground Motion Simulations

Simulation Method

- Deterministic approach (0~10 Hz)
- Stochastic approach (~20 Hz)
- Hybrid approach (0~20 Hz)
  - *- deterministic ground motion (0~1Hz)*
  - *- stochastic ground motion (1~20Hz)*



Basic Steps in Generating a Kinematic Source Model

- Rupture area
- Fault geometry
- Fault Mechanism
- Rupture initiation

} **Empirical Knowledge (Mw, tectonics)**

- Slip distribution
- Rupture initiation time
- Slip rate function

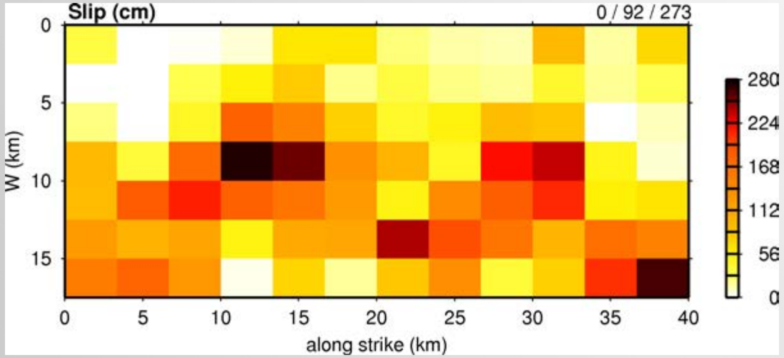
} **Physics-based Modeling**
- Forward dynamic rupture modeling
- Kinematic and dynamic slip inversion of recorded ground motion

Kinematic Rupture Model Generator : Graves and Pitarka Method (2010;2016)

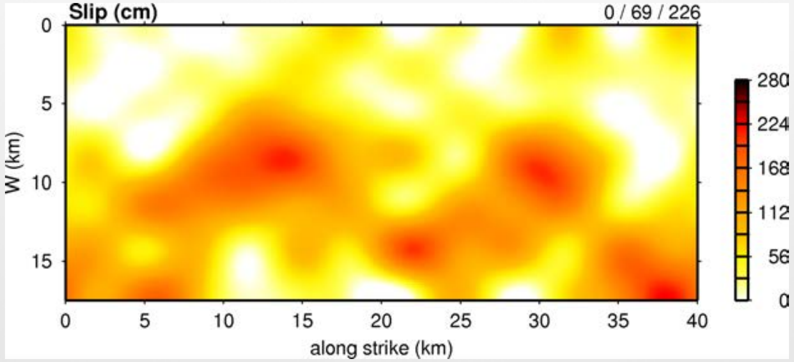
Rupture Model for Past Earthquakes

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

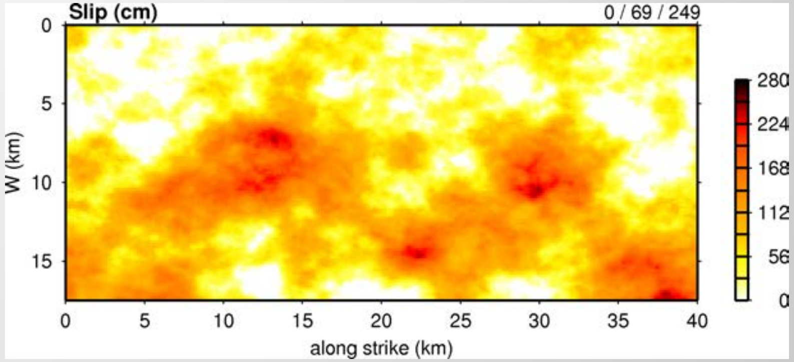
Initial Slip



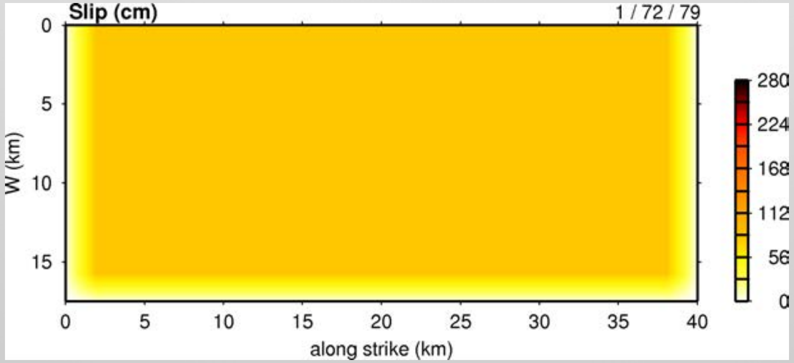
Low-pass Filtered Slip



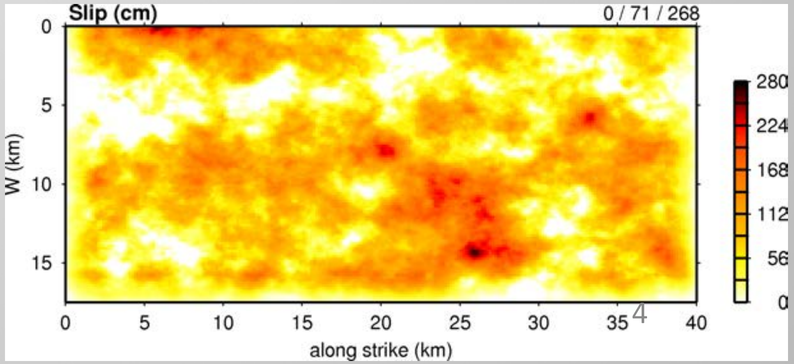
Final Semi-Deterministic Slip



Single Realization of Kinematic Rupture Model for Scenario Earthquakes

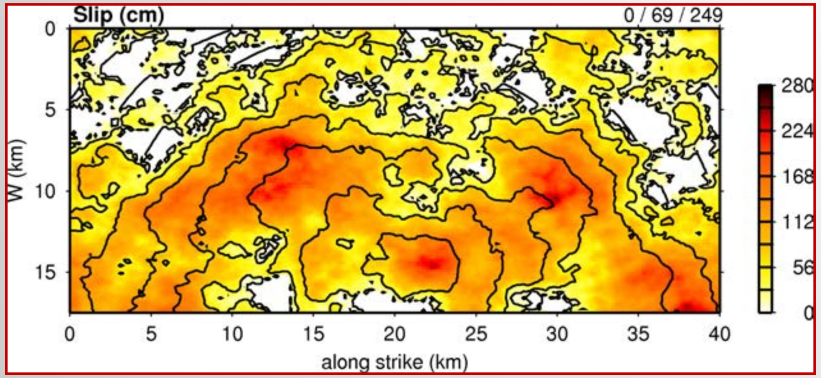


Stochastic Slip

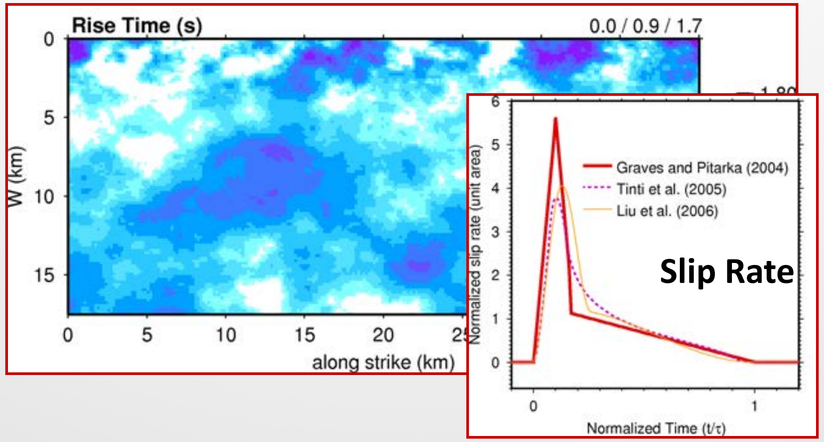


Slip Distribution

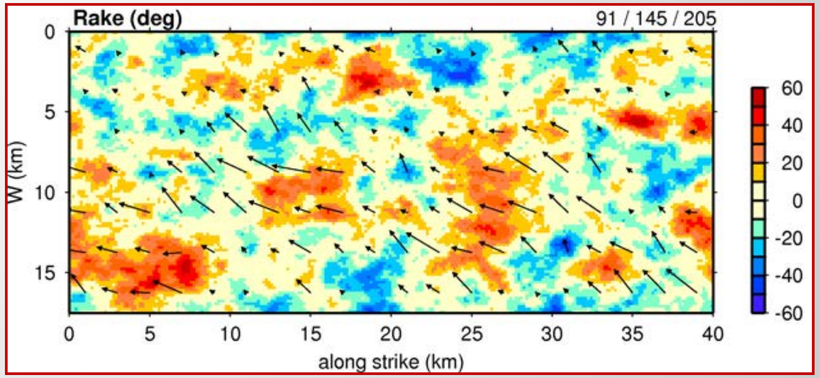
Rupture Initiation Time (Rupture Velocity)



Rise Time



Rake Angle



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

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

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

$\tau = k \cdot D^{1/2}$ 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:

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

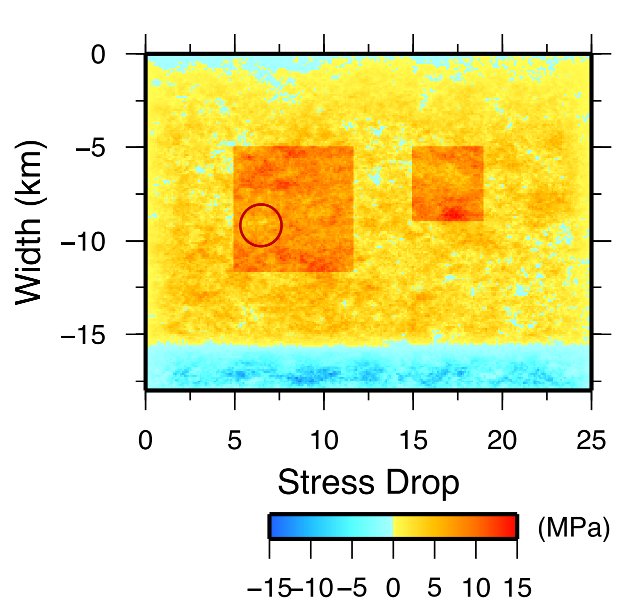
$\lambda = \lambda_o + \varepsilon\,\sigma_\varepsilon = 15^o$

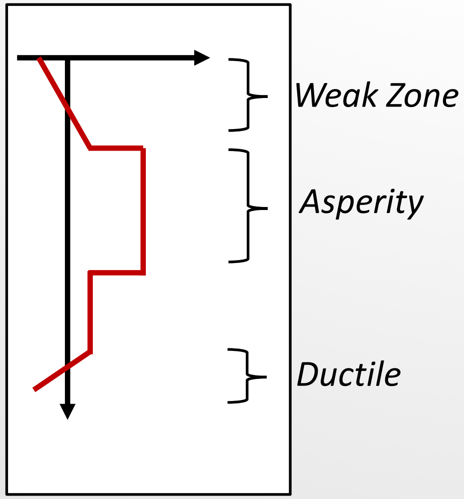
$-60^o < \varepsilon < 60^o$

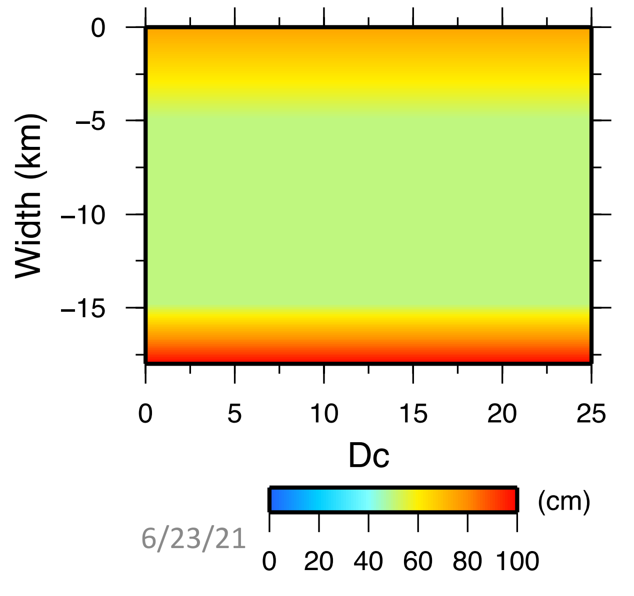
Random perturbations of rake follow spatial distribution given by K^{-2} falloff.

