The Role of Physics-Based Ground Motion Models in Non-Ergodic Site-Specific PSHA Studies

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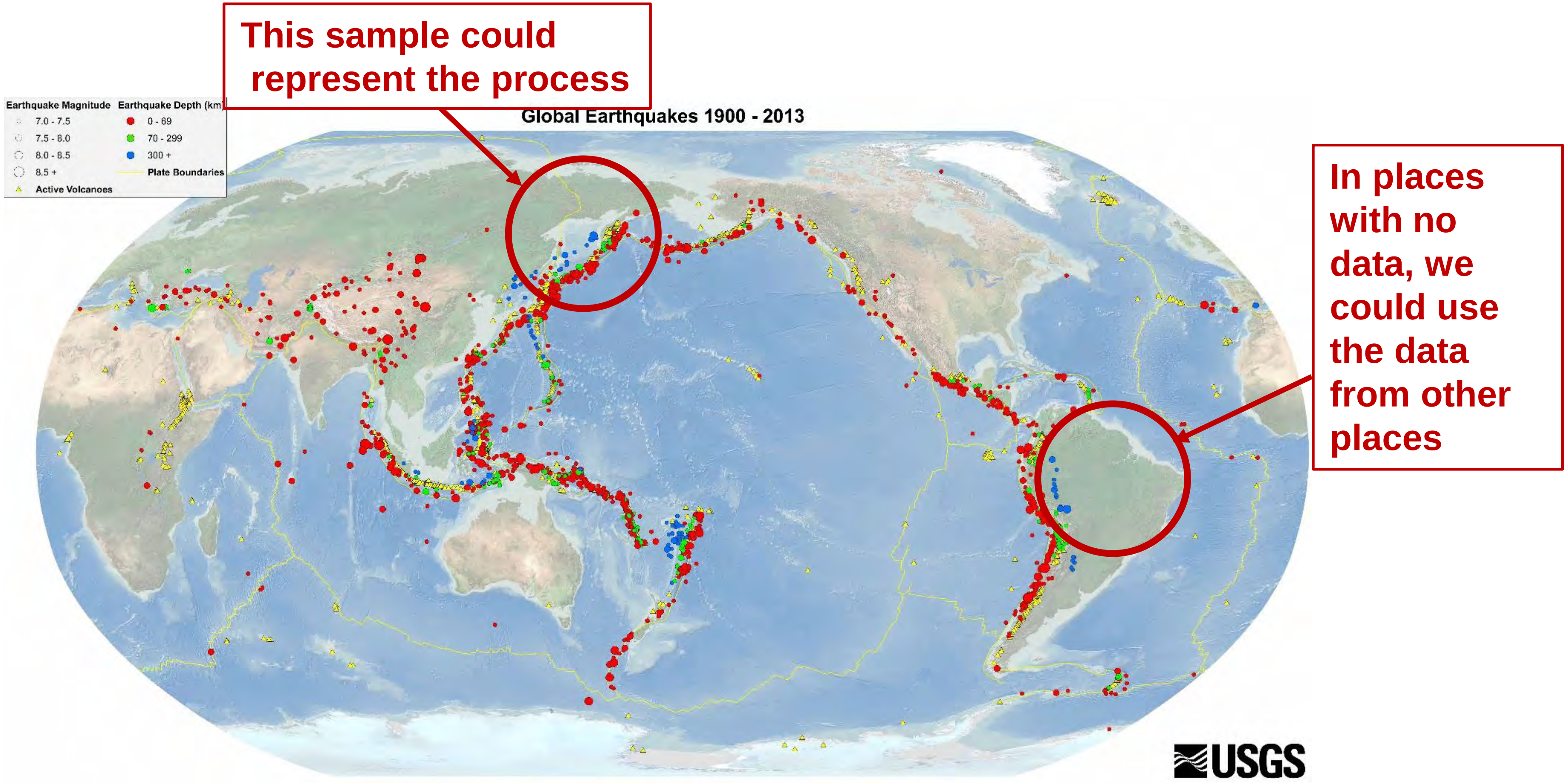
Ergodic and non-ergodic process

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.



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

Current practice in PSHA

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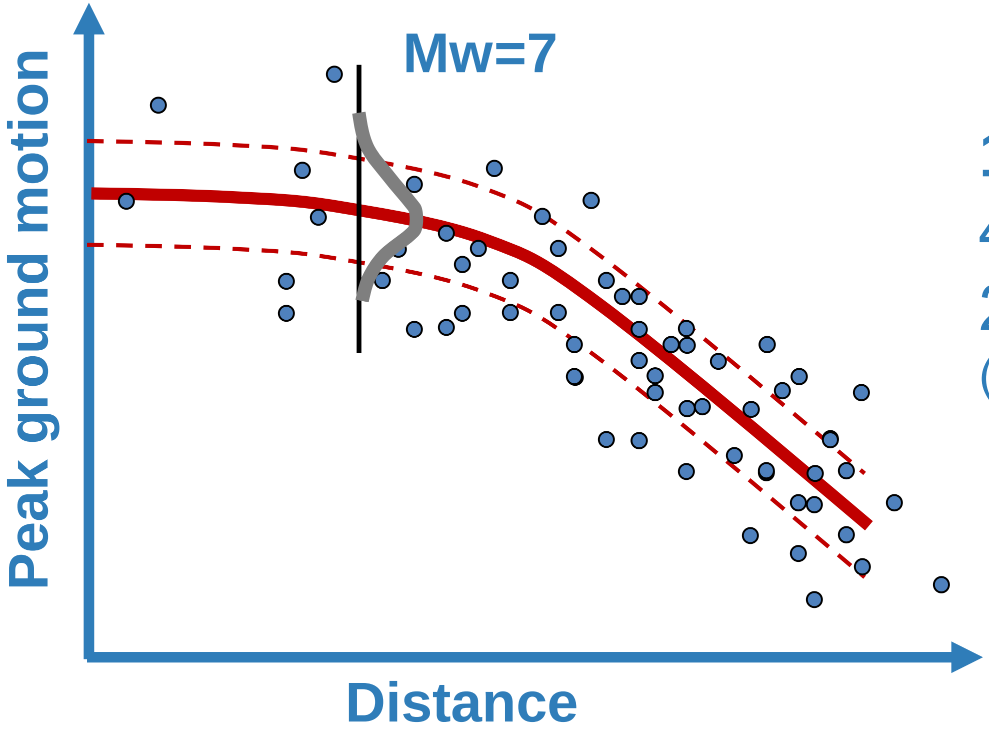
- An ergodic assumption is commonly made in Probabilistic Seismic Hazard Assessment (PSHA)
- Usually empirical GMPEs are used.

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



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

Site-specific PSHA for critical infrastructures

- Must consider details of best available information of region-specific geology, site, seismic sources, etc.
- Ideal environment for non-ergodic PSHA.
- Nevertheless, in practice such models are not used and a site-specific non-ergodic PSHA has not been performed
- Current practice is usually dominated by empirical GMPEs that have been developed most of the time using dataset from other places except from the site of interest.
- Those GMPEs pass for some “adjustments” (e.g. “Host to Target”) to make them applicable
- **The physics-based models** that take into account the finite-fault rupture, the geological and site conditions are ideal candidate models for fully non-ergodic studies because they can be constrained with all the available information of the area of interest.

Site-specific PSHA

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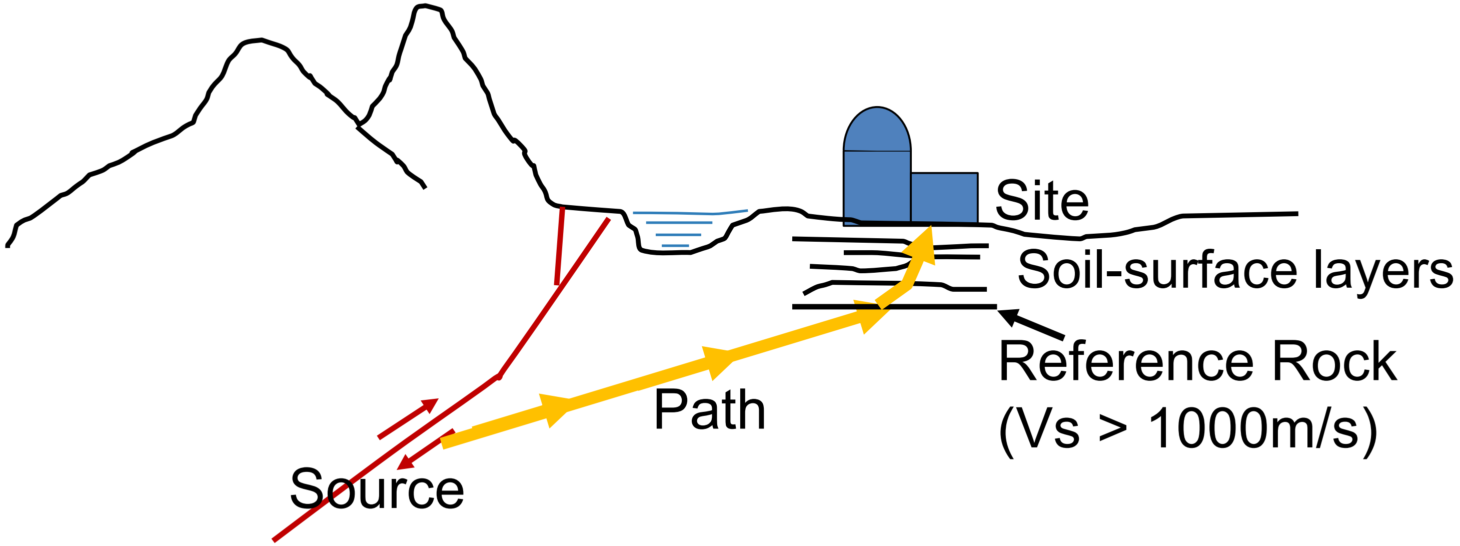

GMPEs:

- Usually is ajusted to predict 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

Physics-based models:

- Can include the whole system in a single model (source, path and site)
- Capture complexities of source, path and site

