Some Insights on Imperial Valley from Kinematic Modeling and Validation

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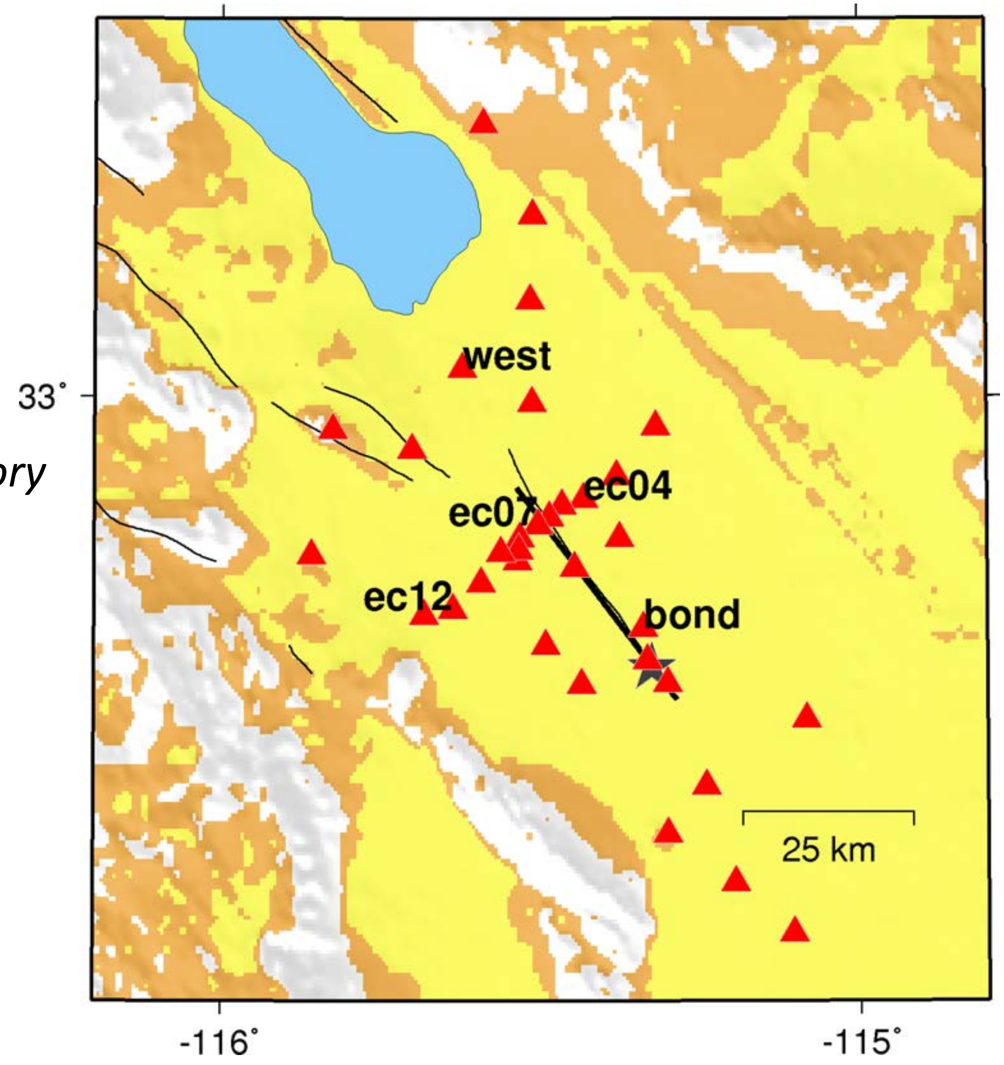

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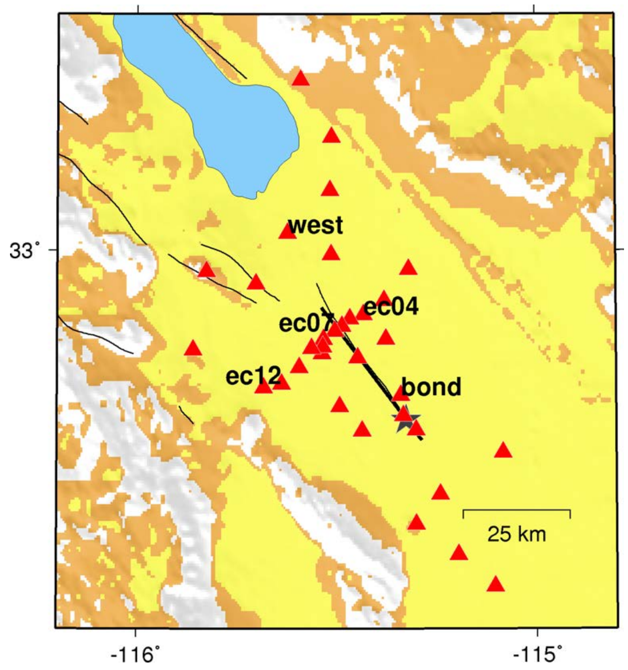
GP2010: Broadband Hybrid Simulation Approach

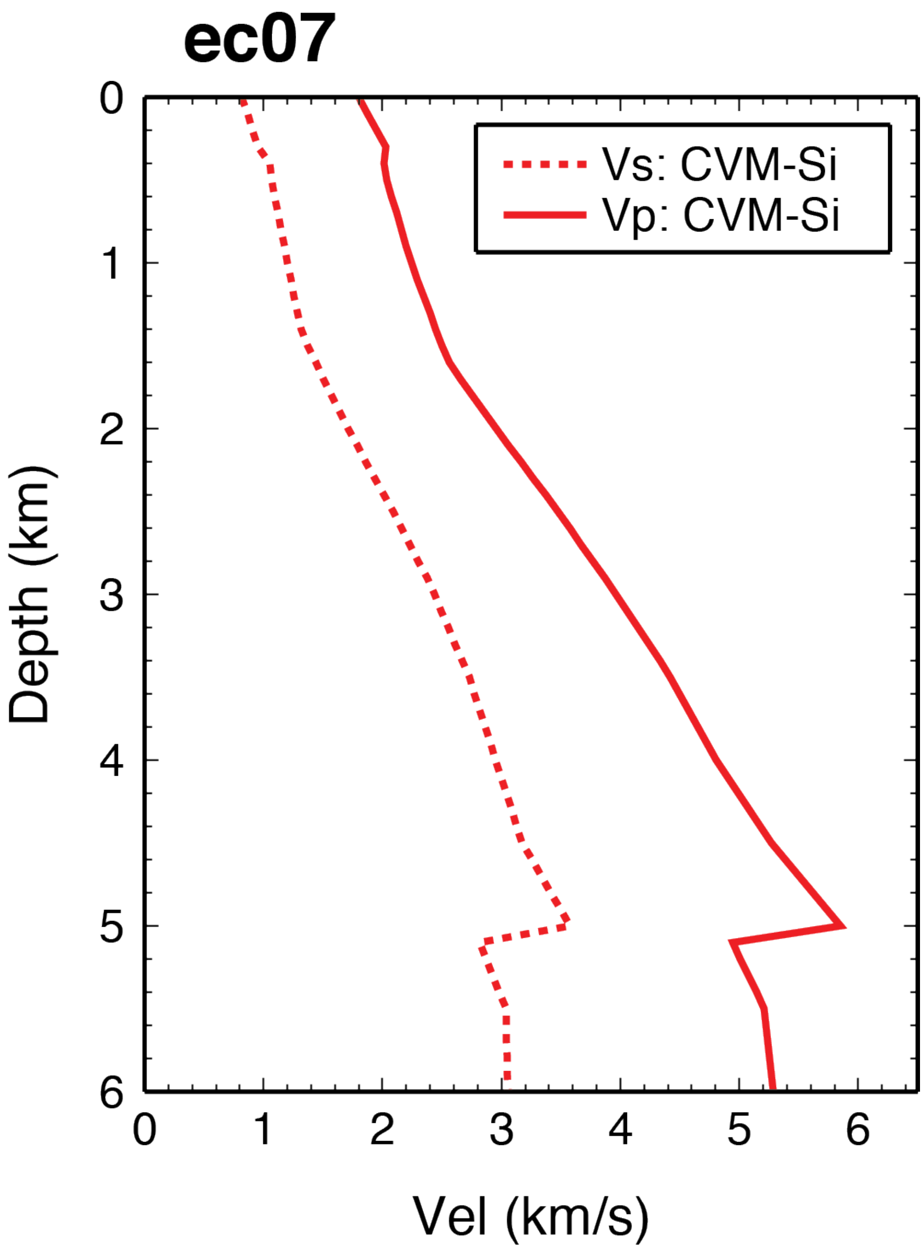
Graves and Pitarka (2010)

- Semi-deterministic approach at low frequencies (f < 1 Hz)
- Semi-stochastic approach at high frequencies (f > 1 Hz)
- Kinematic Rupture Generator
  - Unified scaling rules for rise time, rupture speed and corner frequency
  - Depth scaling of rise time (increase) and rupture speed (decrease) required to model shallow (< 5 km) moment release
- Incorporate 3D velocity structure for low frequency model
- Site-specific Vs30 correction factors

GP2010: Imperial Valley Velocity Structure

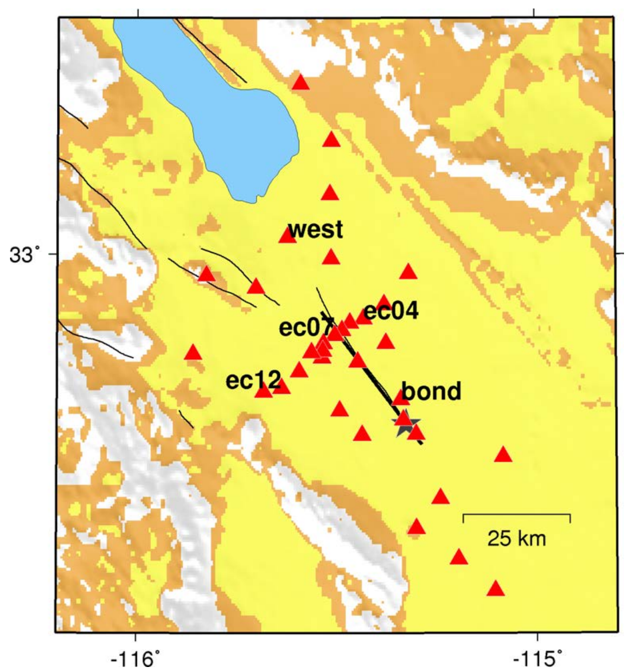
- SCEC Community Velocity Model (CVM-S4, CVM-Si) has unrealistically high Vs in Imperial Valley
- Greater than 800 m/s at ground surface

