Hanging-Wall and Directivity Effects on the Near-Fault Ground Motions

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Simulations and Near-Fault Effects

- Estimation of near-fault effects are hindered by the deficiency of near-fault data
- Simulation tool set has been very valuable
- NGA projects used simulation results to guide the formulation and estimation of
    - Hanging-wall effect (Donahue and Abrahamson, 2014)
    - Nonlinear response of shallow soft soil under strong loading conditions (Walling et al., 2008; Kamai et al., 2014)
    - Basin response (Day et al., 2008)

Simulations and Near-Fault Ground Motions

- Two more examples of the utilities of simulations

  - Hanging-wall effects near a listric fault (dip decreases with depth)
    - Modify published HW factors to account for the change in fault dip at larger depth
    - Simulation method: EXSIM (Atkinson and others, 2016)

  - Directivity effects near a reverse earthquake
    - Whether along-strike rupture contributes to directivity effects of reverse earthquake or not?
    - Simulation method: Graves and Pitarka (2010)

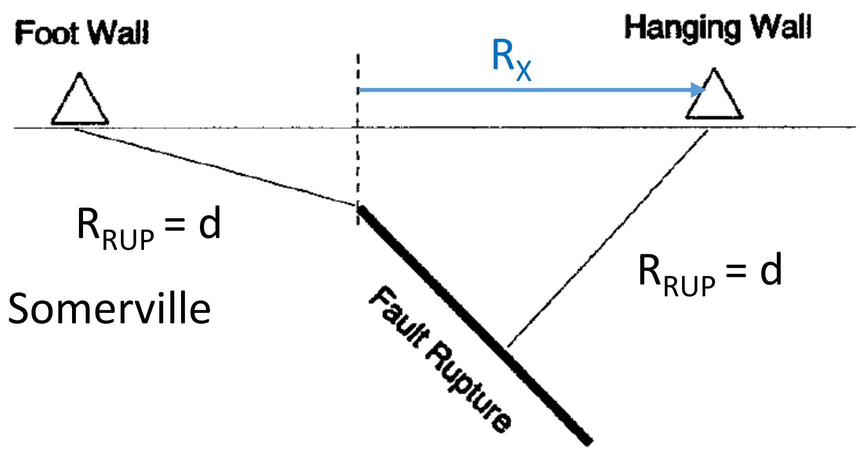
Selecting Simulation Methods

- Must use properly calibrated and validated methods

- As part of the SCEC Broadband Platform (Dreger et al. 2016), both simulation methods have been calibrated and validated against
  - Ground-motion data from a selected set of well-recorded earthquakes (Part A validation)
  - Median predictions of published NGA-2 GMPEs (Part B validation)

Hanging-Wall Effects in NGA GMPEs

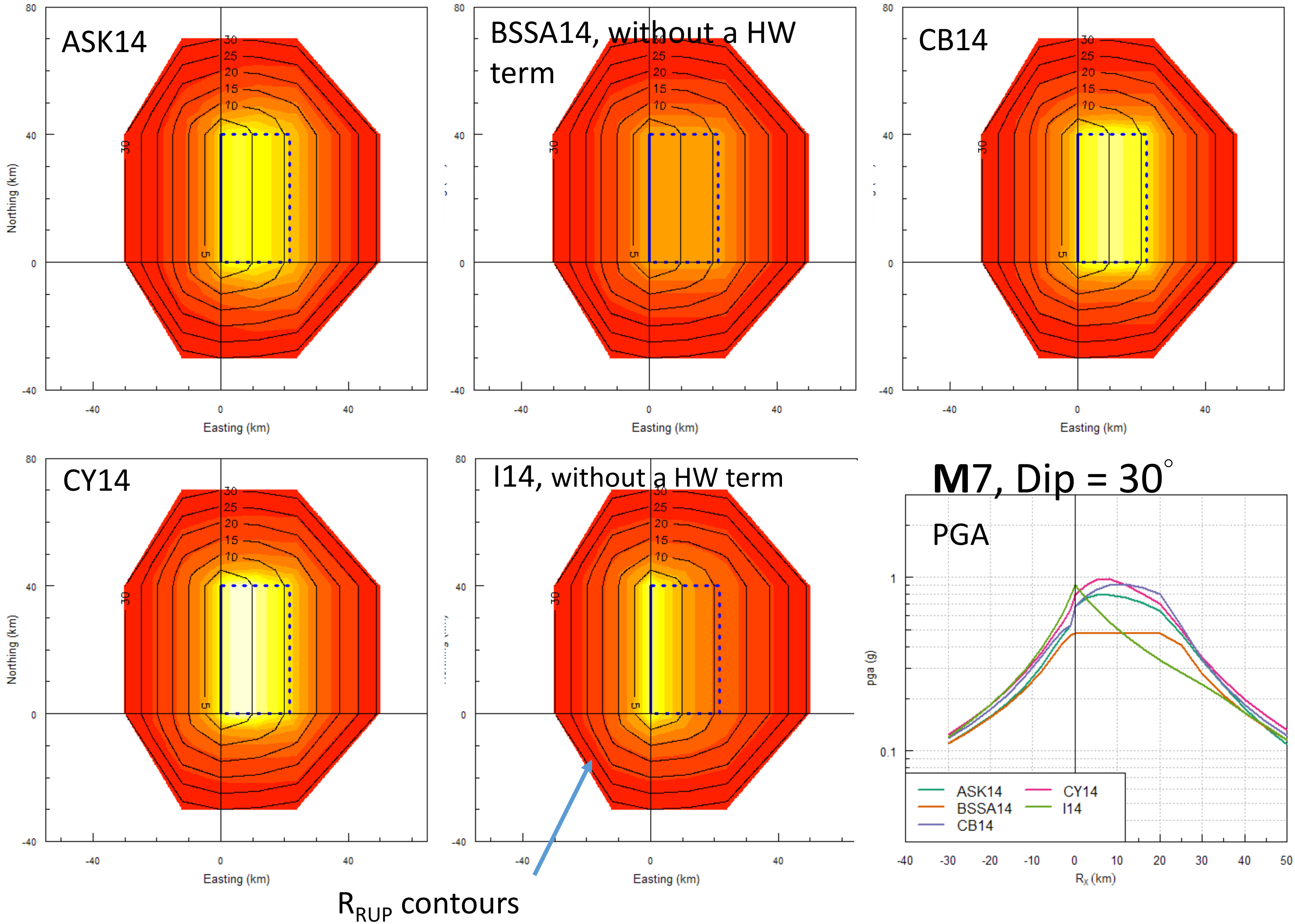
- Larger *psa* on hanging wall (HW) compared to the equal-distance counterpart on foot wall (FW)



From Abrahamson and Somerville (1996)