Combination of Empirical GMPES and Physics-based models

Example of Site-specific PSHA for NPPs

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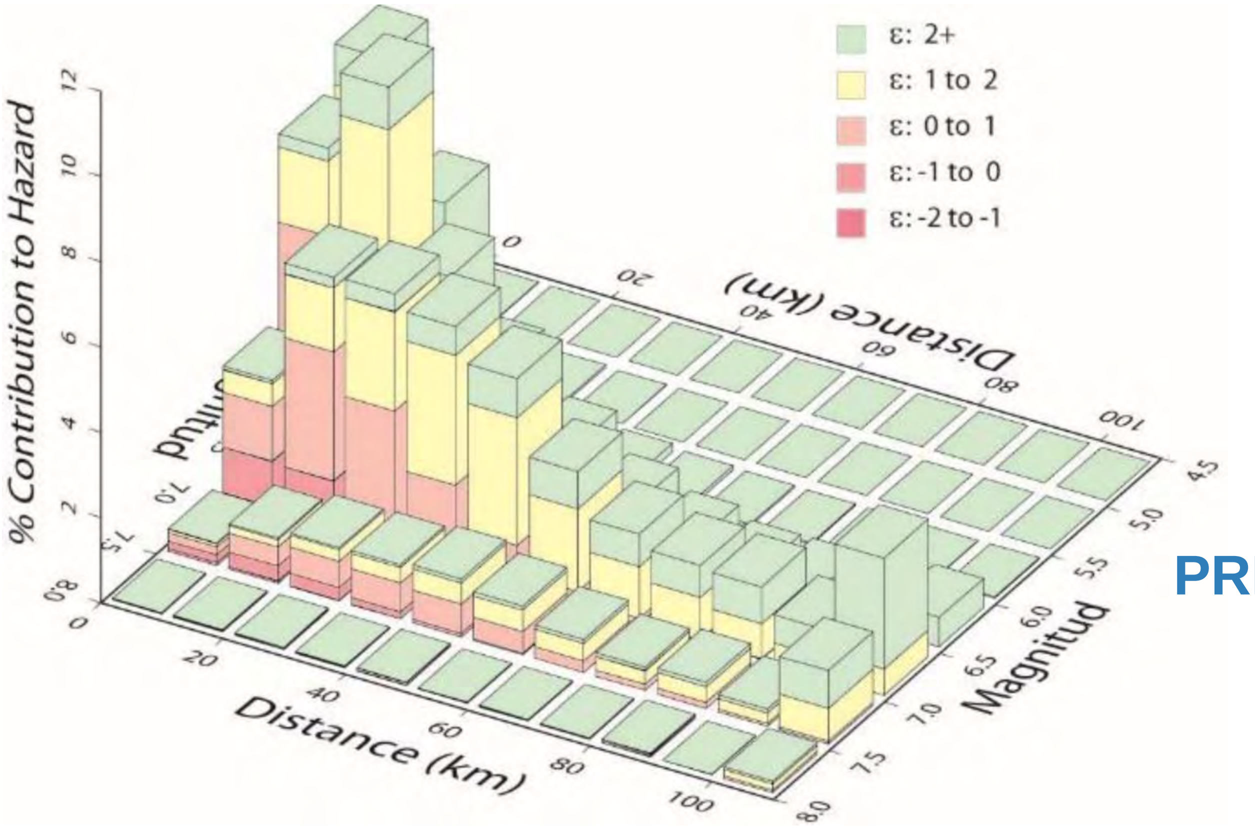
PRP project in Switzerland