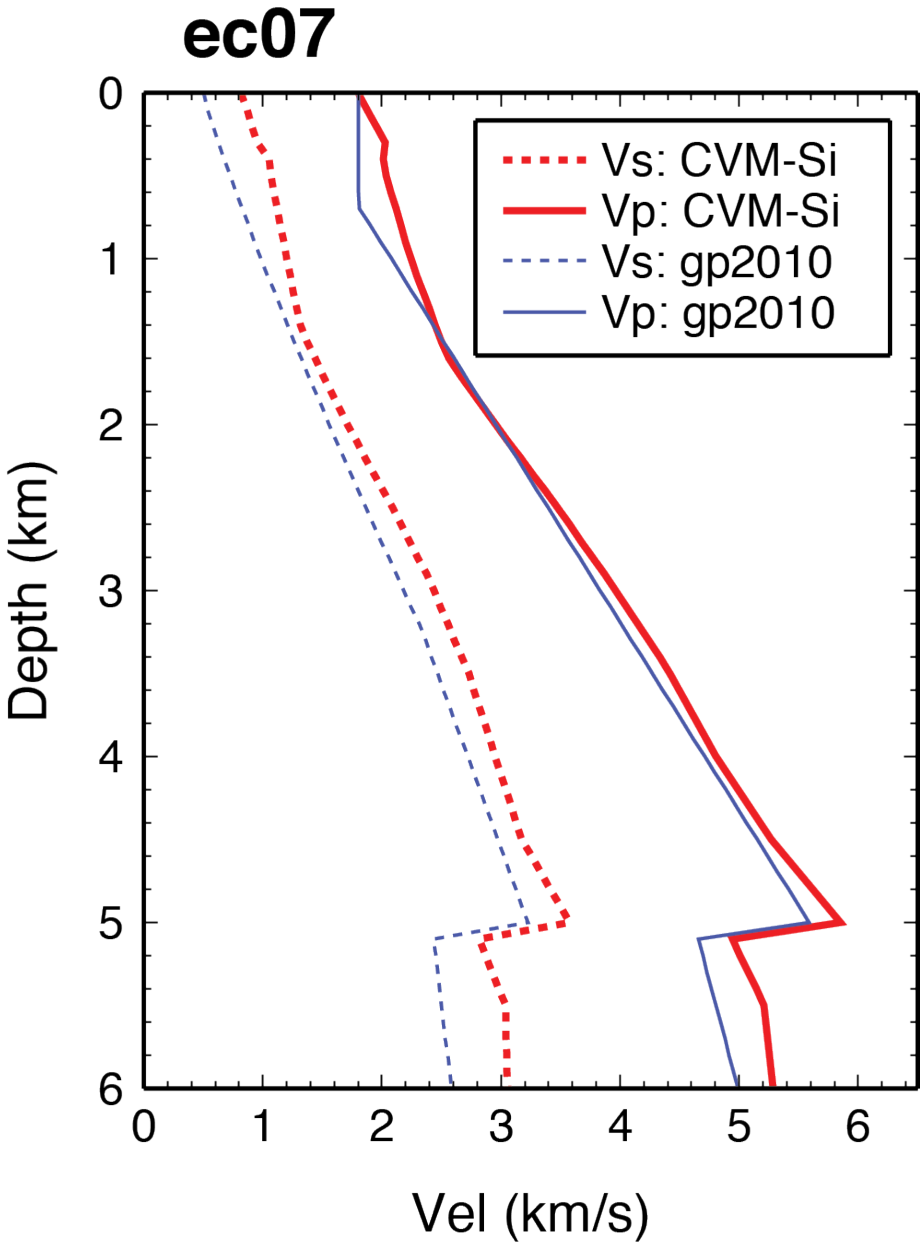




GP2010: Imperial Valley Velocity Structure

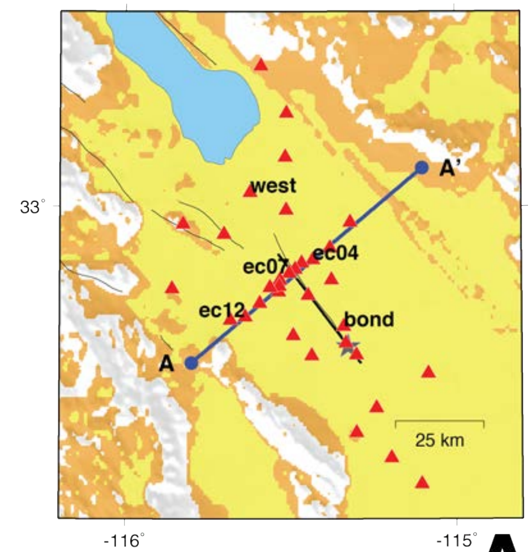
- Modify basin velocity structure to reduce surface Vs to 500 m/s (*most sites have Vs30 around 200 m/s*)
- Accomplished by changing rules embedded in code

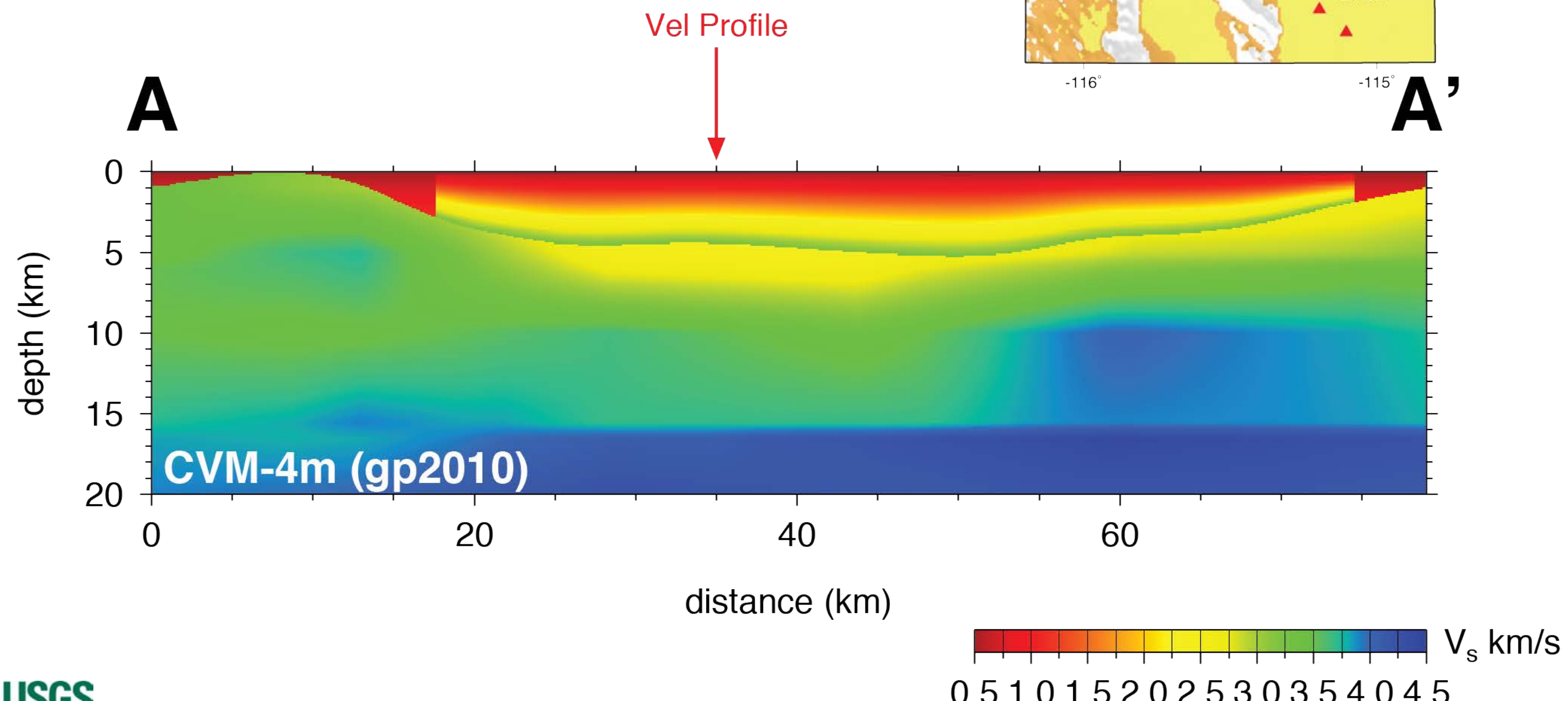




GP2010: Imperial Valley Velocity Structure

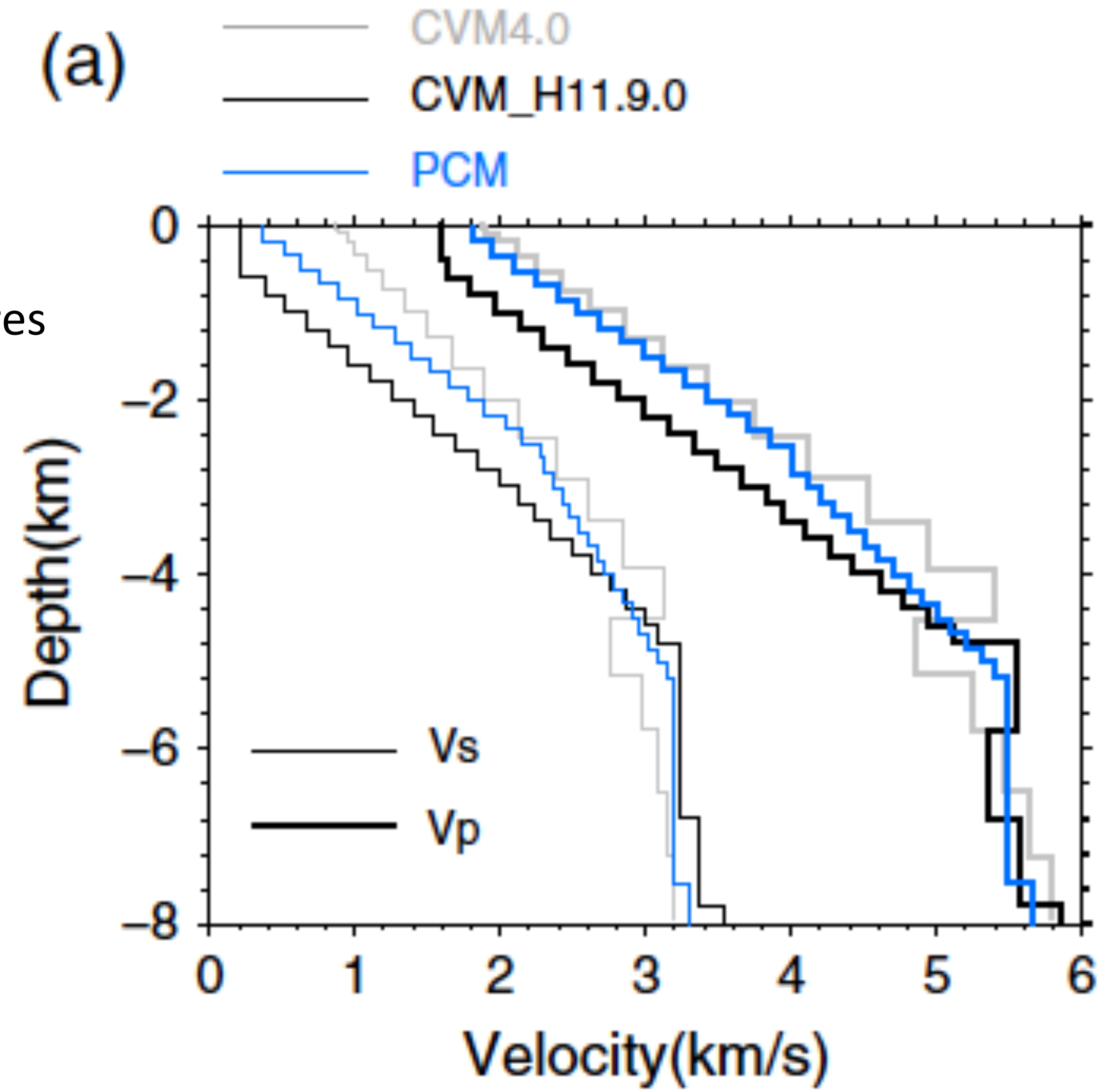
- Modified CVM-S structure still retains some "oddities"
  - Velocity reversal within basin
  - Zone of reduced velocities along basin margins





What about CVM-H?

- Wei et al (2013) examined various 1D velocity structures for Brawley events
- CVM-S: **too fast**
- CVM-H: **too slow**
- PCM: **just right** (*similar to GP2010*)