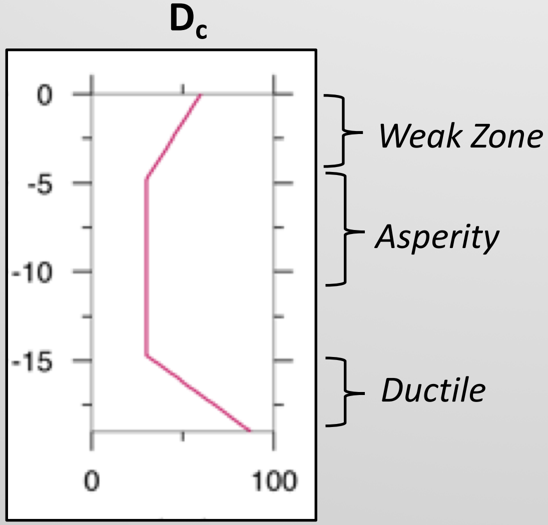
Dynamic Rupture Modeling Using Split Node FD Method (Dalguer and Day 2007)

1- Stress Drop $\Delta\sigma_d$

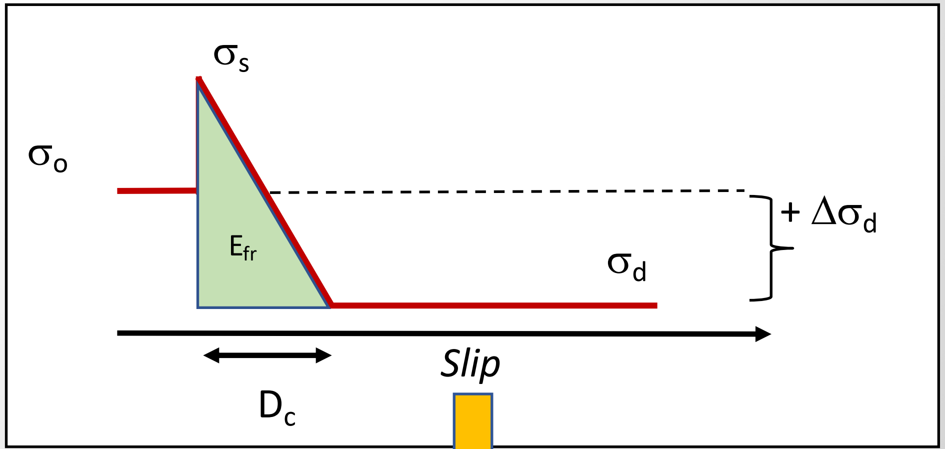




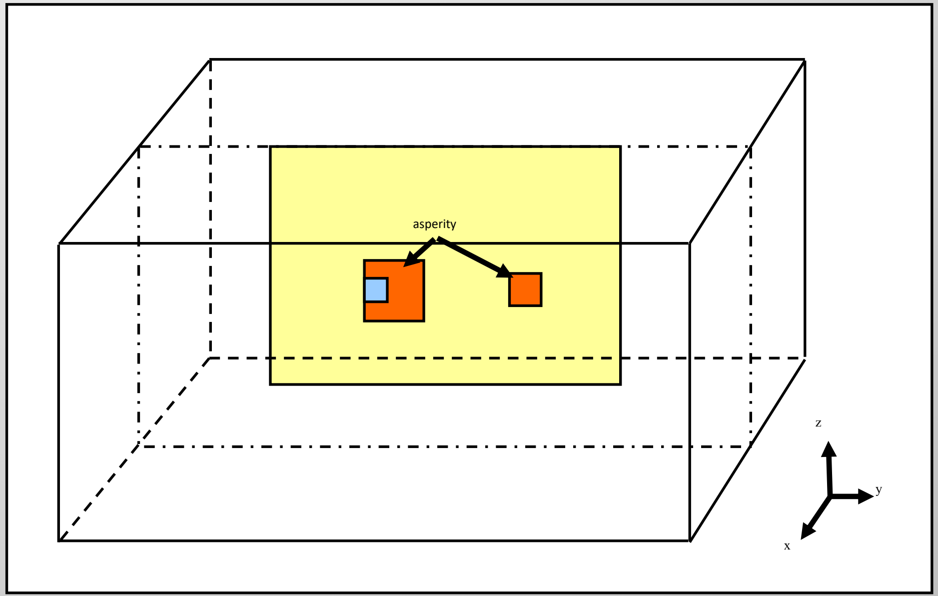




2- Linear Friction Law

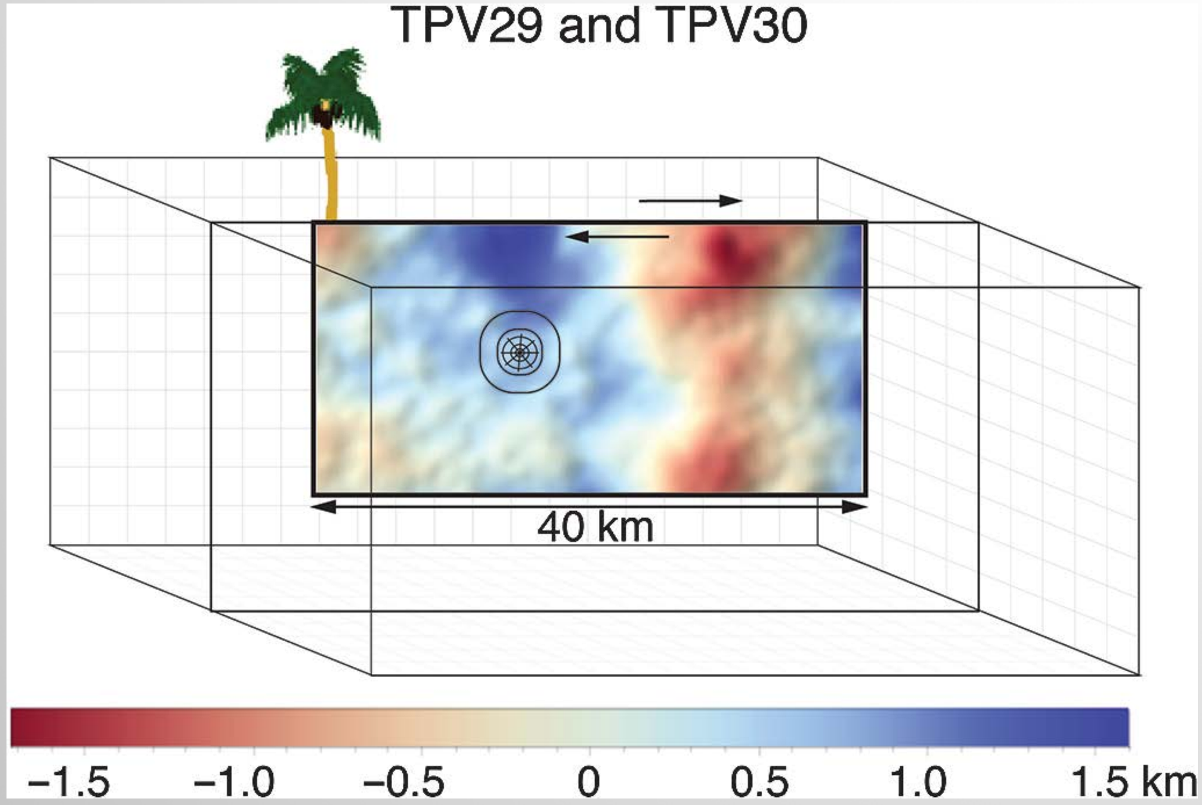


3- 3D Staggered Grid 3D-FDM (Pitarka,1999)

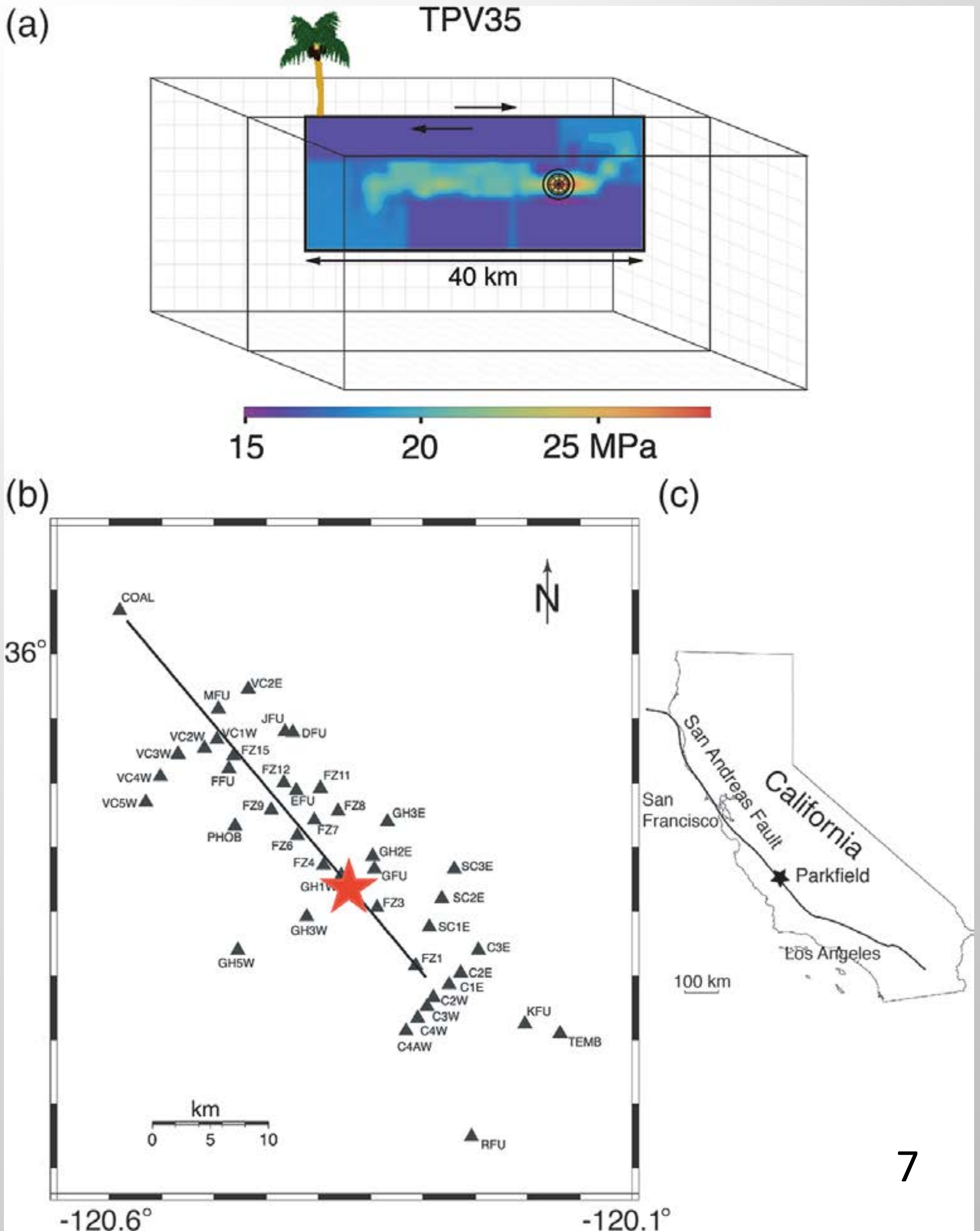


SCEC Dynamic Earthquake Rupture Modeling Codes Verification

Rupture Scenarios



2004 magnitude 6.0 Parkfield, California, earthquake

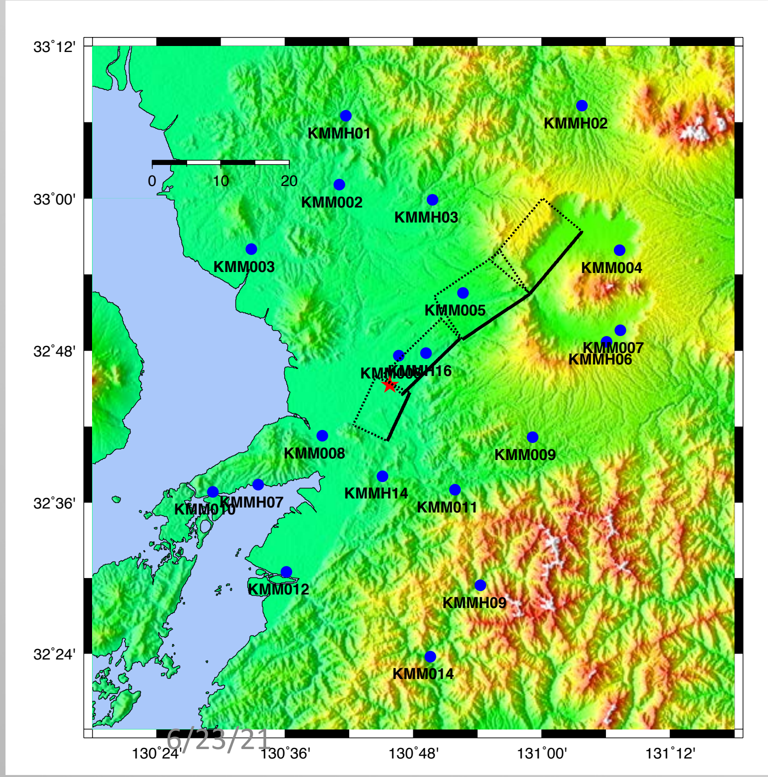


Haris et al., SRL 2018

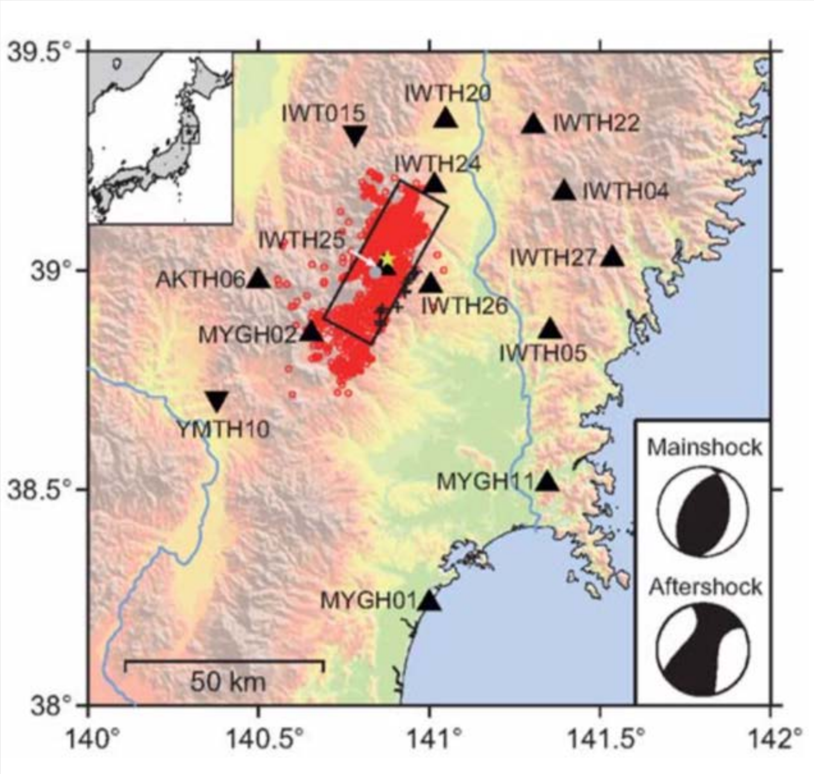
Dynamic Rupture Models of Recorded Crustal Earthquakes

