Inference of soil spatial variability properties from earthquake recordings and near-surface geophysical/geotechnical data

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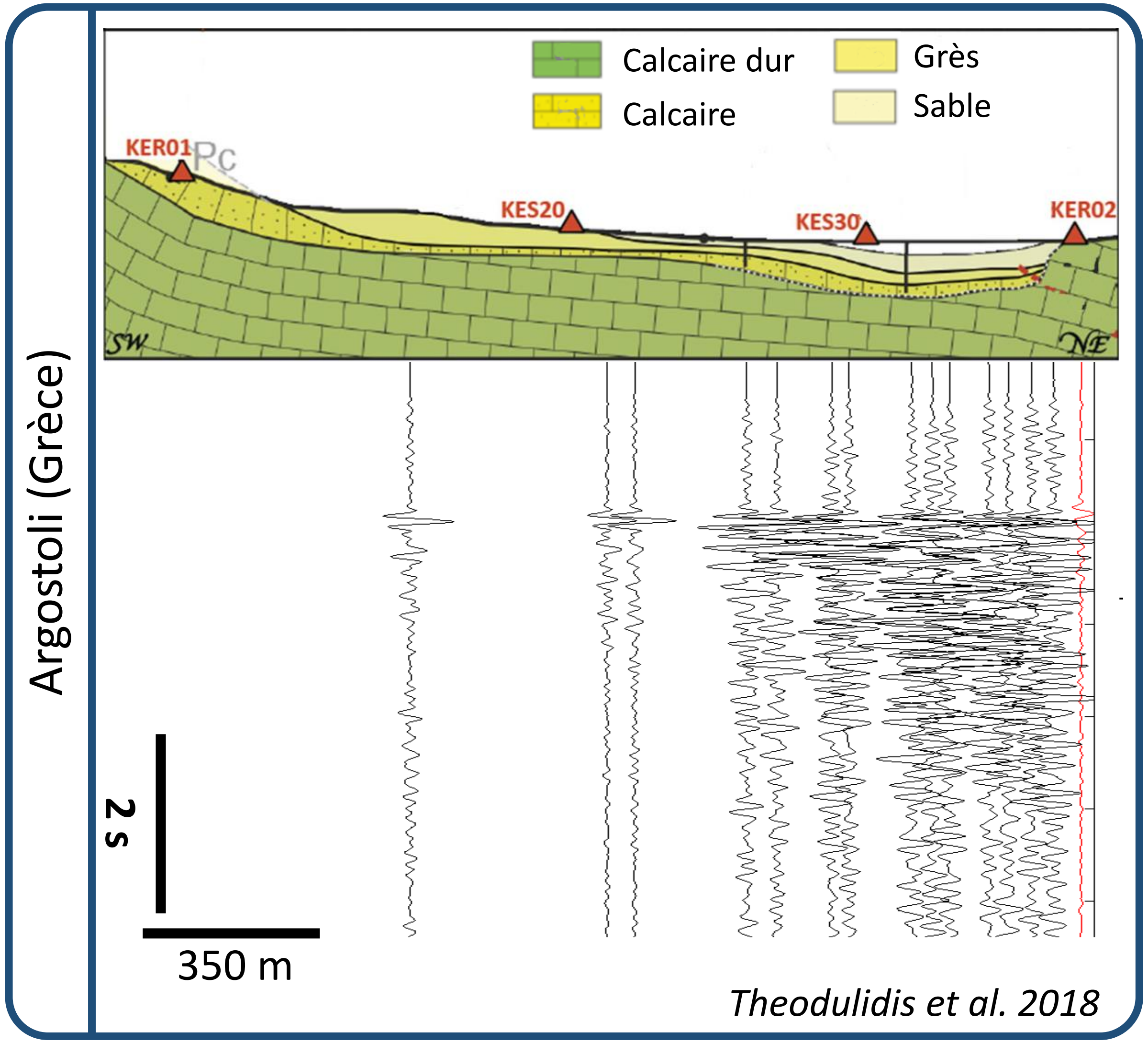
ISTerre, Université Libanaise, Ecole Centrale Paris, EDF, BRGM, EDYTEM