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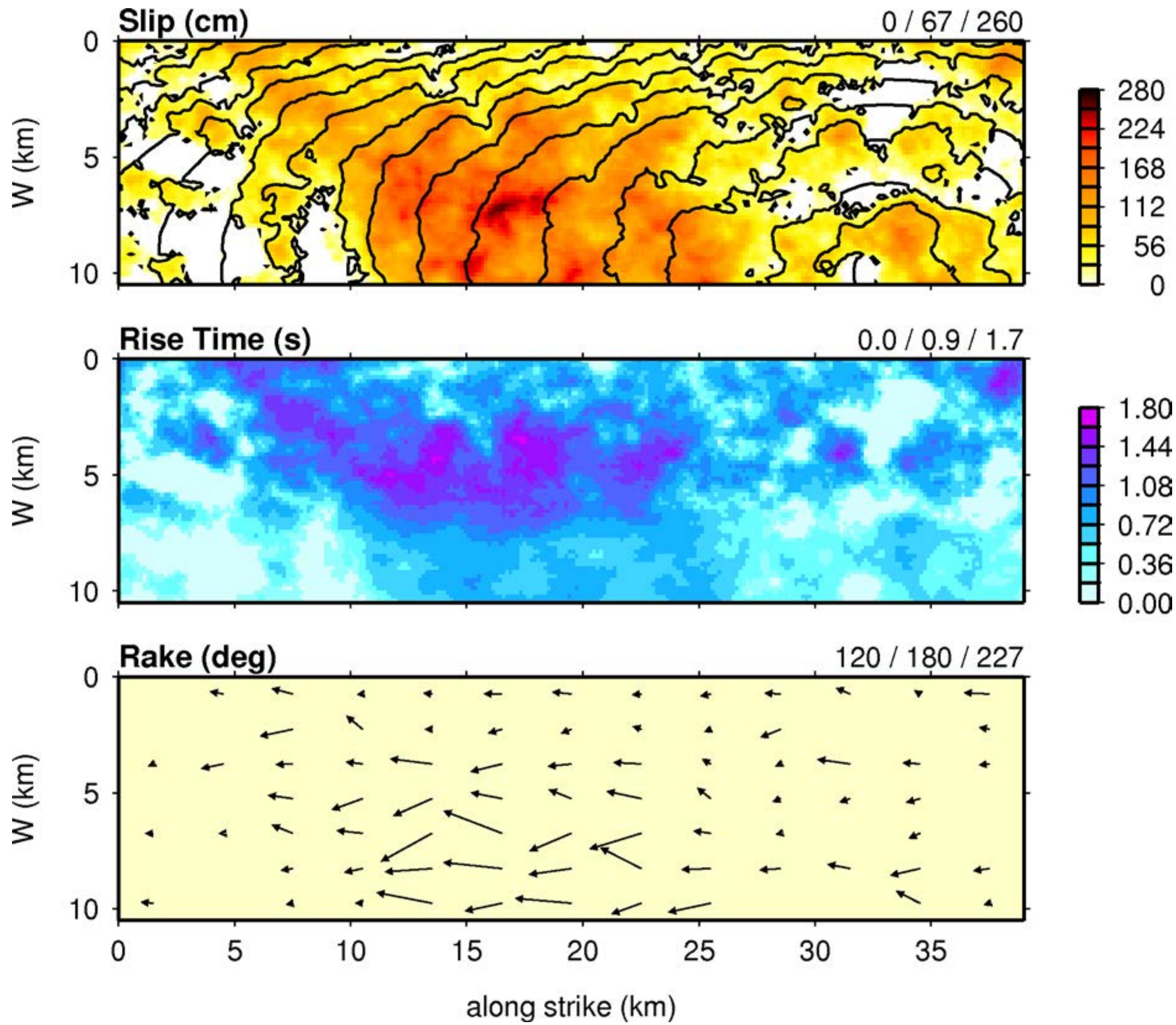
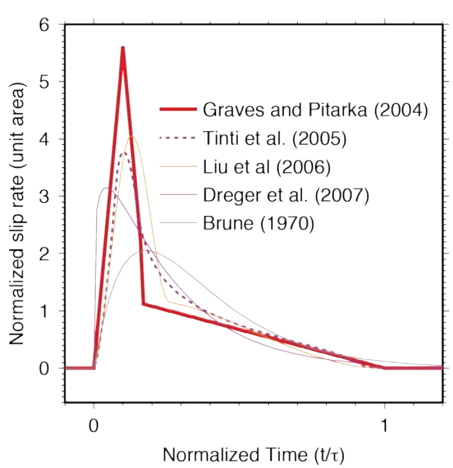
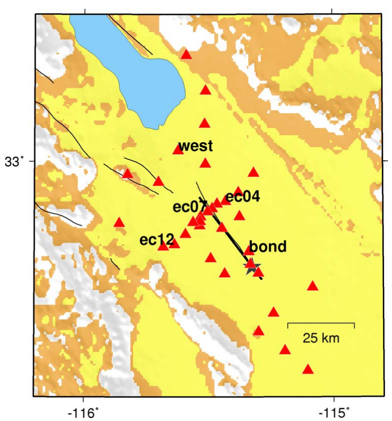
GP2010: Kinematic Rupture Characterization

- Slip distribution modified from Hartzell and Heaton (1982) to have K^{-2} falloff
- Rupture time scales with local Vs, slip and depth
- Rise time scales with sqrt(slip) and depth
- Rake is 180° with random perturbations

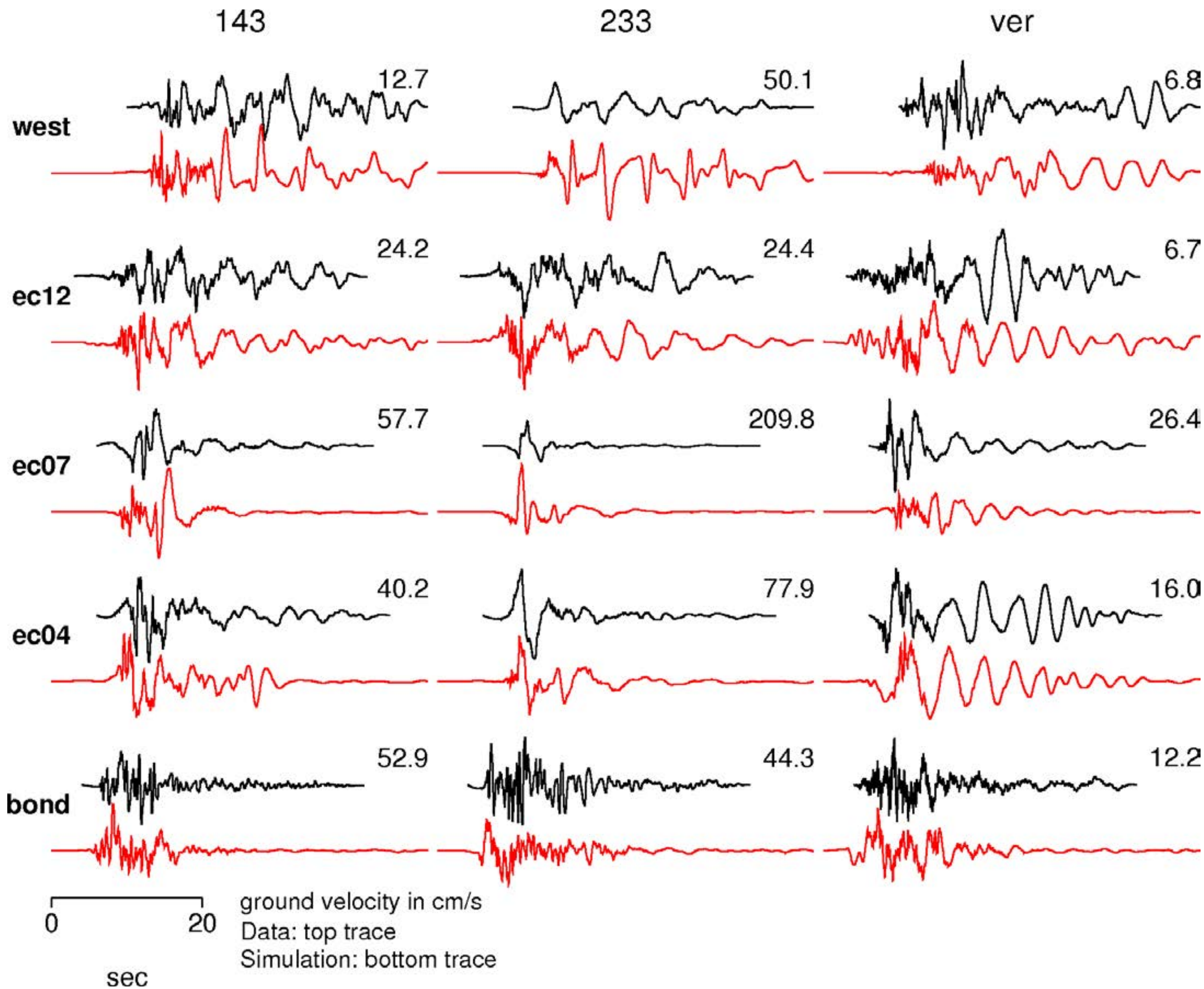




GP2010: Broadband Velocity Waveforms



- Good match to waveform character
- Strong rupture directivity
- Strong basin response



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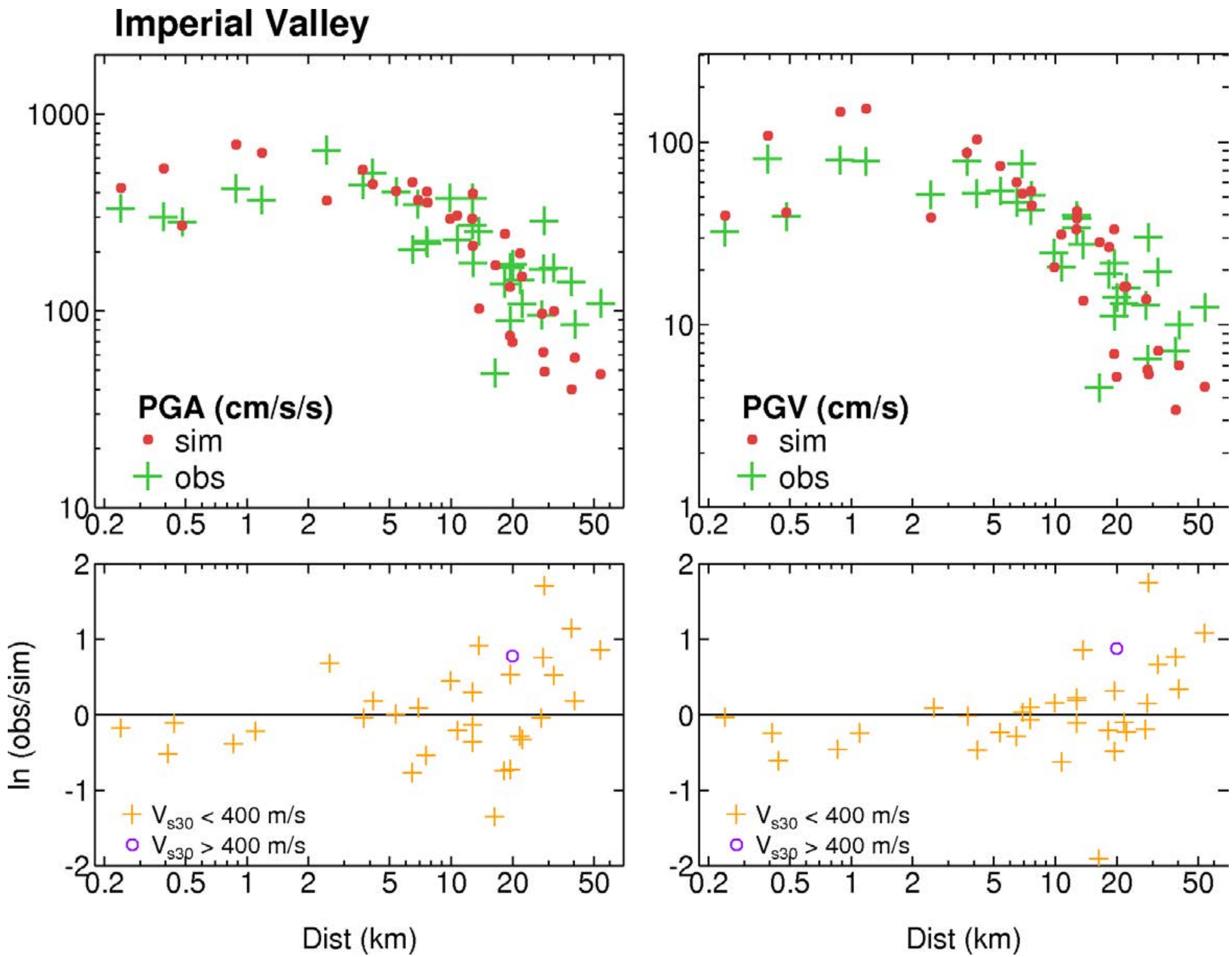
GP2010: Peak Ground Acceleration and Velocity



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GP2010: Spectral Acceleration Goodness of Fit

