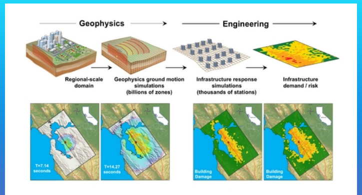

PEER International Pacific Rim Forum
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Pushing the Simulation of Earthquake Ground Motion in the Grenoble Valley to Higher Frequencies. Part II: Verification and Validation Aspects

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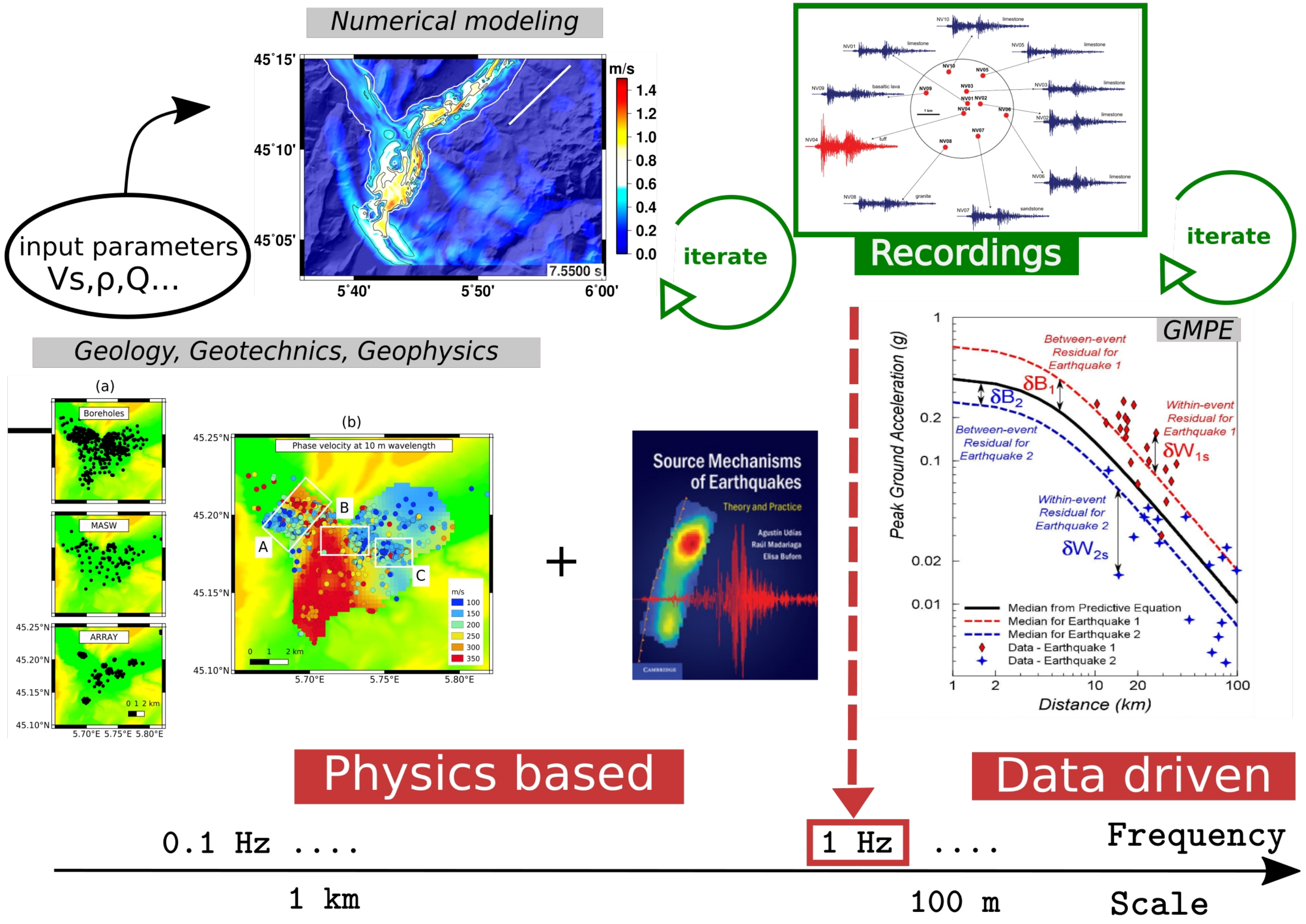
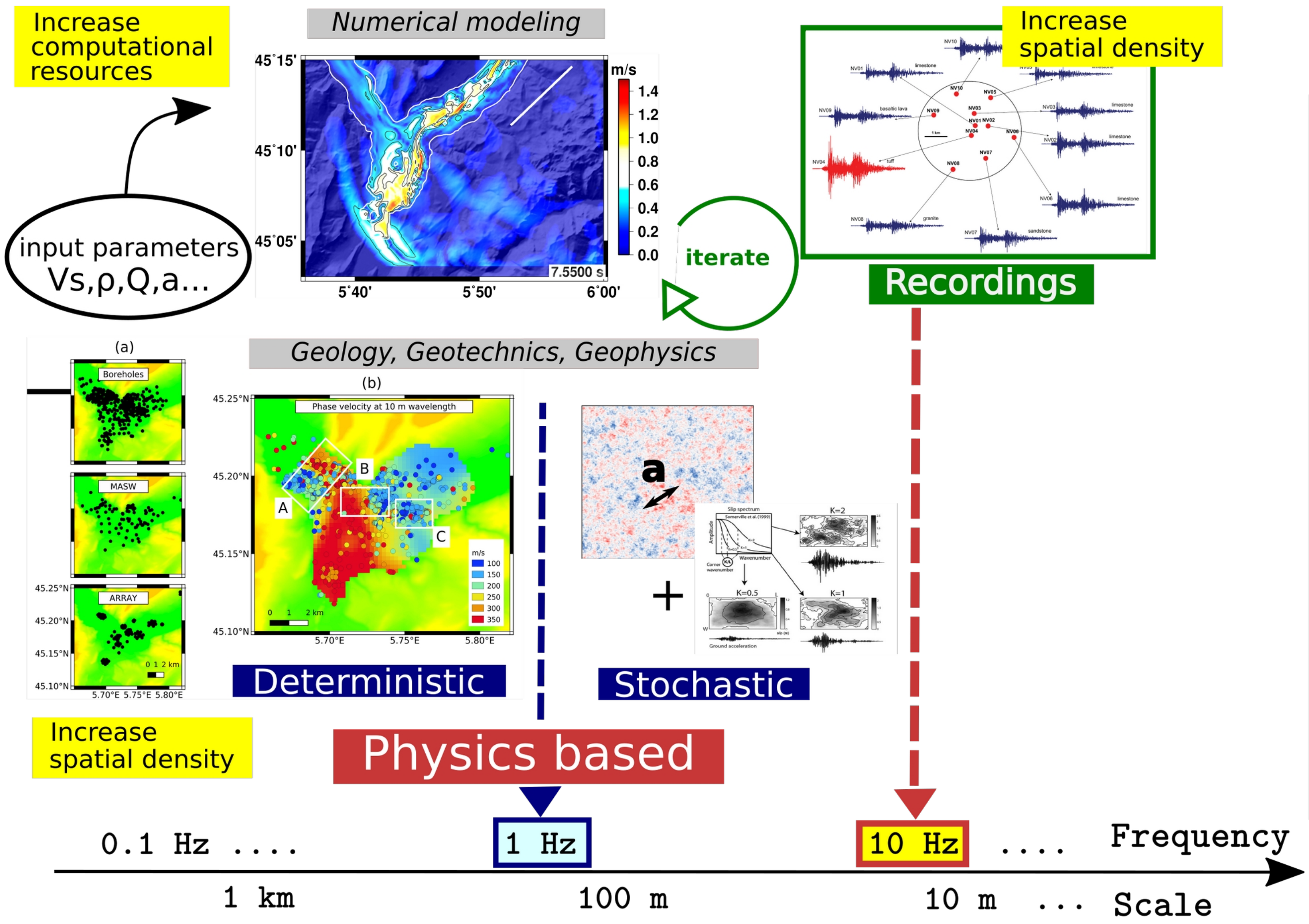
EGM prediction: Physics-based approach



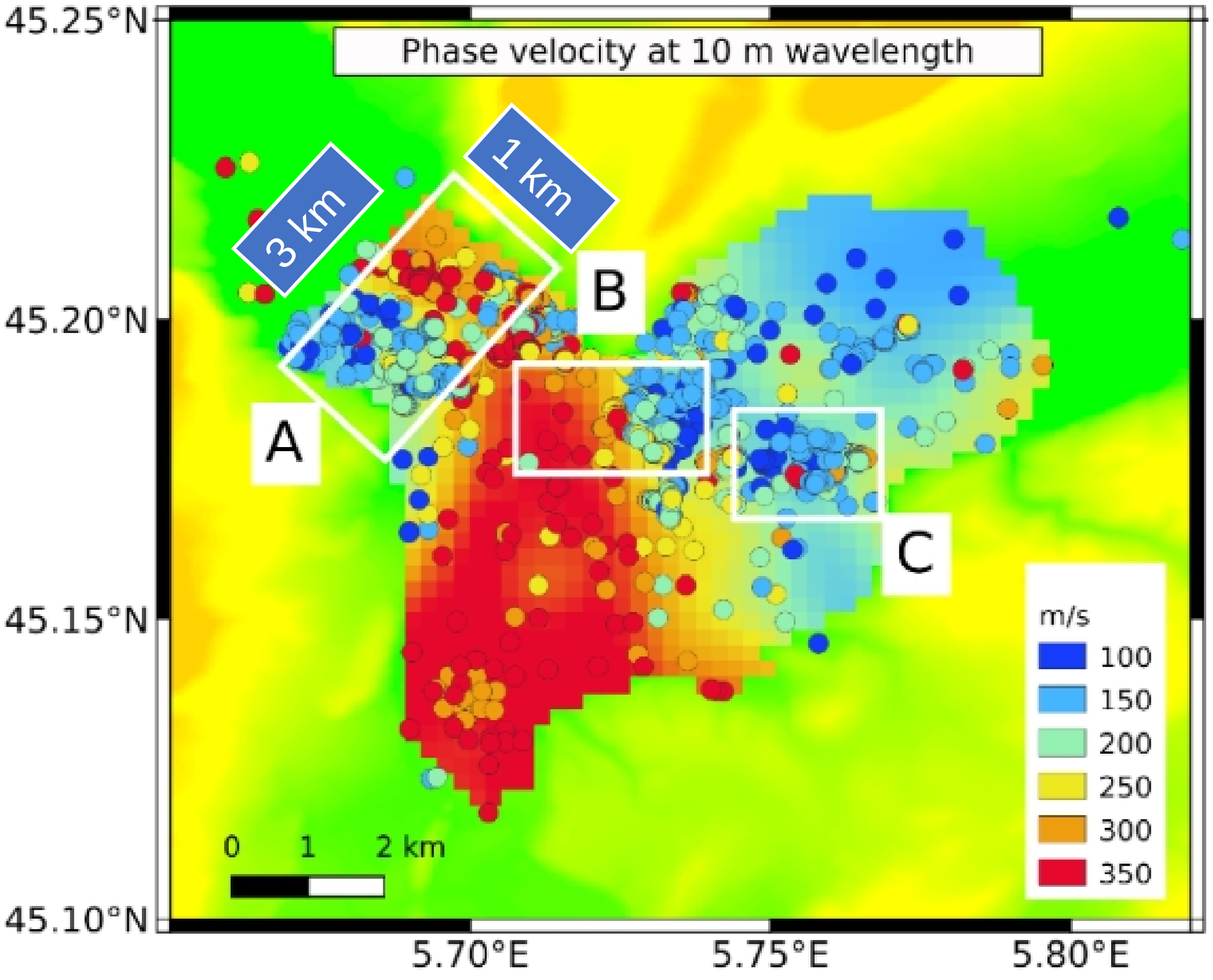
- Direct Numerical Simulation of the physical processes causing EGM : source, propagation, site effects
- Complementary to empirical data-driven approaches
- Naturally limited in frequency (computational resources, lack of information/uncertainty)

Pushing physics-based predictions to higher frequencies



- **More GGG data** to build our models … but
  - Description of medium and source cannot be fully deterministic.
  - Stochastic part has to be controlled and verified
- **More computational resources** (higher Hz and ensemble average)
- More observations with higher spatial resolution for validation (**unaliased wavefields**).