Spatial variation of ground motion at small spatial scale

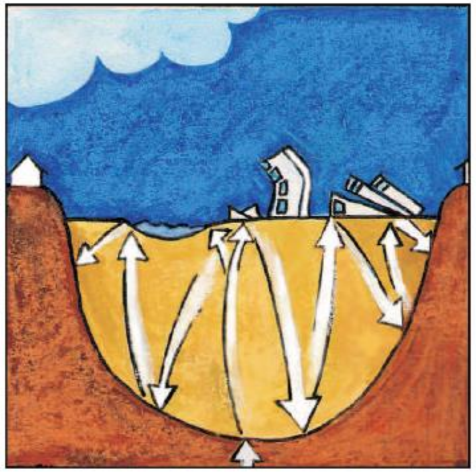
Basin or topography scale



Theodulidis et al. 2018

Basin scale

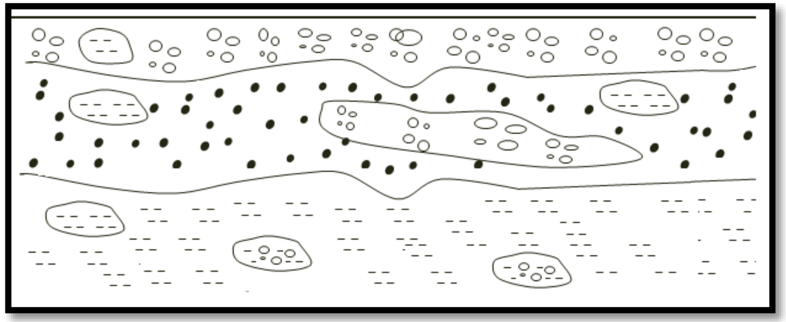
[few tens of m -> few kms]



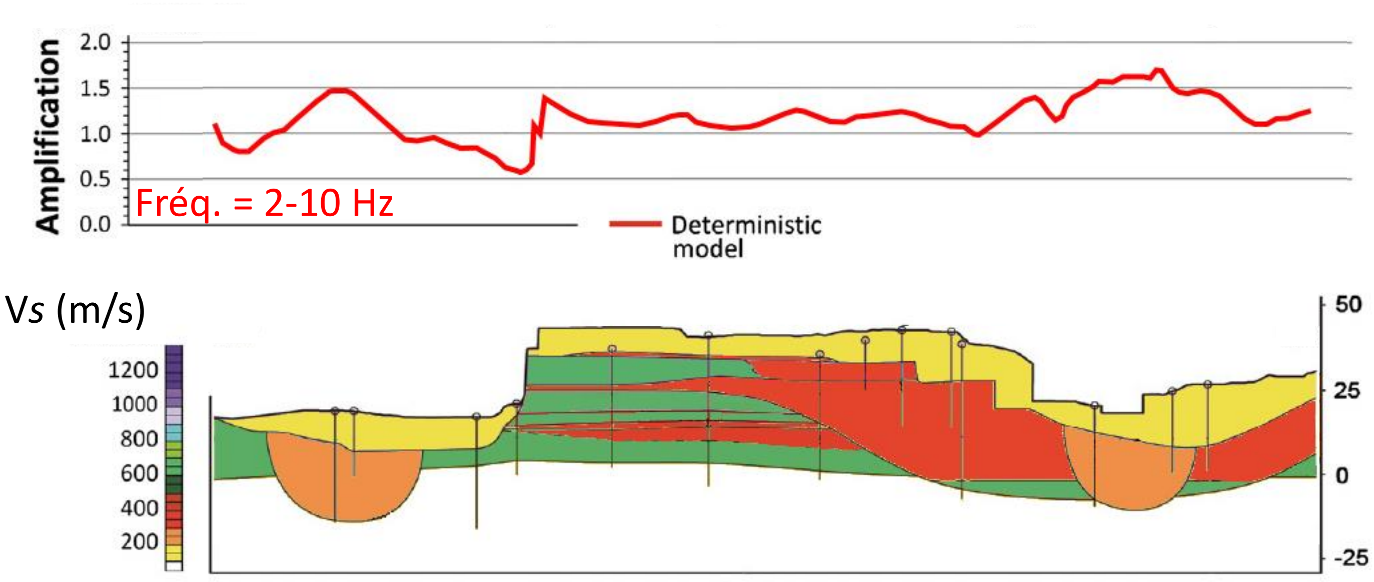
Source : Laurence Barret

Near-surface heterogeneities

[few m -> few tens of m]