Residual:

$$r_j(T_i) = \ln[O_j(T_i)/S_j(T_i)],$$

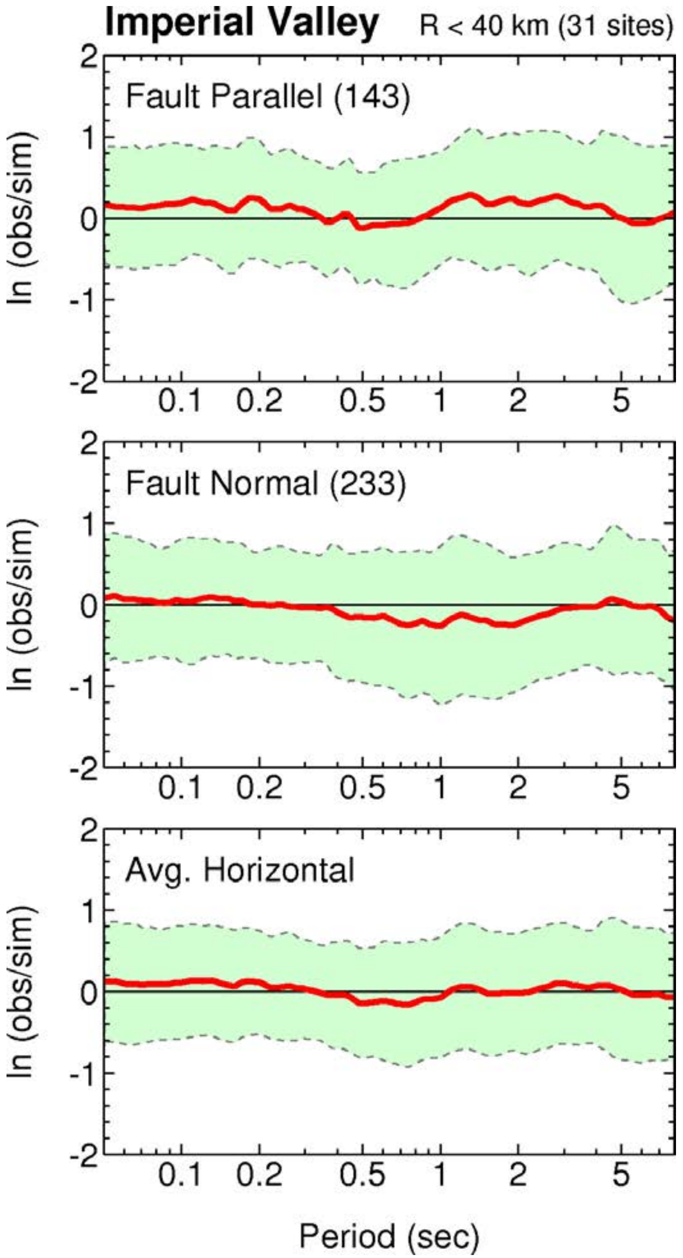
Bias:

$$B(T_i) = \frac{1}{N} \sum_{j=1,N} r_j(T_i),$$

Standard deviation:

$$\sigma(T_i) = \left\{ \frac{1}{N} \sum_{j=1,N} [r_j(T_i) - B(T_i)]^2 \right\}^{1/2}$$

- Bias is centered near zero: good
- Sigma near 0.8 indicates large scatter in residuals



Recent Refinements to the GP Approach

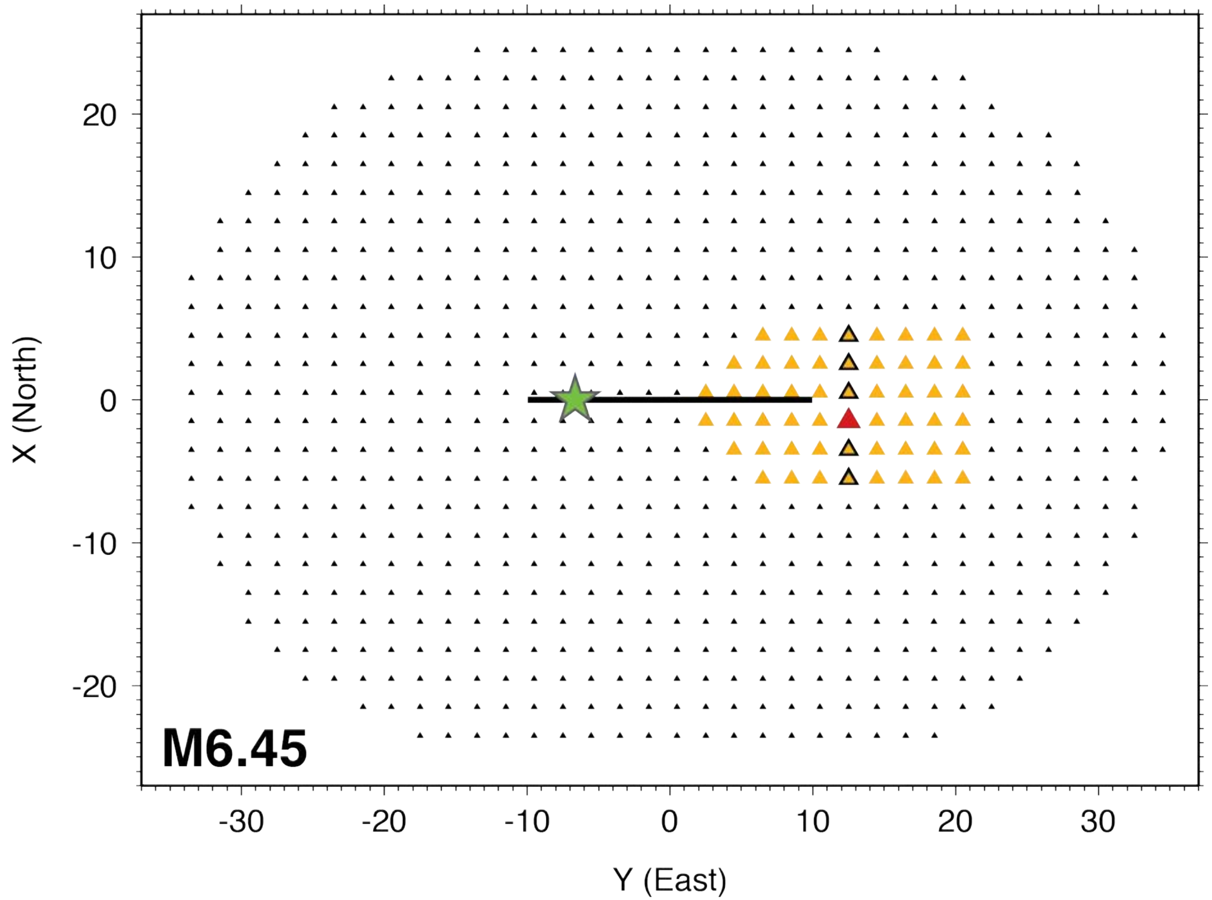
GP15.4 (Graves and Pitarka, 2016): Incorporate features that lead to homogenization of radiation pattern effects and saturation of amplitude levels as the deterministic approach is pushed to higher frequencies.

- Relax correlation structure among slip, rupture speed, and rise time
- Incorporate geometric complexities in fault surface
- Add stochastic 3D perturbations to velocity structure
- Incorporate near-fault low velocity region: “damage zone”

Simulation Model

3D finite-difference computation using grid step of 25 meters.

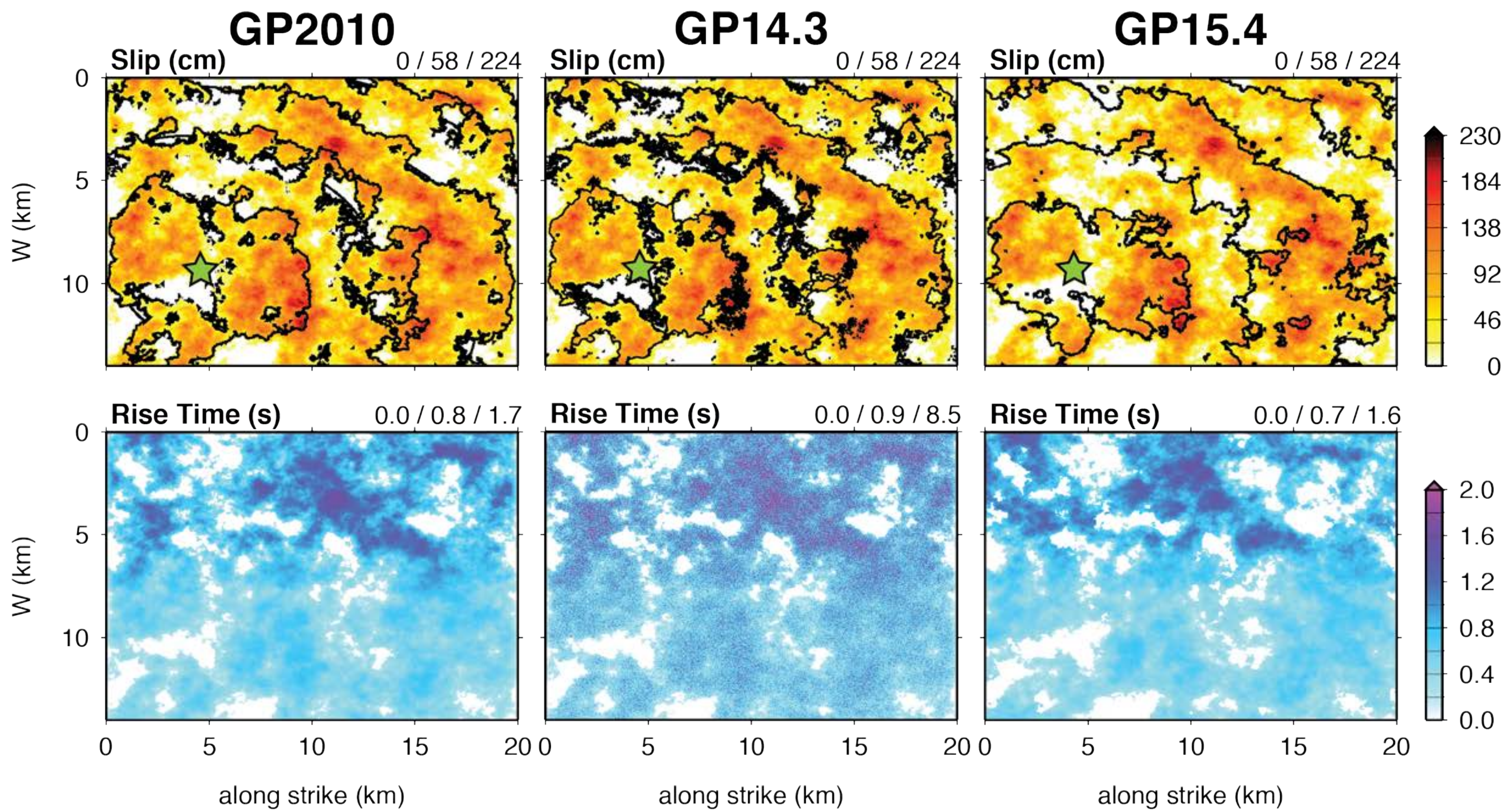
Upper frequency limit is about 8 Hz.



Not exact representation of Imperial Valley, but I wanted to get a sense of statistical properties of ground motions.

Can you spot the differences?

Slip distribution is same in all models



Refinements are subtle in appearance, but lead to significant differences in radiated ground motions.

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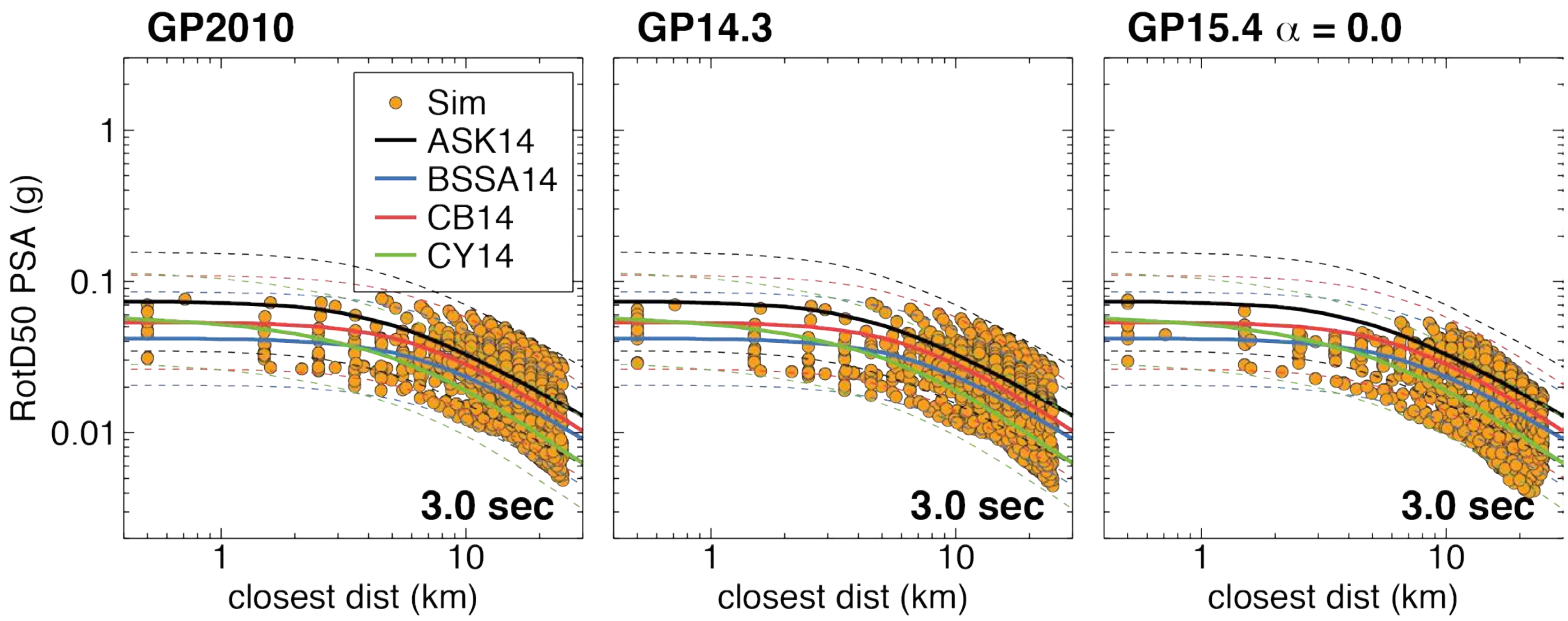
Can you spot the differences?



