Recent Developments in Kinematic Rupture Modeling

2024 PEER - LBNL Workshop

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**Ideas & guidance from Arben Pitarka, Art Frankel, and many others*

Jan. 18, 2024

Presentation Outline

- Basics of kinematic rupture characterization
- Slip characterization including shallow fault effects → Hybrid model with long-wavelength shallow slip and short-wavelength deep slip
- Guidance on subfault size given maximum simulation frequency → $H_{max} = \alpha / f_{max}$

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Dynamic Rupture Model

Describes underlying physical features of the problem, e.g., state of stress, strength of rocks, frictional properties, etc. Rupture occurs spontaneously as frictional strength is surpassed by imposed stress.

Kinematic Rupture Model

Describes movement of the fault but does not directly address the underlying physics. Fault rupture is simply prescribed by the slip time function that occurs at each point on the fault.

Kinematic Rupture Basics

- Slip(**x**,*t*) across finite-fault

  Fault location, dimensions and geometry

  Seismic moment and hypocenter

  Rules for generating slip(**x**,*t*)

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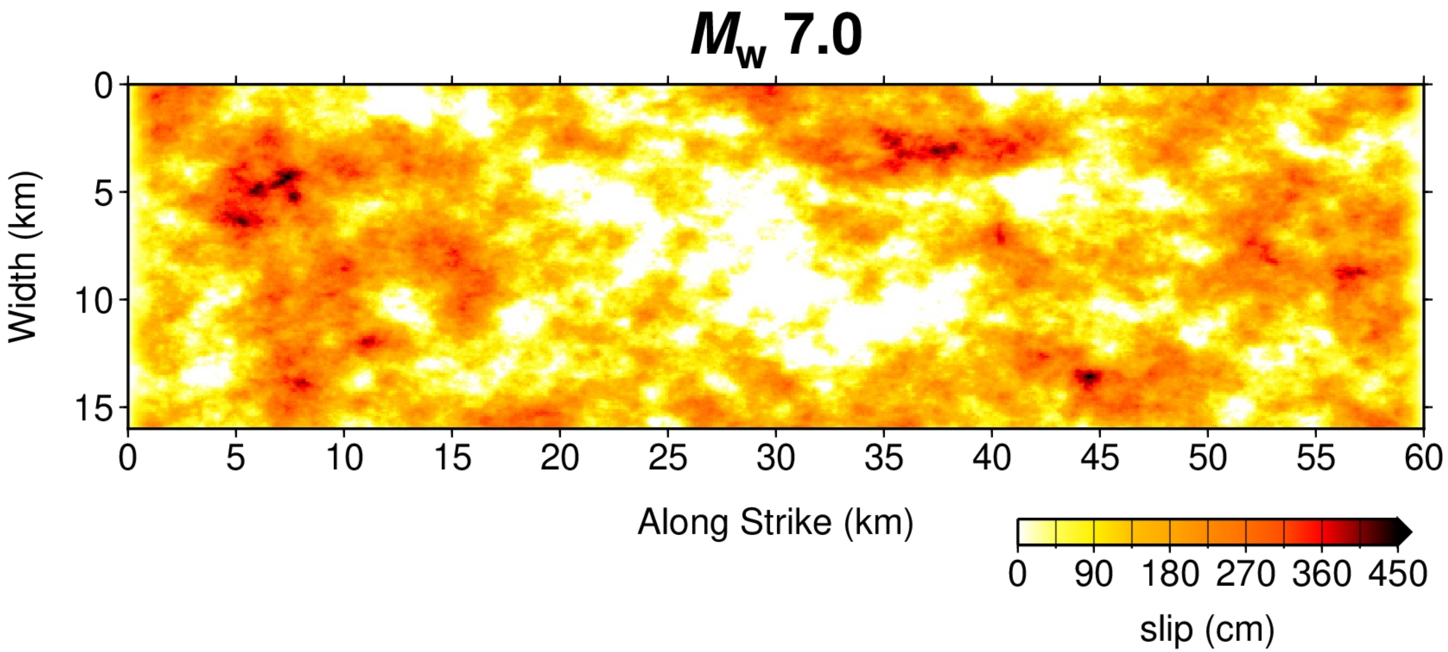

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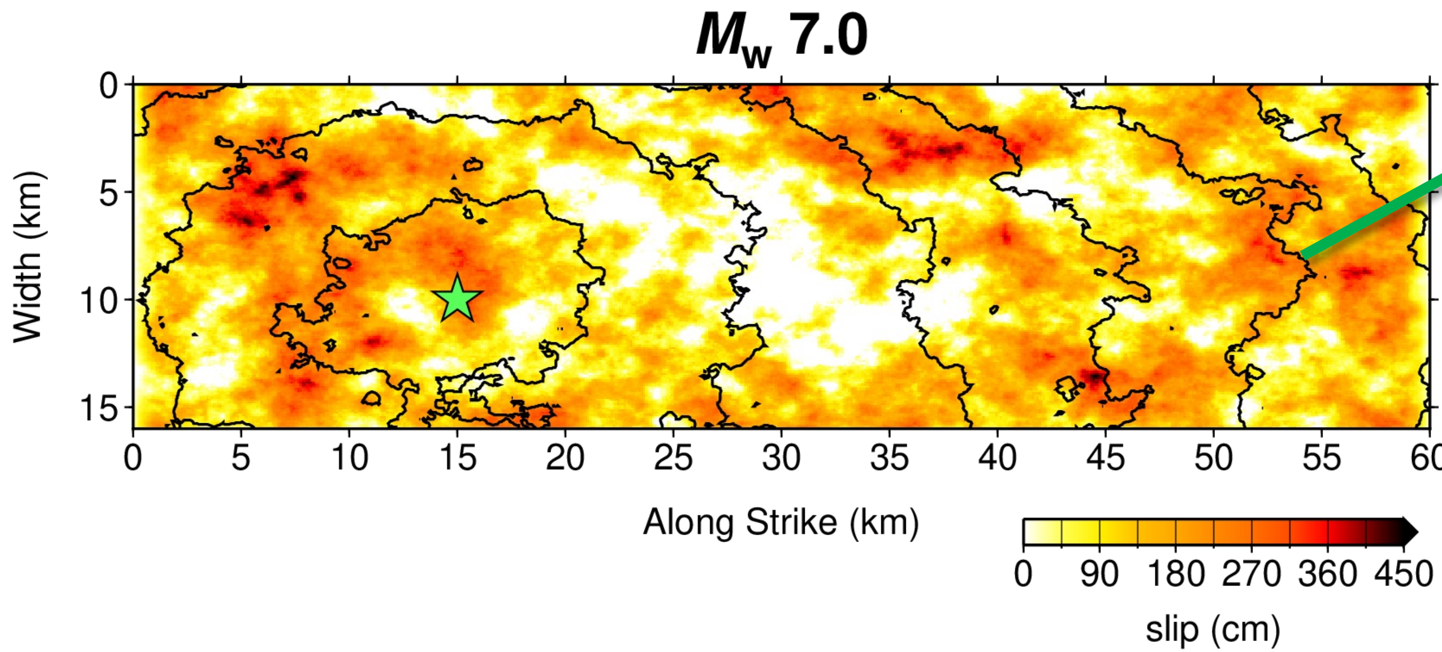
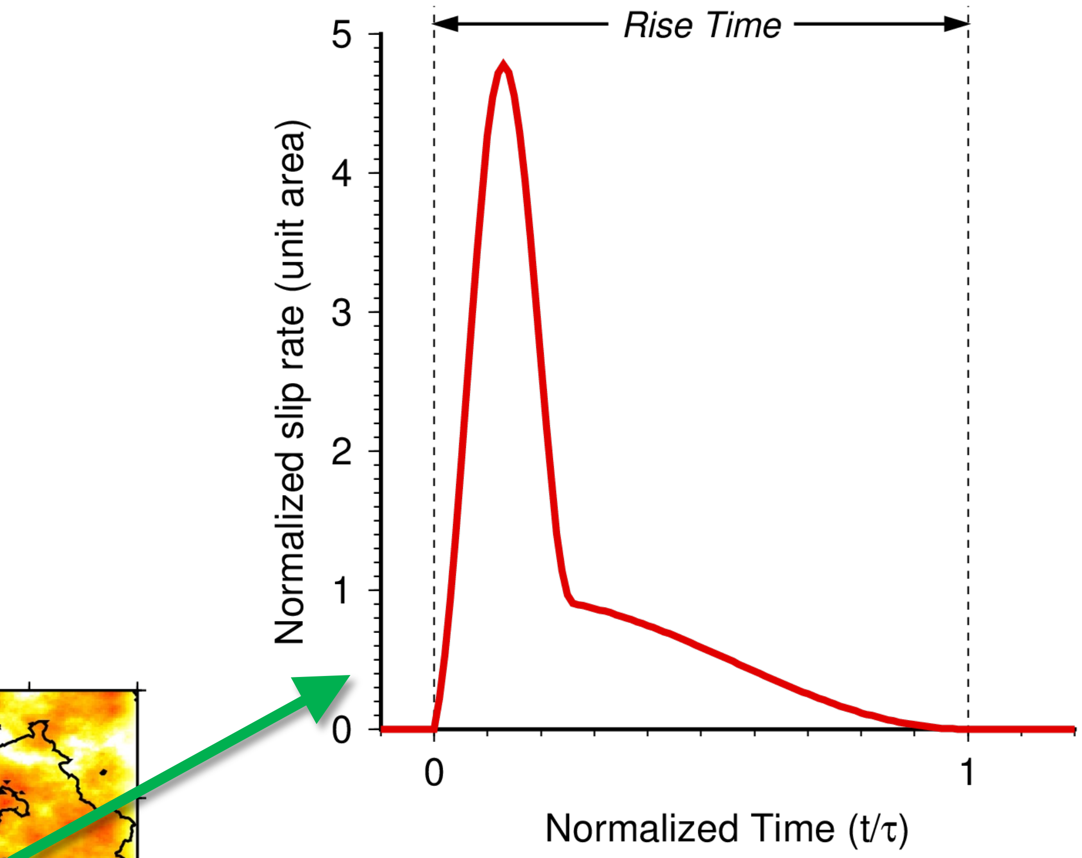




