Ground motions from dynamic models: Contribution of earthquake dynamics to strong ground motion prediction

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- Ergodic and non-ergodic process: Ground Motion Variability and the role of GMPEs and Physics-Based models.
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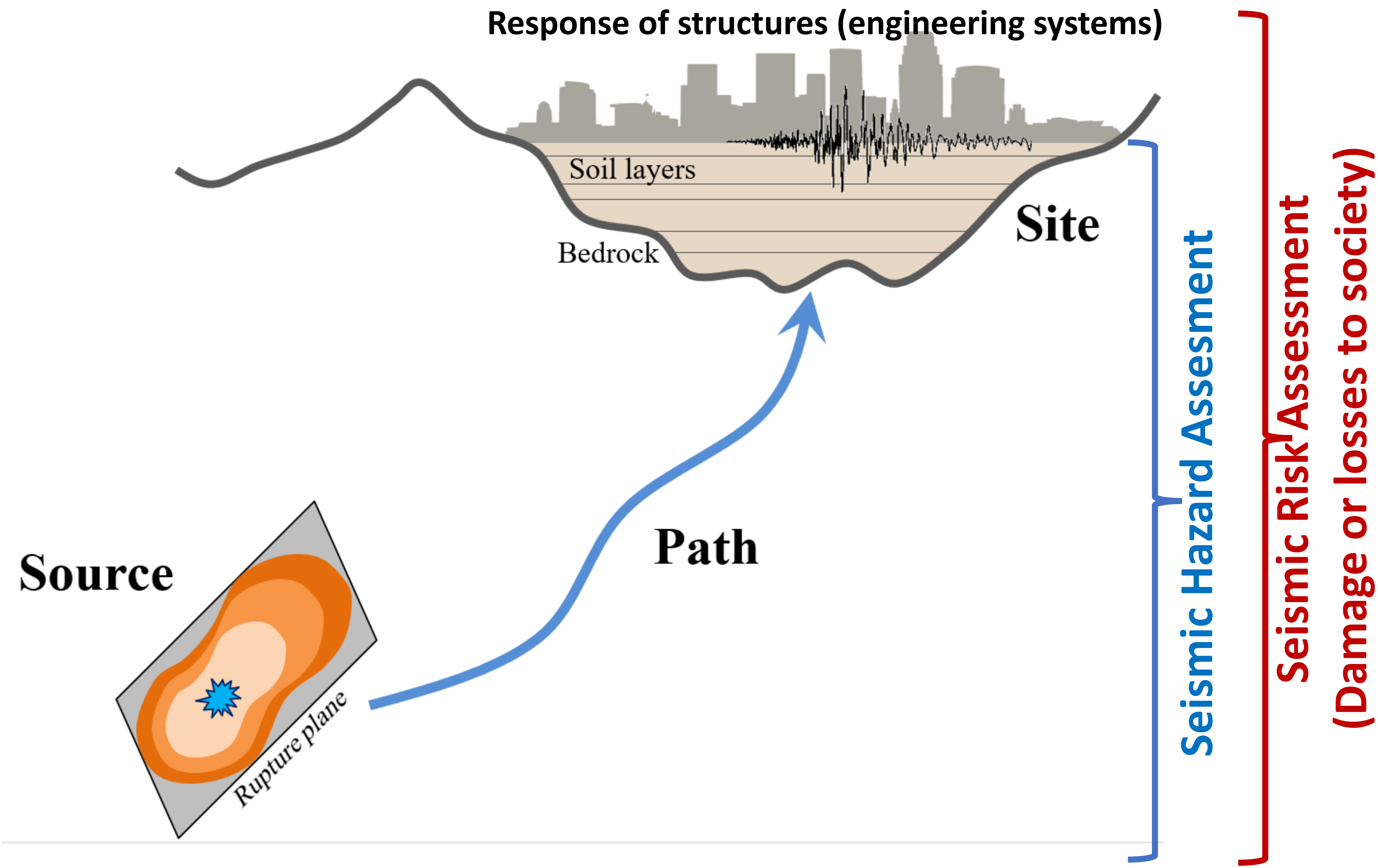
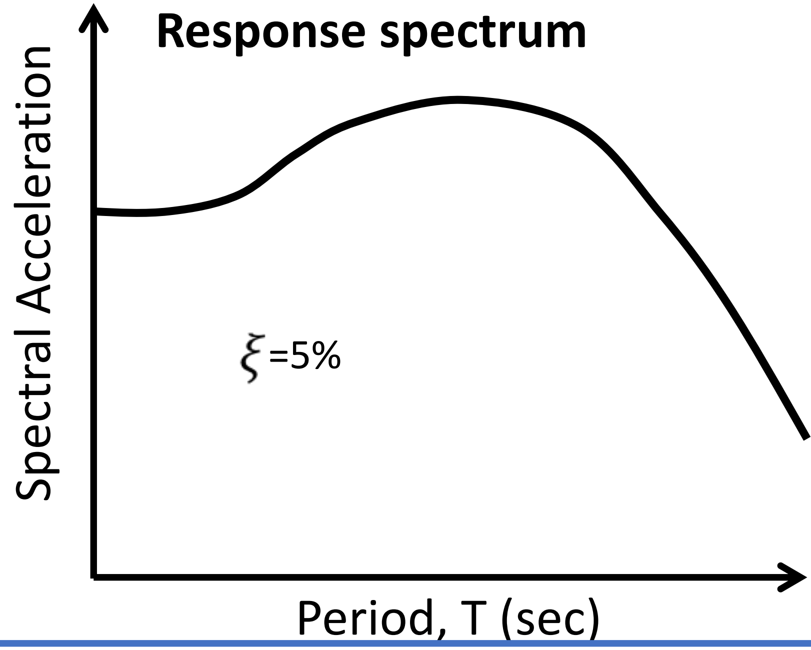
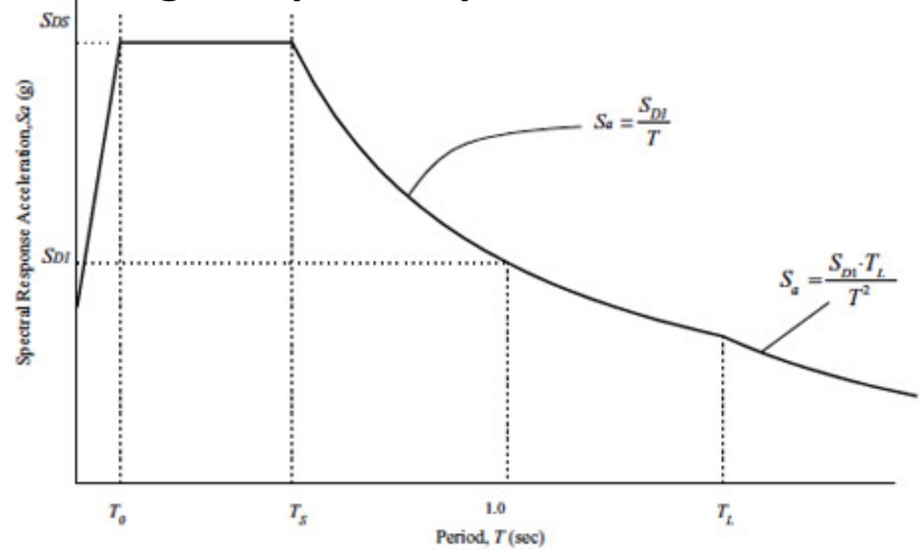
Problem statement for Seismic Hazard and Risk



Ground motion representation for Engineering

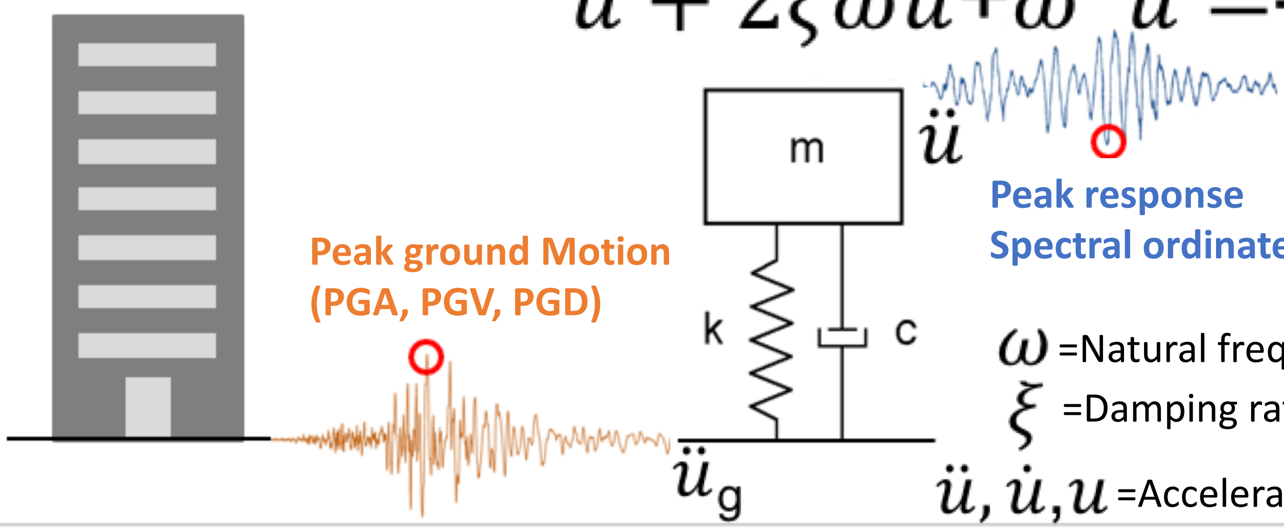


Design response spectrum



SDOF oscillator response

$$\ddot{u} + 2\xi\omega\dot{u} + \omega^2 u = -\ddot{u}_g$$

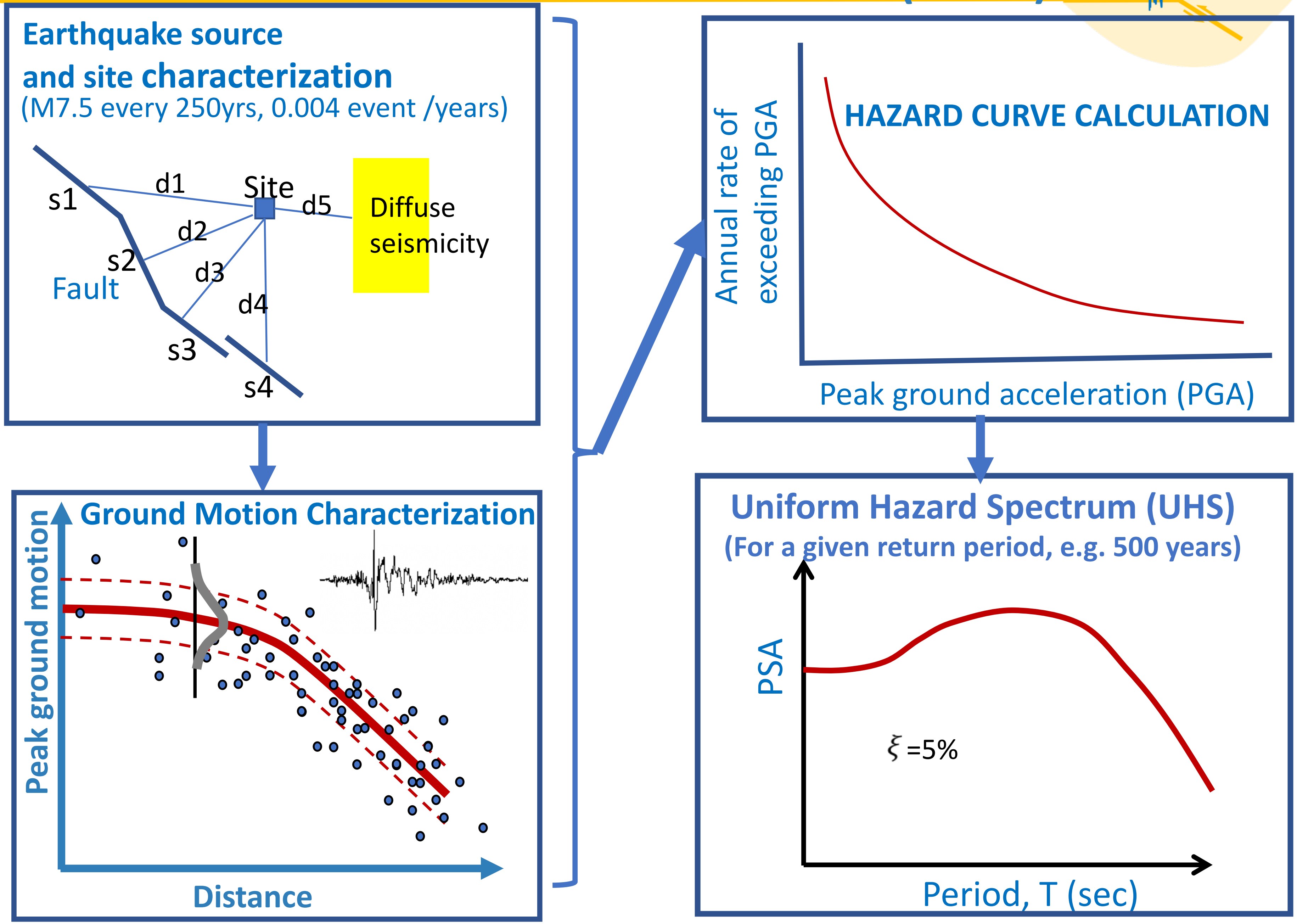


ω =Natural frequency of the SDOF system

ξ =Damping ratio

$\ddot{u}, \dot{u}, u$ =Acceleration, velocity, displacement

Probabilistic Seismic Hazard Assessment (PSHA)



Role of Ground Motion Models in PSHA

- Seismic hazard results are driven mainly by two key inputs (and their uncertainty):

I. Rate of earthquakes in areas near the site;

II. Ground-motion models (GMMs, or GMPEs)

- In many cases the ground-motion models drive the hazard results

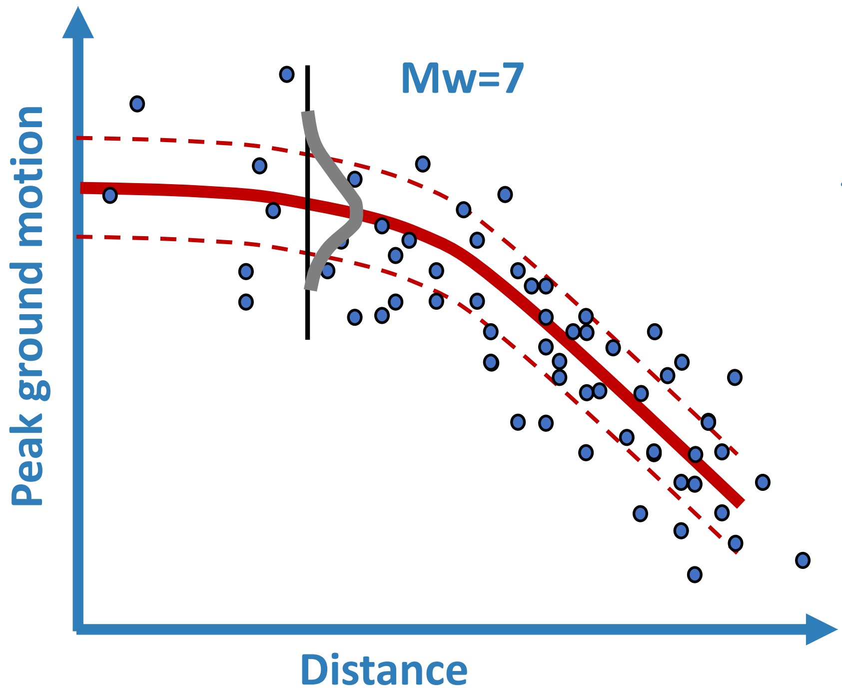
- Current practice of PSHA is usually dominated by empirical Ground Motion Prediction Equations (GMPEs) that have been developed most of the time using dataset from other places except from the site of interest.

Ground Motion Prediction Equations (GMPEs) and limitations

Current practice in PSHA and GMPEs

- An ergodic assumption is commonly made in Probabilistic Seismic Hazard Assessment (PSHA)
- Current practice usually uses empirical GMPEs that are usually based on worldwide database (there are also for region specific)
- GMPEs Predict only one component of ground motion (e.g. Geo Mean)

$$\ln(Y) = f_{src}(M, \ldots) + f_{path}(R, M, \ldots) + f_{site}(Vs_{30} \ldots) + \Delta$$



1964-2017:
432 empirical GMPEs -> PGA
277 empirical GMPEs ->PSA
(Douglas, 2017, http://www.gmpe.org.uk)

Evolution of empirical GMPEs

Abrahamson and Young (1992): $\ln y = a + bM + d\ln(r+c) + eF$

Abrahamson et al (2014)

$$\ln \mathrm{Sa} = f_1 + F_{RV} f_7 + F_N f_8 + F_{AS} f_{11} + f_5 + F_{HW} f_4 + f_6 + f_{10} + \mathrm{Regional}$$

$$f_1 = \begin{cases} a_1 + a_5(M-M_1) + a_8(8.5-M)^2 + [a_2 + a_3(M-M_1)]\ln R + a_{17} r_{rup} & M > M_1 \\ a_1 + a_4(M-M_1) + a_8(8.5-M)^2 + [a_2 + a_3(M-M_1)]\ln R + a_{17} r_{rup} & M_2 \le M < \\ a_1 + a_4(M_2-M_1) + a_8(8.5-M)^2 + a_6(M-M_2) + a_7(M-M_2)^2 & \\ +[a_2 + a_3(M_2-M_1)]\ln R + a_{17} r_{rup} & M < M_2 \end{cases}$$

$$R = \sqrt{r_{rup}^2 + c_{4M}^2}$$

$$c_{4M} = \begin{cases} c_4 & M > 5 \\ c_4 - (c_4-1)(5-M) & 4 < M \le 5 \\ 1 & M \le 4 \end{cases}$$

$$f_7 = \begin{cases} a_{11} & M > 5 \\ a_{11}(M-4) & 4 \le M \le 5 \\ 0 & M < 4 \end{cases}$$

$$f_8 = \begin{cases} a_{12} & M > 5 \\ a_{12}(M-4) & 4 \le M \le 5 \\ \dots \end{cases}$$

If R_{y0} not available:

$$T_5 = \begin{cases} 1 & r_{jb} = 0 \\ 1 - \frac{r_{jb}}{30} & r_{jb} < 30 \\ 0 & r_{jb} \ge 30 \end{cases}$$

$$f_6 = \begin{cases} a_{15}\frac{Z_{TOR}}{20} & Z_{TOR} < 20\,\mathrm{km} \\ a_{15} & Z_{TOR} \ge 20\,\mathrm{km} \end{cases}$$

$$f_{10} = \begin{cases} a_{43}\ln\left(\frac{Z_1+0.01}{Z_{1,ref}+0.01}\right) & V_{s,30} \le 200\,\mathrm{m/s} \\ a_{44}\ln\left(\frac{Z_1+0.01}{Z_{1,ref}+0.01}\right) & 200 < V_{s,30} \le 300\,\mathrm{m/s} \\ \dots & \dots 500\,\mathrm{m/s} \\ & \dots\mathrm{m/s} \end{cases}$$

GMPEs are becoming very complex to use!!

$$V_{s,30}^* = \begin{cases} \dots \\ V_1 & V_{s,30} \ge V_1 \end{cases}$$

$$V_1 = \begin{cases} 1500 & T \le 0.5\,\mathrm{s} \\ \exp\left[-0.35\ln\left(\frac{T}{0.5}\right) + \ln(1500)\right] & 0.5 < T < 3\,\mathrm{s} \\ 800 & T \ge 3\,\mathrm{s} \end{cases}$$

$$f_4 = a_{13} T_1 T_2 T_3 T_4 T_5$$

$$T_1 = \begin{cases} (90-\mathrm{dip})/45 & \mathrm{dip} > 30^\circ \\ 60/45 & \mathrm{dip} < 30^\circ \end{cases}$$

$$T_2 = \begin{cases} 1 + a_{2HW}(M-6.5) & M \ge 6.5 \\ 1 + a_{2HW}(M-6.5) - (1-a_{2HW})(M-6.5)^2 & 5.5 < M < 6.5 \\ 0 & M \le 5.5 \end{cases}$$

$$T_3 = \begin{cases} h_1 + h_2(R_x/R_1) + h_3(R_x/R_1)^2 & R_x < R_1 \\ 1 - \left(\frac{R_x-R_1}{R_2-R_1}\right) & R_1 \le R_x \le R_2 \\ 0 & R_x > R_1 \end{cases}$$

$$T_4 = \begin{cases} 1 - \frac{Z_{TOR}^2}{100} & Z_{TOR} \le 10\,\mathrm{km} \\ 0 & Z_{TOR} > 10\,\mathrm{km} \end{cases}$$

$$T_5 = \begin{cases} 1 & R_{y0} - R_{y1} \le 0 \\ 1 - \frac{R_{y0}-R_{y1}}{5} & 0 < R_{y0} - R_{y1} < 5 \\ 0 & R_{y0} - R_{y1} \ge 5 \end{cases}$$

$$R_1 = W\cos(\mathrm{dip})$$
$$R_2 = 3R_1$$
$$R_{y1} = R_x \tan(20)$$
$$h_1 = 0.25$$
$$h_2 = 1.5$$
$$h_3 = -0.75$$

$$Z_{1,ref} = \begin{cases} \frac{1}{1000}\exp\left[\frac{\dots}{4}\ln\left(\frac{\dots}{1360^4+570.94^4}\right)\right] & \text{for California} \\ \frac{1}{1000}\exp\left[\frac{-5.23}{2}\ln\left(\frac{V_{s,30}^2+412.39^2}{1360^2+412.39^4}\right)\right] & \text{for Japan} \end{cases}$$

$$f_{11} = \begin{cases} a_{14} & CR_{jb} \le 5\,\mathrm{km} \\ a_{14}\left[1 - \frac{CR_{jb}-5}{10}\right] & 5 < CR_{jb} < 15\,\mathrm{km} \\ 0 & CR_{jb} \ge 15\,\mathrm{km} \end{cases}$$

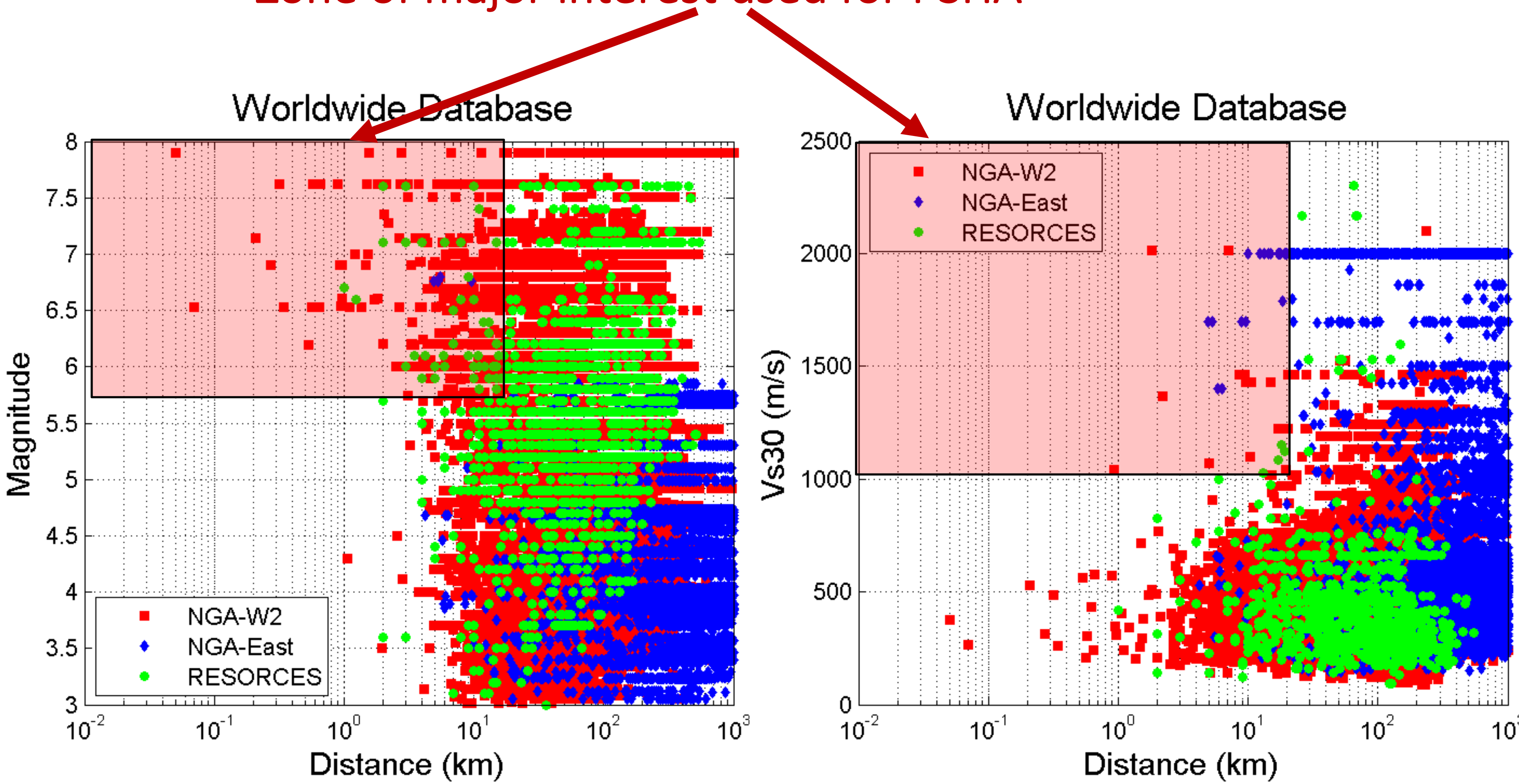
$$\mathrm{Regional} = F_{TW}(f_{12} + a_{25} r_{rup}) + F_{CN} a_{28} r_r up + F_{JP}(f_{13} + a_{29} r_{rup})$$

$$f_{12} = a_{31}\ln\left(\frac{V_{s,30}^*}{V_{Lin}}\right)$$

$$f_{13} = \begin{cases} a_{36} & V_{s,30} < 200\,\mathrm{m/s} \\ a_{37} & 200 \le V_{s,30} < 300\,\mathrm{m/s} \\ a_{38} & 300 \le V_{s,30} < 400\,\mathrm{m/s} \\ a_{39} & 400 \le V_{s,30} < 500\,\mathrm{m/s} \\ a_{40} & 500 \le V_{s,30} < 700\,\mathrm{m/s} \\ a_{41} & 700 \le V_{s,30} < 1000\,\mathrm{m/s} \\ a_{42} & V_{s,30} \ge 1000\,\mathrm{m/s} \end{cases}$$

