Broadband strong ground motion modeling using planar dynamic rupture models with fractal parameters

František Gallovič, Ľubica Valentová

Charles University, Faculty of Math. and Physics, Dept. of Geophysics, Czech Republic

Introduction

- Dynamic rupture modeling of strong ground motions in wide frequency range (0-10Hz) useful for seismic engineers have not yet attained a wide-spread use for the following reasons:
  - Simple dynamic models with smooth distributions of initial stress and frictional parameters on planar faults result in ground motions with depleted high-frequency content, exhibiting underestimation of ground motion models (GMMs) at periods shorter than 1-2Hz. Solution accepted generally by the community: rough faults (Shi and Day, 2013; Mai et al., 2017; Withers et al., 2019; Taufiqurrahman et al., subm.).
  - Heavy numerical problem due to fine discretization.

- Our proposed solution:
  - Use of very efficient code FD3D_TSN for planar rupture (Premus et al., 2020).
  - Supplementing dynamic rupture parameters with small-scale variations to built upon the fractal model of Ide and Aochi (2005).

Introduction

- Baumann and Dalguer (2014)

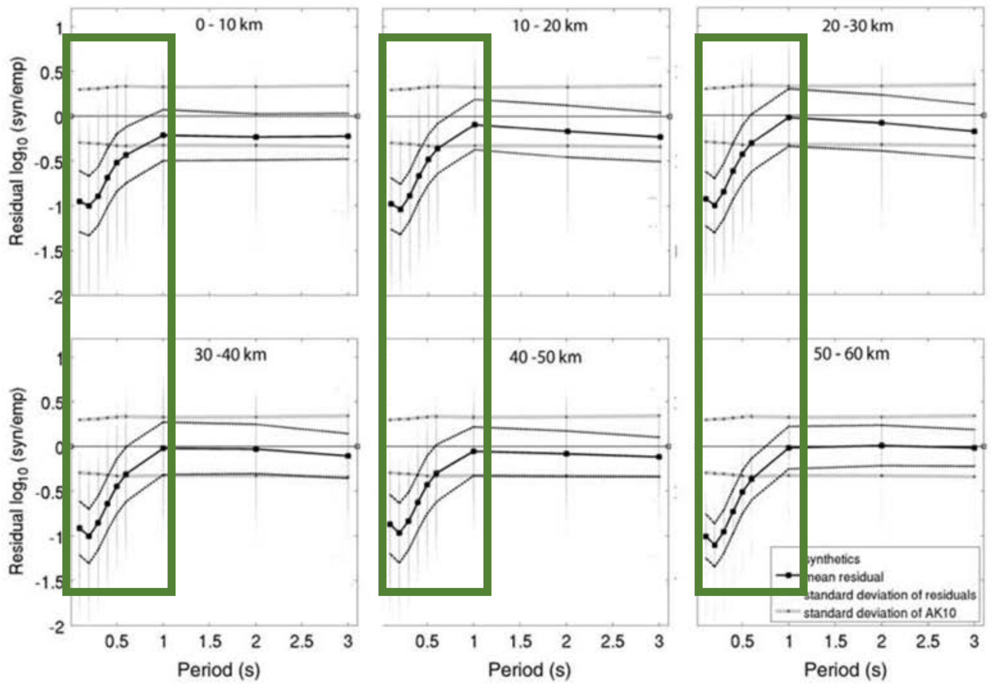
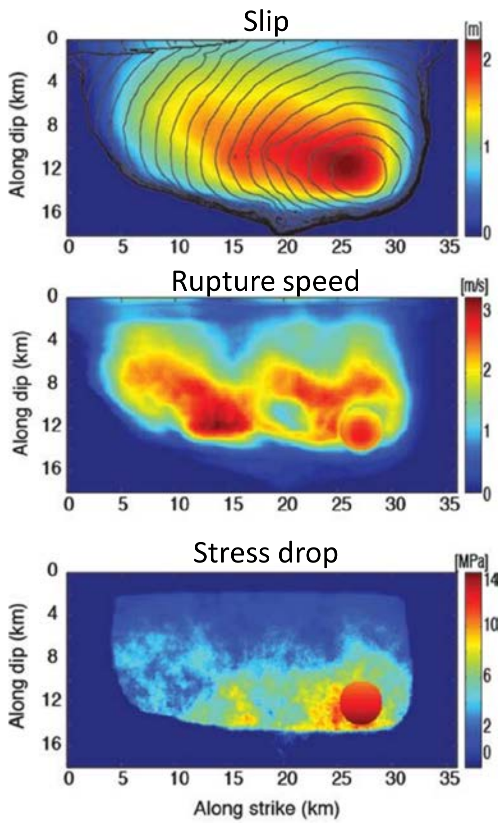
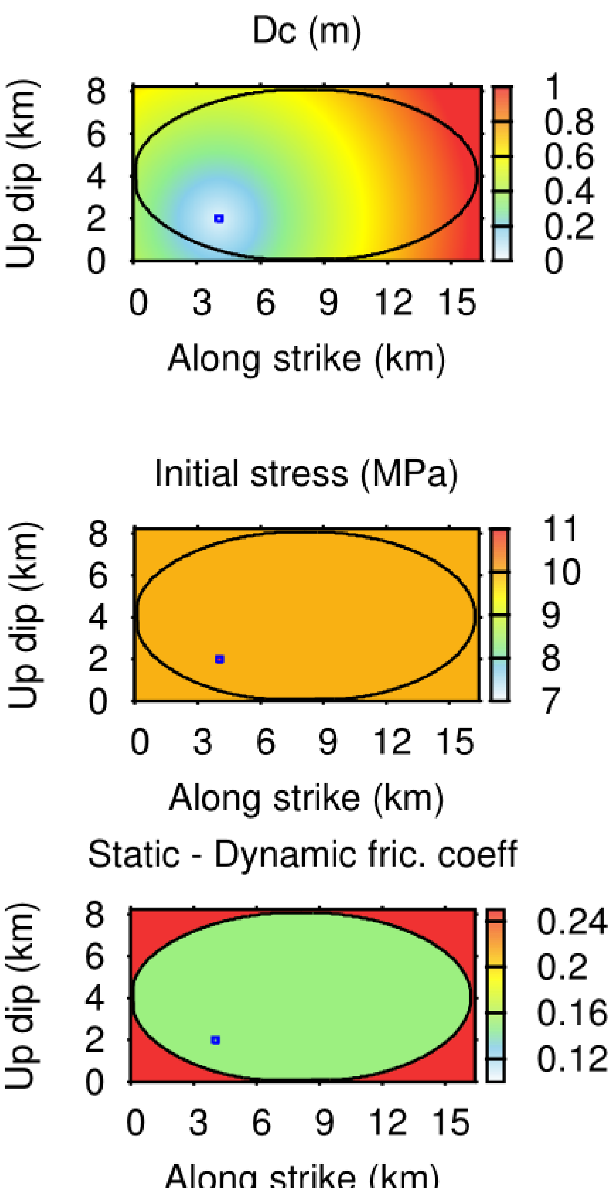


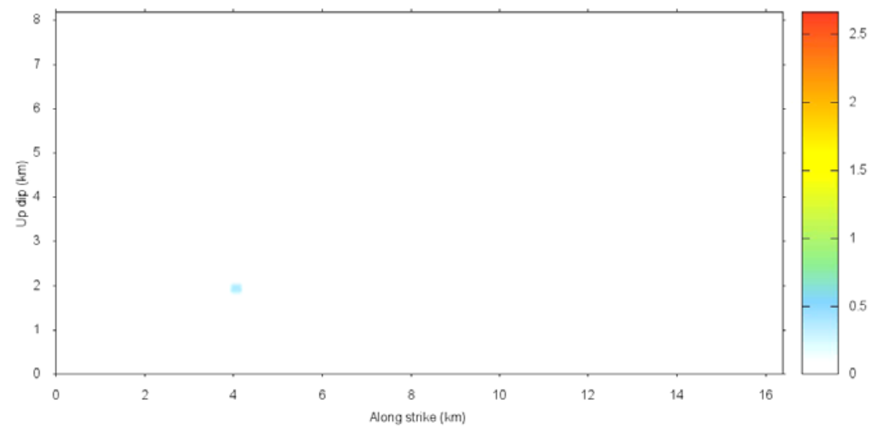
Figure 12. Spectral acceleration residuals at periods of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 1, 2, and 3 s for 283 selected models as a function of JB distances of 10 km intervals. Residuals are calculated with respect to the mean values of the GMPE of AK10. The selected models are those in which the mean residual of each individual model falls into the $\pm\sigma$.



- Similar conclusion by Valentová et al. (BSSA 2021)

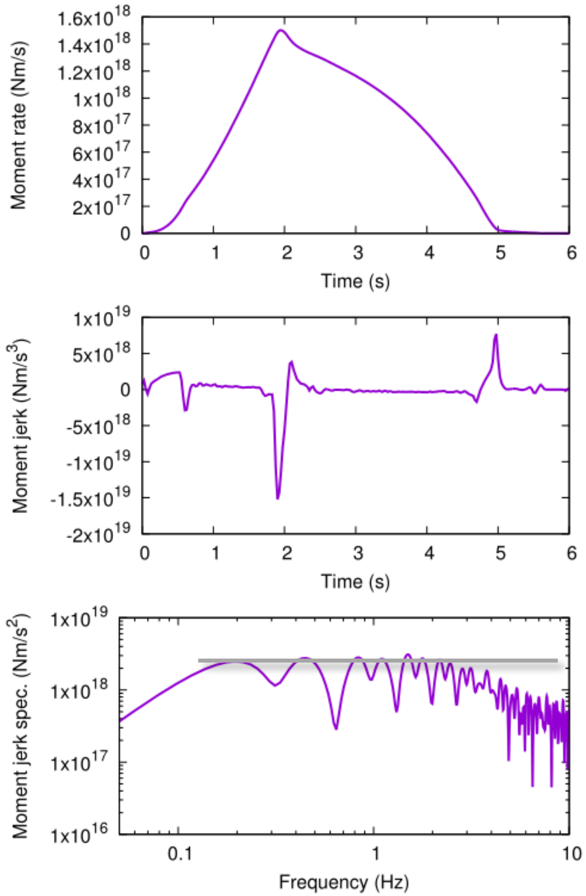
Rupture with (approx.) constant Vr

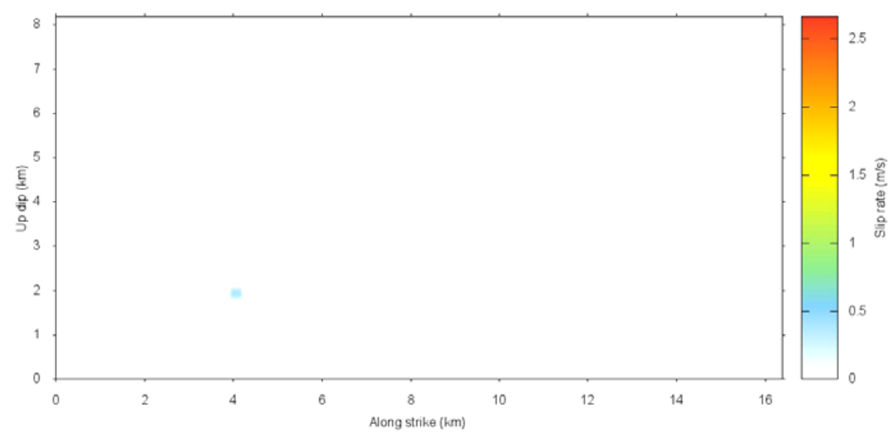




Rupture simulation up to 10 Hz in 30 mins on a GPU using efficient code FD3D_TSN for planar rupture (Premus et al., 2020)

Rupture with (approx.) constant Vr





Rupture simulation up to 10 Hz in 30 mins on a GPU using efficient code FD3D_TSN for planar rupture (Premus et al., 2020)

How to introduce small-scale perturbations in dynamic modeling?

- Requirements:
  - Application to a large-scale rupture model from dynamic inversion or ad-hoc smooth dynamic model scenario
  - Sustained high-frequency radiation during the rupture propagation
  - Omega-square (apparent) source time functions
  - Stability of the rupture propagation with respect to random realizations of the perturbations
  - Improved fit of real-data recordings and GMPEs in wide frequency range (0-10Hz)

Fractal Gc model of Ide and Aochi (2005)

- Fractal distribution of D_c assuming discrete patches

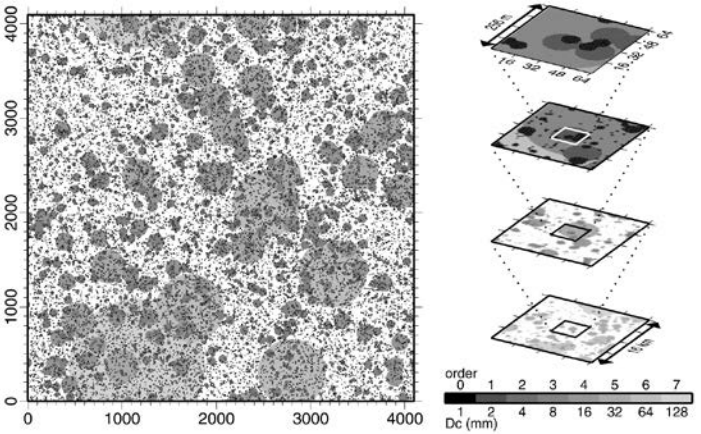


Figure 3. An example of D_c distribution in two dimensions using a set of circular patches. We randomly distribute eight different orders of patches in 4096 × 4096 model space with periodic boundaries, which we consider to be 16 km × 16 km. This model space is treated as four subspaces of different scale through three renormalizations as shown at the right.