- ***Slip rise time*** *is length of time fault is slipping at a single point*
- *Total duration of rupture is much longer*

Heterogeneous Slip Characterization

- Pseudo-dynamic approach constrains kinematic parameters using dynamic rupture statistics (*e.g.*, *Guatteri et al, 2004*; *Schmedes et al, 2010*)

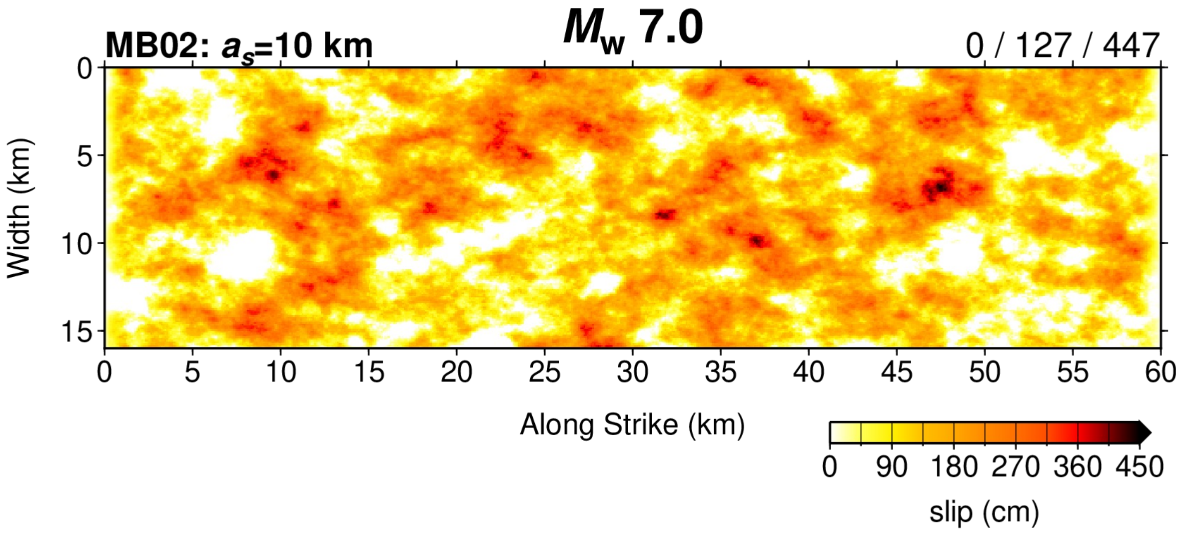
- Spatial random field models constrained by slip inversions (*e.g.*, *Somerville et al, 1999*; *Mai and Beroza, 2002*; *Suzuki et al, 2022*)

  Slip inversion wavenumber spectra used to derive correlation lengths and high-wavenumber falloff (k^{-x}, x~2)

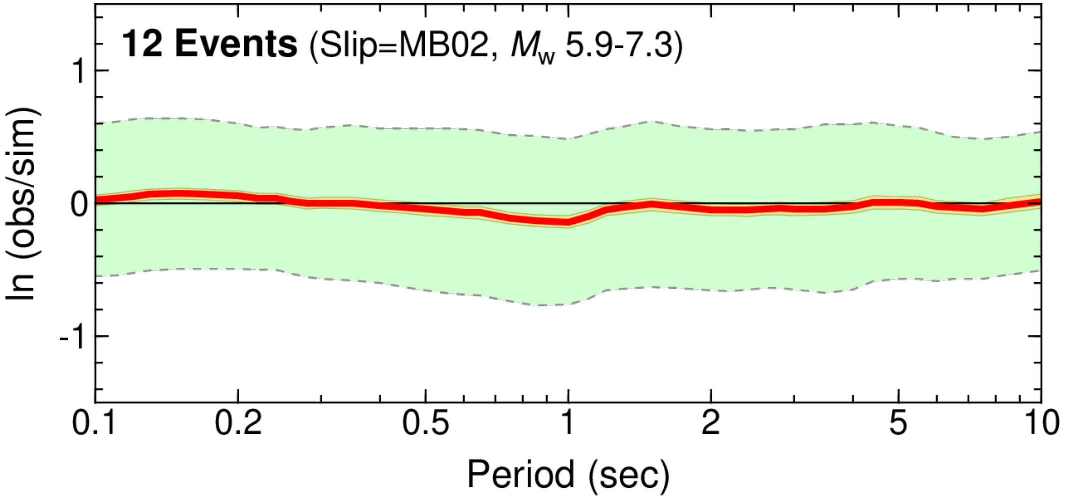
  Magnitude dependent correlation lengths

  - Somerville et al (1999): $\log_{10} a_s = \frac{1}{2} M_w - 1.72$ (*2D Butterworth*)
  - Mai and Beroza (2002): $\log_{10} a_s = \frac{1}{2} M_w - 2.50$ (*von Karman*)
  - Suzuki et al (2022): $\log_{10} a_s = \frac{1}{2} M_w - 1.70$ (*von Karman*)

Heterogeneous Slip Characterization



- **MB02** (*Mai and Beroza, 2002*) model validated against GMMs and strong motion recordings of past earthquakes (*e.g.*, *Frankel, 2009*; *Graves, 2021*)



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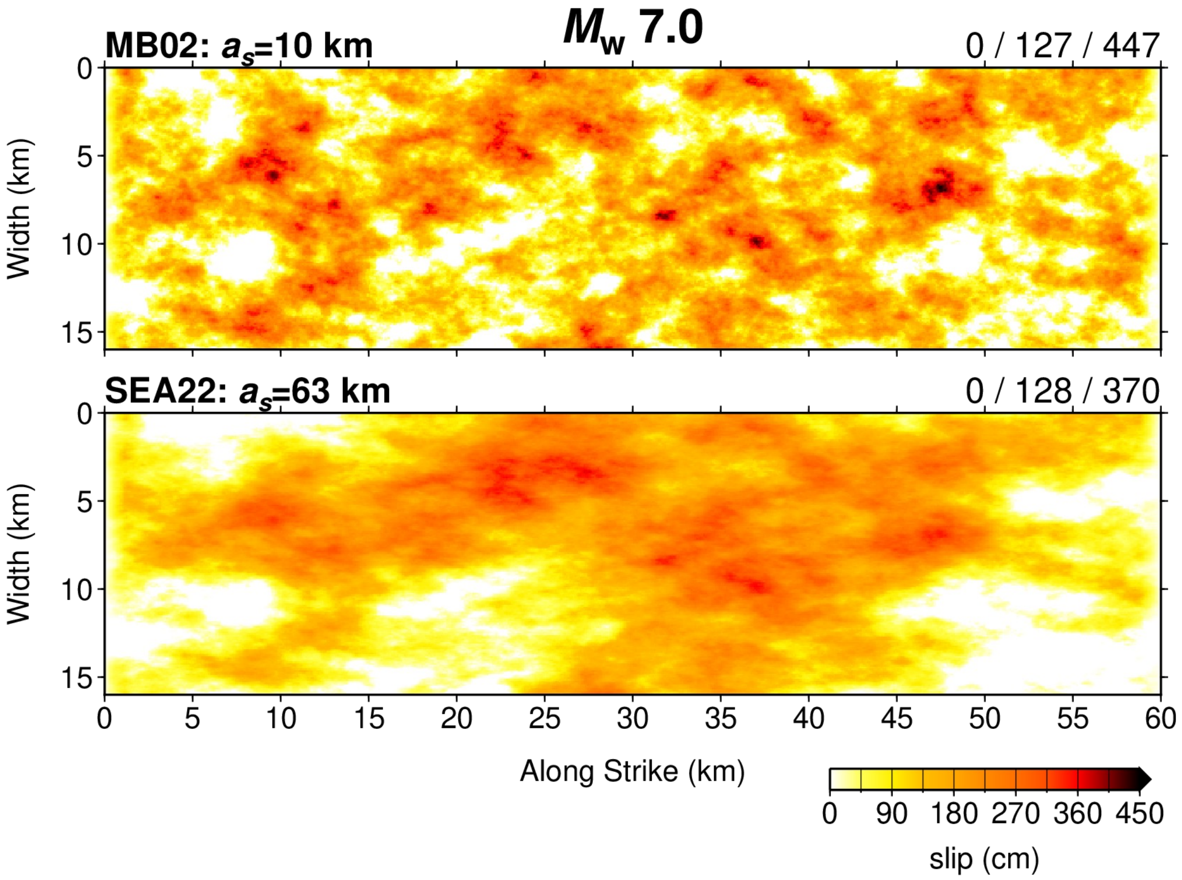
Heterogeneous Slip Characterization