Limitations of empirical GMPEs

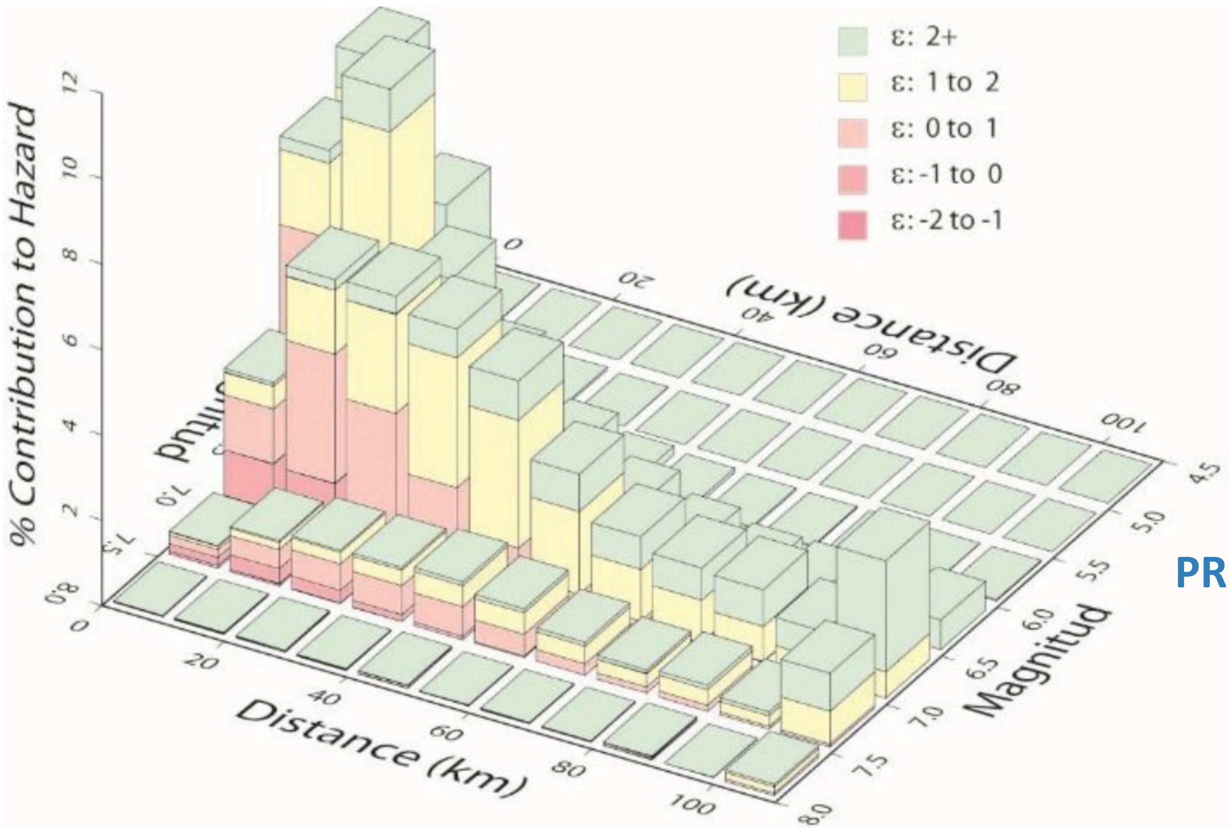
Zone of major interest used for PSHA



Ground-motion records in region of interest is sparse and in magnitude-distance range of most engineering interest

Example of Site-specific PSHA for NPPs

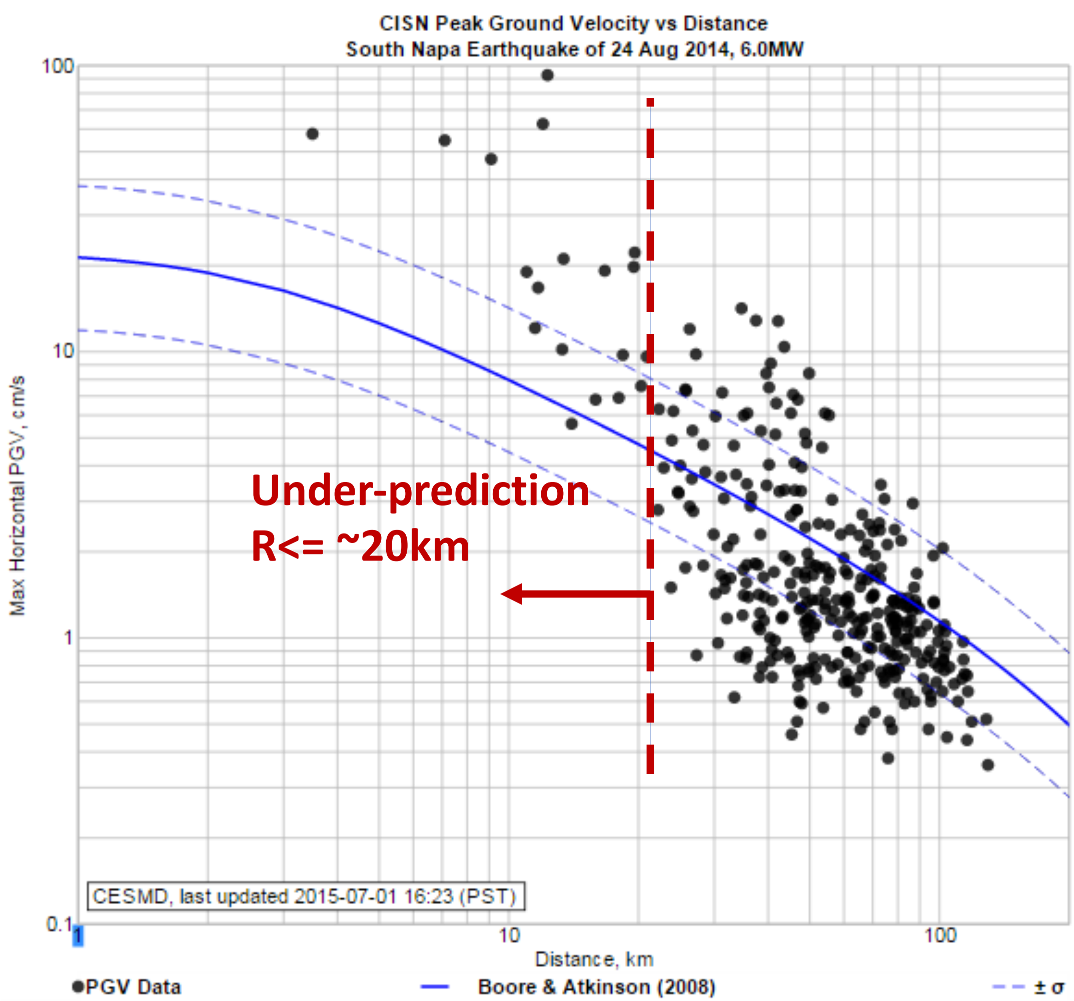
PRP project in Switzerland



PRP deaggregation

Hazard is controled by Mw ~ 6 and R <= 20km (near fault)

Limitations of empirical GMPEs



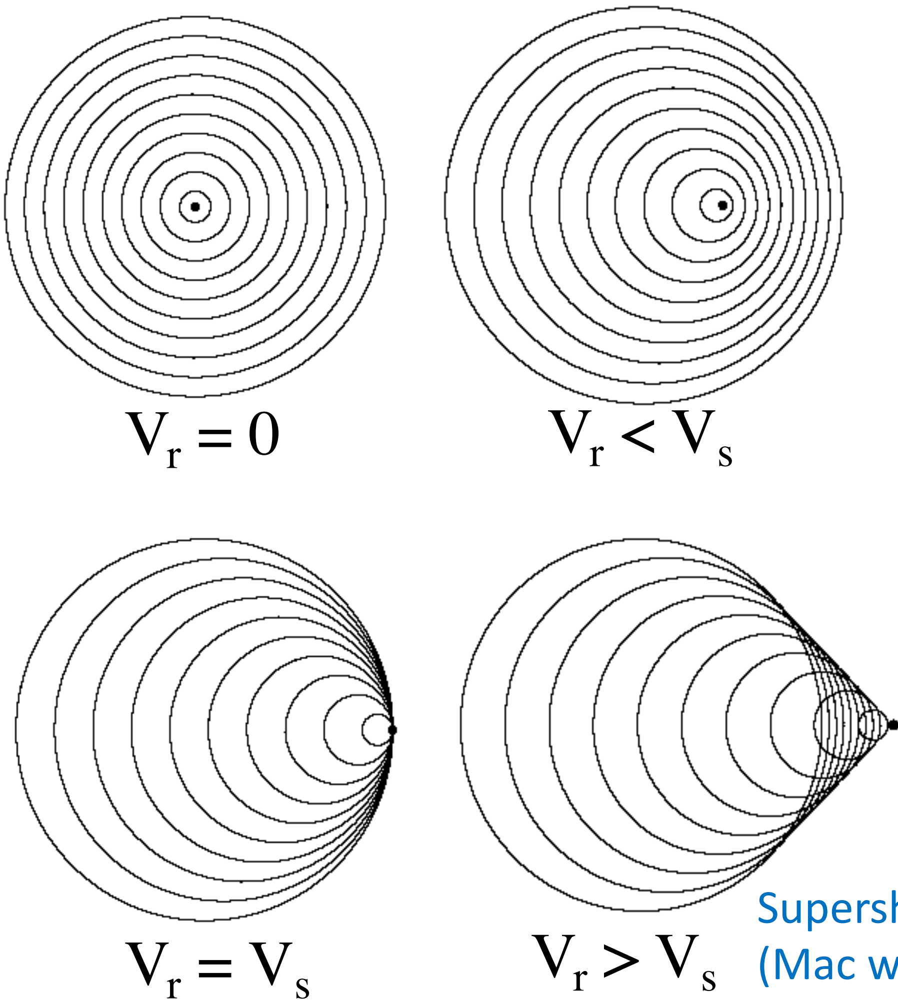
(Courtesy of Roberto Paolucci)

GMPEs predict earthquakes similar to events from their database only

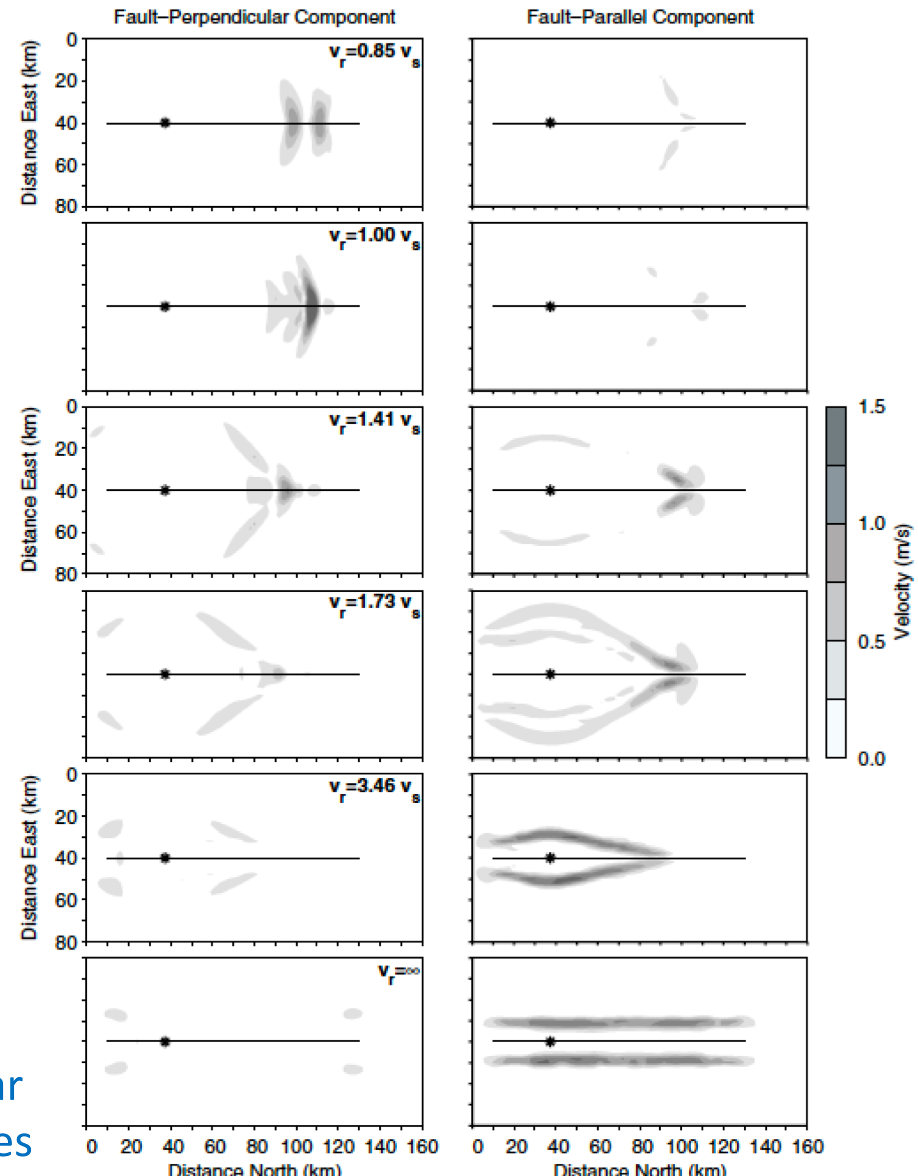
Source-dominated ground motion: Physics-based rupture Models and limitations

Source dominated near-source ground motion

Effect of Rupture speed: Subshear and Supershear



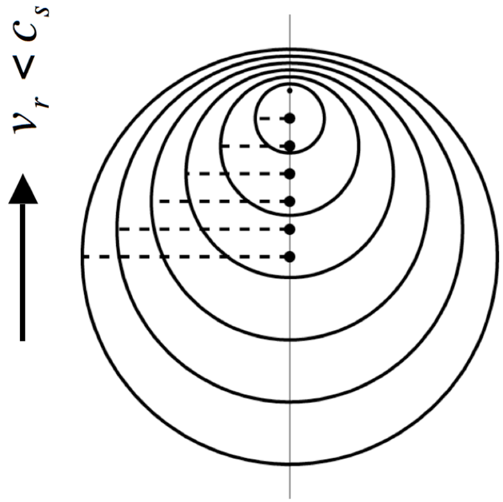
Supershear (Mac waves are generated)

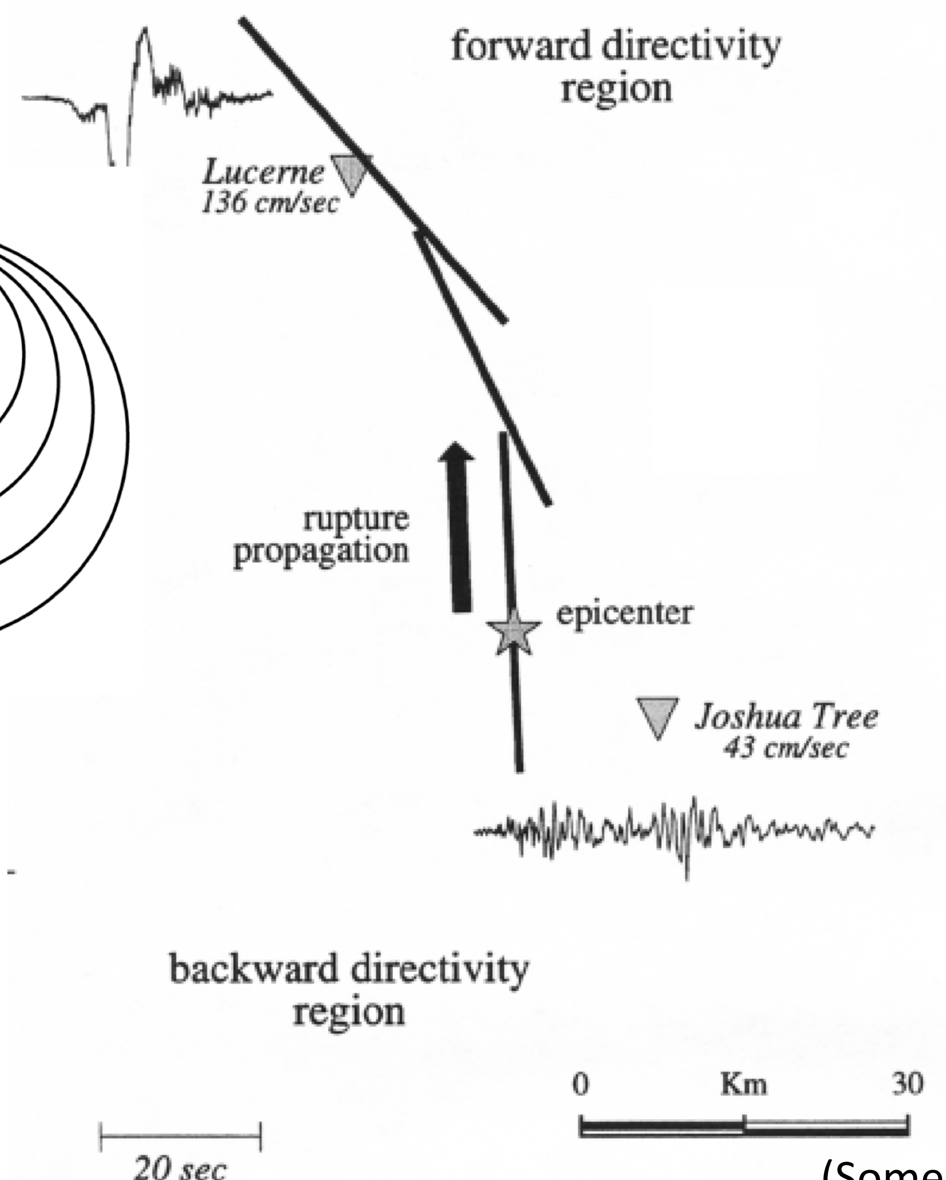


(Aagard and Heaton 2004)

Source dominated near-source ground motion

Directivity during Mw7.3 1992 Landers Earthquake

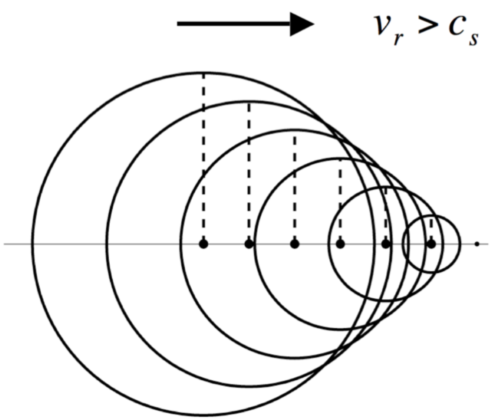




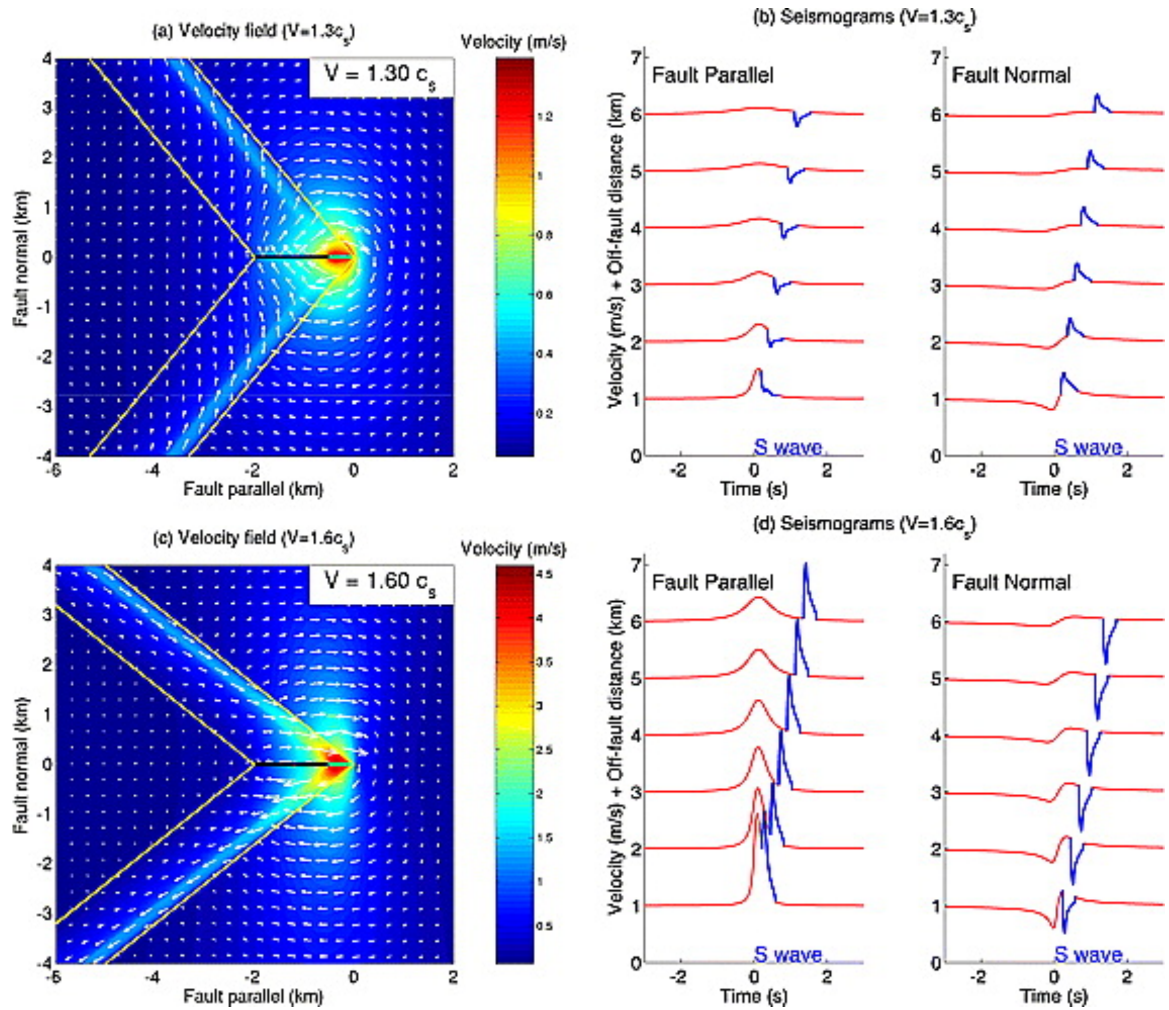
(Somerville et al., 1997)

Source dominated near-source ground motion

Super-shear rupture: Velocity pulses transmit large amplitude motion. Because Shear Mach waves are emanated from the rupture front



-Planar wavefronts emanate from the leading and trailing edges of the slip zone.
- The shear field carries an exact history of the slip velocity that appears in both the FP and FN velocity components



(Dunham and Archuleta (2005)

Source dominated near-source ground motion

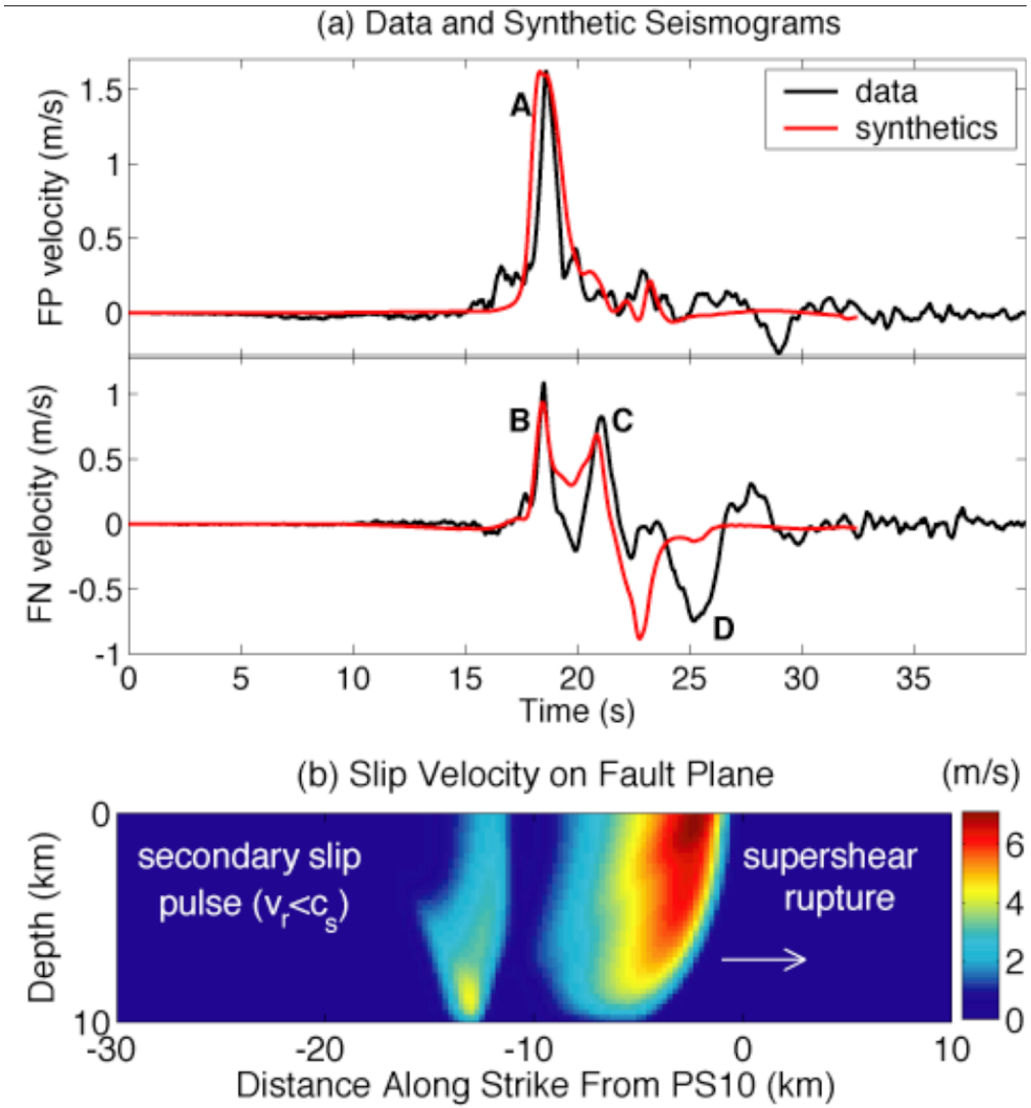
Supershear rupture speed During Mw7.9 2002 Denali Earthquake

Waveforms at Pump Station 10 (PS10), 3km distance from fault.