Pushing physics-based predictions to higher frequencies: example of the Grenoble Valley



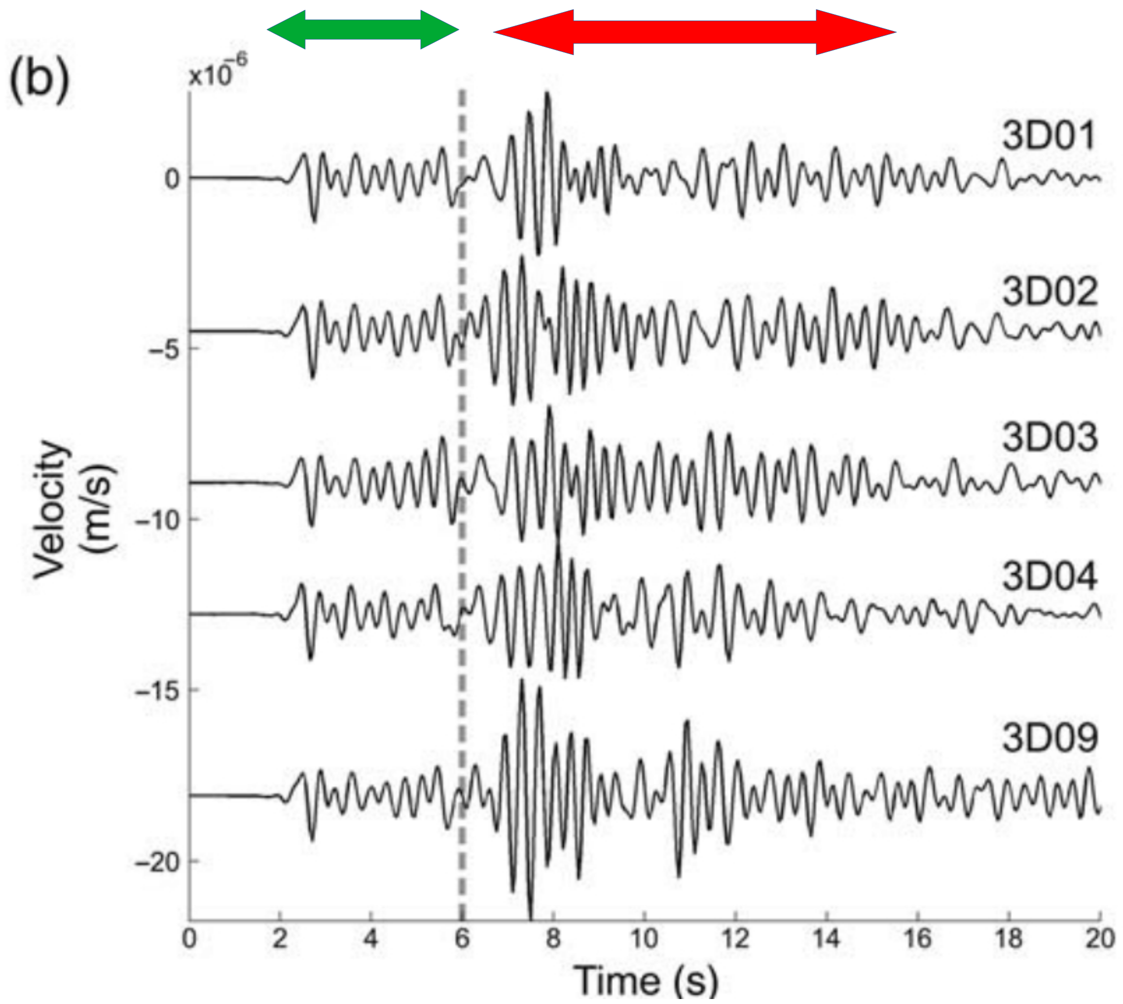
Two-scales model (Cornou et al., prev pres)
Deterministic, macrozones (clays, gravels)
Stochastic fluctuations

Focus on the A zone (left) **3 km x 1 km**
Insitut Laue Langevin (ILL, neutron reactor)
French ANR-EXAMIN project

3D simulations of EGM with SEM
Fmax = 5 Hz
Point source and extended faults (not today)

Questions:
Effects of macrozones (amplification, duration)?
Effects of fluctuations?

Epistemic errors in EGM simulation : the role of (unresolved) small scales



E2VP projet, Mygdonian basin in Greece

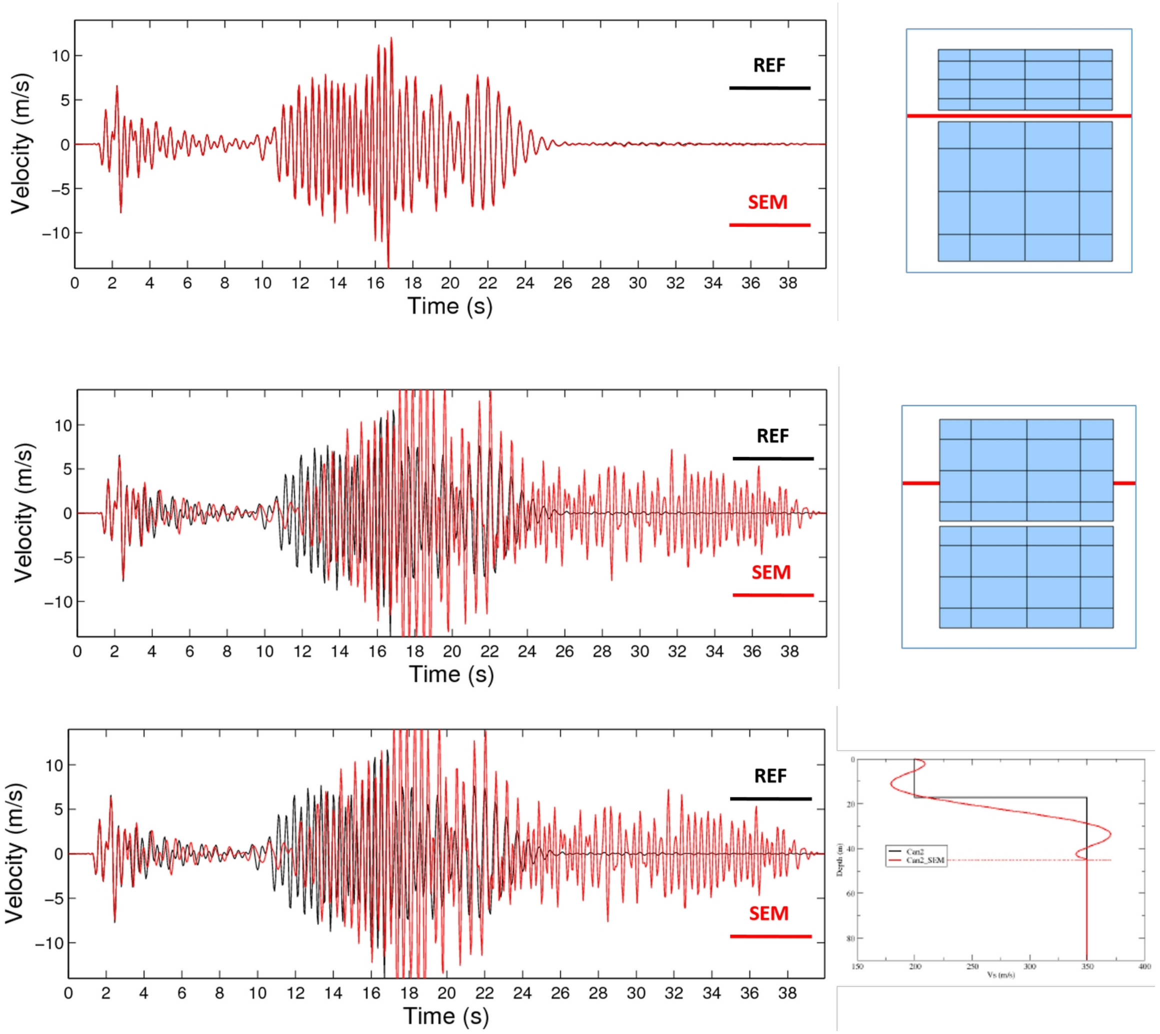
Maufroy et al. BSSA, 2015

Comparison between different 3D numerical predictions of EGM up to 4 Hz in sedimentary basins show:

- **Good agreement** for first, body-wave, arrivals
- **Increasing level of error** for late, diffracted surface-wave arrivals

- Those errors depend on the **smoothness** of the propagation medium (the smoother the better)

Epistemic errors in EGM simulation : the role of small scales



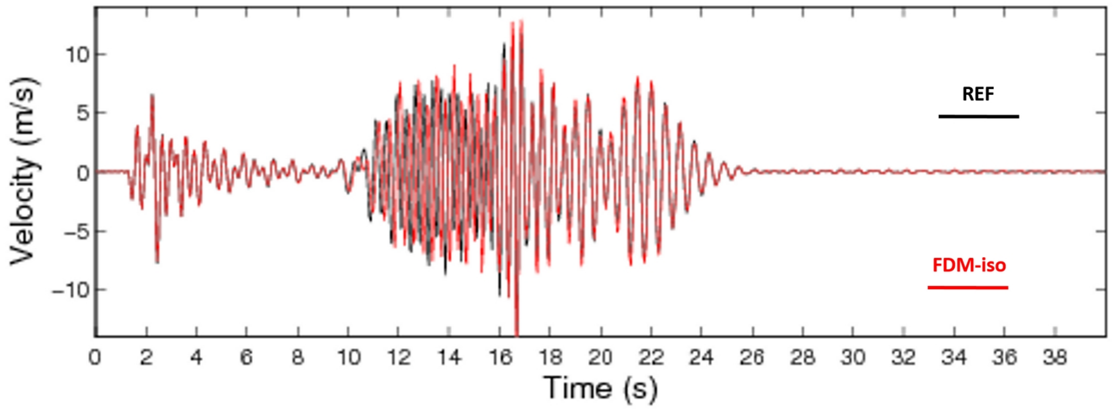
SEM synthetics in a three-layers basin structure

