2020 Update to the Bayless and Somerville (2013; BS13) Directivity Model

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June 16, 2020

Outline

1. Overview
2. Improvements, Assumptions, Limitations
3. Model Form
4. Development Approach
5. Examples
6. Future Steps

(1) Overview

- The directivity adjustment model is for RotD50, developed from within-event residuals from simulations and NGA-W2 data and 3 GMMs: BSSA14, ASK14, CB14.

- Supersedes our previous models (BS13, Somerville et al 1997)

- The model is based on the two Somerville et al (1997) conditions for forward directivity:
  1. the rupture front propagates toward the site (at velocity close to Vs)
  2. the direction of slip on the fault is aligned with the site

- Includes a median adjustment and aleatory variability adjustment

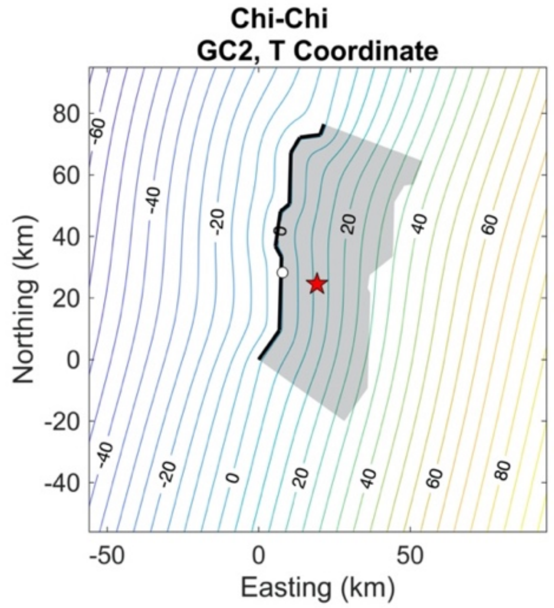
- Maintains the relative simplicity of our previous models

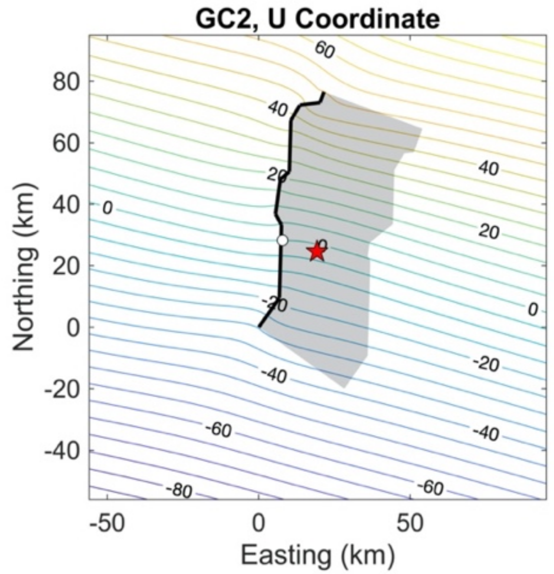
- appropriate over the period range 0.01 to 10 seconds, in the magnitude range **M**5.0-8.0, and has a footprint which is magnitude and style-of-faulting dependent, with a maximum of 80 km distance from the fault trace.

(2) Improvements

- Treatment of complex rupture geometries is handled using the generalized coordinate system GC2, as formulated by Spudich and Chiou (2015). With this formulation, the model features greatly improved flexibility compared with previous versions.
  - Strike normal (T) and strike-parallel (U) coordinates
  - Based on weighted (1/r^2) average distances from all segments
  - Results in smoothly varying coordinates in space
  - the weighting integral can be solved in closed form rather than by brute force
  - Origin is up-dip from the hypocenter

- is centered because it is based on a residual analysis and therefore does not alter the GMM magnitude or distance scaling.





(2) Improvements

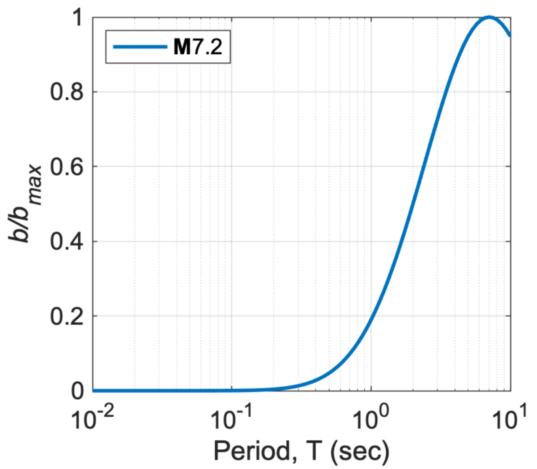
– is narrowband (the peak effect scales with magnitude)

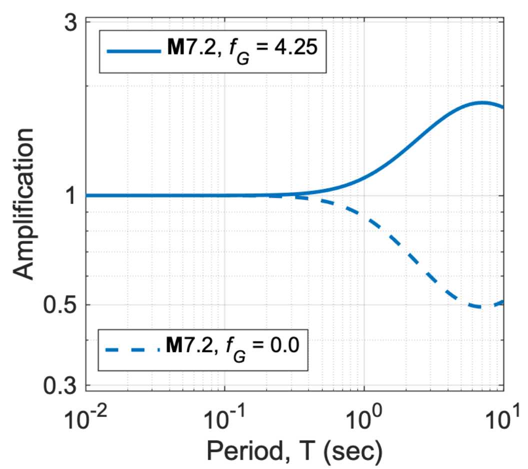
– is guided by finite-fault simulations with dense station arrays and strong azimuthal coverage.

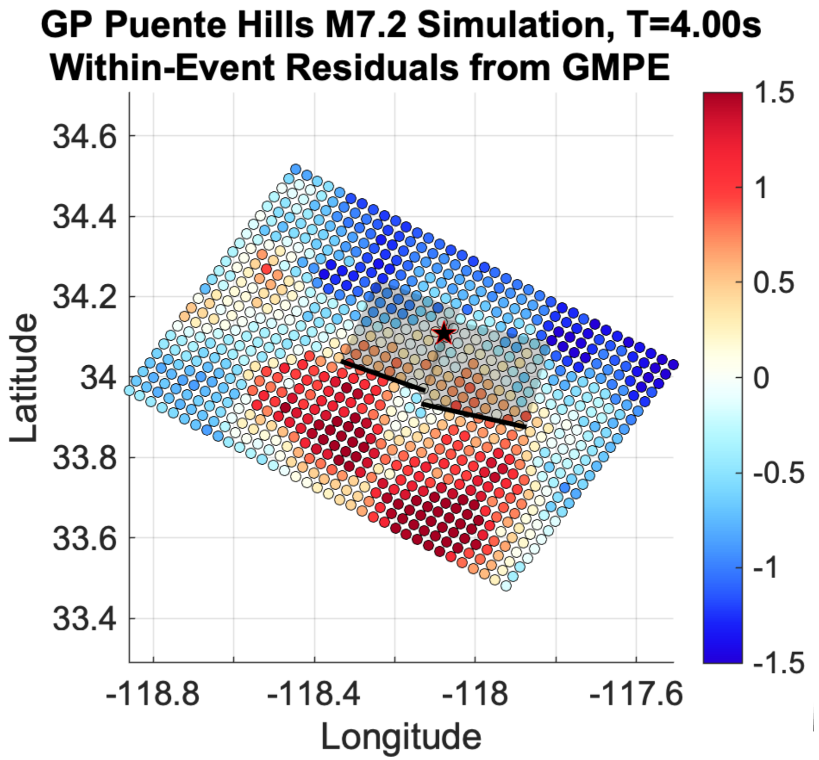
– Includes an aleatory variability adjustment

– Maintains relative model simplicity but features improved formulation

– Enhanced model documentation/instructions







(2) Assumptions/Limitations

– Rupture geometry

– U -> S conversion

– Simplified description of multi-segment ruptures
  - One hypocenter with characteristic style of faulting, rake, and dip

– Three assumptions are leftover from the PEER (2013) model:
  1. Simple distance tapers based on observation, period-independent

  2. For reverse/normal faulting ruptures the model assumptions have a strong effect on predictions (relatively fewer data for these, including sims)

  3. Since it is an intuitive model, the predictors are ad-hoc and although they appear to work well, for scenarios with little or no data the model is strongly based on the assumptions about the behavior of these predictors

(2) Assumptions/Limitations

- Two rupture classes: predominantly strike slip and all other
  - Can be determined by rake angle or manually selected
  - Strike slip class assumes bilateral rupture propagation
  - All other class, up-dip rupture propagation is assumed
  - both categories, assume that the earthquake rupture is, to some degree, propagating in the same direction as the slip. In reality, the direction of rupture propagation and its consistency with the slip direction will affect the degree of forward rupture directivity.