Two rupture fronts:

Pulses A, B: from supershear

Pulses C, D: from subshear

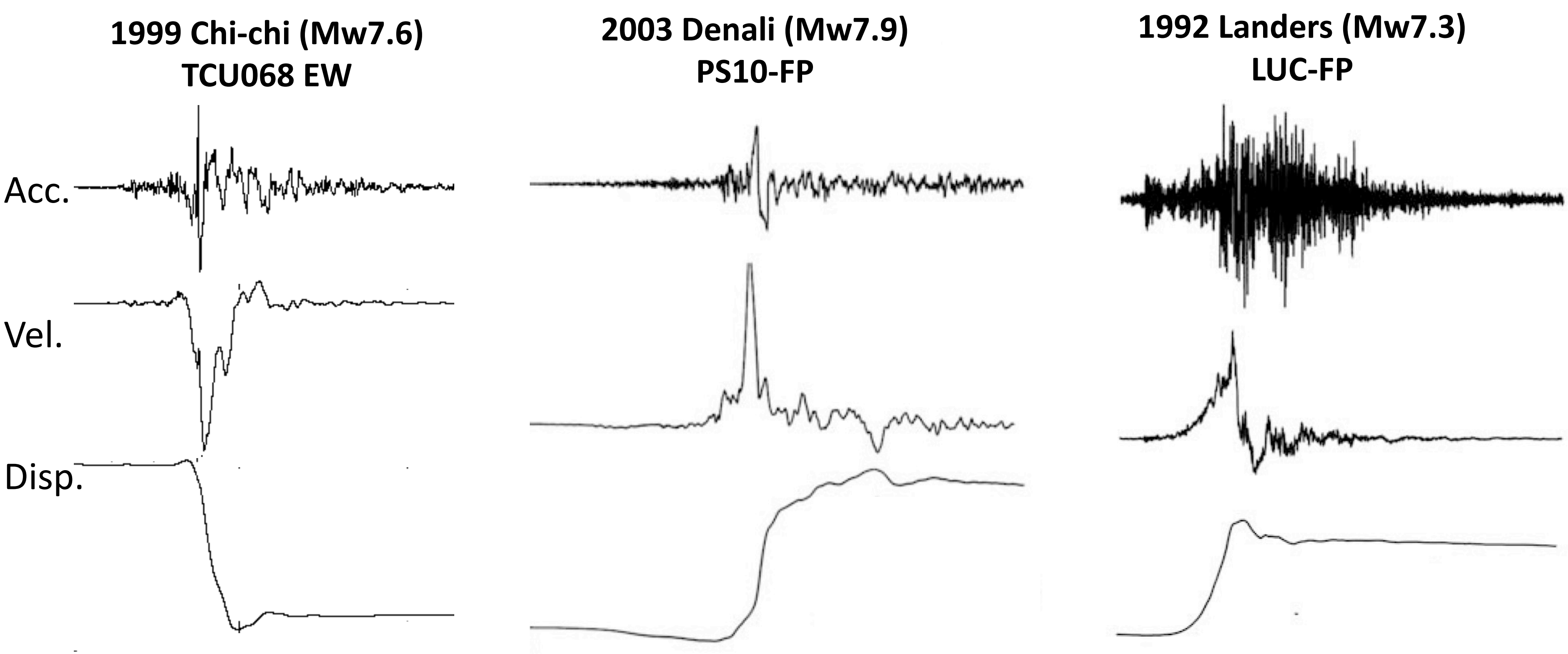


(Dunham and Archuleta (2005))

Source dominated near-source ground motion

Pulses causing permanent displacement from surface rupture

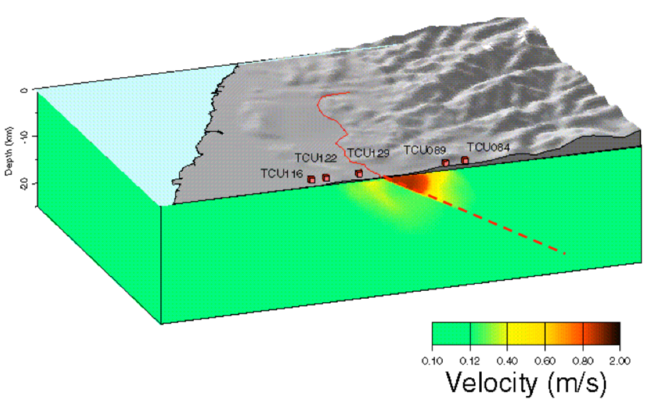
Permanent displacement (fling step) are formed from coherent long period velocity pulses caused mainly by the offset of the ground surface when fault-rupture extends to the earth surface



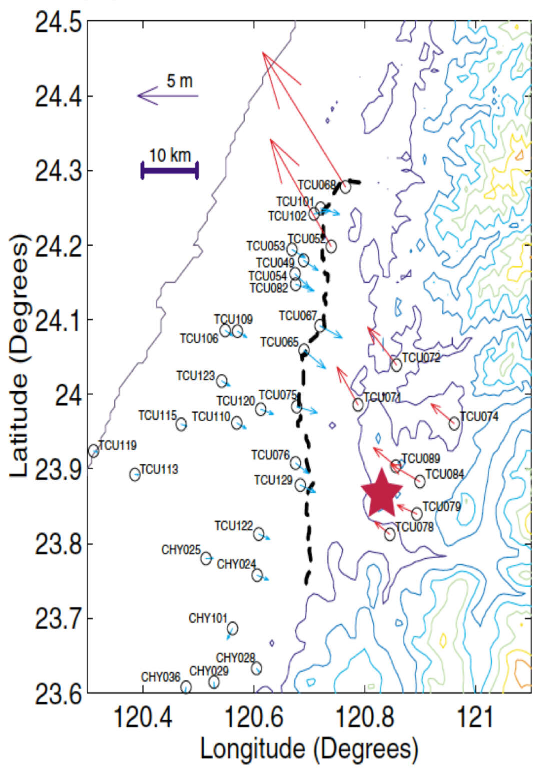
Source dominated near-source ground motion

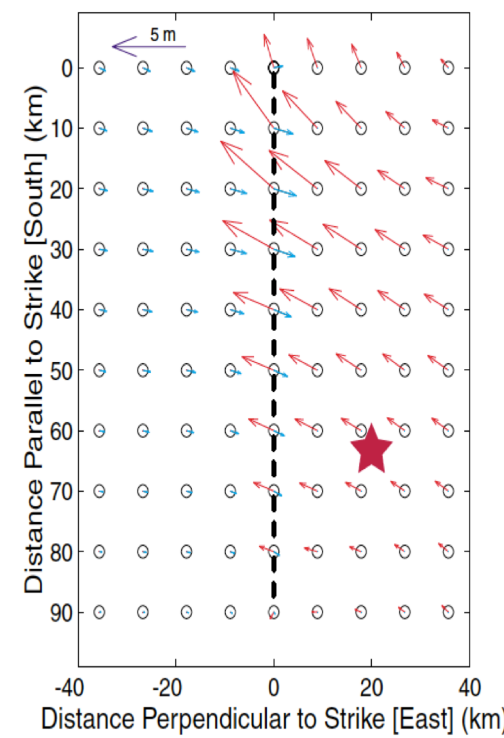
Effect of asymmetric geometry of dipping faults:
Example the Mw7.6 1999 Chi-Chi earthquake

- Interaction of reflected waves (coming from the free-surface of the hanging wall side) with the ongoing rupture propagation causes rapped waves in the hanging wall and rotation of rake angle enhanced at the edge of the fault trace with considerable strike slip components.
- These source complexities causing hanging wall moving more than the footwall, producing amplification of the ground motion in the wedge of the hanging wall.
- The rake rotation generates directivity pulses combined with the “fling” pulses caused surface rupture



(Dalguer et al., 2001)





(Oglesby and Day, 2001)

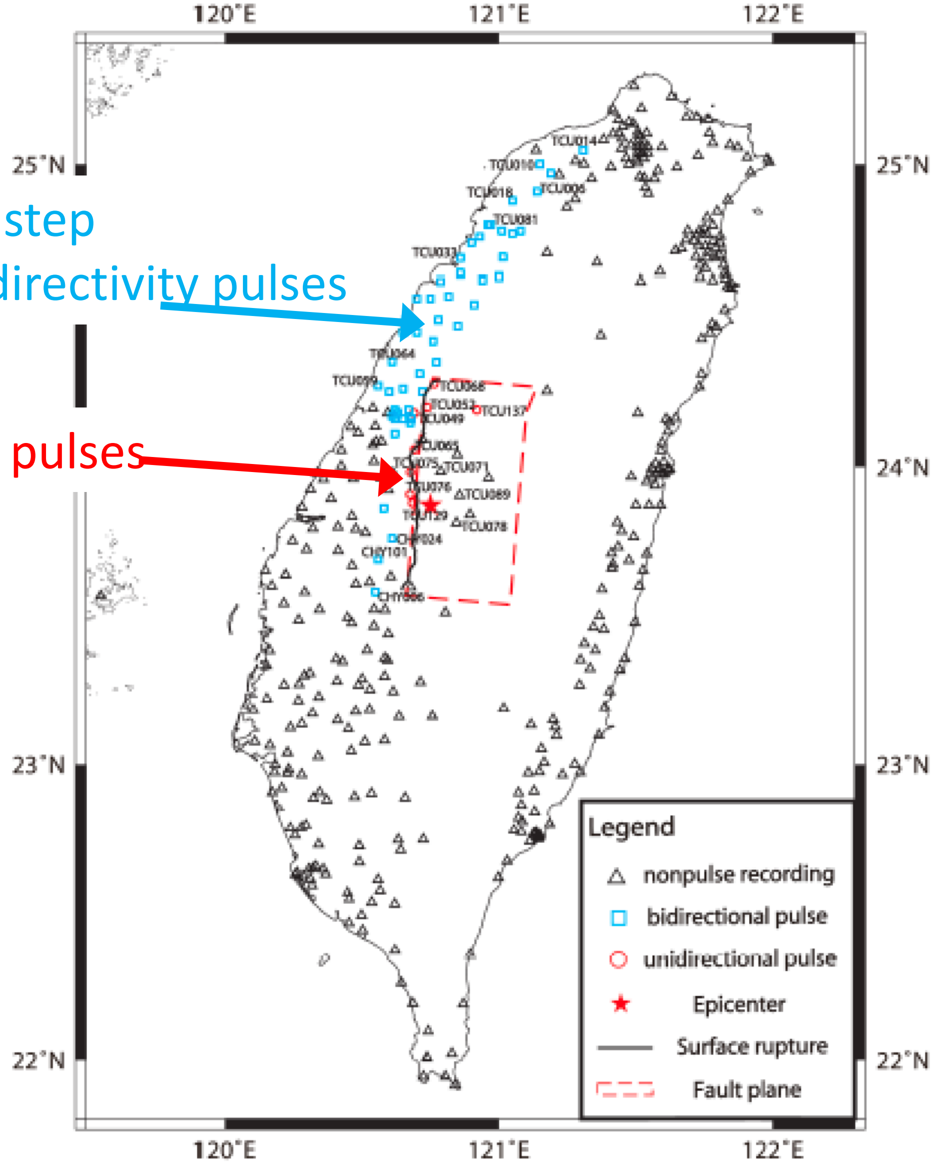
Source dominated near-source ground motion

Example the Mw7.6 1999 Chi-Chi earthquake

- The rake rotation generates directivity pulses combined with the “fling step” pulses caused surface rupture

Coupled fling step
and forward directivity pulses

Fling step pulses

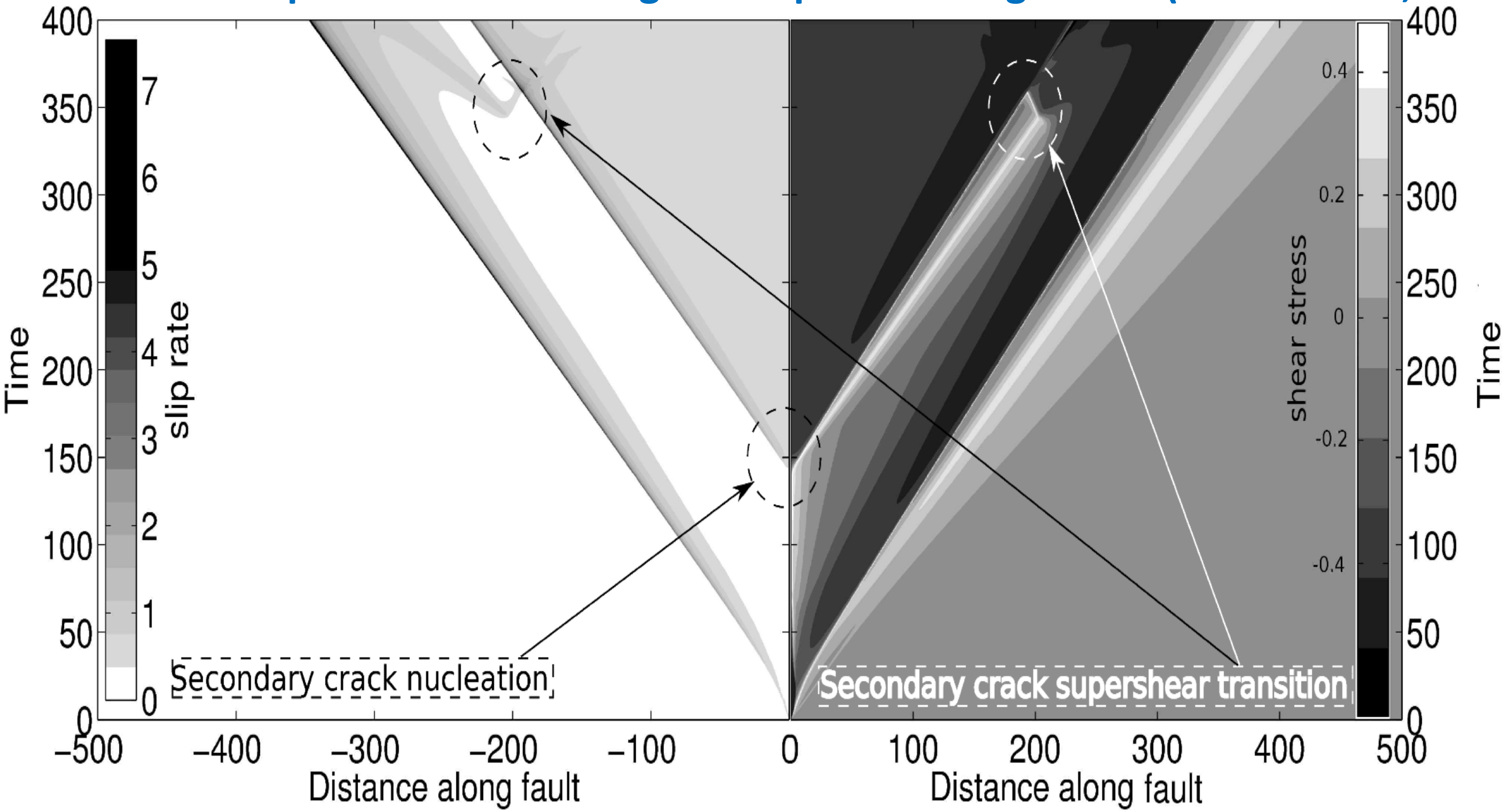


Xie, 2019)

Source dominated near-source ground motion

Rupture reactivation mechanism:

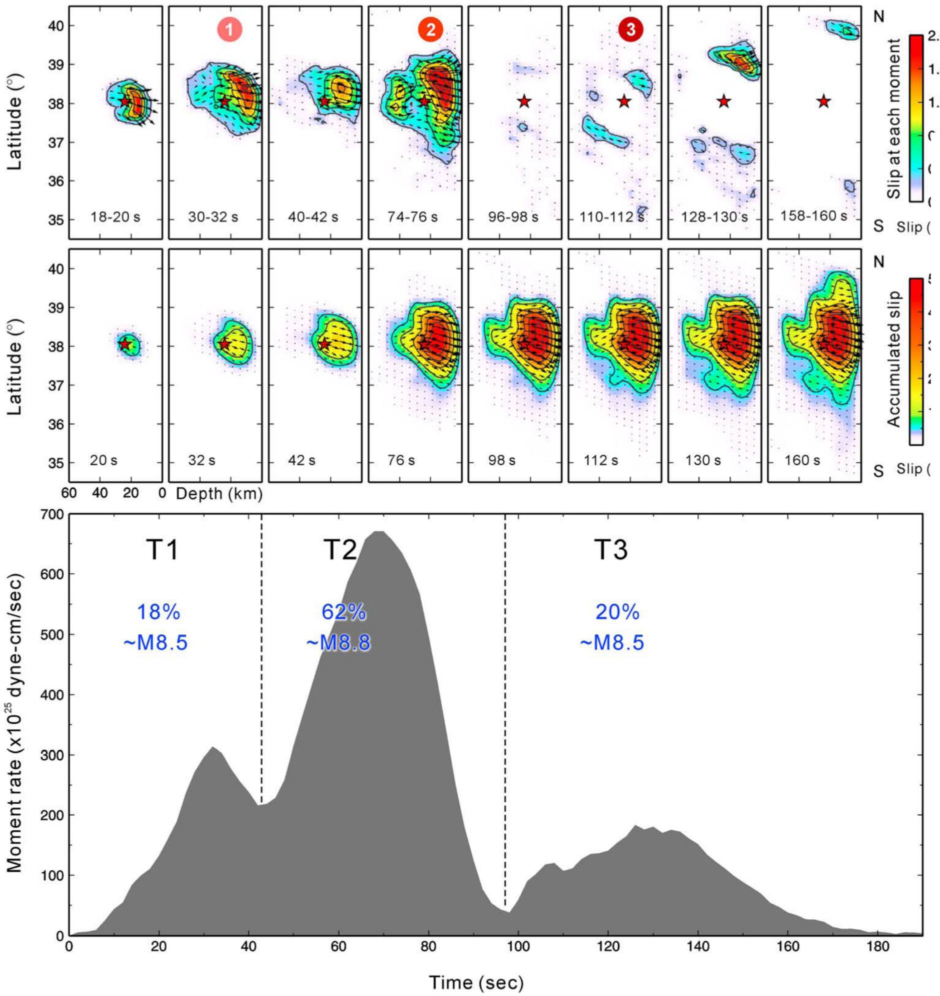
- Transition from pulse to crack like rupture, stress accumulation due to healing reactivate rupture (Gabriel et al., 2012)
- Double drop of frictional strength in slip weakening model (Galvez et al., 2016)



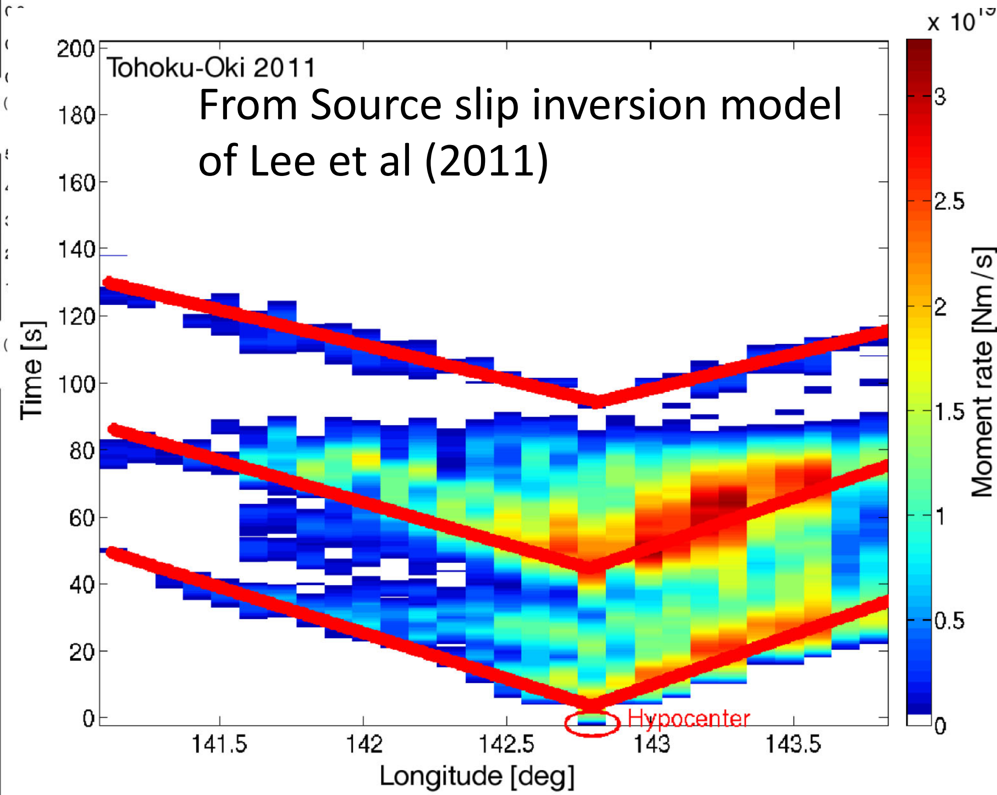
Gabriel et al. (2012)