Fractal Gc model of Ide and Aochi (2005)

- Events stop spontaneously without requiring a special stopping mechanism.
- G_c scales with moment in agreement with observation.

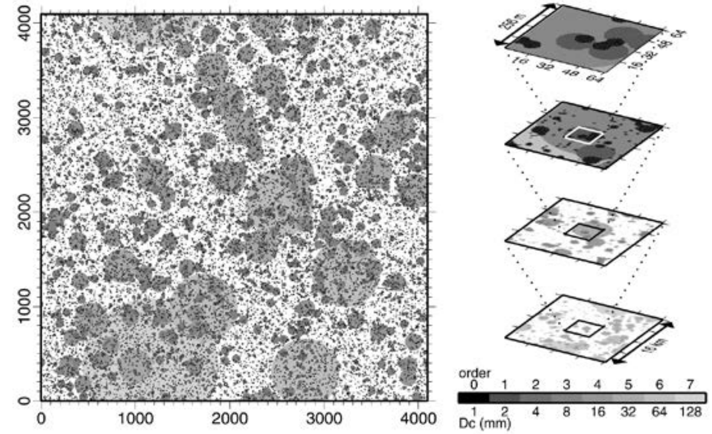
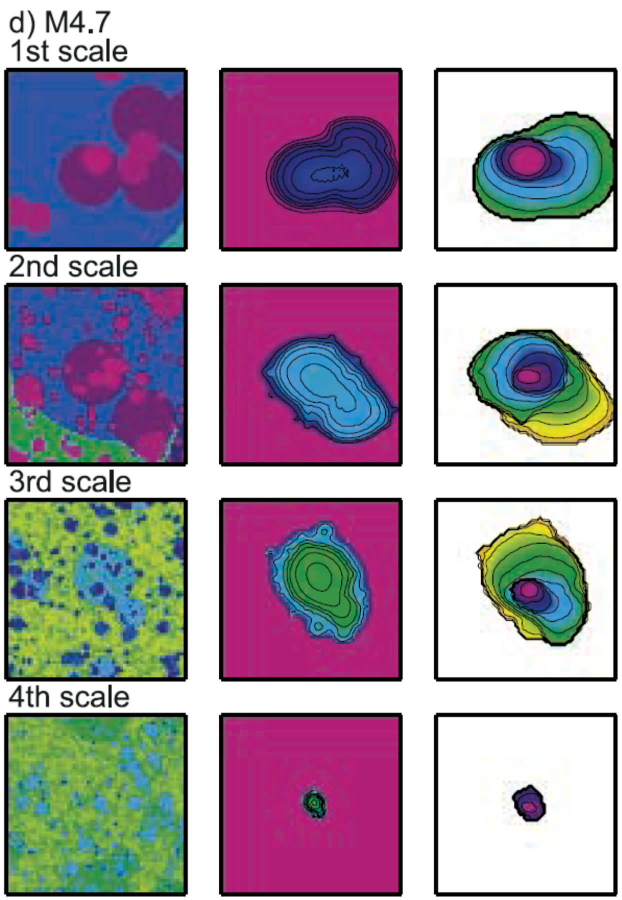


Figure 3. An example of D_c distribution in two dimensions using a set of circular patches. We randomly distribute eight different orders of patches in 4096 × 4096 model space with periodic boundaries, which we consider to be 16 km × 16 km. This model space is treated as four subspaces of different scale through three renormalizations as shown at the right.



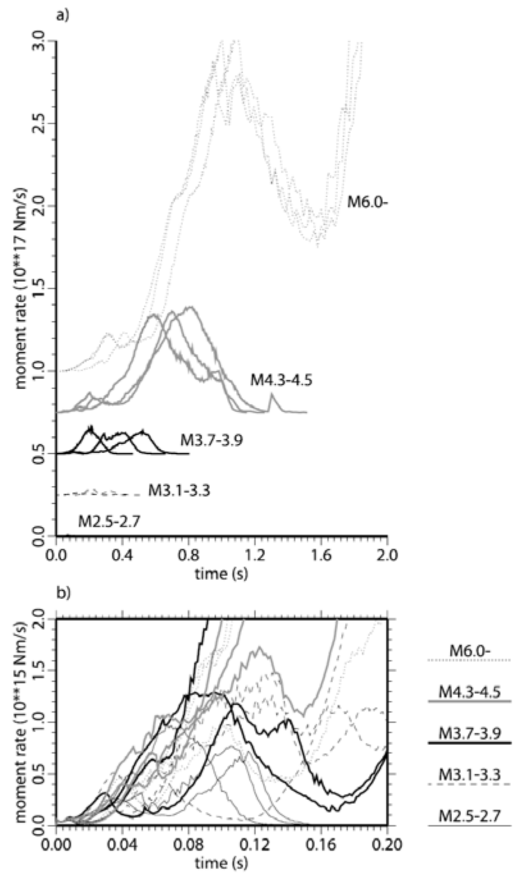


Figure 7. (a) Moment rate functions for events of different sizes. Baselines of different sizes have offsets. (b) Comparison of the first 0.2 s of all functions. Different line types represent different sizes.

Multiscale Dc model

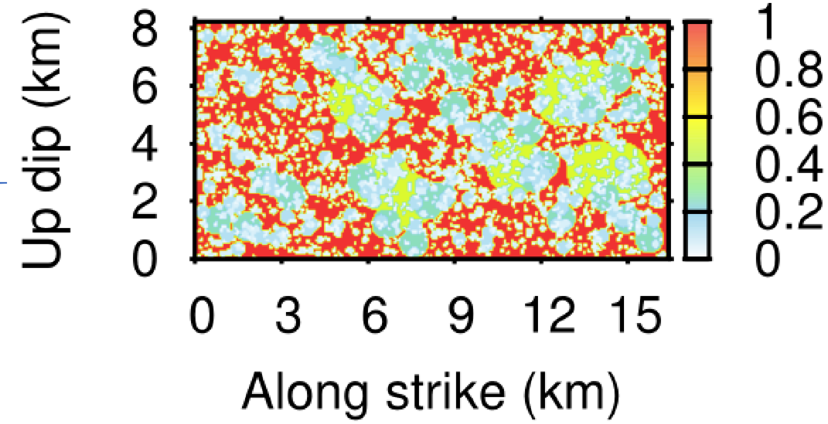
$$n = 1..n_{levels}$$
$$r_n = 2^{-n} r_0$$
$$N_n = 2^{Dn} N_0$$
$$D = 2$$
$$D_n^c = 2^{-n}$$

Ide and Aochi (2005)

$$r_0 = {}^{1}\!/_{8} \min(L, W)$$
$$N_0 = {}^{L}\!/_{W}$$

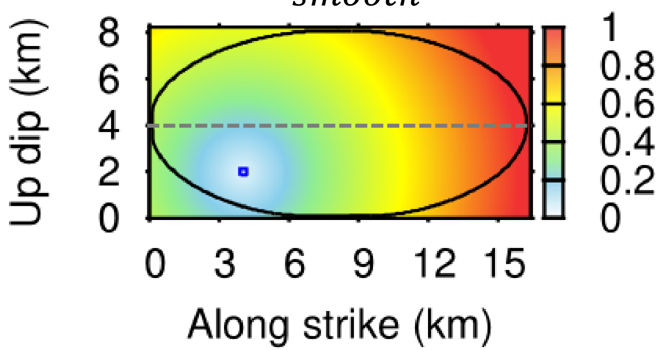
$$D_0^c = 1 \text{ (background)}$$

D^c ($n_{levels} = 5$)

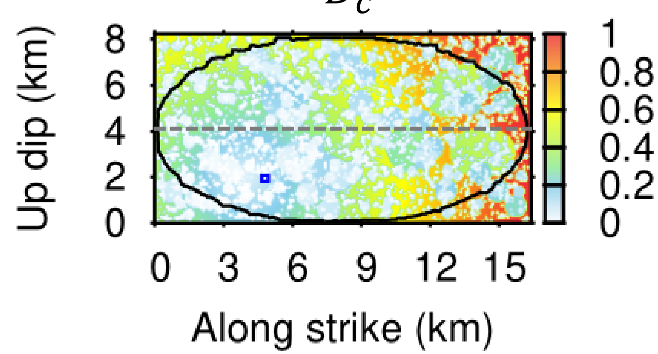


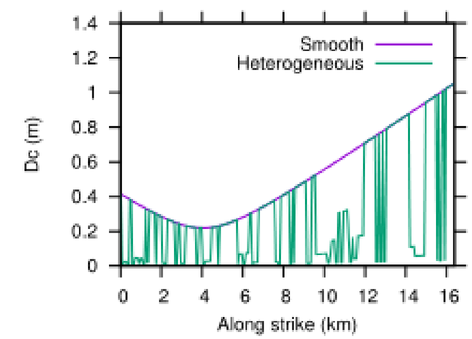
$$D_c = D_{smooth}^c D^c$$

D_{smooth}^c



D_c

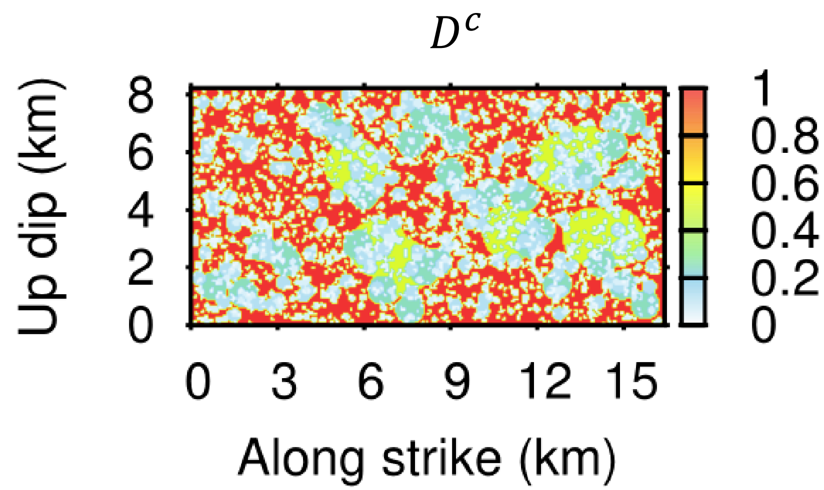




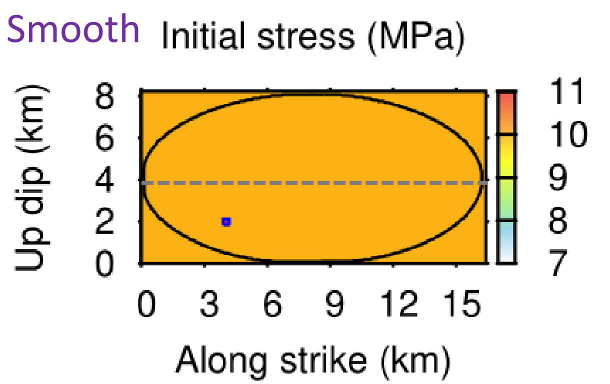
Multiscale Dc model

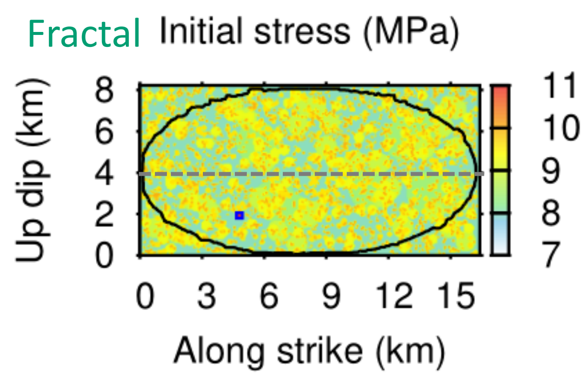
$$T_{ini} = T_{smooth}\left(1 - 0.2\frac{\log\frac{\min(D^c)}{D^c}}{\log\min(D^c)}\right)$$