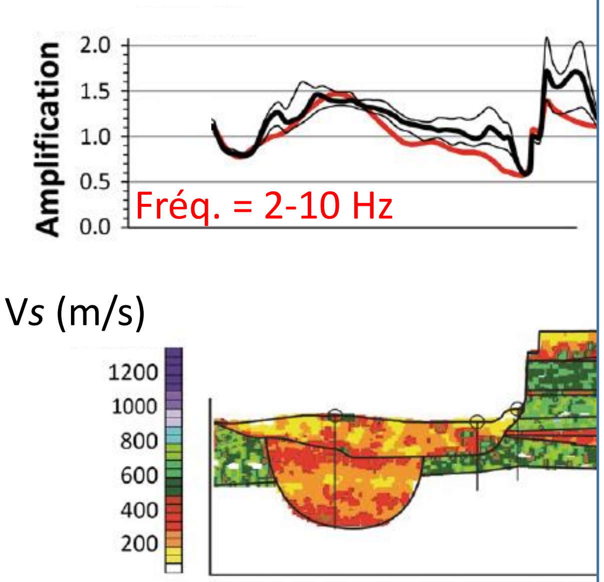
Example of small scale variability on surface ground motion



Rome, Italie

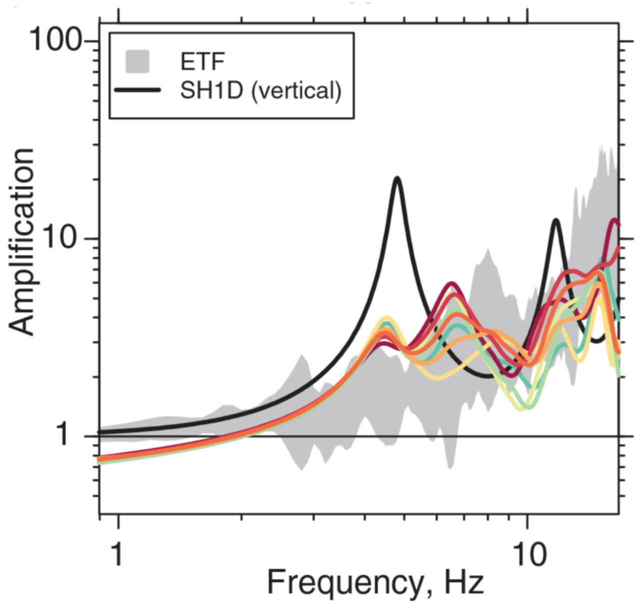
Pagliaroli et al., 2014 - Modifiée par Emeline Maufroy)

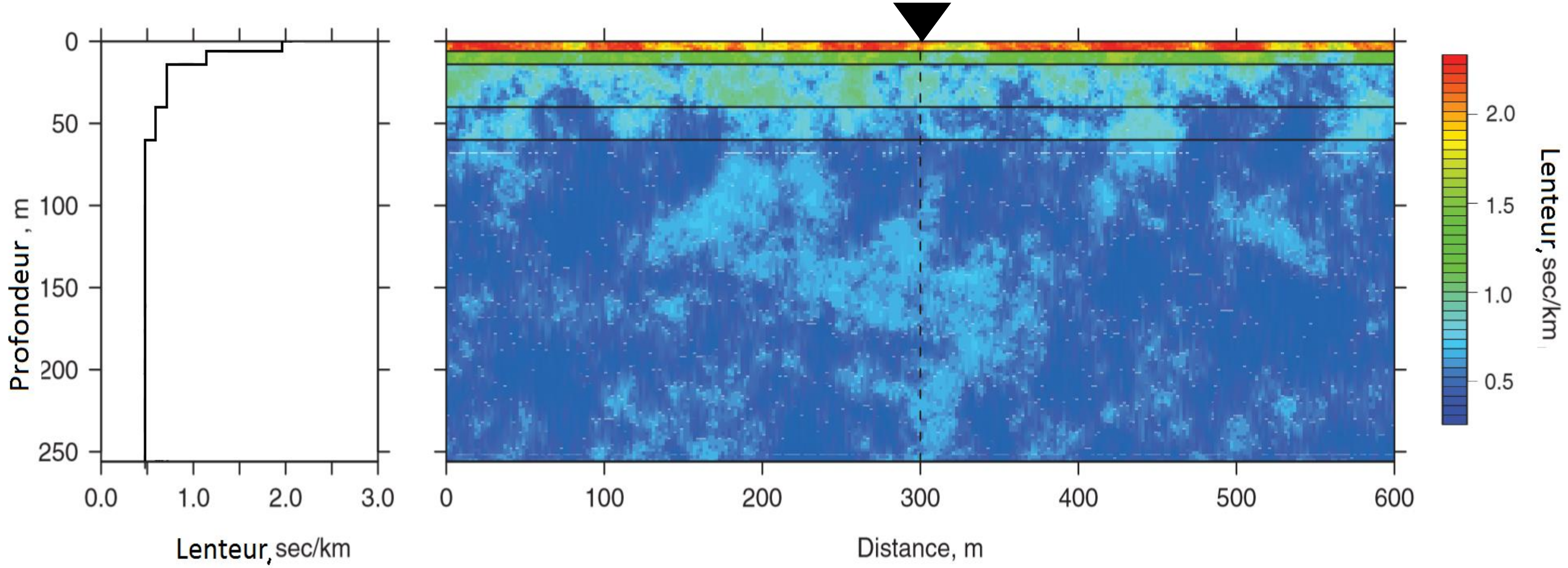
Example of small scale variability on surface ground motion