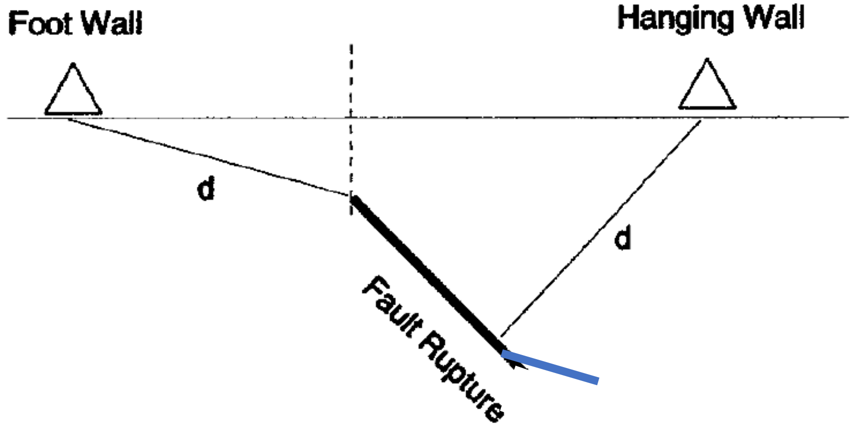
- Geometric effect

$$F_{HW} = \frac{psa_{HW}}{psa_{FW}} > 1$$


ASK14
BSSA14, without a HW term
CB14
CY14
I14, without a HW term
M7, Dip = 30°
PGA
Northing (km)
Easting (km)
30
25
20
15
10
5
80
40
0
-40
pga (g)
1
0.1
-40
-30
-20
-10
0
10
20
30
40
50
R_X (km)
ASK14
BSSA14
CB14
CY14
I14
R_{RUP} contours

- HW Amplification Factor (F_{HW}) is dependent on **M**, R_X, Dip, Z_{TOR}, spectral period (T)
  - Reduced as Dip increases
  - Reduced as Z_{TOR} increases
  - Reduced as spectral period increases

Are the NGA GMPEs Still Applicable if Dip Changes with Depth?

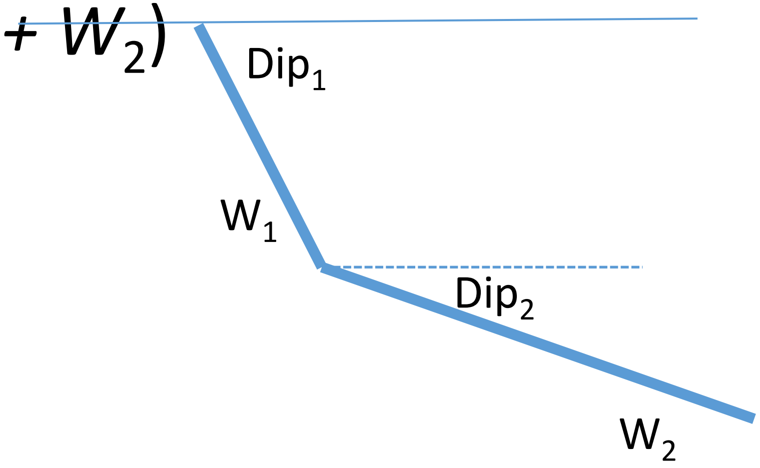


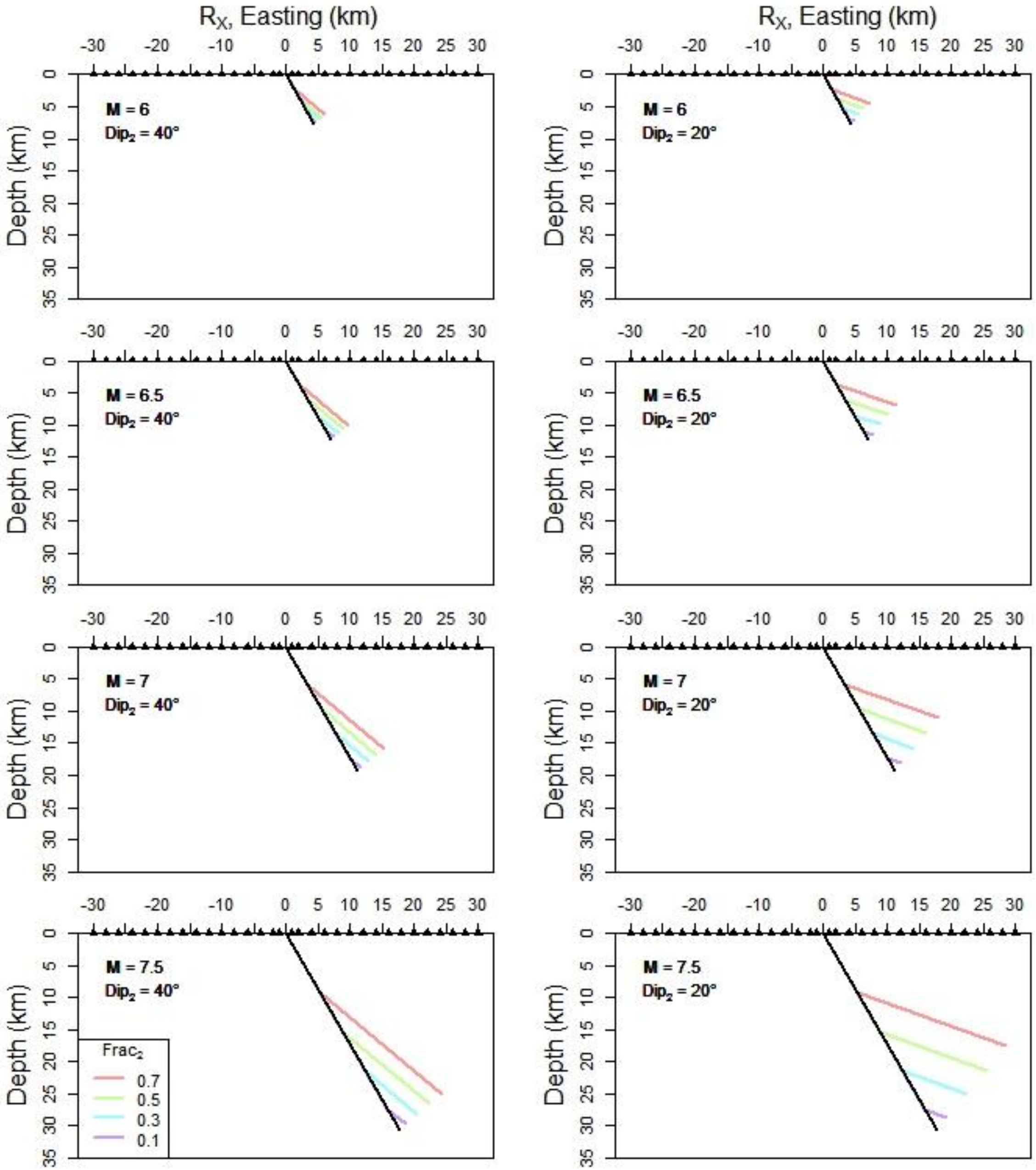
Simulate Ground Motions of Listric Faults

- Use EXSIM
  - It is calibrated and validated
  - It captures the geometrical effect that cause hanging wall amplification
  - It is easy to use and efficient computationally
    - 1080 simulations at 32 sites took less than 48 hours on a i5 (2.2 GHz) laptop
  - It is straightforward to extend EXSIM to model the geometry of listric fault (and complex fault)