(3) Model Form

Median directivity adjustment (ln units)

$$f_D(\boldsymbol{M}, T, x, SOF) = \left(a(\boldsymbol{M}, T) + b(\boldsymbol{M}, T) f_G(x, SOF) \right) f_{dist}(M, SOF) \quad (1)$$

Key terms of Equation 1

$$f_G(x, SOF) = f_{S2}(x) f_\theta(x, SOF) f_\phi(x, SOF) (2a)$$

$$b(\boldsymbol{M}, \mathrm{T}) = b_{max}(\boldsymbol{M}) \exp\left(\frac{(\log_{10} \frac{\mathrm{T}}{\mathrm{T}_{peak}(\boldsymbol{M})})^2}{-2\sigma_g{}^2}\right) (2b)$$

$$a(\boldsymbol{M}, \mathrm{T}) = -b(\boldsymbol{M}, \mathrm{T})\, f_{G0}(\boldsymbol{M}) (2c)$$

(3) Model Form

where

$$b_{max}(\boldsymbol{M}) = b_1 + b_2\boldsymbol{M} (3a)$$

$$\log_{10} T_{peak}(\boldsymbol{M}) = c_1 + c_2\boldsymbol{M} (3b)$$

$$f_{G0}(\boldsymbol{M}) = d_1 + d_2\boldsymbol{M} (3c)$$

$$f_{S2} = \ln(S_2) \; (4a)$$

$$S_2 = \begin{cases} D & For\ SOF = 2\ and\ S\cos(Rake) < 0 \\ \sqrt{D^2 + (S\cos(Rake))^2} & Otherwise \end{cases} \quad (4b)$$

$$f_\theta = \begin{cases} |\cos(2\theta)| & For\ SOF = 1 \\ \sin(\theta) & For\ SOF = 2 \end{cases}$$

$$f_\phi = \cos(2\phi)$$

Expressions for θ, ϕ given in our report

(3) Model Form

Model coefficients are all period independent, as is predictor f_G . Narrow-band period dependence is modeled using the gaussian distribution of Eqn 2b.

To use the model requires:

1. Definition of the earthquake rupture, which includes **M,** segment coordinates, segment lengths, segment strike angles, the depth to the top of rupture, the rupture characteristic down-dip width, the rupture characteristic rake angle, the rupture characteristic dip angle, the characteristic style of faulting, and a primary hypocenter location.

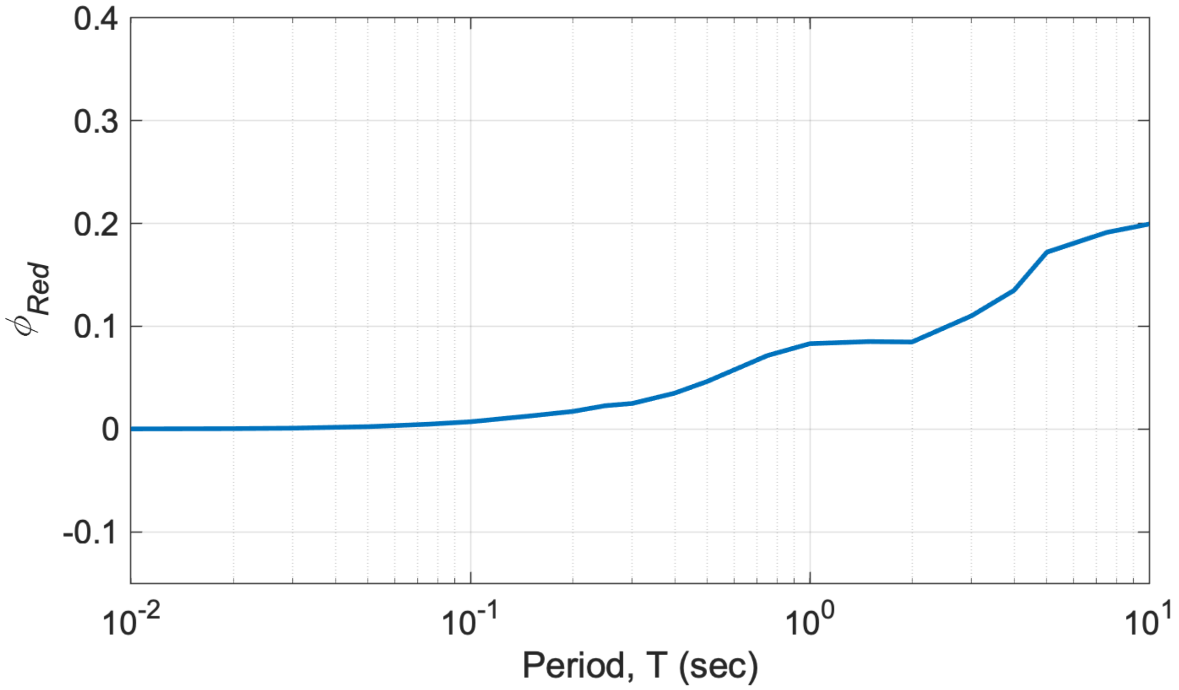
2. The position of the site relative to the rupture, U and T, derived from the earthquake description and the site coordinates.

3. The spectral period of interest.

Please see the report for a short list of imposed constraints on select parameters.

(3) Model Form

- Aleatory variability adjustment
  - Based on NGA-W2 residual analysis
  - It is still a small reduction
  - This does not account for the increased variability introduced in a PSHA implementation (by way of randomizing hypocenter locations). This is addressed later



$$\sigma = \sqrt{\tau^2 + \varphi^2}$$

$$\varphi_{Dir}^2 = \varphi_{NoDir}^2 - \varphi_{Red}^2$$

$$\varphi_{Red}(T, R_{rup}, \boldsymbol{M}, SOF) = \begin{cases} e_1(T) & For\ R_{rup} < R_{max}(M, SOF) \\ 0 & For\ R_{rup} \geq R_{max}(M, SOF) \end{cases}$$

(4) Approach Overview

– Stage 1: Simulations
– Stage 2: NGA-W2 data
– Stage 3: Iteration, composite result
– Stage 4: Regression

(4) Approach Overview

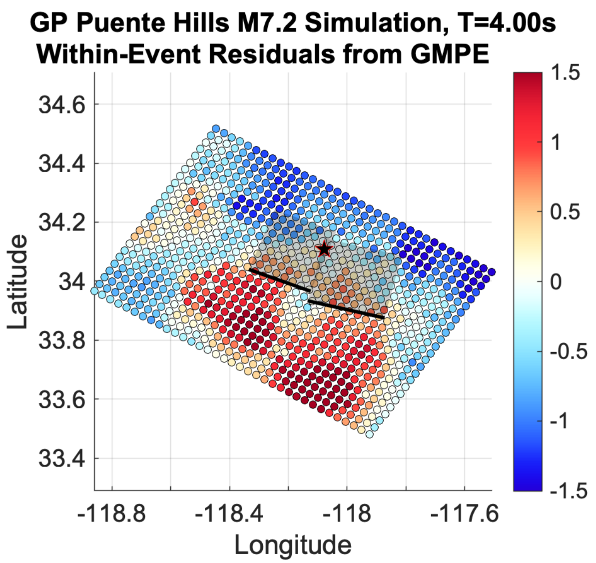
Stage 1: Simulations

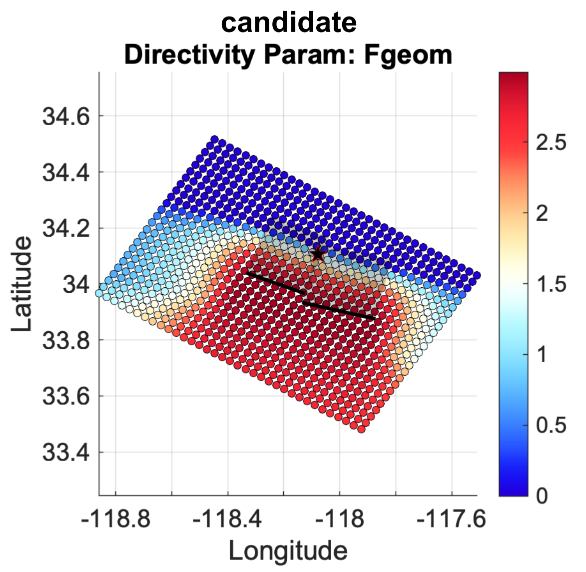
- Used to explore the directivity predictor variable space. The dense azimuthal coverage is beneficial