Source dominated near-source ground motion

Slip reactivation during Mw 9.0 2011 Tohoku



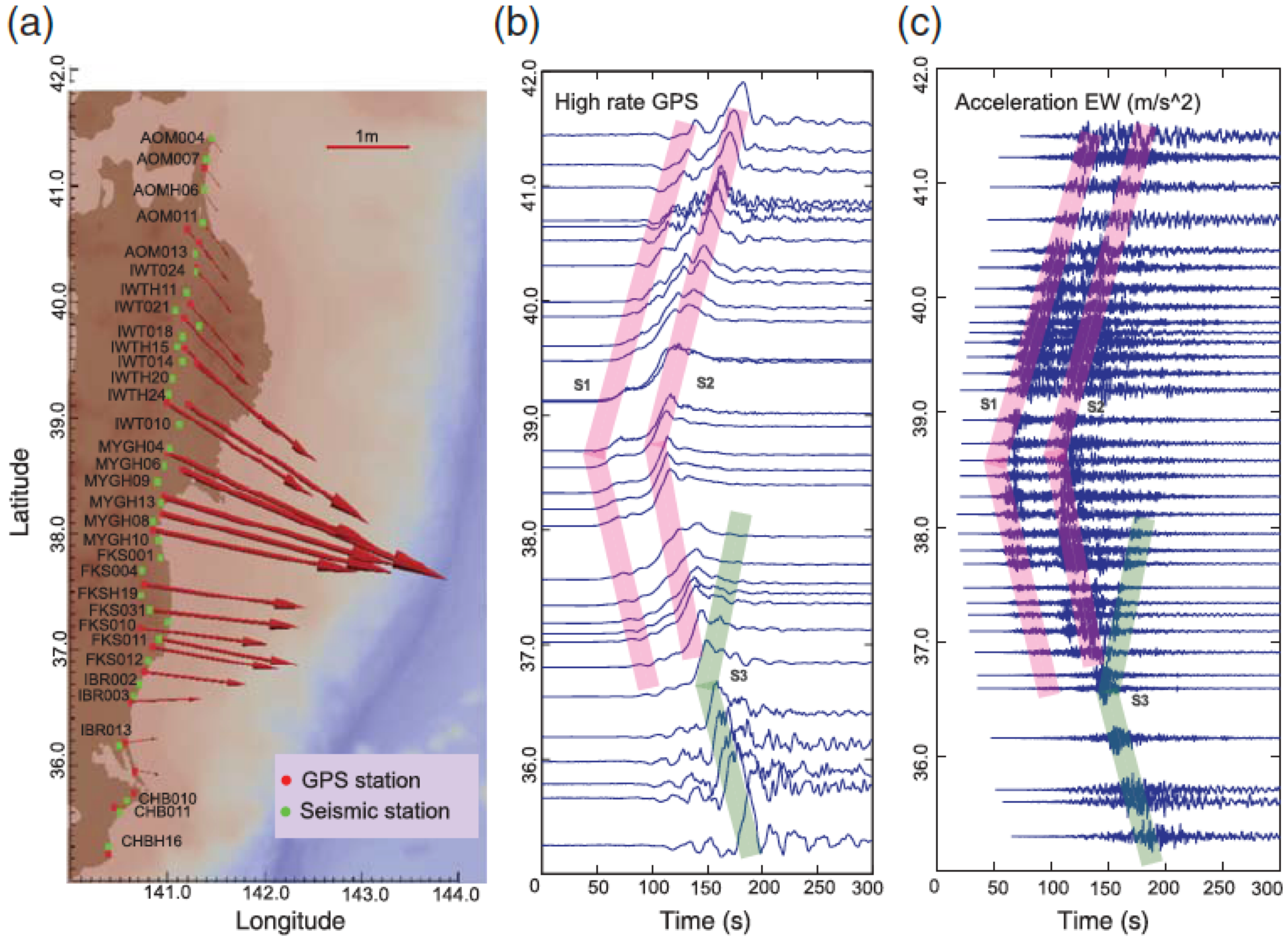
(Lee et al, 2011, GRL)



Galvez et al. (2016)
Gabriel et al. (2012)

Source dominated near-source ground motion

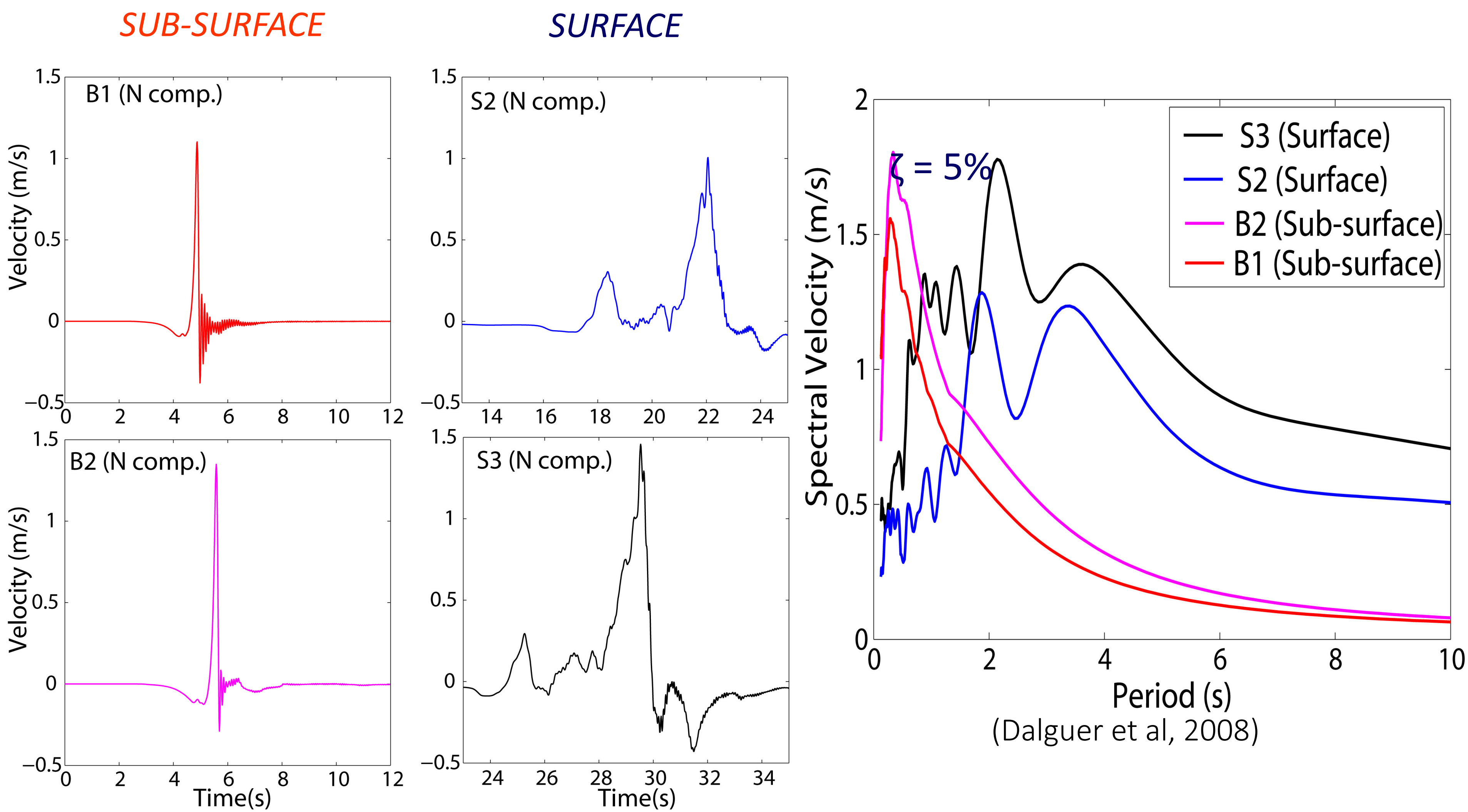
Slip reactivation: case Mw9.0 2011 Tohoku earthquake



Galvez et al., 2016)

Source dominated near-source ground motion

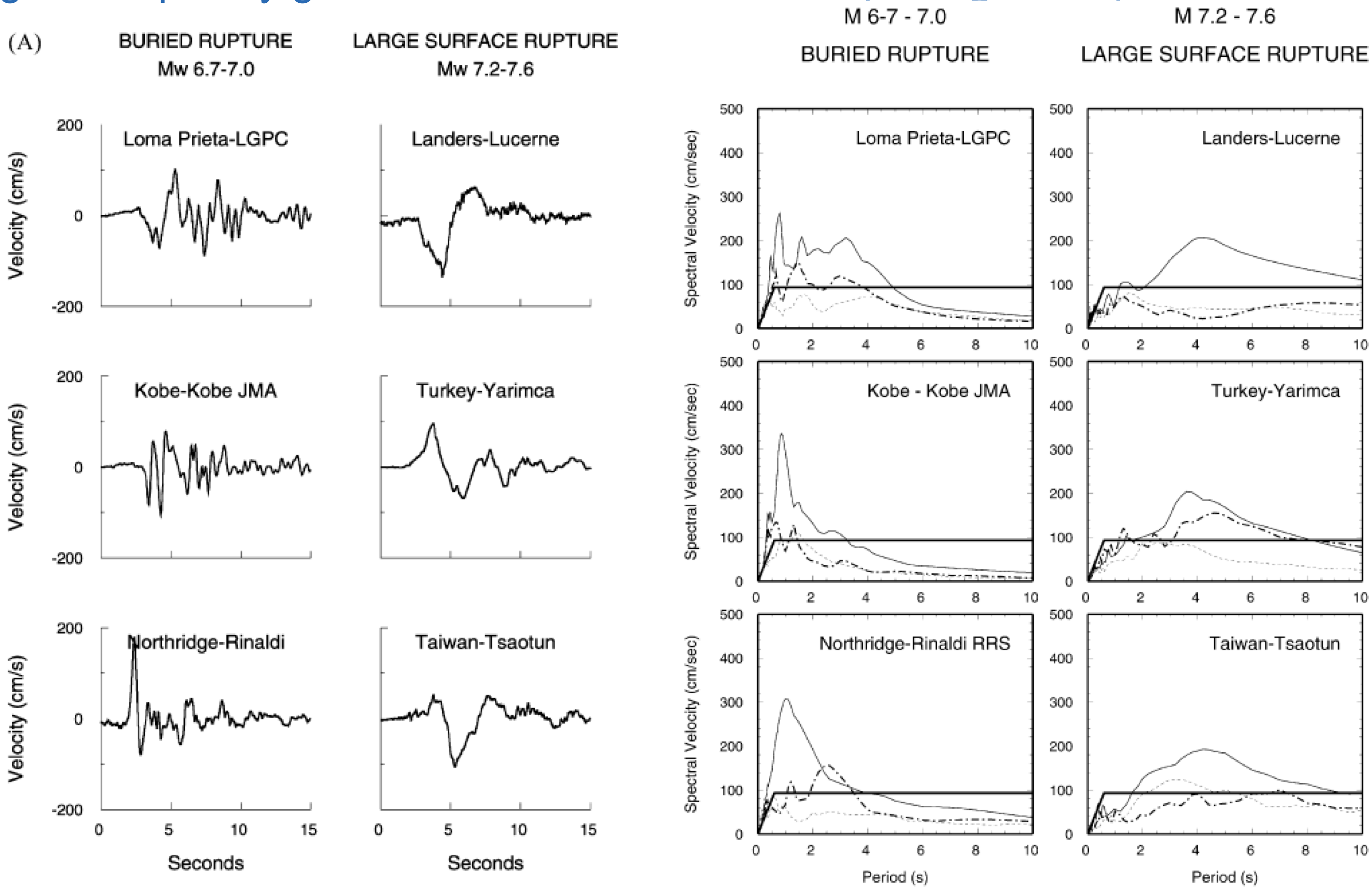
Surface Vs Subsurface Earthquakes: Buried rupture can propagate higher frequency ground motion than Surface-rupturing earthquakes



(Dalguer et al, 2008)

Source dominated near-source ground motion

Surface Vs Subsurface Earthquakes: Buried rupture can propagate higher frequency ground motion than Surface-rupturing earthquakes

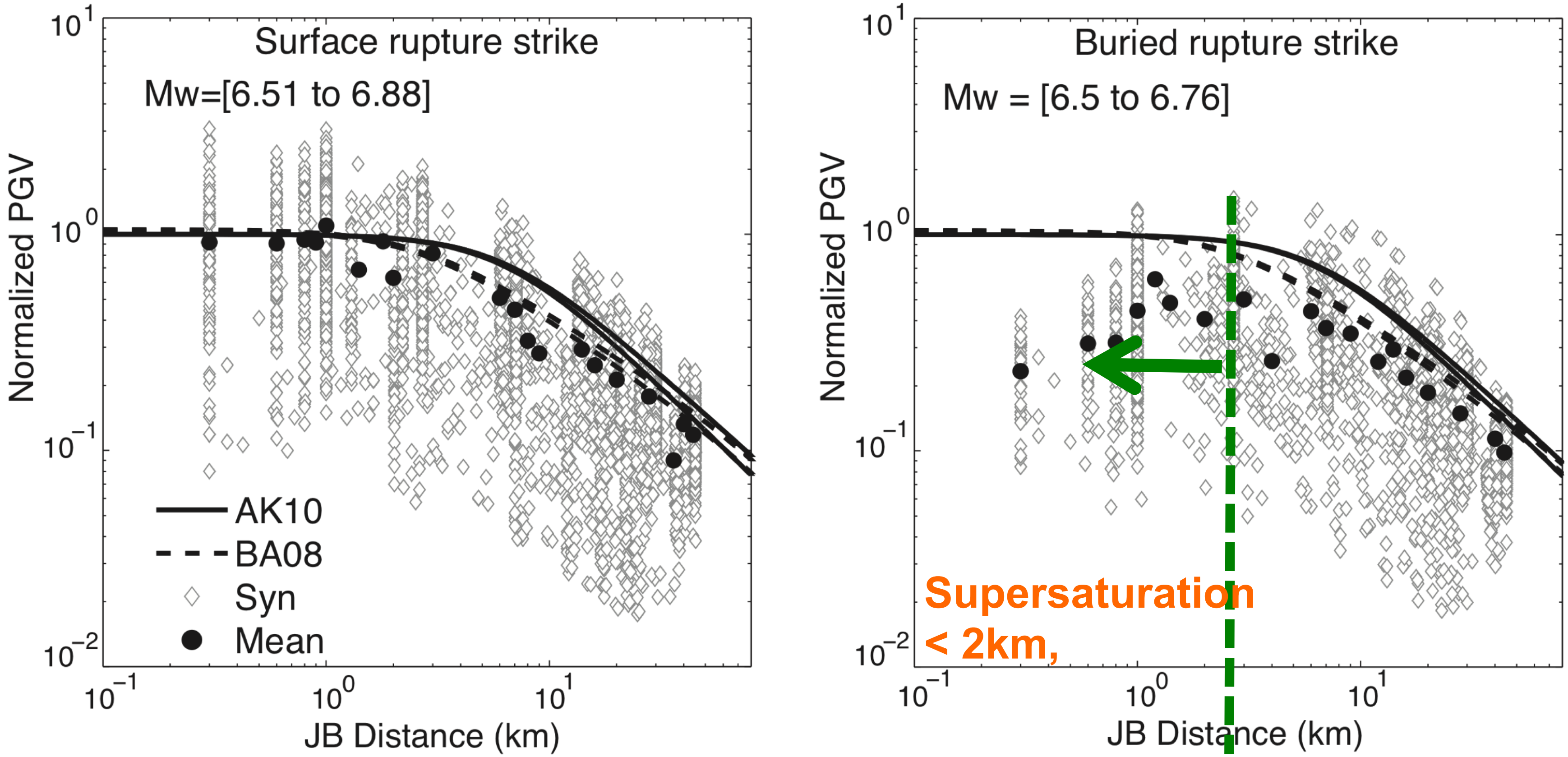


(Somerville, 2003)

Source dominated near-source ground motion

Surface Vs Subsurface Earthquakes:

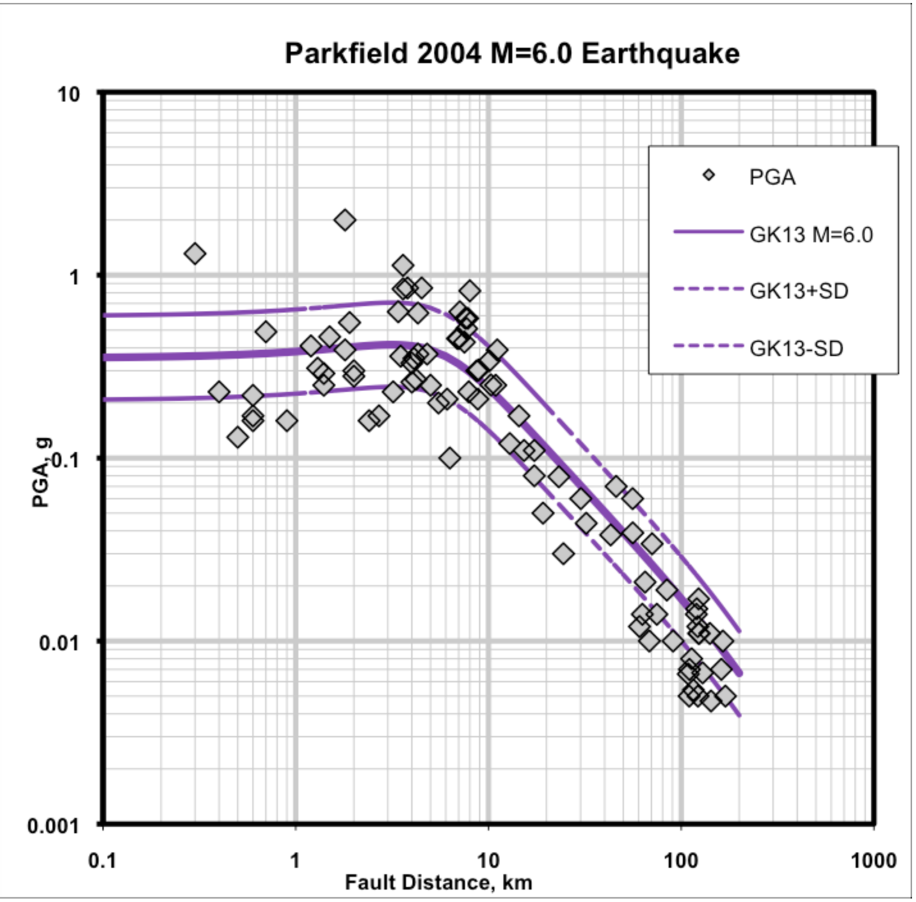
Strike-slip buried rupture may produce supersaturation

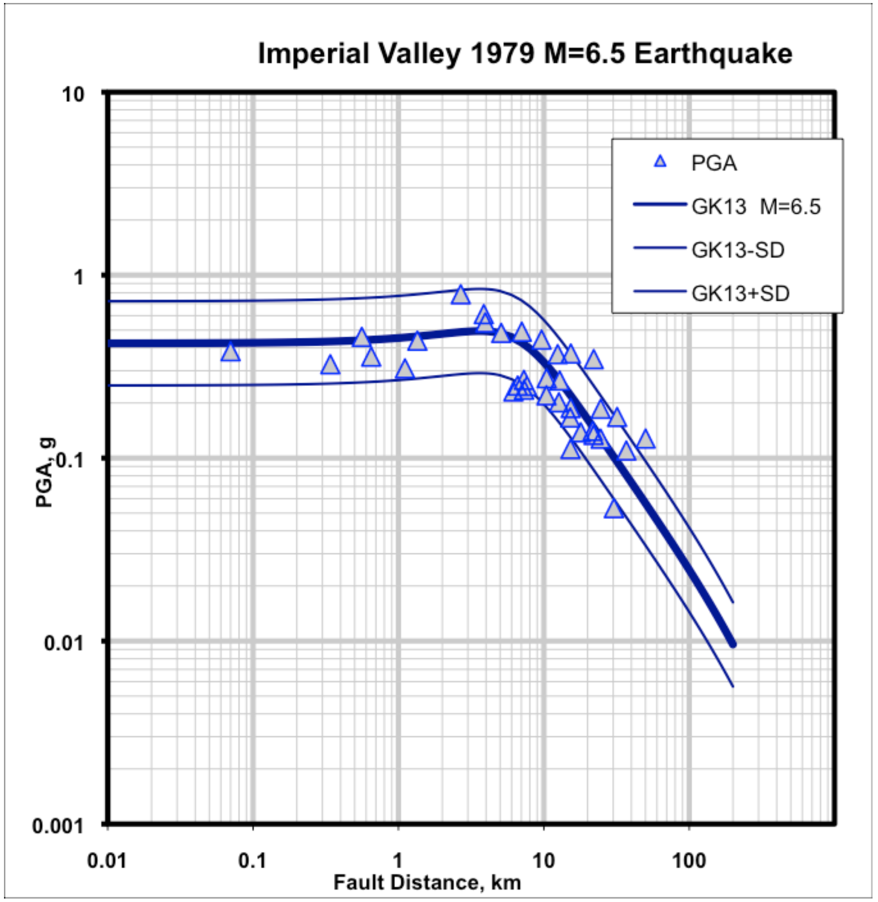


(Baumann and Dalguer, 2014, BSSA)

Source dominated near-source ground motion

Earthquakes with apparent supersaturation (Parkfield and Imperial Valley)

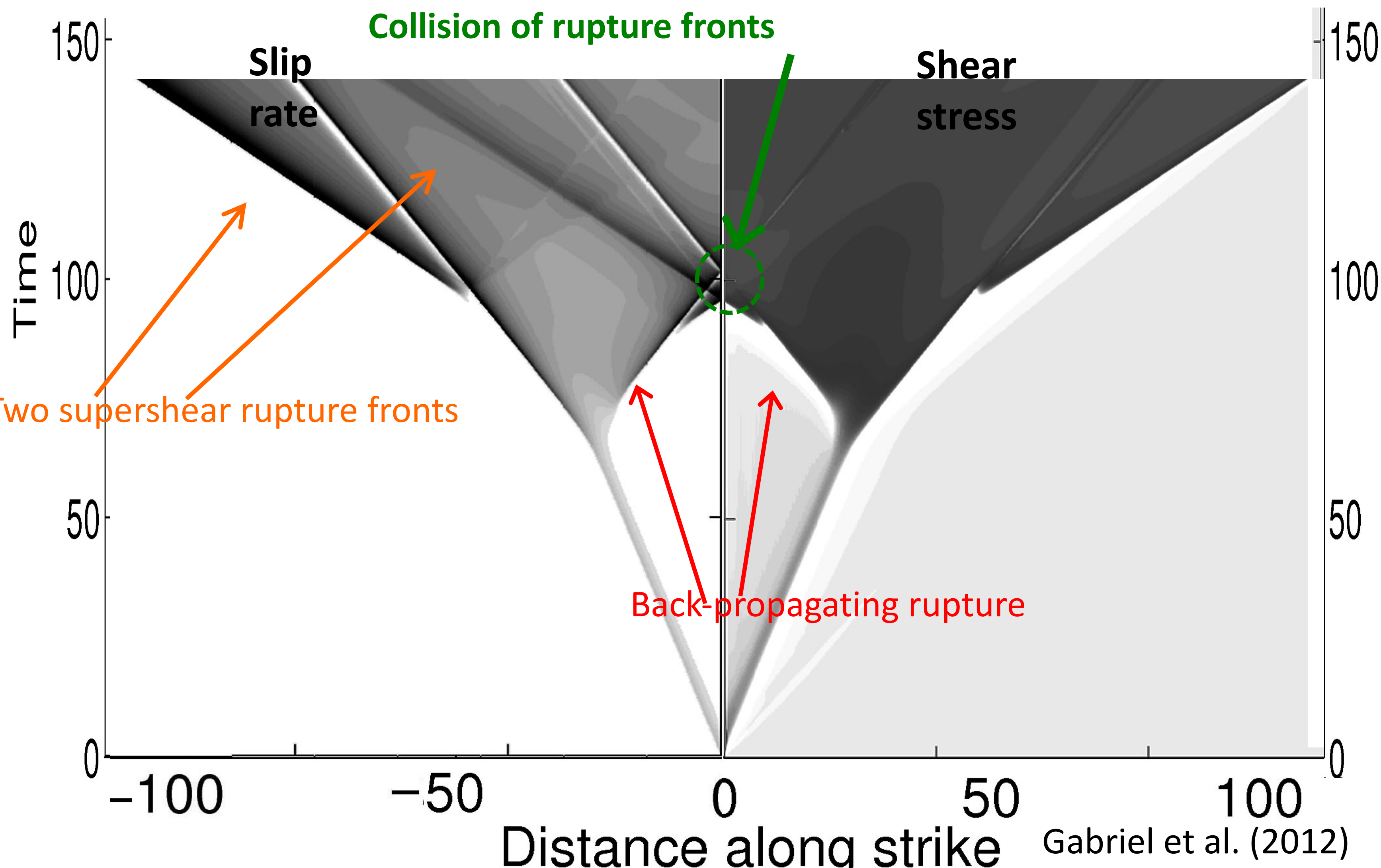




(Graizer and Kalkan, 2011)