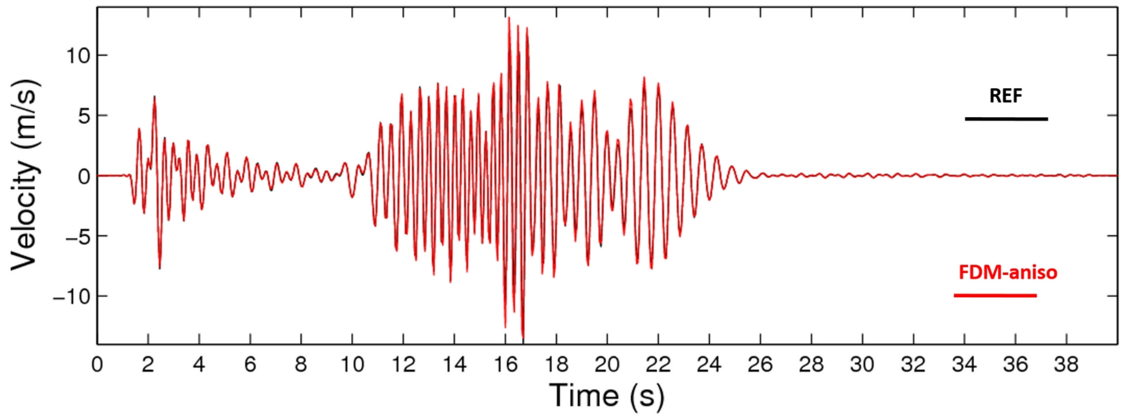
Chaljub et al. GJI, 2015

- SEM has the ability to account for physical discontinuities: the mesh has to follow the interfaces.
- If not possible (e.g. basin edges) the interface can not be represented on the local polynomial basis.
- The loss of accuracy can be spectacular when errors accumulate (e.g. surface waves along poorly represented horizontal interfaces)
- This is true for any grid-based method

  (FDM, FEM, DGM, SEM…) and any kind of sub-scale heterogeneity.

Solution: low-pass filter small scales by defining effective, homogenized media





Isotropic effective media (Moczo et al. BSSA, 2002)
(2 elastic parameters)

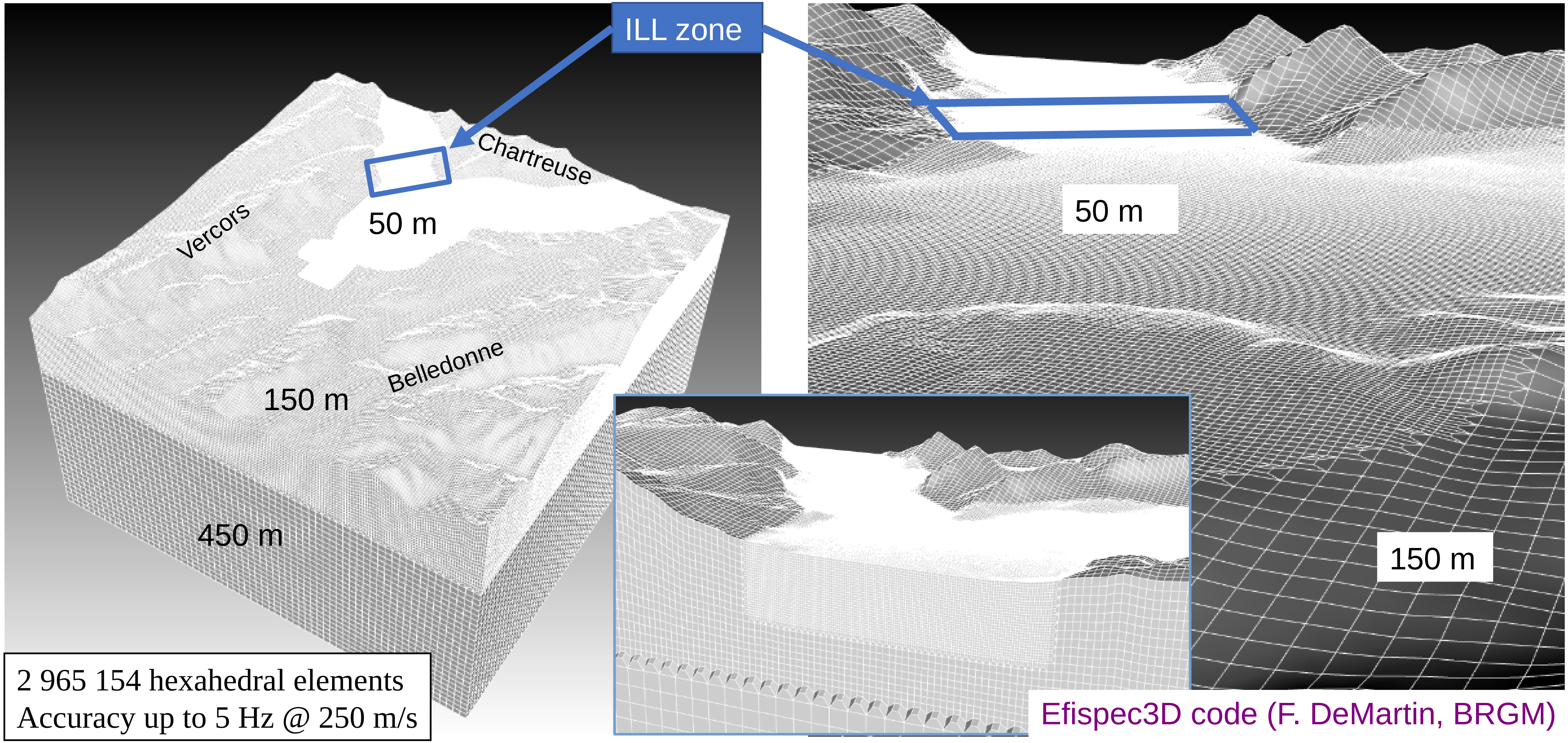
Orthorhombic effective media (Kristek et al. GJI, 2017)
(9 parameters)

(21 parameters)

- Seismic waves make an average of the small-scales
- The effective (aka homogenized/up-scaled) medium is smooth and fully **anisotropic** (e.g. Capdeville et al. 2020)
- Some simplified effective media have been proposed in the last decades

- Effective media can be computed in a pre-processing phase
- Smooth effective media are easy to mesh (no need to follow the interfaces)

Grenoble Valley SEM mesh

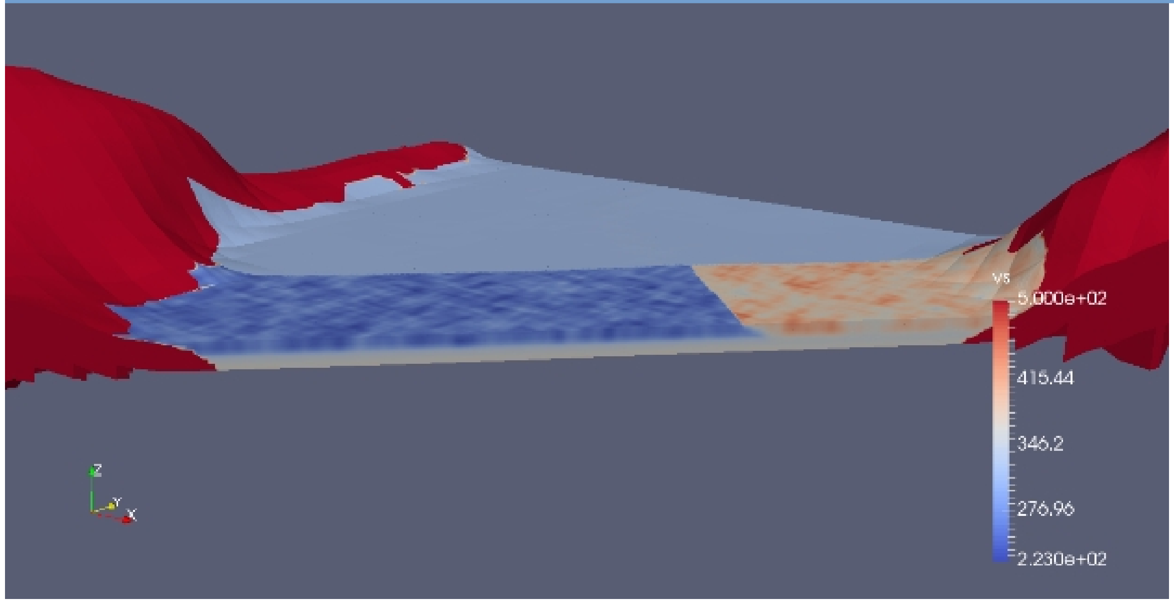


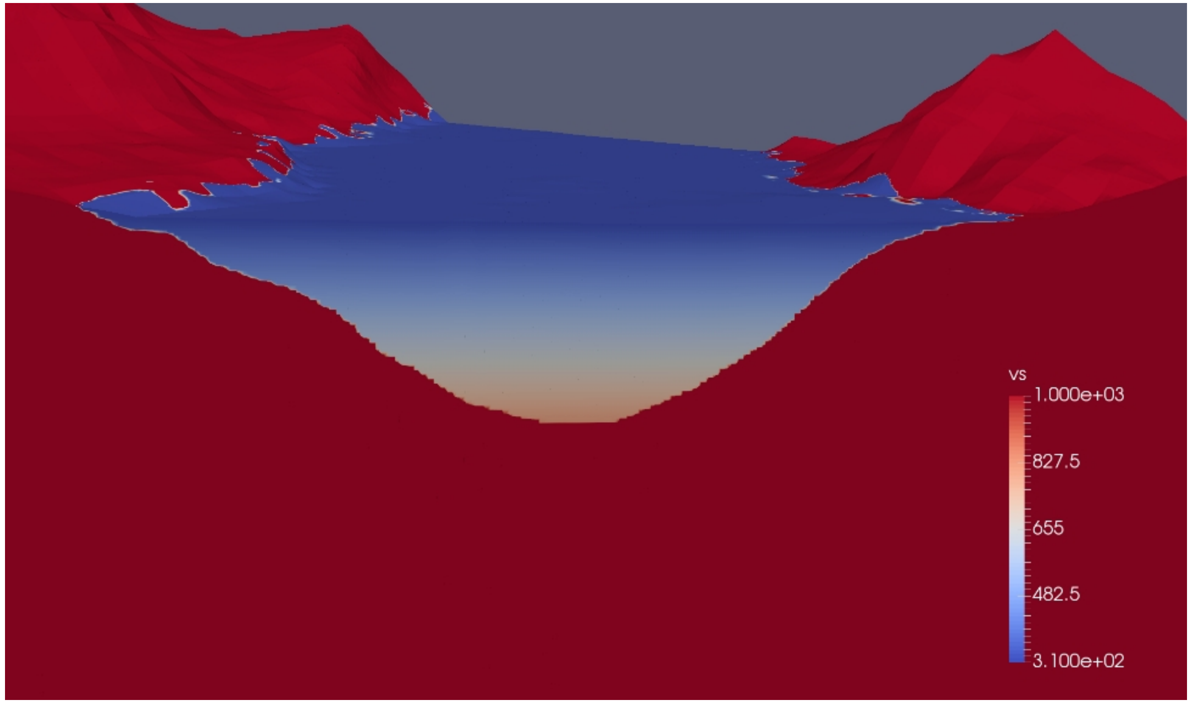
2 965 154 hexahedral elements
Accuracy up to 5 Hz @ 250 m/s