- **MB02** (*Mai and Beroza, 2002*) model validated against GMMs and strong motion recordings of past earthquakes (*e.g., Frankel, 2009; Graves, 2021*)
- **SEA22** (*Suzuki et al, 2022*) model has reduced short-length scale variations compared to **MB02** → difficult to adequately replicate strong motion features

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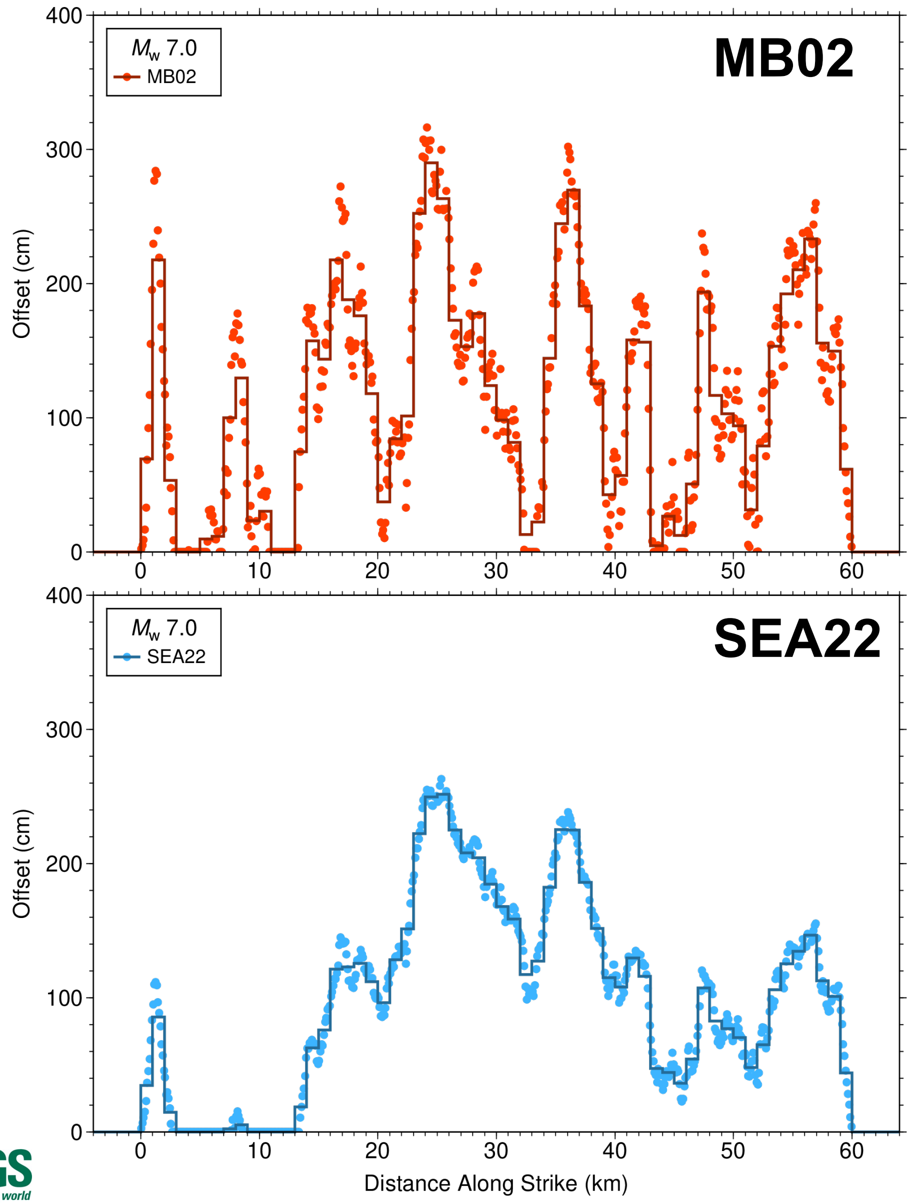
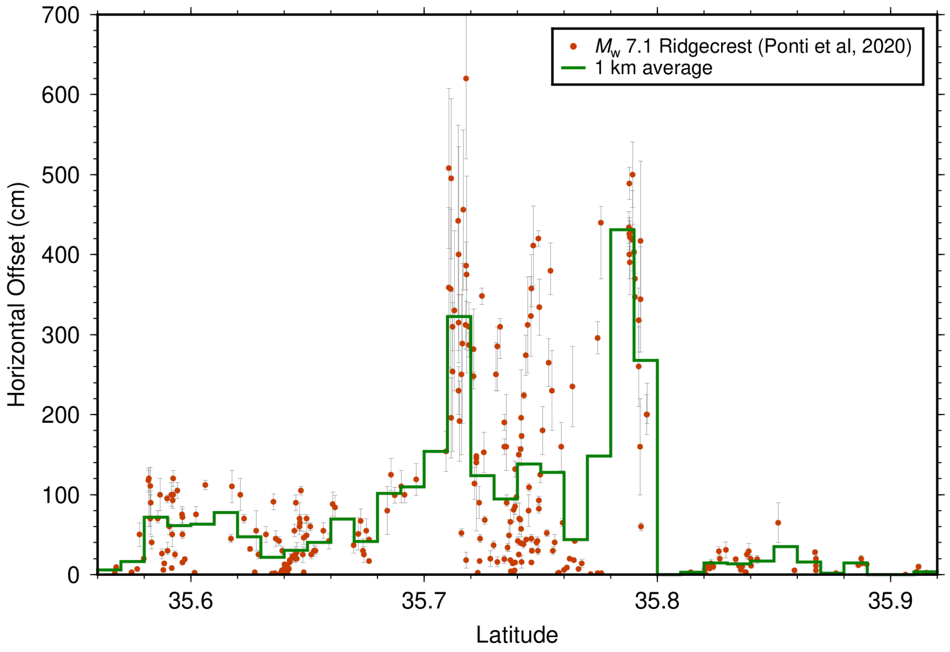
Shallow Slip Features