Source dominated near-source ground motion

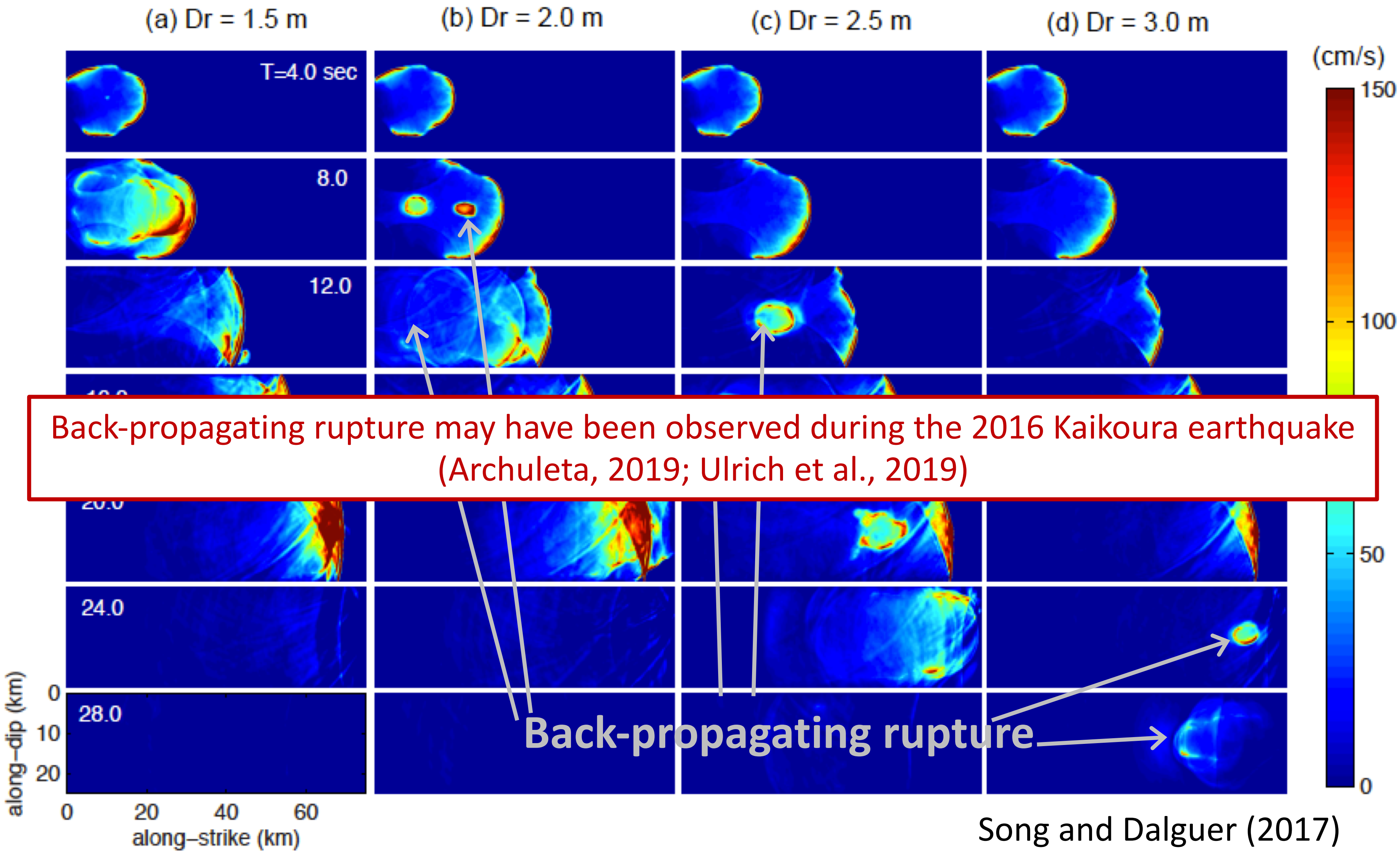
Earthquake Rupture complexity: Multi-type of ruptures



Gabriel et al. (2012)

Source dominated near-source ground motion

Earthquake Rupture complexity



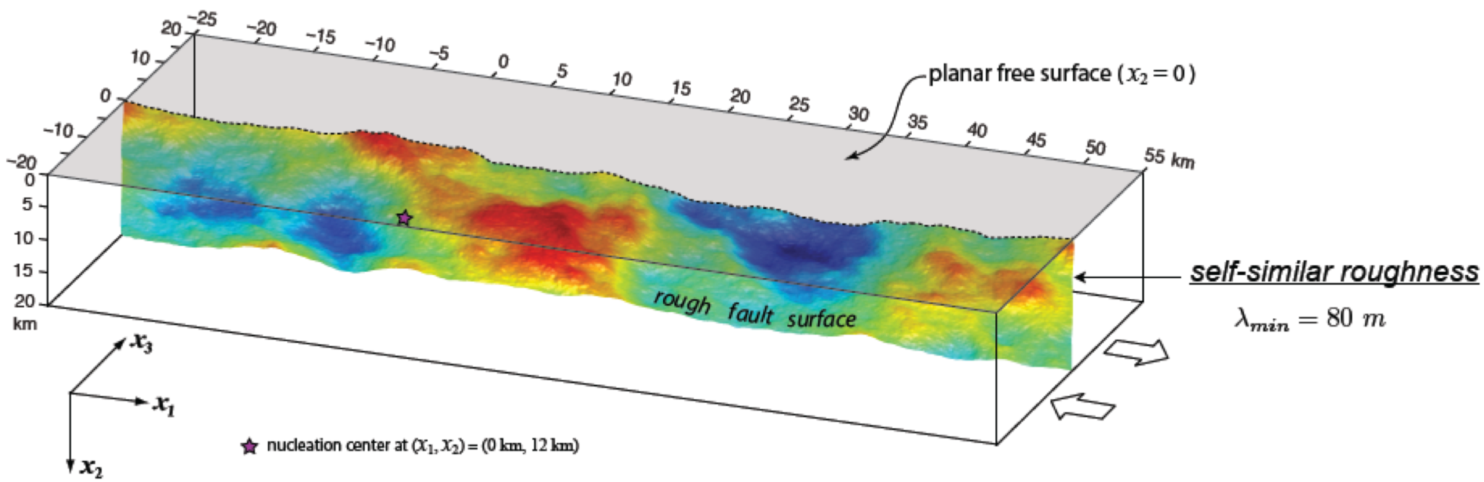
Back-propagating rupture may have been observed during the 2016 Kaikoura earthquake (Archuleta, 2019; Ulrich et al., 2019)

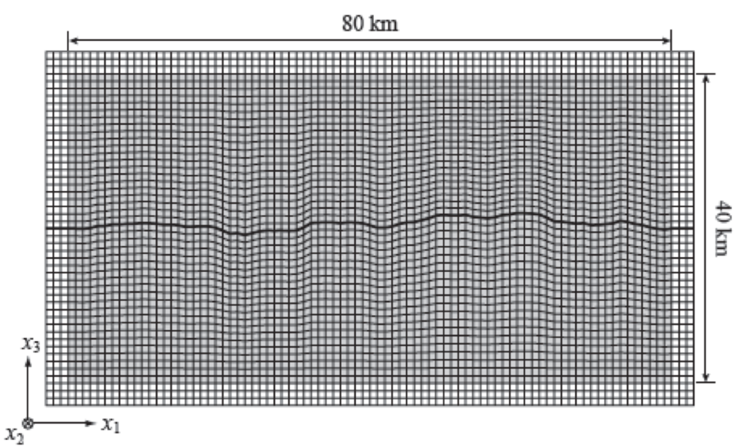
Song and Dalguer (2017)

Source dominated near-source ground motion

High Frequency (HF) radiation from the source

Raugh-Fault simulations (Shi and Day, 2013): Fault geometry and meshing resolution





SORD [*Ely et al.*, 2008, 2009, 2010; *Shi and Day*, 2013]

Hexahedral mesh

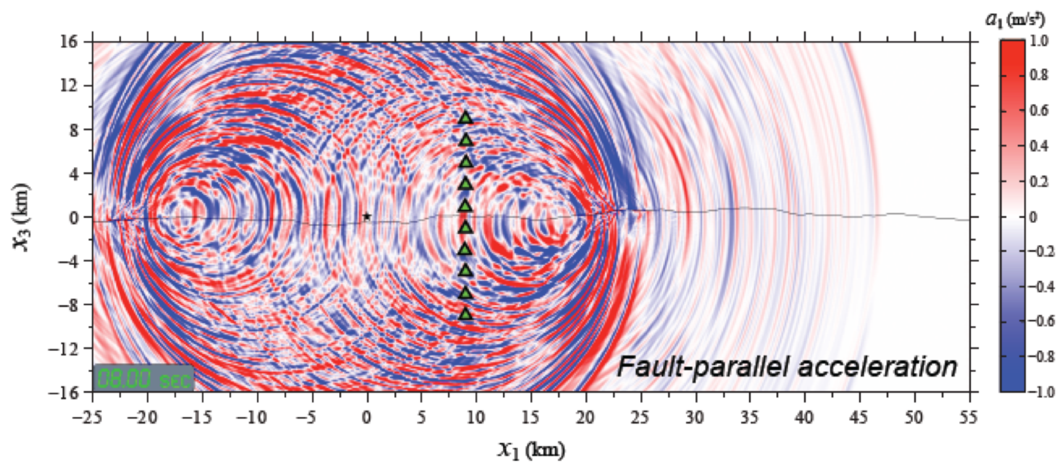
$\Delta x \sim 20\ m$

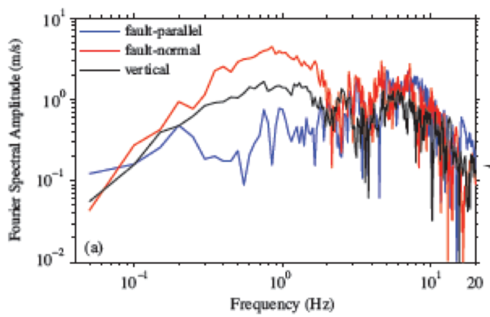
Highest resolvable frequency $f_{\mathrm{resl}} = \min(V_s)/100$
e.g., $f_{\mathrm{resl}} = 15$ Hz for $\min(V_s) = 1500$ m/s

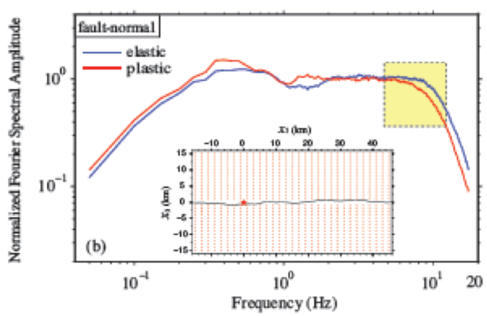
Source dominated near-source ground motion

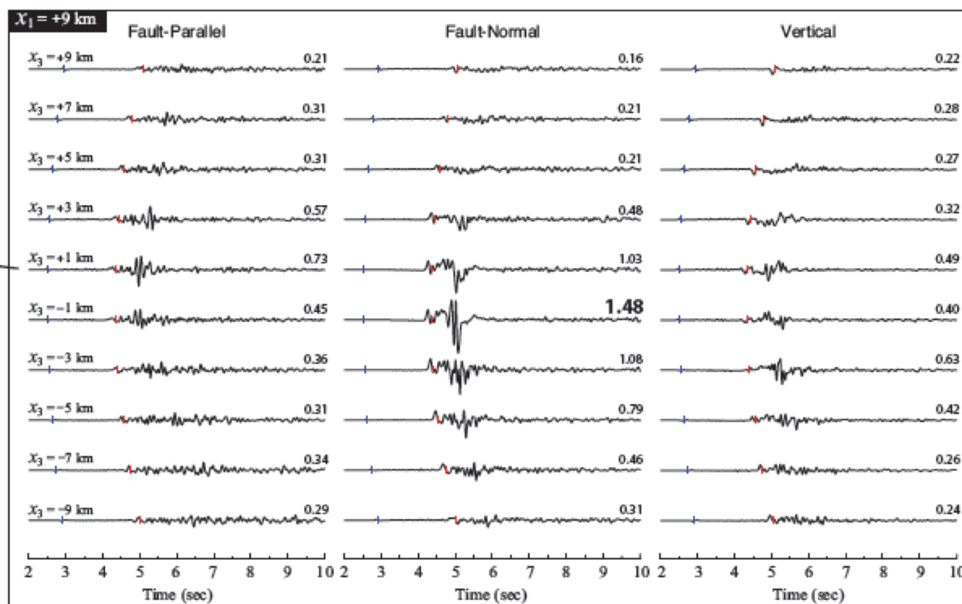
High Frequency (HF) radiation from the source

Raugh-Fault simulations (Shi and Day, 2013): Simulations results (ground motion)



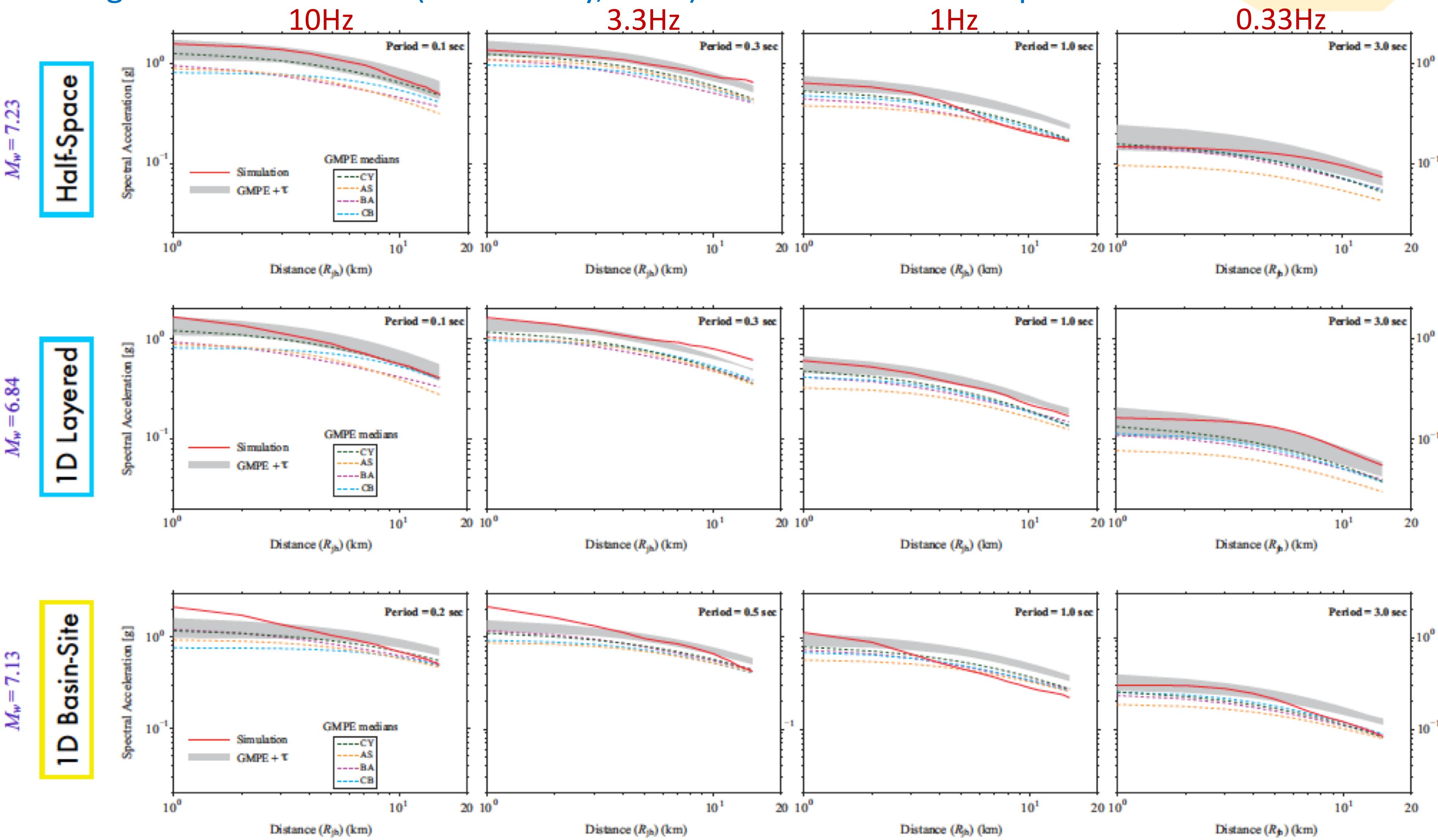






Source dominated near-source ground motion

Raugh-Fault simulations (Shi and Day, 2013): Ground motion compared with GMPEs



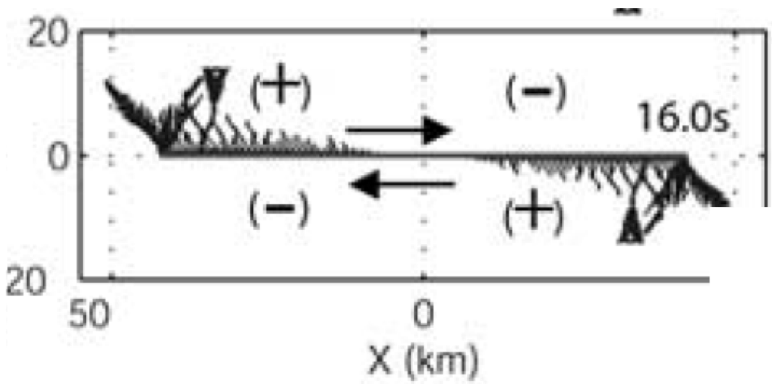
Corrected for generic WNA rock site

Corrected for generic basin site with V_{S30} = 300 m/s, κ = 0.066 sec

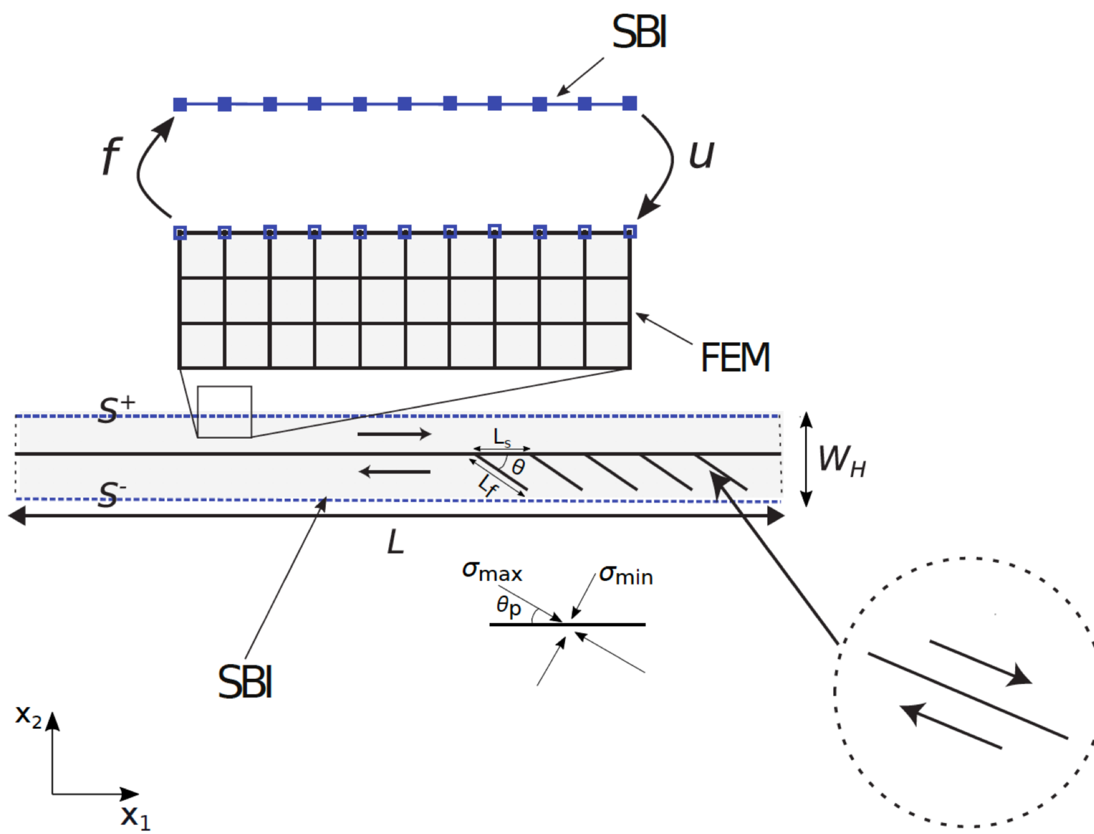
Source dominated near-source ground motion

High Frequency (HF) radiation from the source

Fault with small scale branches:



(Dalguer et al., 2003)



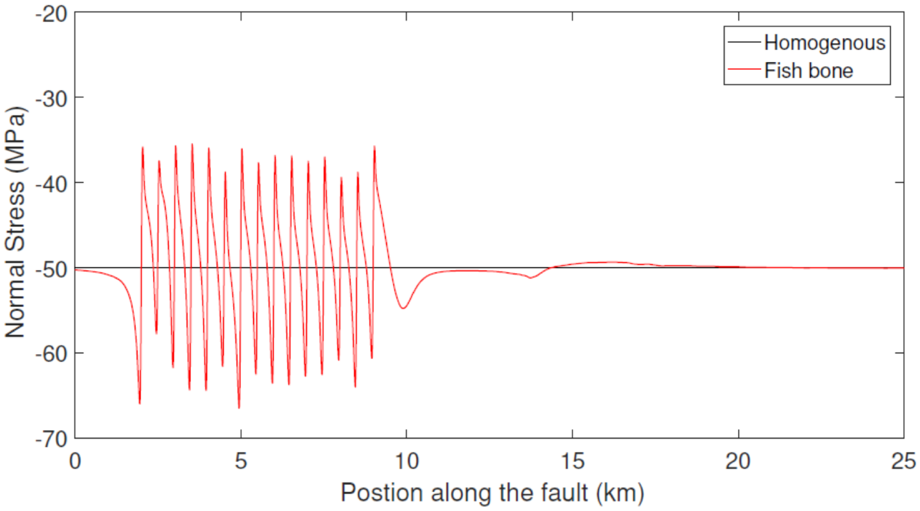
(Ma and Elbanna, 2019)

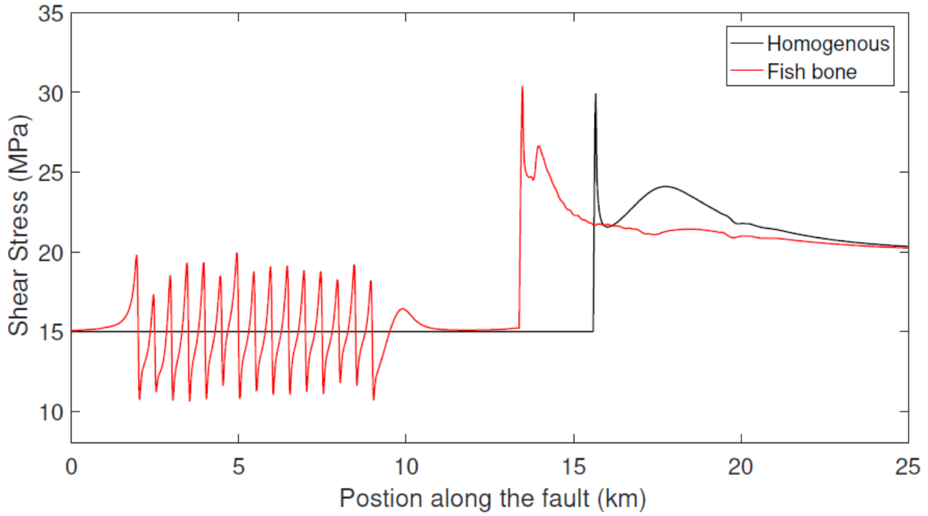
Source dominated near-source ground motion

High Frequency (HF) radiation from the source

Fault with small scale branches (Ma and Elbanna, 2019) in 2D: Effect on stress

Significant stress heterogeneity caused by the fish bone structure (branches)



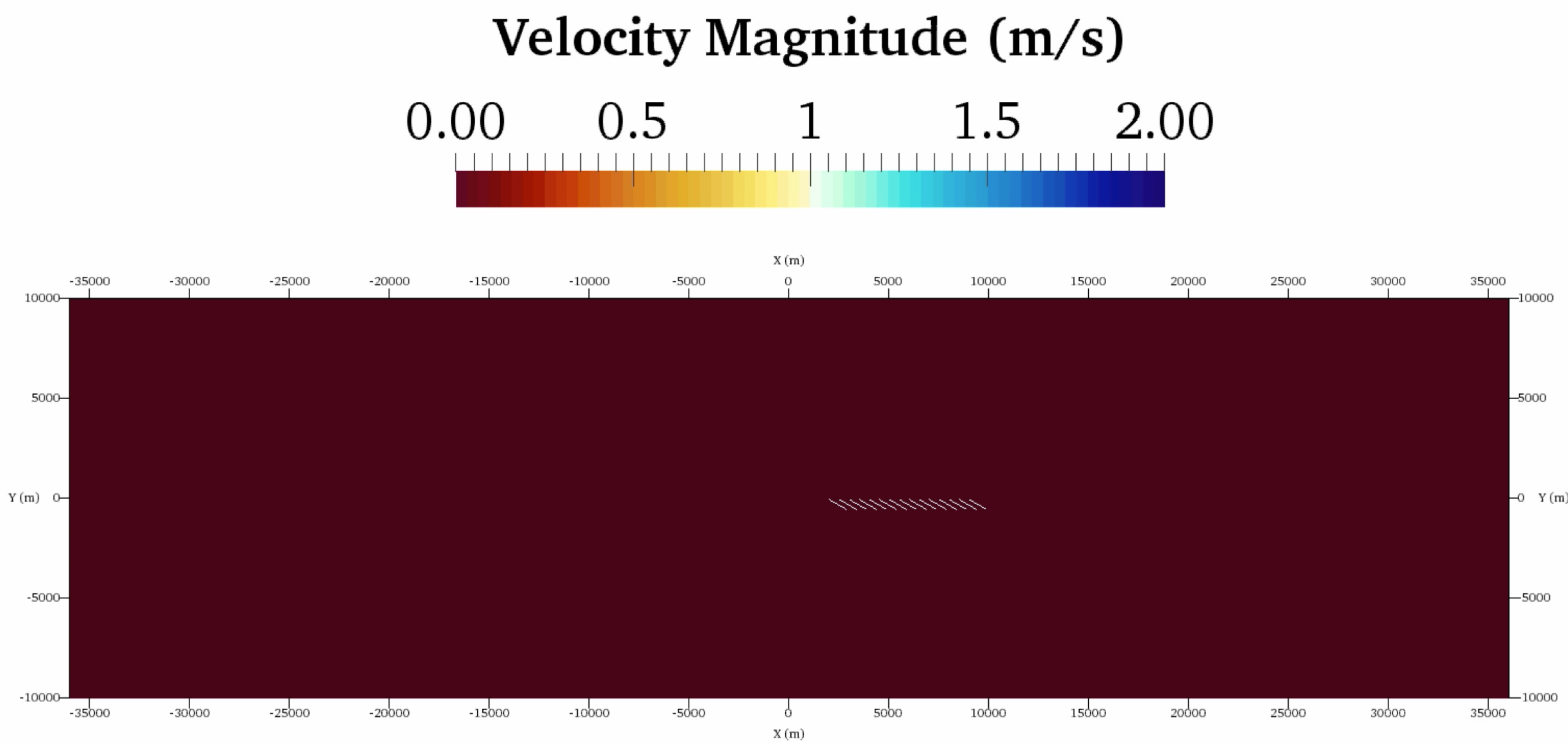


Source dominated near-source ground motion

High Frequency (HF) radiation from the source

Fault with small scale branches (Ma and Elbanna, 2019) in 2D: Ground motion

- HF velocity ground motion is generated by the models with branches
- These HF radiations are emerging from the interference between seismic radiation from the main and secondary faults.