Efispec3D code (F. DeMartin, BRGM)

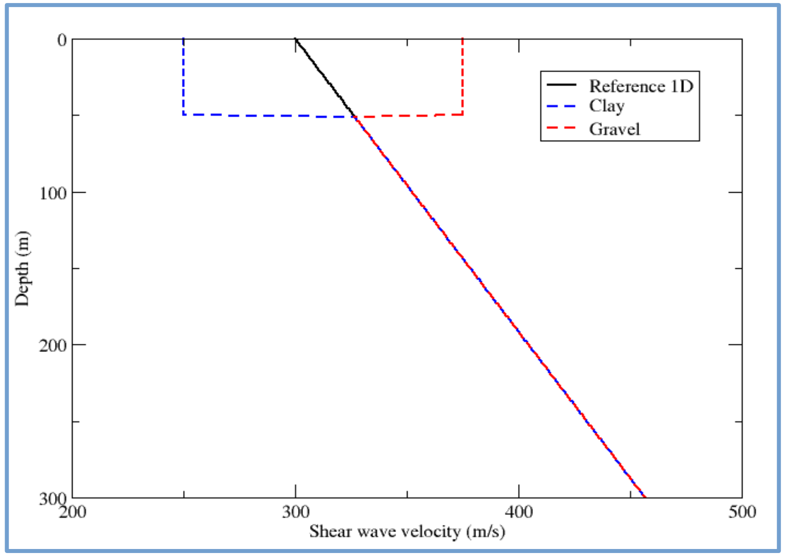
- Cubit/Trelis tripling refinement scheme
- No need to follow valley edges (1D isotropic effective media)

Grenoble Valley SEM mesh + macrozones



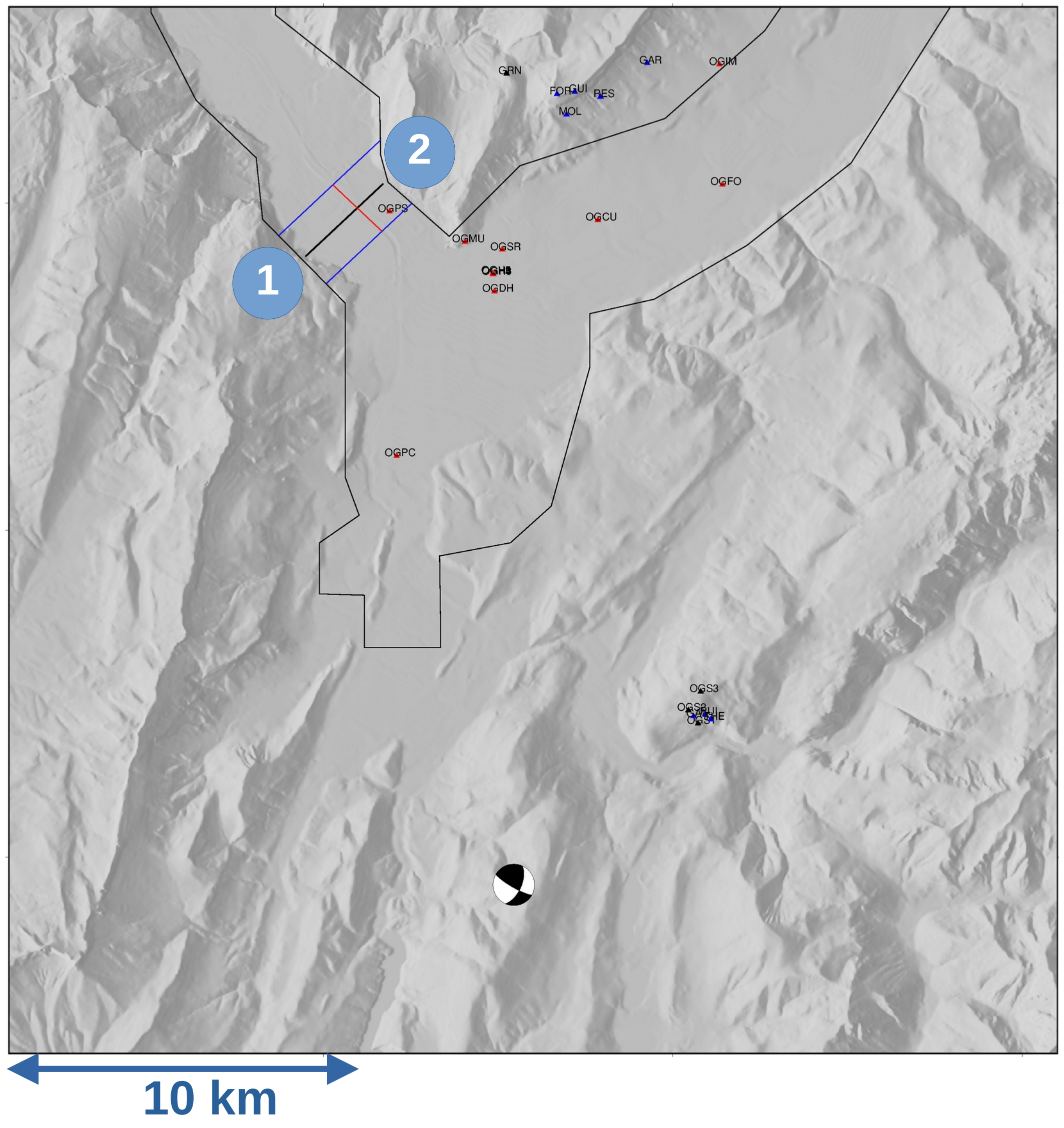


- 1D linear velocity model in the basin
- 50 m thick shallowmost part is changed to account for macrozones
  - V_S = 250 m/s for clays
  - V_S = 375 m/s for gravels

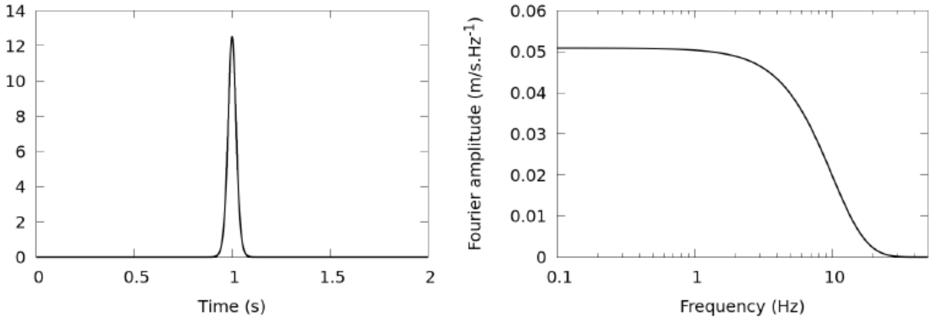


Layer	Hmax	ρ	Vs	Vp	Qs	Qp
	m	kg/m³	m/s	m/s	–	–
Gravel	50	2140	375	1450	50	50
Clay	50	1700	250	1200	50	50
Lacustrine Sediments	855	2140-2246	300-855	1450-2476	50	800
Bedrock1	6175	2720	3200	5600	5000	5000
Bedrock2	–	2720	3430	5920	5000	5000