At low frequencies, all models produce similar ground motion levels

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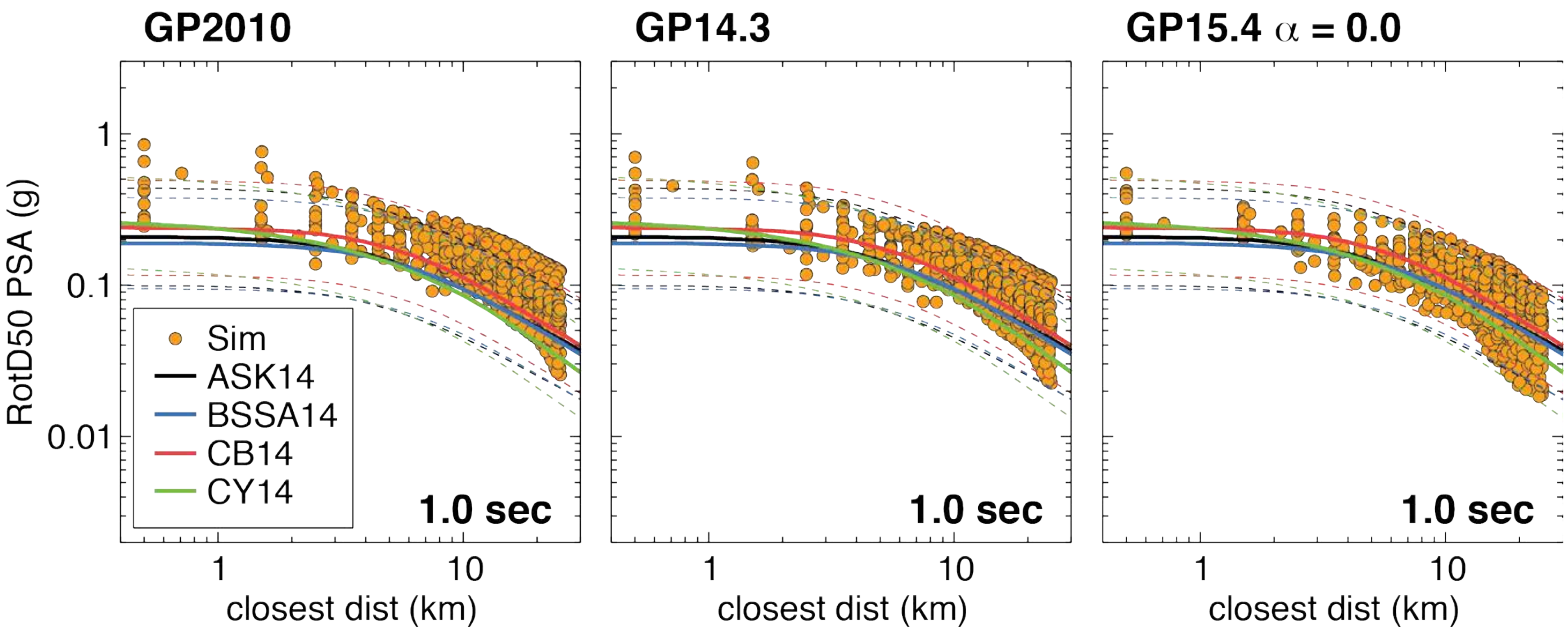
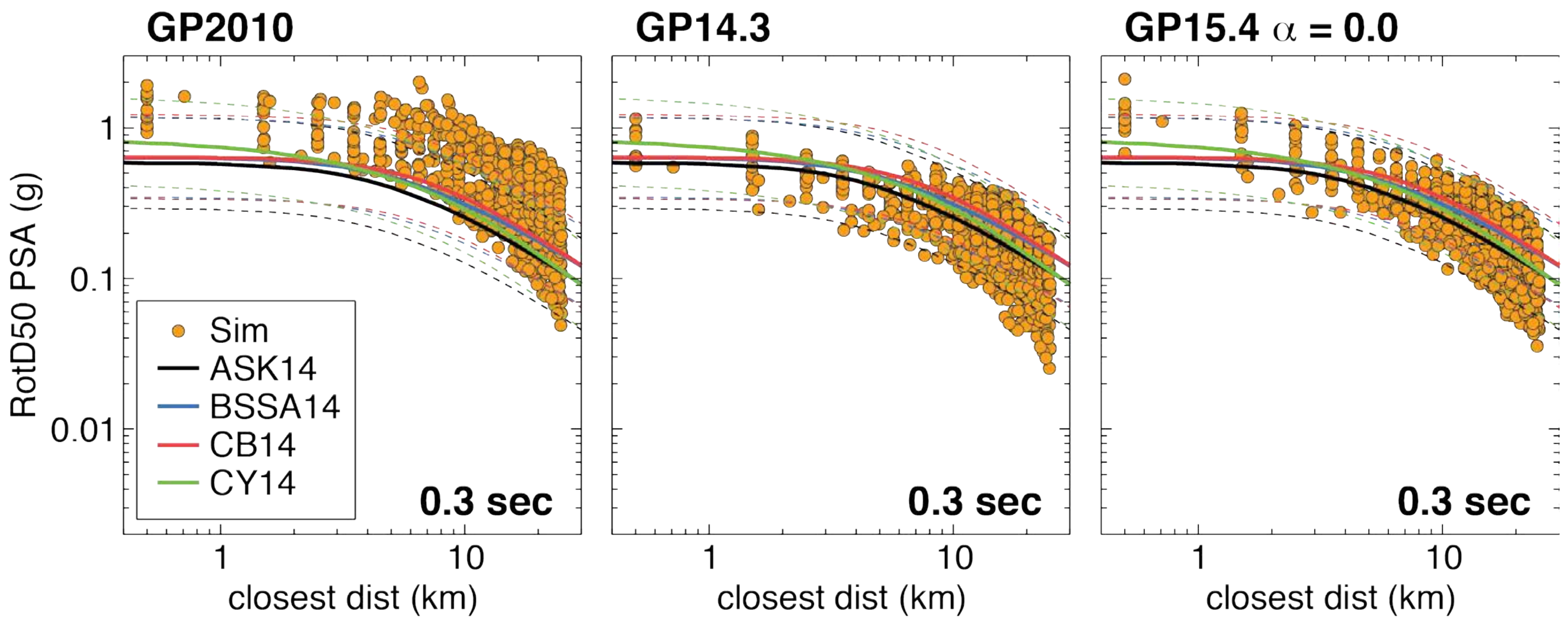
Can you spot the differences?



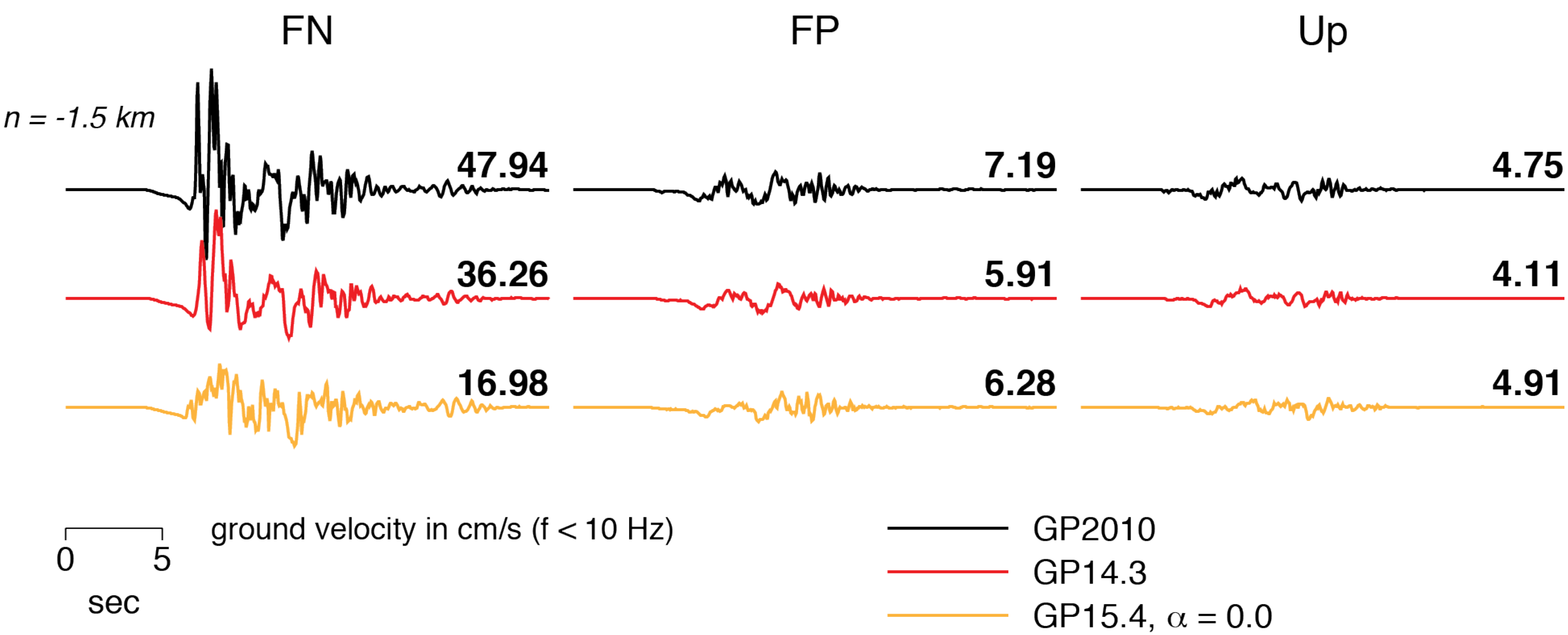
Moving to higher frequencies, the coherence in GP2010 begins to produce elevated ground motion levels

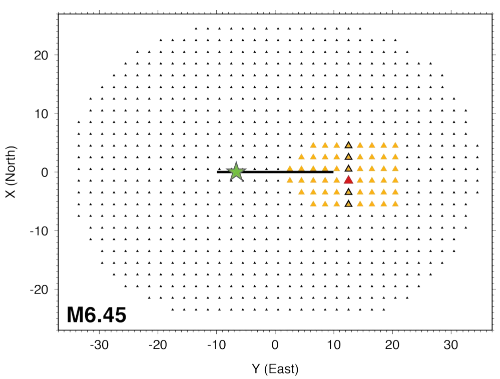
Can you spot the differences?



At even higher frequencies, this trend only gets worse

Can you spot the differences?





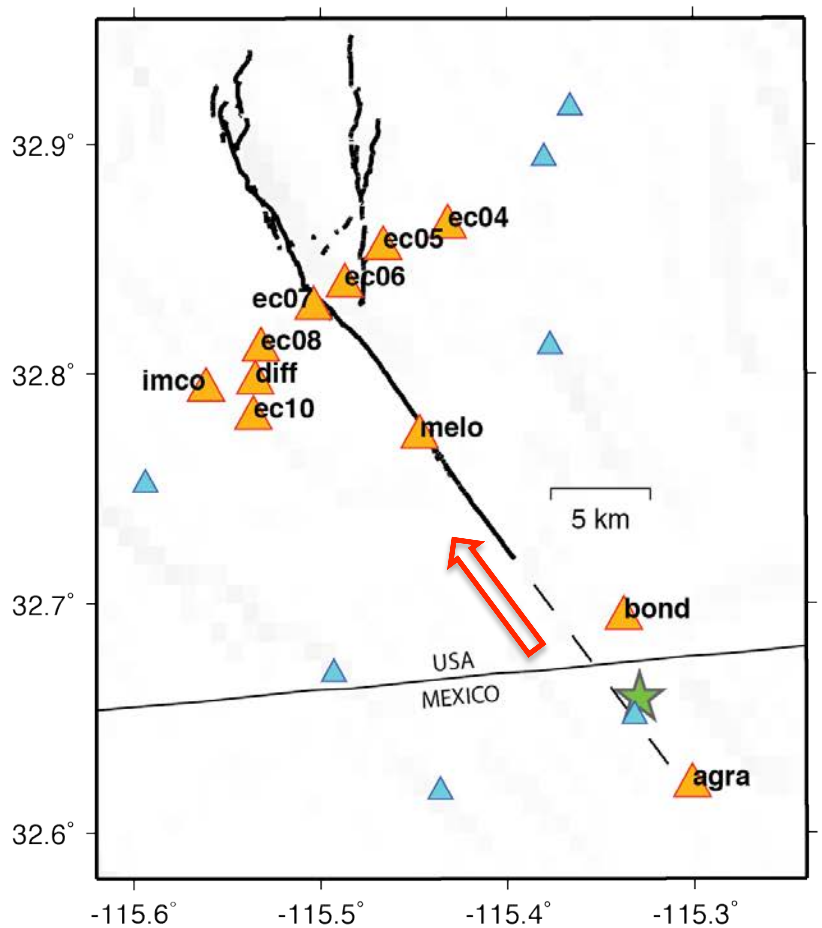
Strong coherency in GP2010 rupture leads to very strong rupture directivity effects (FN/FP ≈ 6, too strong?)