Time: 0.08 s

Source dominated near-source ground motion

High Frequency (HF) radiation from the source

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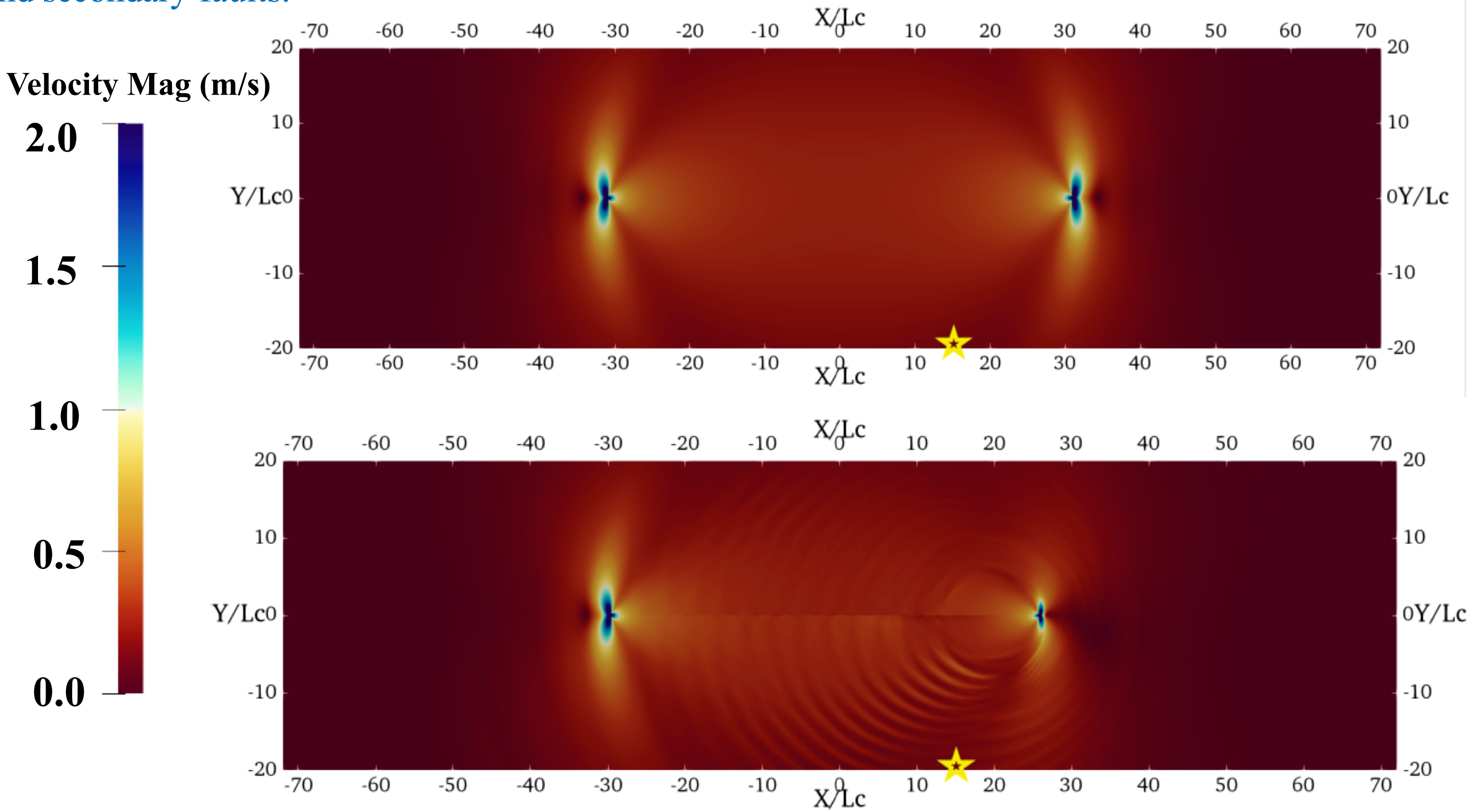
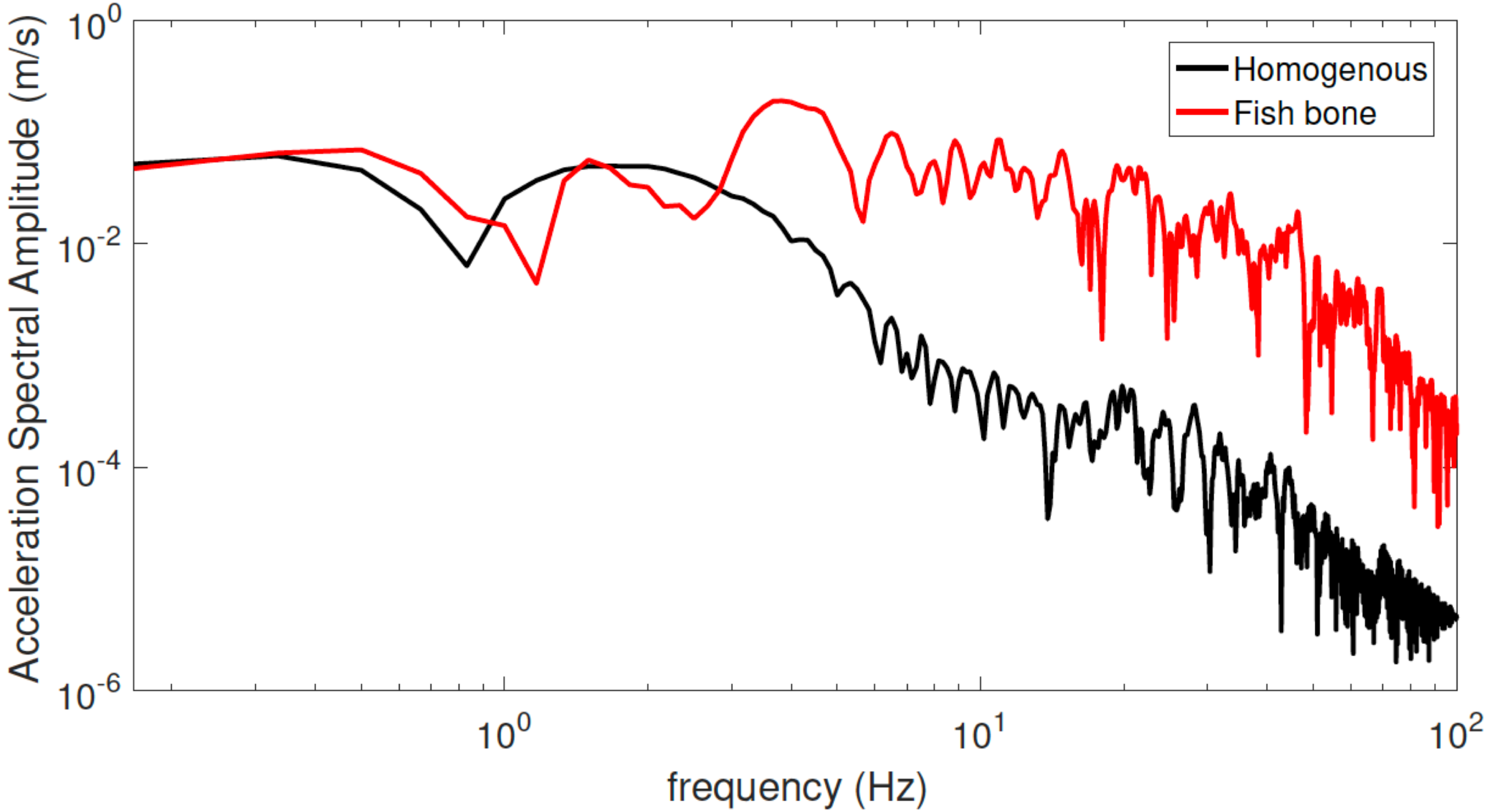


Source dominated near-source ground motion

High Frequency (HF) radiation from the source

Fault with small scale branches (Ma and Elbanna, 2019) in 2D: Ground motion

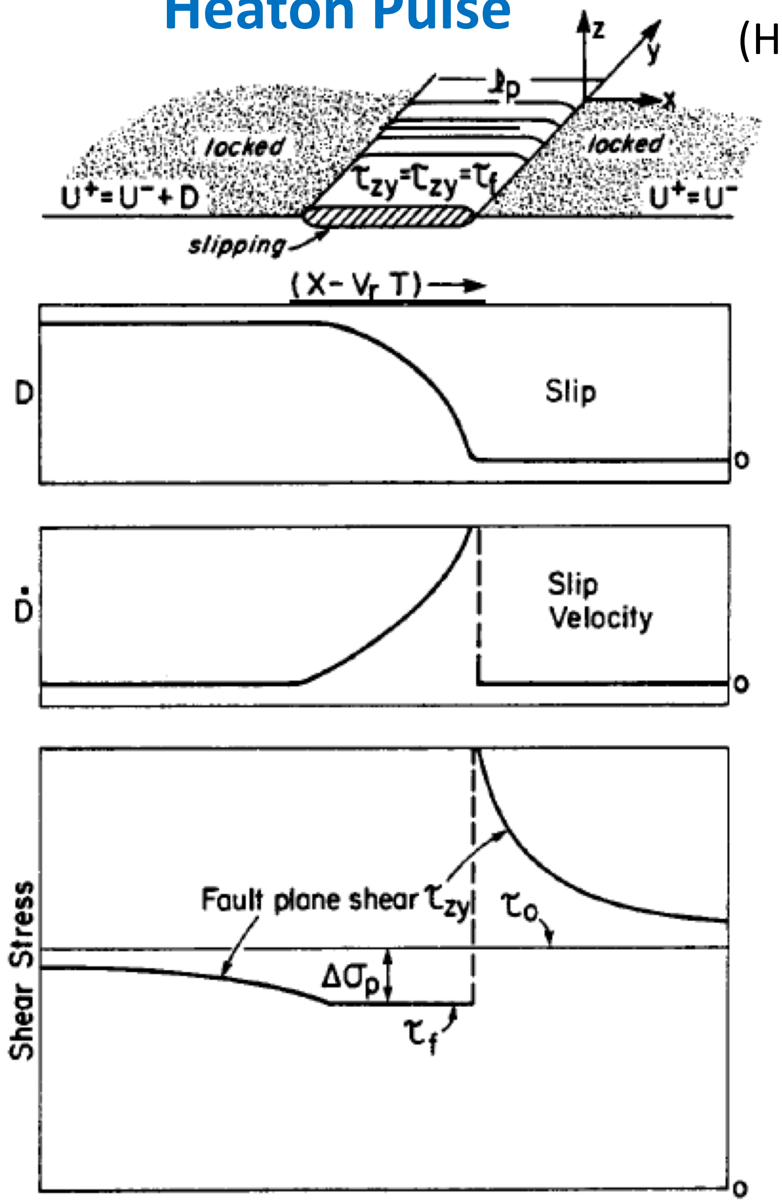
HF acceleration up to larger than 40Hz is modeled in 2D.



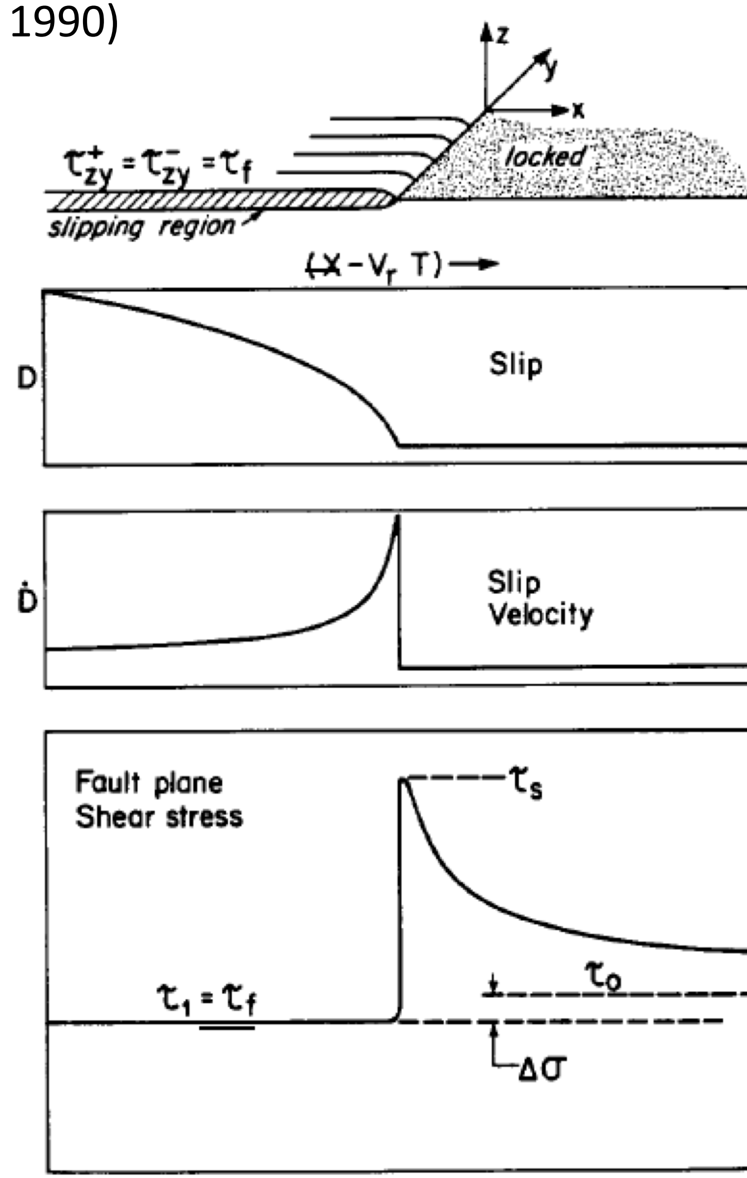
Crack-like and Pulse-Like: Implications on source spectra

Heaton Pulse

(Heaton, 1990)

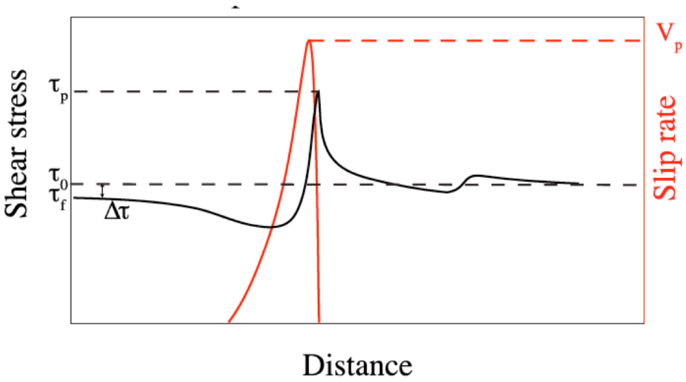


Crack-Like



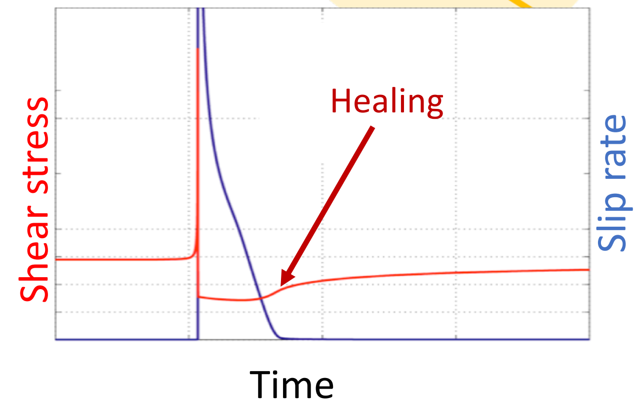
Crack-like and Pulse-Like: Implications on source spectra

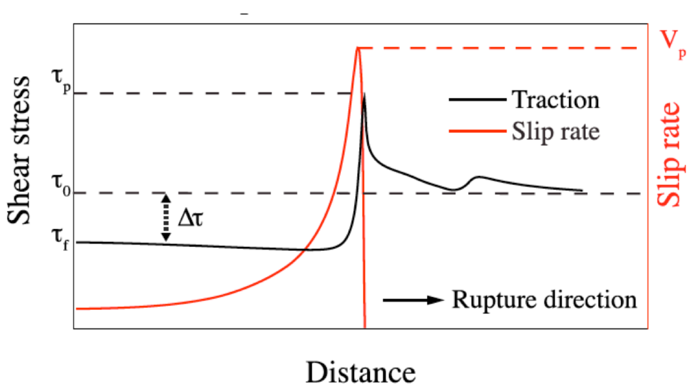
Stress and slip rate



Pulse-like rupture:

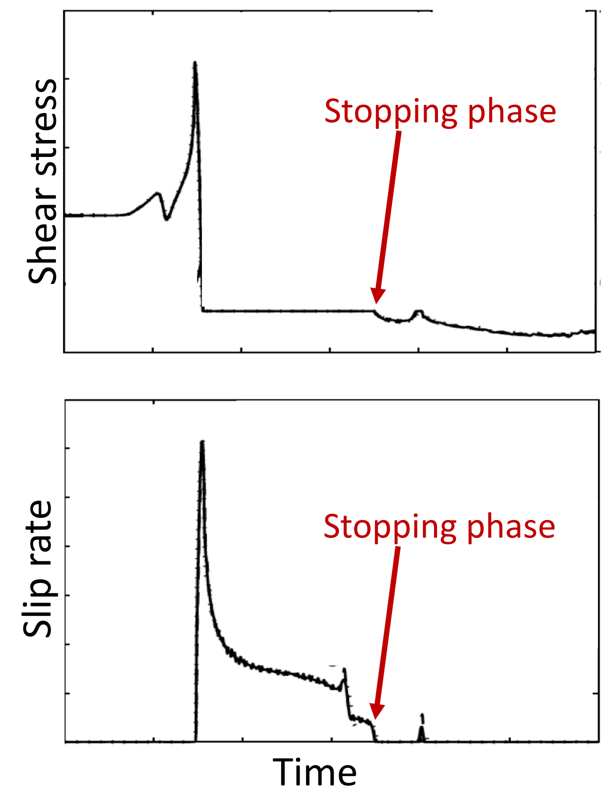
- Frictional Stress develops healing process
- Slip stops due to healing
- Slip duration depends on healing
- Shorter rise time than crack-like





Crack-like rupture:

- Stress remains constant during slipping
- No healing
- Slip continues until get signals of stopping faces
- Longer rise time than pulse-like

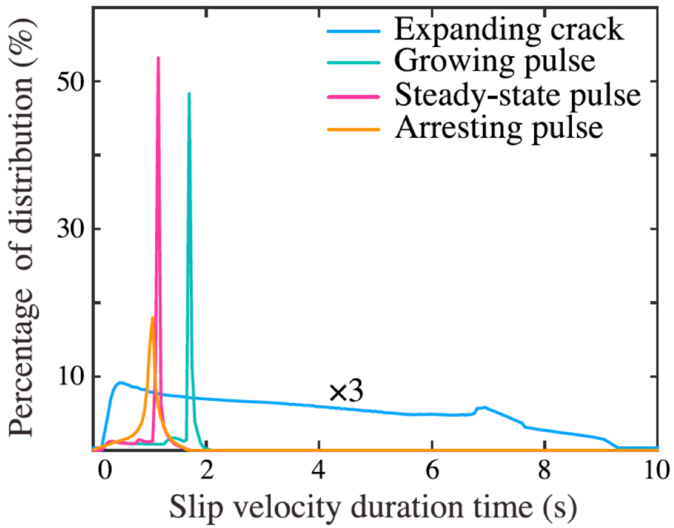


(Wang and Day, 2017)

Crack-like and Pulse-Like: Implications on source spectra

Effect on seismic source spectra (far field)

a) **Slip duration distribution**



- Crack-like models generate one corner frequency (depends on fault dimensions, i.e. source rupture duration). (most commonly used source in practice for ground motion modeling)
- Pulse-like rupture models generate double corner frequency (depends on slip rate duration). (double corner frequency has been observed in observations, e.g. Atkinson and Silva, 1997)

Brune-type source spectral model:

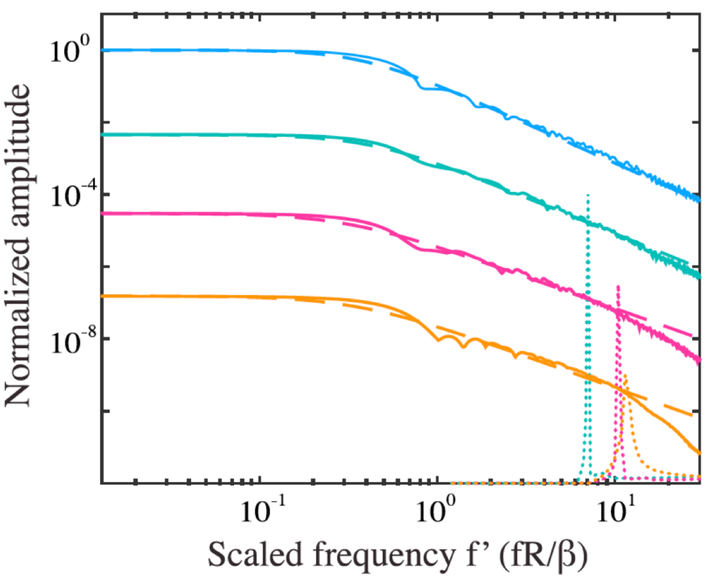
$$S f) = \frac{\Omega_o}{1 + (f/f_c)^n}$$

Ω_0=Long period spectral level $\sim M_0$

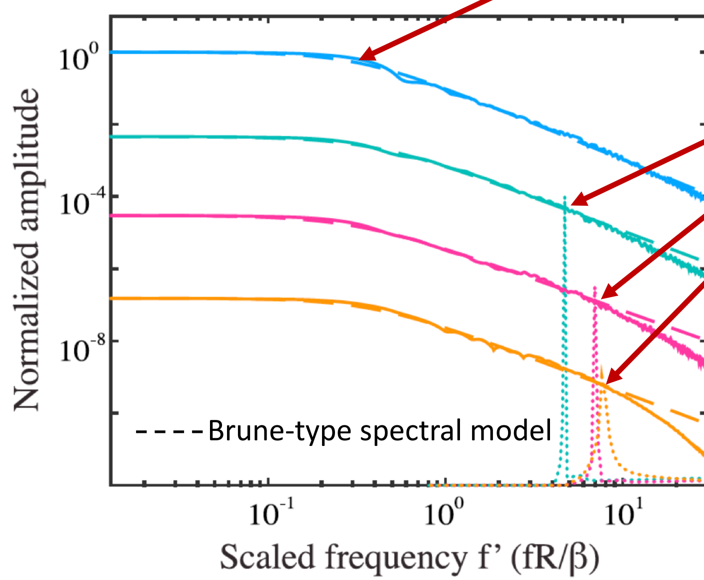
R=Rupture radius
β=S wave velocity
k=Constant

First corner frequency $f_c^{1st} \approx k\frac{\beta}{R}$

b) **Stacked P-wave spectra**



c) **Stacked S-wave spectra**



Second corner frequency

$$f_c^{2nd} \approx \frac{K}{T}$$

T=Slip velocity duration
K=Constant

Wang and Day, 2017)