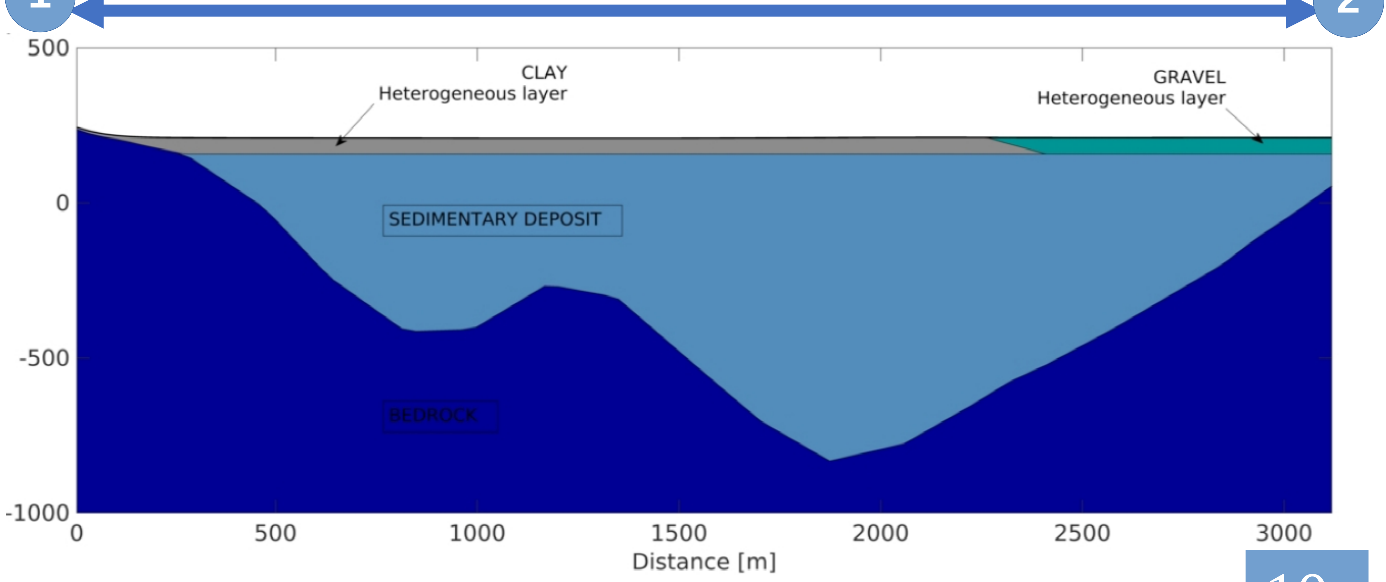
Grenoble Valley: effects of macrozones



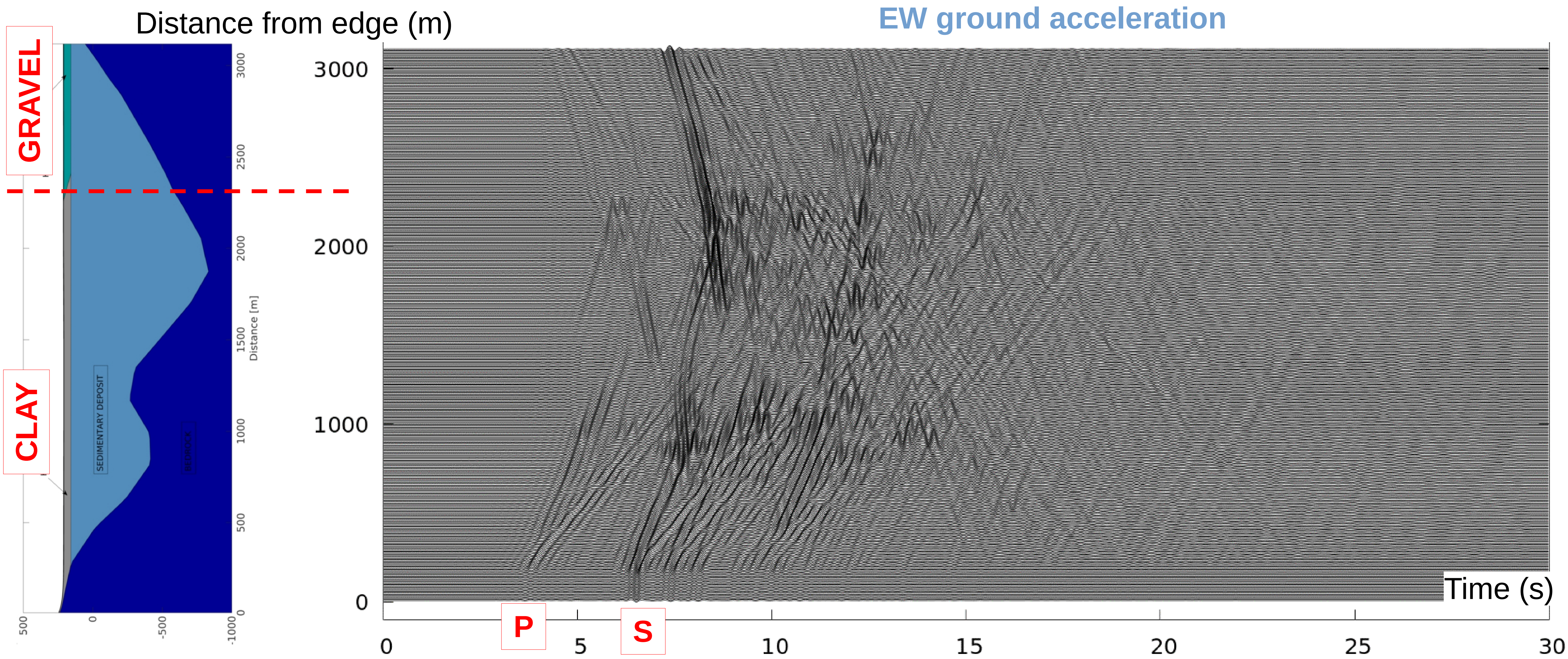
- Response to a local M3.5 event
- Point-source, strike-slip
- Flat far-field displacement spectrum



2D analysis

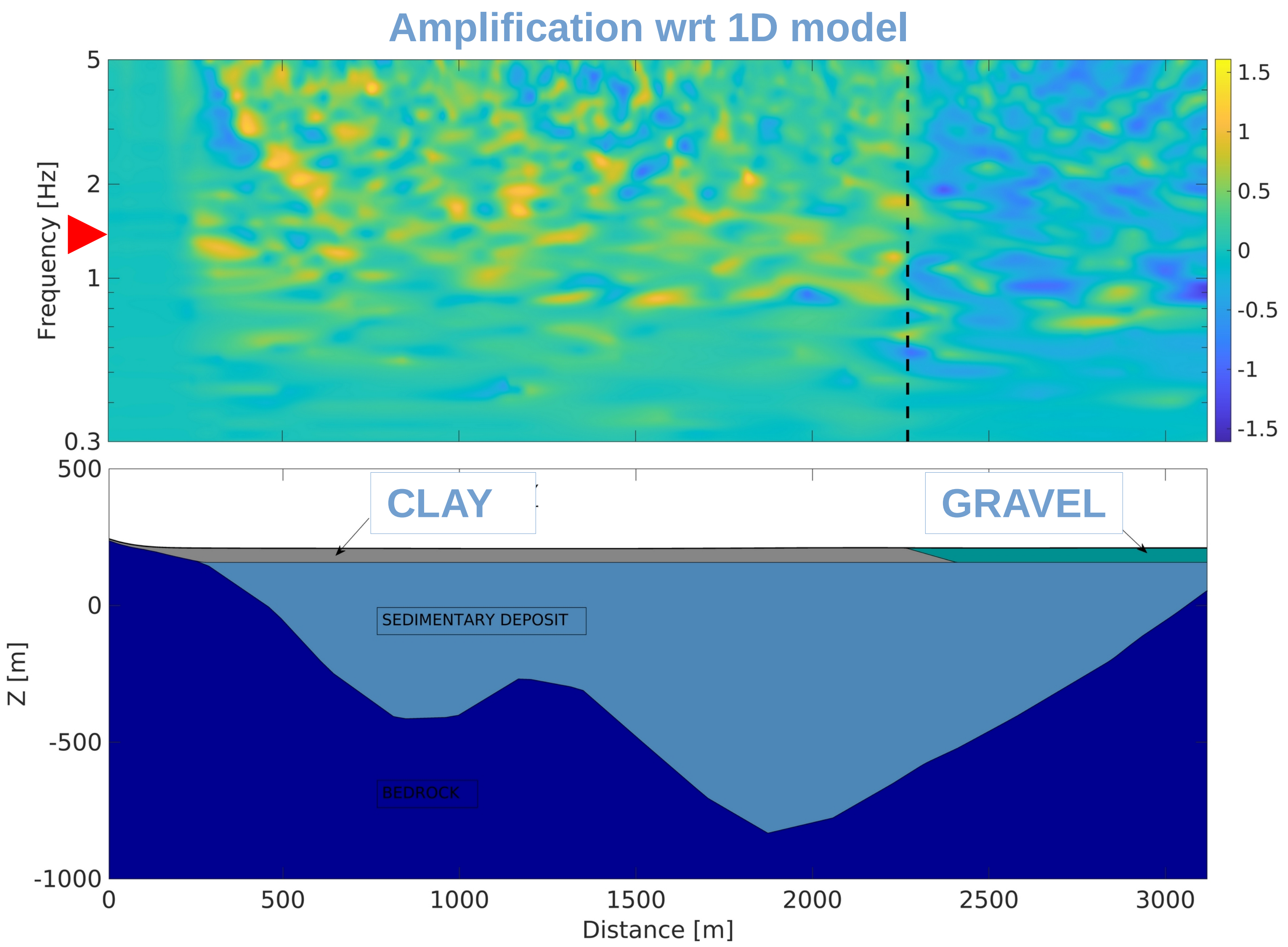


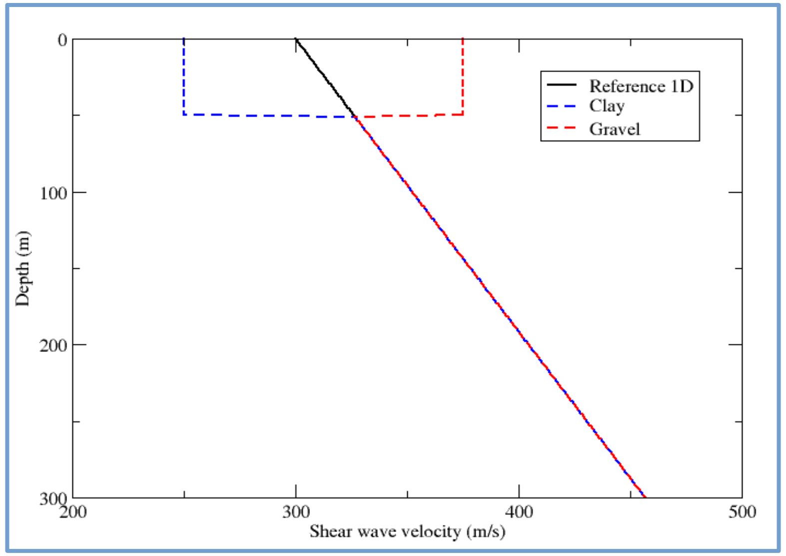
Grenoble Valley: effects of macrozones



- **Focusing/defocusing** due to bedrock geometry
- **Back-scattering** of local surface waves off the gravel zone
- Amplification and lengthening of duration in the clay zone?