- 1992 M_w7.3 Landers, California earthquake
- 2004 M_w6   Parkfield, California earthquake
- 2016 M_w7 Kumamoto Japan earthquake
- 2008 M_w6.9 Iwate Miyagi, Japan earthquake
- 2019 M_w7.1 Ridgecrest, California earthquake

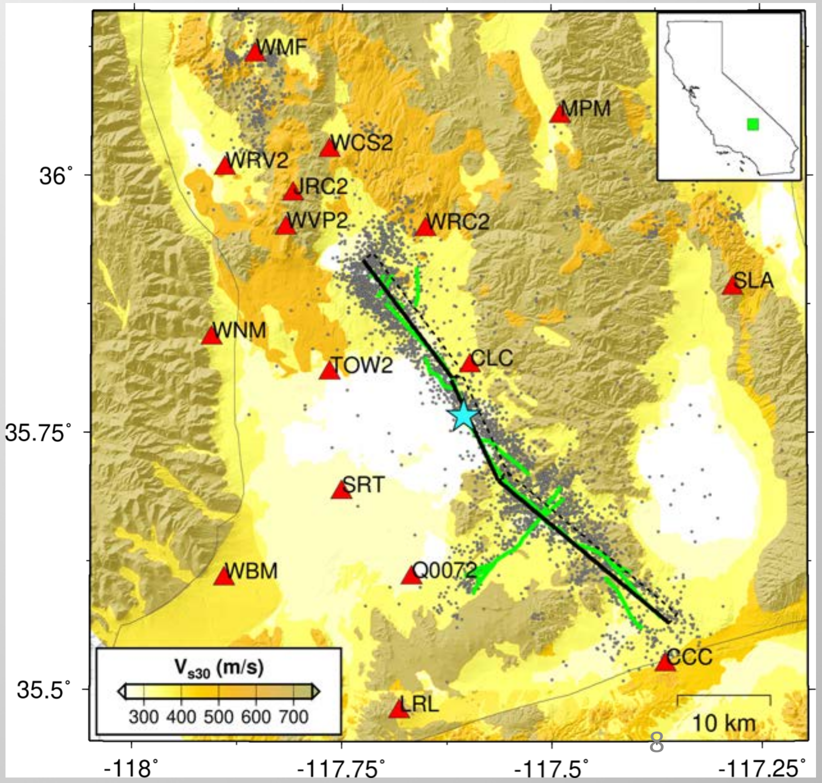
M_w7 2016 Kumamoto (strike slip)



M_w6.9 2008 Iwate Miyagi (thrust)



M_w7.1 Ridgecrest (strike slip)

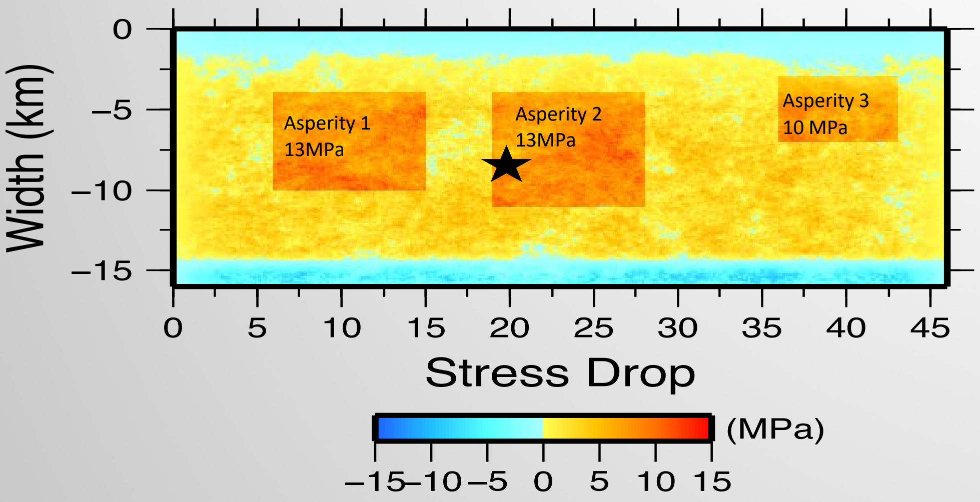


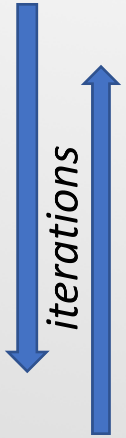
Dynamic Rupture Model of the Mw7.1 Ridgecrest Earthquake

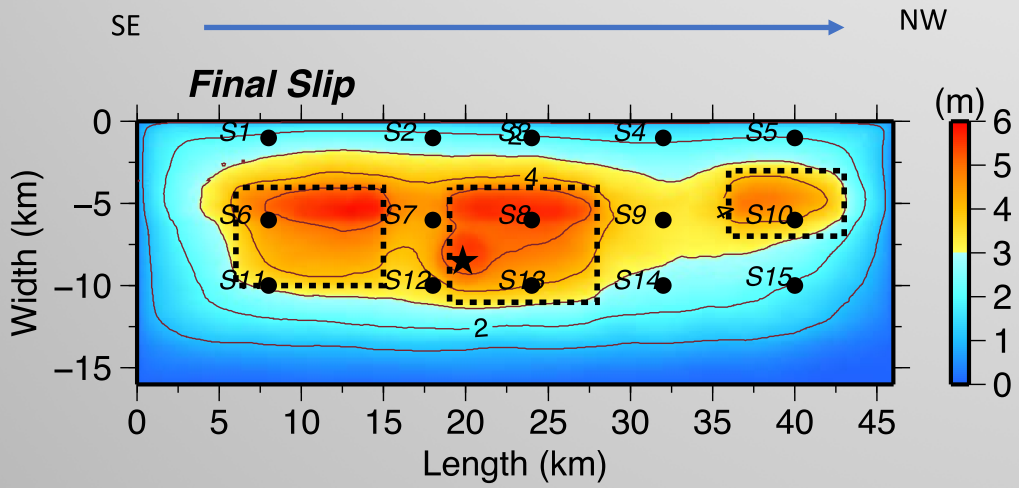
(iterative technique)