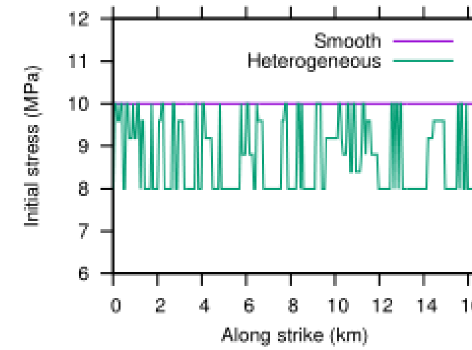
$$\Delta\mu = \Delta\mu_{smooth}\left(1 + 0.4\frac{\log\frac{\min(D^c)}{D^c}}{\log\min(D^c)}\right)$$

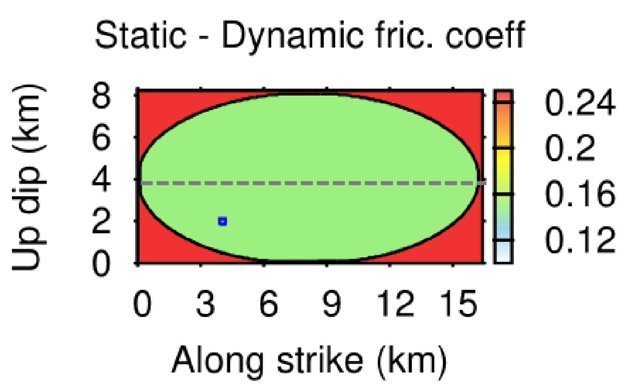


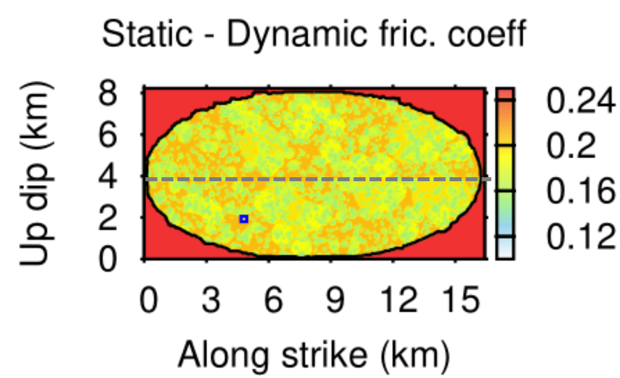
$\downarrow r_n \quad \downarrow D_c \quad \uparrow T_{ini} \quad \downarrow \Delta\mu$

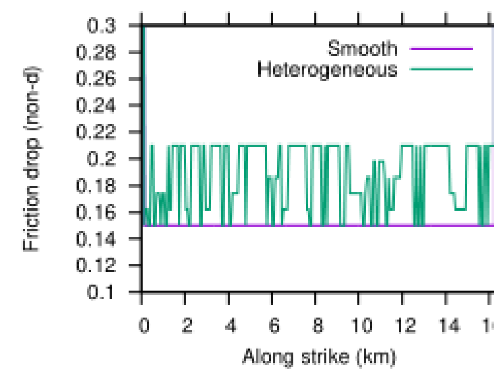








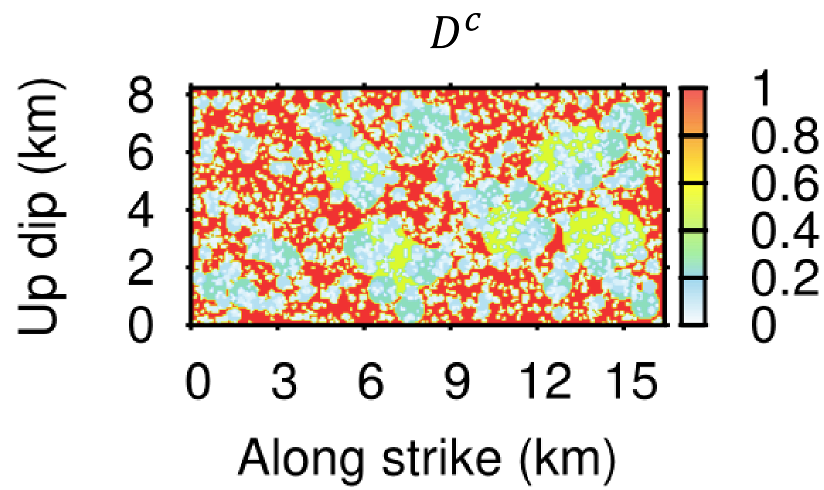




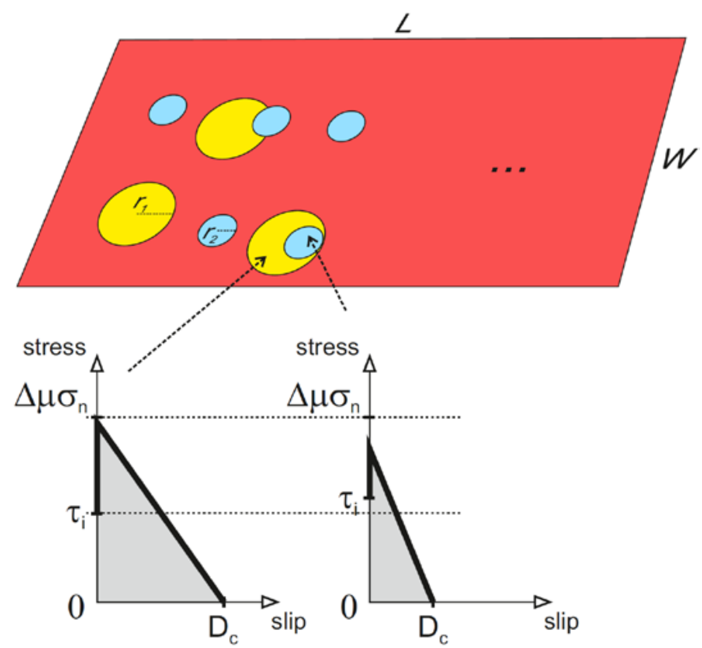
Multiscale Dc model

$$T_{ini} = T_{smooth}\left(1 - 0.2\frac{\log\frac{\min(D^c)}{D^c}}{\log\min(D^c)}\right)$$

$$\Delta\mu = \Delta\mu_{smooth}\left(1 + 0.4\frac{\log\frac{\min(D^c)}{D^c}}{\log\min(D^c)}\right)$$



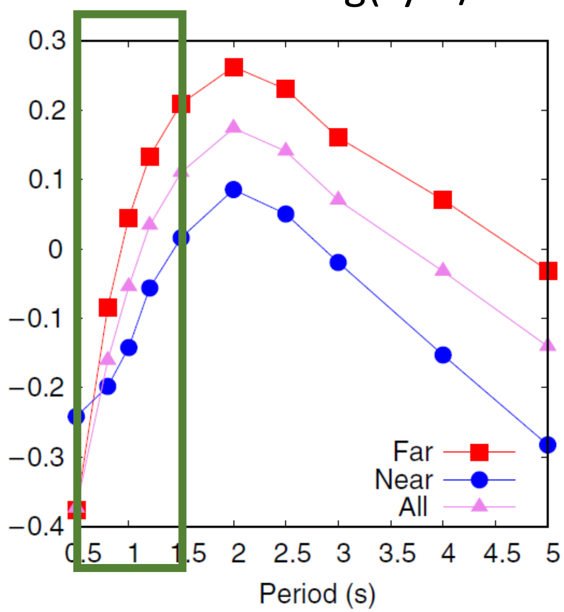
$\downarrow r_n$ $\downarrow D_c$ $\uparrow T_{ini}$ $\downarrow \Delta\mu$



Introduction

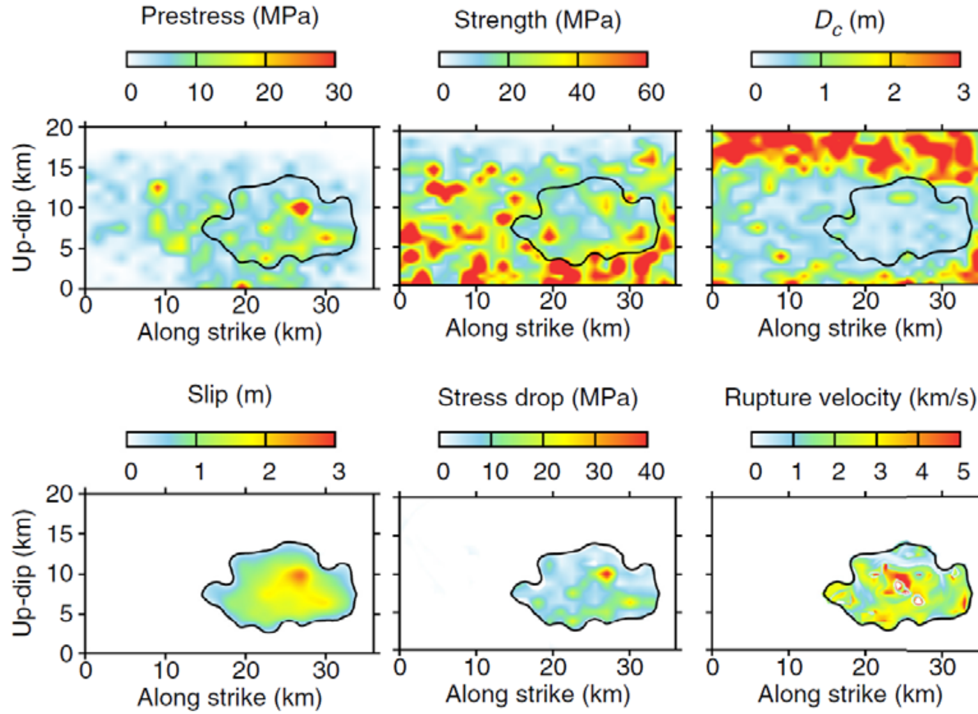
- Valentová et al. (BSSA 2021)

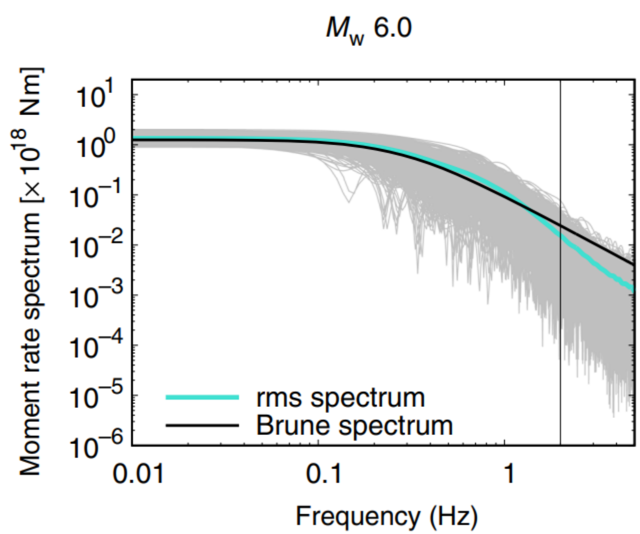
SA residuals = log(sym/GMPE)



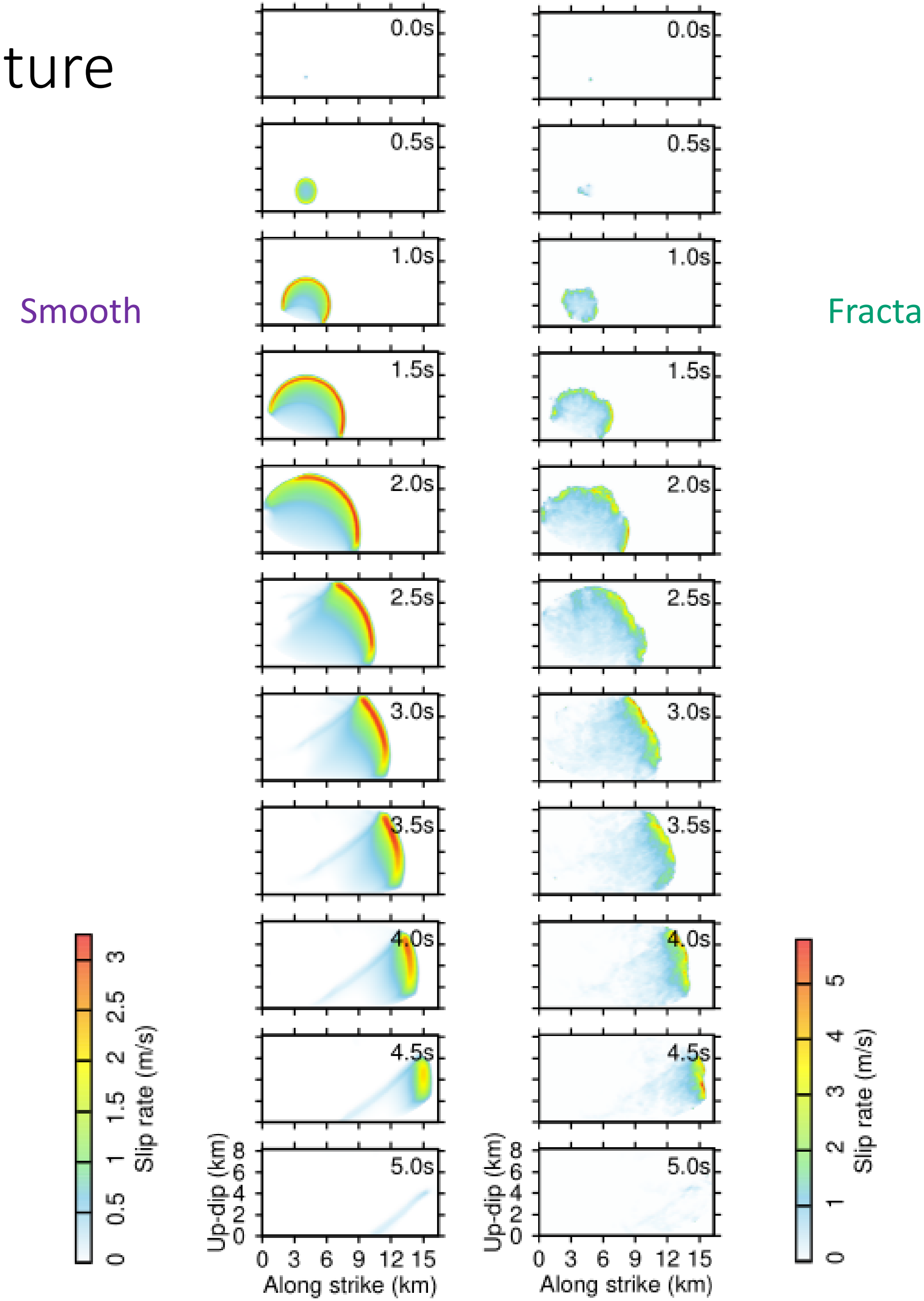
GMPE: Boore et al. (2014)