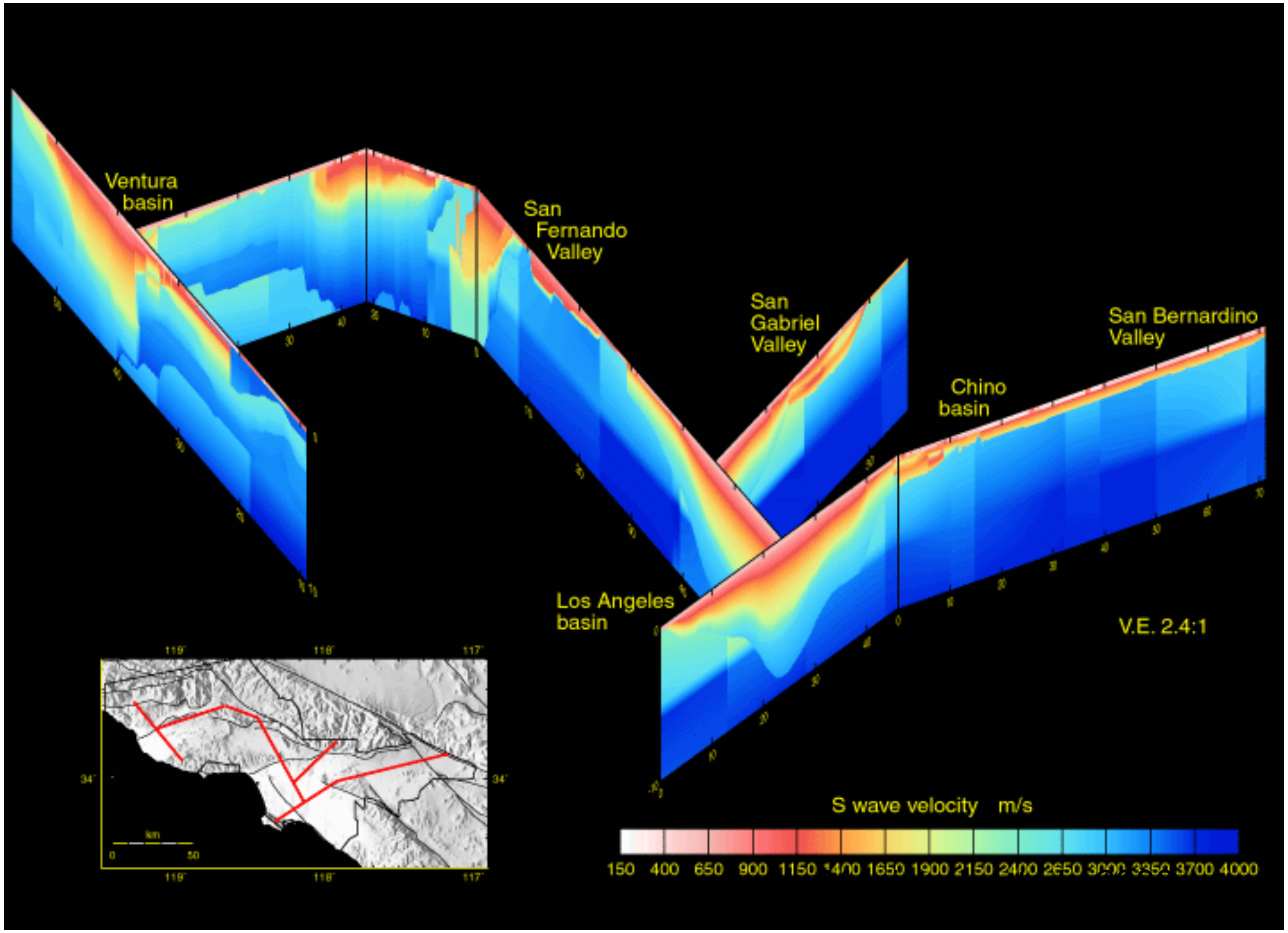
Source dominated near-source ground motion

ShakeOut Scenarion

Mw 7.81±0.06 from the southern San Andreas fault

Source dominated near-source ground motion

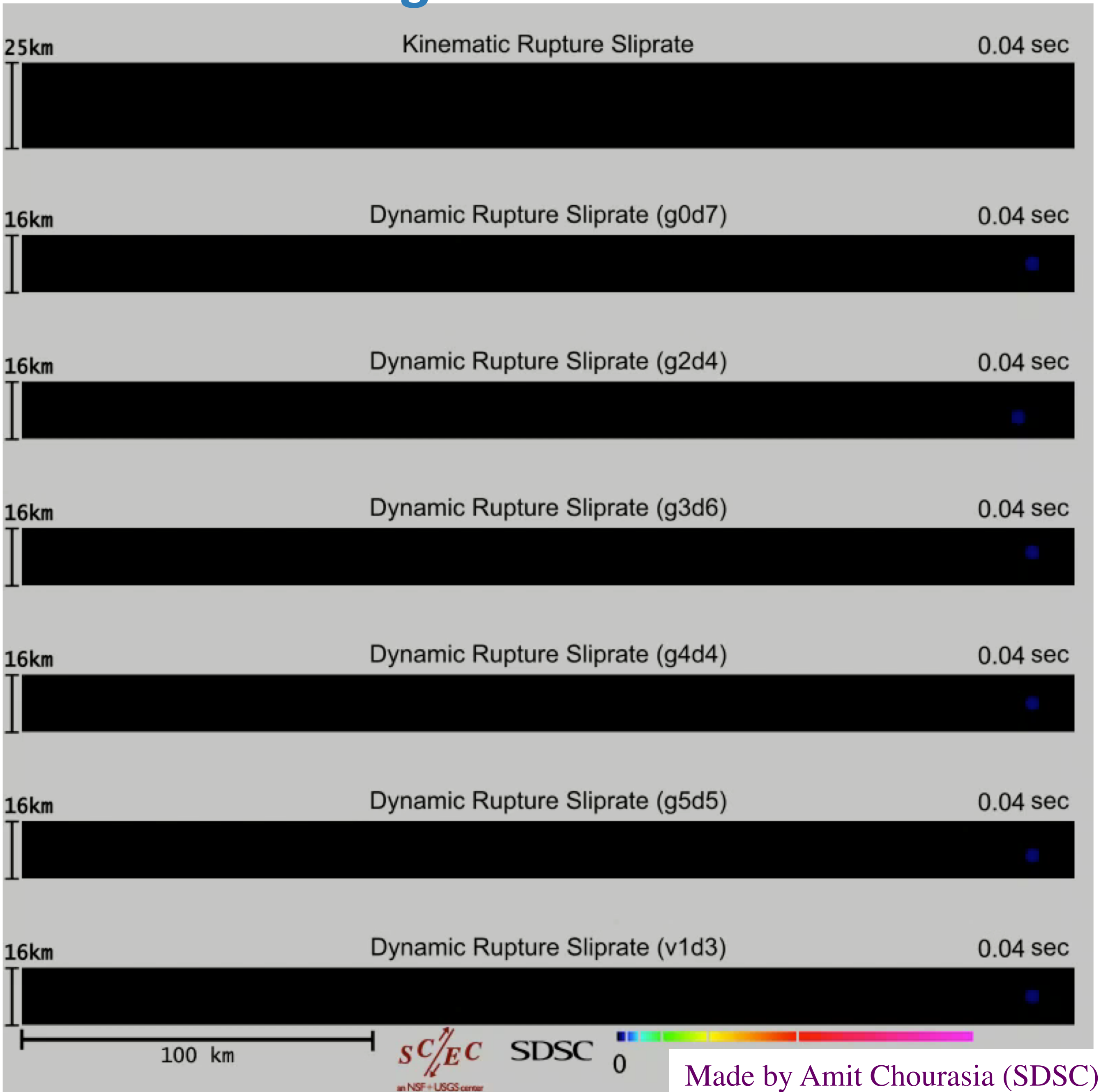
SCEC Community Velocity Model



Source dominated near-source ground motion

Kinematic

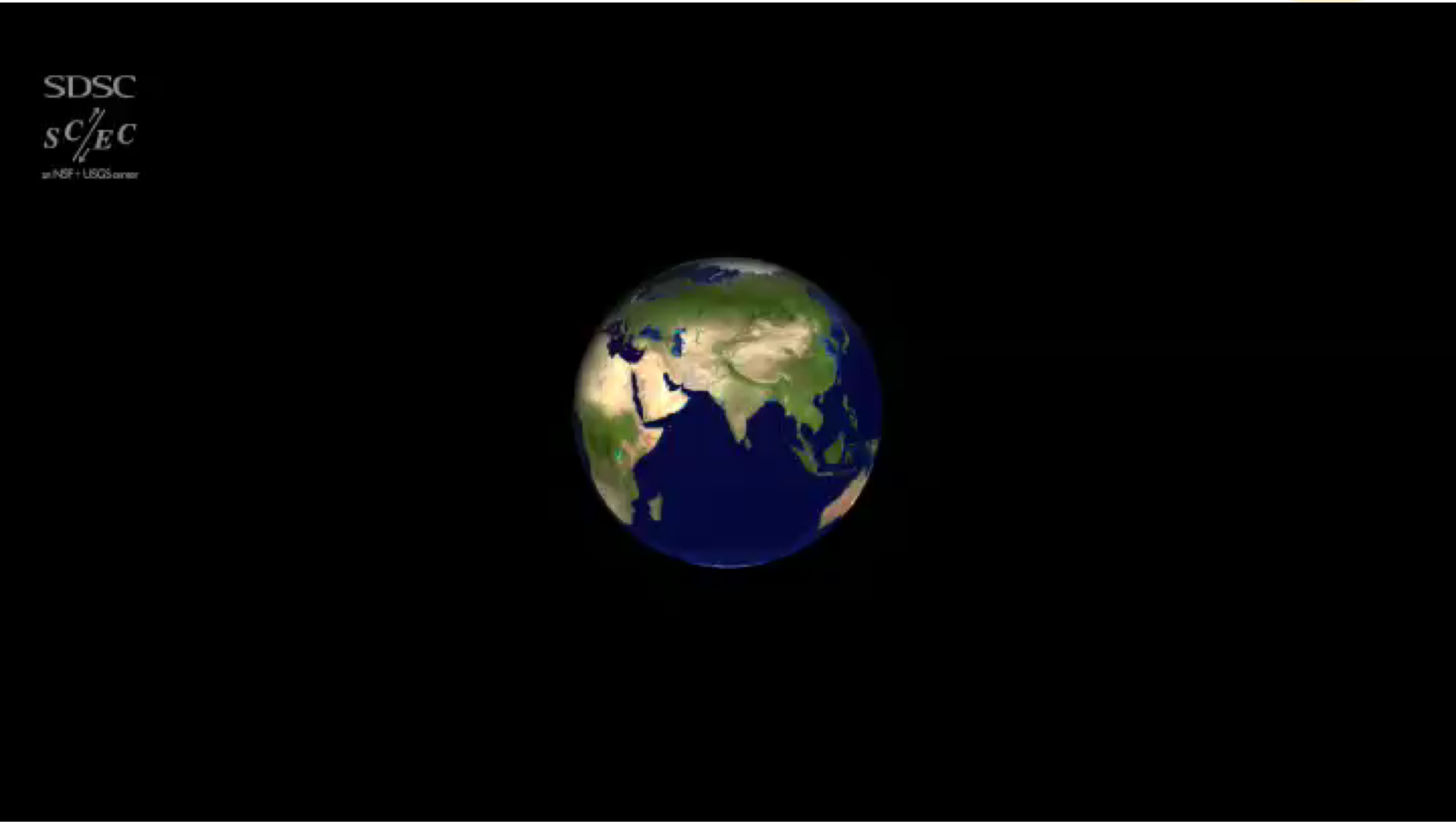
Dynamic



Made by Amit Chourasia (SDSC)

Source dominated near-source ground motion

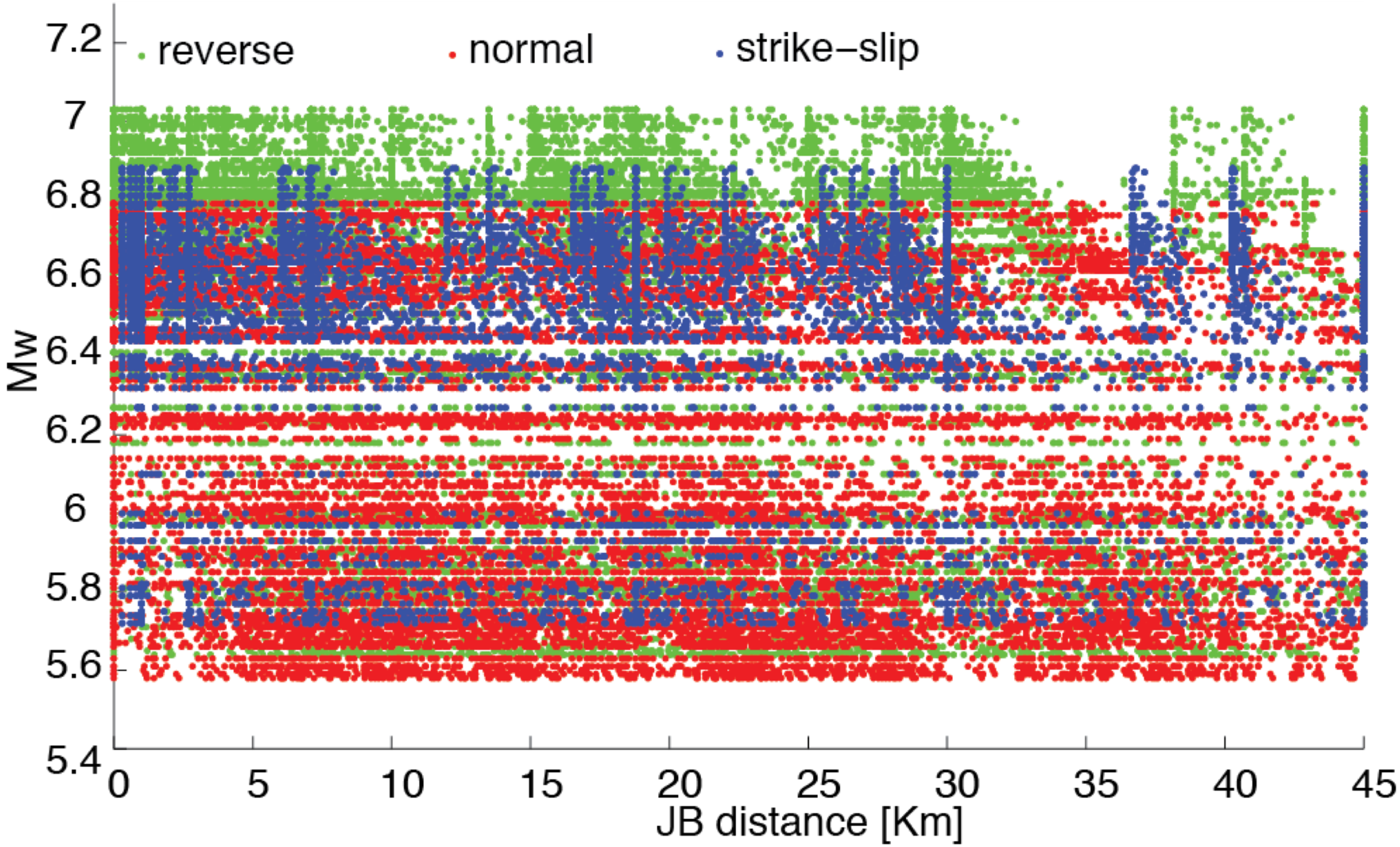
ShakeOut Ground motion modeling



Made by Amit Chourasia (SDSC)

Physics-based earthquake simulation

We can develop a database of synthetic earthquakes To fill the gaps of lack of data (Dalguer and Mai, 2011)



Physics-based earthquake simulation

Developments of Physics-based earthquake models

- Contribute to substantial advances in our understanding of different aspects related to earthquake mechanism and near-source ground motion.
- Input data to the model (fault geometry and geological structure) can be generic or constrained to the site or region of interest

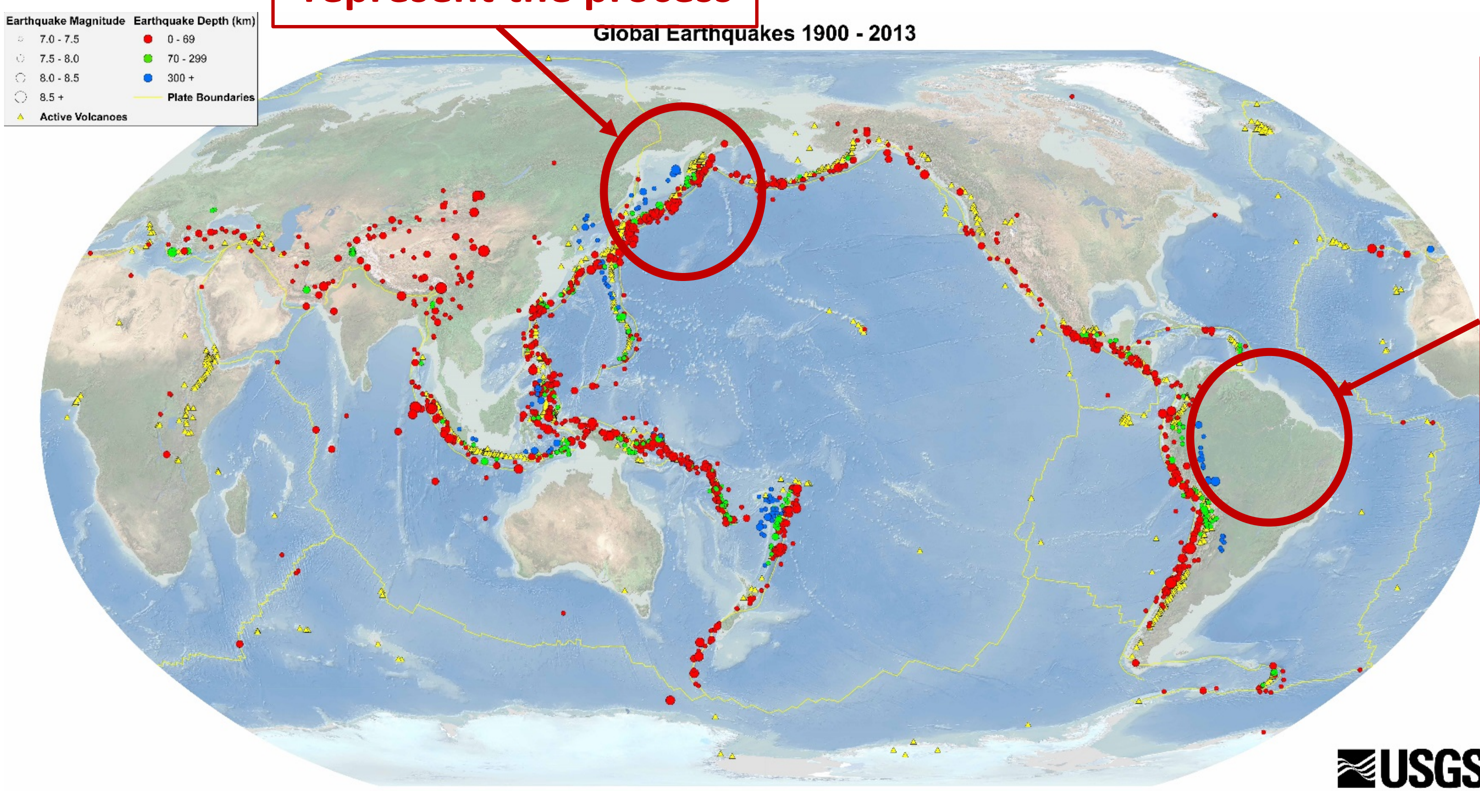
Limitations of Physics-based models

- Can be computational expensive. But evolution of modern computer capabilities is reducing this limitation
- Observational constrains in the source parameterization are limitted. But assumptions are supported by meaningful physical foundations.
- For best performance:
  - Need best information of source (limitted)
  - Need best information available of the geological structure and site (limitted)

Ergodic and non-ergodic process

Ergodic: The statistical properties of a process can be deduced from a representative singles sample. It means, any sample of the process is completely representative of the process as a whole.

This sample could represent the process



In places with no data, we could use the data from other places

Non-ergodic: Processes for which this property does not hold.

Ergodic and non-ergodic process

Ground Motion Variability of GMPEs

GMPE: $\ln(Y) = f_{src}(M, \ldots) + f_{path}(R, M, \ldots) + f_{site}(Vs_{30} \ldots) + \Delta$

Total variability: $\Delta = \Delta B + \Delta W$

ΔB is the ***between-events variability*** *with* standard deviation τ

- Earthquake-to-earthquake variability
- Represent average source effects
- Effects of stress drop, slip velocity, rupture speed, geometrical fault complexity, etc. not captured by the source terms in the GMPE

ΔW is the **within-events variability** with standard deviation ϕ

- Record-to-record variability
- Represent azimutal variation in source, path and site effects
- Effects of crustal heterogeneities, deeper geologicat structures, basins, near surface layering, etc, not captured by the path and site terms in the GMPE

ΔB and *ΔW* are uncorrelated, then total standard deviation is

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

Note: The variability or residuals are the deviation of the observed quantity with respect to the median predictor model

Ergodic and non-ergodic process :Ground Motion Variability

Components of *ΔW*: $\delta W_{es} = \delta S2S_s + \delta Amp_{es} + \Delta P2P_{sl} + \delta W^0_{esl}$

$$\phi = \sqrt{\phi^2_{S2S} + \phi^2_{Amp} + \phi^2_{P2P} + \phi^2_{0,G}}$$

$\delta S2S_s$: Site-to-site amplification residuals

δAmp_{es}: site amplification residuals (record-to-record variability of the amplification)

$\delta P2P_{sl}$: Path-to-path residuals (deviation of observed site-specific region specific)

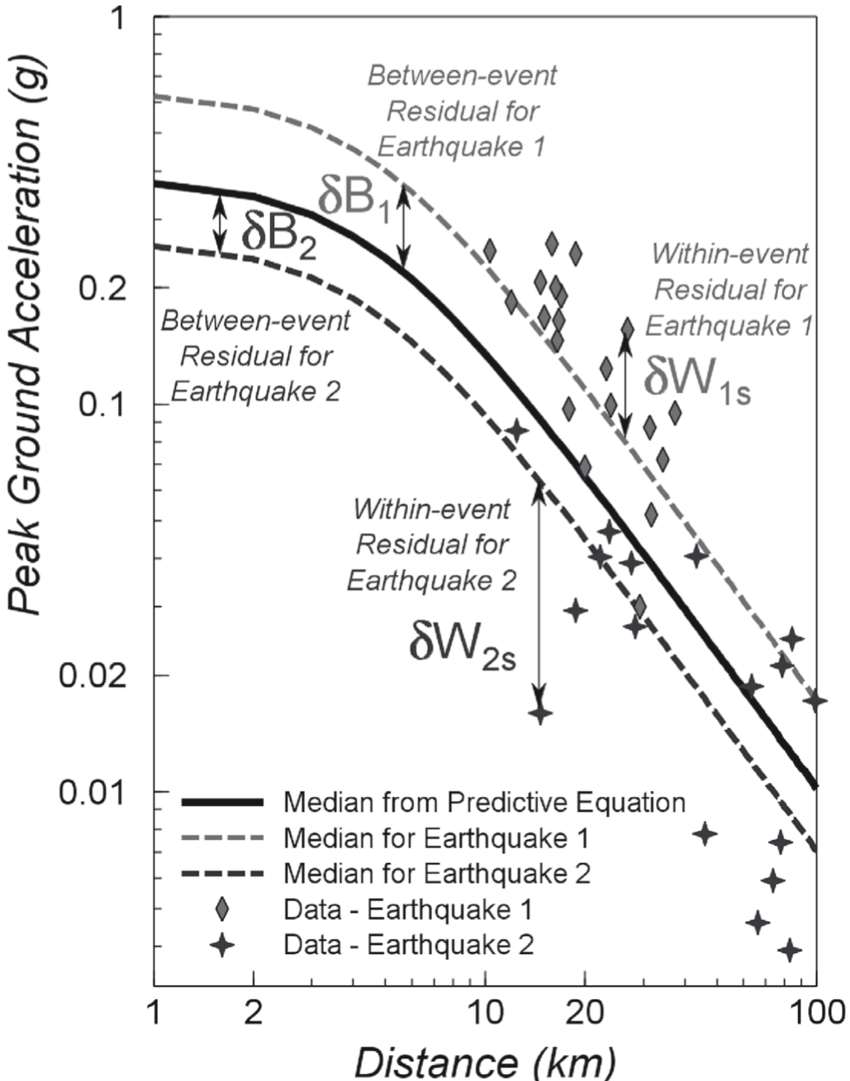
δW^0_{esl}: Remaining unexplained path and radiation pattern

Components of *ΔB* $\delta B_e = \delta L2L_l + \delta B^0_{el}$

$$\tau = \sqrt{\tau^2_{L2L} + \tau^2_0}$$

$\delta L2L_l$: Source Location-to-location residuals (deviation of a single region comperared to the global model (effects of stress drop, etc)

δB^0_{el}: Remaining residual after removing the earthquake location-specific effect.