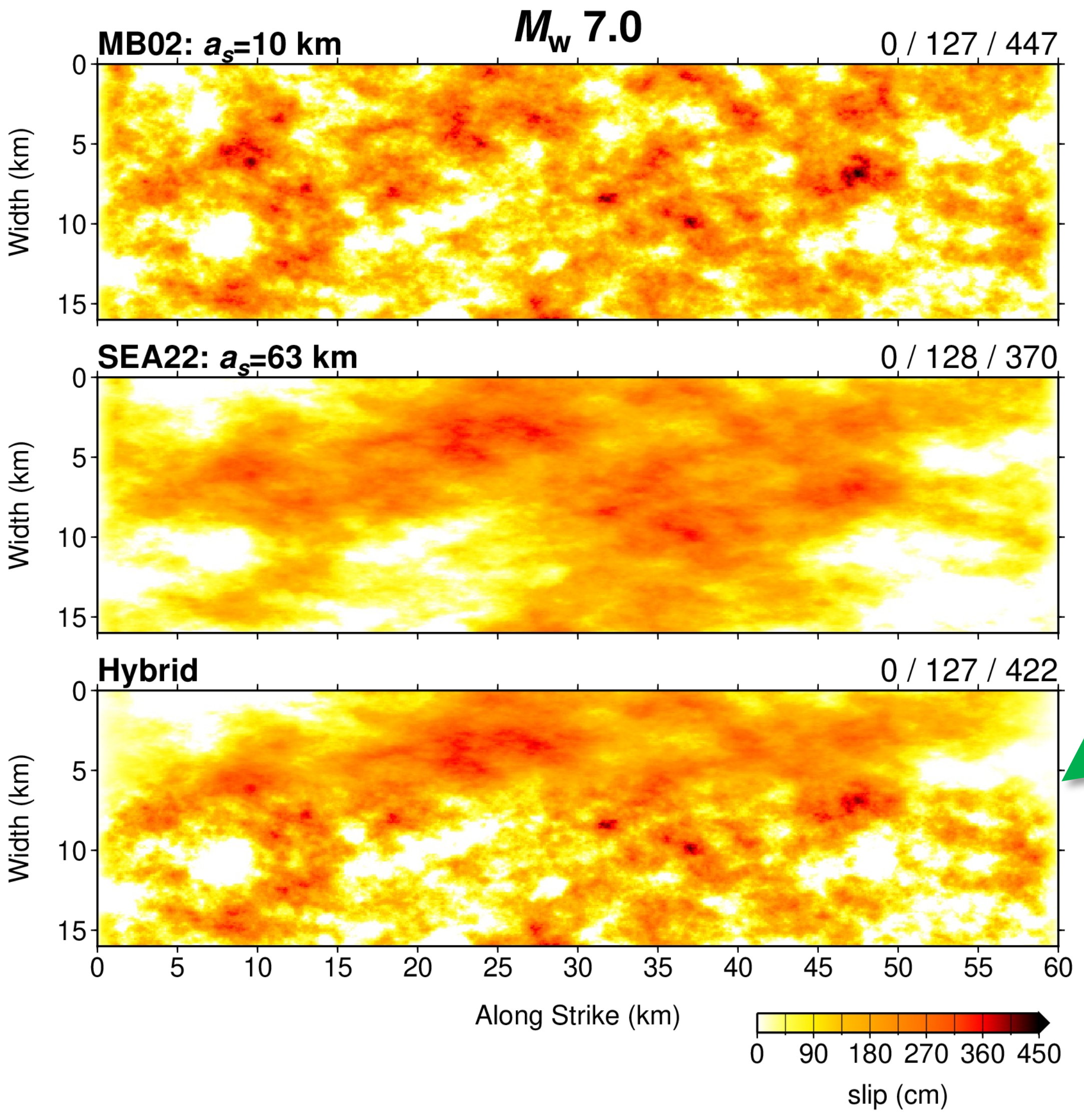
- **MB02** has quasi-periodic short-length scale features that don't fit shallow slip characteristics particularly well
- **SEA22** has enhanced longer-length scale features that better capture expected & observed characteristics



Shallow vs. Deep Rupture Characteristics

- Shallow rupture observed to generate weak high-frequency ground motions compared with deeper rupture (*e.g., Kagawa et al., 2004; Pitarka et al., 2009; Frankel, 2023*).
- 2011 $\boldsymbol{M}_w$ 9.0 Tohoku earthquake is classic example (*e.g., Kurahashi and Irikura, 2011; Frankel, 2013*)
- Dynamically modeled as velocity strengthening or low-to-negative stress drop at shallow depths (*e.g., Marone and Scholz, 1988; Dalguer et al., 2008*)
- Kinematically modeled with reduction of rupture speed and lengthening of rise time along shallow fault (*e.g., Graves and Pitarka, 2010*) or superposition of high stress-drop deep subevents on smooth slip background (*e.g., Frankel et al, 2018*)

Hybrid Slip Model



- Proposed **Hybrid** slip distribution combines **MB02** and **SEA22** models to further account for depth-dependent effects

$$\mathbf{Hybrid} = \mathbf{MB02} \cdot [1 - f(z)] + \mathbf{SEA22} \cdot f(z)$$

$$f(z) = \begin{cases} 1 & z < z_0 \\ 1 - \frac{(z - z_0)}{(z_1 - z_0)} & z_0 \leq z \leq z_1 \\ 0 & z > z_1 \end{cases}$$

$$z_0 = 5 \text{ km}, \; z_1 = 8 \text{ km}$$

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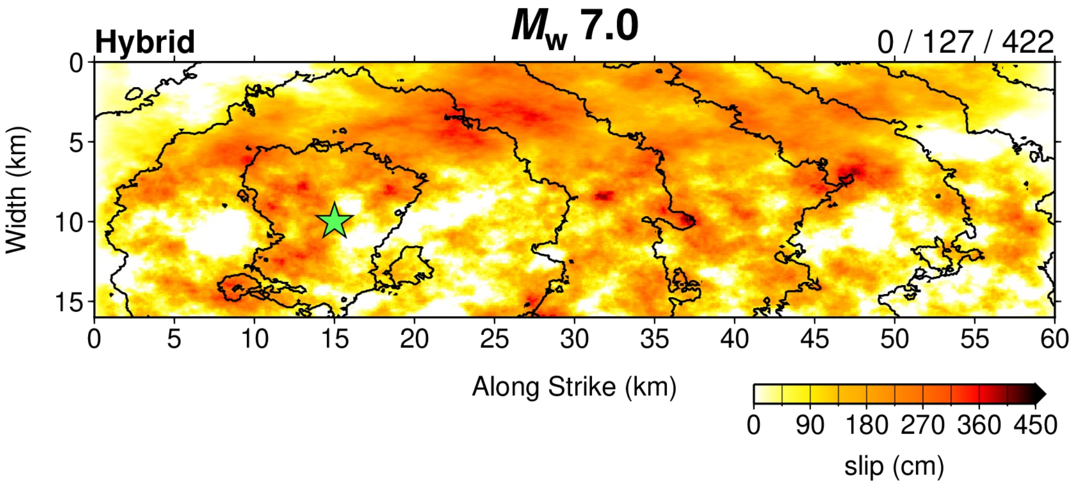
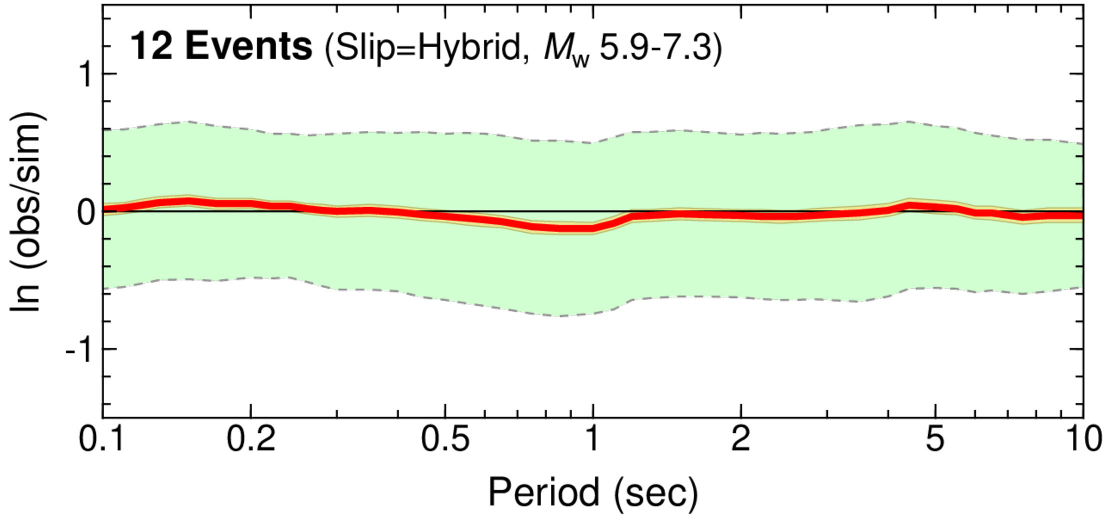
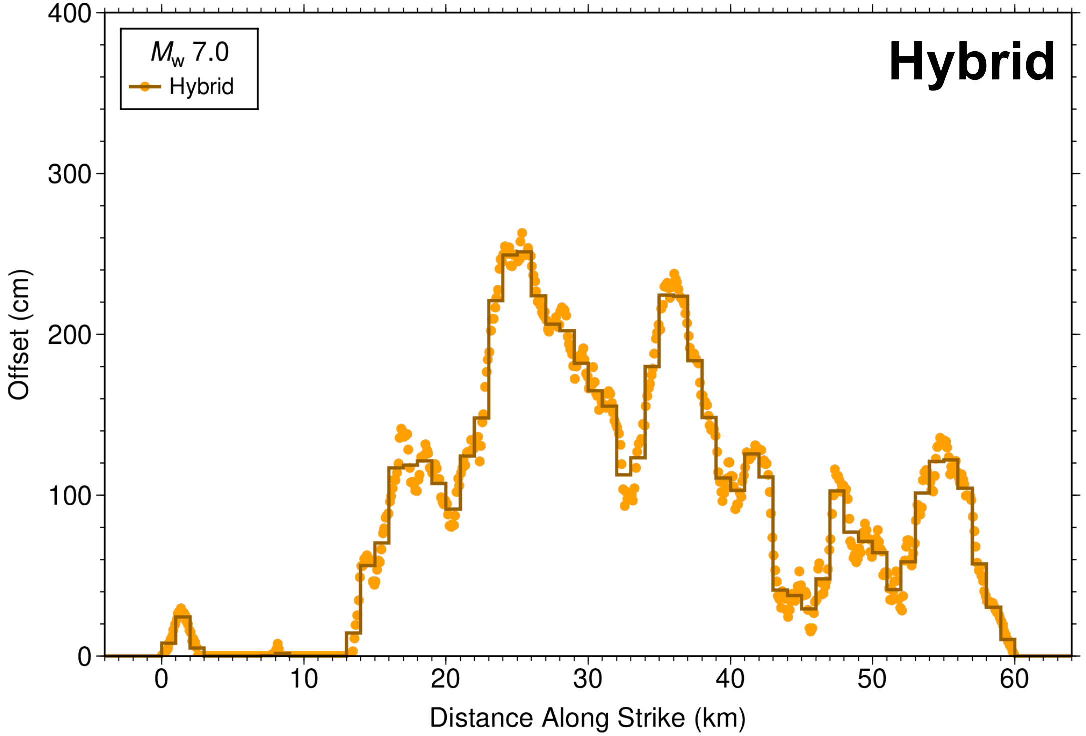
Hybrid Slip Model