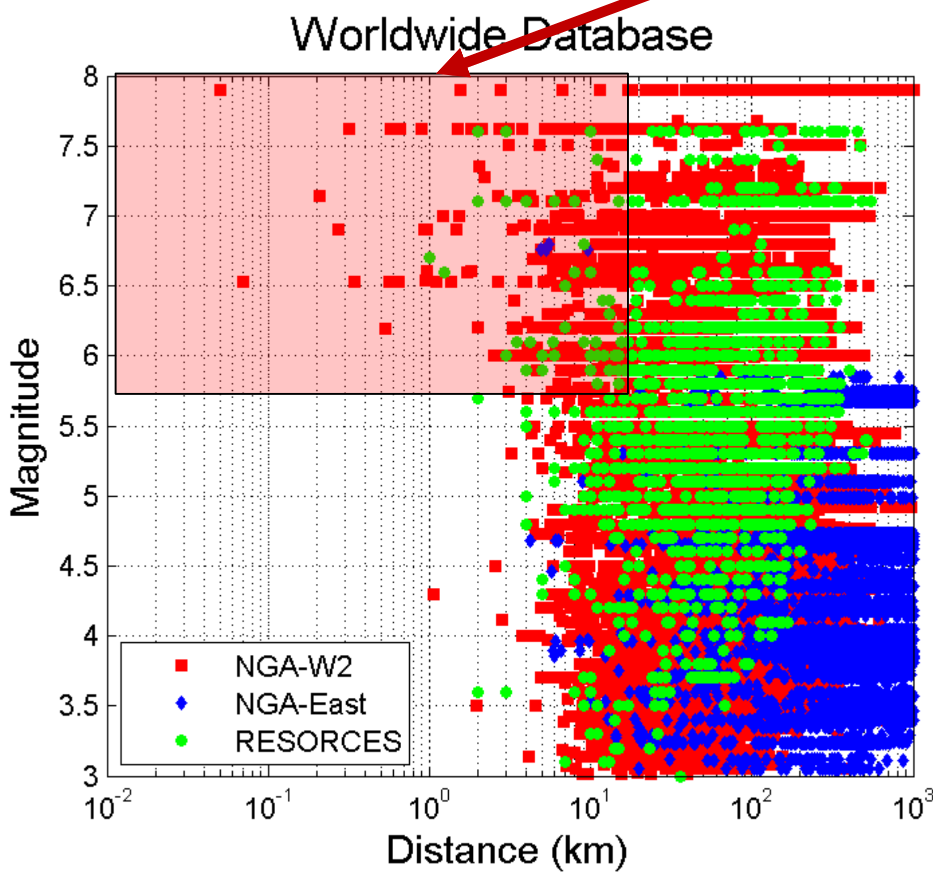


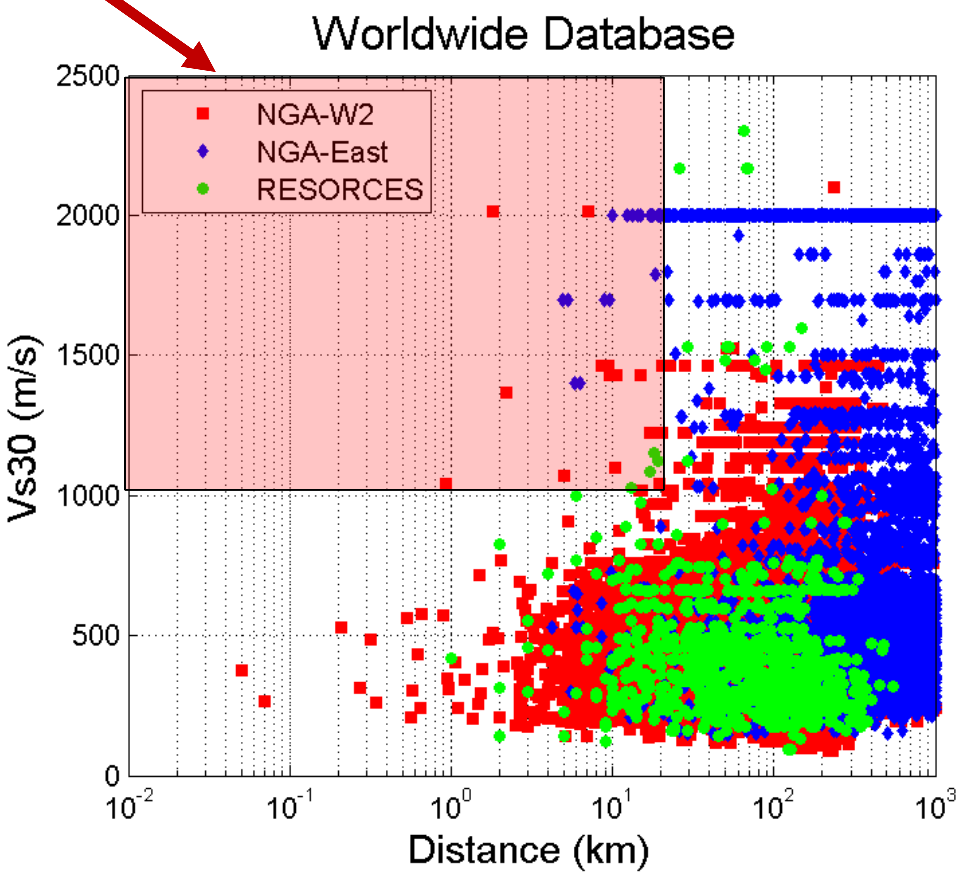
PRP deaggregation

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

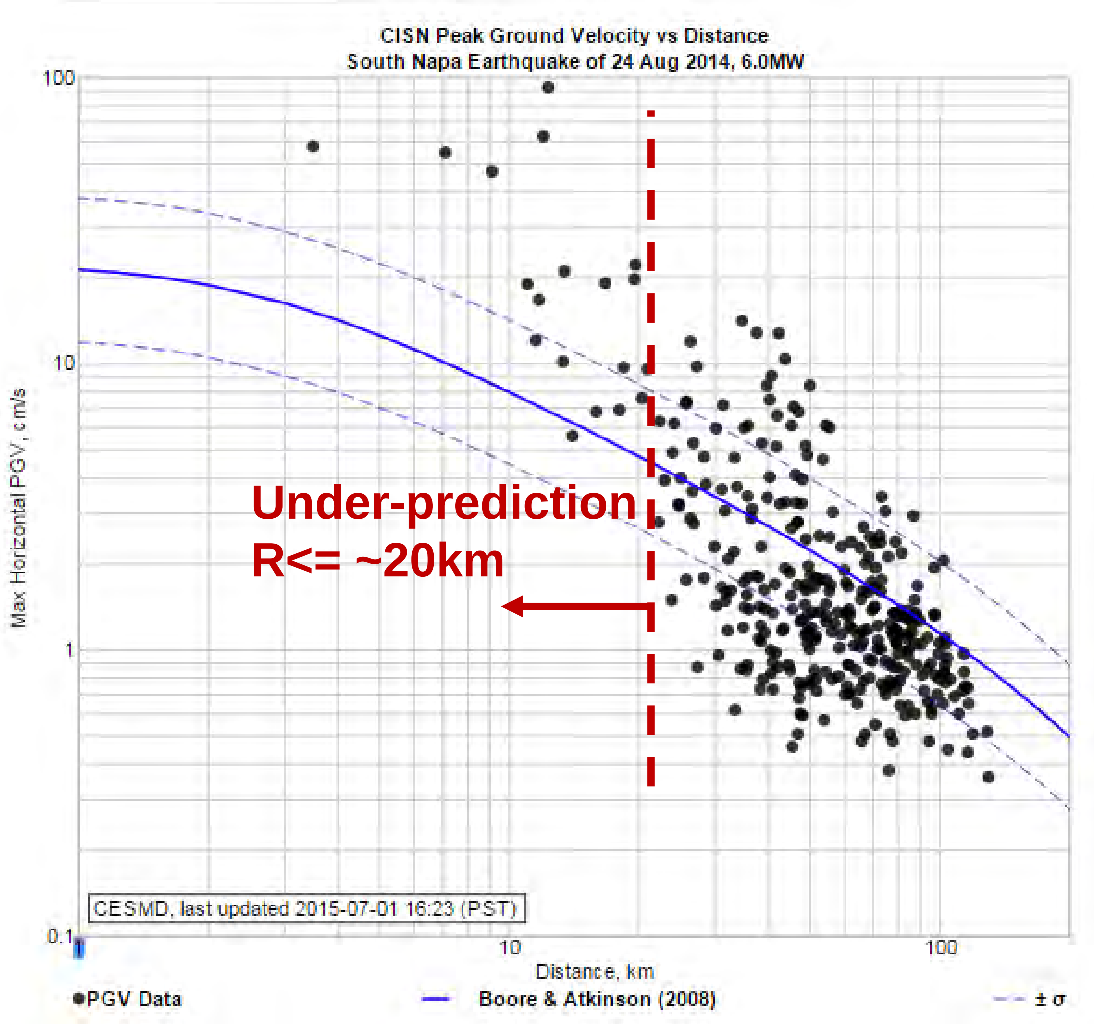
Limitations of empirical GMPEs

Zone of major interest for NPPs





Limitations of empirical GMPEs



(Courtesy of Roberto Paolucci)

GMPEs predict earthquakes similar to events from their database only

Evolution of empirical GMPEs

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

Abrahamson et al (2014)

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

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

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

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

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

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

f_5

GMPEs are becoming very complex to use!!

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

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

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

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

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

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

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

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

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

If R_{y0} not available:

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

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

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

$$Z_{1,ref} = \begin{cases} \frac{1}{1000}\exp\left[\frac{-7.15}{4}\ln\left(\frac{\ldots}{1360^4 + 570.94^4}\right)\right] & \text{for California} \\ \frac{1}{1000}\exp\left[\frac{-5.23}{2}\ln\left(\frac{V_{s,30}^2 + 412.39^2}{1360^2 + 412.39^4}\right)\right] & \text{for Japan} \end{cases}$$

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

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

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

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

Full physics-based GM models

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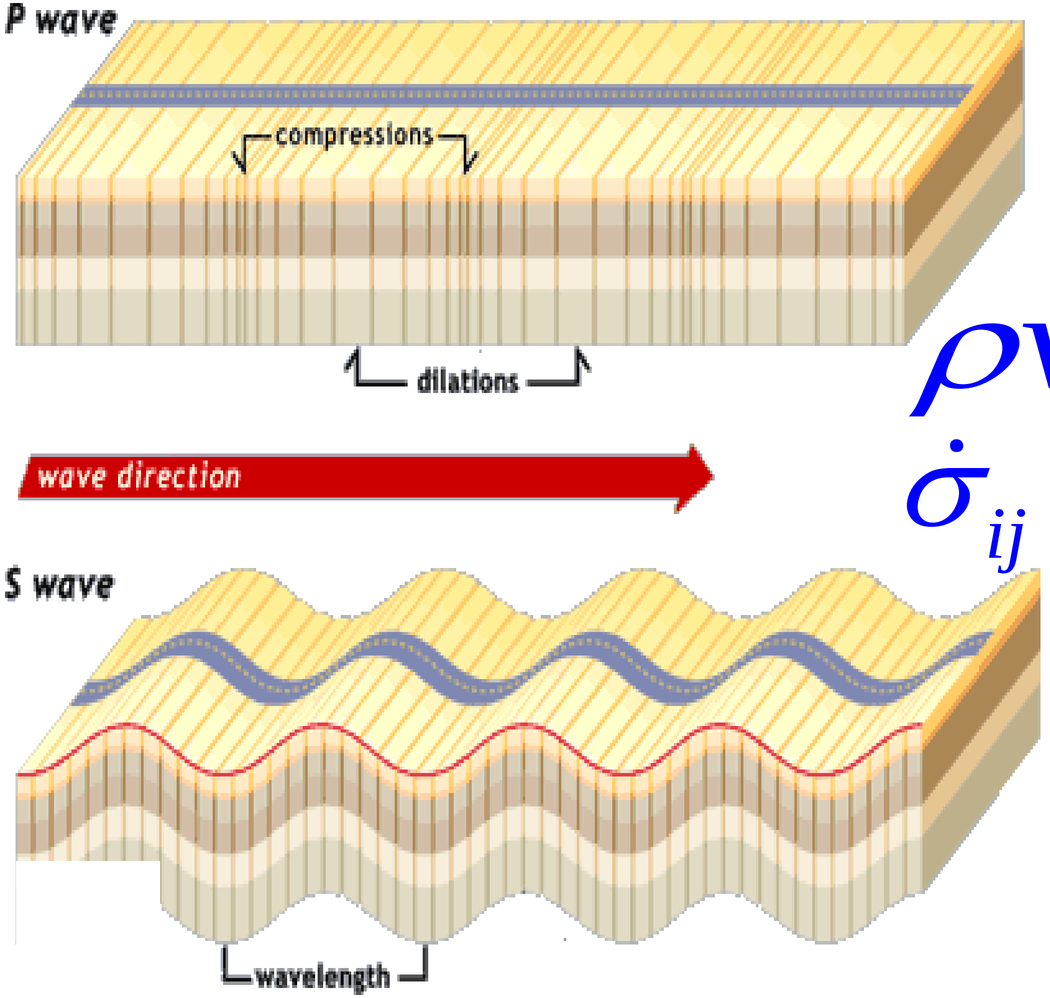
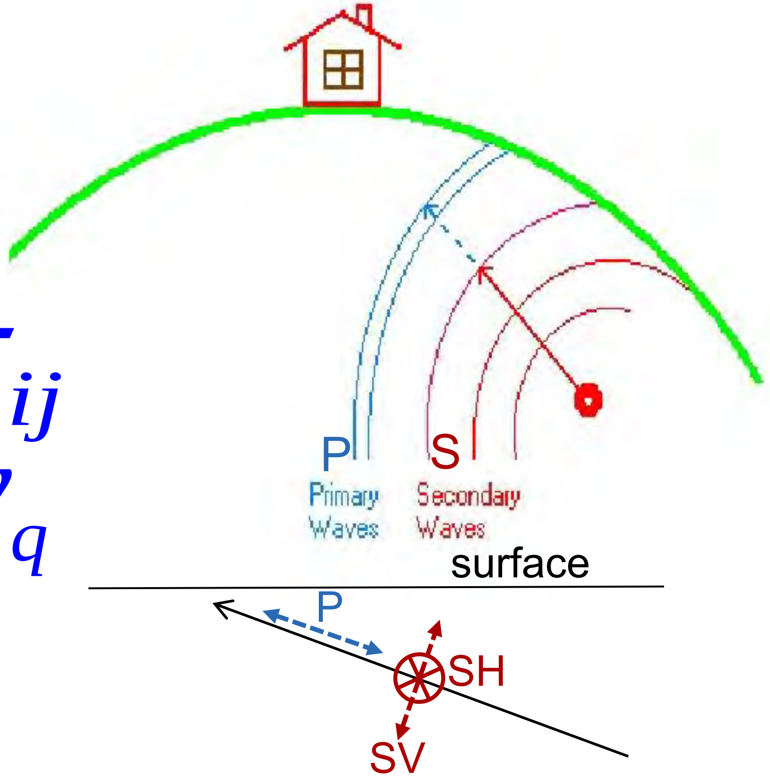
-The physics of wave propagation are now well developed and well understood



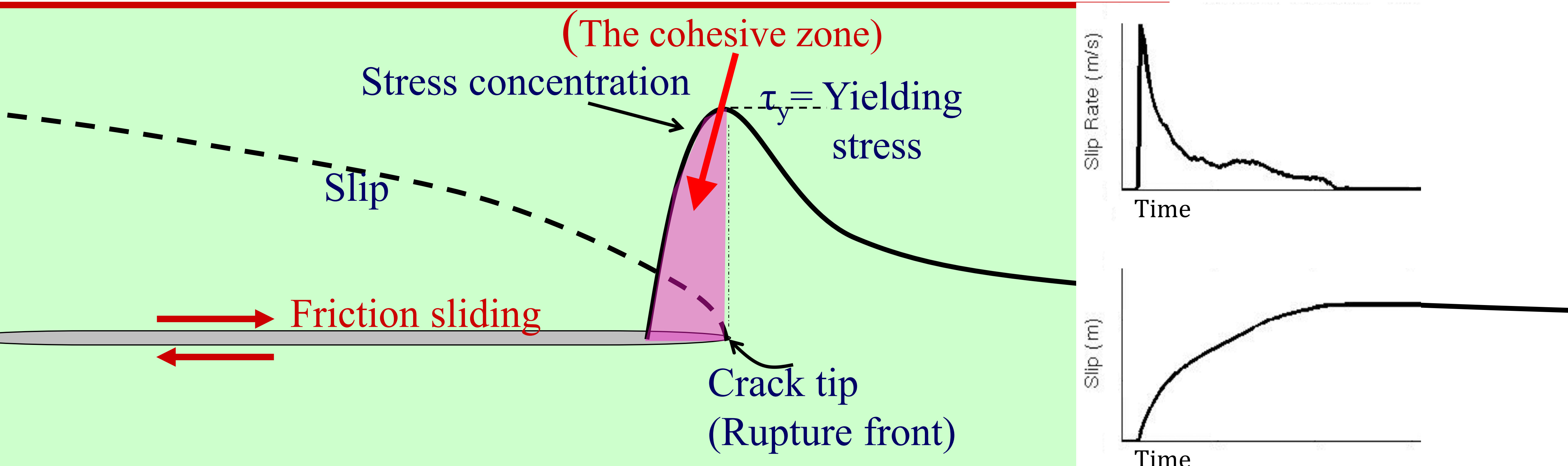
$$\rho \dot{v}_i = \partial_i \sigma_{ij}$$
$$\dot{\sigma}_{ij} = C_{ijpq} \partial_p v_q$$



Full physics-based GM models

Dynamic rupture model: The physics of stress and friction at fault interface are also well understood

The earthquake rupture can be described as a two-step process: (1) formation of crack and (2) propagation or growth of the crack. The crack tip serves as a stress concentrator due to driving force; if the stress at the crack tip exceeds some critical value, then the crack grows unstably accompanied by a sudden slip and stress drops.