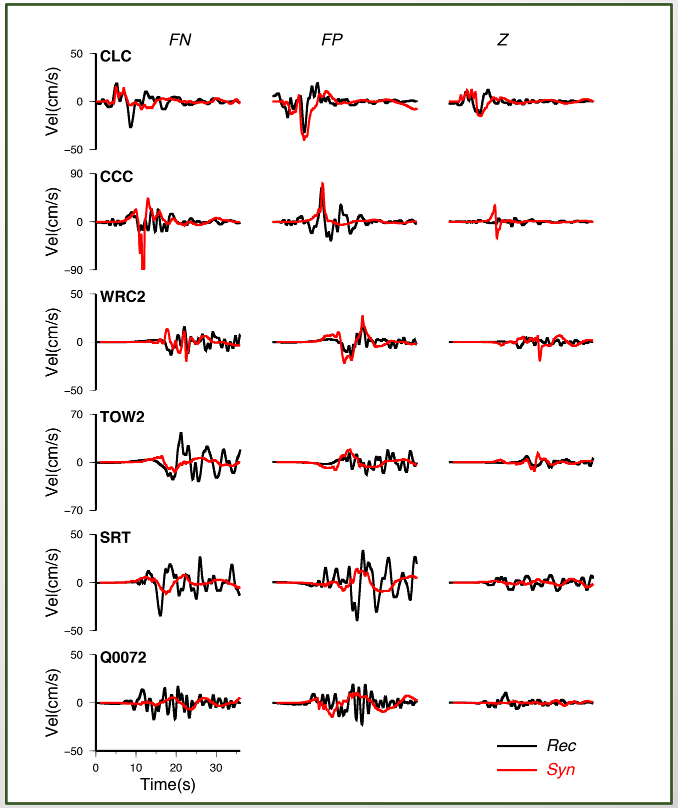
Velocity 0-2 Hz

Stress Drop Model

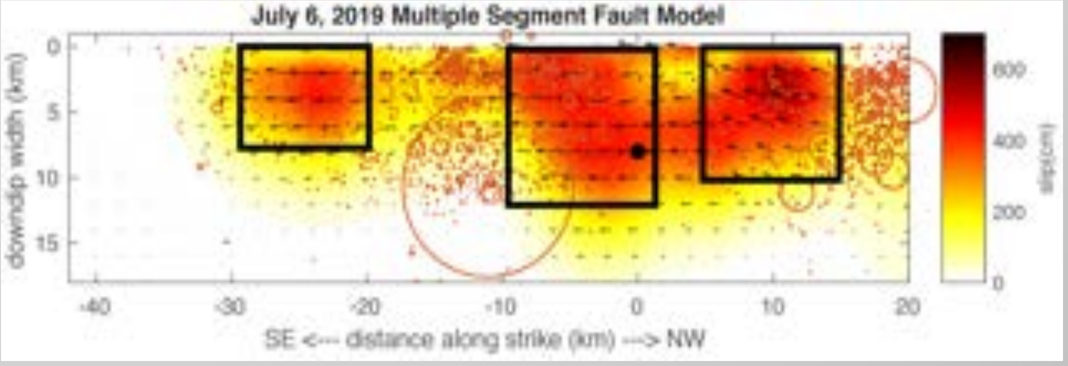




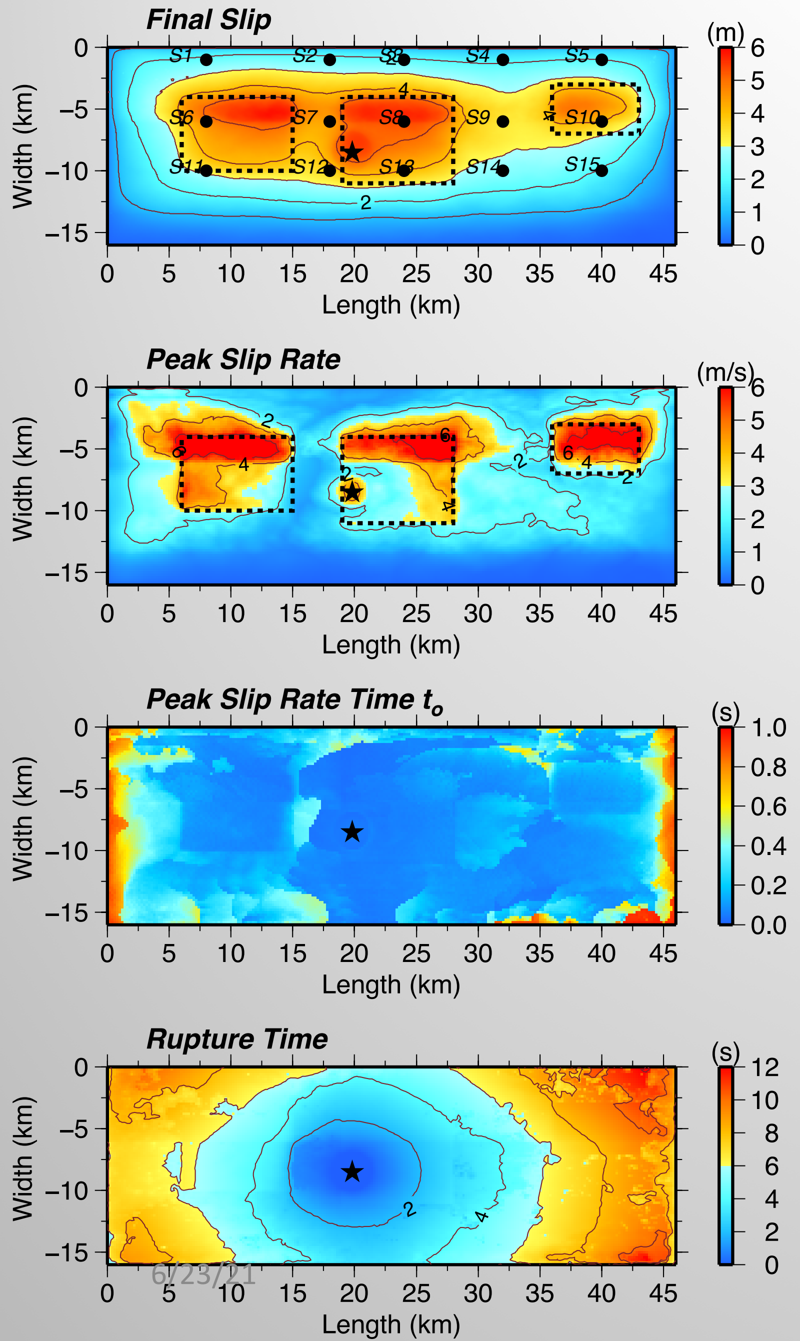




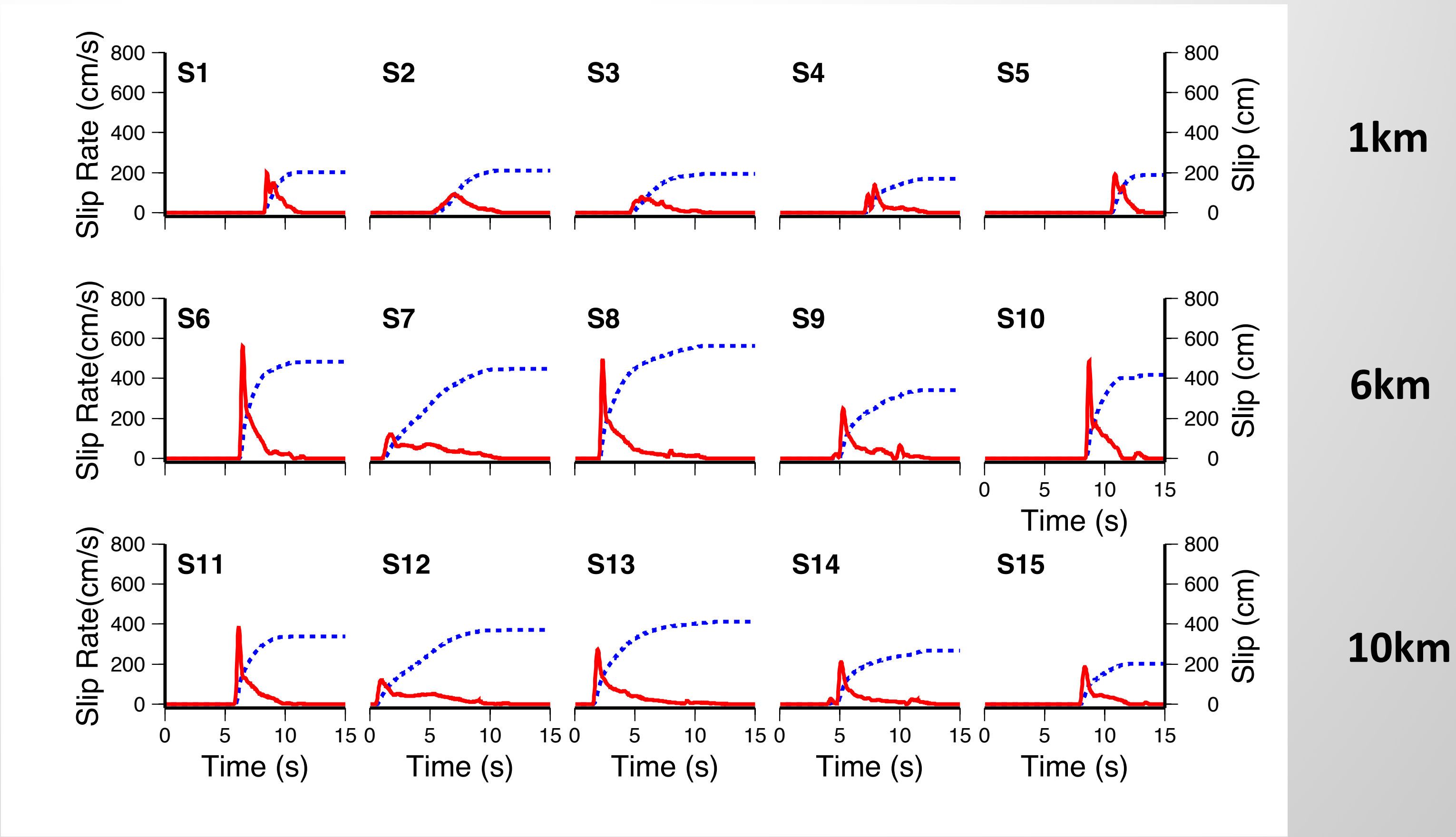
Target Slip Model (Wang et al., 2021)

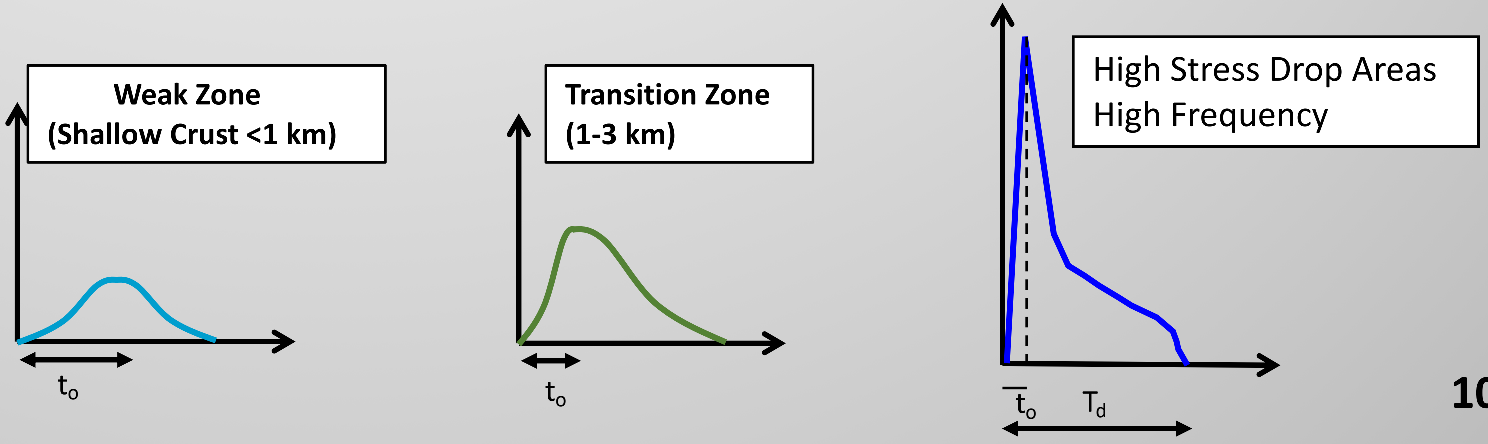


Dynamic Rupture Model



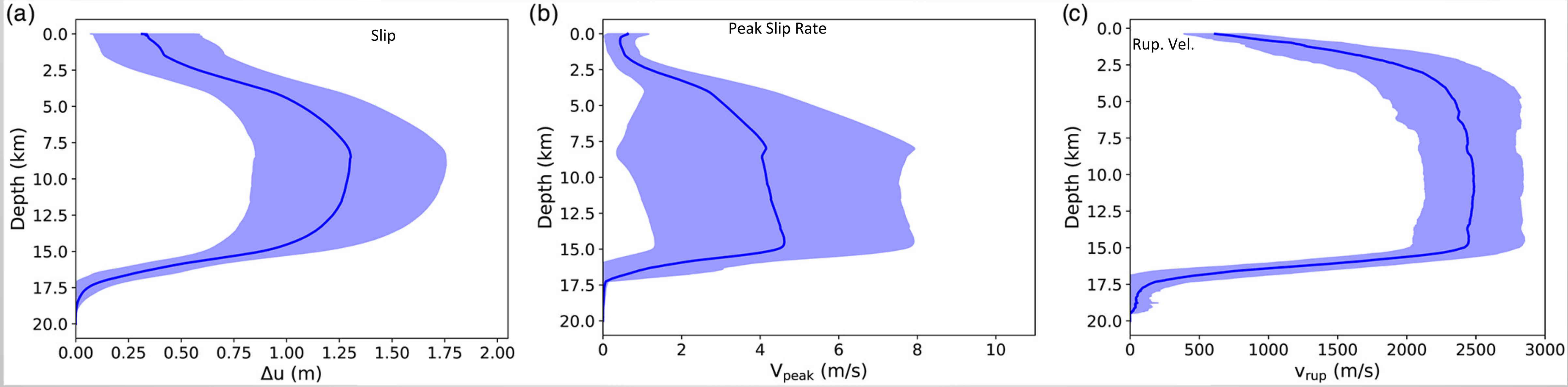
Slip Rate from the Dynamic Rupture Modeling





Depth-Dependent Rupture Parameters Based on 3-D Spontaneous Rupture Simulations Along Geometrically Rough Faults (100 rupture scenarios)

Savran and Olsen (2020)

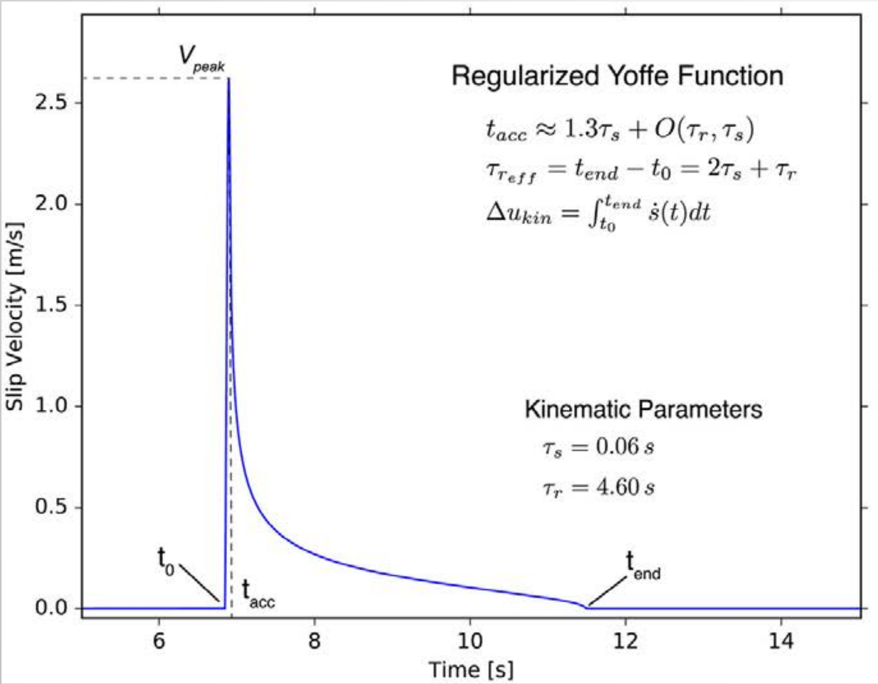


Proposed Depth Dependent Slip Rate Function for use in Deterministic BB Ground Motion Simulations

(Grave's presentation)

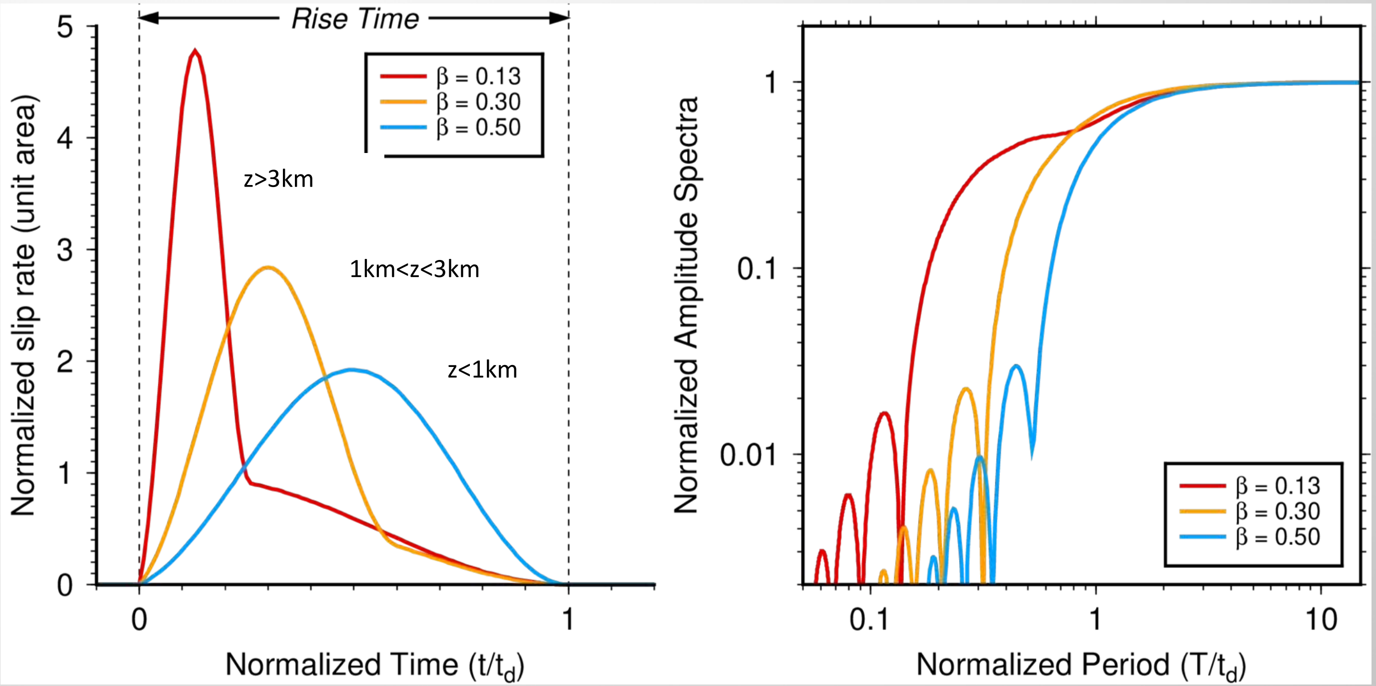
Yoffe Function

Savran and Olsen (2020)



Liu Function

(Liu et al., 2006)