- **Hybrid** rupture model does well in reproducing strong ground motions ***and*** capturing surface displacement characteristics

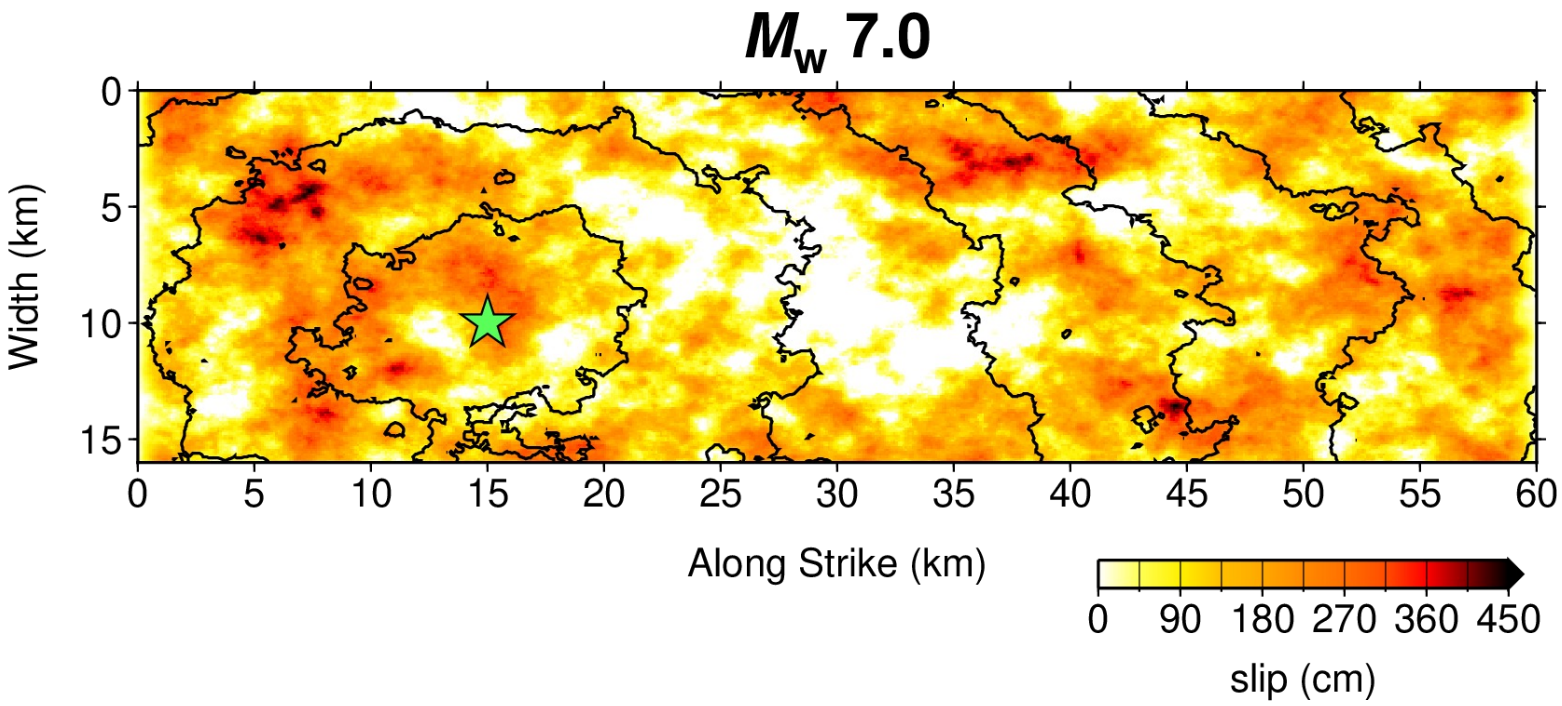


Subfault Size and Frequency Resolution

- Given maximum resolved simulation frequency ($\mathbf{f_{max}}$), what is maximum subfault size ($\mathbf{H_{max}}$) that accurately represents kinematic source?

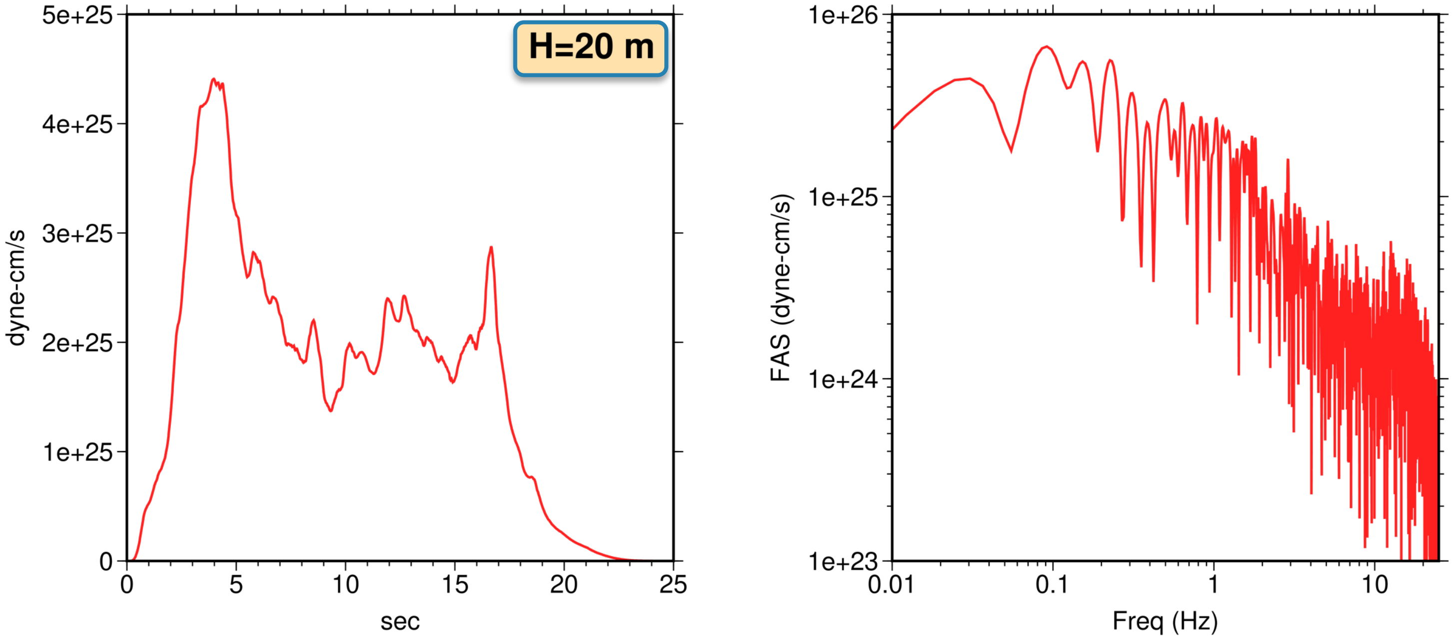
- Investigate empirically using M_w 7 ruptures having different subfault sizes