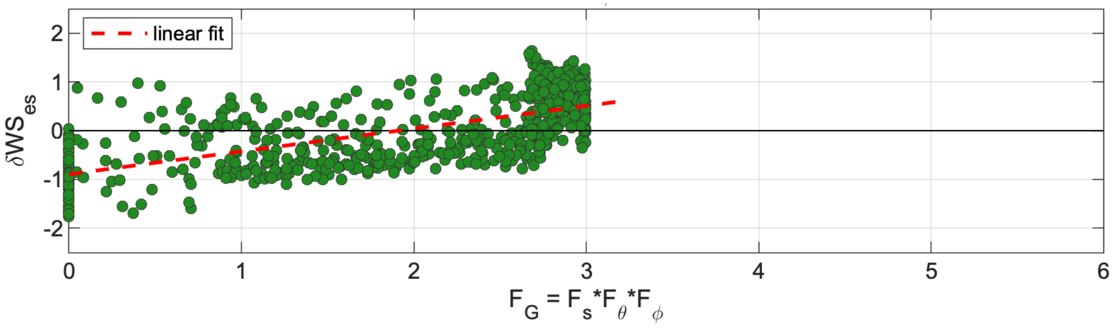
- For each set a database of 5% damped RotD50 is created,

- We calculate ground-motion residuals from three NGA-West2 GMMs

- The residuals at a given spectral period are mapped to evaluate the spatial trends and plotted versus the directivity parameters we consider candidates to use in the model, based on the SSGA principles of forward directivity described previously







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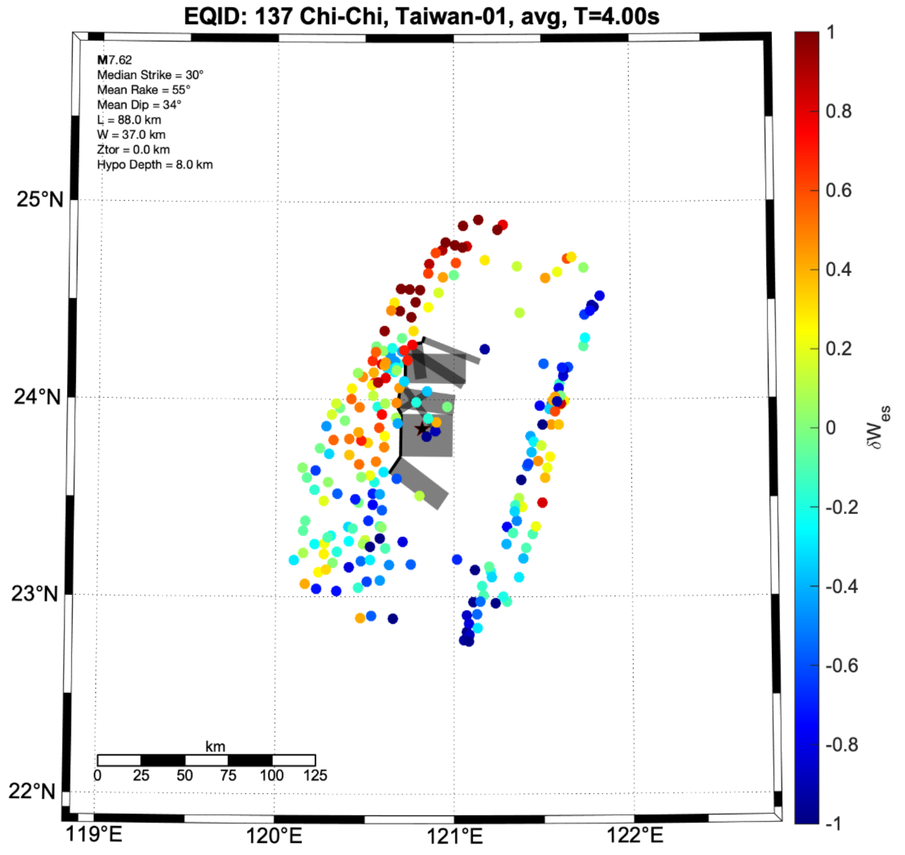
(4) Approach Overview

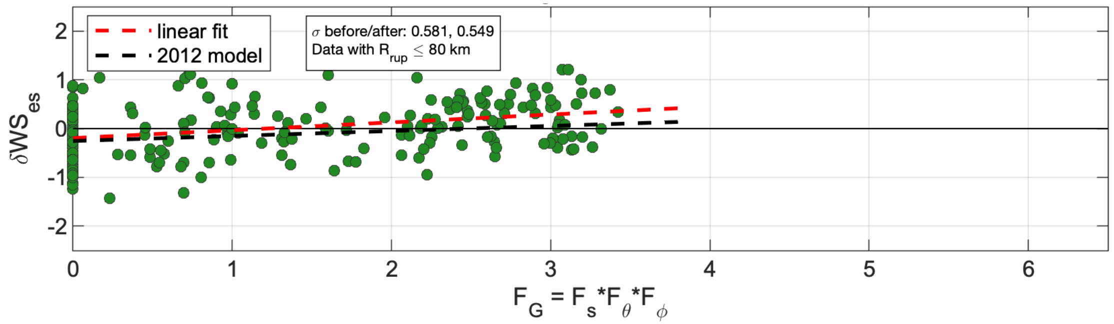
Set #	Simulation Method Name	Event/Scenario Name	Additional References	Simulation Method Detail	M	1D/3D Velocity model	Highest Usable Freq (Hz)	Style of Faulting
1	Graves & Pitarka (2014)	Generic strike-slip with stations at 20, 50 km	Dreger et al., (2013, 2015); Goulet et al., (2015)	Hybrid, Broadband	6.2	1D	10	Strike-Slip
2	Crempien and Archuleta (2014)	Generic strike-slip with stations at 20, 50 km	Dreger et al., (2013, 2015); Goulet et al., (2015)	Broadband Deterministic, theoretical GFs	6.2	1D	10	Strike-Slip
3	Graves and Pitarka v2016	Generic strike-slip	Graves and Pitarka (2014)	Finite Difference, Low Freq	6.45	3D	5	Strike-slip
4	Graves & Pitarka (2014)	Generic strike-slip with stations at 20, 50 km	Dreger et al., (2013, 2015); Goulet et al., (2015)	Hybrid, Broadband	6.6	1D	100	Strike-Slip
5	Crempien and Archuleta (2014)	Landers 1992	Dreger et al., (2013, 2015); Goulet et al., (2015)	Broadband Deterministic, theoretical GFs	7.22	1D	10	Strike-Slip
6	Graves & Pitarka (2014)	Landers 1992	Dreger et al., (2013, 2015); Goulet et al., (2015)	Hybrid, Broadband	7.22	1D	100	Strike-Slip
7	Frankel (2009)	Generic Strike-Slip	~	Hybrid, Broadband	7.5	1D	20	Strike-Slip
8	Graves (2009)	San Francisco 1906	Aagaard et al., (2009)	Hybrid: Staggered-Grid Finite Element, Stochastic for f >1 Hz	7.8	Both (3D low F, 1D high F)	10	Strike-Slip
9	Graves & Pitarka (2014)	Generic reverse with stations at 20, 50 km	Dreger et al., (2013, 2015); Goulet et al., (2015)	Hybrid, Broadband	5.5	1D	10	Reverse
10	Graves & Pitarka (2014)	Generic reverse with stations at 20, 50 km	Dreger et al., (2013, 2015); Goulet et al., (2015)	Hybrid, Broadband	6.6	1D	10	Reverse
11	Crempien and Archuleta (2014)	Generic reverse with stations at 20, 50 km	Dreger et al., (2013, 2015); Goulet et al., (2015)	Broadband Deterministic, theoretical GFs	5.5	1D	10	Reverse
12	Graves and Pitarka (2010)	Puente Hills blind thrust	Graves and Somerville (2006; 2010)	Hybrid; 3D Finite Difference for F<1, 1D Stochastic for F>1	7.2	Both (3D low F, 1D high F)	10	Reverse

(4) Approach Overview

Stage 2: NGA-W2 Data

– The same procedure is repeated for the data from 21 events with a finite fault model





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(4) Approach Overview

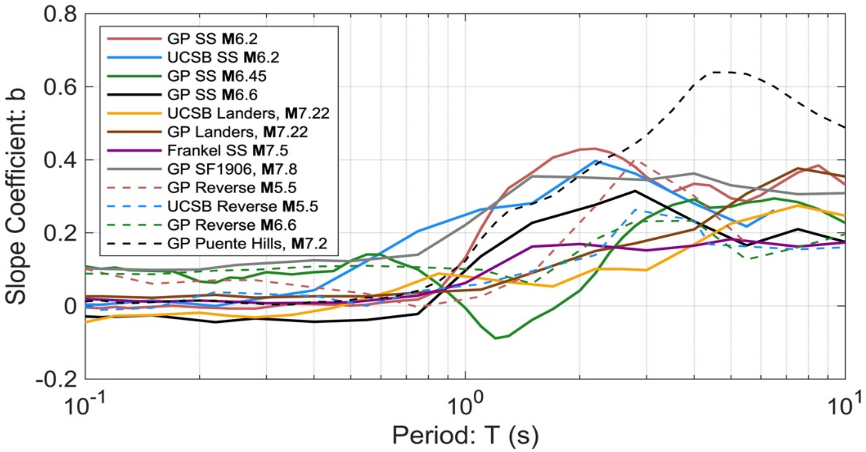
Stage 3: Iteration and Composite Result

– iterate between Stages 1 and 2 to reconcile inconsistencies between the Stage 1 model and the directivity observed in the data