Grenoble Valley: amplitude effects of macrozones



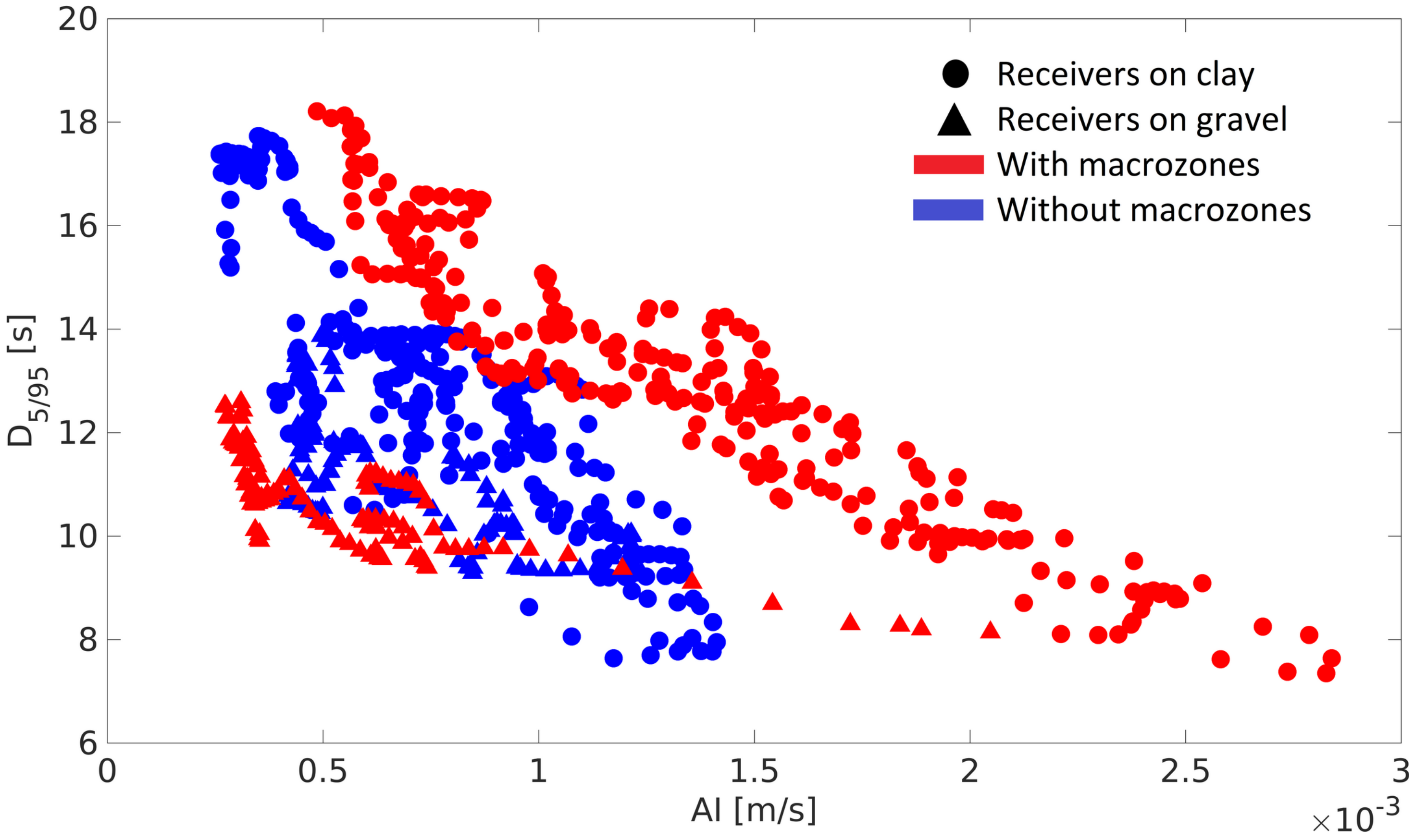


- SSR taking 1D model as reference
- Higher level of amplification for clays
- No 1D resonance effect

▶ f_0=1.25Hz (clay)

- Possible shielding effect for gravels

Grenoble Valley: duration effects of macrozones

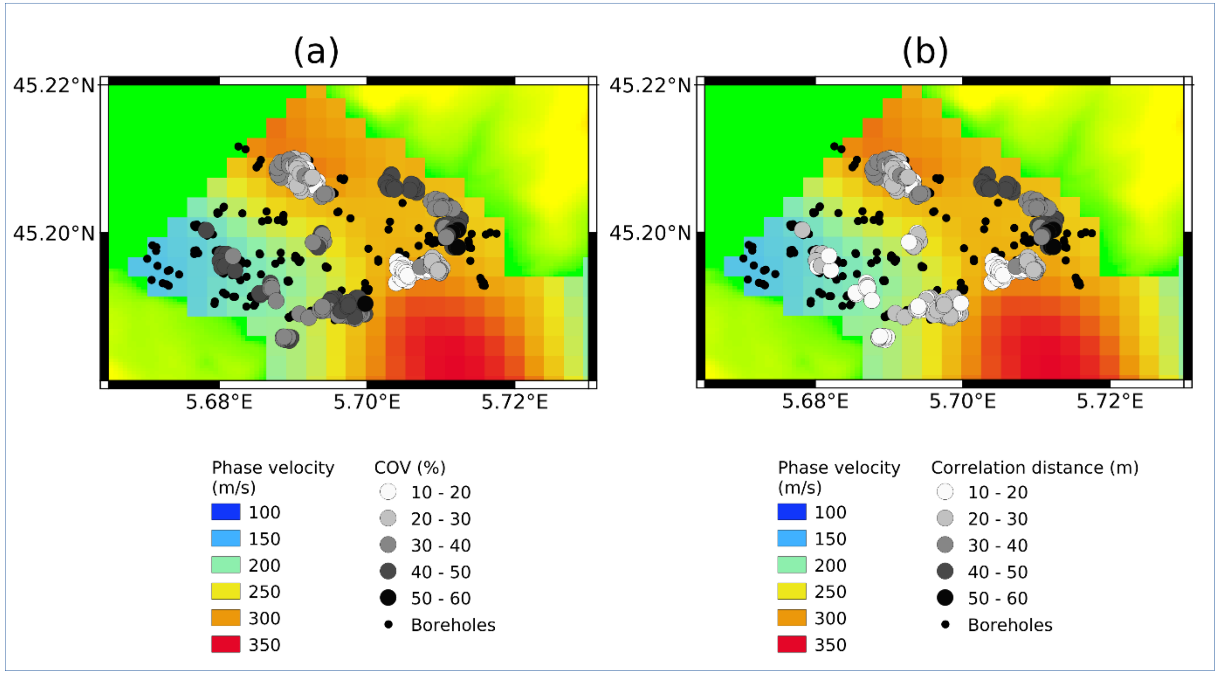


- Amplitude : Arias Intensity (~ 3 – 5 Hz)
- Duration : Arias Duration (5 – 95 %)

- Amplitude & Duration are **anti-correlated**

- Effect of macrozones
  - Significant **increase of amplitude** (clays)
  - Slight increase of duration
  - **Clustering effect** in the AD-AI space

Stochastic fluctuations: implementation and verification



Target values for Vs fluctuations

COV ~ 40 % +/- 4 %
Correlation lengths
~ 20 m +/- 5% horizontally
1:10 V/H ratio

A few open questions

- Which parametrization/representation?
  Not addressed yet
- Which implementation?
  Spectral Vs spatial approaches
- How to check accuracy?
  2D verification example

Implementation of random media: spectral approach

Classical approach for crustal studies

Fluctuations in velocity (or density)

$$V(\mathbf{x}) = V_0 + \delta V(\mathbf{x}) = V_0 [1 + \xi(\mathbf{x})]$$

Zero-mean, **stationary** random process, with ACF

$$R(\mathbf{x}) \equiv \langle \xi(\mathbf{y}) \xi(\mathbf{y}+\mathbf{x}) \rangle$$

Generated in Fourier domain from the PSD (FT of ACF) and back to space with FFT^{-1}

$$\xi(\mathbf{x}) = \frac{1}{(2\pi)^3} \iiint_{-\infty}^{\infty} \sqrt{P(\mathbf{m})} e^{i\phi(\mathbf{m})} e^{i\mathbf{m}\mathbf{x}} d\mathbf{m}$$

$\boldsymbol{m}$: angular spatial frequency (wavenumber)

$\sqrt{P(\mathbf{m})}$: Fourier amplitude $\phi(\mathbf{m})$: random phase

Amplitude (COV)

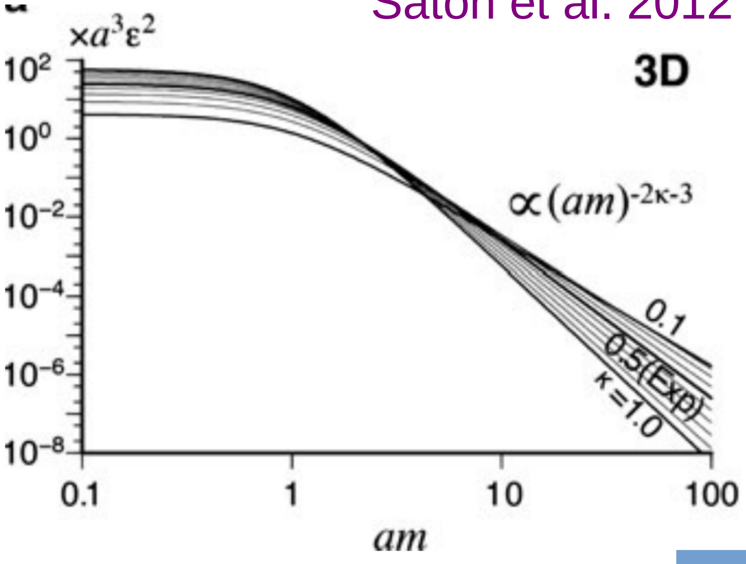
$$\varepsilon^2 \equiv R(0)$$

Correlation length **a**

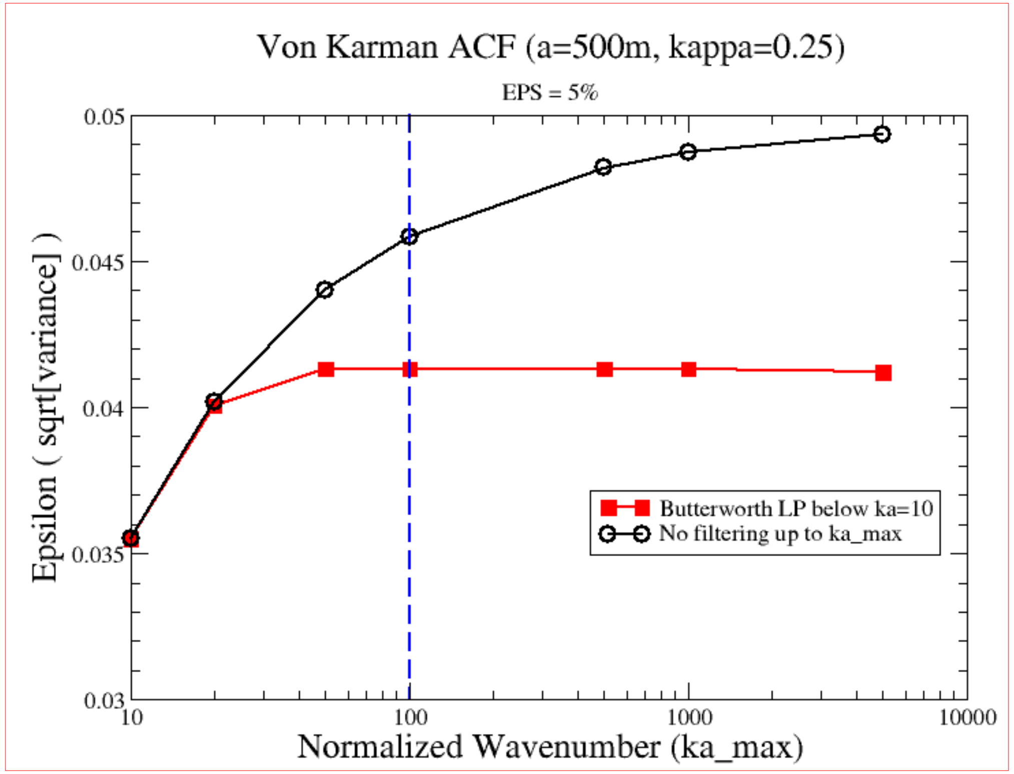
$$R(a) = \varepsilon^2 / e$$

3D Von Karman PSD

Satoh et al. 2012



Implementation of random media: spectral approach



Recipe

- Synthetize PSD up to max normalized wavenumber ***ma***_max
- Low-pass filter below ***ma***_c < ***ma***_max
- Compute fluctuations with FFT^{-1}
- Interpolate on computational grid

Some drawbacks

- Total standard deviation (**COV**) of fluctuations **is always reduced** wrt target values (~ 70–80 % of target)
- **COV cannot be too high** (< 20 %) because of the parametrization used (negative values!)