  start with Δlen = Δwid = H = 20 m



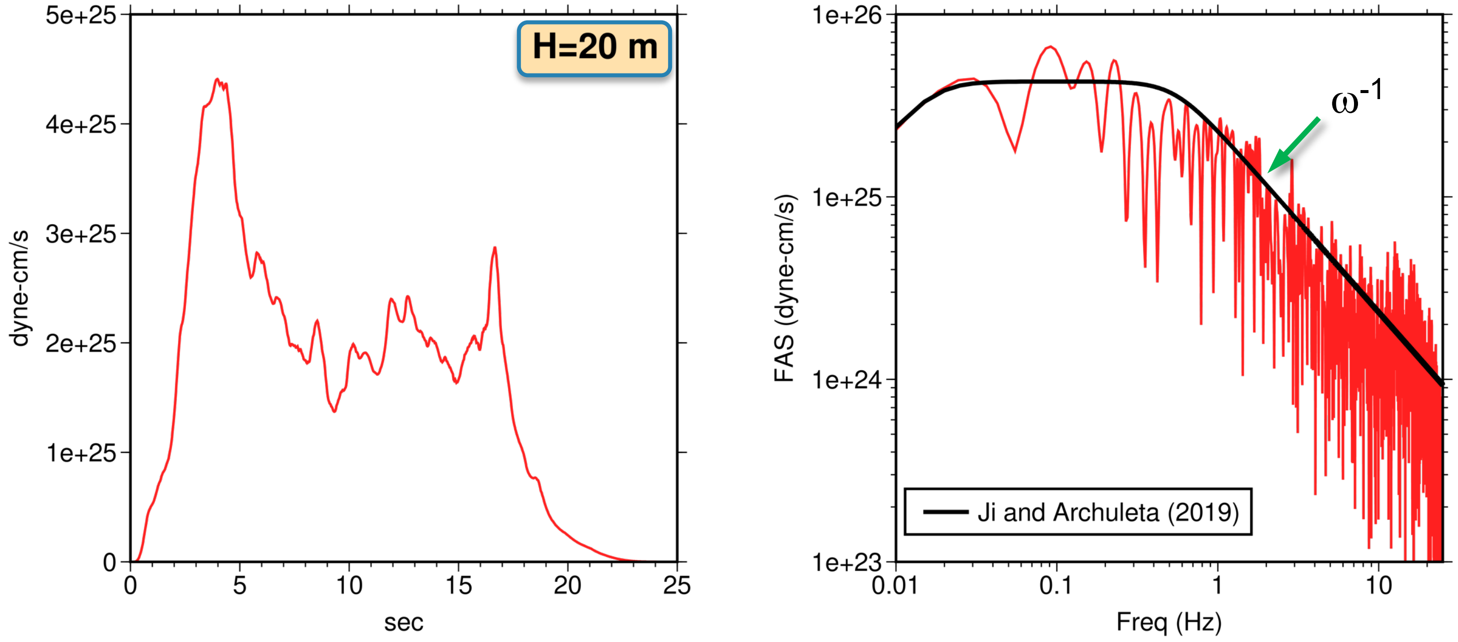
Subfault Size and Frequency Resolution

- Compute moment-rate function across entire rupture



Subfault Size and Frequency Resolution

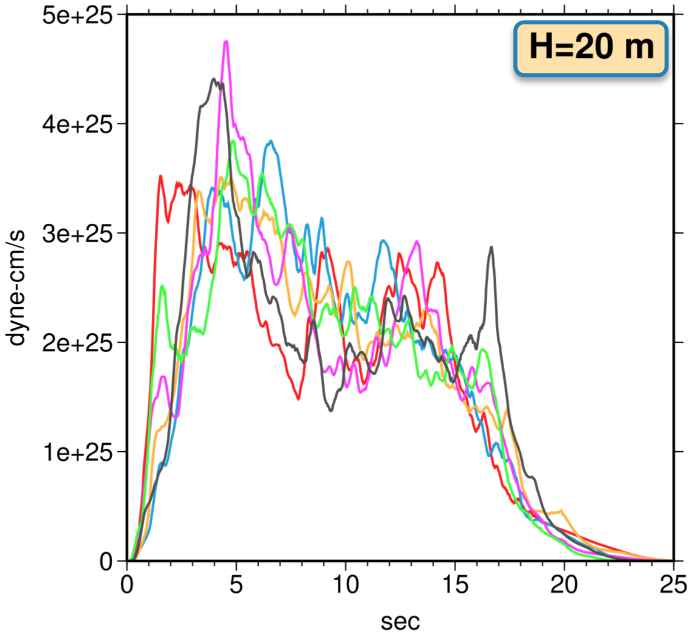
- Compute moment-rate function across entire rupture
- Spectrum agrees well with theoretical double-corner model of Ji and Archuleta (2019)

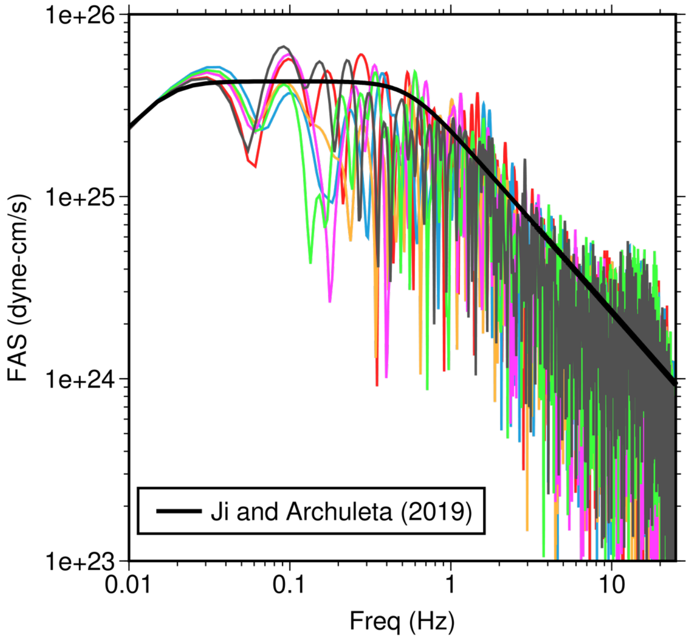


High-frequency falloff follows ω^{-1} to beyond 10 Hz (consistent with "ω^{-2}" model)