Scenario example





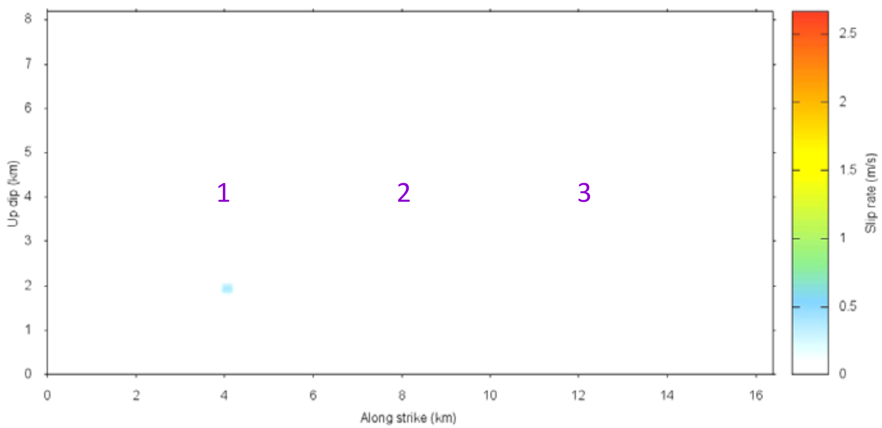
Example – elliptical rupture



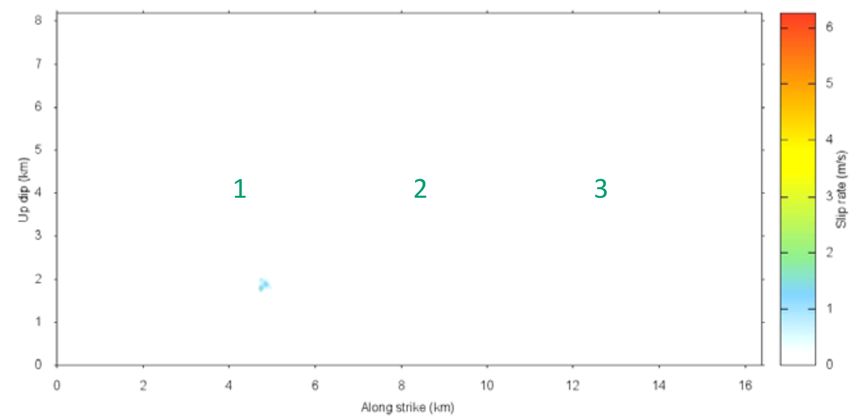
Example – elliptical rupture

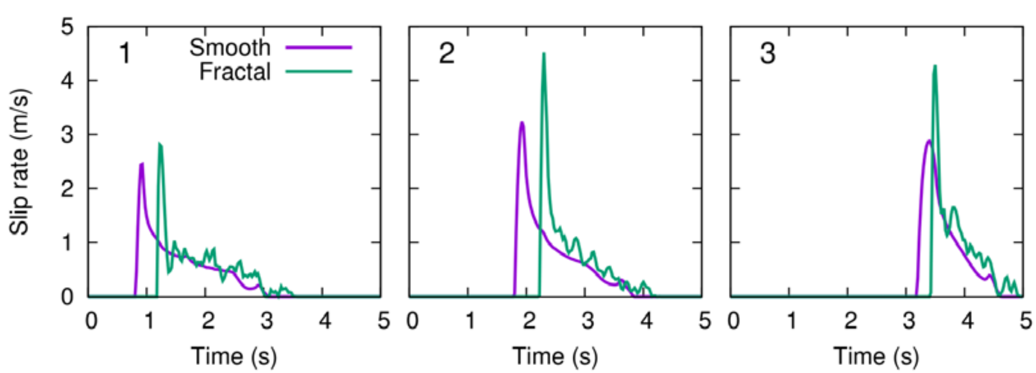
Solver: FD3D_TSN (Premus et al., 2020)	
Spatial discretization	32 m
FD half-domain size (along strike x normal x along-dip)	512 x 300 x 256
Duration of slip-rate functions	10 s
Time step	0.001 s

Smooth

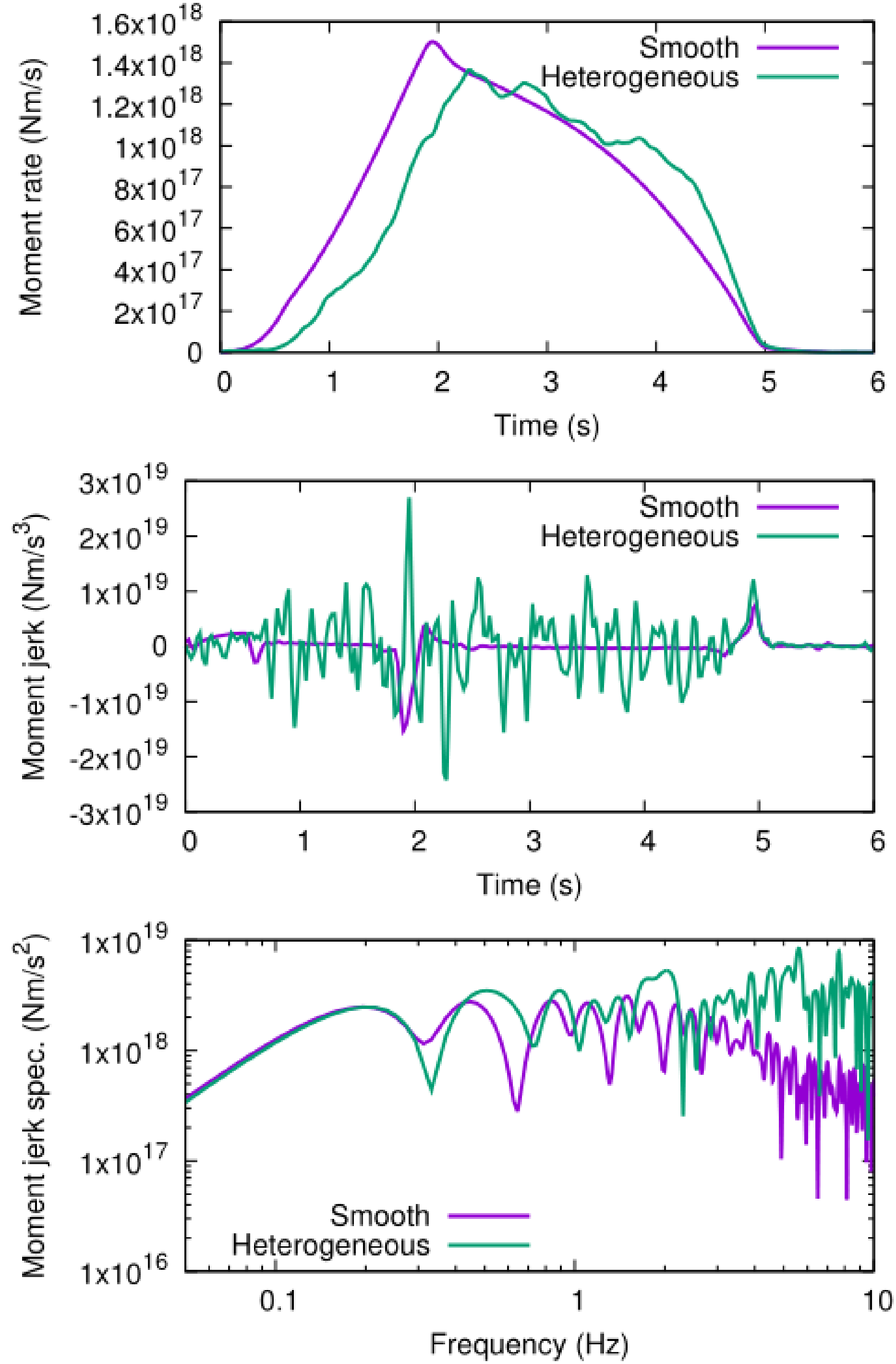


Fractal





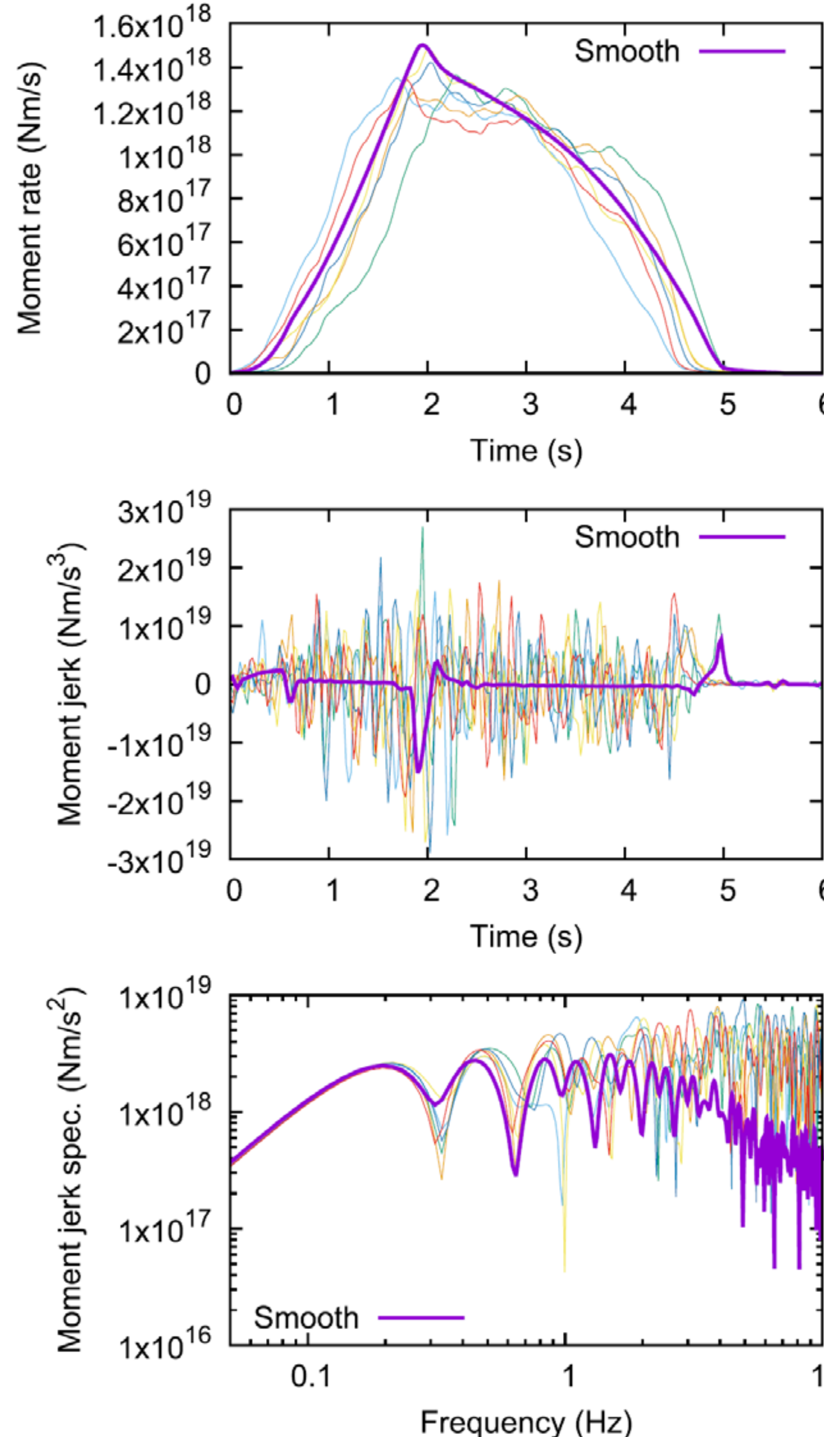
Example – elliptical rupture



-> The model radiates omega-squared during the whole rupture propagation due to the random acceleration and deceleration of the rupture (Madariaga, 1977)