IV79: Finite-fault Rupture Effects

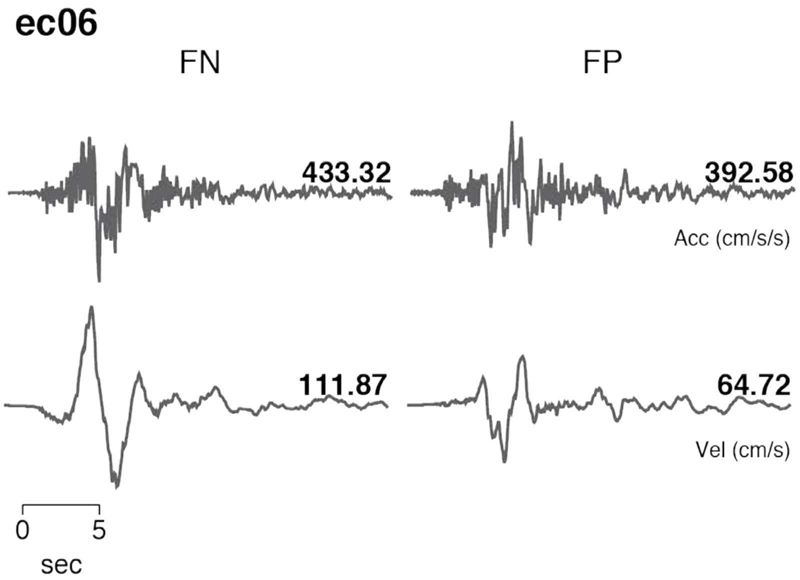
Rupture directivity can lead to strong pulse-like ground velocity motions at lower frequencies

Strong polarization onto **Fault Normal** component

a)



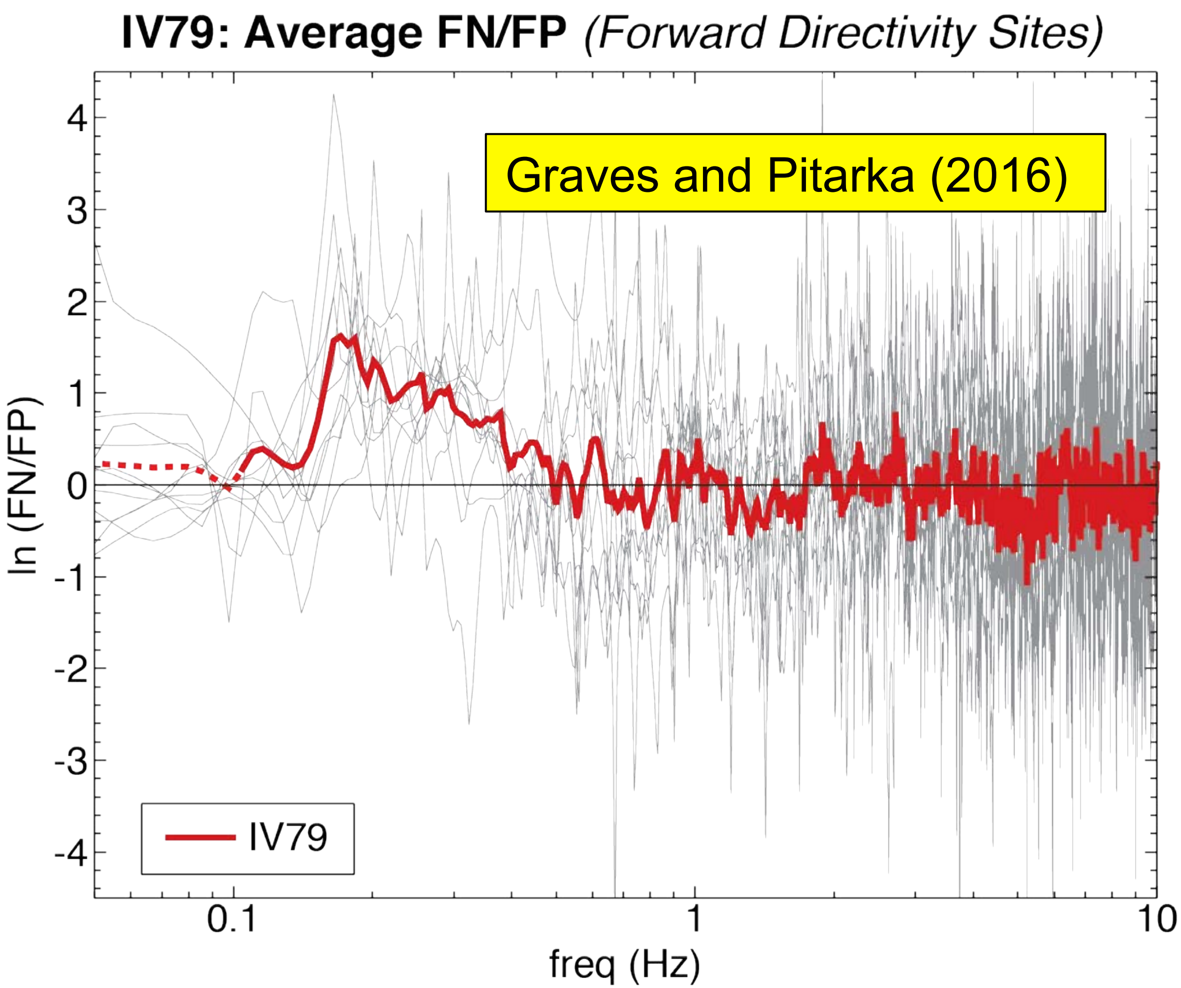
Imperial Valley 1979



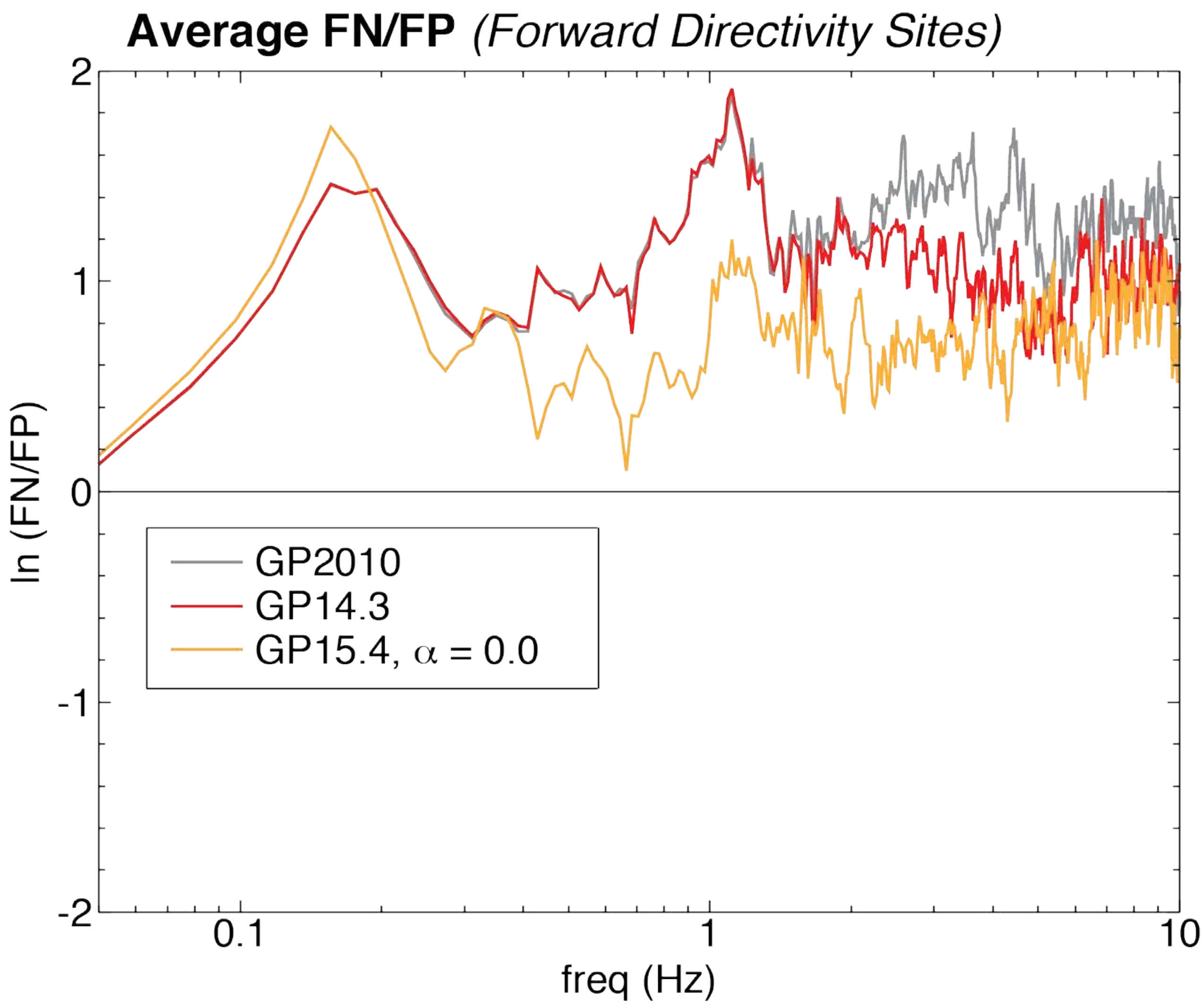
IV79: Finite-fault Rupture Effects

Strong forward directivity leads to **Fault Normal** > **Fault Parallel** for frequencies less than about 1 Hz

Fault Normal ≈ Fault Parallel for f > 1 Hz



How do simulations perform?