Subfault Size and Frequency Resolution

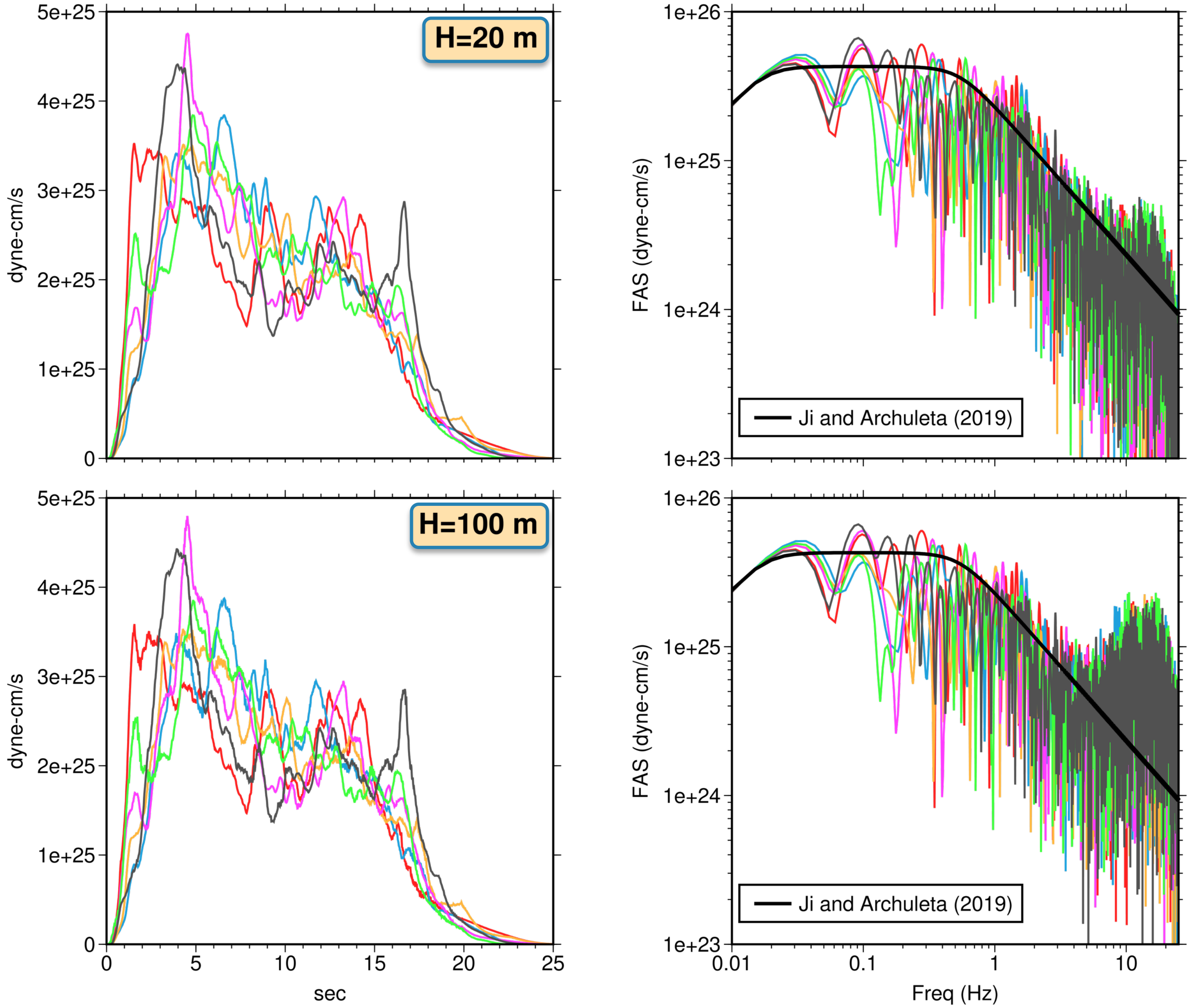
- Consider multiple realizations →





Subfault Size and Frequency Resolution

- Consider multiple realizations →
- Consider larger subfault size →



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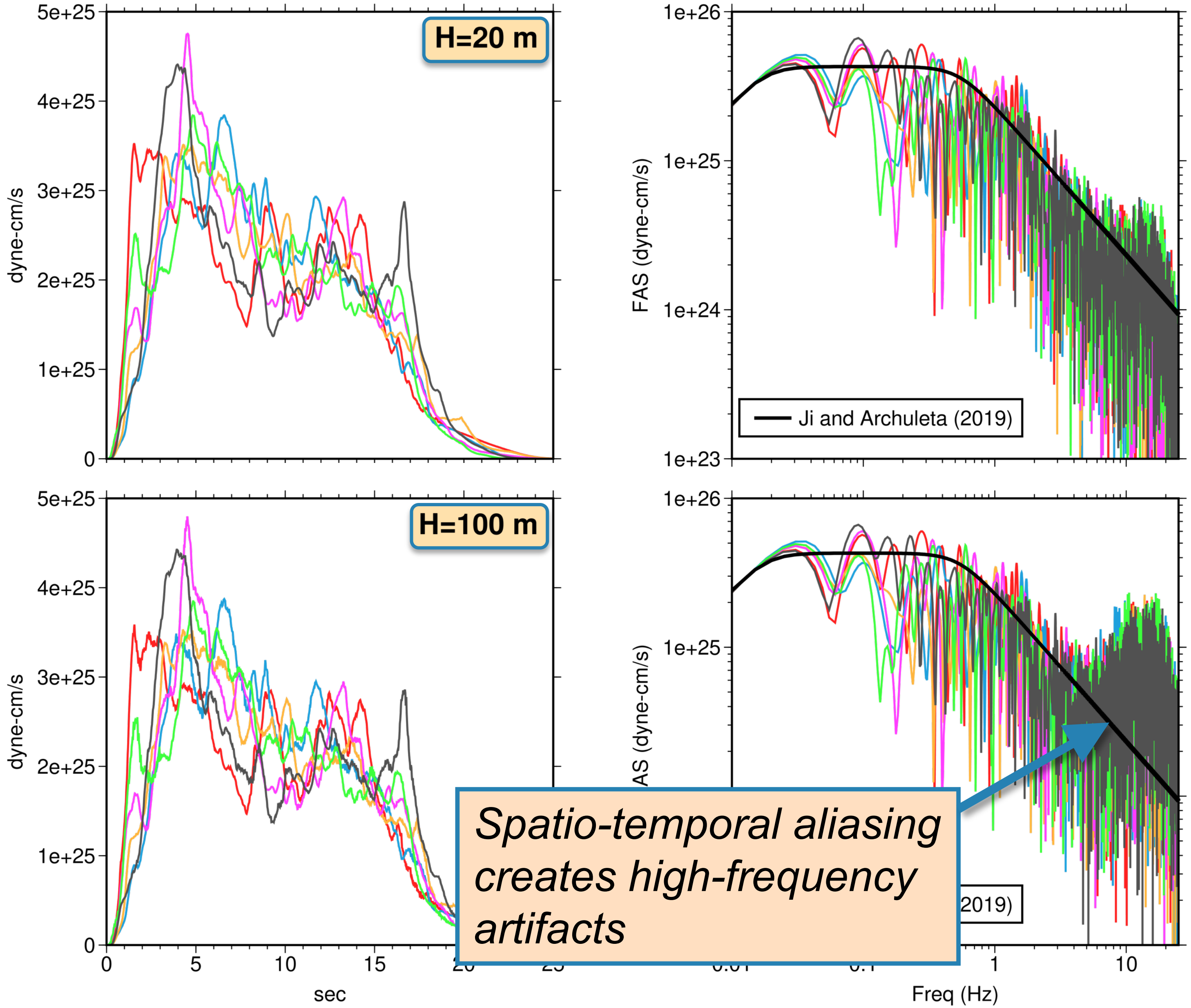
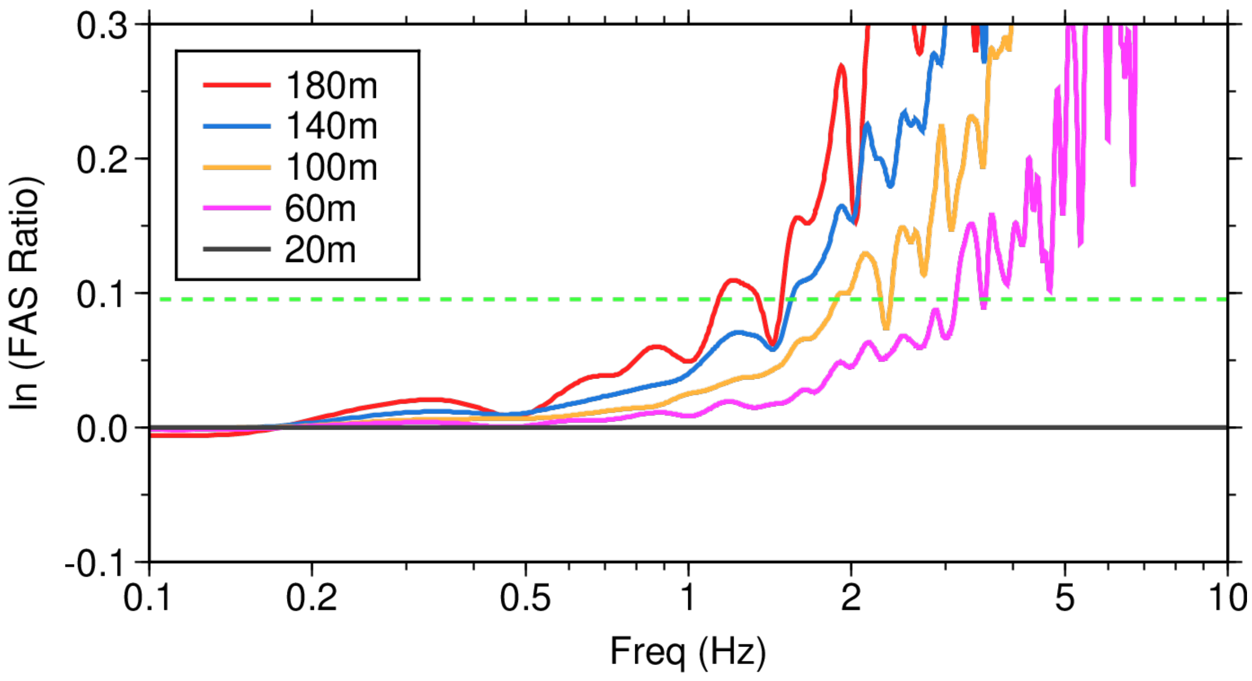
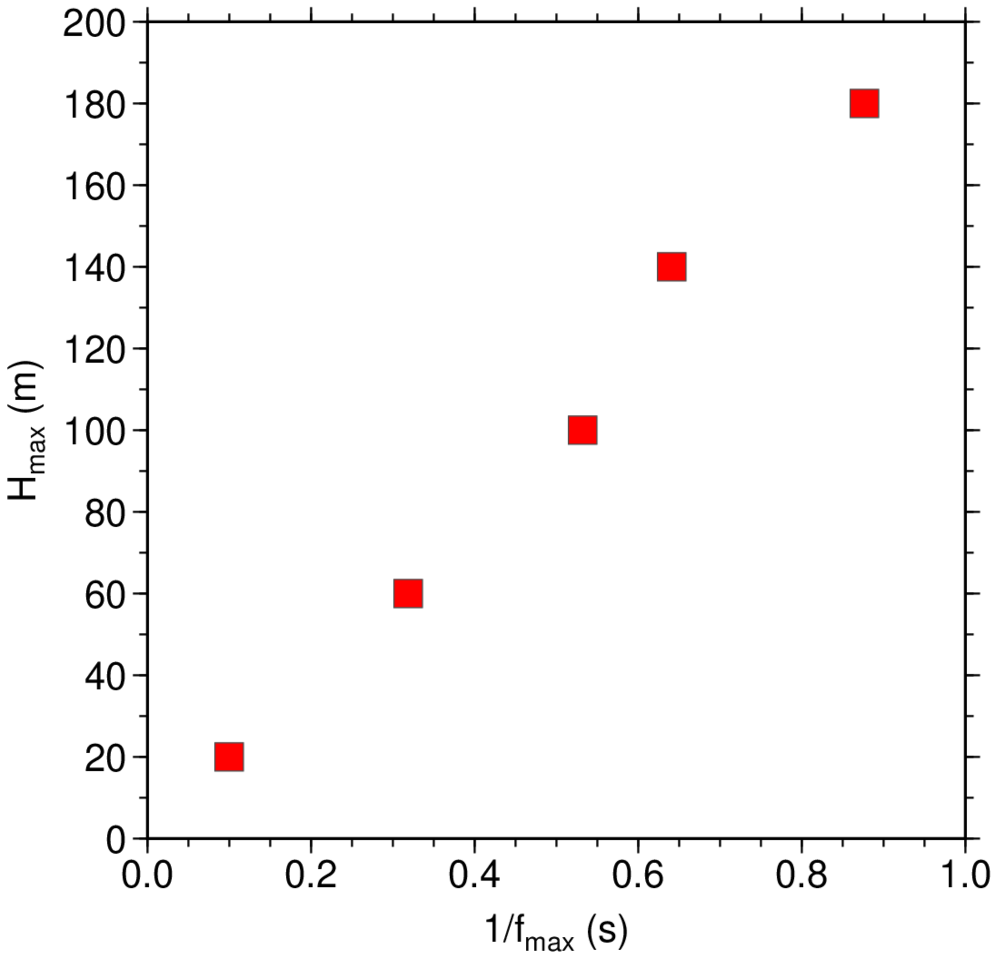