Attributes of the Second Segment of a Two-Segment Listric Fault

- Dip_2 (< Dip_1)
- $Frac_2 = W_2 / (W_1 + W_2)$

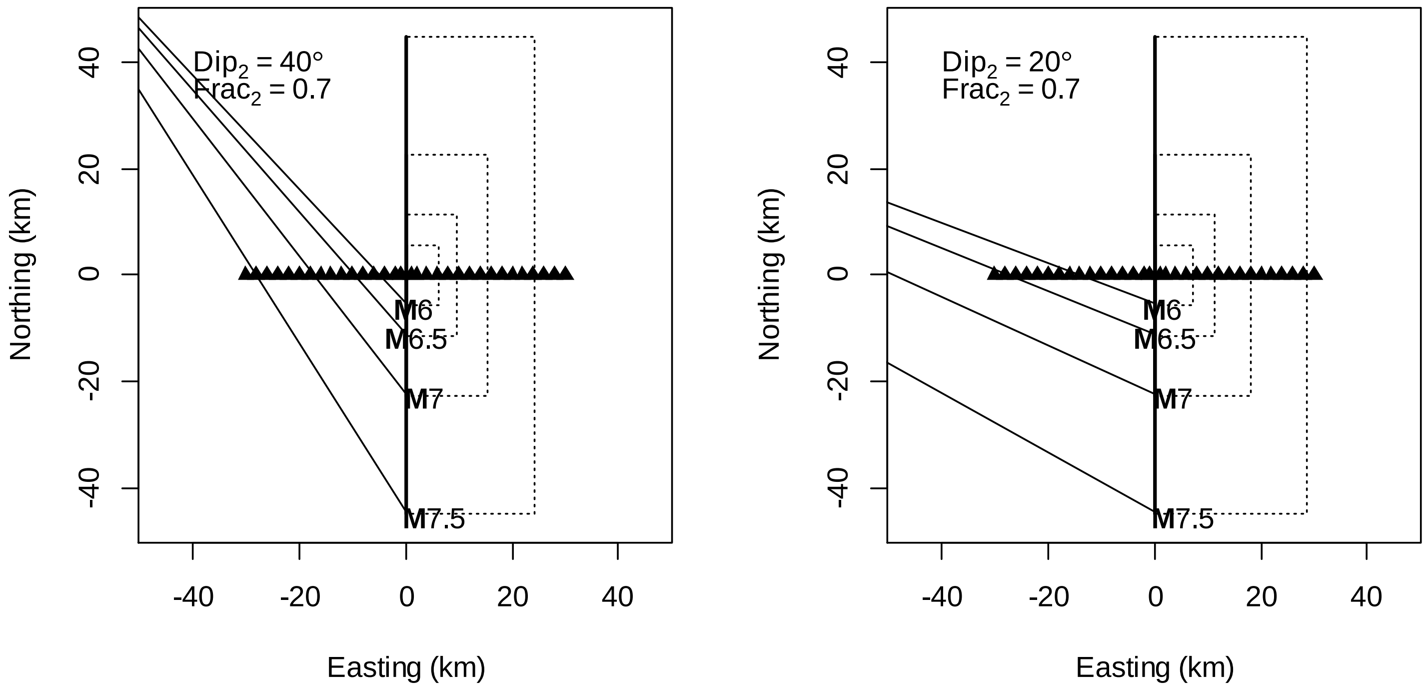




- $Dip_1 = 60^{\circ}$
- $Z_{TOR} = 0$
- **M** = 6, 6.5, 7.0, 7.5
- $Frac_2$ = 0.1, 0.3, 0.5, 0.7
- $Dip_2 = 40^{\circ}, 20^{\circ}$

36 Faults

- 30 realizations of slip and hypocenter position

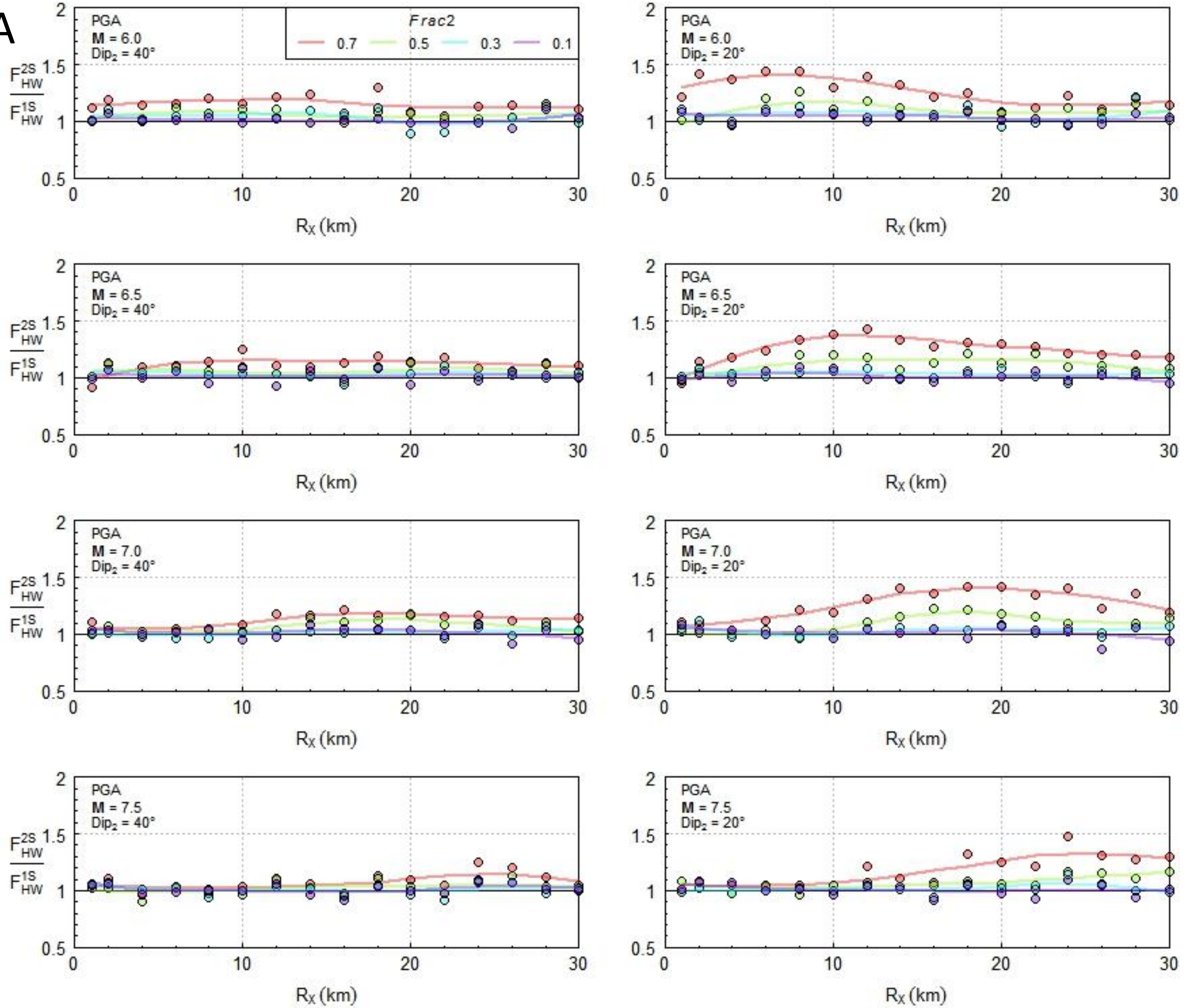


$Dip_2 = 40°$
$Frac_2 = 0.7$
M6
M6.5
M7
M7.5
Northing (km)
Easting (km)
40
20
0
-20
-40
$Dip_2 = 20°$
$Frac_2 = 0.7$
M6
M6.5
M7
M7.5
Northing (km)
Easting (km)