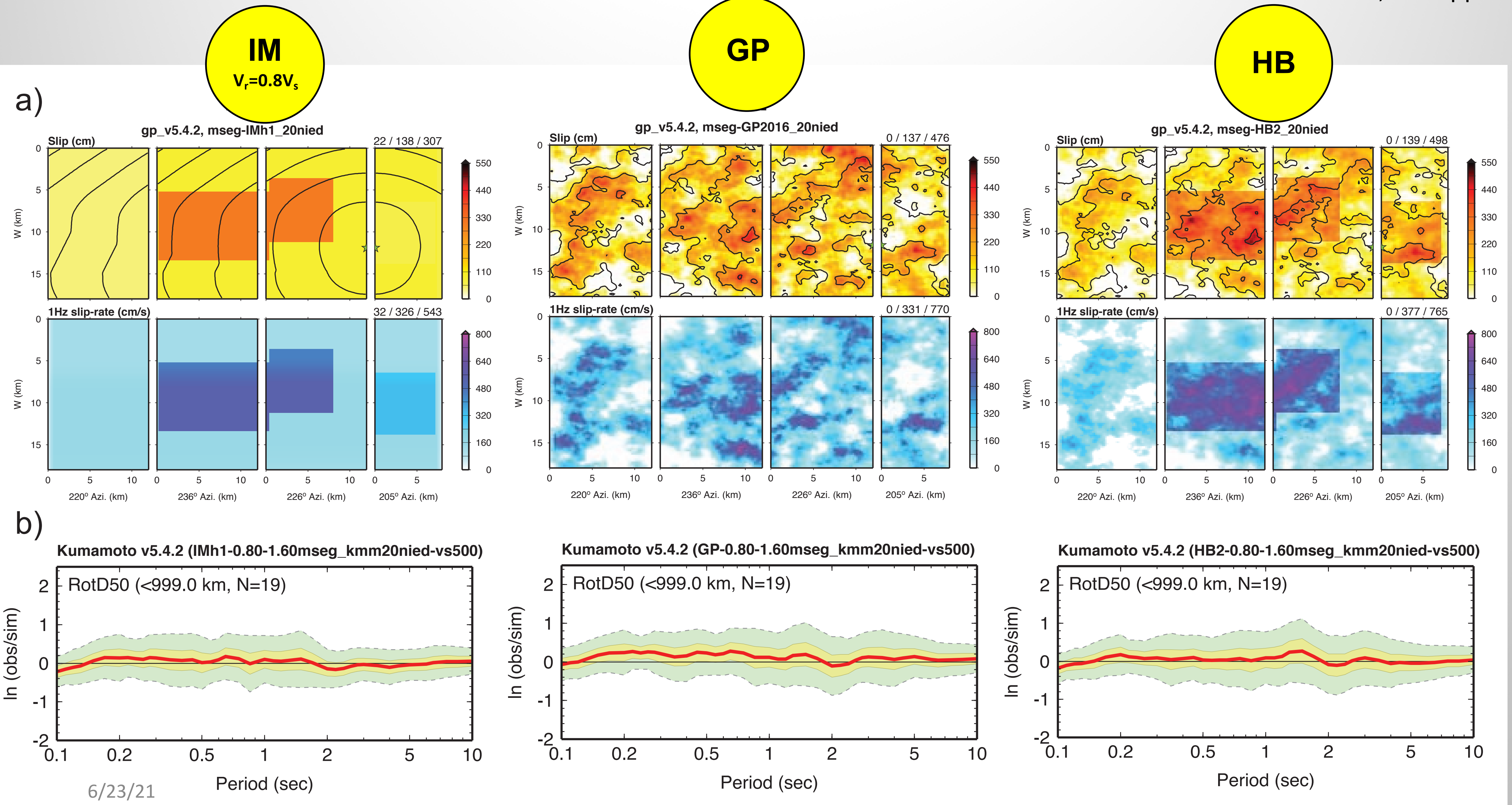


Analytical Formula of the Slip Rate Function

$$\dot{s}(t) = \begin{cases} A[0.7 - 0.7\cos(\pi t/t_0) + 0.6\sin(0.5\pi t/t_0)] & t < t_0 \\ A[1.0 - 0.8\cos(\pi t/t_0) + 0.2\cos(\pi(t-t_0)/(t_d-t_0))] & t_0 \le t < 2t_0 \\ A[0.2 + 0.2\cos(\pi(t-t_0)/(t_d-t_0))] & 2t_0 \le t < t_d \end{cases}$$

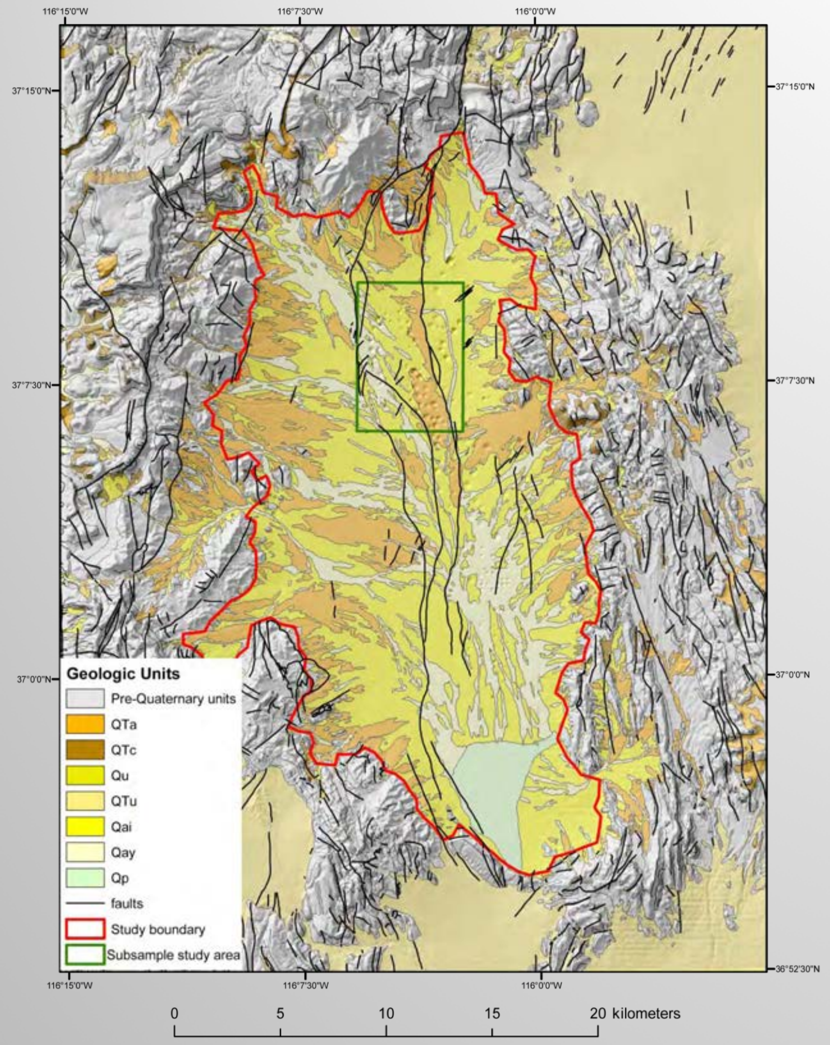
Validation of the Rupture Model Generators Using Kumamoto Earthquake Data

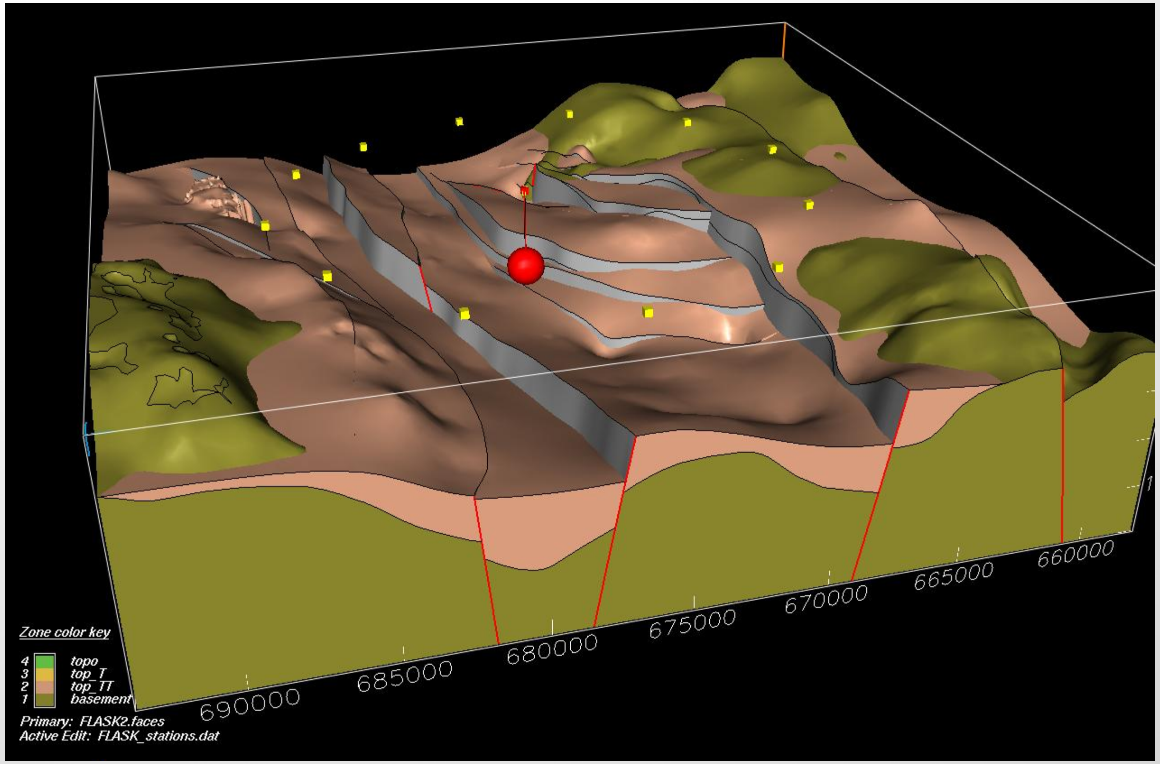
Pitarka et al., Pur.App.Geo.2020



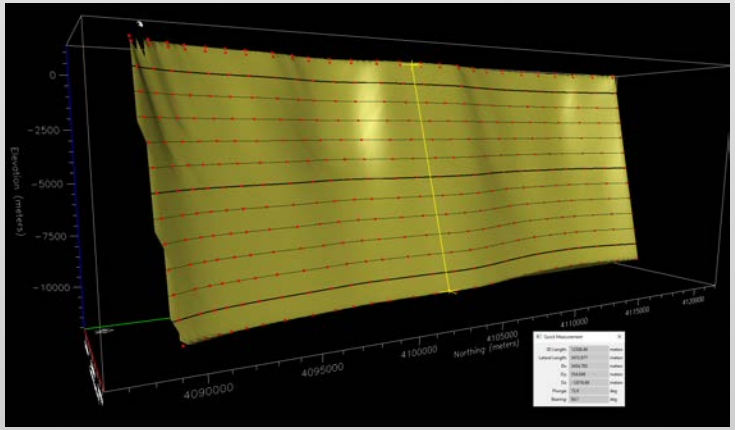
Yucca Fault Geometry

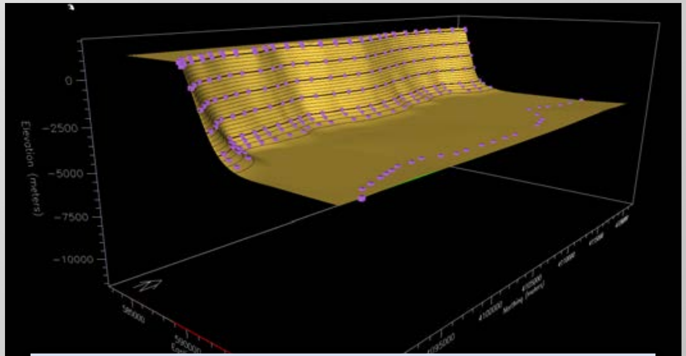
Mapped Faults in the Yucca Fault Basin





Proposed Fault Geometries provided by L. Prothro

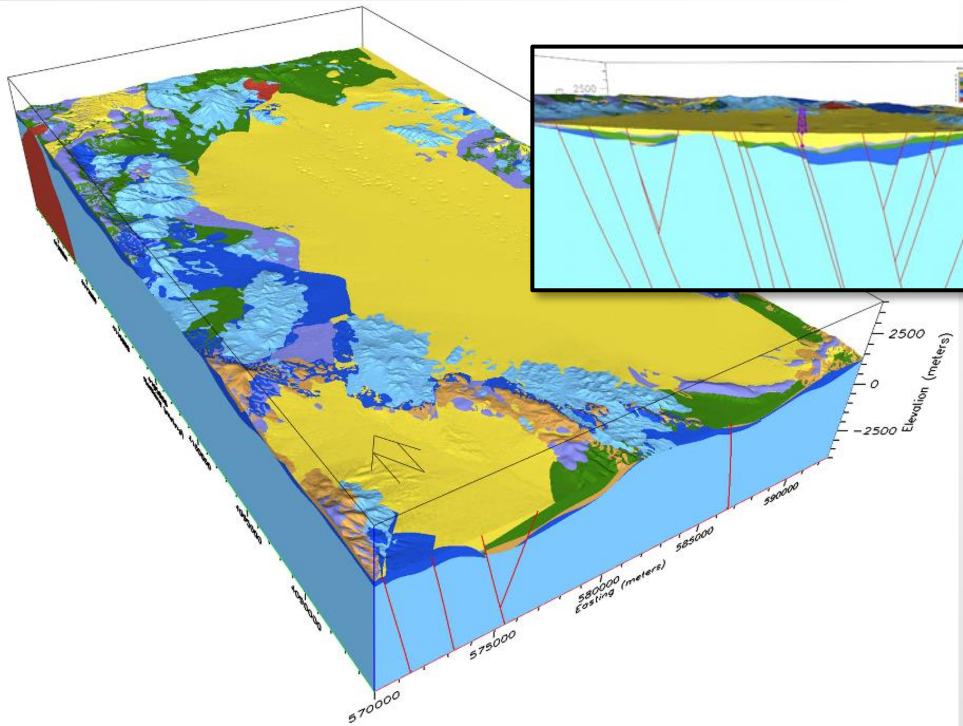


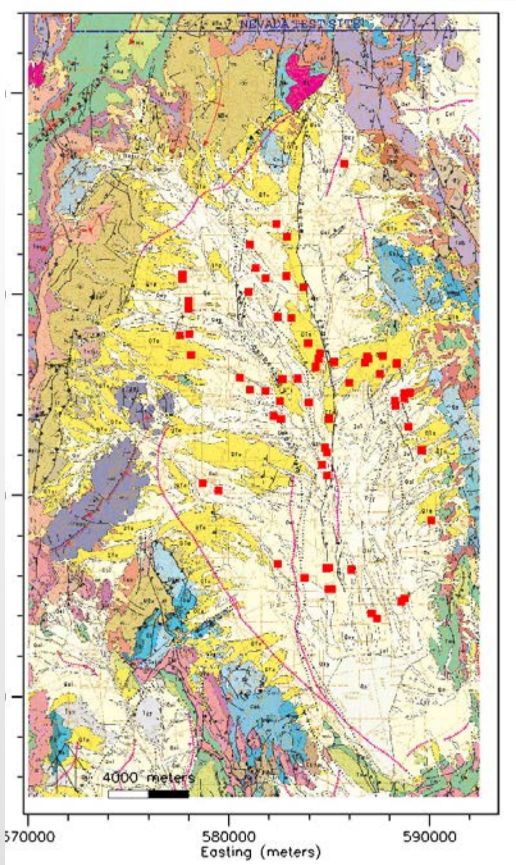


Complex fault geometry at depth

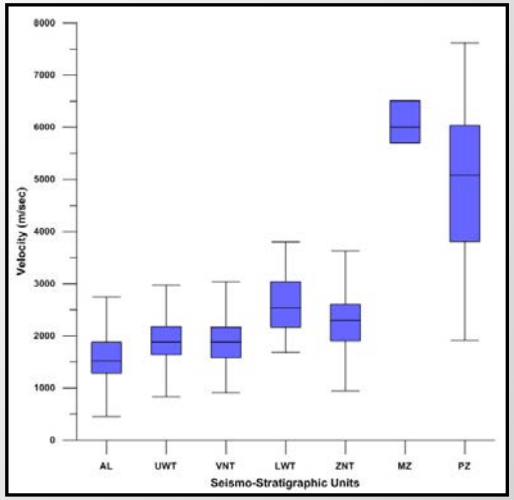
Yucca Flat Basin Seismic Velocity Model (SVM) Prothro, Wagoner, et al. 2018