Pagliaroli et

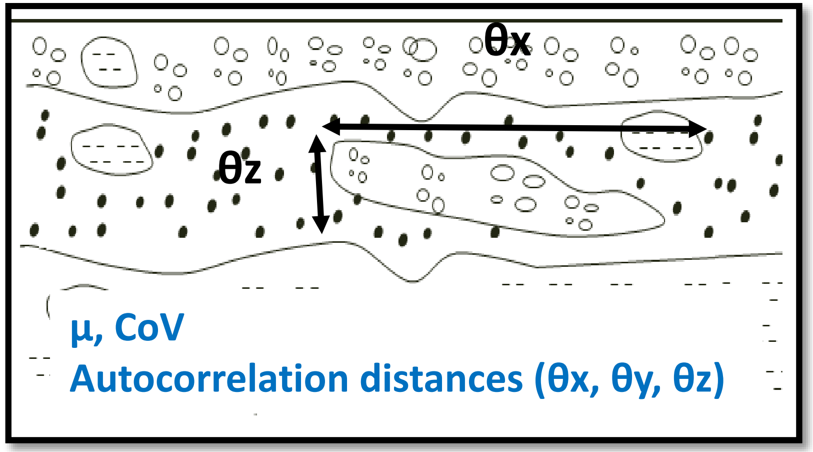
KIKNET, Thompson et al. 2009



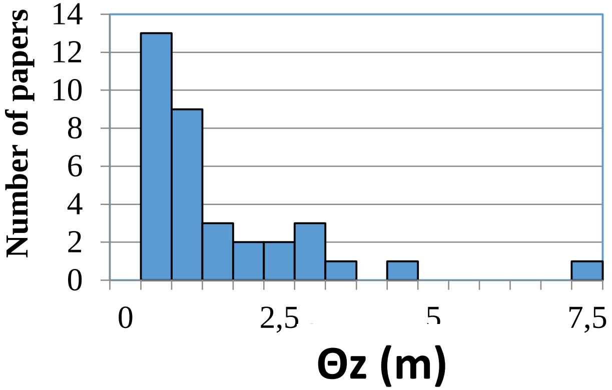


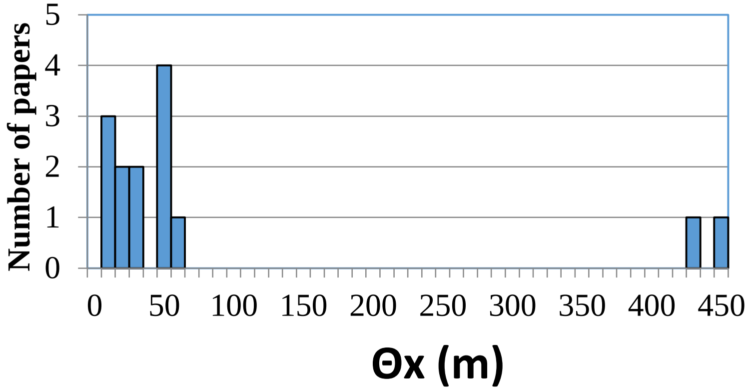
See presentations of J. Kristek, E. El Haber, I. Zentner, C. Gélis, F. Lopez-Caballero, F. Hollender, ….