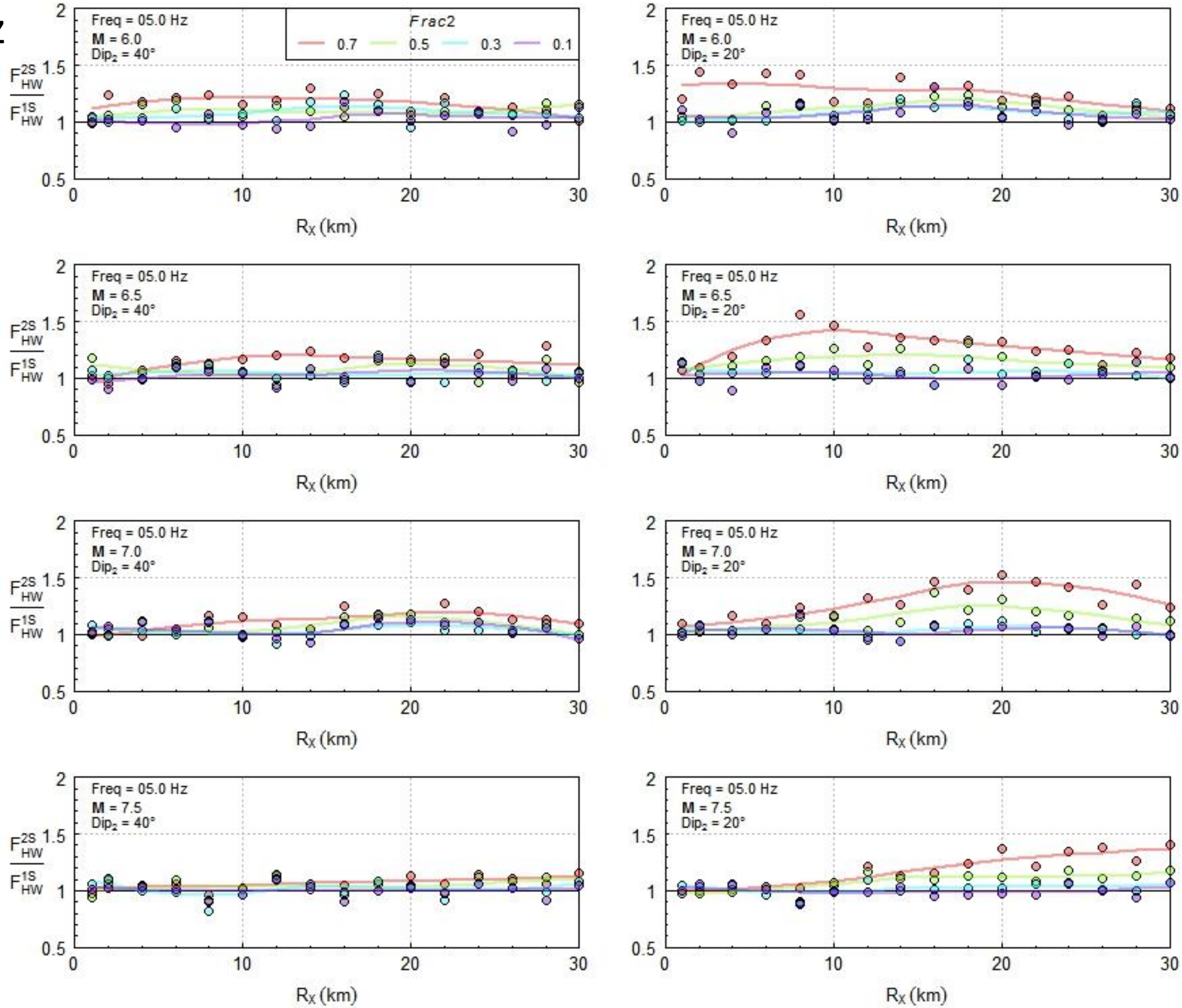
32 Sites

- Impact on F_{HW} is quantified as the ratio $\frac{F_{HW}^{2S}}{F_{HW}^{1S}}$
  - F_{HW}^{2S} = simulated HW factor for 2-segment fault
  - F_{HW}^{1S}= simulated HW factor for 1-segment (straight) fault

PGA


PGA
M = 6.0
Dip₂ = 40°
Frac2
0.7
0.5
0.3
0.1
PGA
M = 6.0
Dip₂ = 20°
PGA
M = 6.5
Dip₂ = 40°
PGA
M = 6.5
Dip₂ = 20°
PGA
M = 7.0
Dip₂ = 40°
PGA
M = 7.0
Dip₂ = 20°
PGA
M = 7.5
Dip₂ = 40°
PGA
M = 7.5
Dip₂ = 20°
F2S HW / F1S HW
Rx (km)

5Hz


Frac2
0.7
0.5
0.3
0.1
Freq = 05.0 Hz
M = 6.0
Dip2 = 40°
Freq = 05.0 Hz
M = 6.0
Dip2 = 20°
Freq = 05.0 Hz
M = 6.5
Dip2 = 40°
Freq = 05.0 Hz
M = 6.5
Dip2 = 20°
Freq = 05.0 Hz
M = 7.0
Dip2 = 40°
Freq = 05.0 Hz
M = 7.0
Dip2 = 20°
Freq = 05.0 Hz
M = 7.5
Dip2 = 40°
Freq = 05.0 Hz
M = 7.5
Dip2 = 20°
F2S HW / F1S HW
RX (km)

Are the NGA GMPEs Still Applicable if Dip Changes with Depth?

- $Frac_2$ = 0.1 and 0.3
  - $\frac{F_{HW}^{2S}}{F_{HW}^{1S}} \sim 1$
- $Frac_2 > 0.3$
  - Further correction may be required
  - $\frac{F_{HW}^{2S}}{F_{HW}^{1S}}$ depends on Dip_2, R_X, $\mathbf{M}$, and spectral period

Directivity Effects

- Somerville et al. (1997)