Implementation of random media: spatial, Karhunen-Loève approach

Fluctuations are generated from a basis of eigenfunctions built upon the covariance function C

$$\hat{\varpi}(x,\theta) = \bar{\varpi}(x) + \sum_{i=1}^{M} \sqrt{\lambda_i}\,\xi_i(\theta)\,f_i(x)$$

M : number of modes

$\xi_i(\theta)$: zero mean **Gaussian** variables

Fredholm Integral eigenproblem

$$\int_D C(x_1,x_2)\,f_i(x_1)\,\mathrm{d}x_1 = \lambda_i f_i(x_2)$$

Connexion to the spectral approach

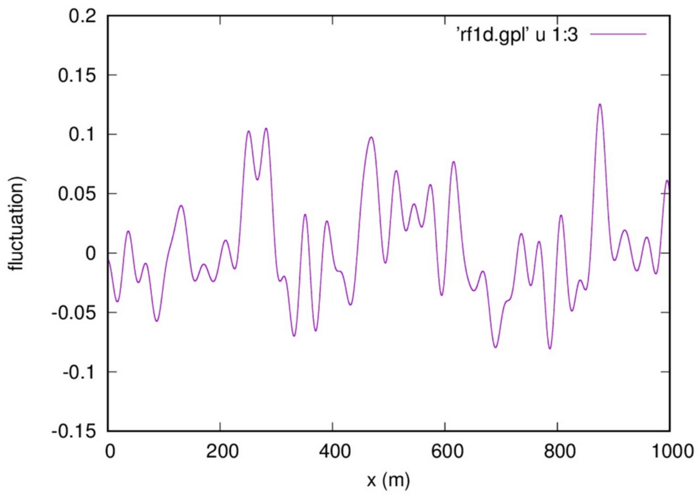
The eigenvalues of C are the values of the PSD Function:

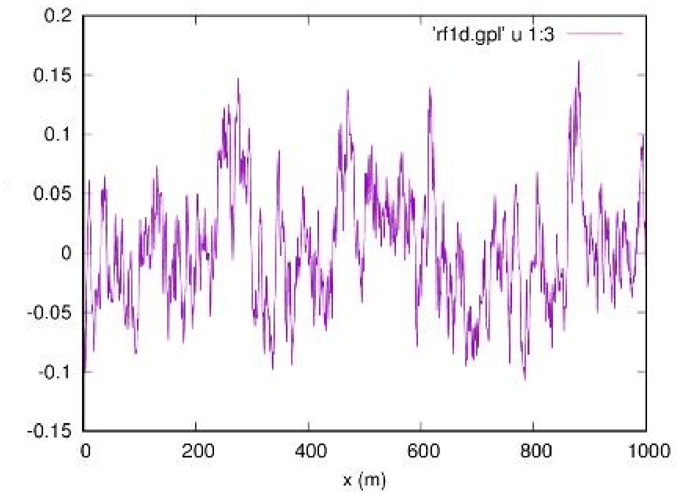
$$\lambda = \int_{-\infty}^{\infty} C(x_2 - x_1)\,\mathrm{e}^{-\mathrm{i}\omega(x_2-x_1)}\,\mathrm{d}x_1 = S(\omega)$$

Huang et al., IJNME, 2001

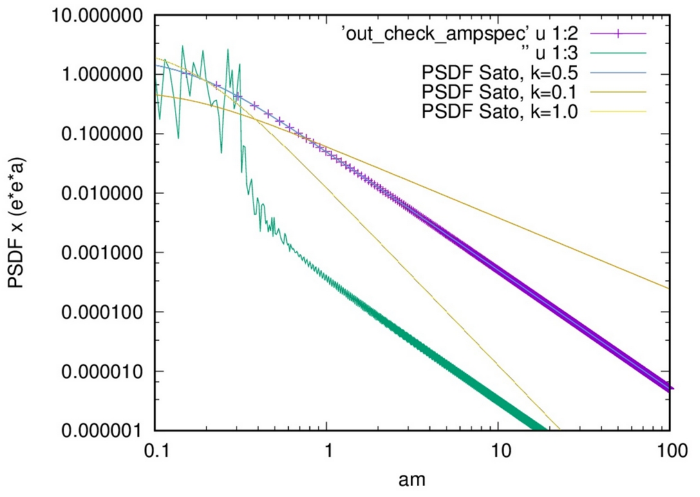
Implementation of random media: spatial KL approach

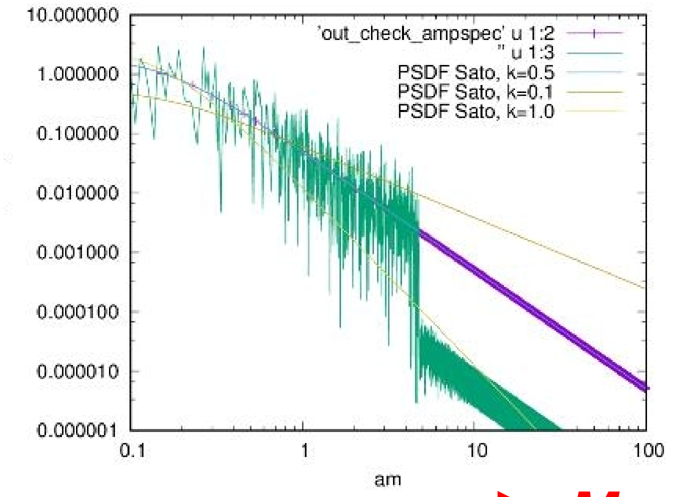
Space





Fourier





M

1D example: Exponential ACF with correlation length ***a***

Increasing number of eigenmodes *M*, up to ***am*** = 2 (***m*** wavenumber)

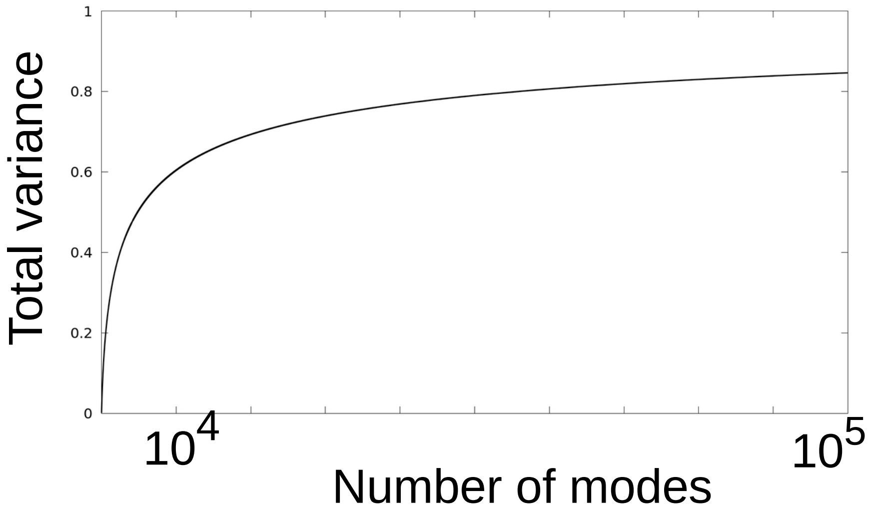
Some Pros /// Cons

- Direct generation of fluctuations at any point (**no interpolation**)

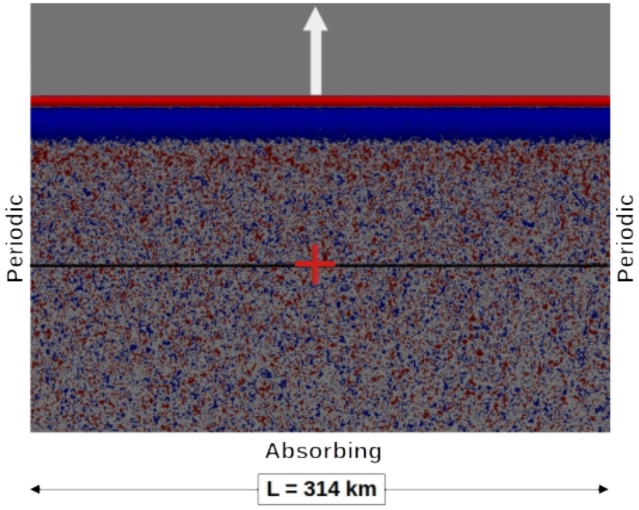
///

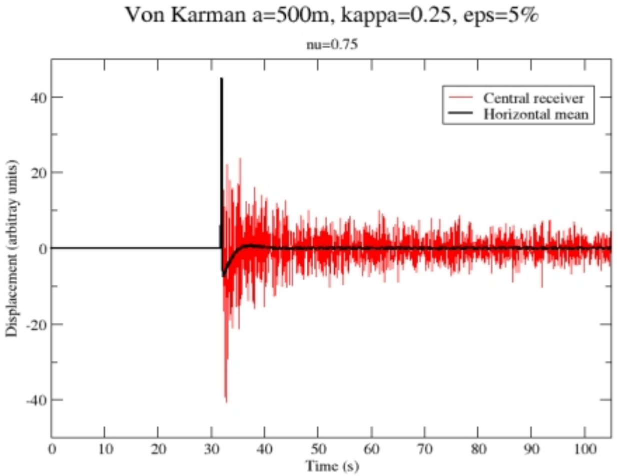
- PSD is reached only in average
- Total variance is never reached
- # of modes to compute is large

3D example 8 km^3 Lc=50m

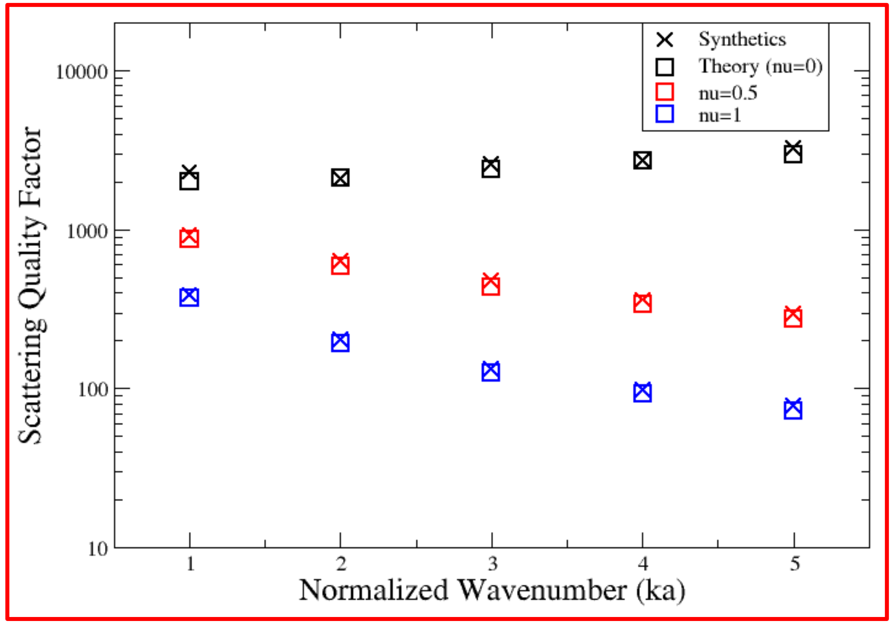


Verification in 2D random media





Specfem2D (geodynamics.org)