What do we know about characteristic sizes of near-surface heterogeneities ?

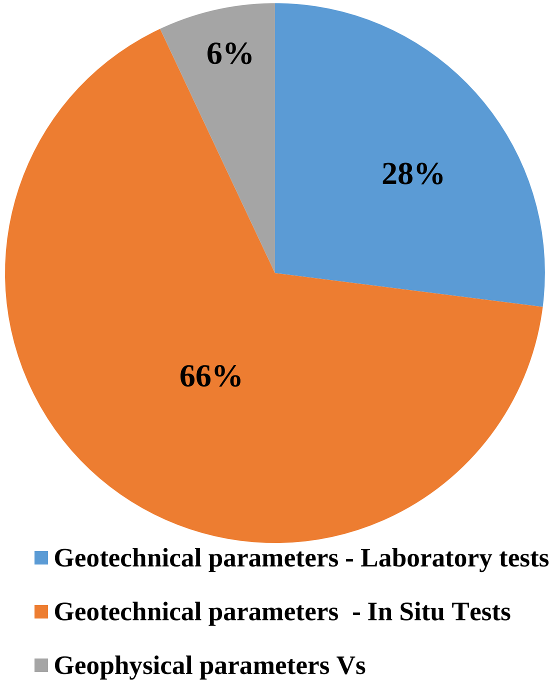


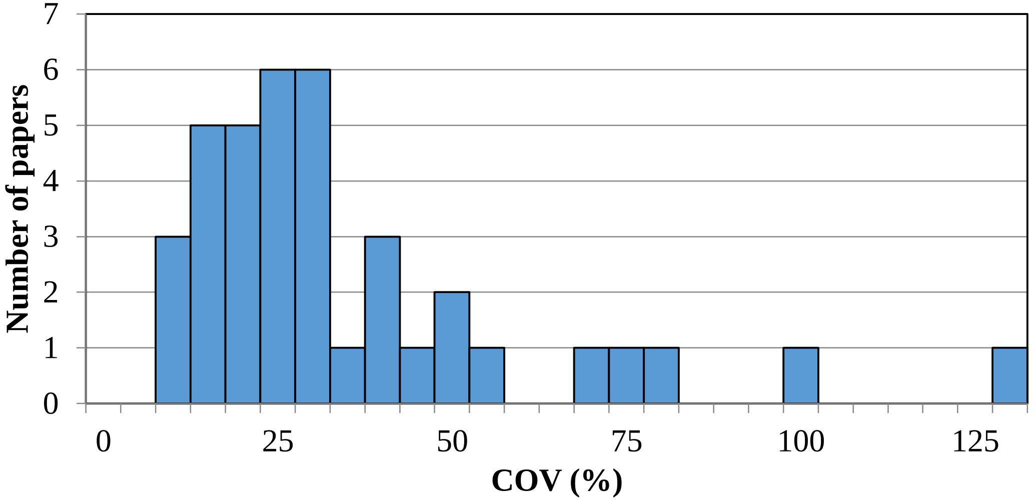
Spatial sampling theorem not respected !