- NGA-W2 Directivity Working Group (Spudich et al., 2013, 2014) accomplishments

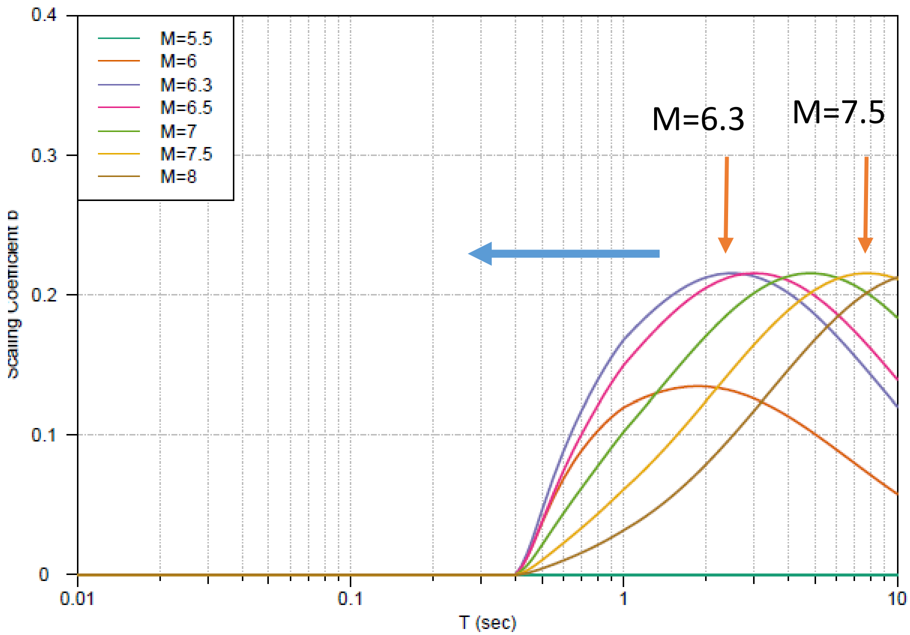
    - De-normalized predictor (so that directivity effect scales with magnitude)

    - Reference directivity condition (centering of predictor)

    - Some directivity models are narrow band

Narrow-band vs. broadband model

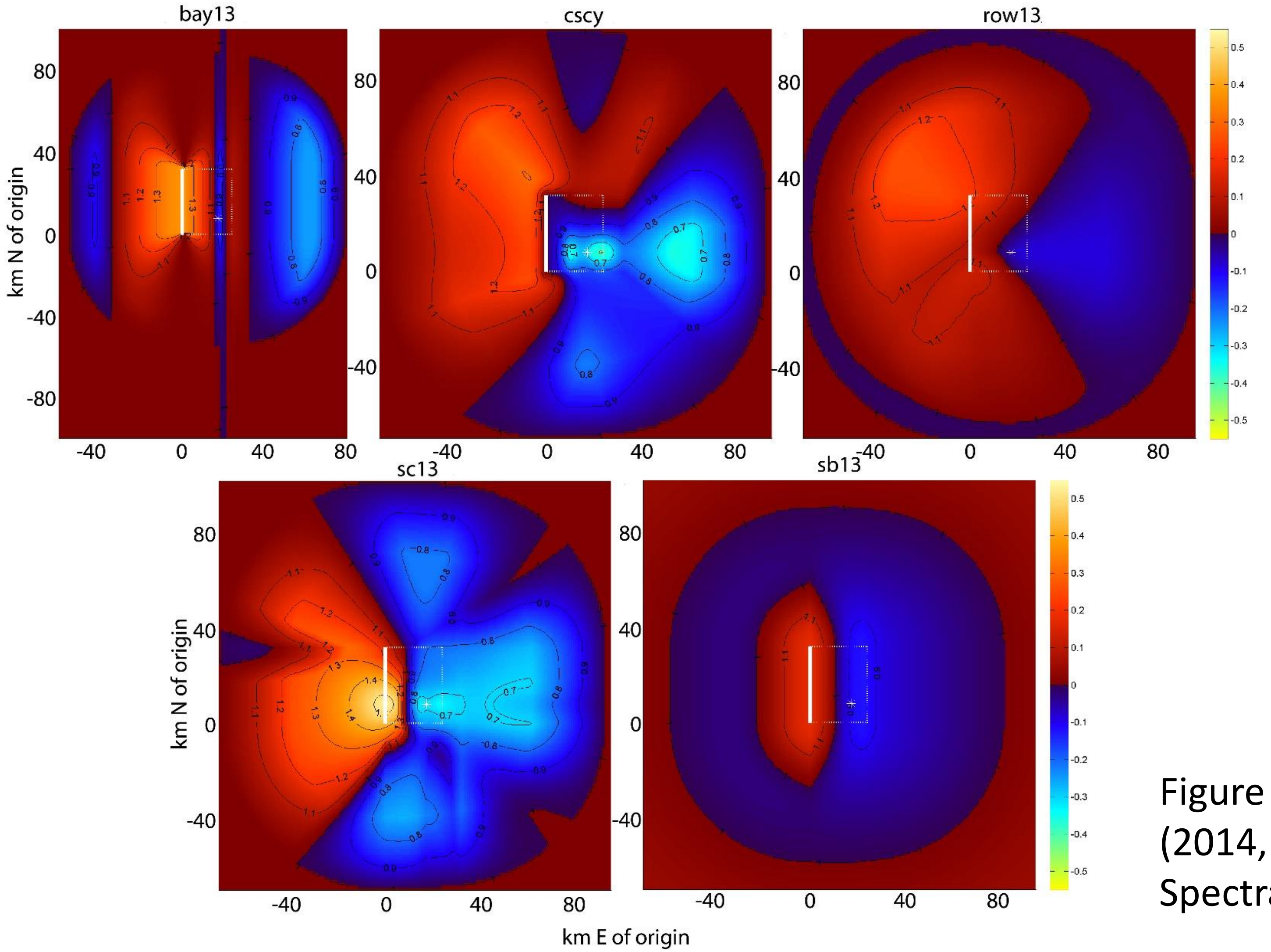
- Directivity effect is limited to a finite range of period
- The period of maximum effect increases with increasing magnitude



Directivity scaling of CY14

A model that transitions smoothly to small magnitude, if we have finite fault models for small and moderate earthquakes (M < 5.5)

T = 5 sec



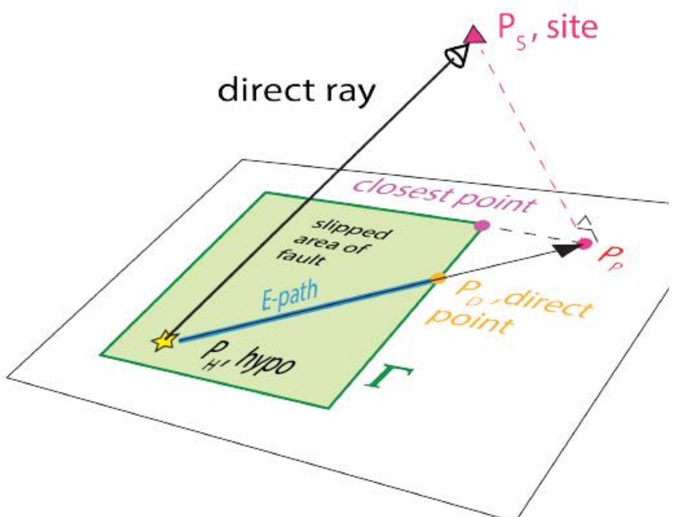
M7, Reverse, Dip = 30°

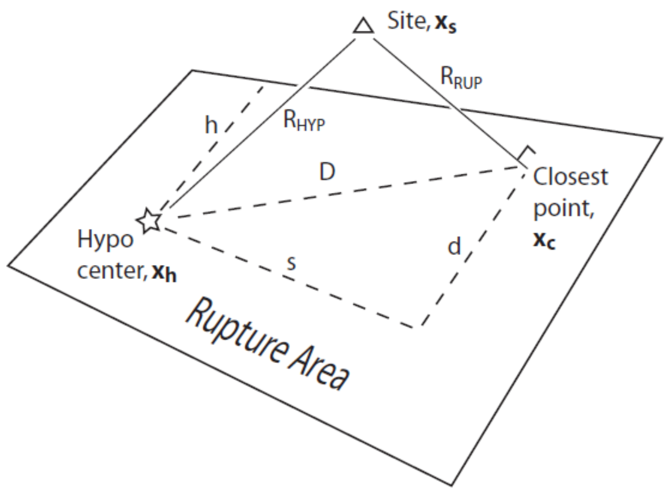
Figure 7 of Spudich et al. (2014, Earthquake Spectra)