– The combined database (simulations and data) is used to develop an ad-hoc composite model, which serves as a comparison for the regression-based model in Stage 4

– In the first three stages, the narrowband formulation is established. We closely follow the algorithm set forth by Spudich and Chiou (2013) to model the magnitude- and period- dependence of the directivity effect.
  - The bandwidth of the peak period is modeled by fitting the period-dependence of the slope parameter (trend in the residuals versus the directivity predictor) to a Gaussian function

$$\frac{b}{b_{max}} = \exp\left(\frac{-\left[\log_{10}\left(\frac{T}{T_{peak}}\right)\right]^2}{2\sigma_g^2}\right)$$



Period dependence of the slope parameter (b) of within-event residuals for the simulations

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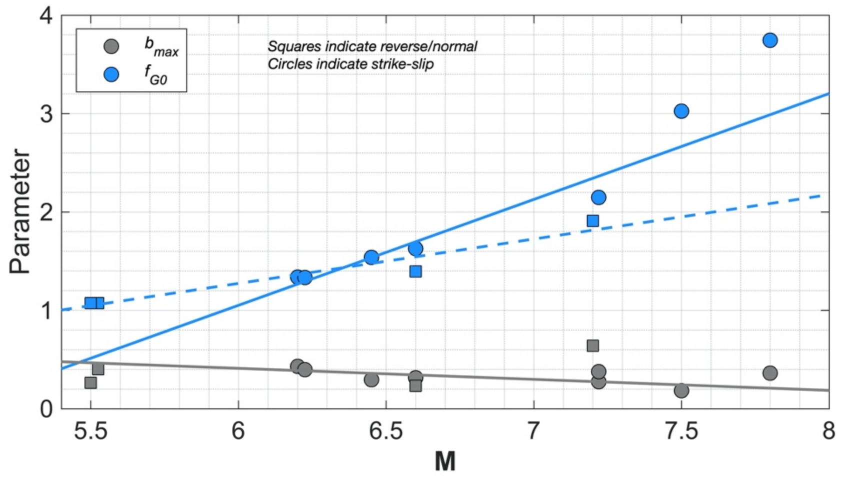
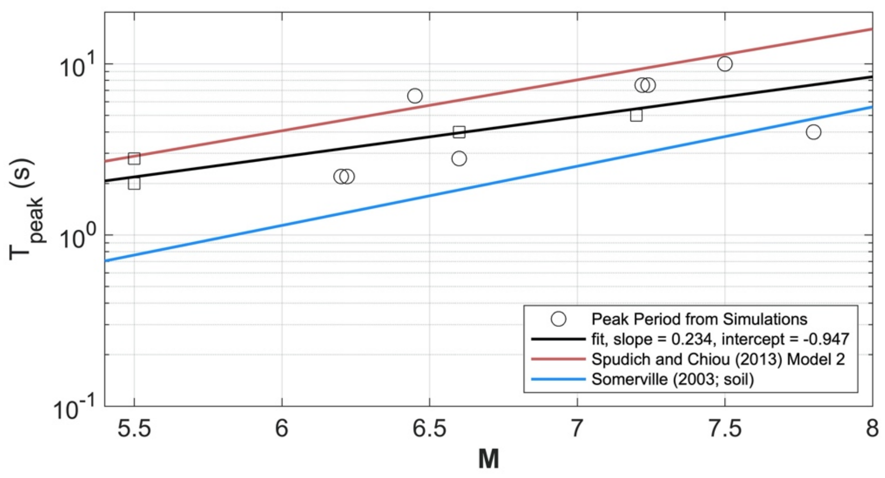
(4) Approach Overview

Stage 3: Iteration and Composite Result

– In each of these three stages we develop relationships for the peak slope, period of the peak slope, and the directivity predictor x-intercept (the value of the directivity predictor for which the directivity effect is zero on average) as a function of magnitude.





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(4) Approach Overview

Stage 4: Regression

- A nonlinear least squares regression is performed using the combined database (simulations and data) to derive the final model coefficients

- The aleatory variability adjustment model is derived from analysis of the NGA-W2 finite-faults events (see description in report for more details)

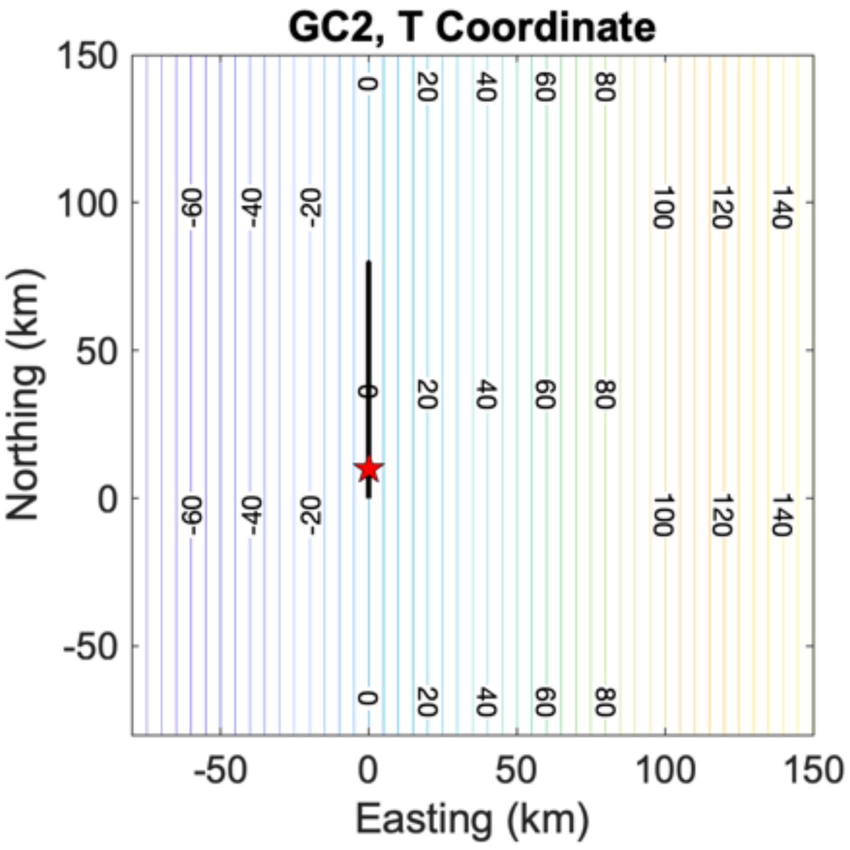
(5) Examples

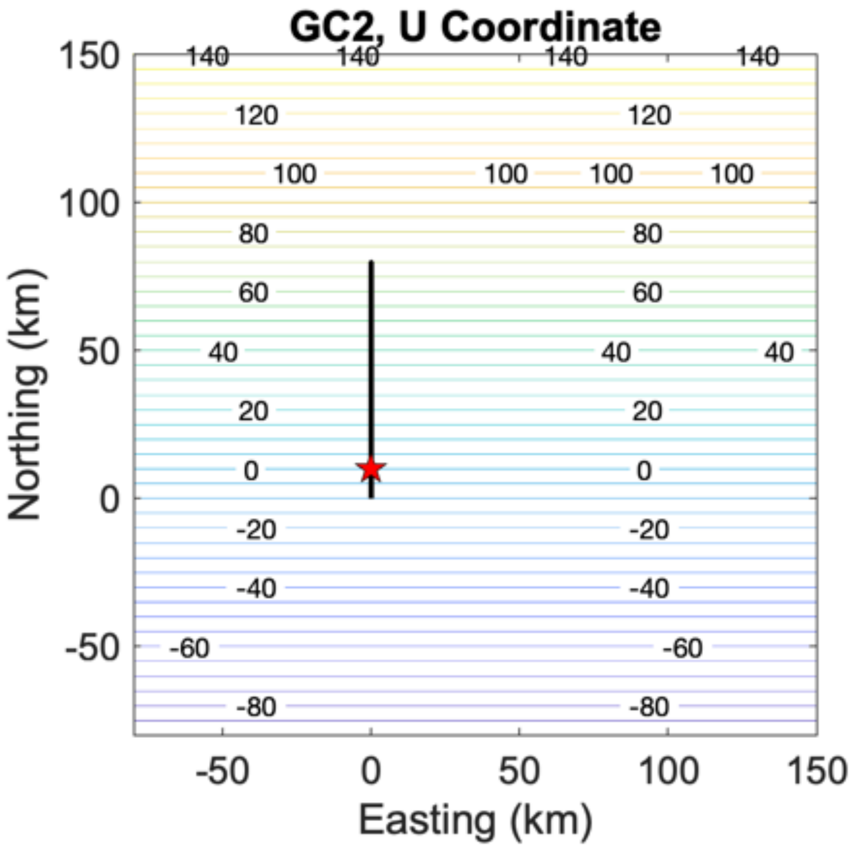
A selection of examples from our USGS report, see that report for more