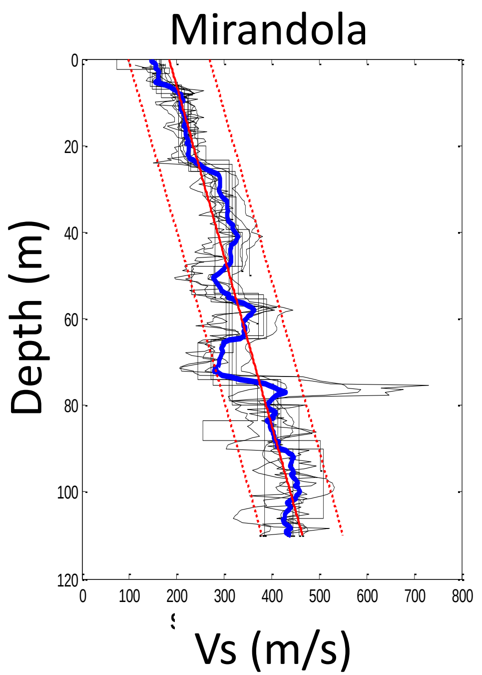
33 papers; 10-20 first top meters

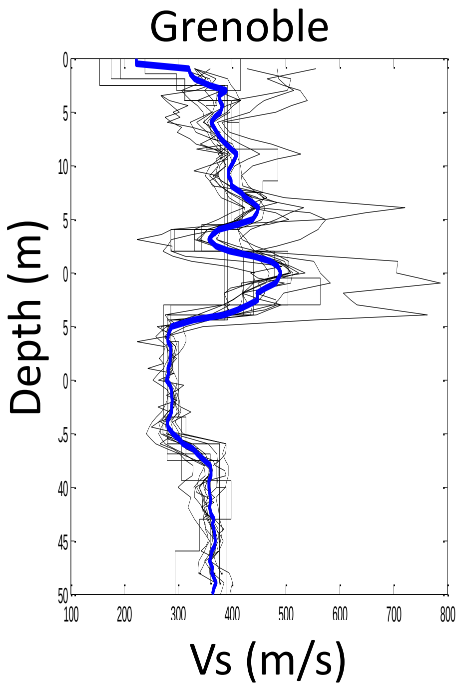


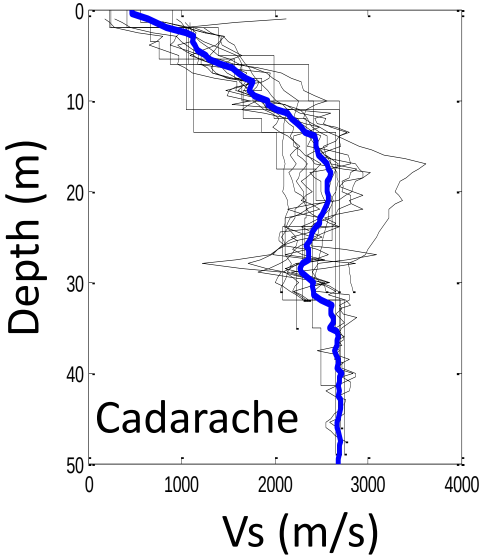


Youssef Abdel-Massih et al. 2018, submitted

What do we know about characteristic sizes of near-surface heterogeneities ?