Geological Framework Model (GFM)



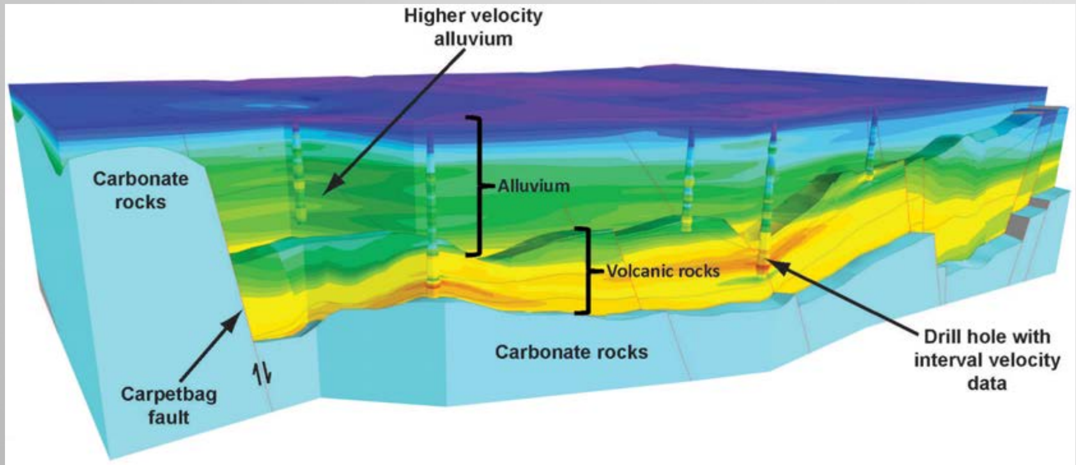


Velocity Values for GFM Layers

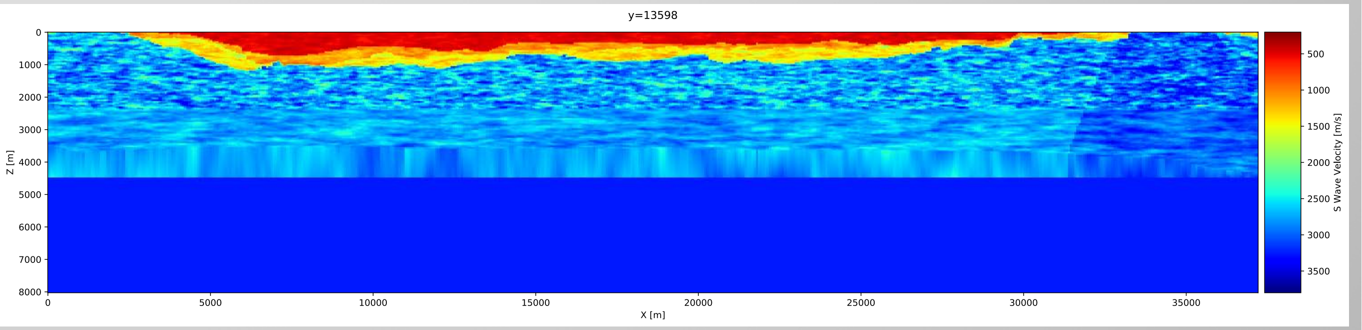


	GFM Layer	Interval Velocity (m/s)				
		Mean	Standard dev	Min	Max	Count
AL	Alluvium	**1601**	497	359	4482	2672
UWT	Upper welded tuff	**1982**	567	837	5080	535
VNT	Vitric nonwelded tuff	**1937**	529	610	5019	756
LWT	Lower welded tuff	**2693**	712	1683	3802	11
ZNT	Zeolitic nonwelded tuff	**2430**	687	802	7589	1174
PZ	Paleozoic rocks	**4967**	1554	1911	7622	72

Shallow Geotechnical Layers provided by MSTS



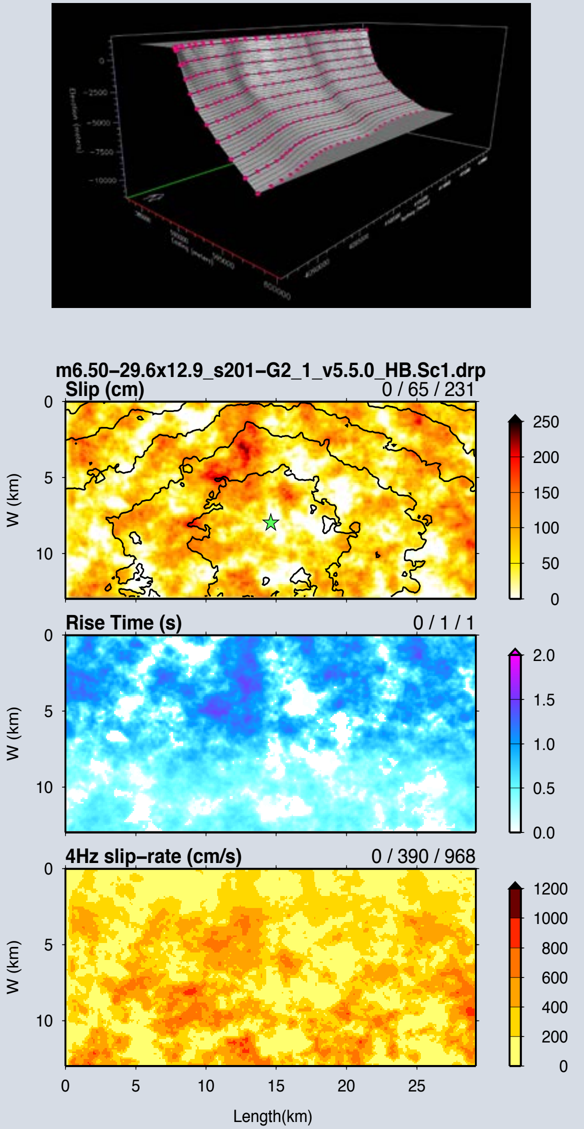
Stochastic SVM



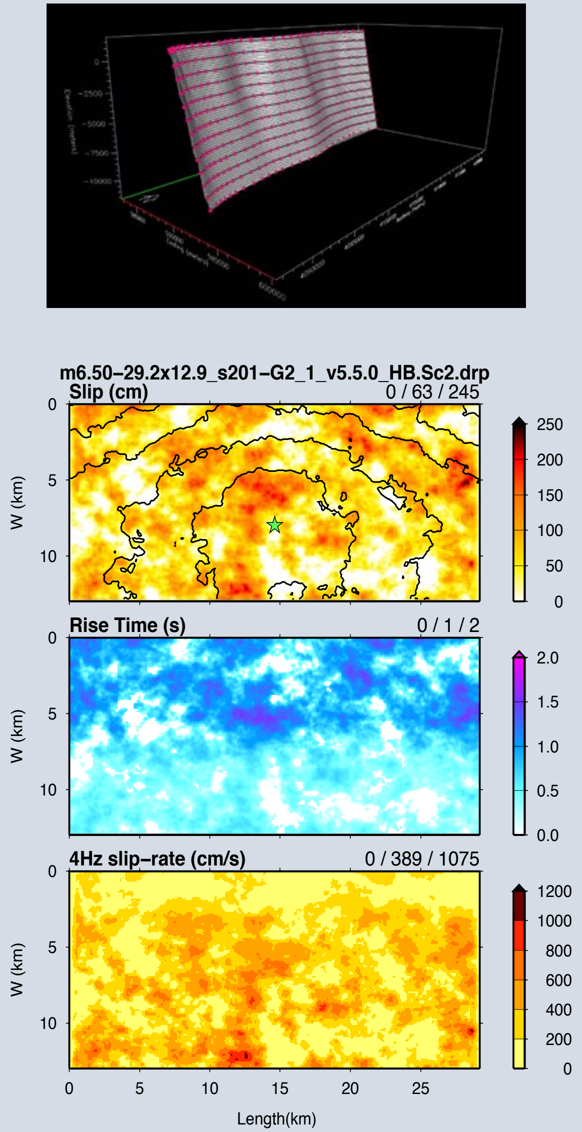
M6.5 Bilateral Earthquake Rupture Scenarios on the Yucca Fault

(Pitarka et al., 2021)