Main Input for dynamic rupture models

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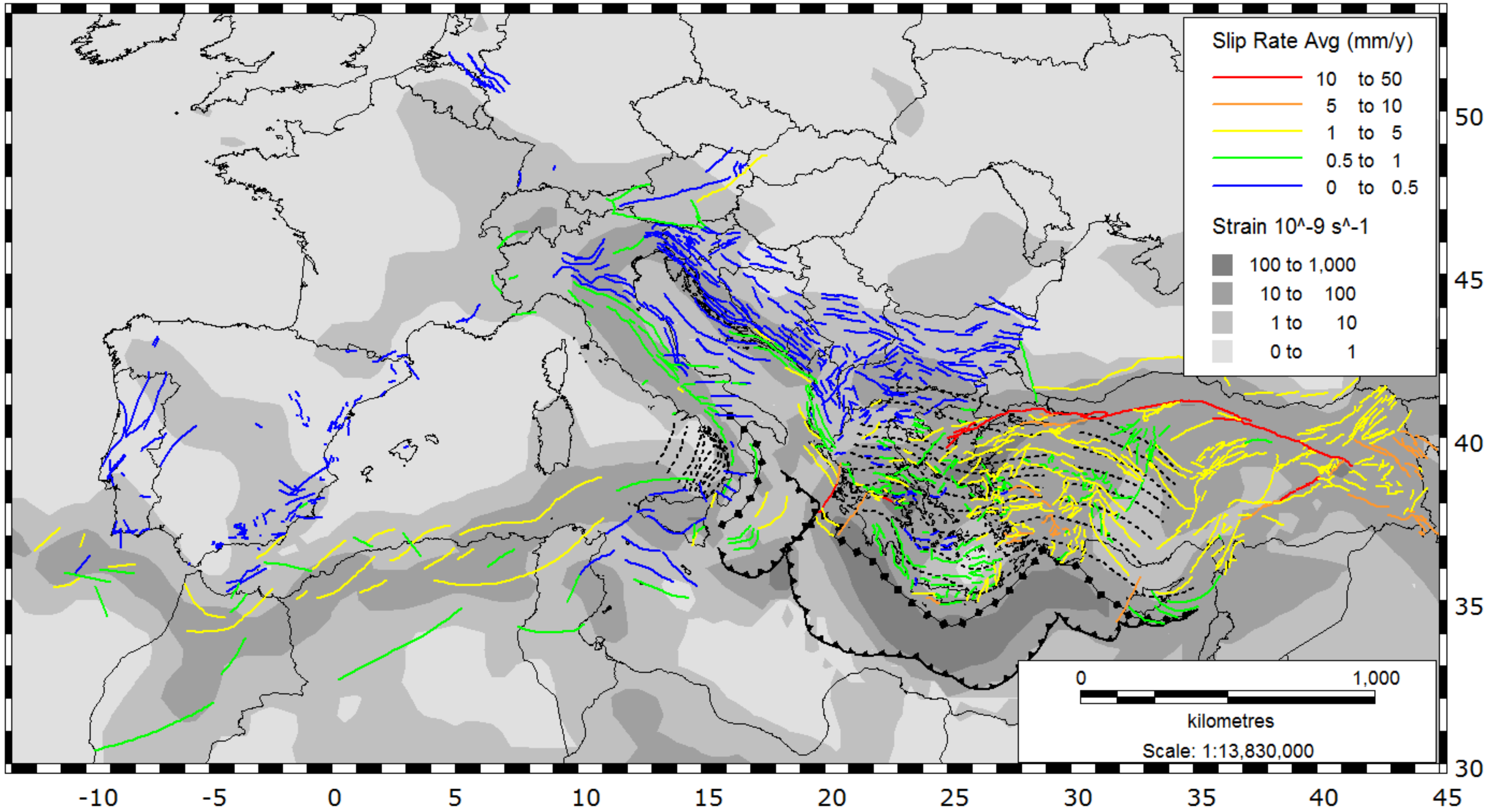
The best information of source (faults)



Euro-Mediterranean Fault Database (SHARE)

Main Input for dynamic rupture models

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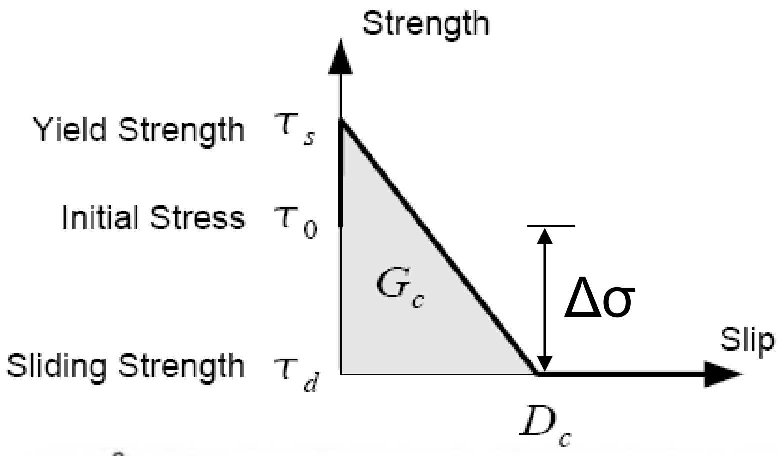
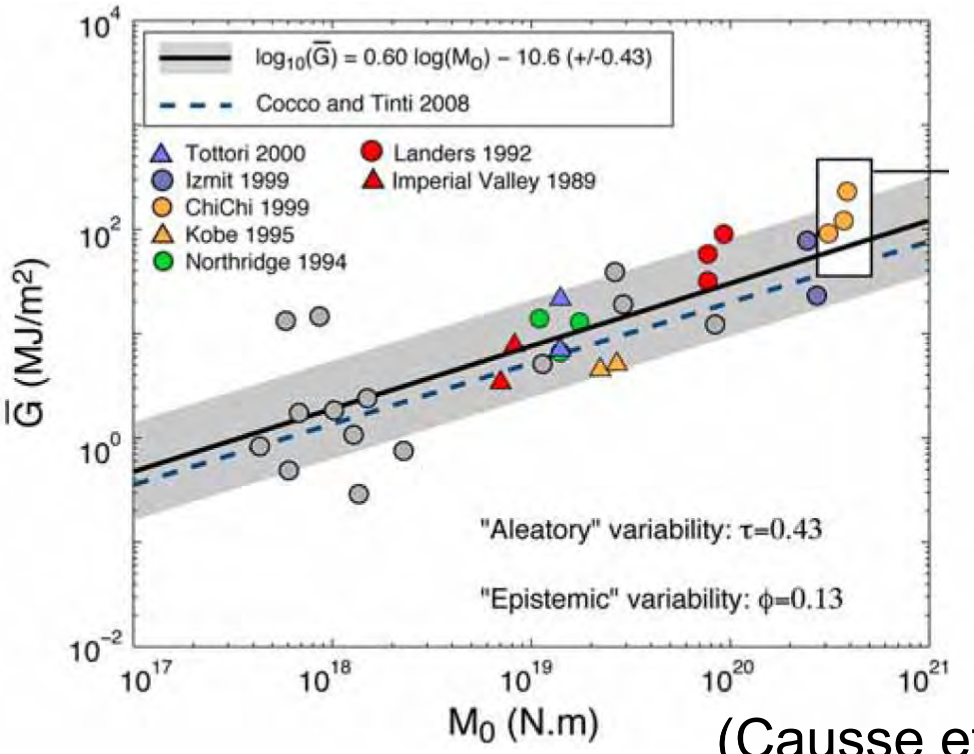
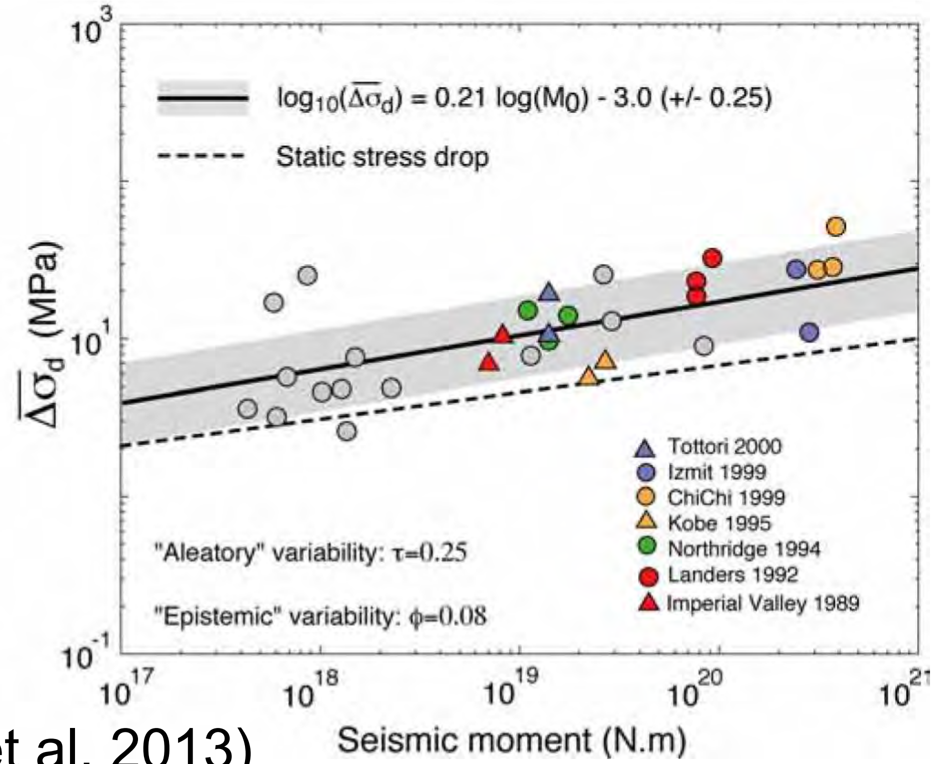
Fault friction model:

From seismological considerations

- Fracture Energy (G_c)
- Stress drop ($\Delta\sigma$)