(5) Examples

Example 1: Vertical Strike Slip

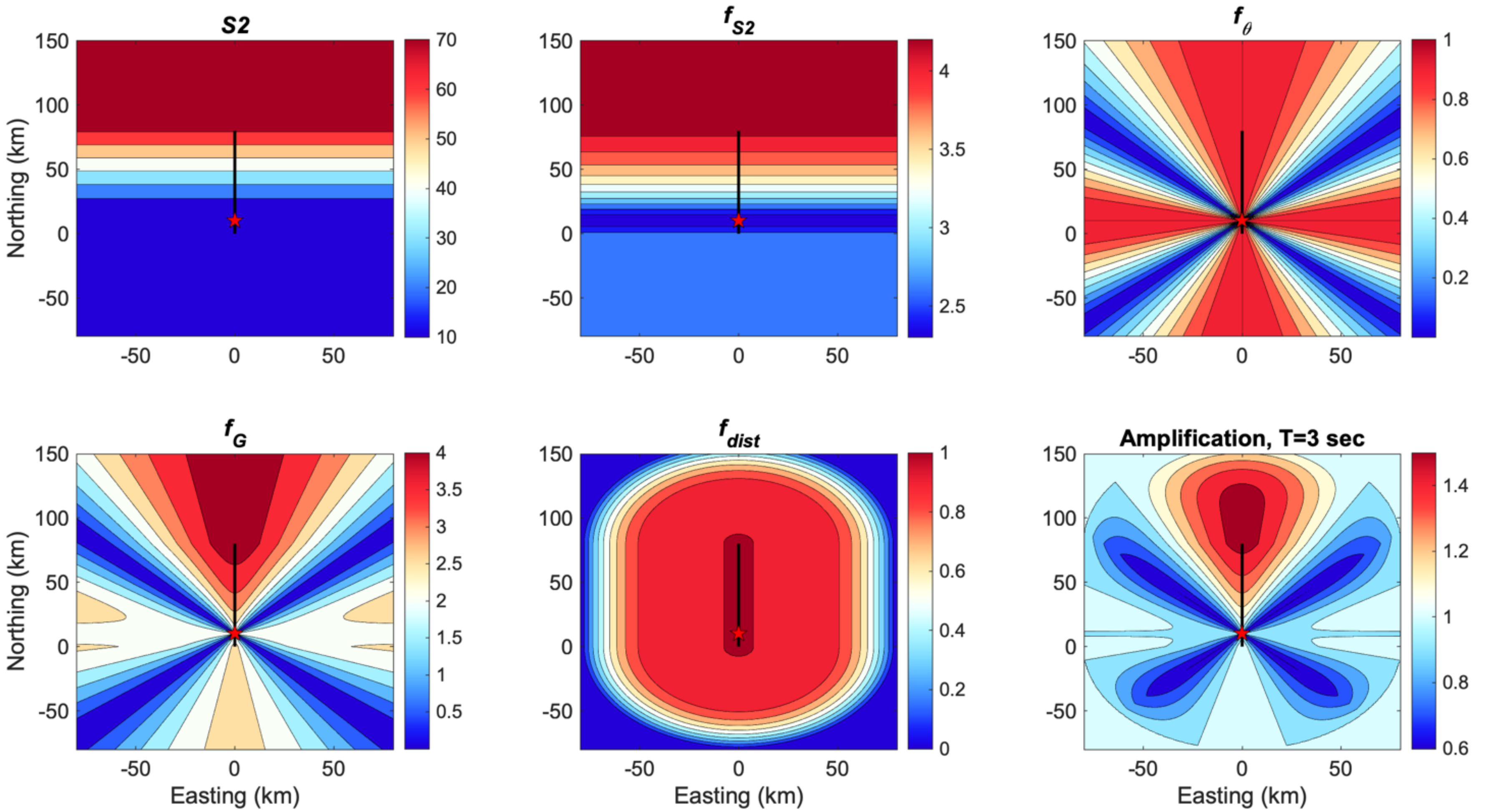
- A **M**7.2 vertical strike-slip rupture with rake angle of 180 degrees, and with length of 80 km and down-dip width of 15 km. The hypocenter is located 10 km from the southern end of the rupture, at 10 km depth





(5) Examples

Example 1: Vertical Strike Slip



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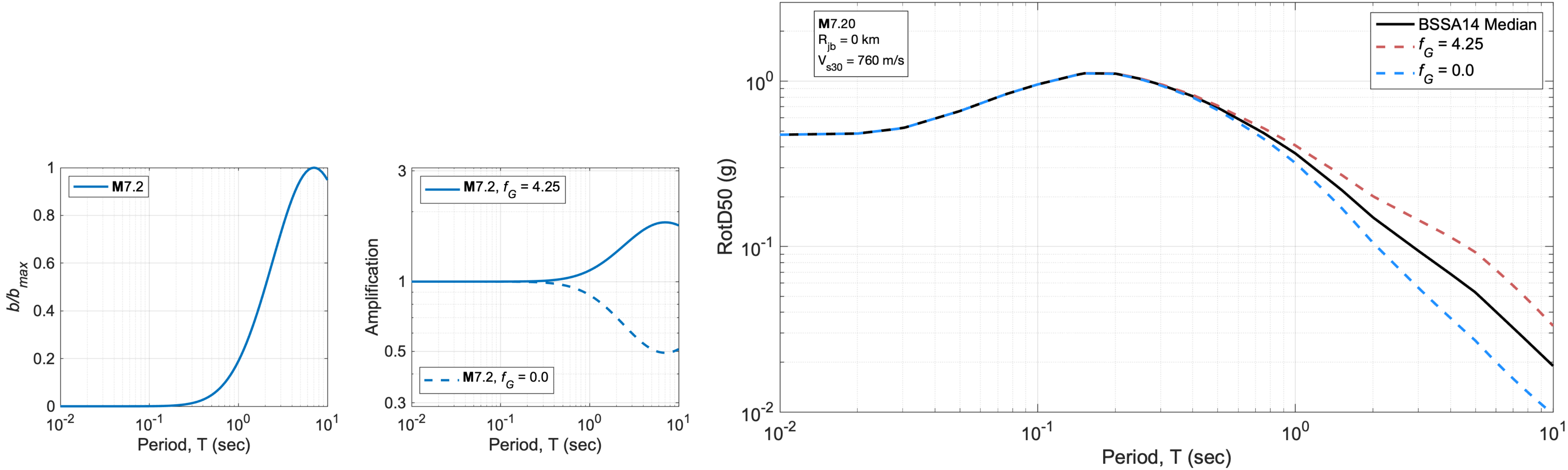
(5) Examples