Reduced correlations in GP15.4 lead to decrease in radiation coherence of higher frequency motions

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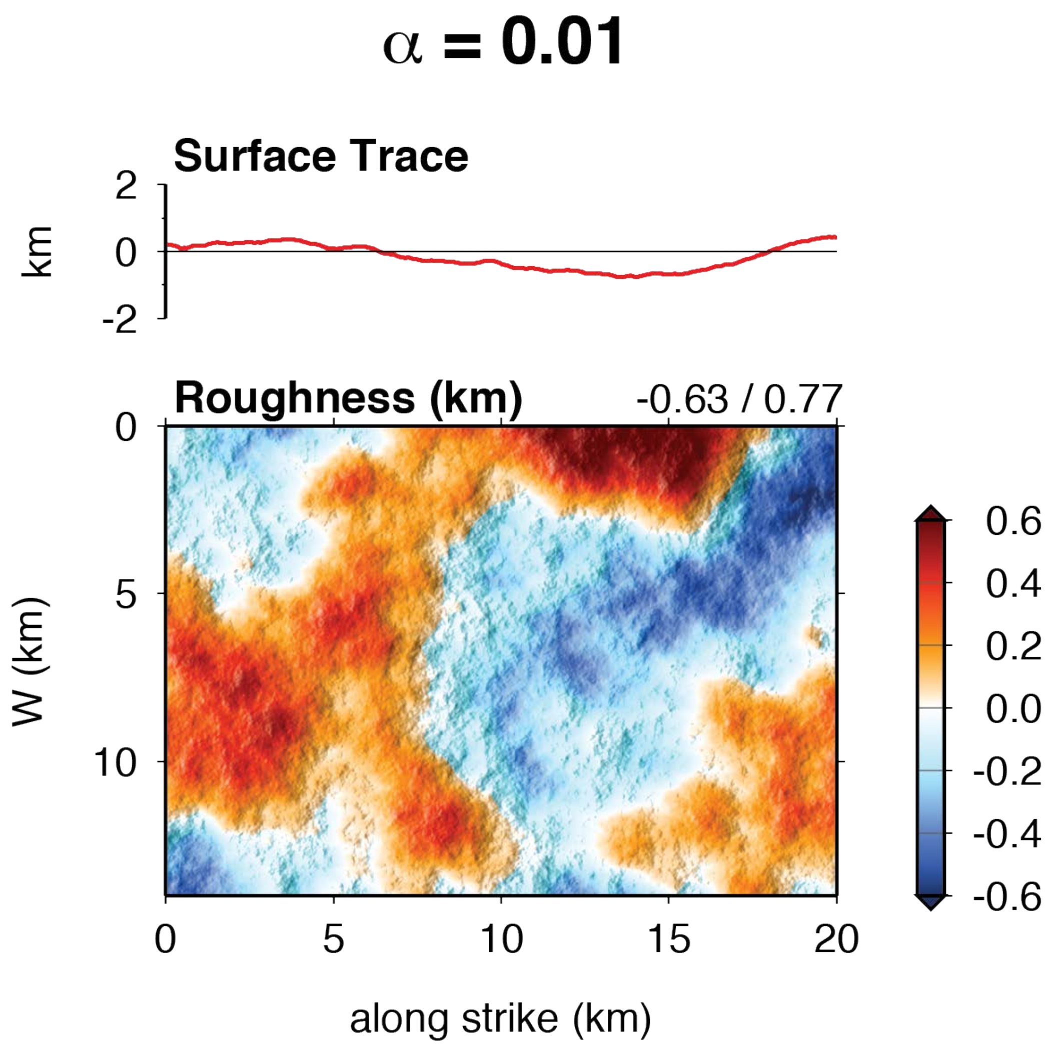
Rough Fault Parameterization

Roughness is stochastic, but follows a power-law distribution (e.g. Shi and Day, 2013).

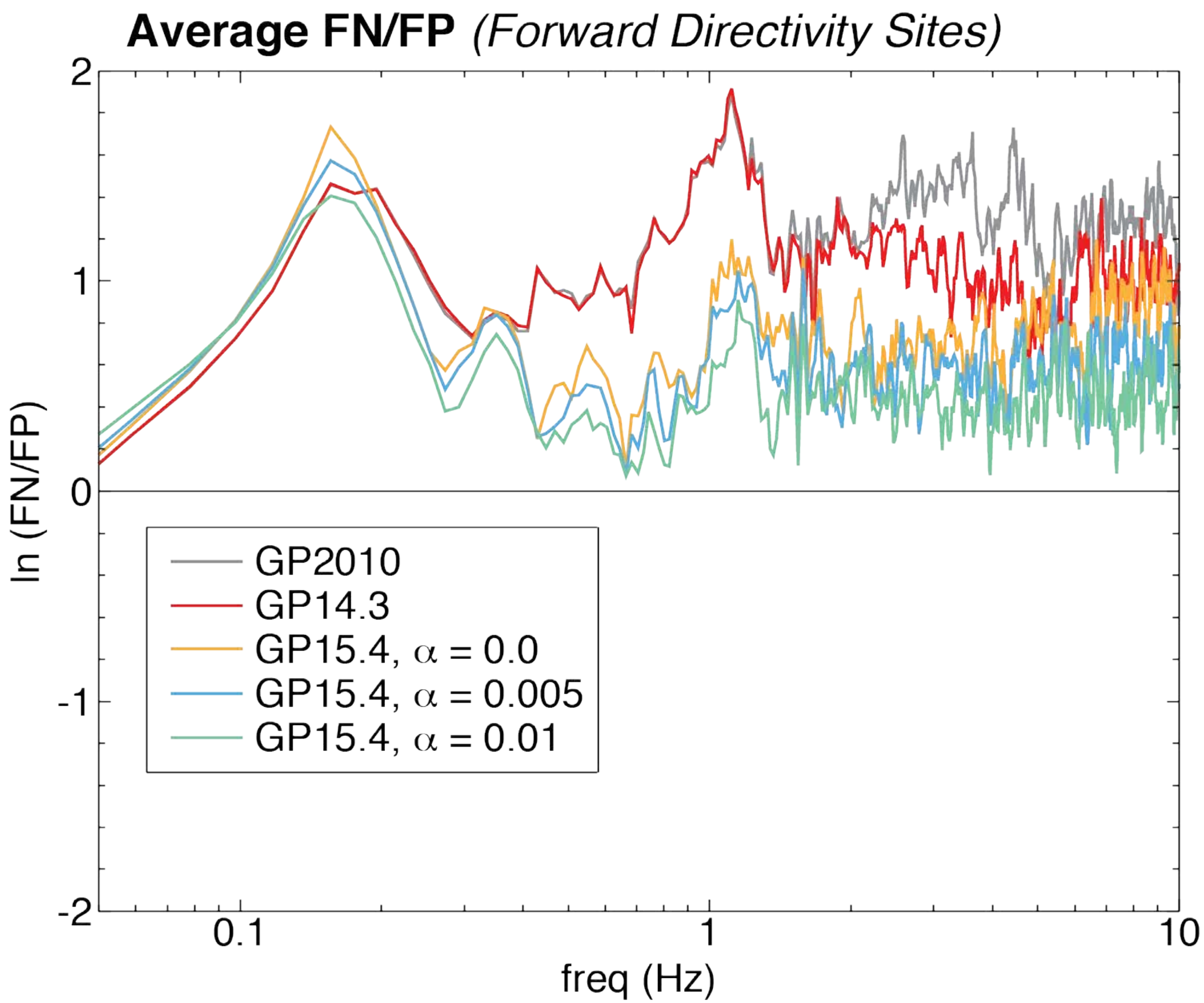
Alpha parameter controls the height of the deviations and is related to fault length:

$$h_{rms} = \alpha L$$

Estimates of α for real faults range from 0.001 to 0.01.



Now include rough faults



Roughness leads to further decrease in radiation coherence of higher frequency motions

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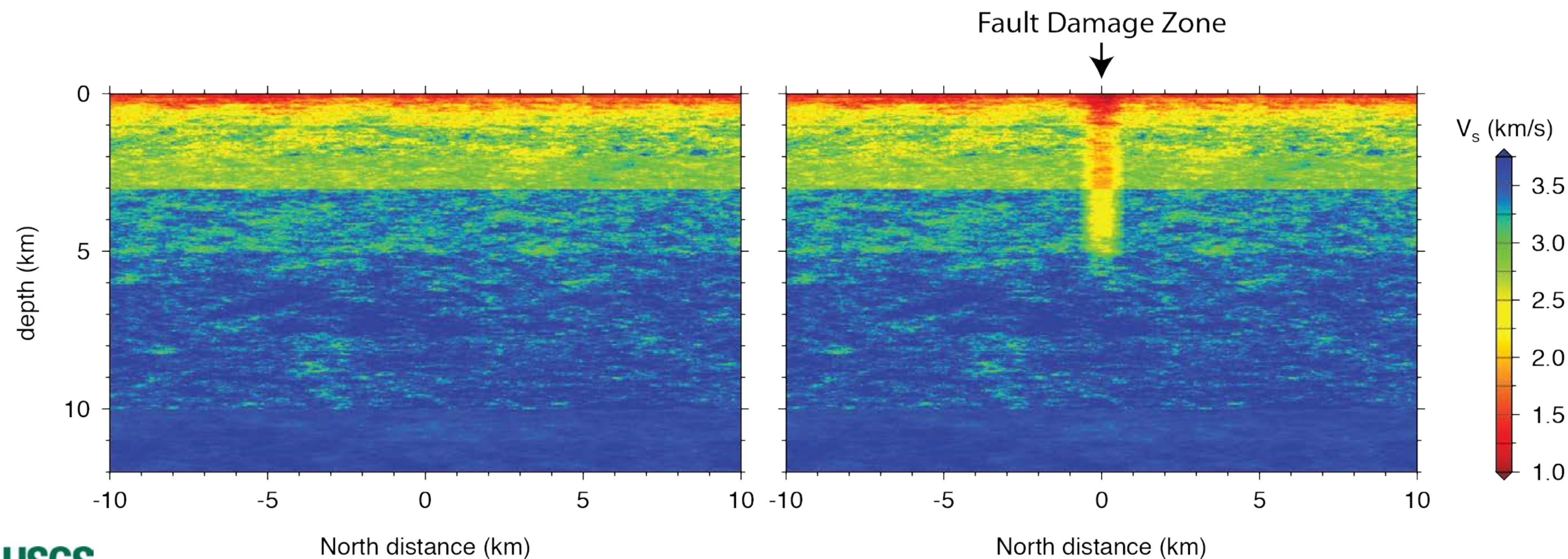
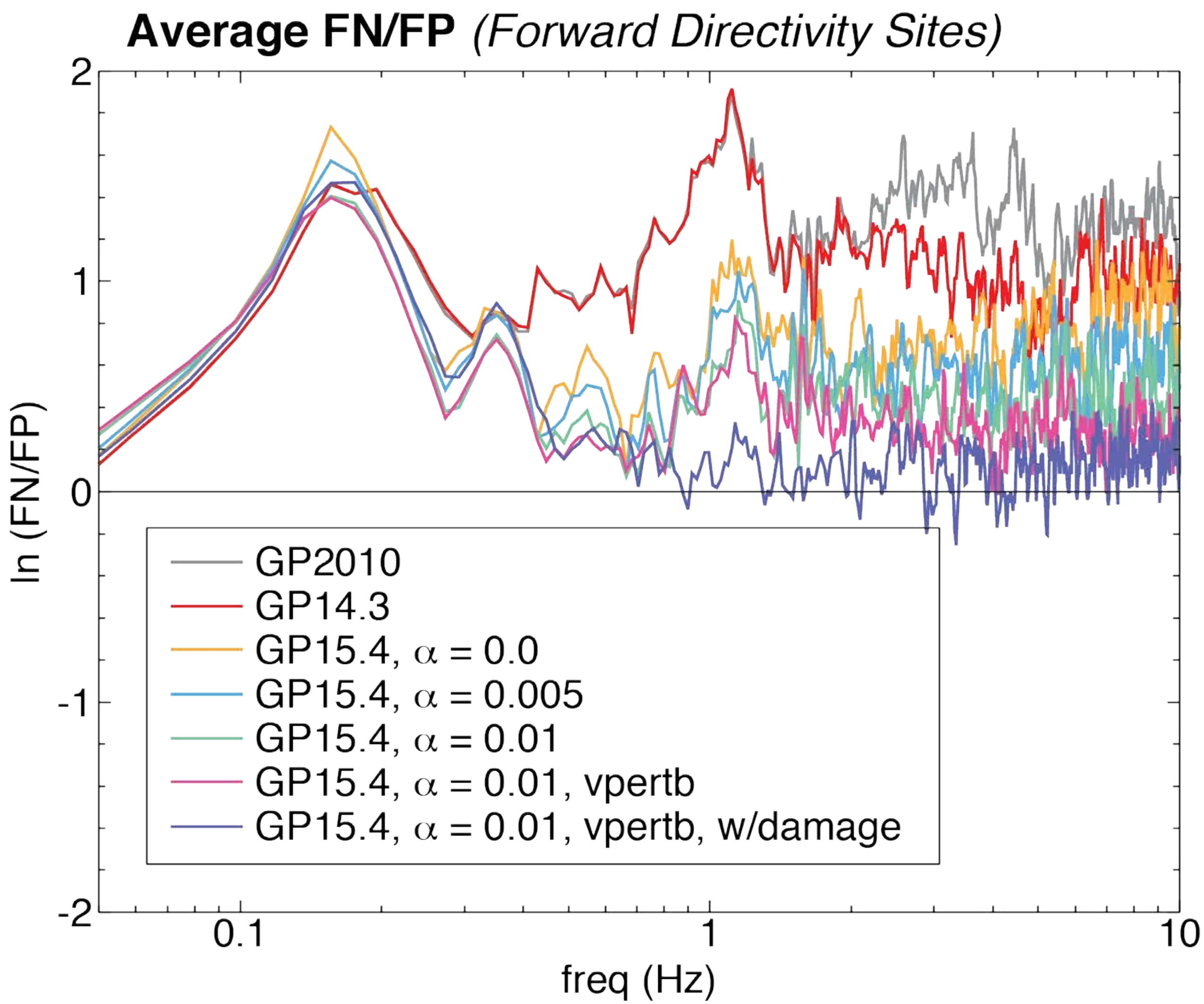
Perturbations to Seismic Velocity Structure

- Following Hartzell et al. (2010), 3D stochastic perturbations are added to the background velocity structure.
- Perturbations follow a von Karman correlation function with correlation lengths ranging from 5-10 km horizontally and 1-2 km vertically. Standard deviations range from 1-10%.
- Surrounding the fault in the upper 5 km we apply a further reduction in seismic velocities to replicate the "damage zone" found along many active fault structures (e.g., Cochran et al, 2009).