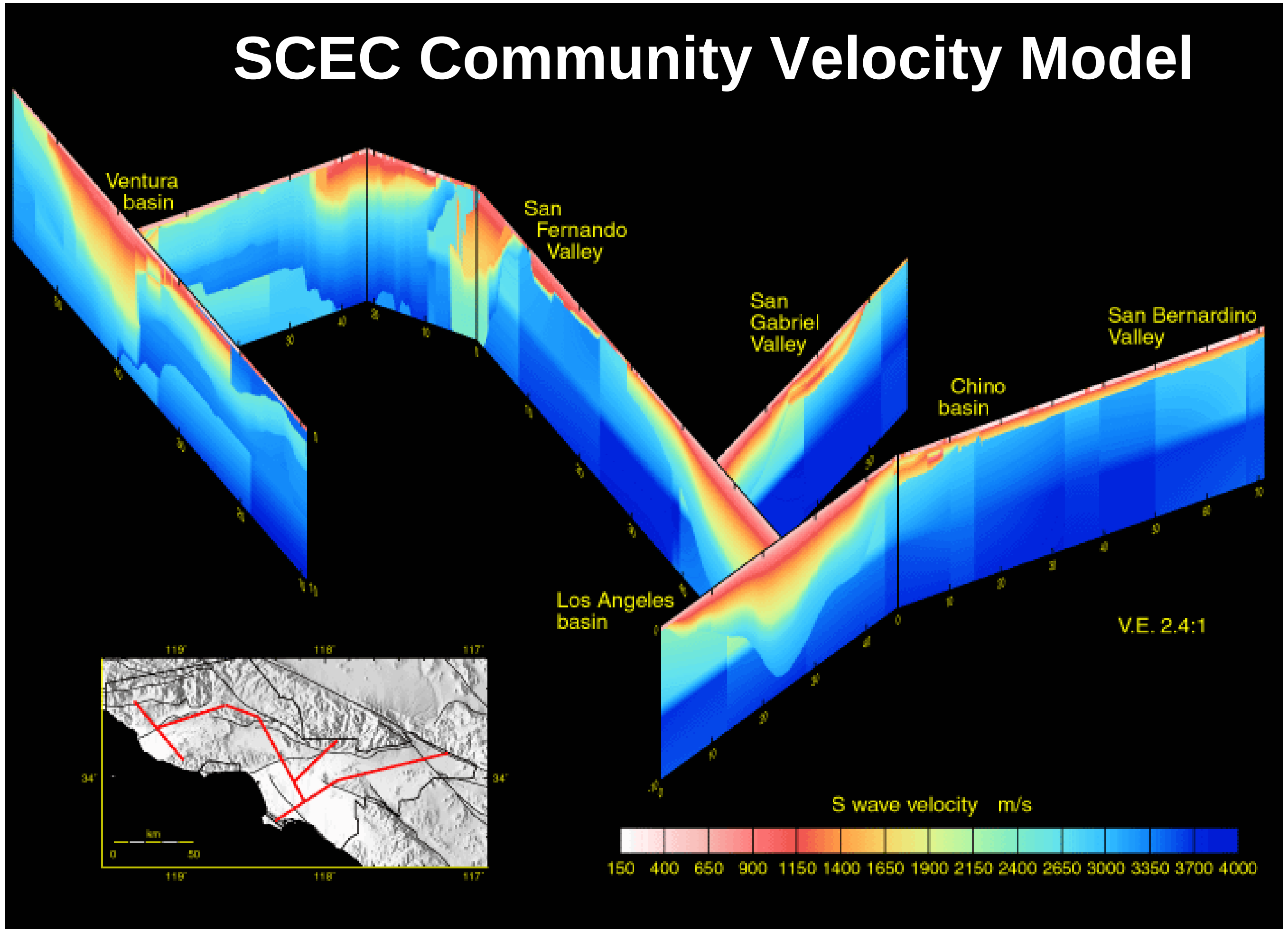




(Causse et al, 2013)

Main Input for dynamic rupture models

The best information available of the geological structure and site



Validation of dynamic rupture models
(Comparison with empirical GMPEs)

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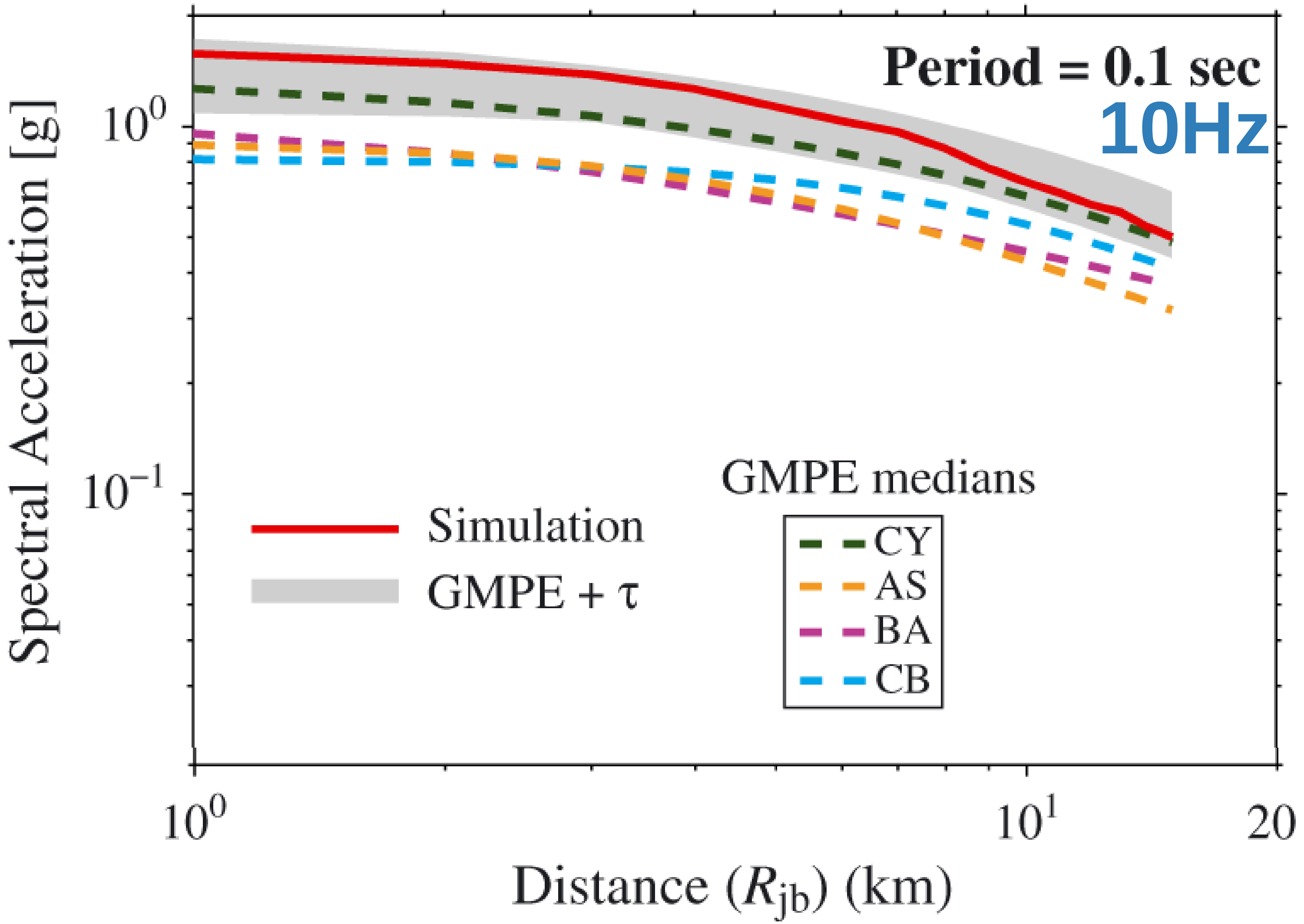
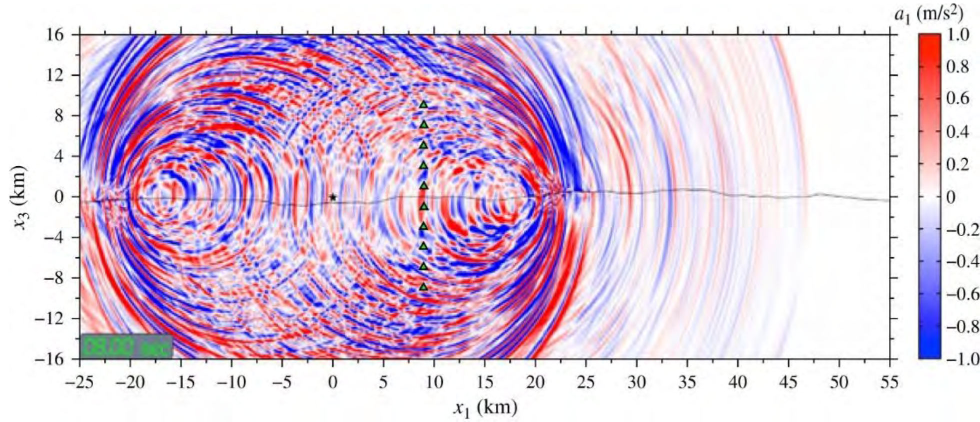
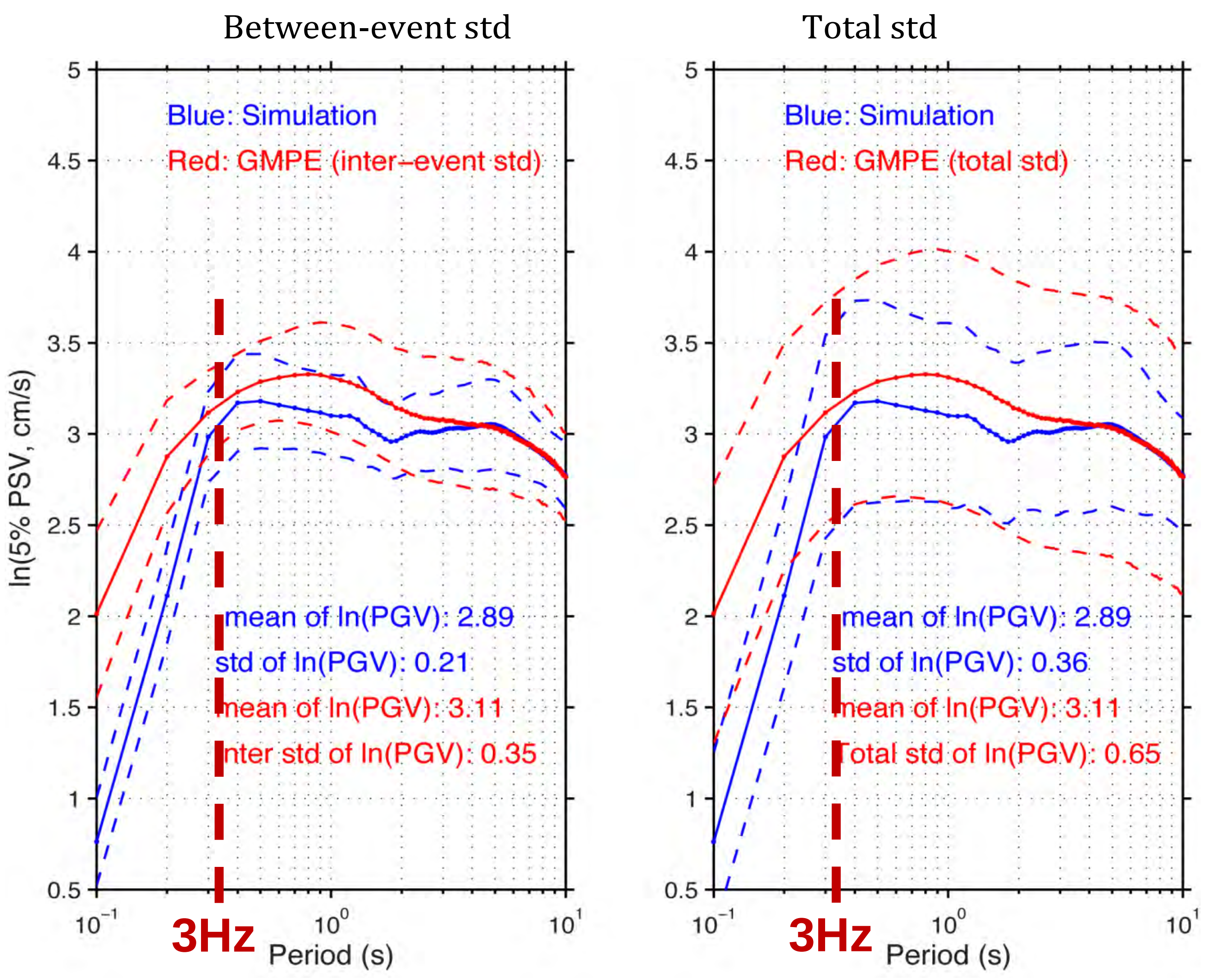