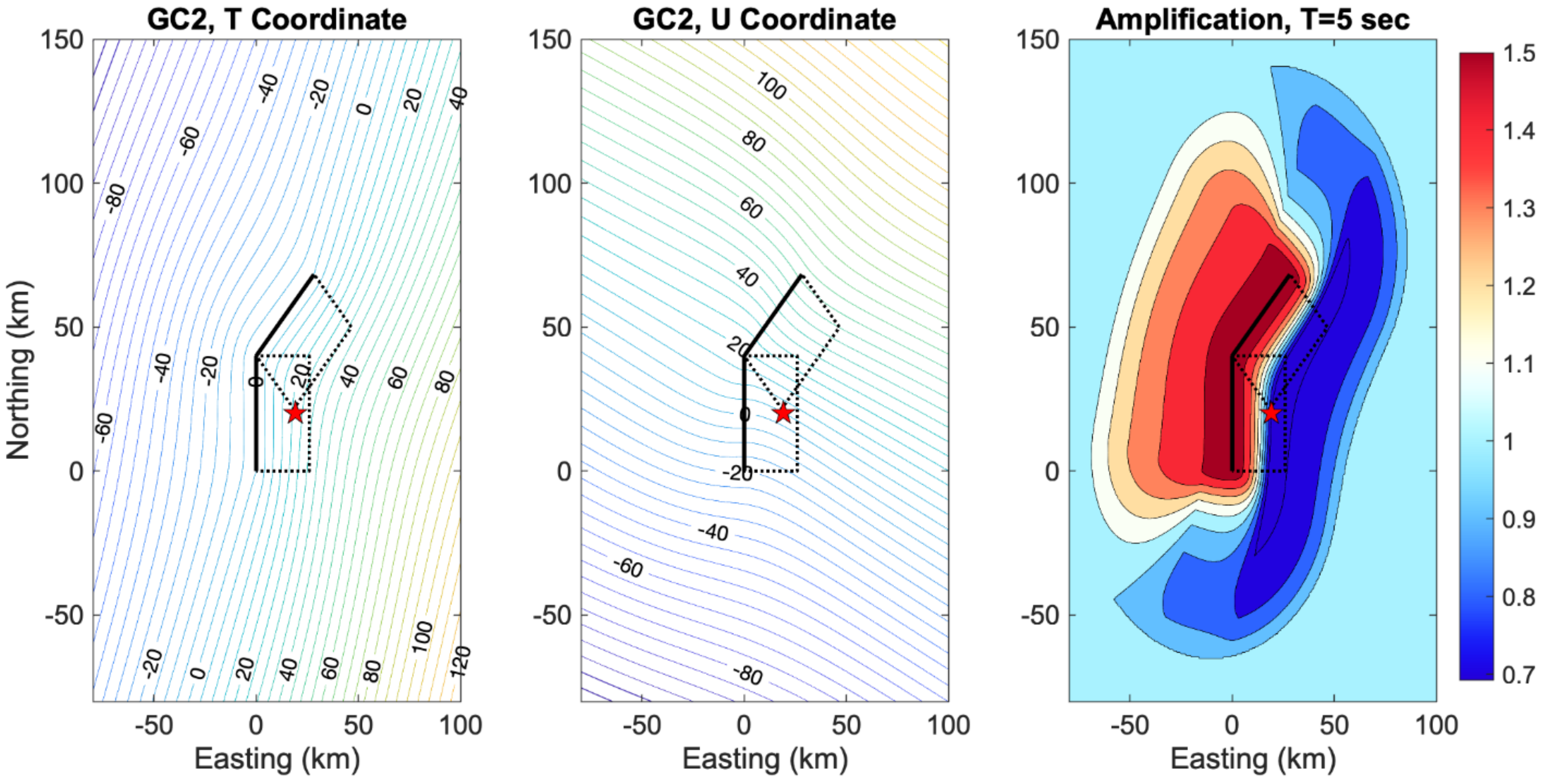
Example 1: Vertical Strike Slip



(5) Examples

Example 4: Two-Segment reverse

– A **M**7.5 reverse faulting rupture with a 45-degree bend at the midpoint. The rupture has 30-degree dip on both segments, 90-degree rake, total length of 80 km, down-dip width of 30 km, and rupture reaches the ground surface. The hypocenter is located 20 km along strike from the southern trace endpoint and at a depth of 11 km



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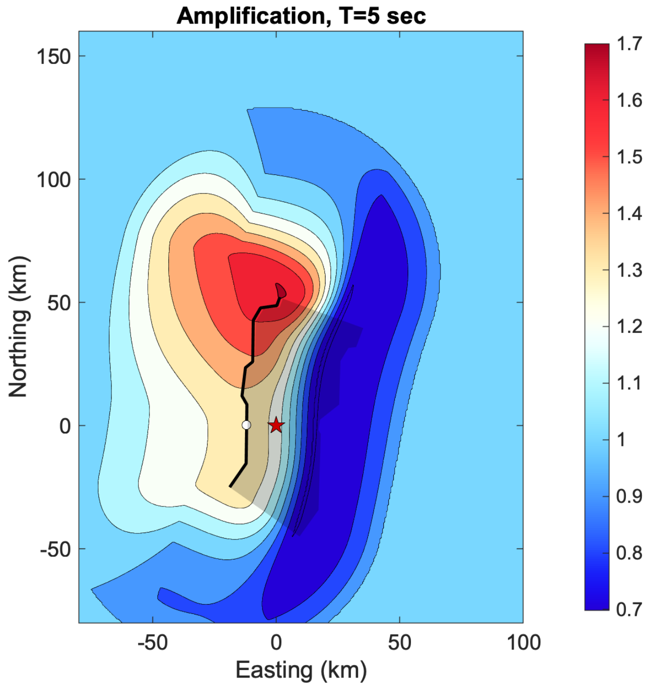
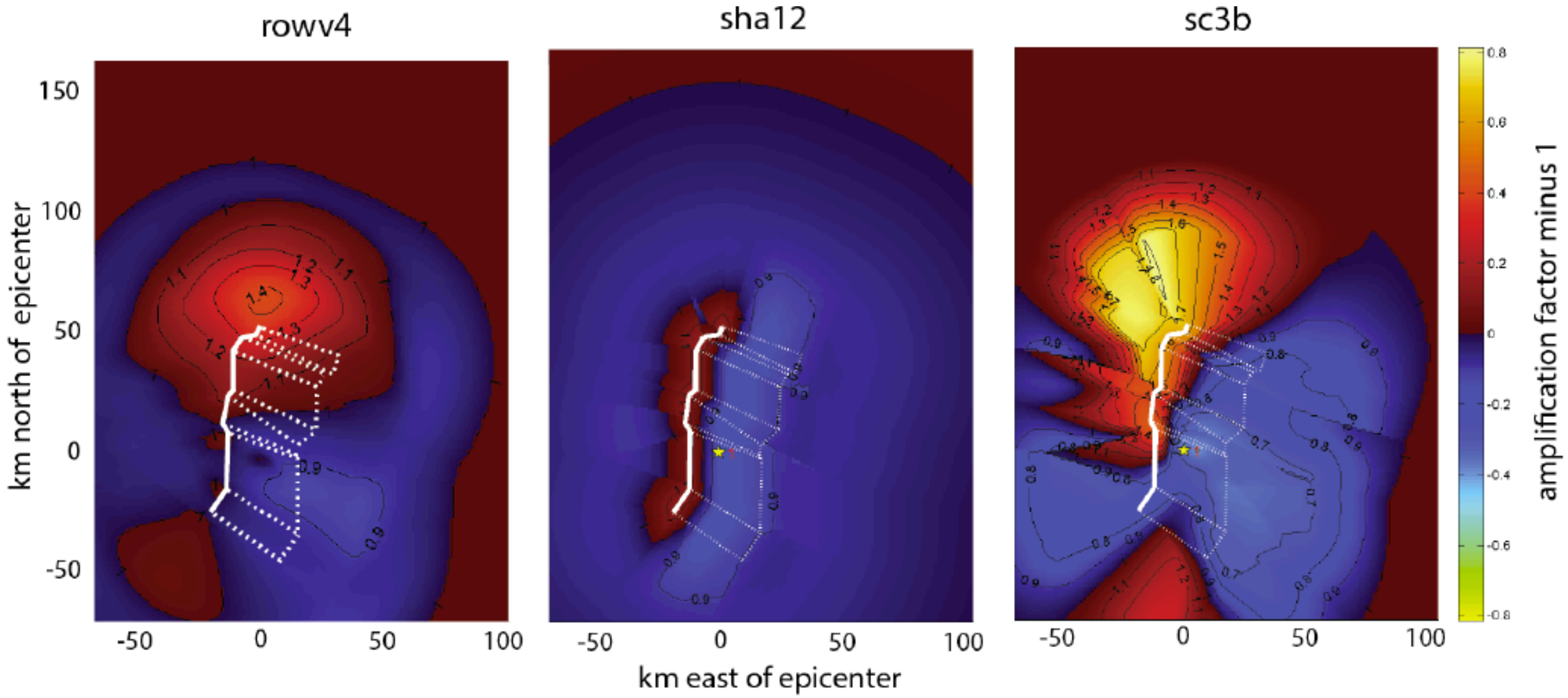
(5) Examples