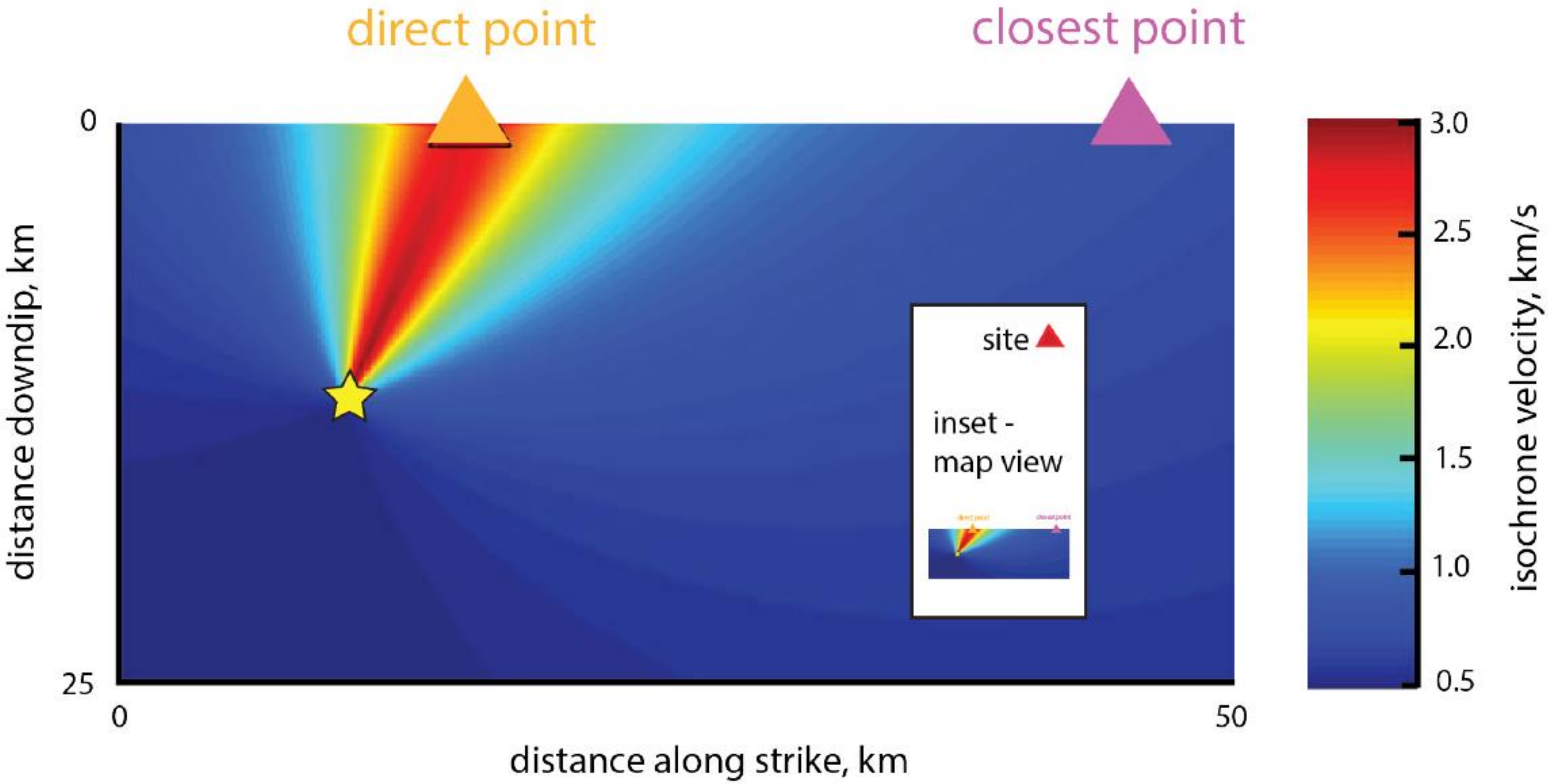
- Predicted amplitudes and spatial patterns of directivity effect differ among the 5 models

- The noted differences are thought to be the results of different assumptions in the directivity formulation

Model Formulation	Bayless & Somerville (bay13)	Chiou & Spudich/Chiou & Youngs (cscy)	Rowshendel (row13)	Shahi & Baker (sb13)	Spudich & Chiou (sc13)
Rupture Finiteness	Line source	Line source	Grid of subfaults	Line source	Line source
End Point of the Line Source	Closest Point	Direct Point	(NA)	Closest Point	Closest Point
The distance the rupture travels toward site	Strike Slip: *s* Dip Slip: *d* Oblique Slip: weighted ave.	Length of line source (*E*)	Sum of dot product $\vec{p} \cdot \vec{q}$	Strike Slip: *s* Dip Slip: *d*	Length of line source (*D*)
Radiation Pattern	Dip Slip: azimuth taper $(\sin(\|Az\|))^2$	Line source radiation pattern	Sum of dot product $\vec{s} \cdot \vec{q}$	Dip Slip: Excluded region	Radiation pattern of hypocenter