(Strasser et al, 2009. Taken from Al Atik, et al, 2010)

Ergodic and non-ergodic process: Current issue

Statistical process	Aleatory	Epistemic	Required recording dataset
Ergodic	$\phi_{0,G}, \phi_{P2P}, \phi_{Amp}, \phi_{S2S}$ τ_0, τ_{L2L}		Global data ... rom earth... ce ... zones of major ... near-source, and ...ude of interest
Partially non-ergodic (single-site)	$\phi_{0,G}, \phi_{P2}$...		...ite-specific: at one site from earthquakes located in different source region . **Issue:** Few earthquakes with few data
F... no... (sing...n)	... $_{0,G}, \phi_{Amp}$ τ_0	ϕ_{P2P}, ϕ_{S2S} τ_{L2L}	Path-specific: at one site from earthquakes in one location **Issue:** No data for statistic analysis

GMPEs alone do not full fill the requirement for partially and full non-ergodic models, and even for ergodic models for the areas of interest

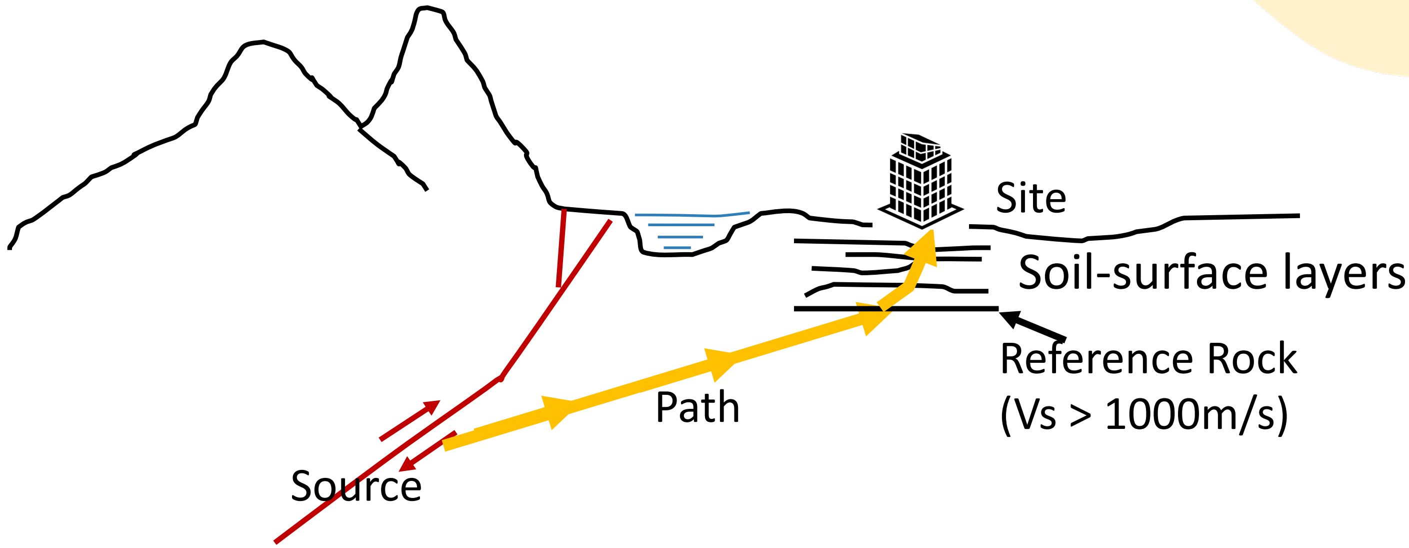
Ergodic and non-ergodic process: Role Physisc-based Models

Role Physisc-based Models

Statistical process	Aleatory	Epistemic	Required re… dataset
Ergodic	$\phi_{0,G}, \phi_{P2P}, \phi_{Amp}, \phi_{S2S}$ τ_0, τ_{L2L}		…data + …ation-based …s to fill the gap in …ervations
Partially non-ergodic (single-site)	$\phi_{0,G}, \phi_{P…}$		Site-specific observed data + Simulations with regional information
Fully… no… (sing…	…ϕ_{Amp} τ_0	ϕ_{P2P}, ϕ_{S2S} τ_{L2L}	Path-specific: Use observed (if available) + Simulations with regional information **(a model dominated by simulations)**

Empirical GMPES and Physics-based models complement each other to full fill the requirement of, ergodic, partially non-ergodic and fully non-ergodic ground motion models

GMPEs vs Physics-based Rupture Model for SHA



GMPEs for SHA:

- Usually is ajusted to predict ground motion for reference rock (Vs > 1000m/s).
- Post processing calculations are done to account for local soil response
- Do not capture complexities of source, path and site
- Extrapolate in areas with sparse or not observed data
- Can not predict ground motion different to pass earthquakes

Physics-based models:

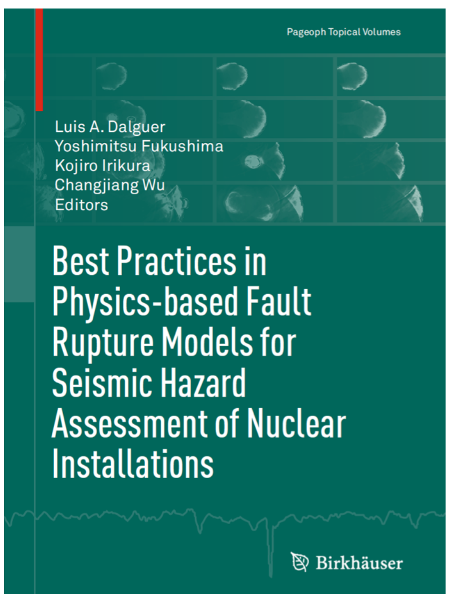
- Can include the whole system in a single model (source, path and site)
- Capture complexities of source, path and site
- Extrapolation is supported with physical foundations
- Ground motion prediction can be different to pass earthquakes, but physically plausible

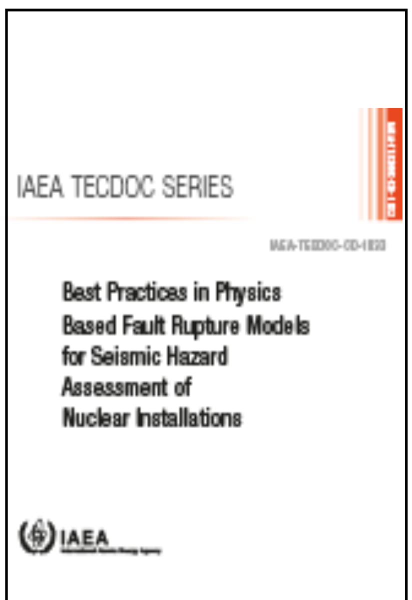
The role of physics-based rupture models in PSHA

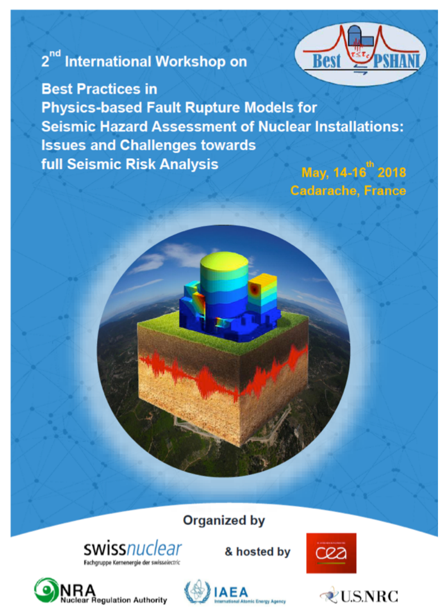
- 3-D physics-based dynamic rupture models are by construction site specifics models, because highly depend on the data of the site of interest. Therefore they are intrinsically non-ergodic models
- Capture details of the site of interest
- Can complement the empirical models by filling the lack of data to improve the representation of the site of study and to be consistent with the non-ergodic process of natural earthquakes.

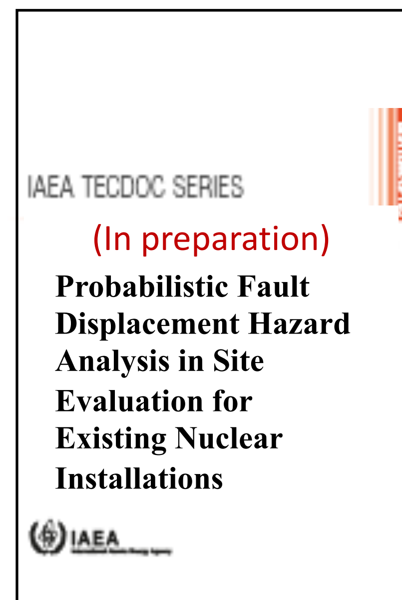
Current IAEA effort to implement Physics-based model in PSHA

- IAEA has already recognised this issue and currently is making the effort to implement the physics-based rupture modelling in practice for PFDHA. But also in PSHA.
- These efforts have been discussed through different international working group activities, being the most outstanding two international workshops on **Best** Practices in **P**hysics-based Fault Rupture Models for **S**eismic **H**azard **A**ssessment of **N**uclear **I**nstallations (BestPSHANI) in 2015 and 2018.
- Currently we are writing an IAEA-TECDOC (Technical Document) on Probabilistic Fault Displacement Hazard Analysis (PFDHA) in Site Evaluation for Existing Nuclear Installations. In this TECDOC we are explicitly describing the use of physics-based dynamic rupture models for PFDHA









Why physics-based Rupture Models

- ➢ Need to fill the gaps of empirical GMPEs
- ➢ Physics of wave propagation
- ➢ Asumptions: physical foundations
- ➢ For best performance:
  - Need best information of source (faults)
  - Need best information available of the geological structure and site

- ➢ Ideal for site-specific seismic hazard assessment
- ➢ Intrinsically, they are featured to be used as non-ergodic ground motion models
- ➢ They can be constrained with all the available information of the area of interest.

Where use physics-based rupture models in practice?

- For region (site) – specific studies (as a non-ergodic model) calibrated with the data from he site of interest.
- For near-source ground motion and large magnitudes to fill the gaps of GMPEs
- For displacement, velocity and acceleration ground motions (3 components) at reliable frequency range
- For surface rupture offset (named by other communities as “fault displacement“)
- Need Validation!

Main Requirements to use physics-based synthetics ground motion

Seismological aspect

- Validation against past earthquakes (e.g. SCEC validation project)
- Verification against empirical GMPEs models in areas where GMPEs use large amount of observed data (e.g. SCEC validation project)

Engineering aspect

- Verification of the response of engineering systems (e.g. Structural response in frequency and time domain).

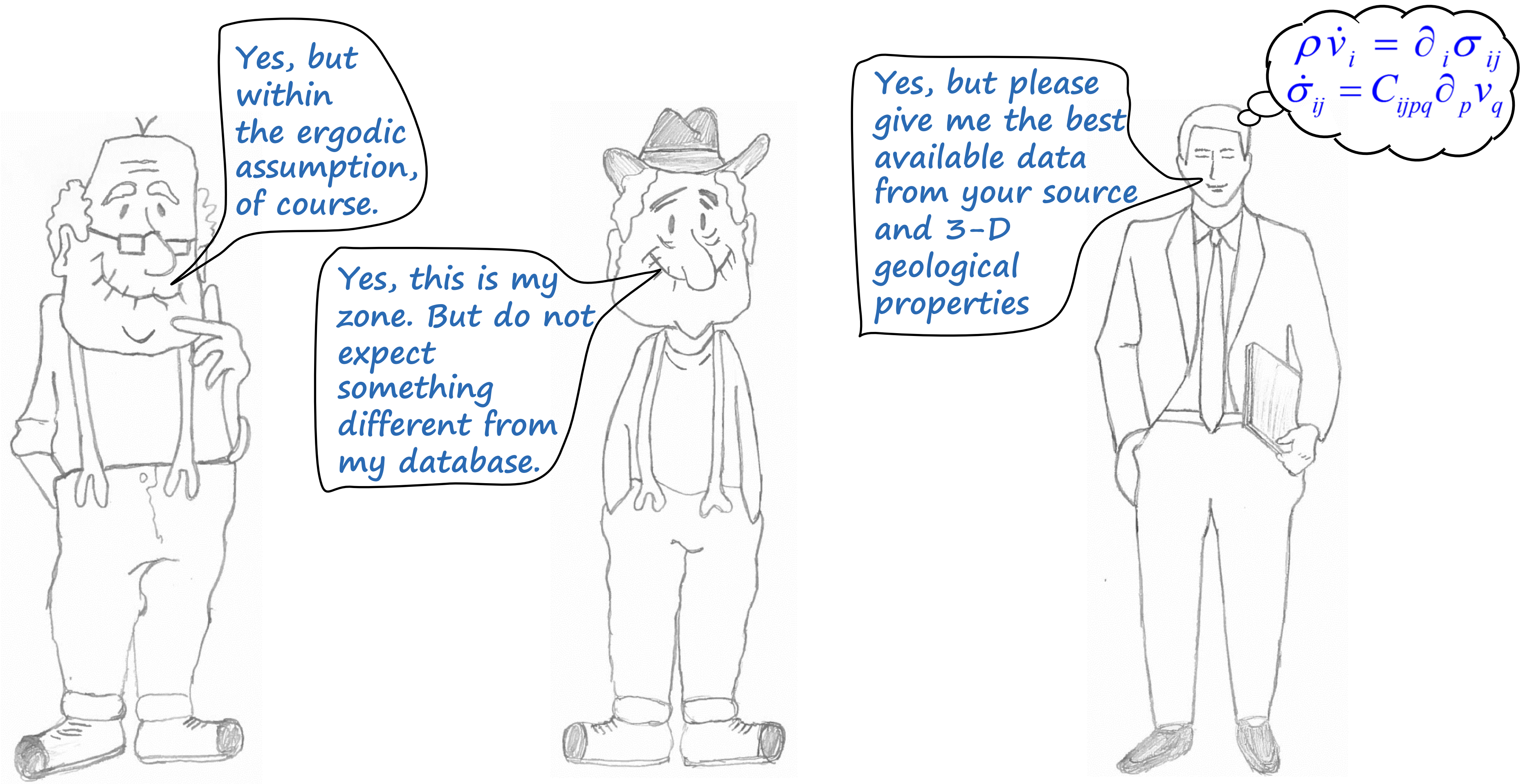
- **Current physics-based models used in practice:**

  -Kinematic models (to develop GMPEs and in PSHA)

  -There has been some attempts to use dynamic models in PSHA

GMPEs vs Physics-based GM simulation

Request 1: Could you make a prediction in zone A for Mw 7 and distance 20km?



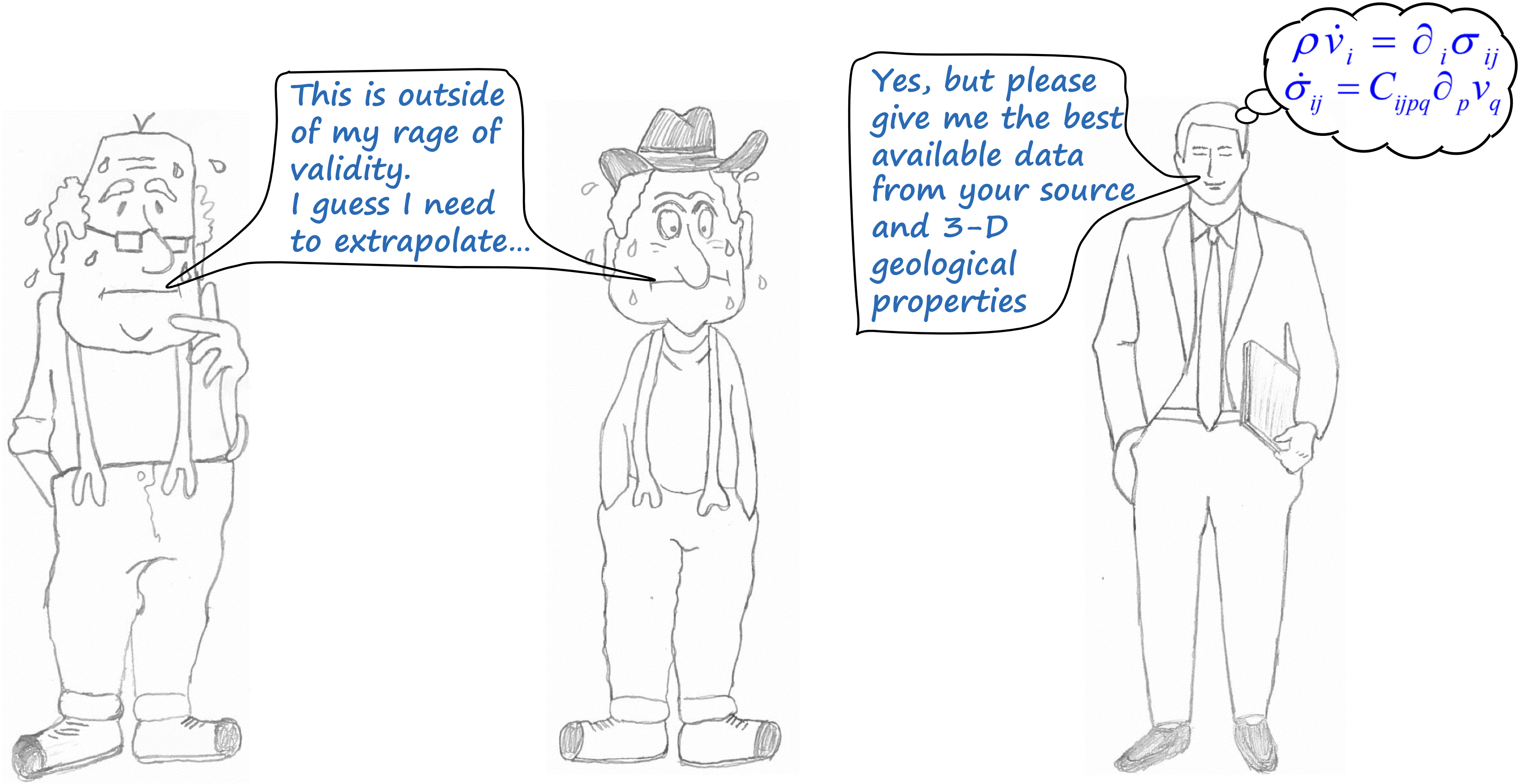
GMPEs (Global and ergodic)

GMPEs (For Zone A maybe partially non-ergodic)

Physics-based GM model (fully non-ergodic)

GMPEs vs Physics-based GM simulation

Request 2: Now a prediction in zone A for Mw 7 very near the fault?



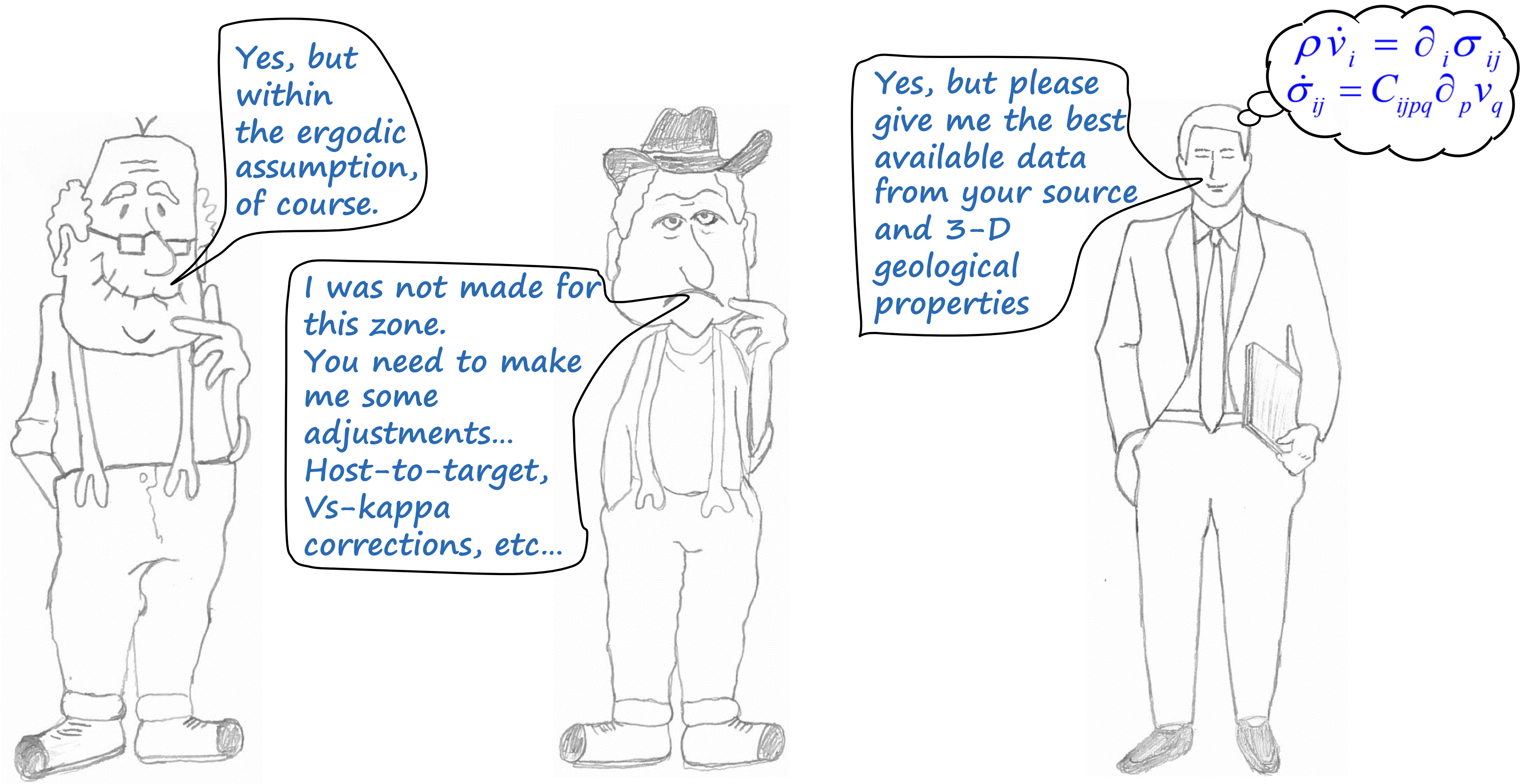
GMPEs (Global and ergodic)

GMPEs (For Zone A maybe partially non-ergodic)

Physics-based GM model (fully non-ergodic)

GMPEs vs Physics-based GM simulation

Request 3: Now please a prediction in zone B?



GMPEs (Global and ergodic)

GMPEs (For Zone A maybe partially non-ergodic)

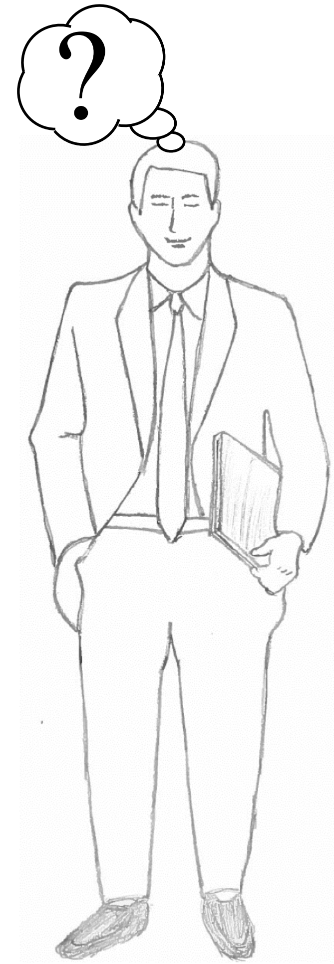
Physics-based GM model (fully non-ergodic)

GMPEs vs Physics-based GM simulation

Request 3: Please a prediction in zone B?

GMPEs
(Global and ergodic)

GMPEs
(Now almost for Zone B maybe partially non-ergodic)



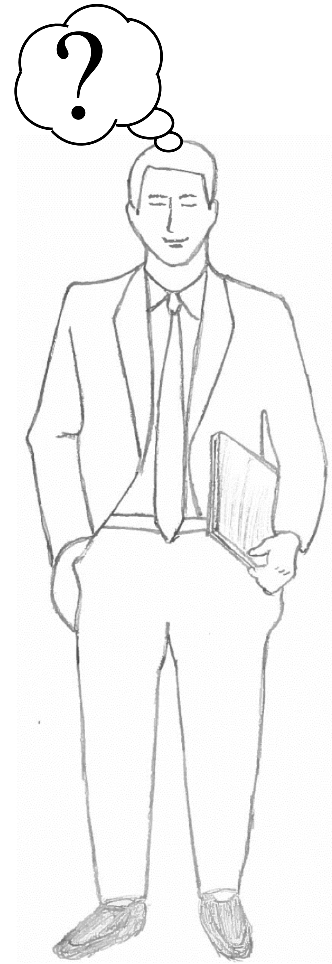
Physics-based GM model
(fully non-ergodic)

GMPEs vs Physics-based GM simulation

Request 3: Please a prediction in zone B?

GMPEs
(Global and ergodic)

GMPEs
(Now for Zone B
maybe partially non-ergodic)



Physics-based GM model
(fully non-ergodic)

Conclusions

- Empirical models (GMPEs) are insufficient for the prediction of ground motion for use in magnitude-distance range of most engineering interest
- At present, combination of Empirical GMPES and Physics-based models are required to full fill the requirement of, ergodic, partially ergodic and fully non-ergodic ground motion models
- Tendency for developments of hybrid GMPEs models (synthetic + observed)
- In the near future, physics-based rupture models may replace GMPE with fully 3-D physics-based rupture models
- For partially non-ergodic and fully non-ergodic models, physics-based rupture and ground motion modeling are needed for meaningful Hazard assessment