Example 5: Chi-Chi

From Spudich et al (2013)
possibly outdated

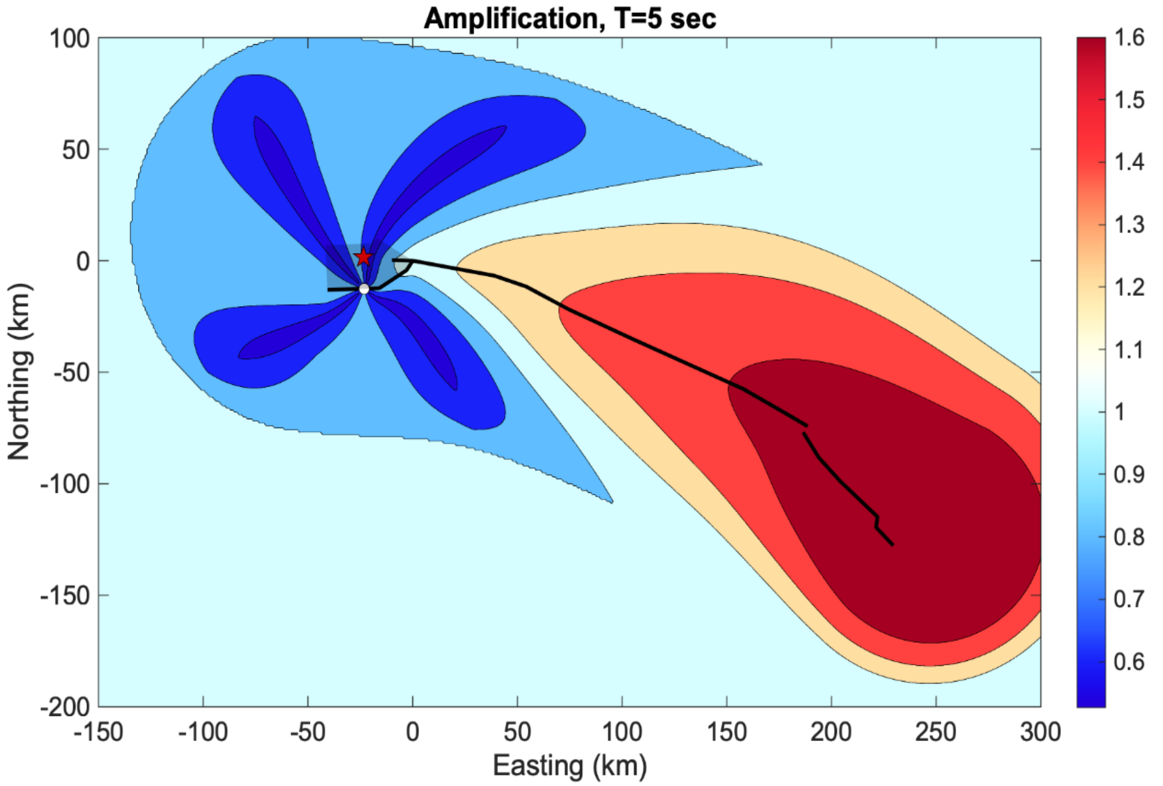


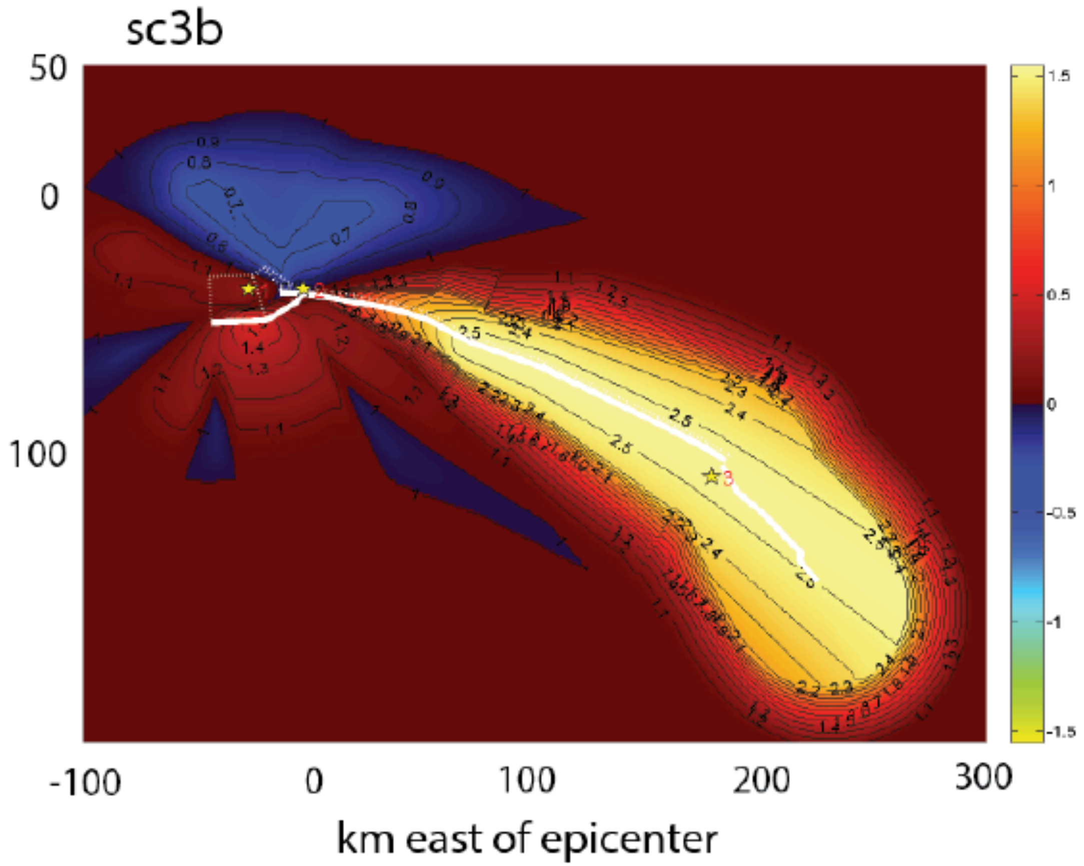


(5) Examples

Example 7: Denali

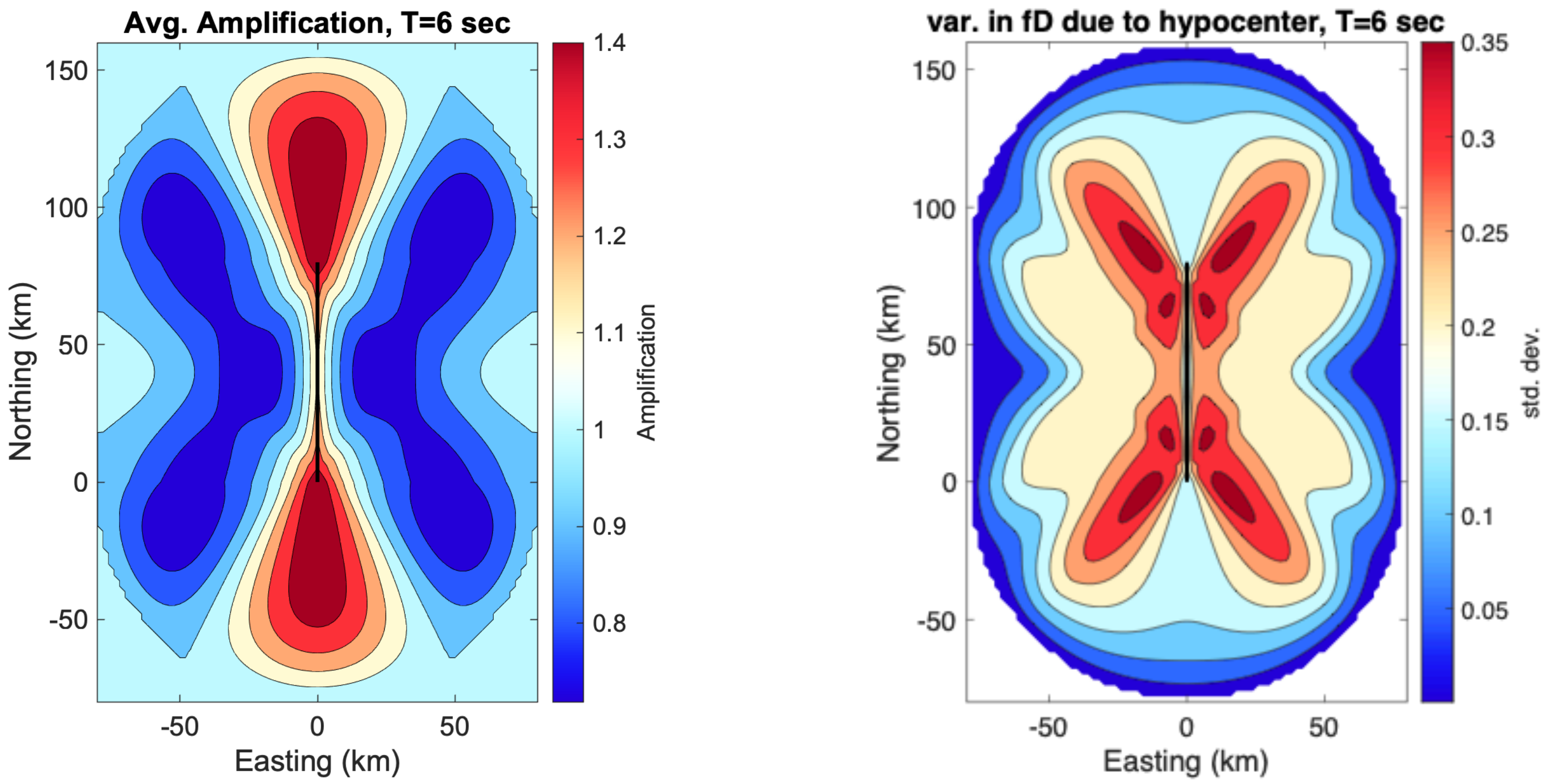
From Spudich et al (2013)
possibly outdated