- 2D SH medium, homogeneous background
- Vertically incident plane wave
- Correlated density and velocity fluctuations

$$\frac{\delta\beta}{\beta} = \nu\frac{\delta\rho}{\rho} \qquad \nu = 0, 0.25, 0.5, 0.75 \text{ and } 1$$

- Spectral approach
- Von Karman ACF, H=0.25, a=500 m
- COV = 5 – 10%
- Horizontal spatial average computed on-the-fly
- Ensemble averages (up to 60 realization)

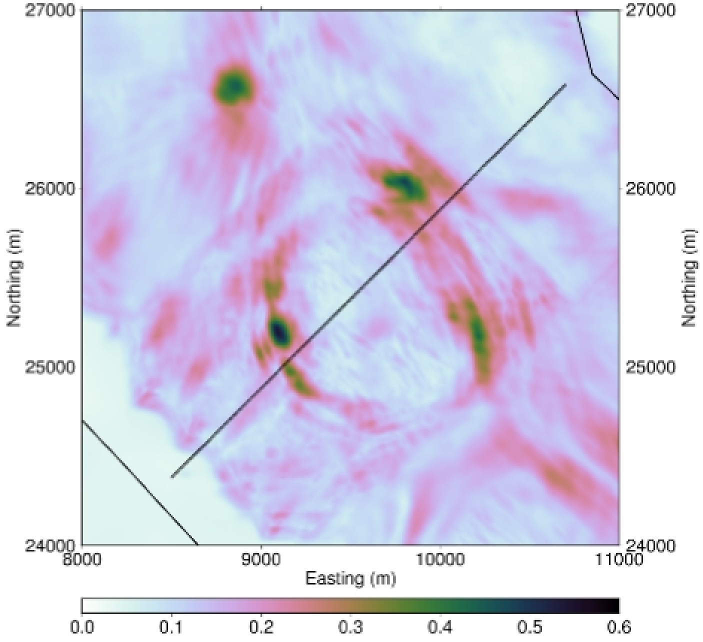
=> Measure of amplitude decay of the **coherent wave** yields Scattering Quality factor

Stochastic fluctuations in 3D Grenoble Valley model

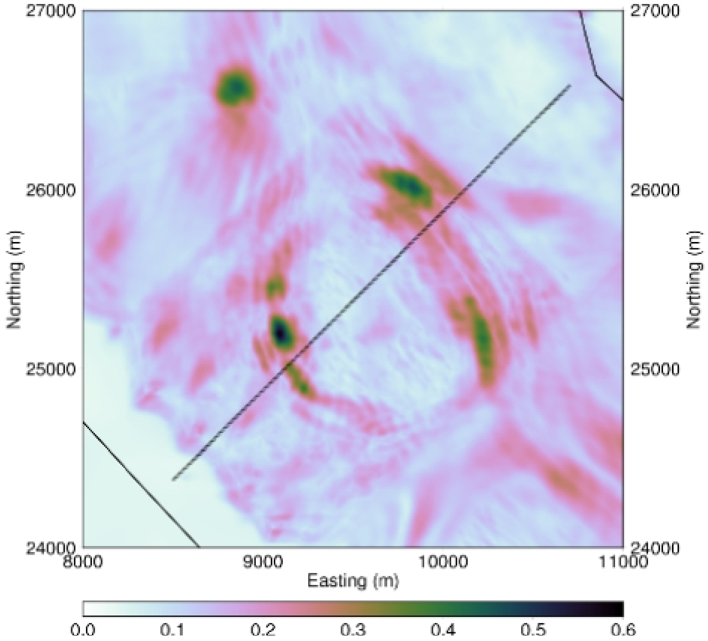
Layer	Hmax	ρ	Vs	Vp	Qs	Qp	Lc	ε	PDF
	m	kg/m³	m/s	m/s	–	–	m	–	–
Gravel	50	2140	375	1450	50	50	50-200	0.05	exp
Clay	50	1700	250	1200	50	50	50-200	0.05	exp
Lacustrine Sediments	855	2140-2246	300-855	1450-2476	50	800	–	–	–
Bedrock1	6175	2720	3200	5600	5000	5000	–	–	–
Bedrock2	–	2720	3430	5920	5000	5000	–	–	–

- Spatial K-L approach
- Only V_S fluctuations
- COV limited to 5%
- Isotropic correlation length : 50, 100, 200 m
- Exponential ACF
- 10 realizations per random medium

Macrozones only

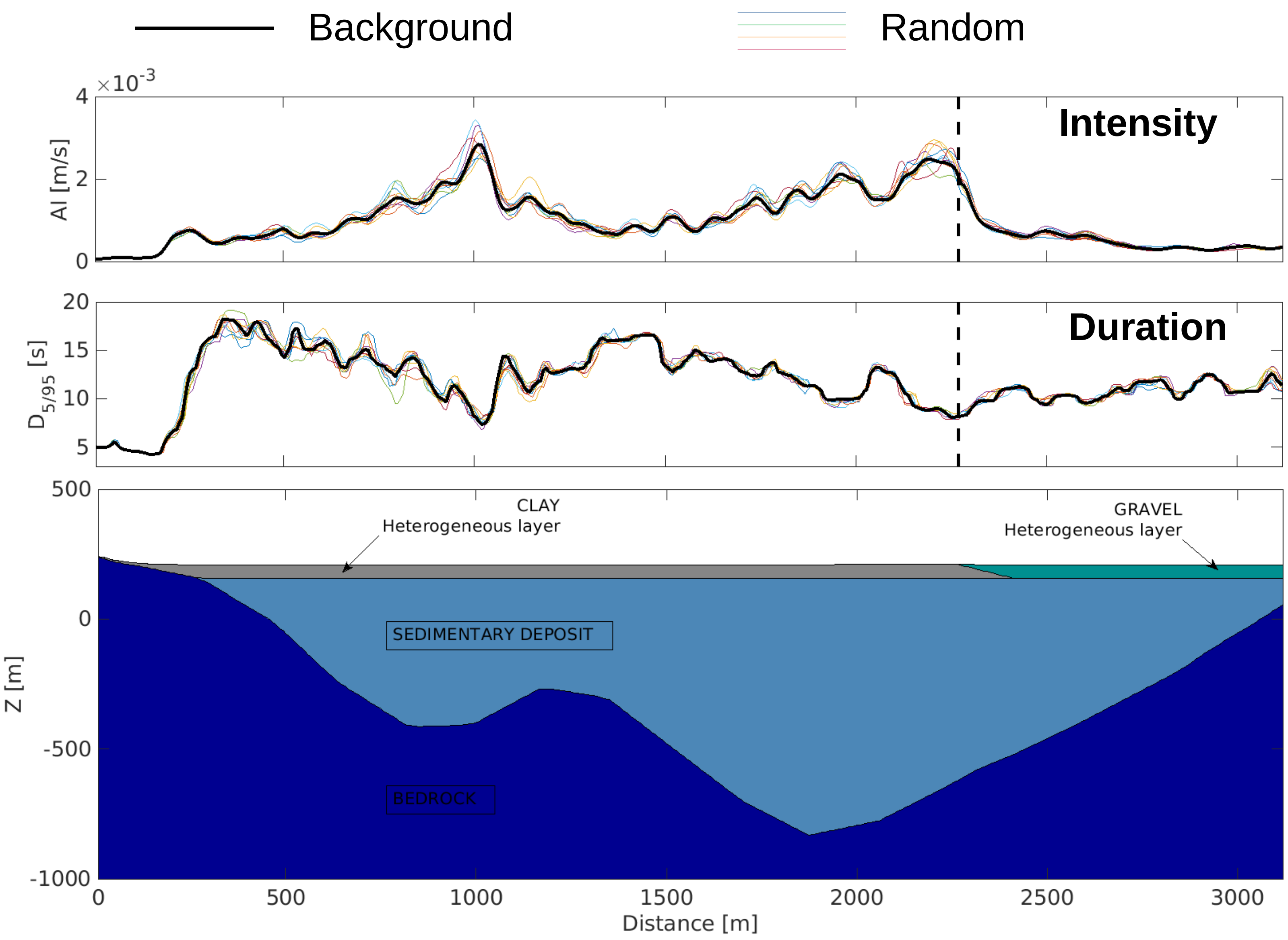


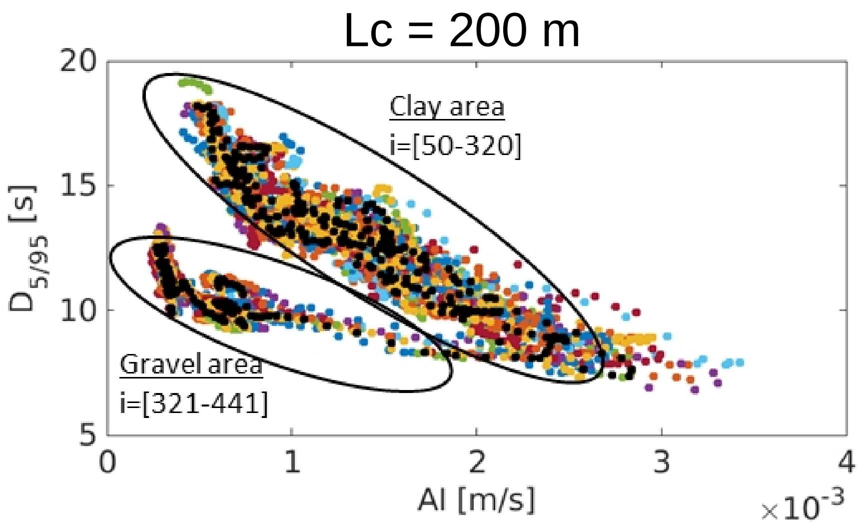
Macrozones + fluctuations



No visible effects on PGA maps
What about other GM parameters?

Stochastic fluctuations in Grenoble Valley model





- Slight variations of AI (15%) and AD (7%), mainly on clay zone, independent of Lc values
- Anti-correlation of AI & AD remains
- Small loss of coherency (not shown)

Concluding remarks

Why such mild effect of random fluctuations on ground motion parameters?

- Too small COV values
- No density perturbations
- Small lapse times, even for surface waves
- High-frequency, forward scattering regime ($2\pi a > \lambda$)

Perspectives

- Change parametrization of fluctuations (log space)
- Extend random areas to whole valley
- Include anisotropic correlation lengths
- Increase frequency range & explore different scattering regimes
- … a lot of work ahead