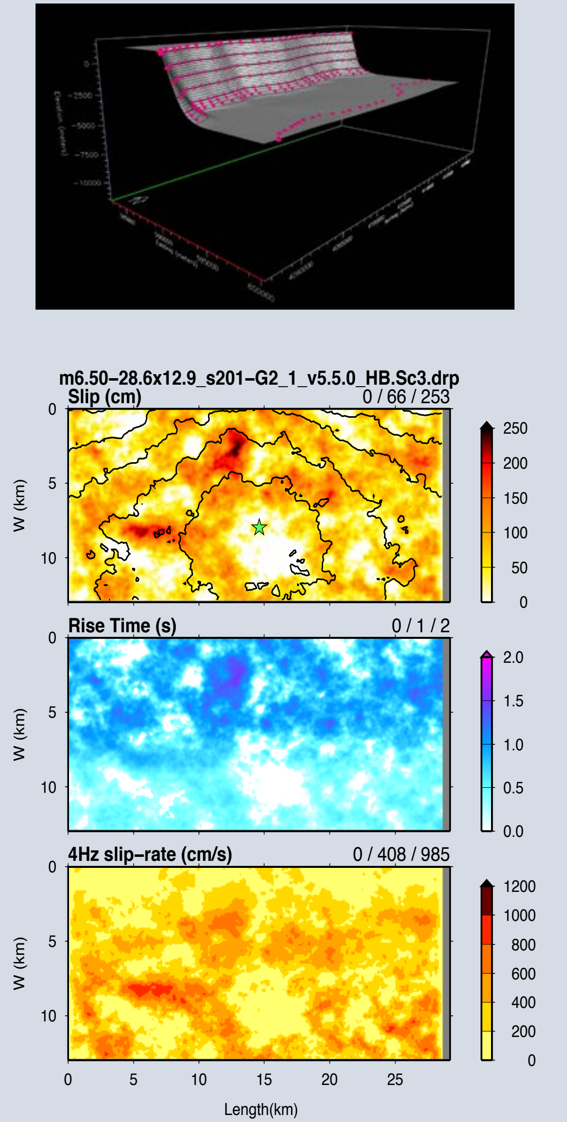
Scenario Sc1



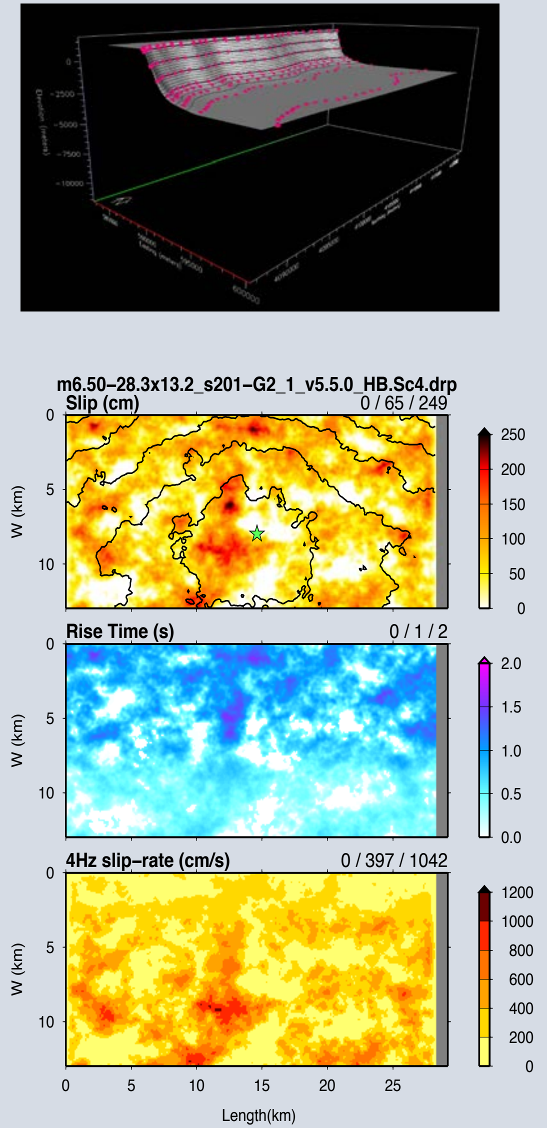
Scenario Sc2



Scenario Sc3

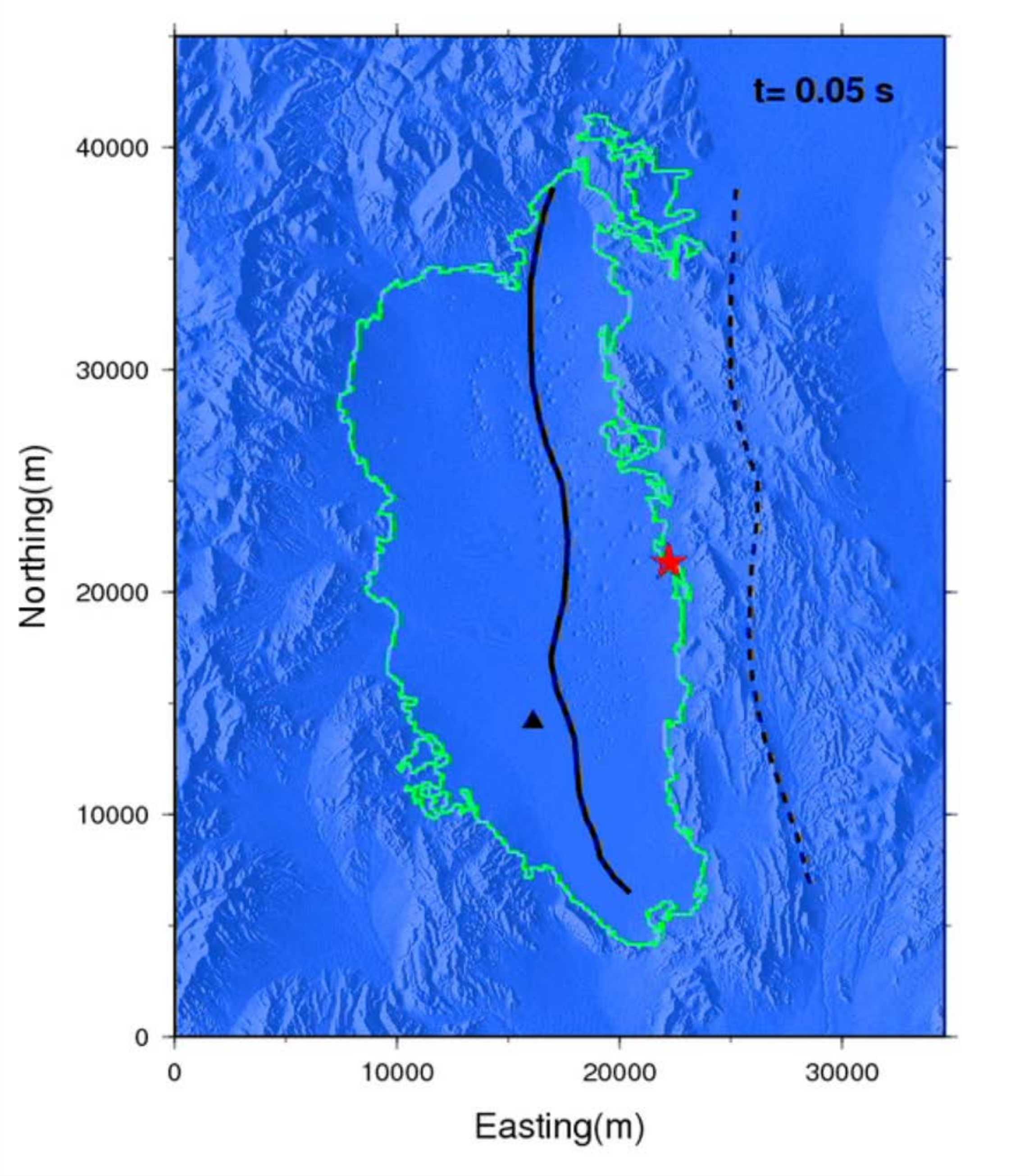


Scenario Sc4

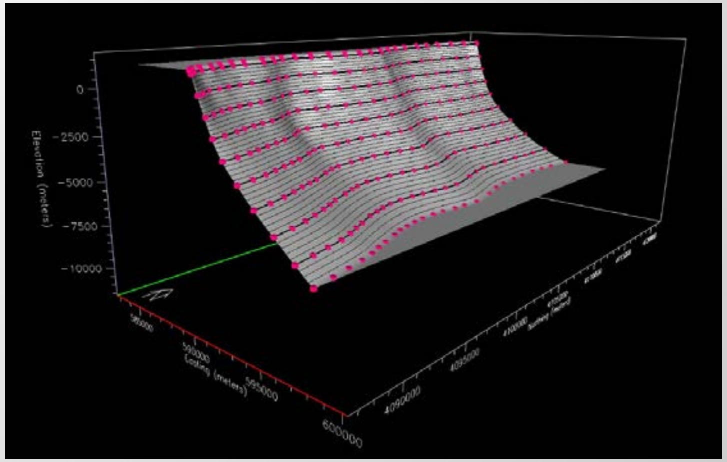


Ground Motion Velocity (0-5Hz)

(Pitarka et al., 2021)



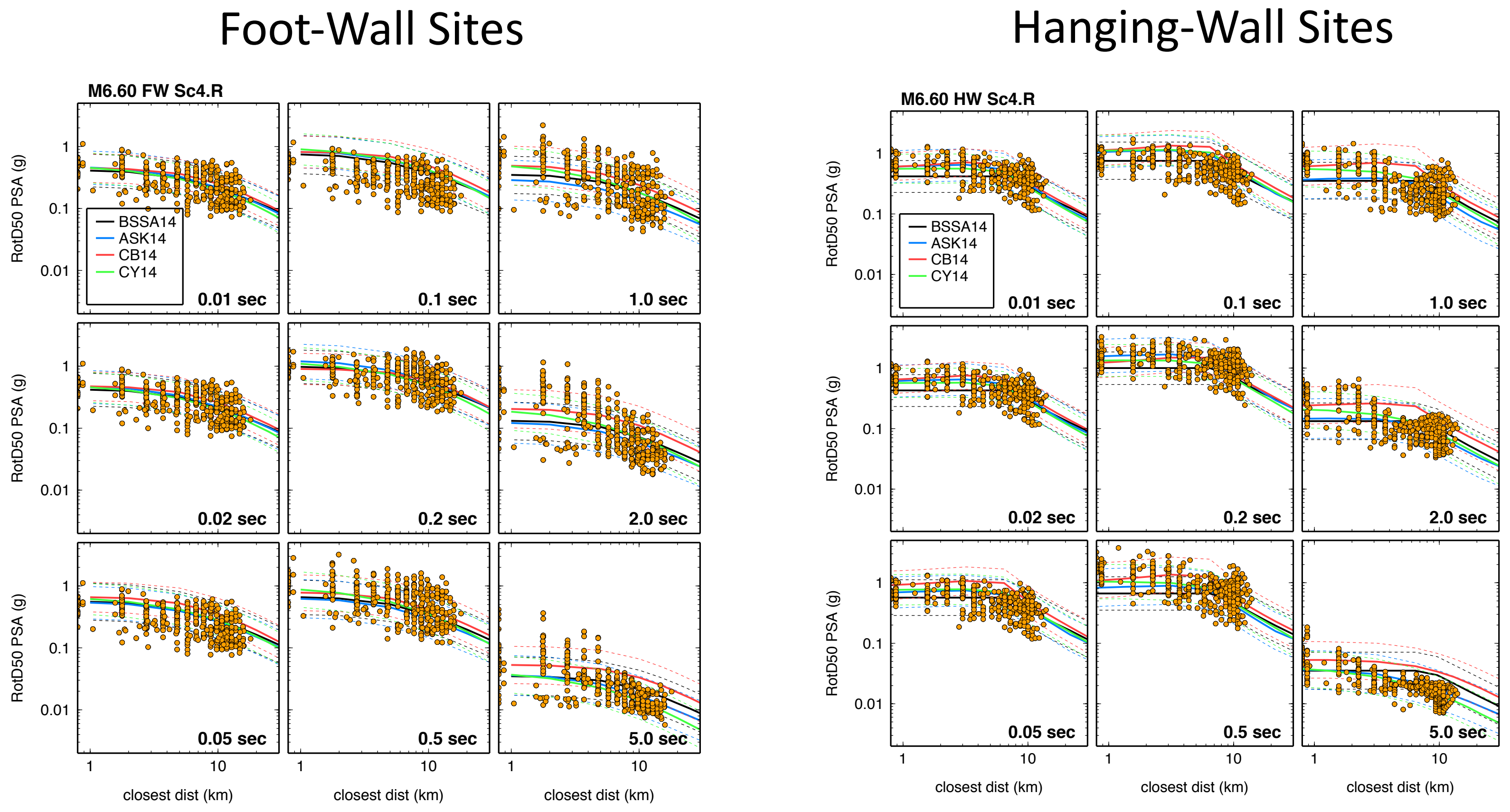
Rupture Scenario Sc1

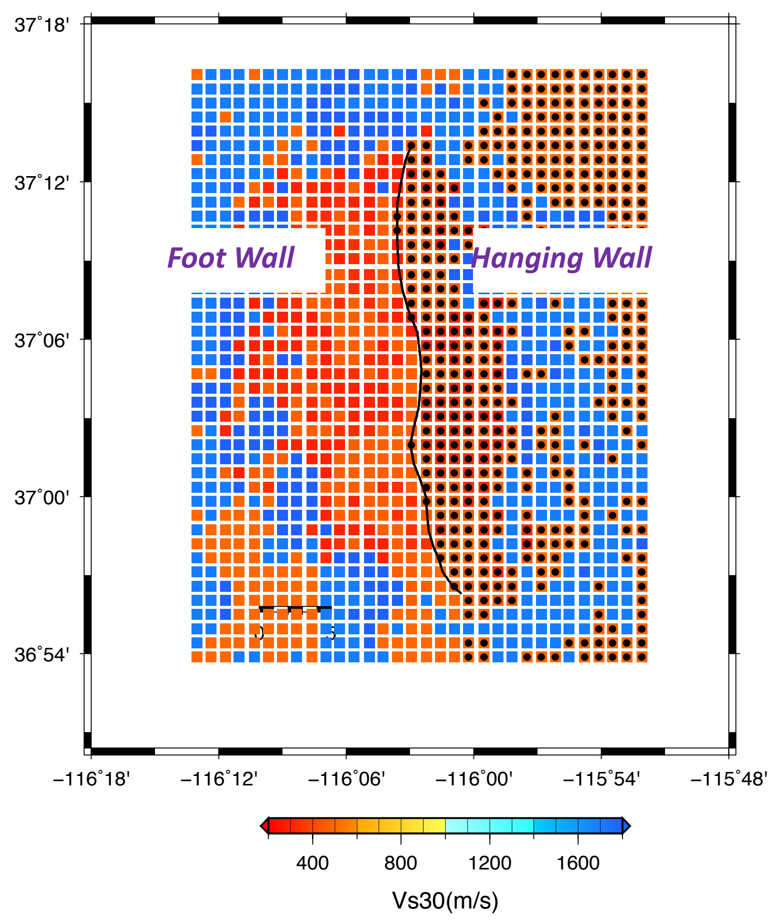


Validation of Simulated Ground Motion using M6.5 GMPEs

Scenario Sc4

Hanging Wall/Foot Wall Sites





Challenges, Gaps and Potential Improvements

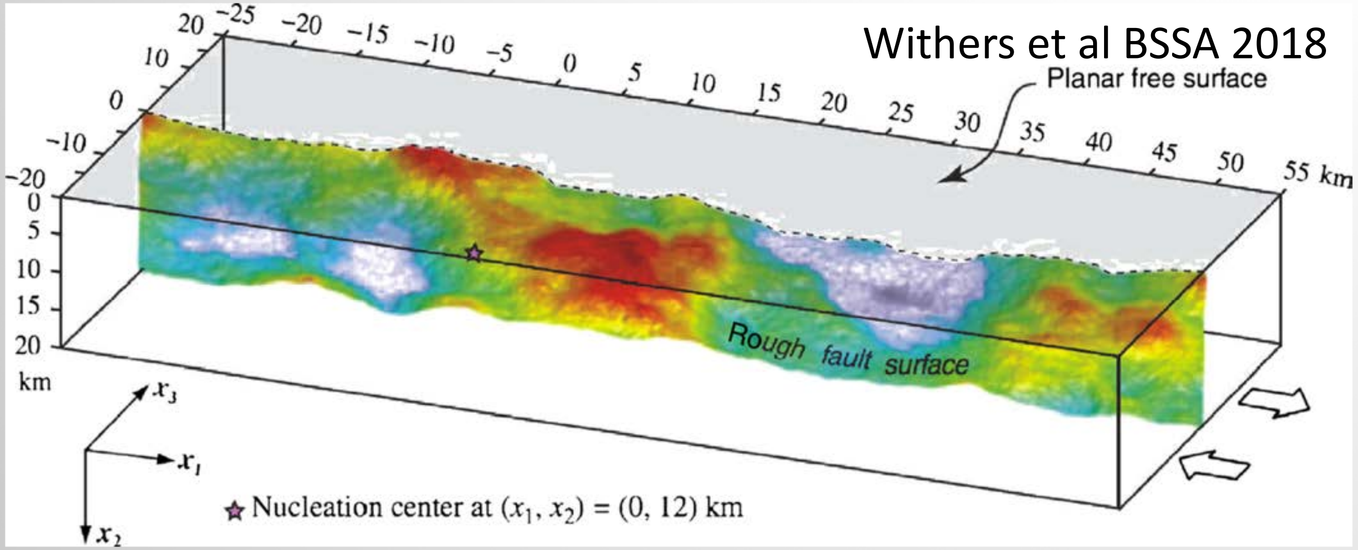
- Geometrical Fault Roughness
- Inelastic off-fault response, fault zone plasticity

Improvements

- Pseudodynamic Rupture Models using one-point and two-points statistics
- Coupled rupture dynamics modeling with elastic wave propagation modeling