(5) Examples

Example 9: Hypocenter randomization



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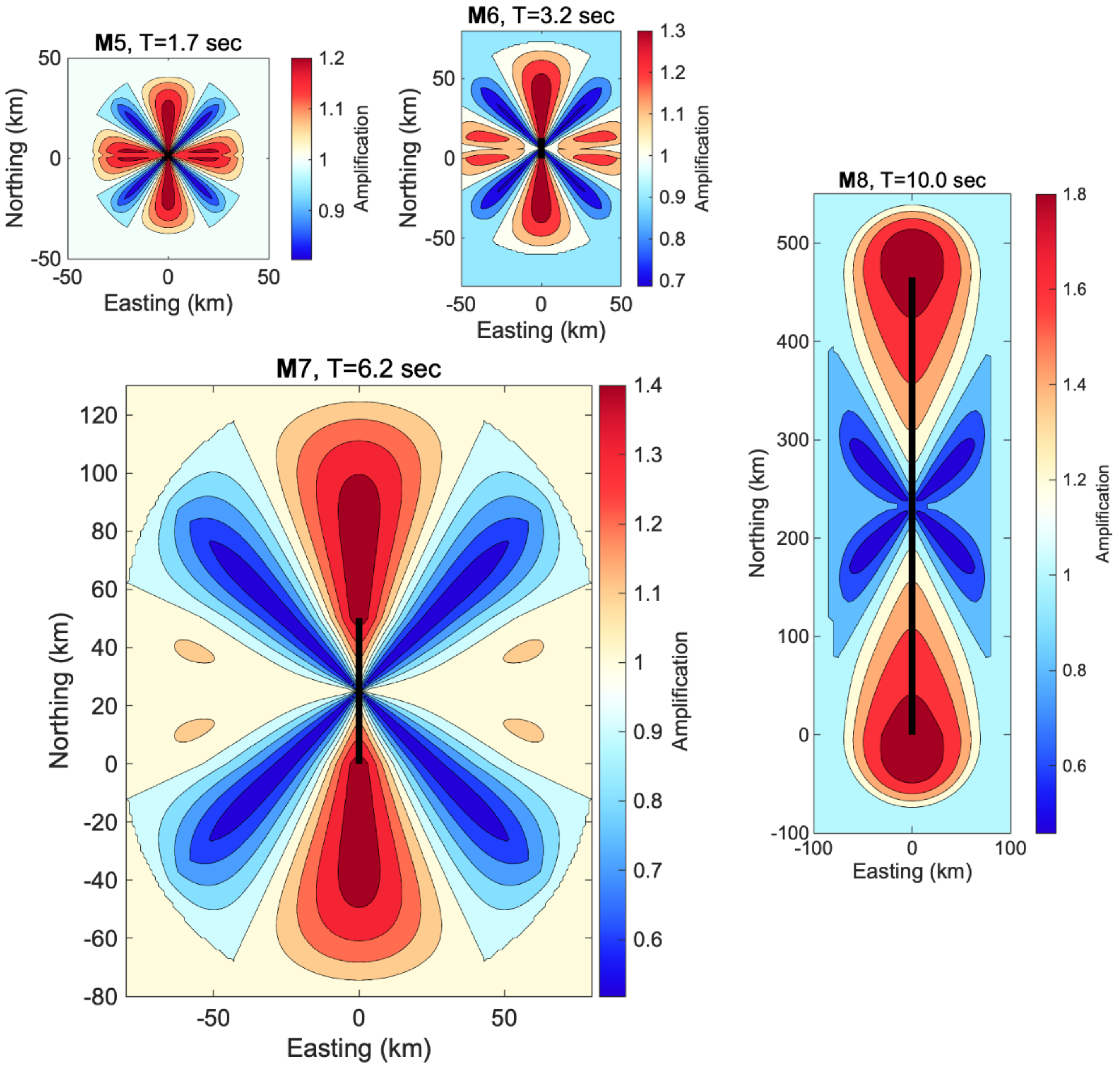
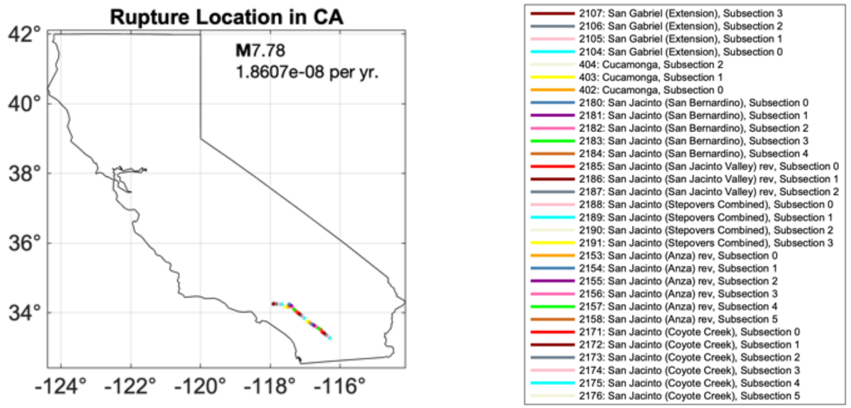
(5) Examples

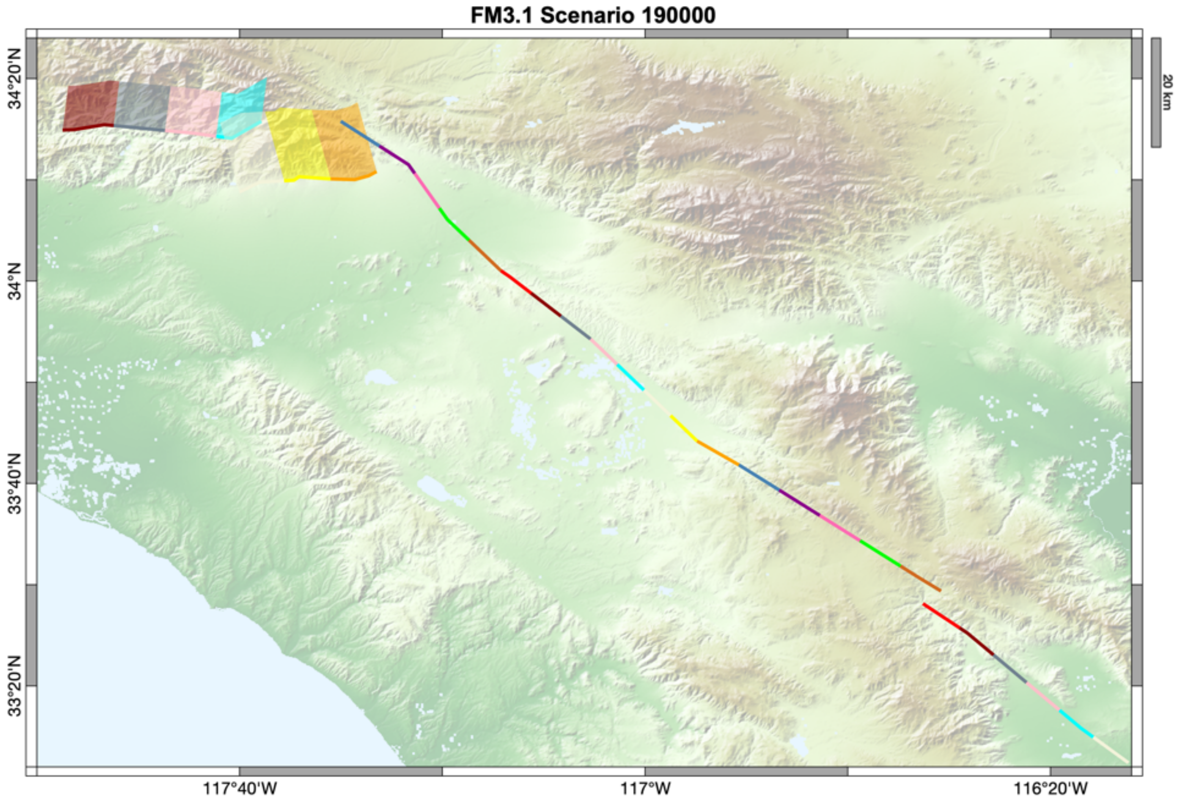
Example 10: Mag-scaling for SS



(6) Future steps

- Check (and potential justification) of the aleatory variability increase associated with hypocenter randomization, compared with the reduction model
- more complete comparison with other directivity models, including BS13 and Chiou and Youngs (2014).
- Provide instructions for using the model in PSHA
- Provide example PSHA implementations for simple earthquake forecasts
- Test the model application to UCERF3-style Ruptures and PSHA (e.g. at right)
- Explore creation of a directivity adjustment map database for the state of California using the catalog of UCERF3 scenarios, including hypocenter randomization? (no hypocenter randomization needed)





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