Courtesy of Paul Spudich

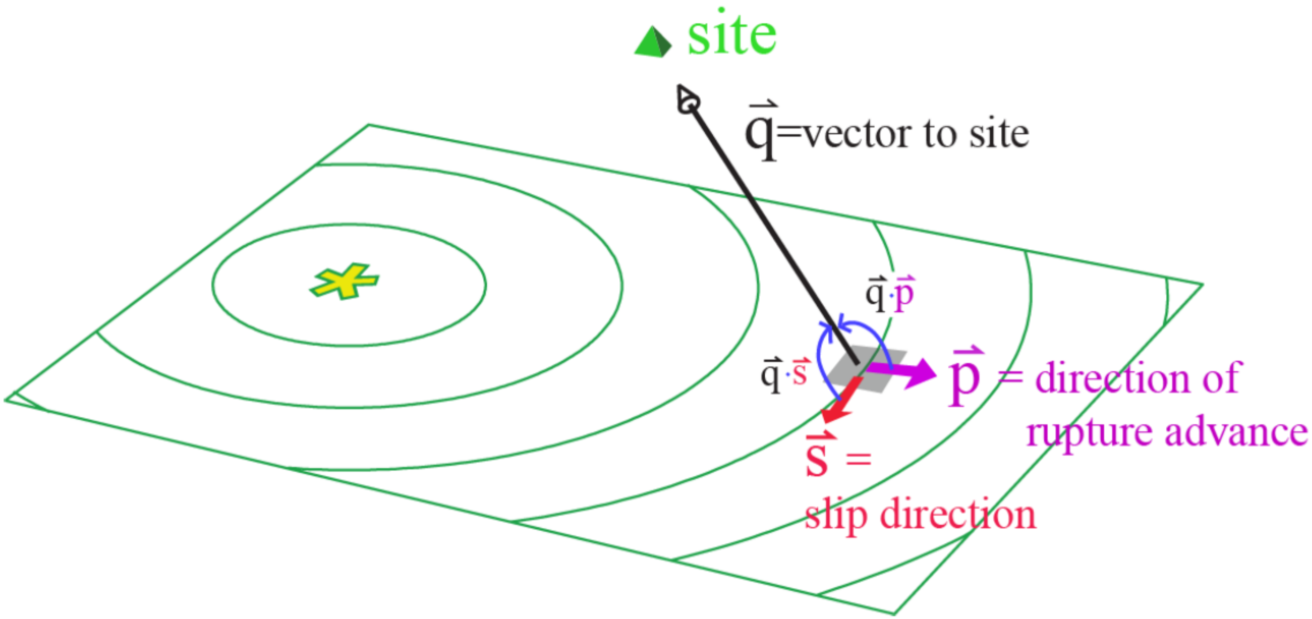


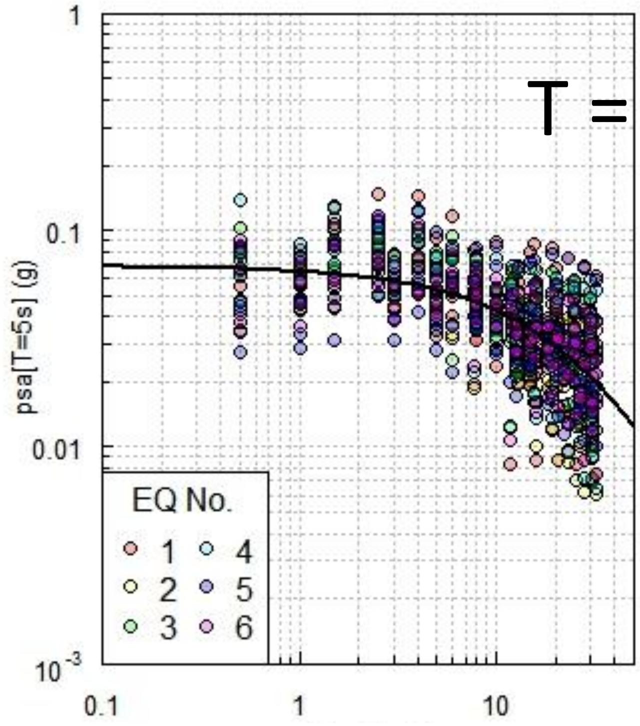
Figure 3.1 Graphical representation of the model.

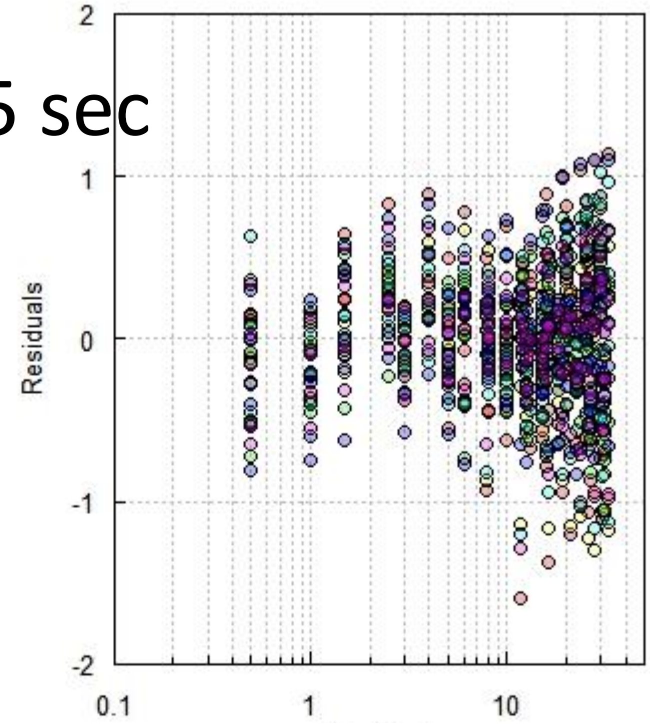
Spudich et al. (2013)

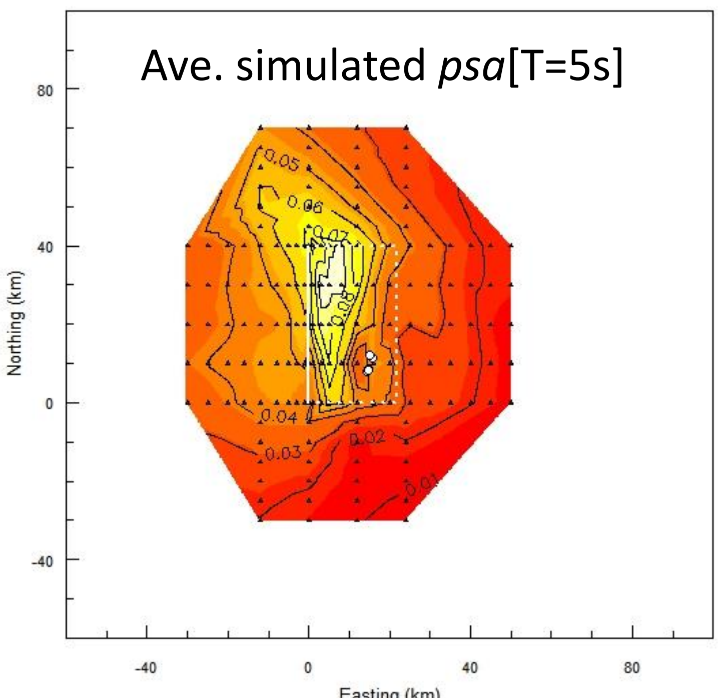
Does the Along-Strike Travel Distance of the Rupture Contribute to the Directivity Effects of Reverse Earthquakes?

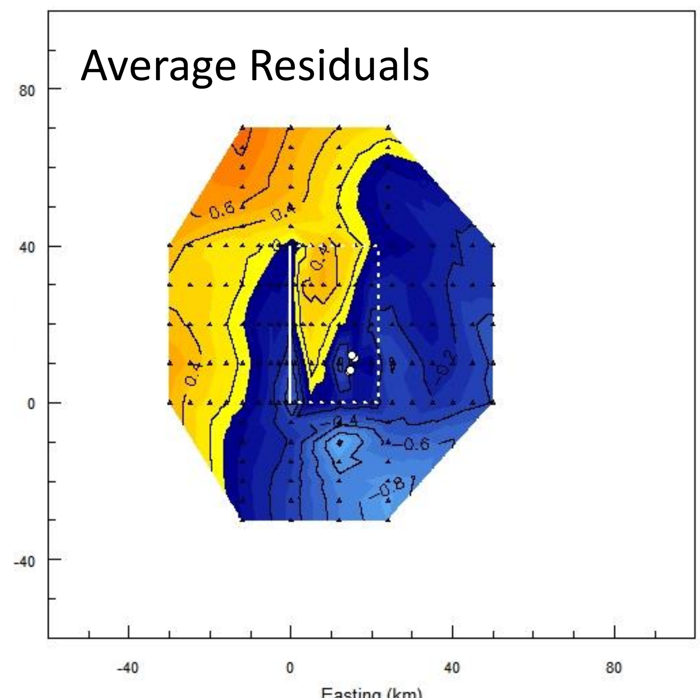
- NGA-W2 Simulations (Donahue and Abrahamson, 2014)
  - Graves and Pitarka (2010) method
  - Theoretical Green's function at short frequencies (f < 1Hz)
- Six scenarios are similar to the reverse fault used in Figure 7 of Spudich et al. (2014)