Example – elliptical rupture

(5 more random realizations)



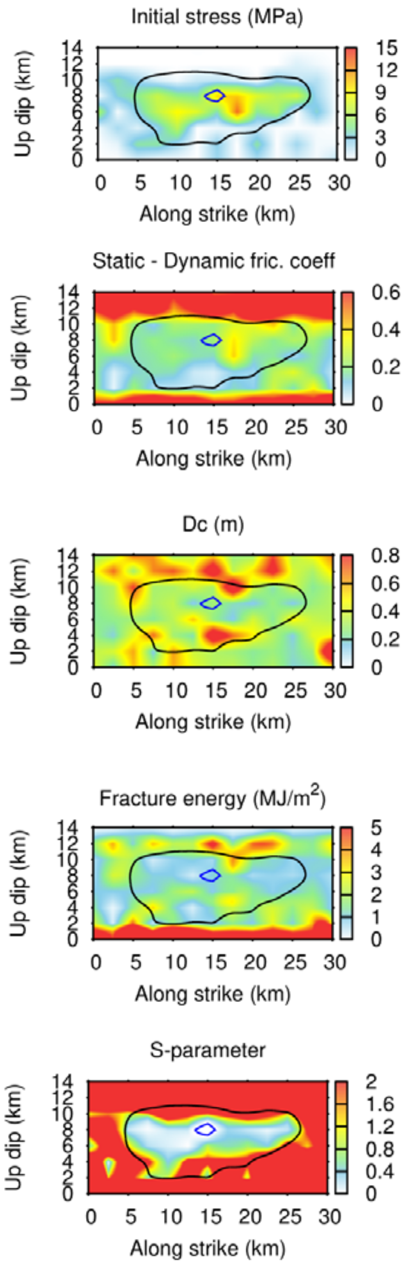
-> Statistically, the general rupture behavior is independent of the particular random realization of the fractal properties.

Overview of the 2016 Central Italy sequence

USGS

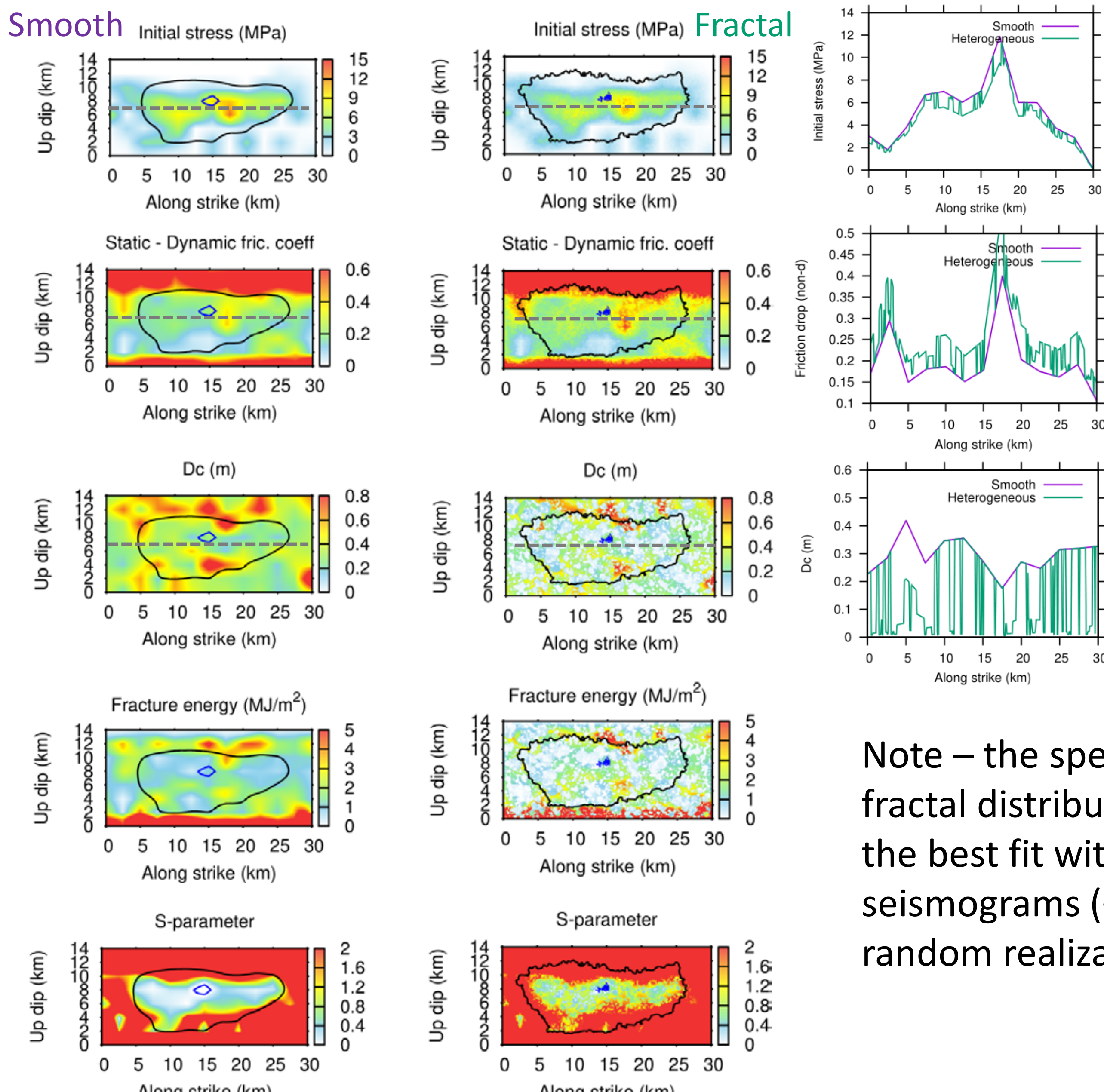
- Apennines, Central Italy
- Three M6 mainshocks
  - **Mw 6.2 Amatrice: August 24, 3:36**
  - Mw 5.9 Ussita: October 26, 21:18
  - Mw 6.5 Norcia: October 30, 08:40
- 300 casualties (mainly due to the 1st event)

Example – Amatrice e.



Smooth model from Gallovič et al. (2019)

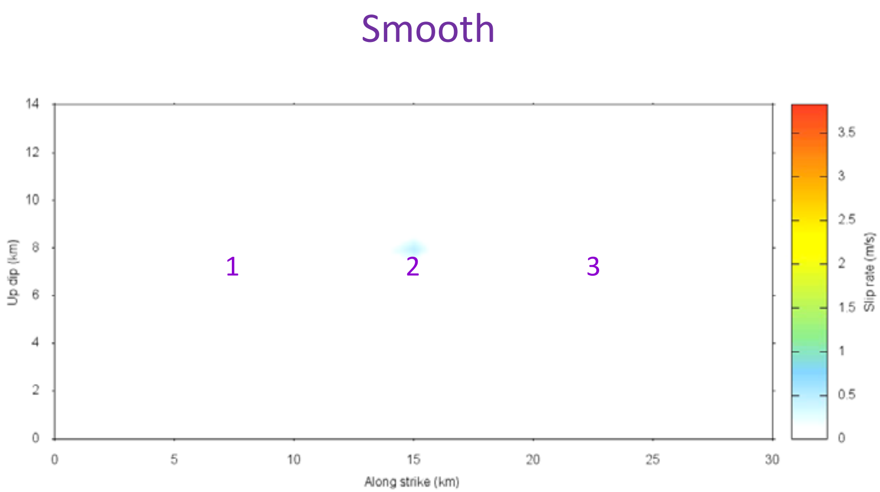
Example – Amatrice

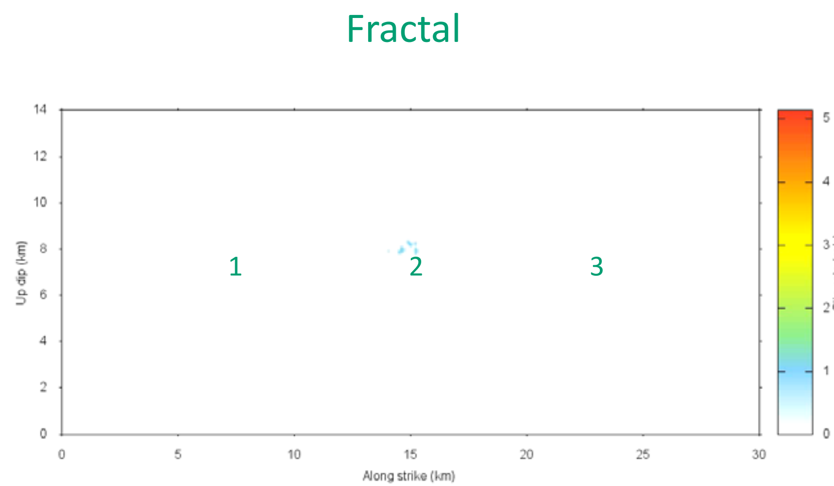


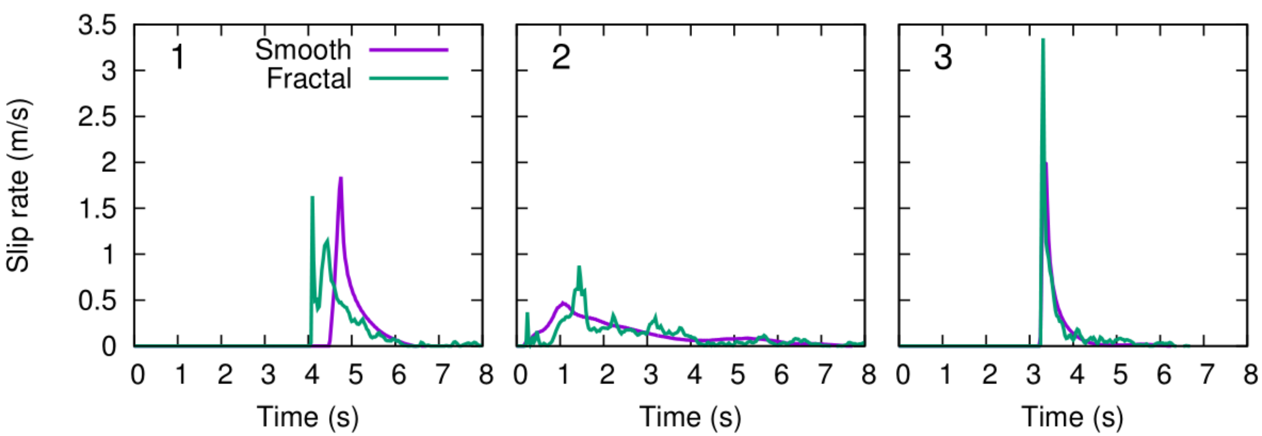
Gallovič et al. (2019)

Note – the specific realization of the fractal distribution found to obtain the best fit with low-frequency seismograms (<0.5Hz) out of 500 random realizations.