Now include velocity perturbations



Velocity perturbations lead to further decrease in radiation coherence of higher frequency motions

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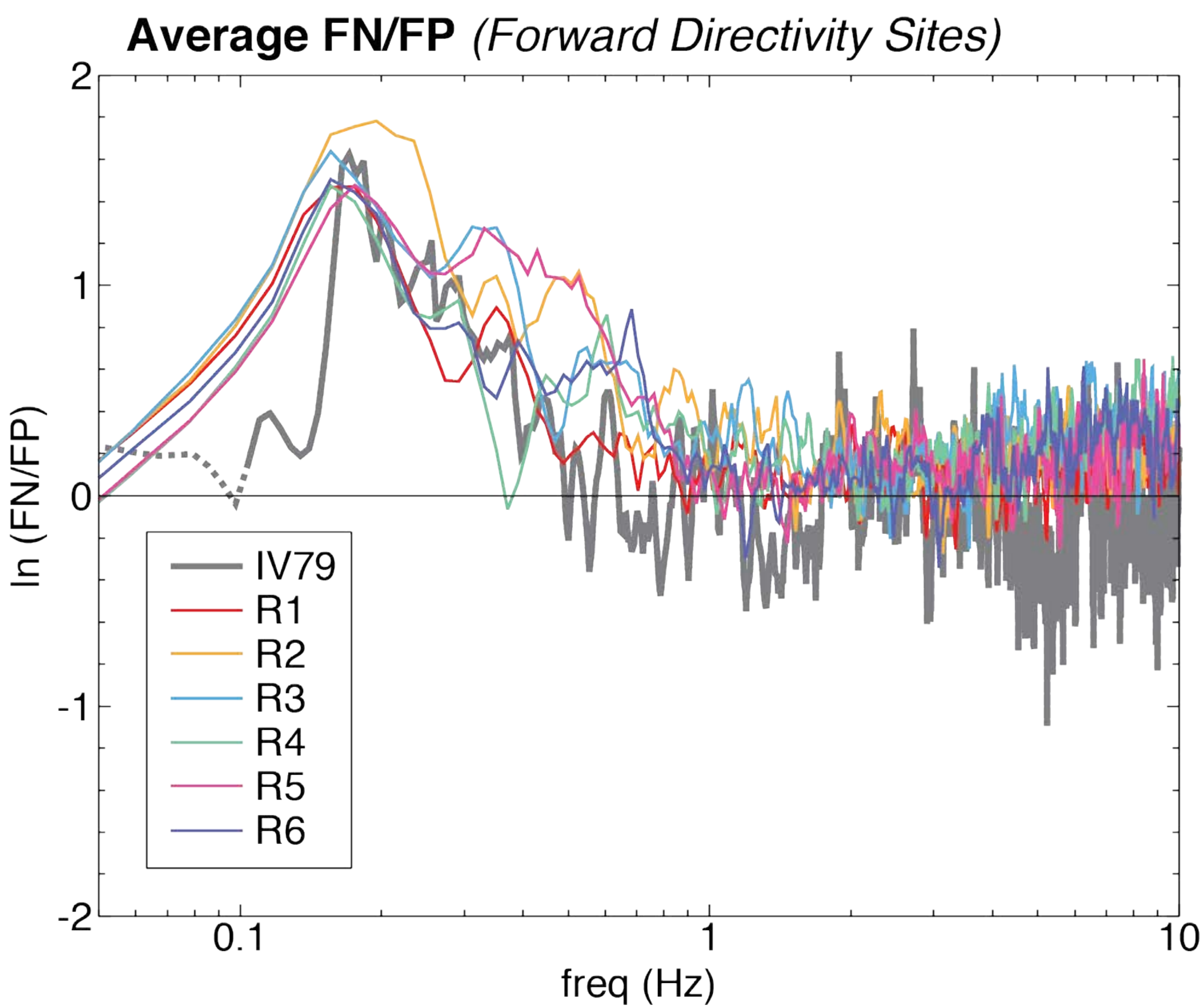
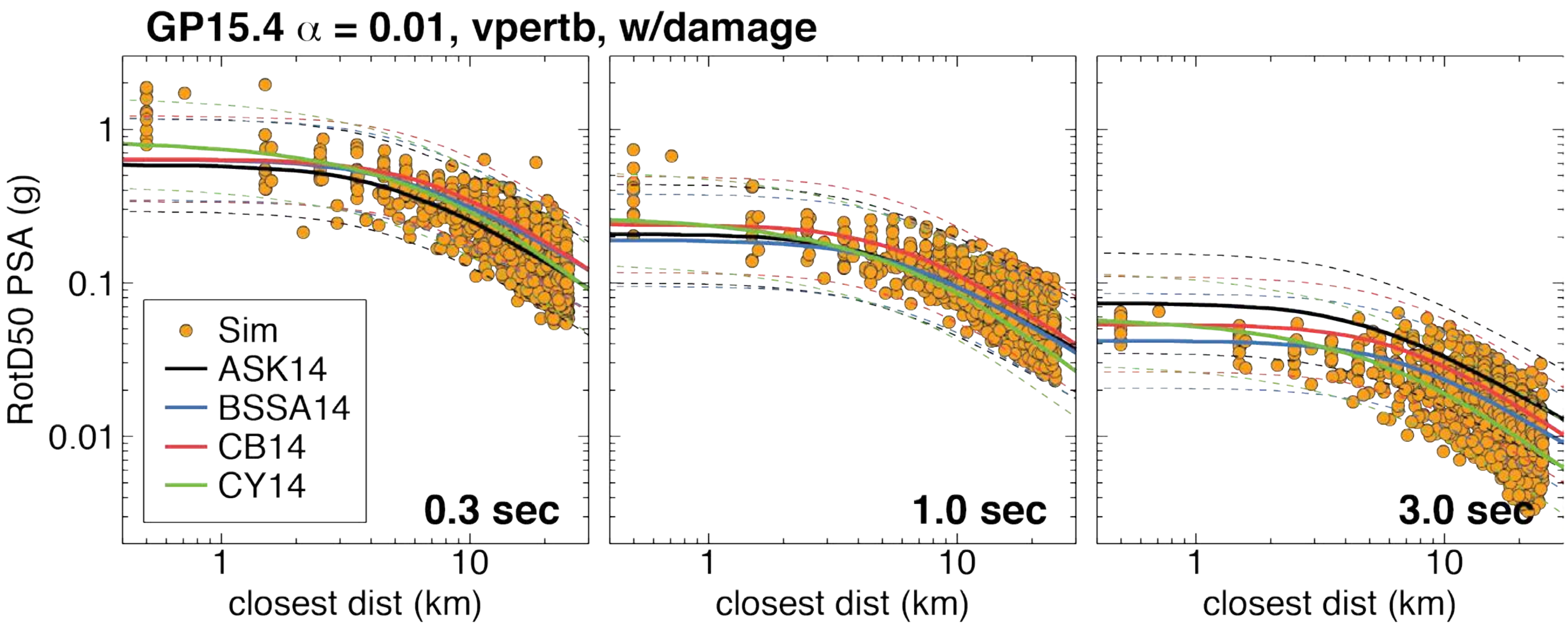
Multiple realizations nicely replicate IV79 behavior

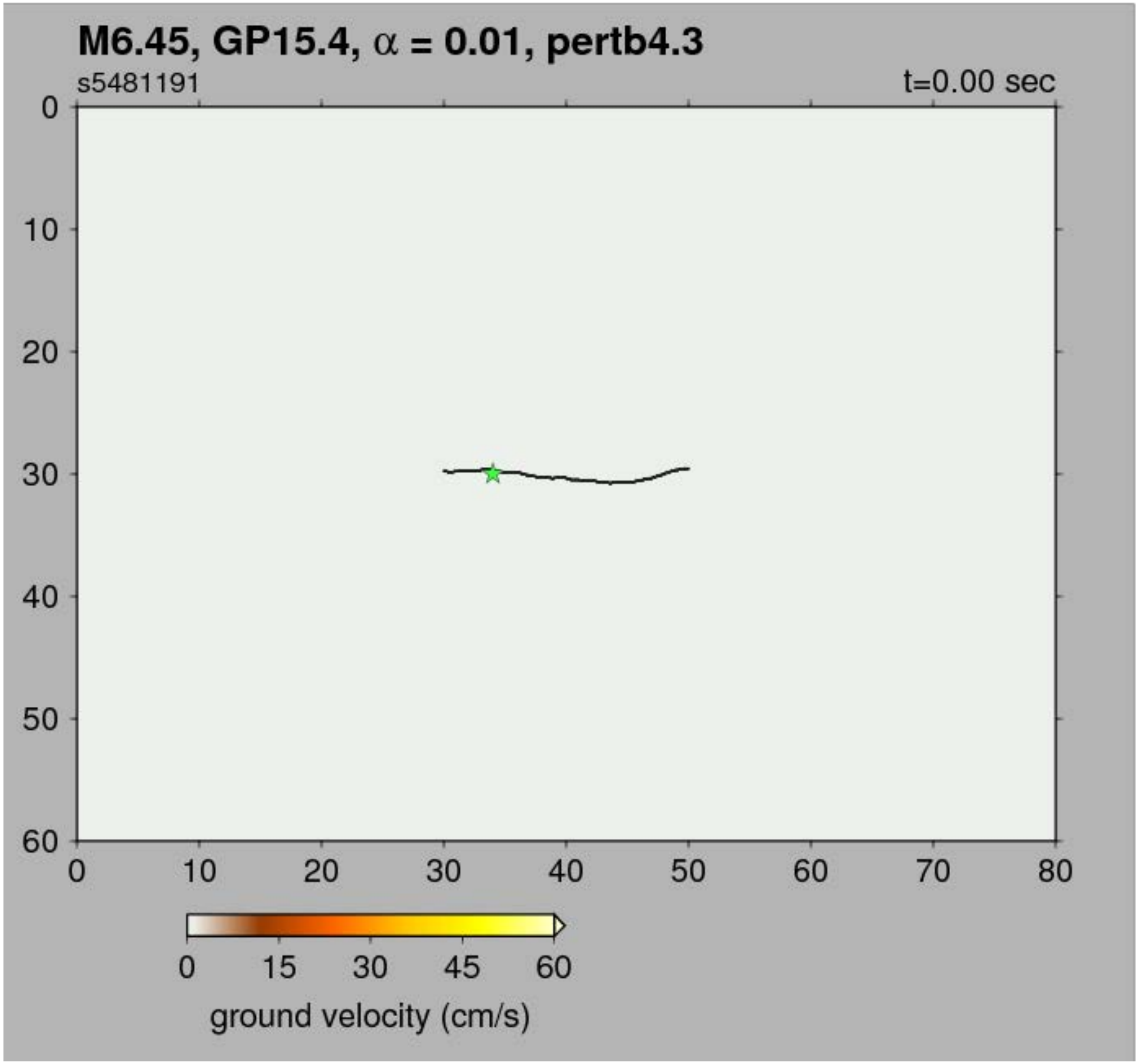


And match expected ground motion levels



Drawback: Computations are intensive (~24 hours on 1600 CPUs)
I have some ideas how to speed things up though …

Animation with all complexities included



Summary

- **Imperial Valley provides key constraints on near fault ground motion behavior**
  - Rupture directivity: pulse-like near fault motions, FN > FP at low frequencies
  - Homogenization of radiation pattern at high frequencies (f > 1 Hz, FN ≈ FP)
  - Saturation of high frequency ground motion levels
- **Kinematic modeling can reproduce many features of Imperial Valley observations**
  - Waveform character
  - PGA/PGV vs. distance
  - Averaged spectral acceleration levels
  - Caveat: some concerns regarding current 3D CVM structure
- **Matching observed frequency dependence requires short-length scale features in rupture and seismic velocity structure**
  - Correlation among rupture parameters (slip, rupture speed, slip-rate, etc)
  - Fault roughness
  - Stochastic perturbations to 3D velocity structure
  - Effects of near fault “damage zone” (upper 5 km)
    - Reduced rupture speed
    - Increased rise time
    - Reduced seismic velocity and lower Q