T = 5 sec

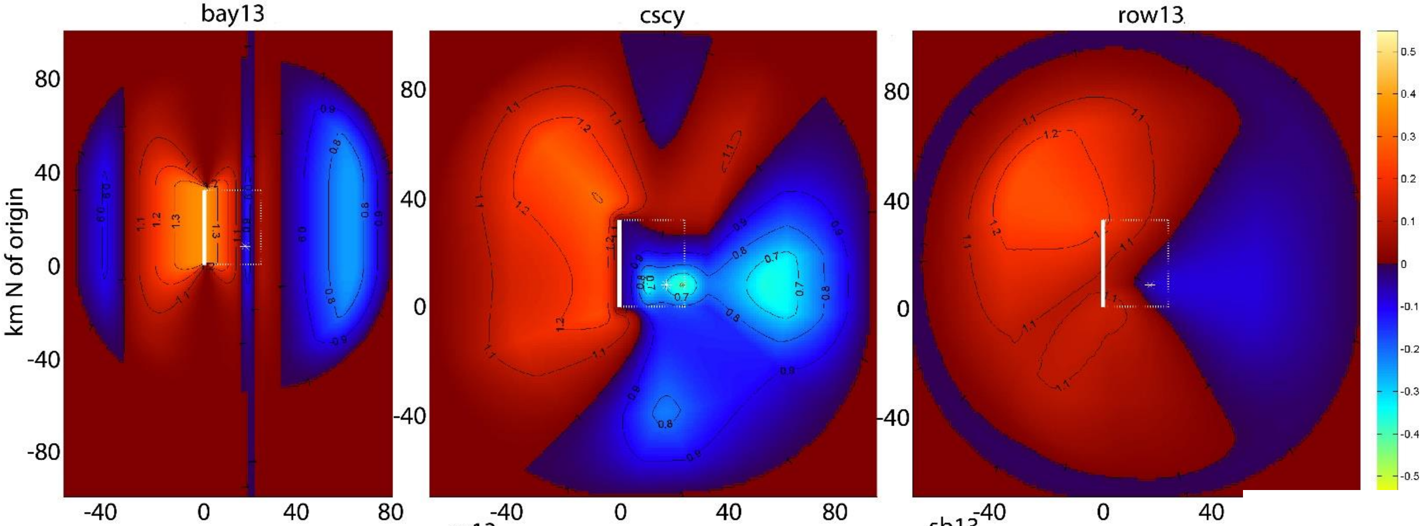

psa[T=5s] (g)
1
0.1
0.01
10^-3
0.1
1
10
EQ No.
1
2
3
4
5
6


Residuals
2
1
0
-1
-2
0.1
1
10

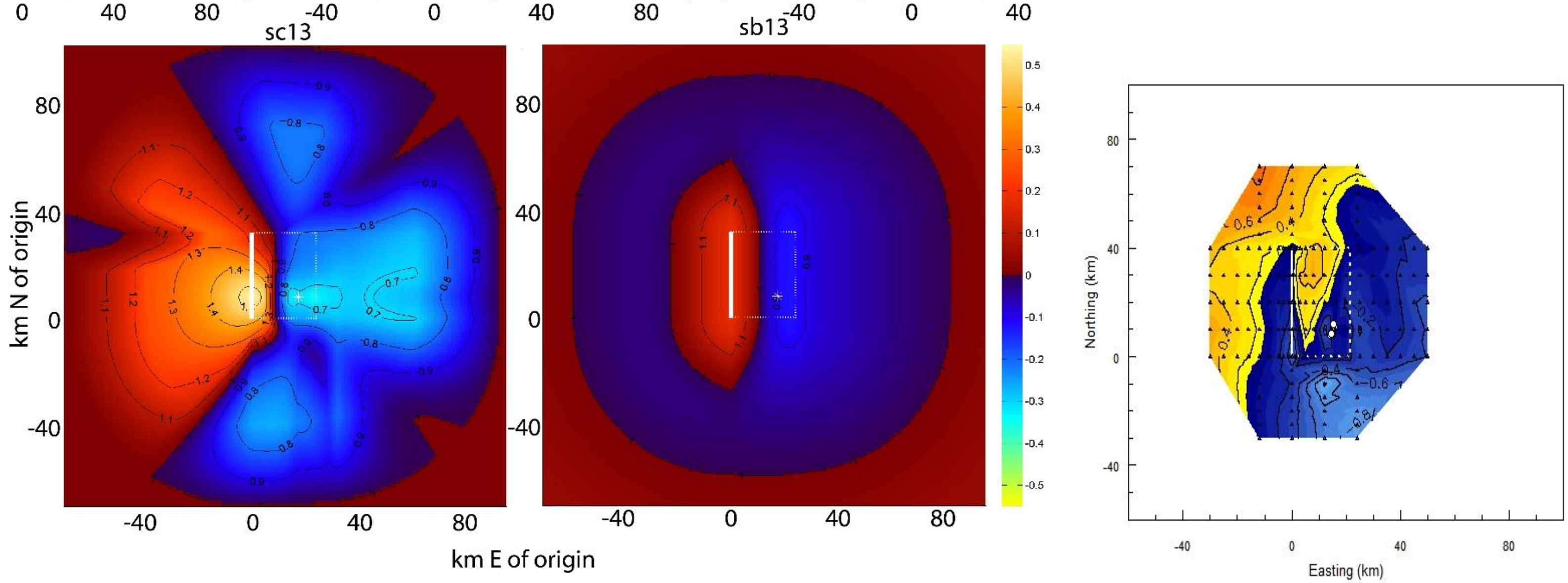

Ave. simulated psa[T=5s]
Northing (km)
Easting (km)
80
40
0
-40
0.05
0.06
0.07
0.08
0.04
0.03
0.02
0.01


Average Residuals
Easting (km)
80
40
0
-40
0.6
0.4
-0.4
-0.6
-0.8

T = 5 sec



M7, Reverse, Dip = 30°



Does the Along-Strike Travel Distance of the Rupture Contribute to the Directivity Effects of Reverse Earthquakes?

- Yes, according to NGA-W2 simulation results
- Simulations can and should be used to evaluate and qualify directivity models for use in hazard analysis

Conclusions

- Simulation is a valuable tool for the studies of near-fault ground motions
- But, must use properly calibrated and validated methods
- Simulation can be used to extend the applicable range of existing GMPEs, such as their applicability to listric faults
- Simulation can (and should) be used to evaluate and qualify models among the set of candidate directivity models
- Can simulation be routinely used to generate ground motion ‘data’ for use in the seismic design of critical structure?