Example – Amatrice

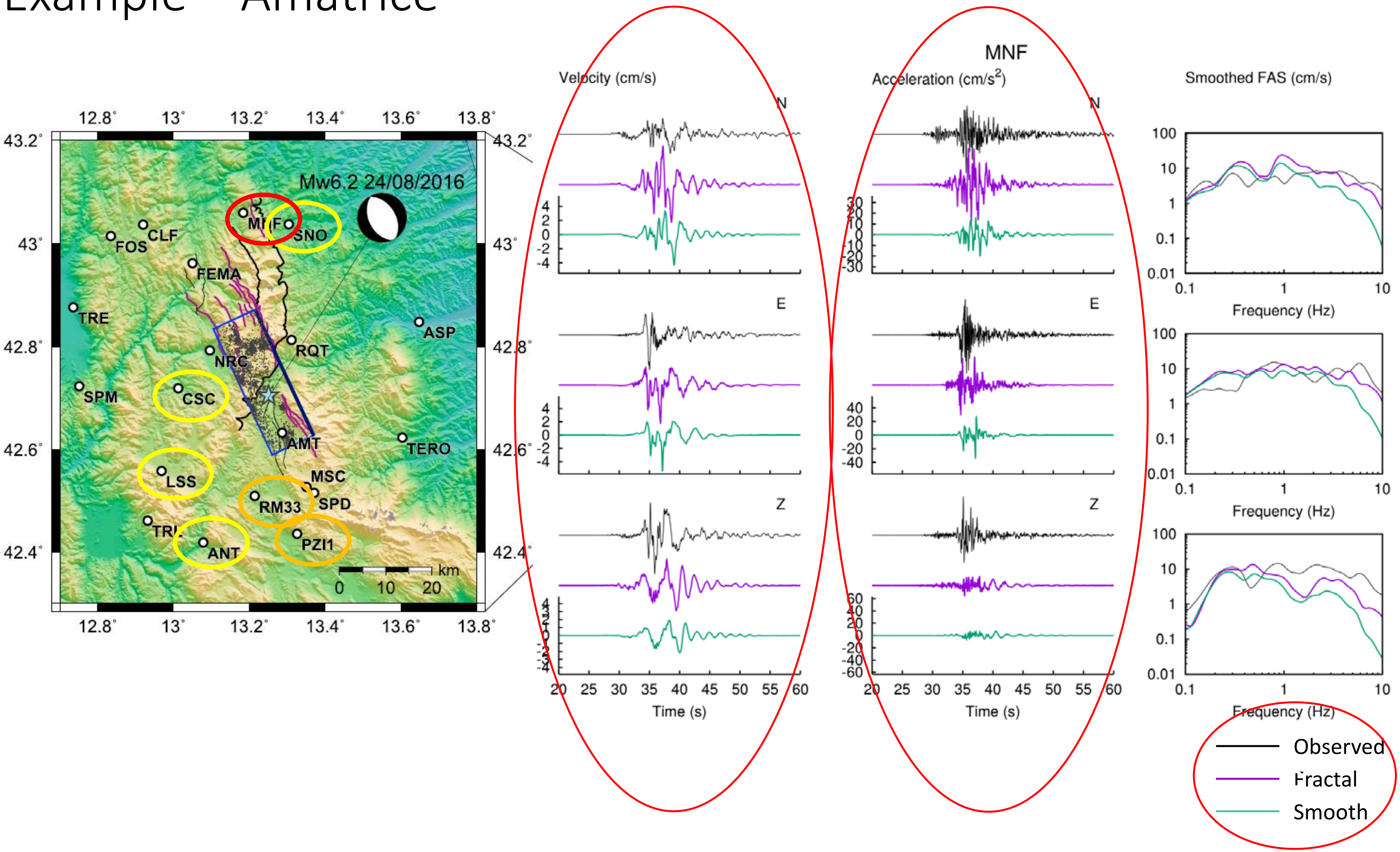




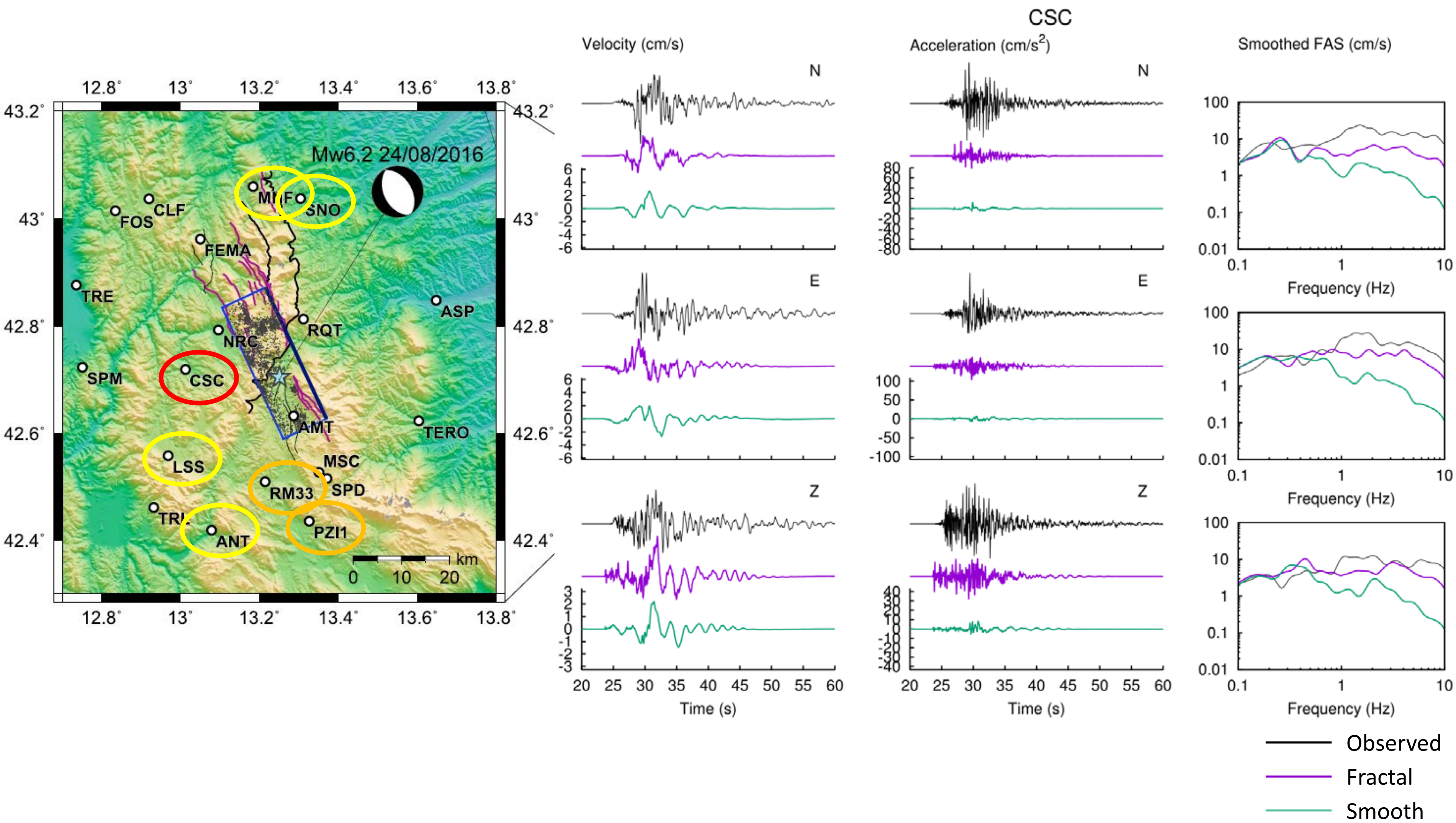


FD3D_TSN performs the calculation in about
30 minutes up to 10 Hz on a single GPU