(Shi and Day, 2016)

Validation of dynamic rupture models
(Comparison with empirical GMPEs of Boore et al, 2014)

Mean spectra and standard deviations



R=10km
Mw=7

(Andrews and Ma, 2016)

Validation of dynamic rupture models

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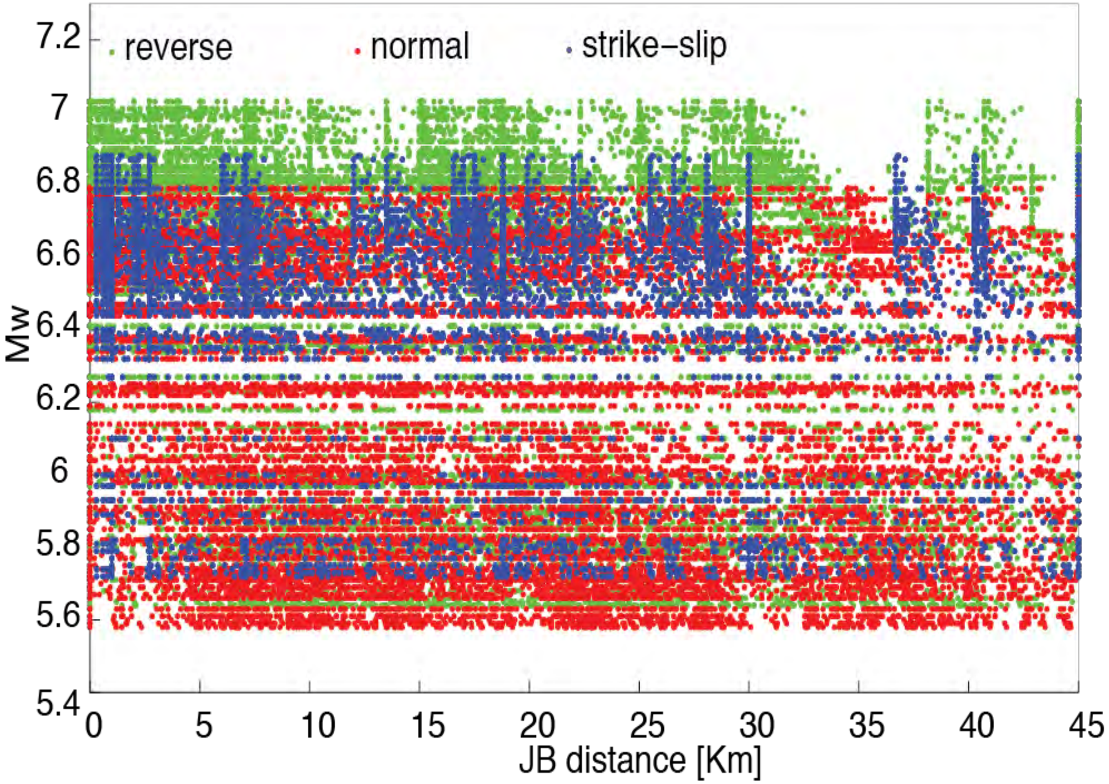
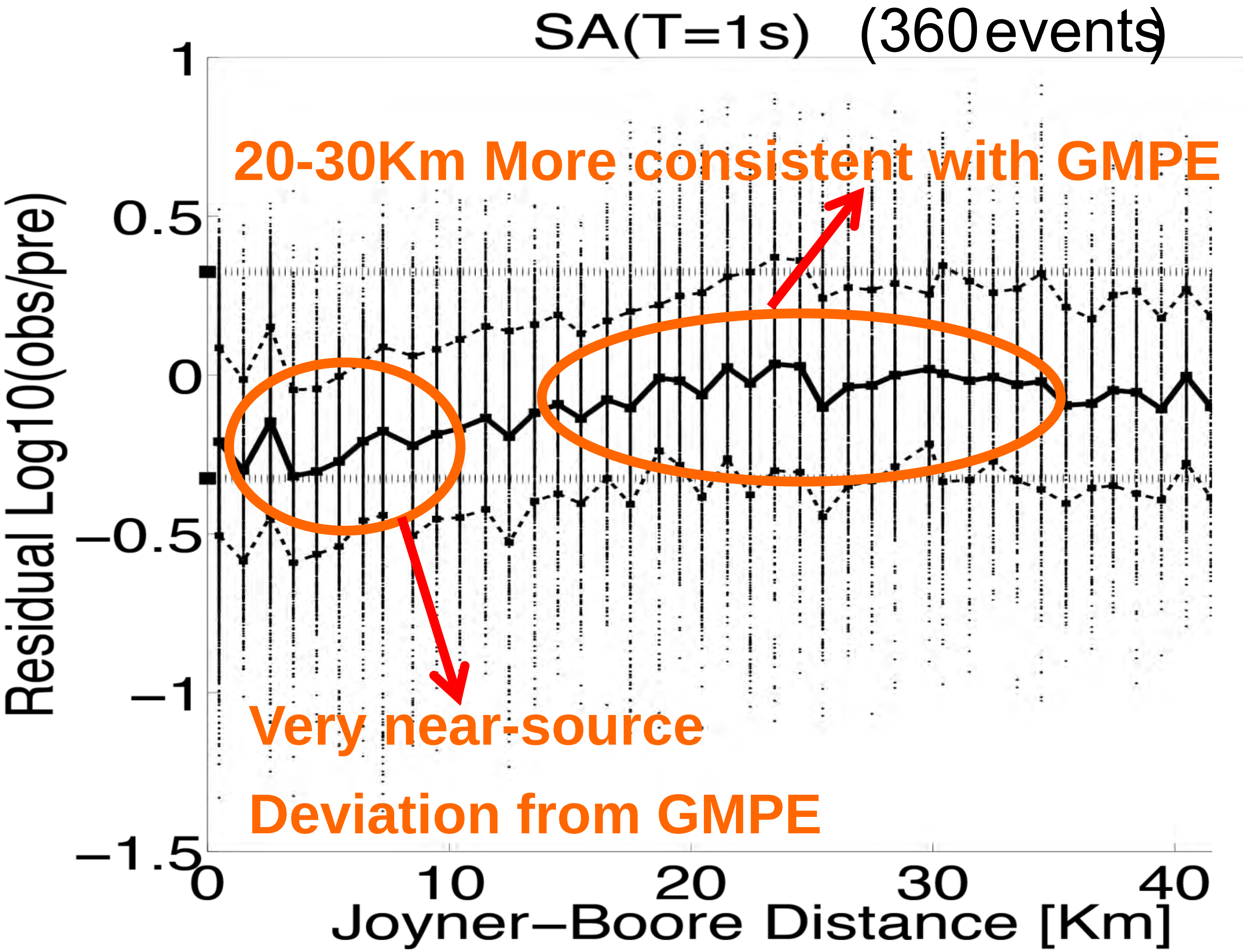
A data base of 360 dynamic rupture models
(Dalguer and Mai, 2011)





(Baumann and Dalguer, 2014, BSSA)