1) Geometrical Fault Roughness

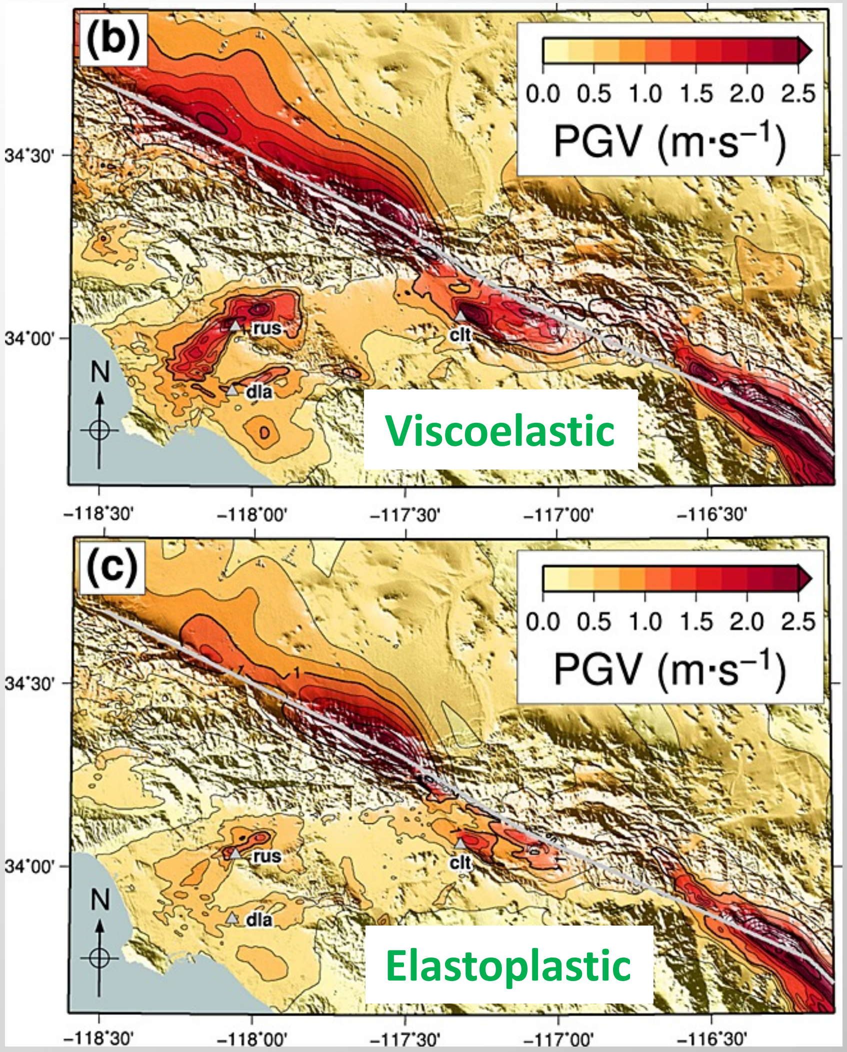
(Wither's presentation)



Two step coupling approach Ripperger et al. (GJR, 2007; BSSA2008)
Step 1:dynamic rupture-kinematic rupture
Step 2:elastic wave propagation modeling

2) Inelastic off-fault response; Fault zone plasticity

Roten et al. GRL, 2014



The near-fault near-surface plasticity limits the peak stresses of strong directivity pulses that would otherwise be channeled into a basin, thereby leading to a reduction of waveguide amplification and therefore to a reduction of PGVs

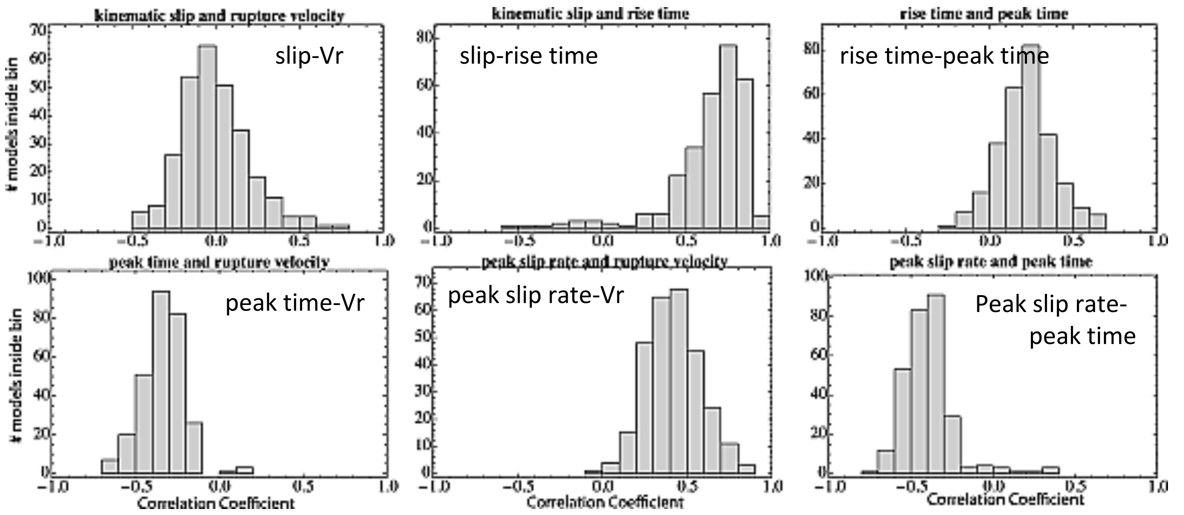
3) Pseudo dynamic rupture Models

Correlation of earthquake source parameters inferred from dynamic rupture simulations

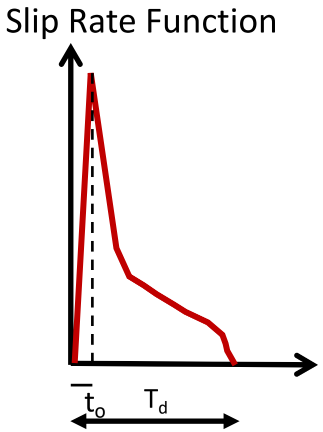
Schmedes et al. (JGR, 2010)

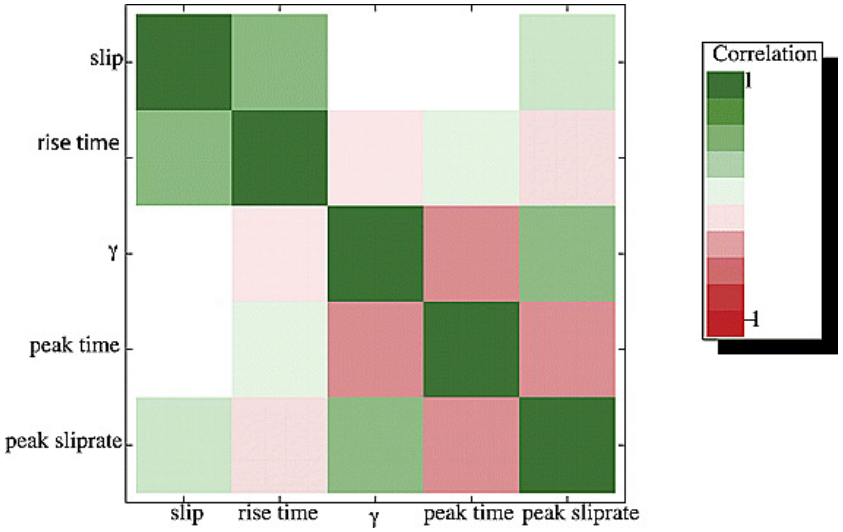
- 315 dynamic strike-slip rupture models computed for frequencies up to 5Hz
- Quantitative understanding of correlations between various rupture parameters

Histograms of Computed Spatial Correlations



Computed Spatial Correlations





Findings

1. slip does not corelate with rupture velocity
2. slip correlates with rise time
3. Peak slip rate correlates with rupture velocity
4. Peak slip rate inversely correlates with peak time

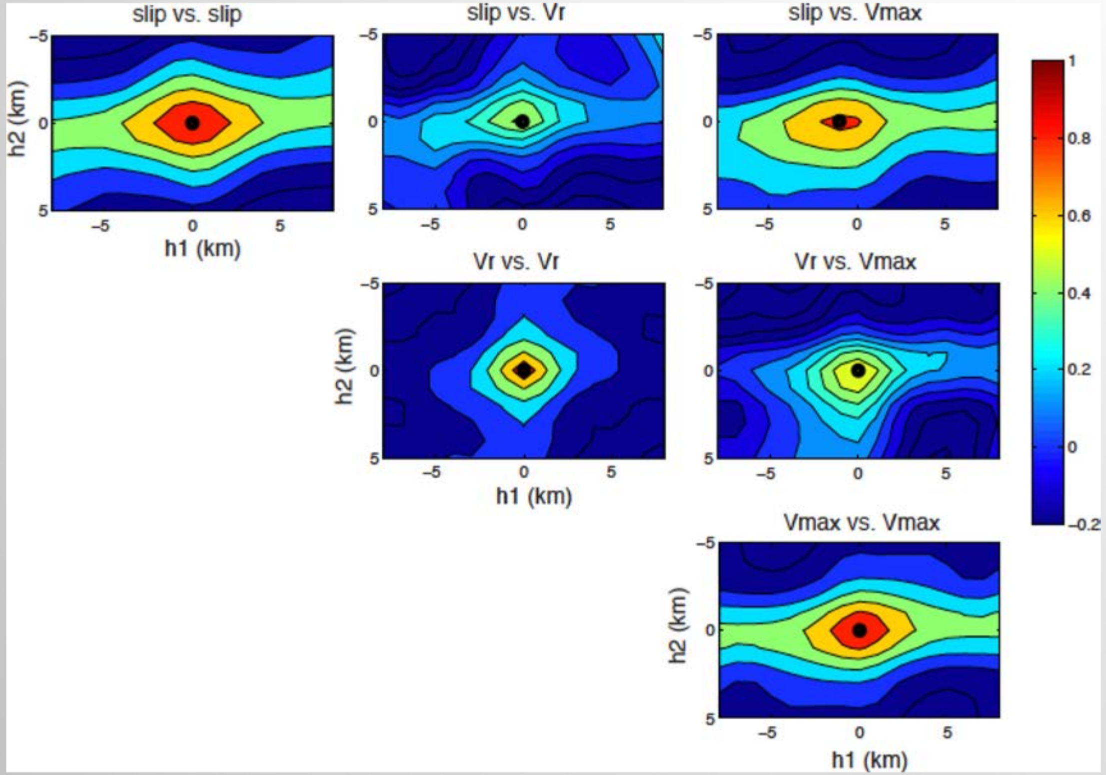
Implications

1. Direct implementation in kinematic rupture generators
2. Use heterogeneous rupture models with correlated random kinematic rupture parameters
3. Study within event and between events

Pseudo-dynamic source modeling with 1-point and 2-point statistics of source parameters

Correlations between rupture parameters

Song, Dalguer, Mai, GJI 2014



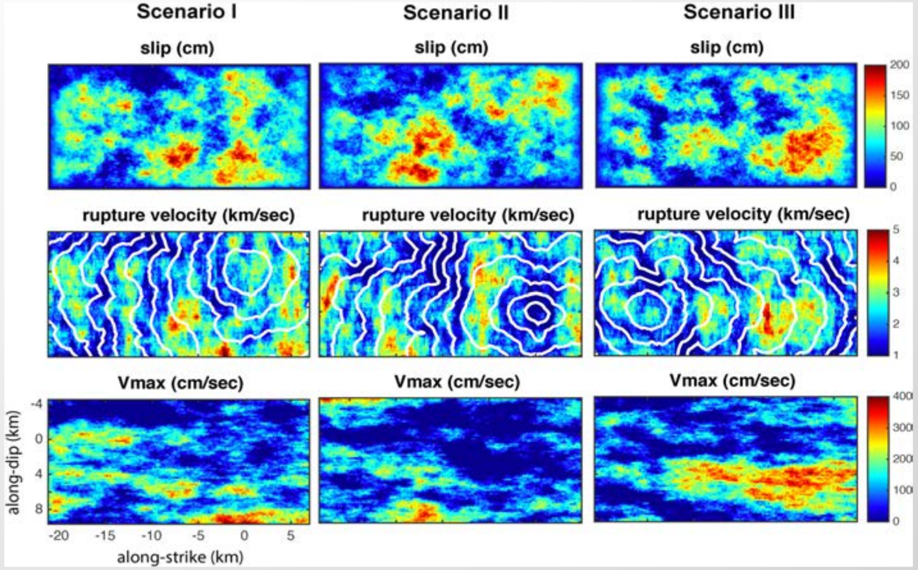
Dynamic source model database (360 5.5 < Mw < 7.0 events)
Dalguer & Mai 2012

2-point correlation structure extracted from the data base events
The diagonal blocks indicate the autocorrelation of each source parameter. off-diagonal blocks indicate the cross-correlation between source parameters.

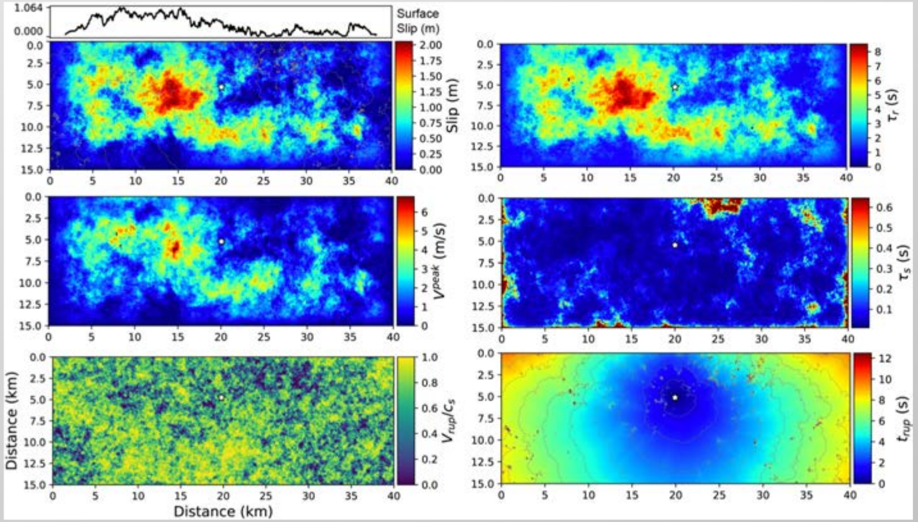
6/23/21

Pseudo-dynamic rupture scenarios

Song GJI, 2016



Savran and Olsen, GJI 2020



Conclusions

- Physics-based kinematic rupture models have improved the performance of deterministic BB ground motion modeling and simulations
- In addition to comparisons with the GMPEs, building response analysis should be used to develop new criteria for synthetic ground motion quality evaluation
- A coordinated effort is necessary for creating synthetic ground motion databases for specific earthquakes and regions that can be used in engineering applications