Subfault Size and Frequency Resolution

- Repeat process for other subfault sizes and compute spectral ratio relative to H=20 m case





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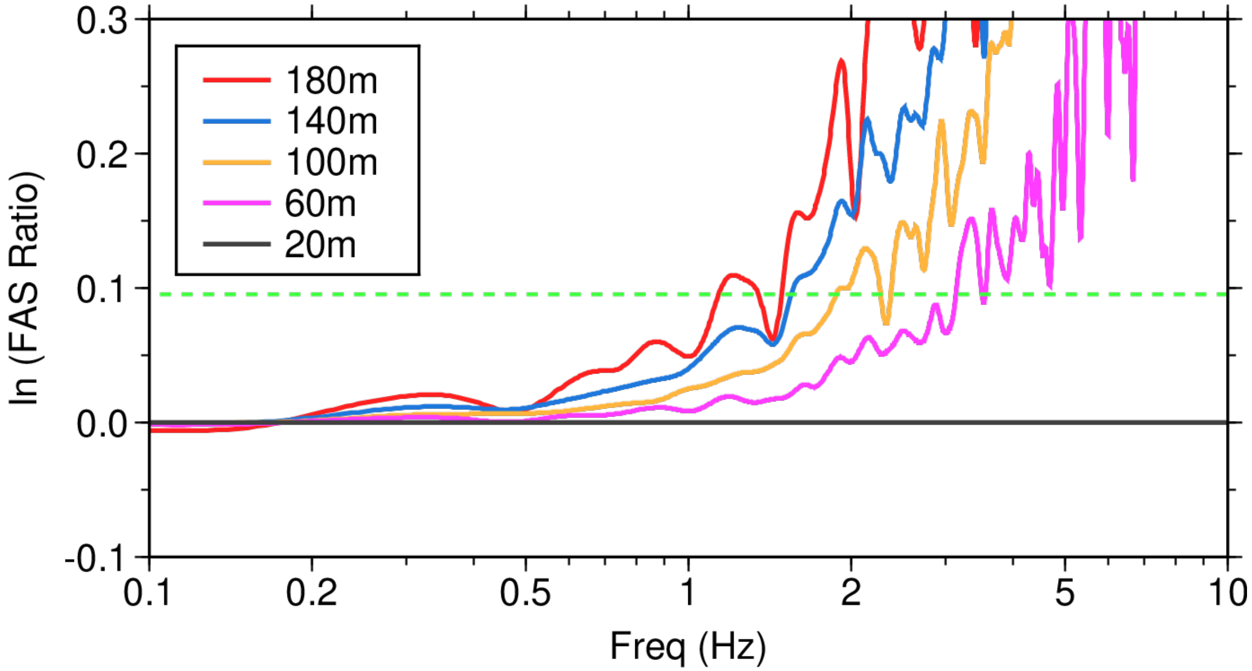

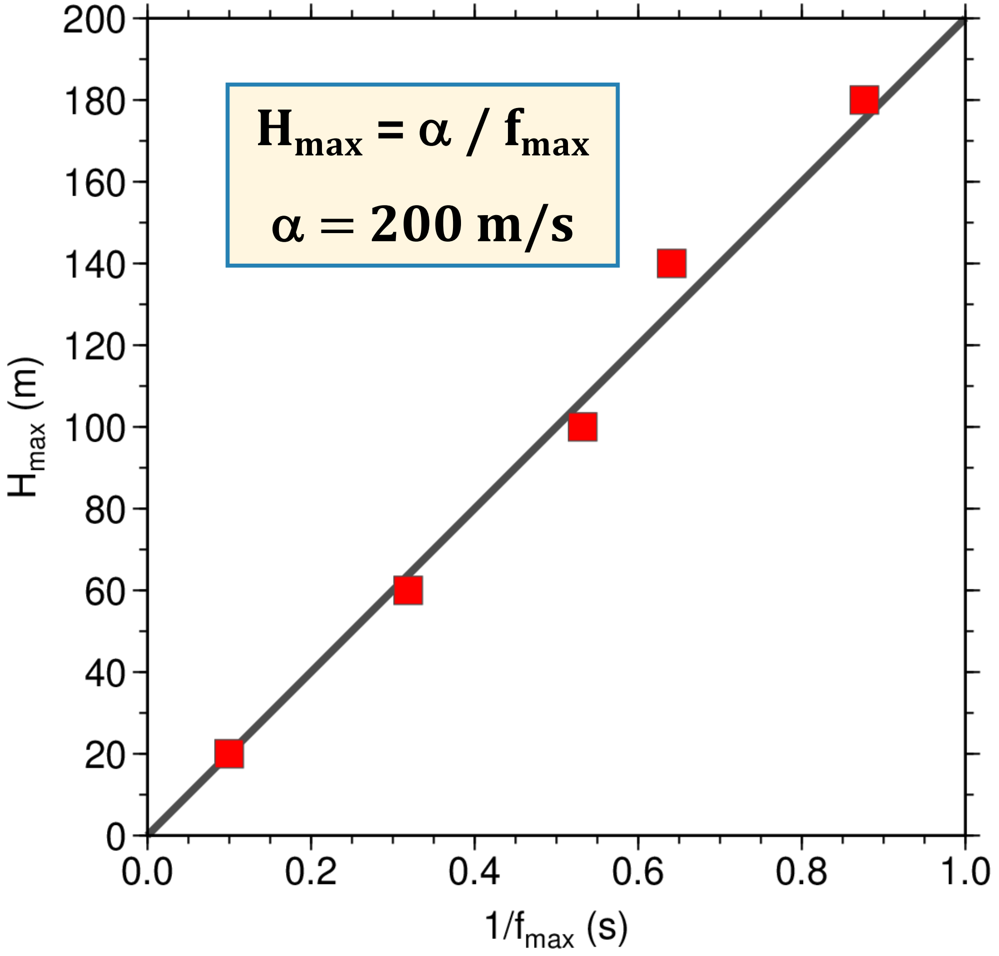

Summary

- Proposed **Hybrid** kinematic slip model combines long-wavelength shallow slip with short-wavelength deeper slip patches. **Hybrid** model does well in matching observed strong motions and shallow fault offset characteristics.

- Accurate modeling of strong motions requires some degree of correlation between local rise time and local slip amplitude. Preferred model is $\tau \sim S$ (*with some randomness*), which gives roughly constant slip-rate across the fault (*e.g., Frankel, 2009*).

- Empirical tests provide guidance for kinematic subfault size given maximum simulation frequency. Rule of thumb is: $\mathbf{H_{max} = \alpha / f_{max}}$ with $\alpha = \mathbf{200\ m/s}$.

- All of the above will benefit from further testing and validation, particularly to ensure consistency with dynamic models.

Thank You

Sampling Kinematic Rupture Parameters

- Rupture speed
- Slip distribution
- Fault rupture area
- Hypocenter
- Creeping zones

Sampling criteria can be problem dependent