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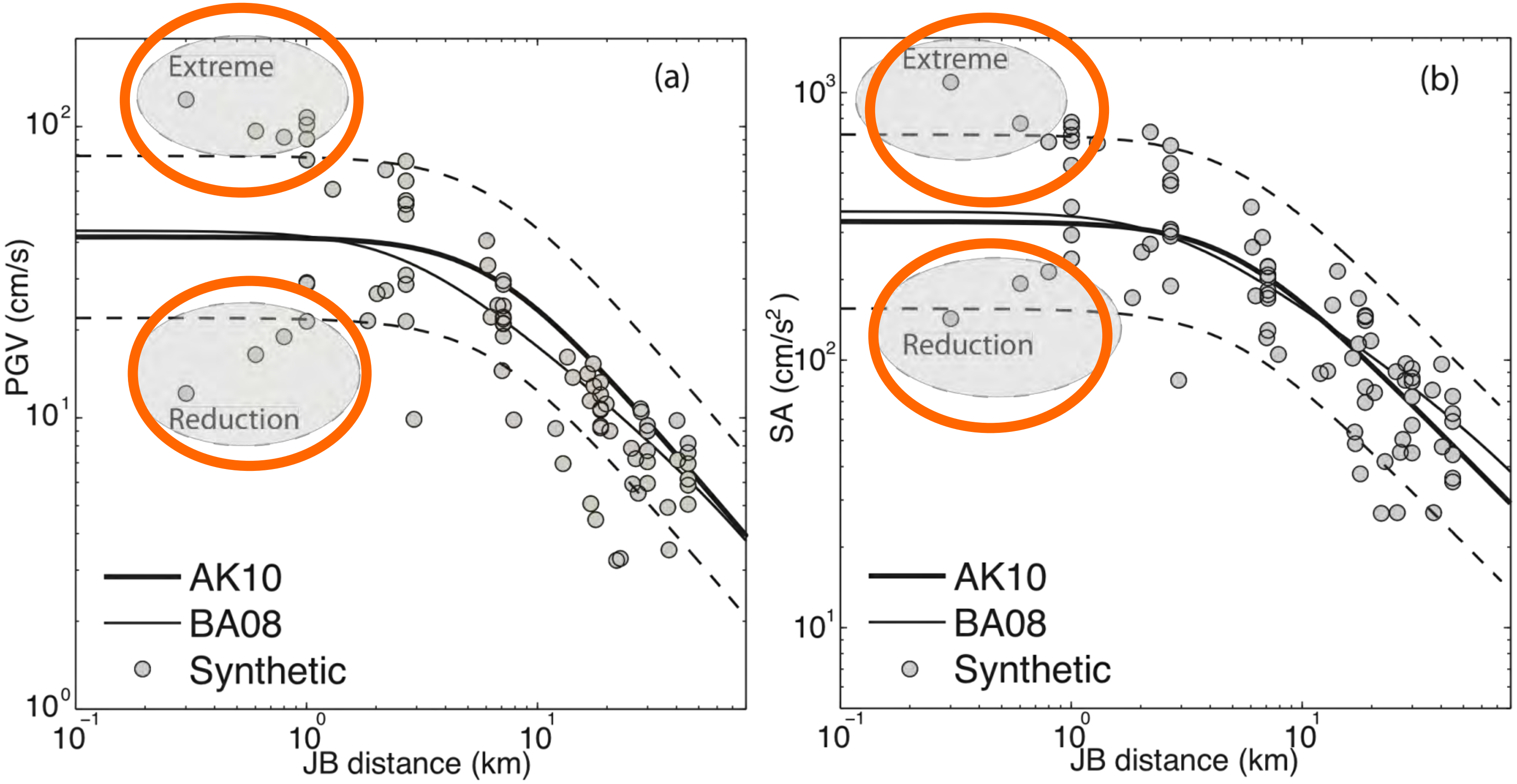
Ground motion of some single events

Very near the fault: Extreme and Reduction of ground motion is observed



(Baumann and Dalguer, 2014, BSSA)

GMPEs vs Physics-based GM simulation

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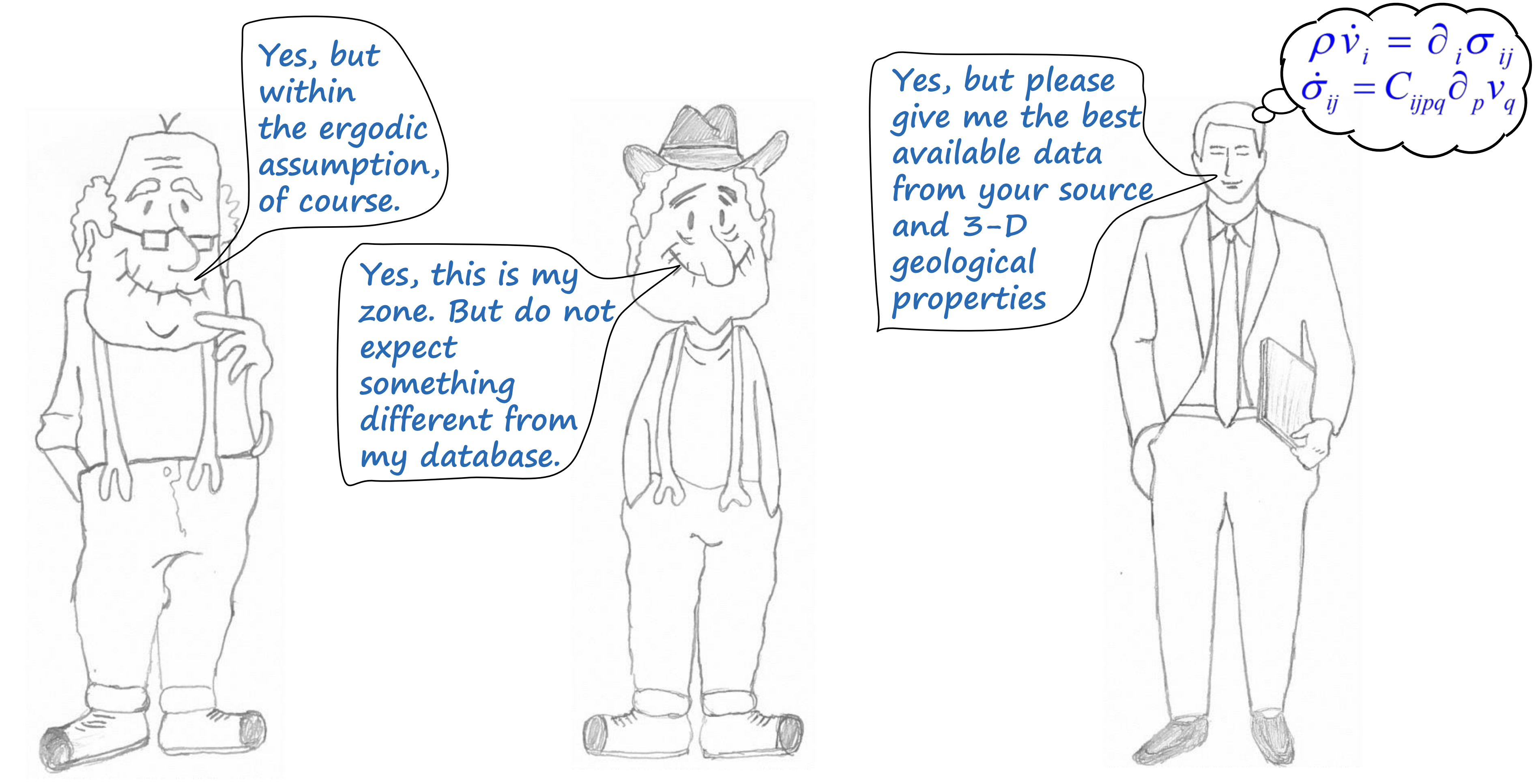
Request 1: Could you make a prediction in zone A for Mw 7 and distance 20km?



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

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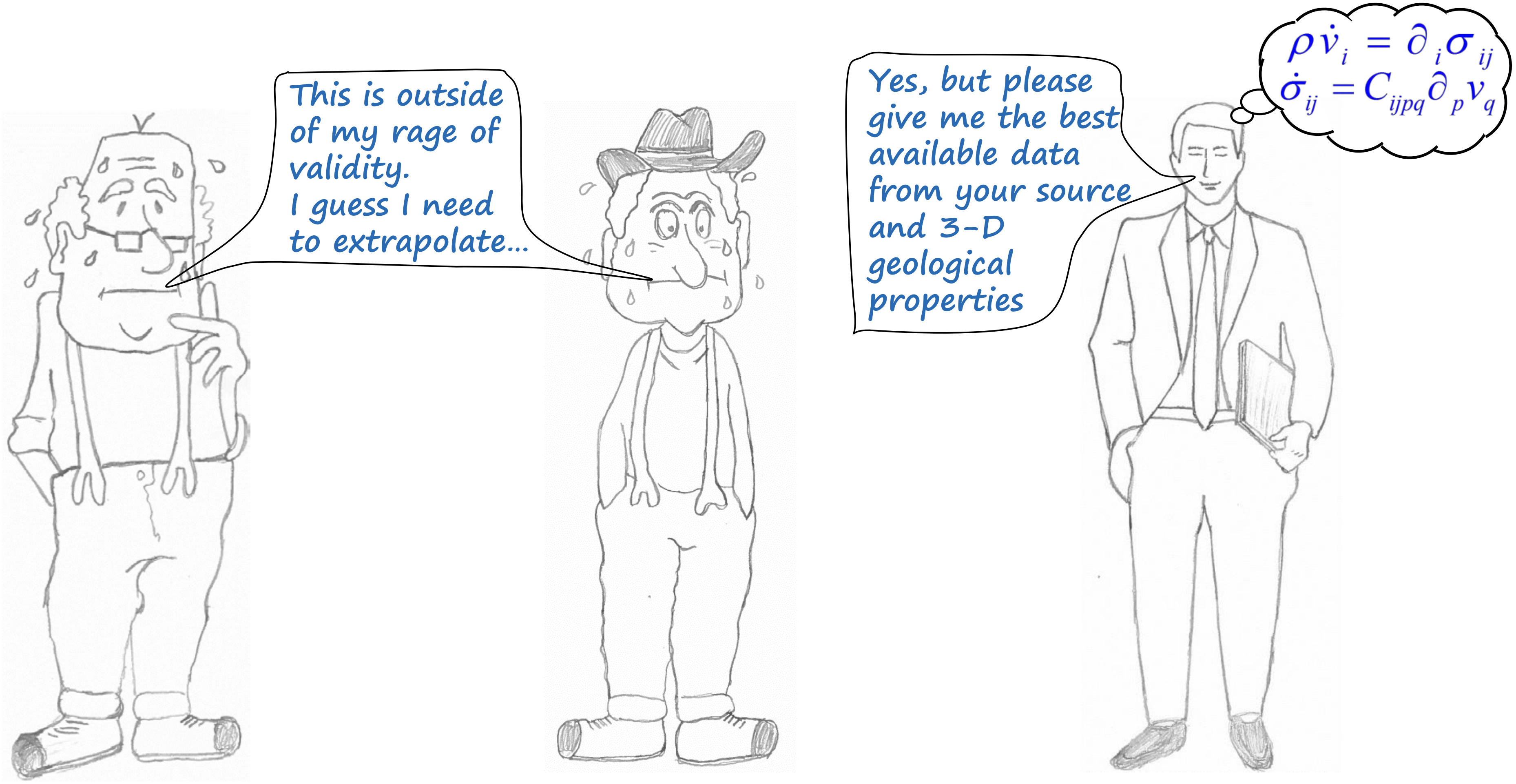
Request2: Now a prediction in zone A for Mw 7 very near the fault?