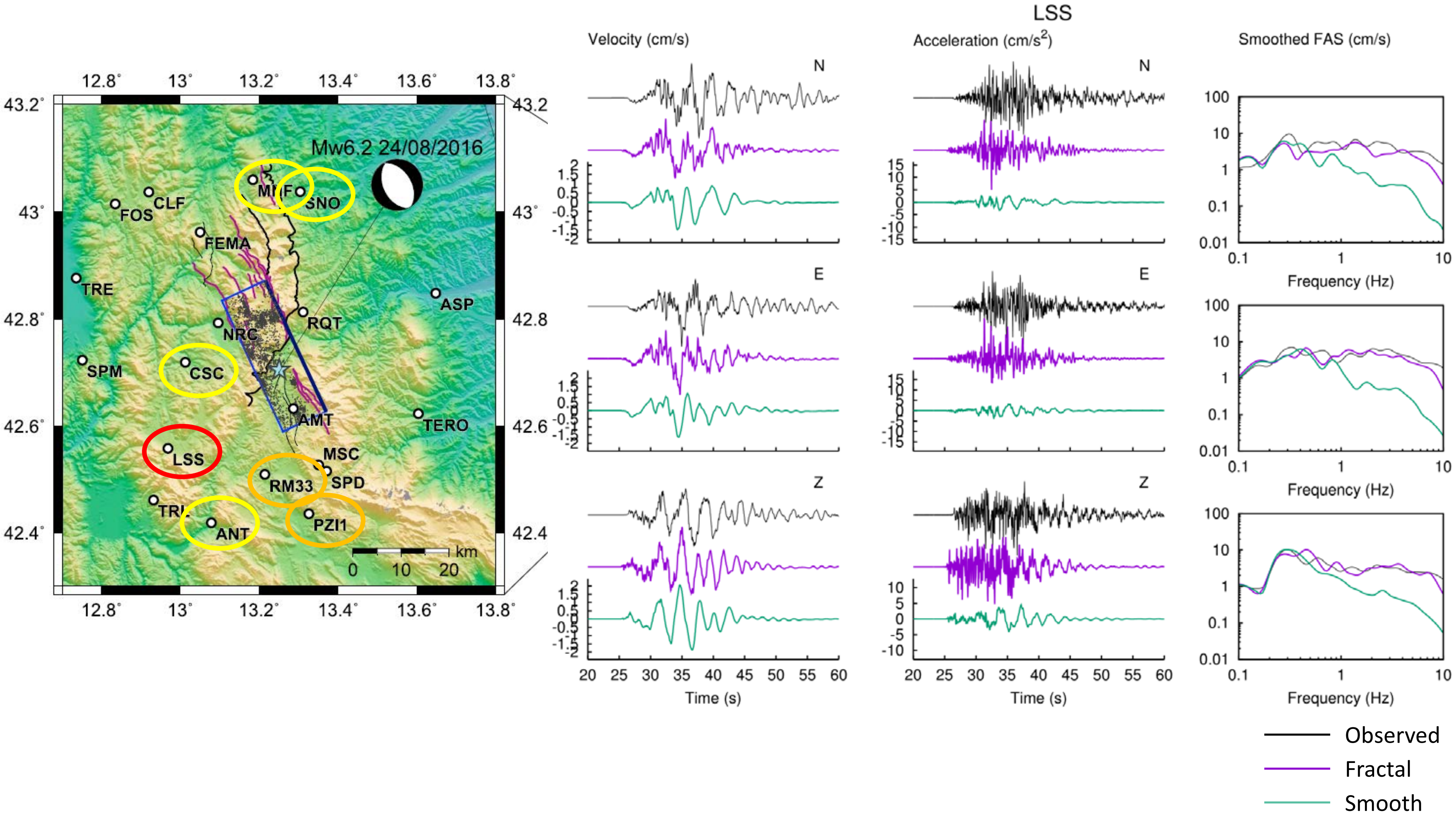
Example – Amatrice



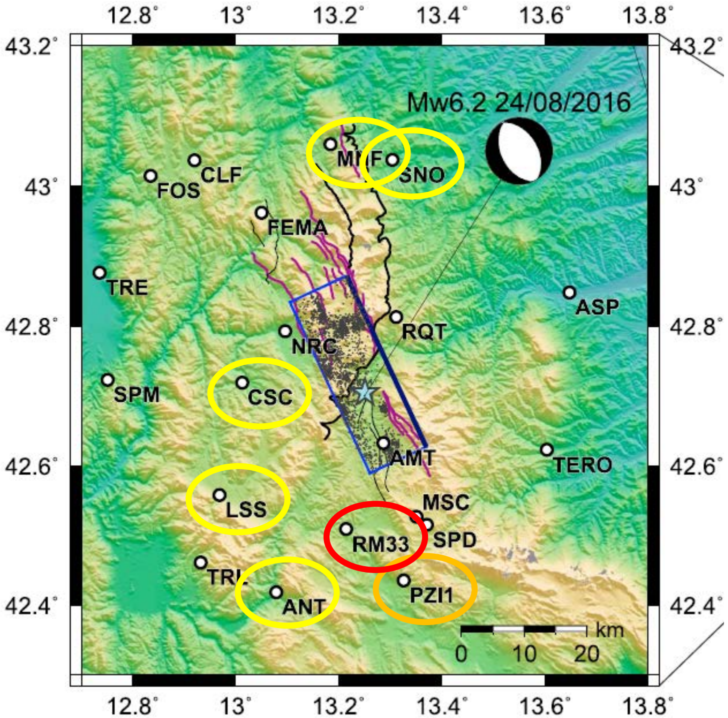
Example – Amatrice

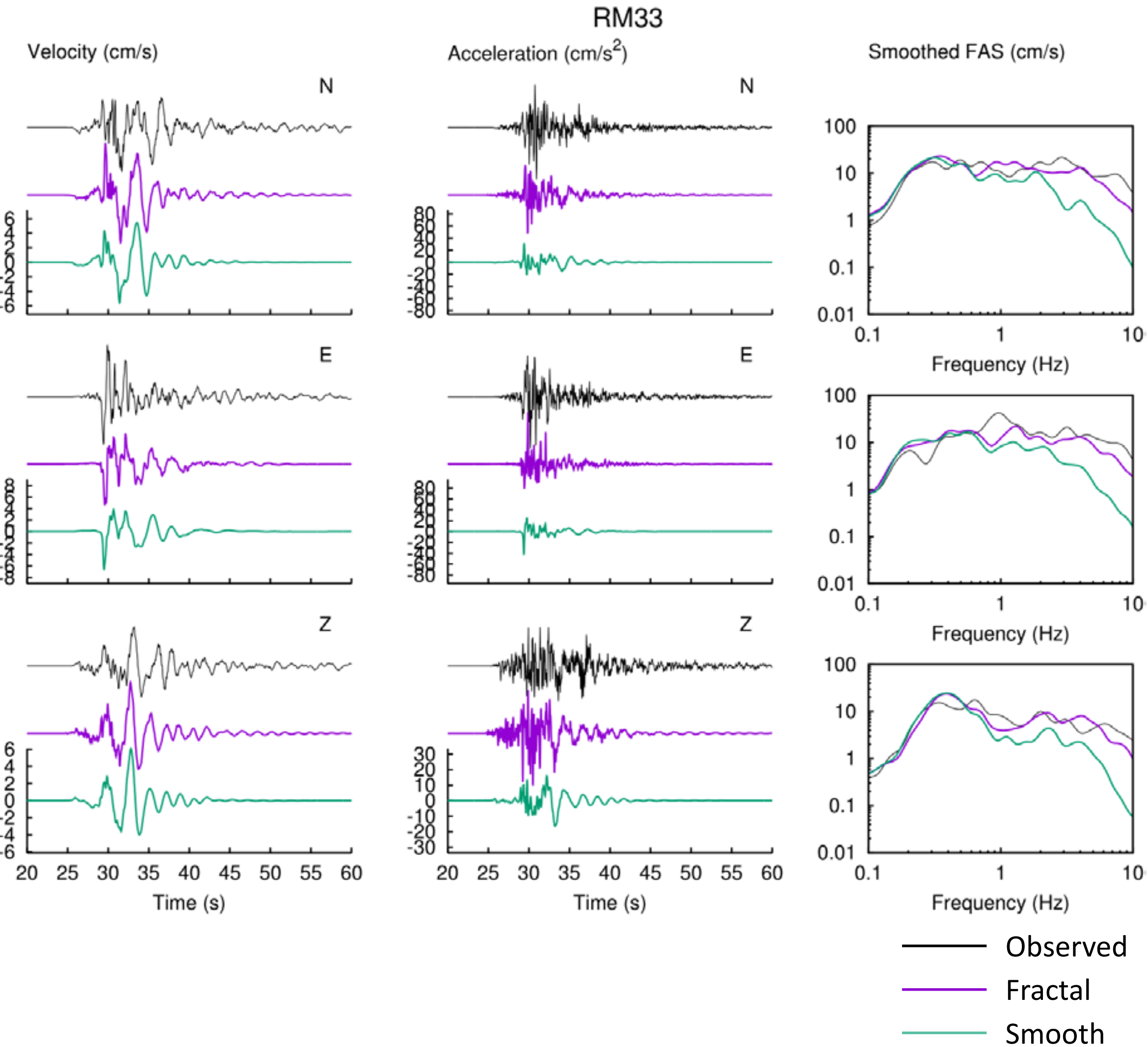


Example – Amatrice

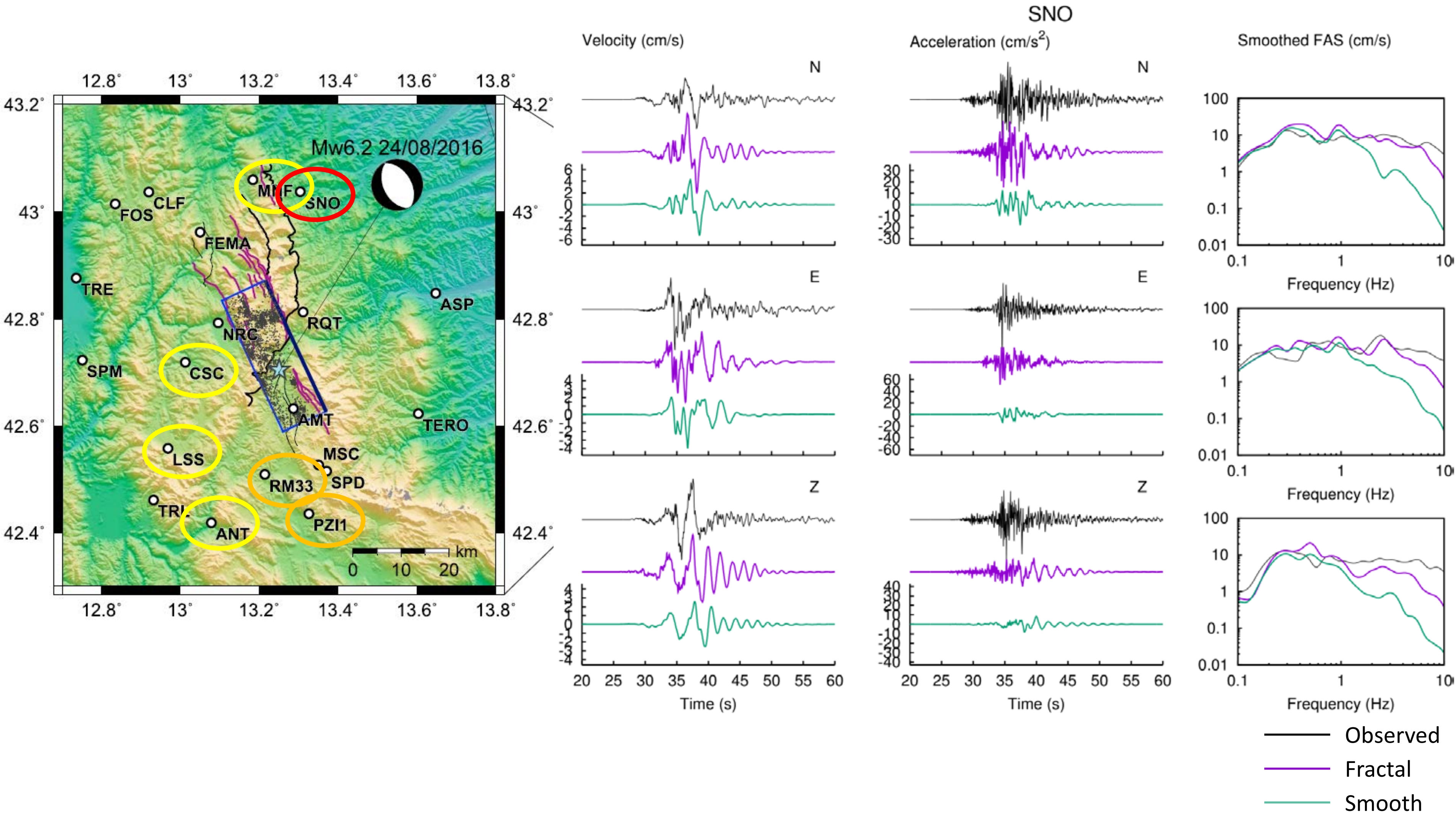


Example – Amatrice

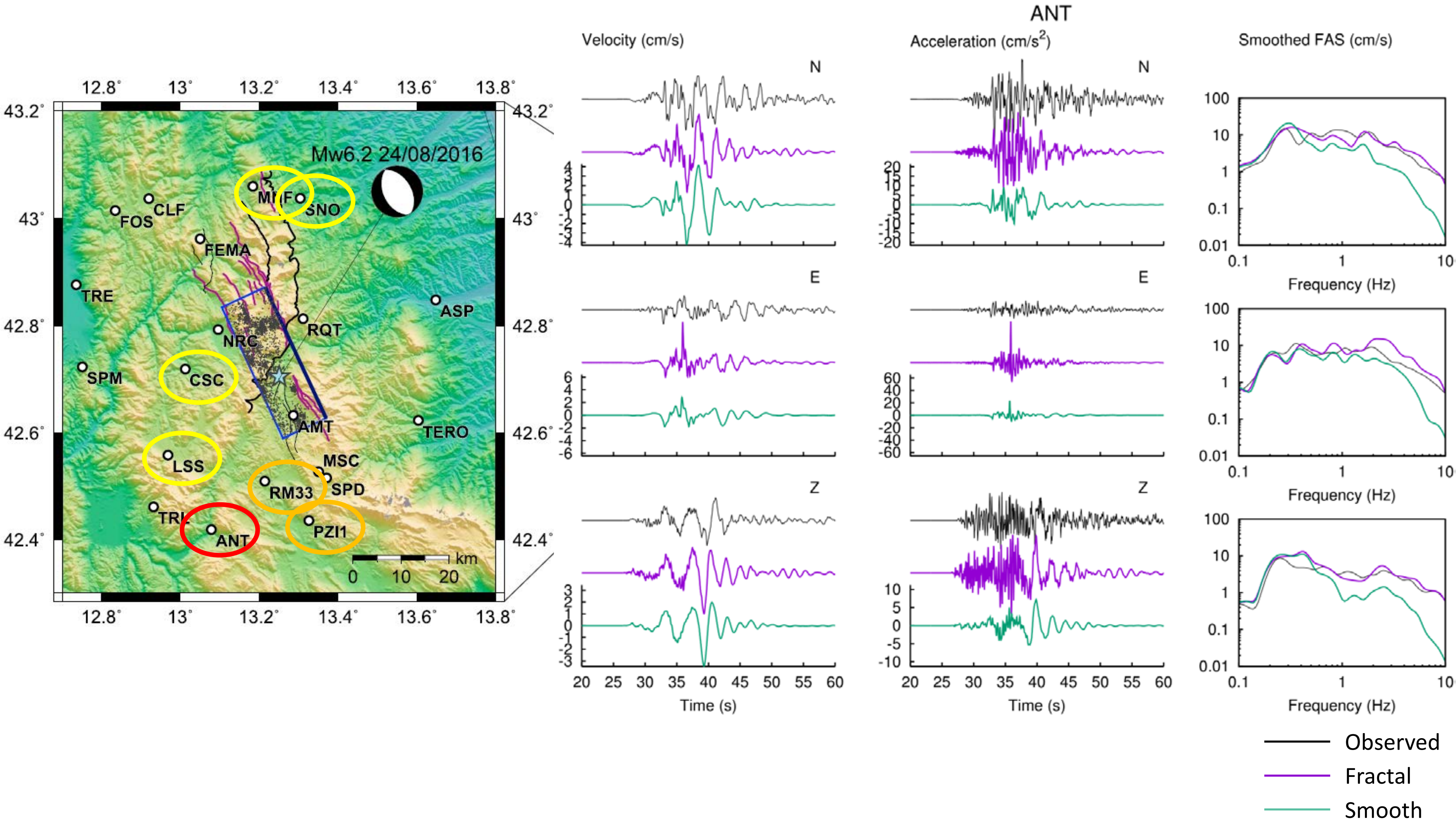




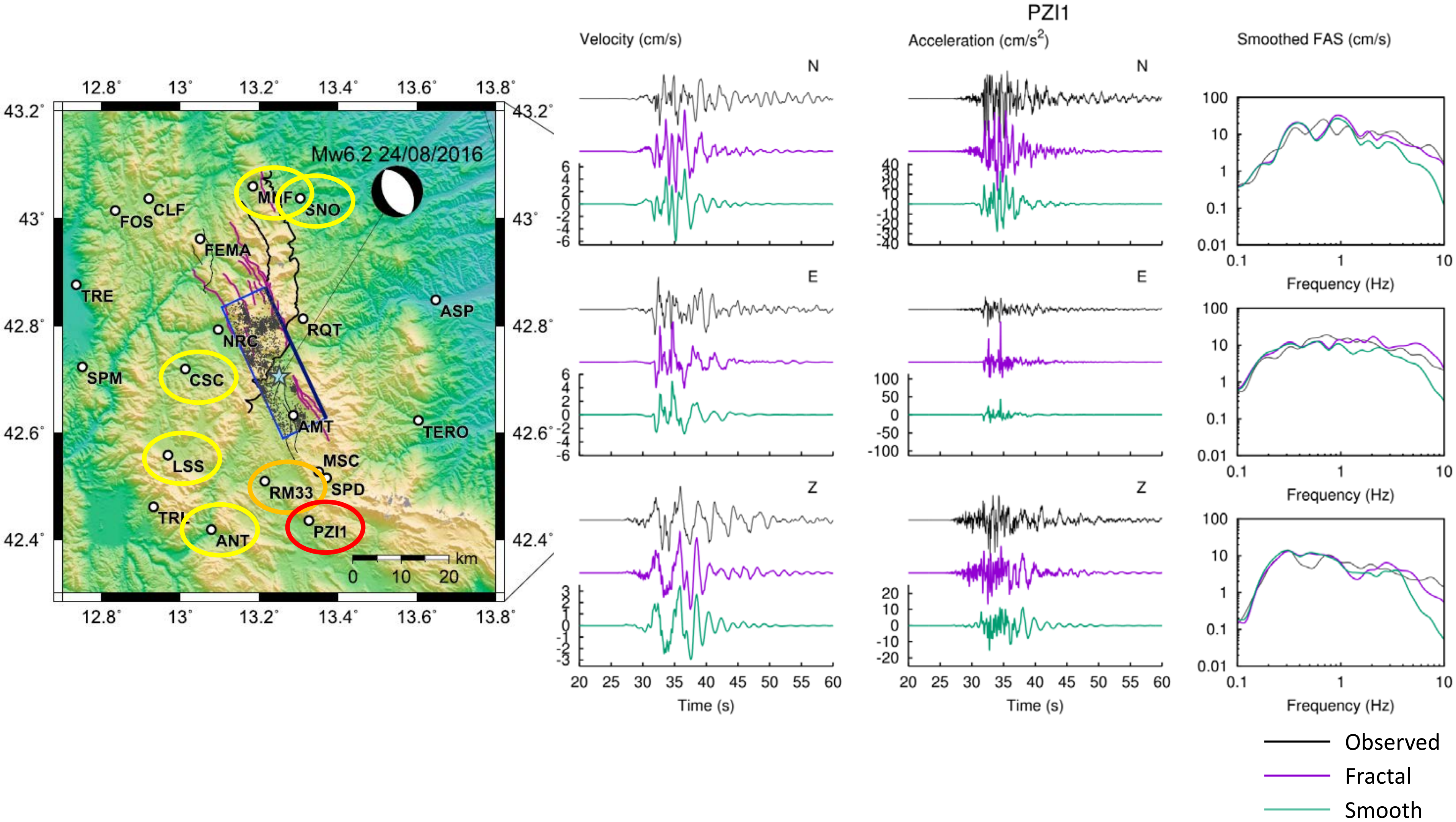
Example – Amatrice



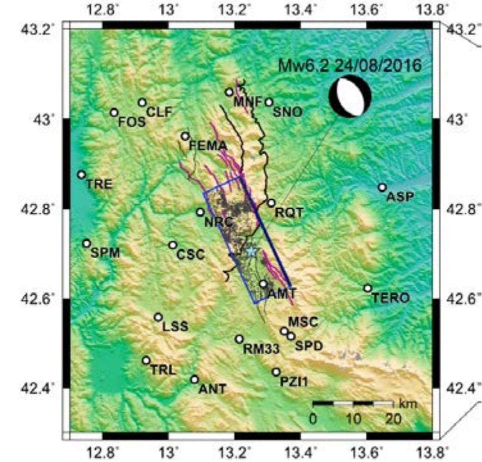
Example – Amatrice



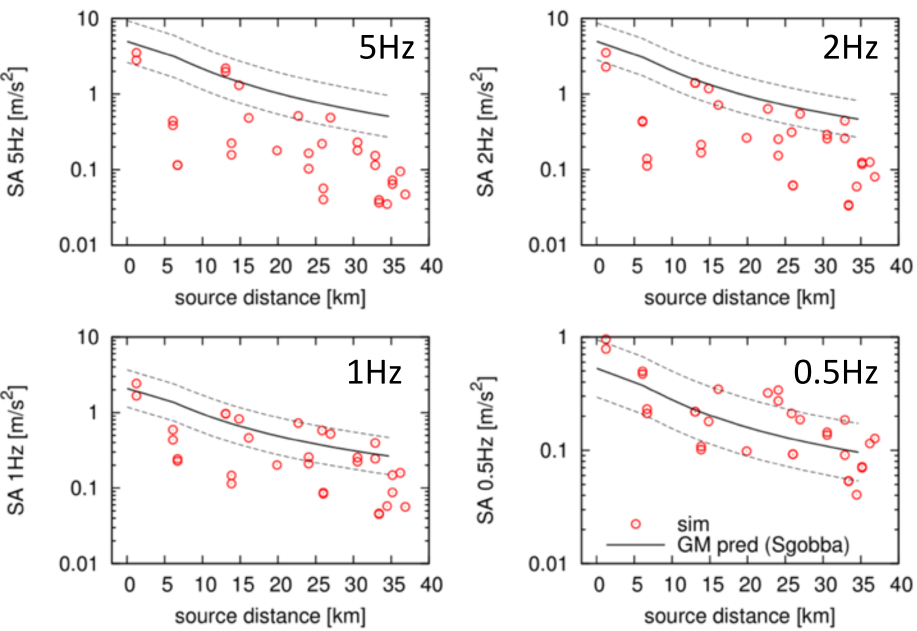
Example – Amatrice



Example – Amatrice (comparison with Ground Motion Model)

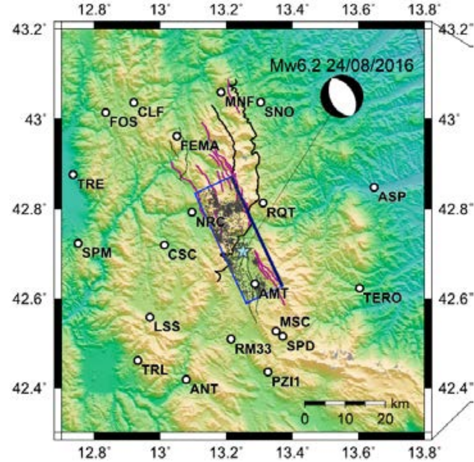


Smooth



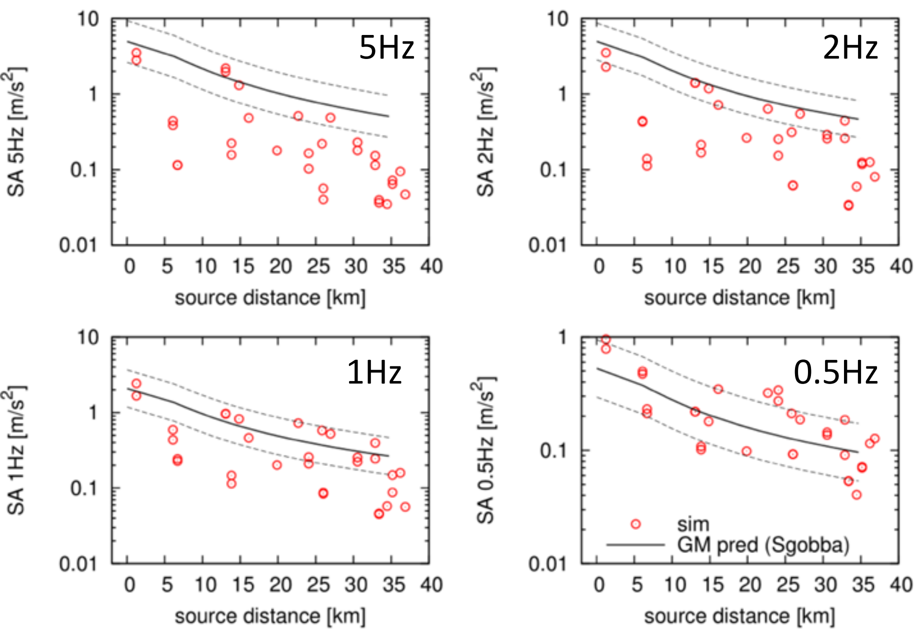
GM pred: Sgobba et al. (2021)

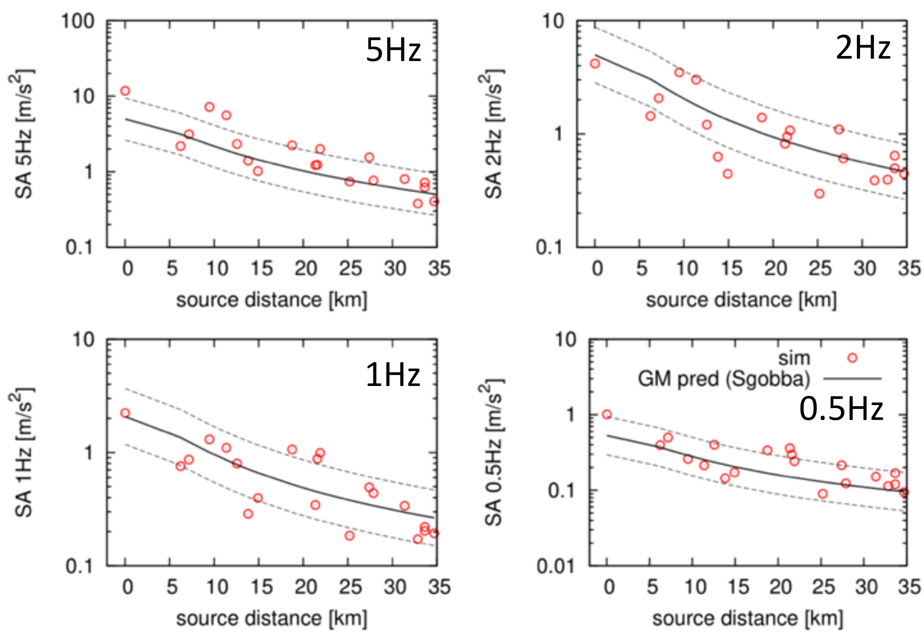
Example – Amatrice (comparison with Ground Motion Model)



Smooth

Fractal

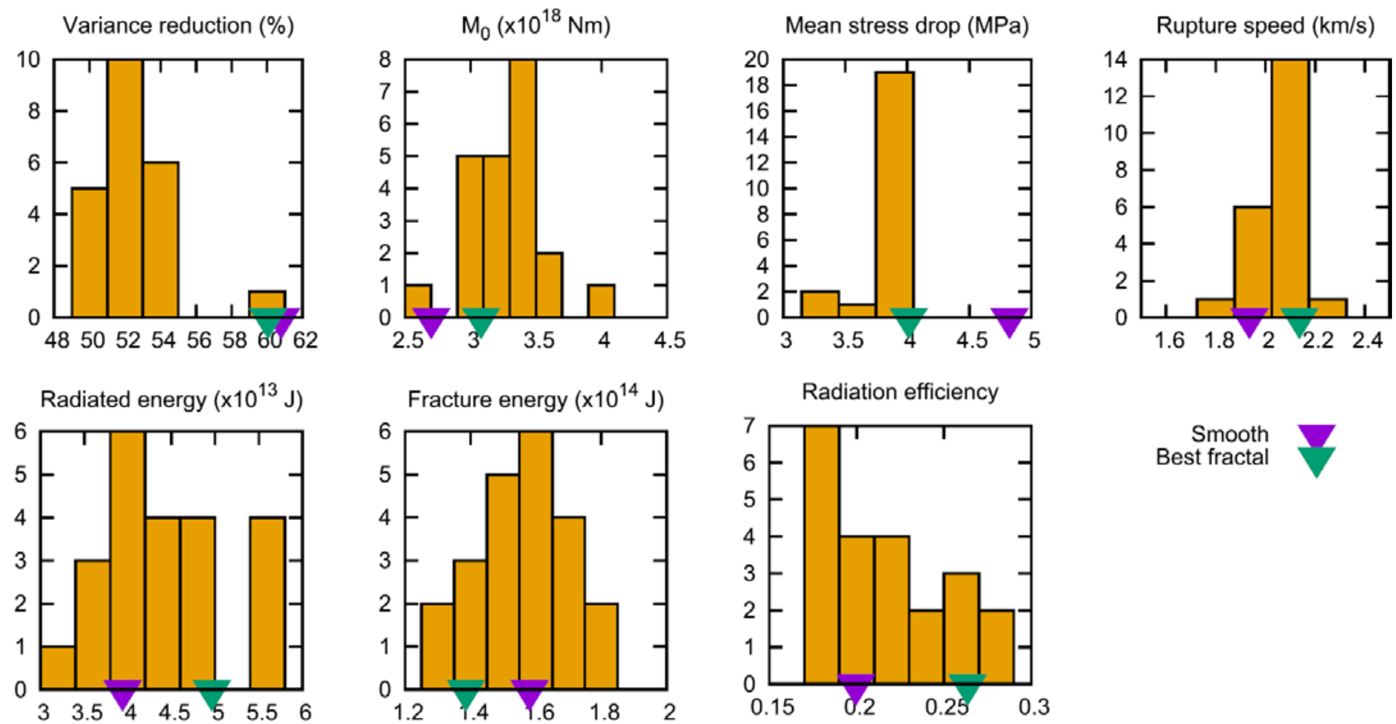




GM pred: Sgobba et al. (2021)

Example – Amatrice

(Spatially) averaged parameters of best 23 models with VR>0.5



-> By construction, gross (average) model parameters of the smooth and fractal models are about the same.

Conclusions

- The proposed fractal perturbations alleviate many issues of simple (smooth and planar) dynamic rupture models:
  - The small-scale dynamic properties result in sustained high-frequency radiation during the rupture propagation mainly due to random acceleration and deceleration of the rupture.
  - The model radiates omega-square (apparent) source time functions.
  - The slip rates are complex on small- and short-scales, resembling delayed or advanced rupturing of overlapping patches in random directions, decreasing the directivity effect at high-frequencies.
  - Gross (average) rupture parameters of the fractal models are about the same as those of the smooth one, warranting low-frequency dynamic source inversions.