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

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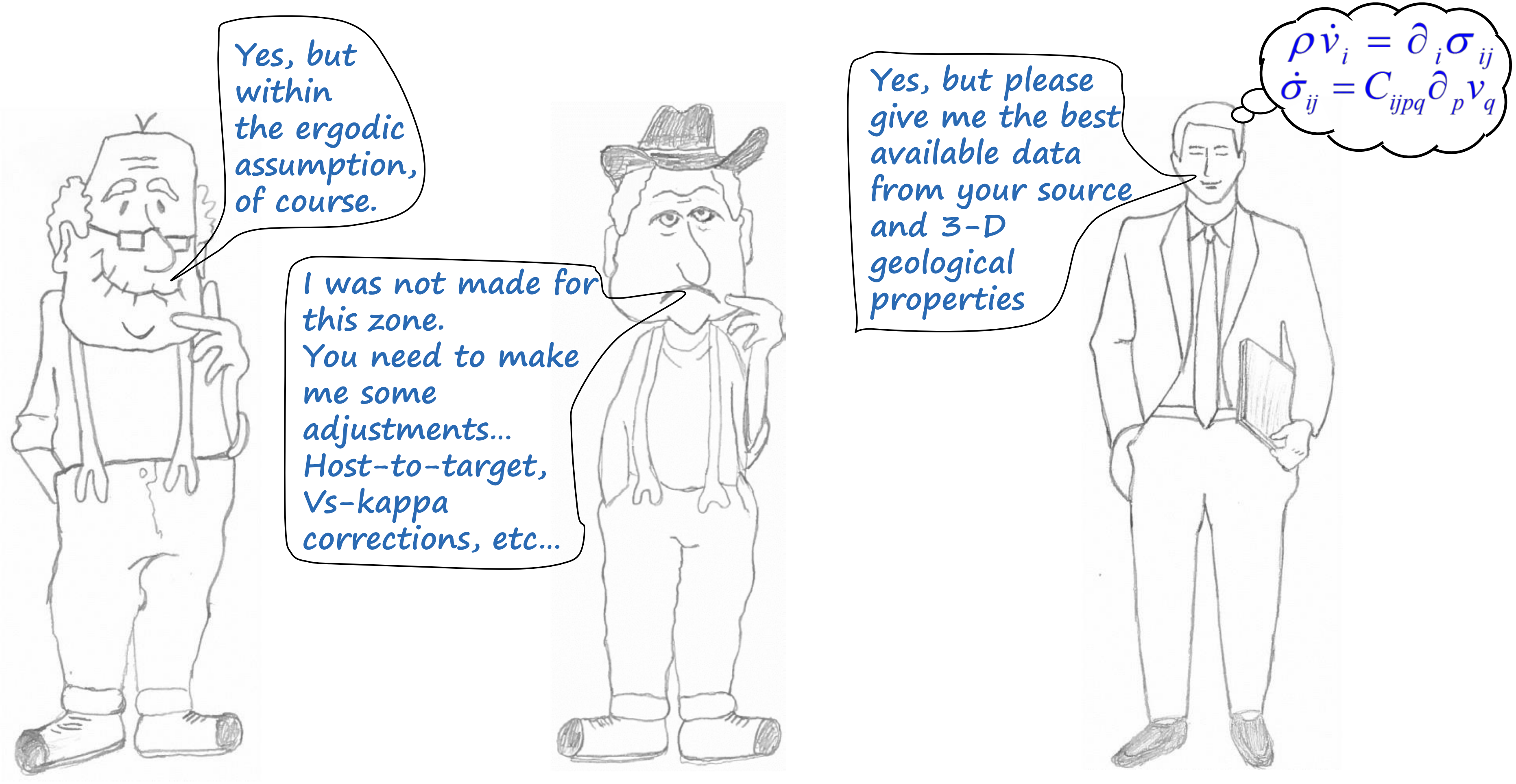
Request3: Now please a prediction in zone B?



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

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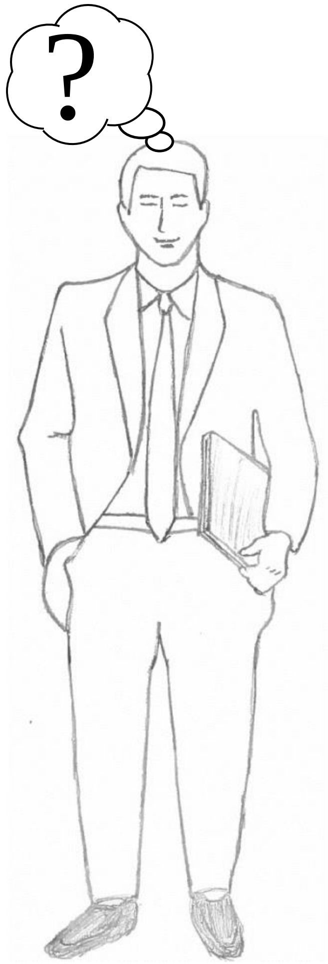
Request3: Please a prediction in zone B?

GMPEs
(Global and ergodic)

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



Physics-based GM model
(fully non-ergodic)

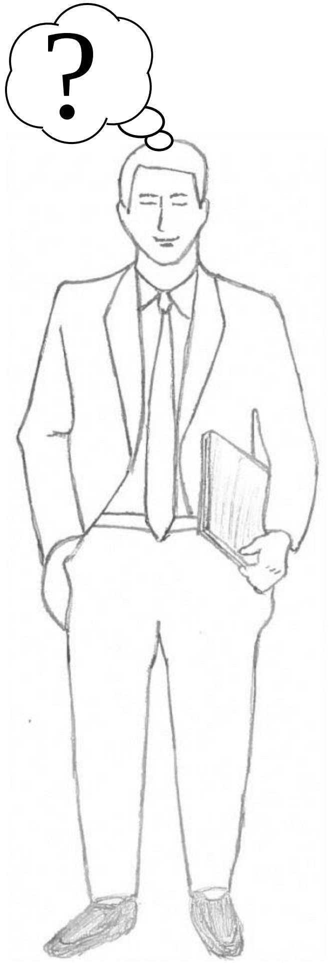
21

GMPEs vs Physics-based GM simulation

Request3: Please a prediction in zone B?

GMPEs
(Global and ergodic)

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

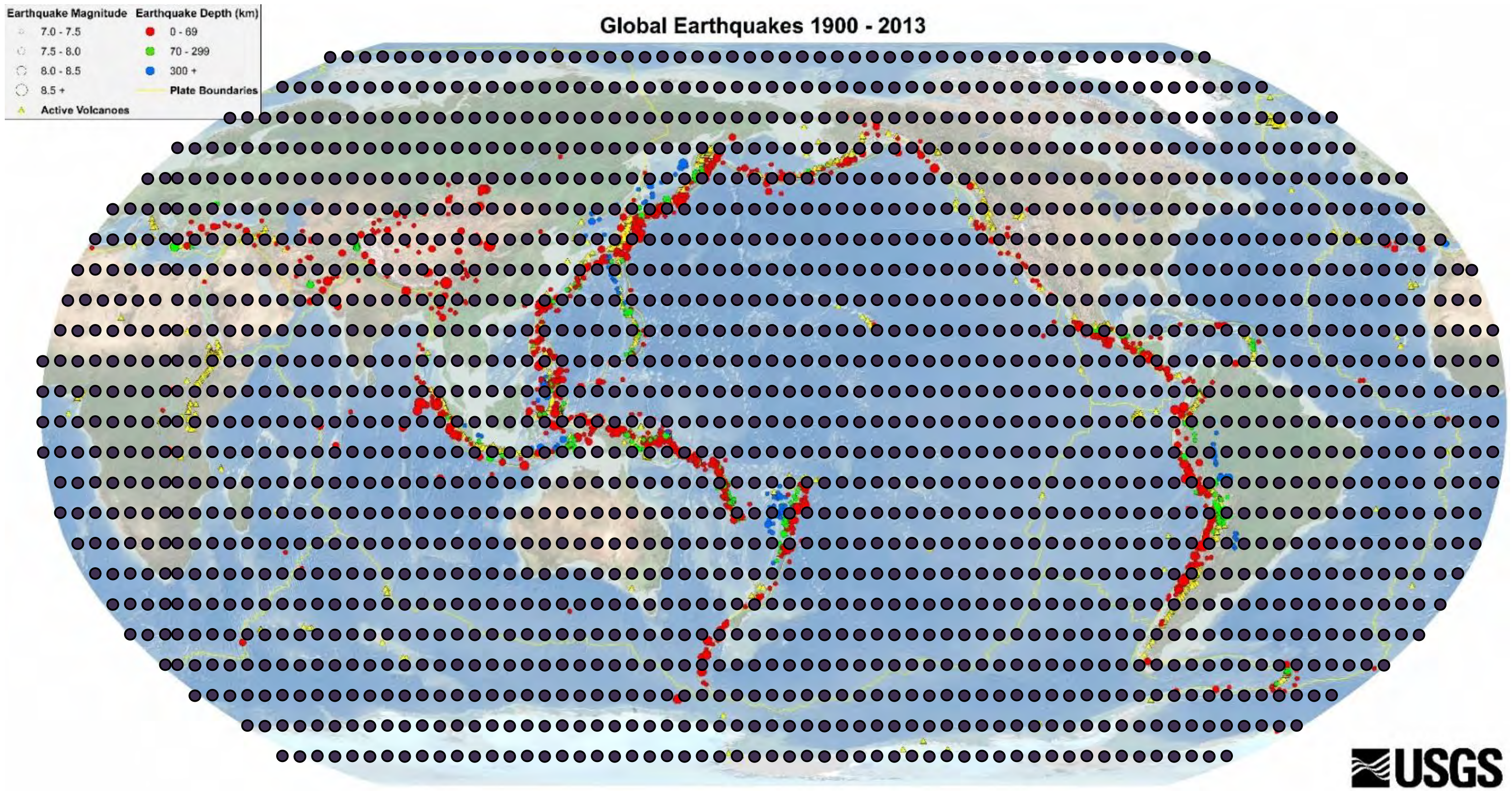


Physics-based GM model
(fully non-ergodic)

22

Conclusions

- Physics-based models are the best models for fully non-ergodic PSHA studies because they account for the effects of fault geometry complexity and 3-D geological conditions
- 3-D numerical models based on physics will substitute the GMPEs
- Improvement of GMPEs by developing hybrid GMPEs
- In the future, synthetic earthquakes will cover the earth.



Physics-based Fault Rupture Models for Seismic Hazard Assessment of Nuclear Installations: issues and challenges towards full Seismic Risk Analysis

Cadarache-Château, France
14–16 May 2018

WS webpage: http://www.institut-seism.fr/en/2nd-workshop-best-psha-ni-may-2018-cadarache-chateau-france/
-Abstract submission deadline: **30 December 2017**
-Full paper submission deadline: **28 February 2018**
-Registration deadline (incl. for the field trips): **30 April 2018**