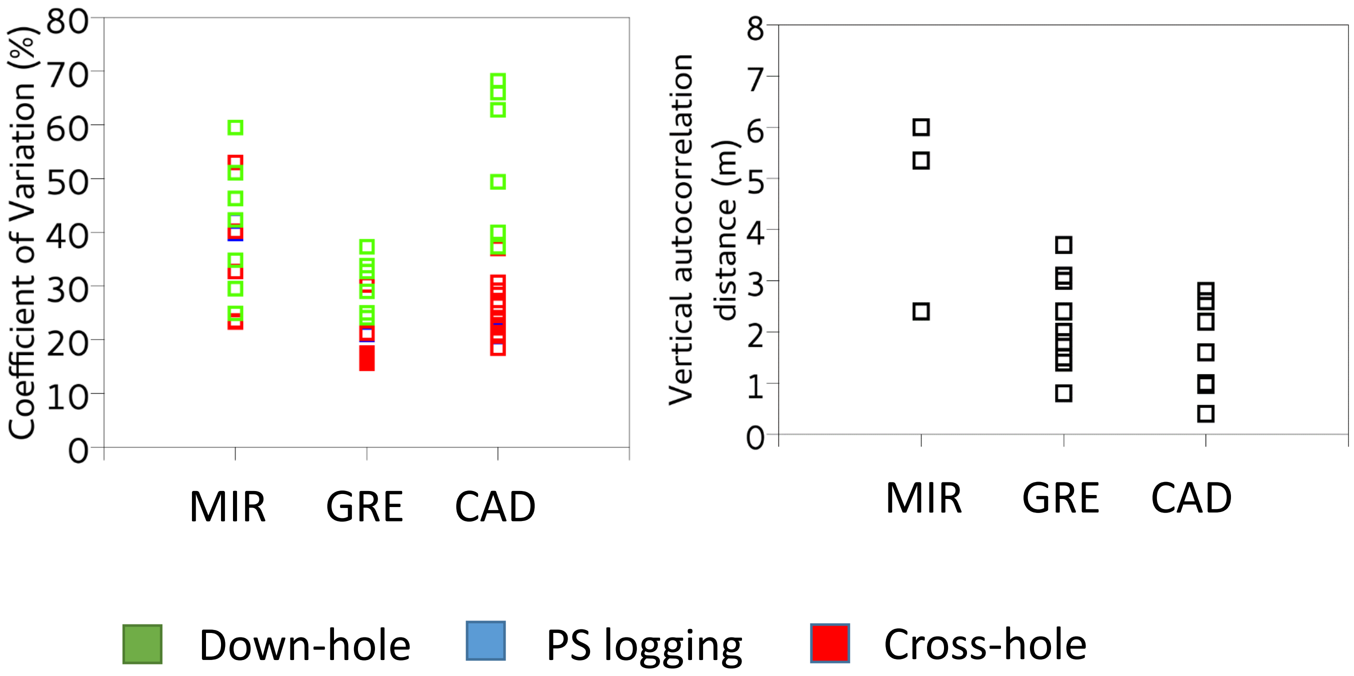




Benchmark INTERPACIFIC

Data:
PS logging, cross-hole,
Down-hole

Garofalo et al. (2016)



Θz : 1 – 6 m

COV : 15 – 70%
Depends on the acquisition and processing method (up to a factor of 2)

Youssef (2018)

How to infer characteristics of near-surface heterogeneities ?

Use of geotechnical boreholes

$\Rightarrow$ need sites with highly spatially sampled geotechnical boreholes

$\Rightarrow$ Example of Grenoble basin

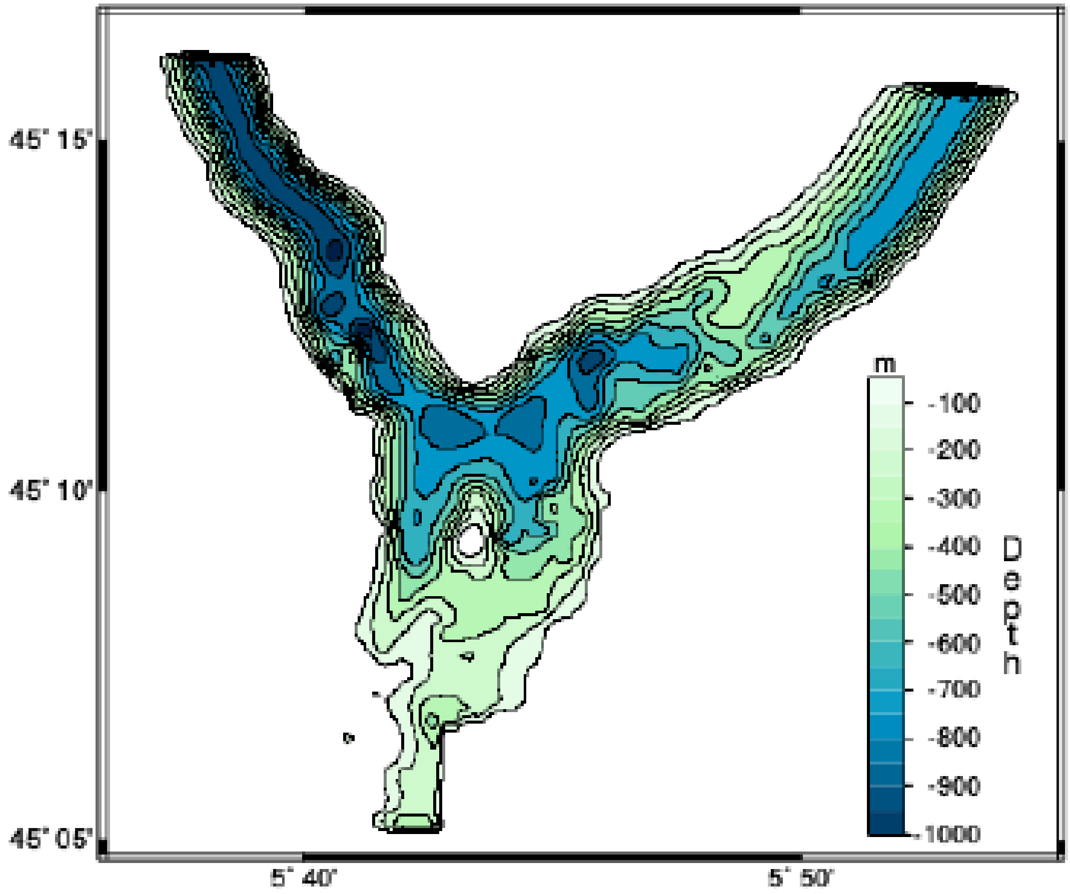
Use of earthquake recordings

$\Rightarrow$ Need of dense arrays

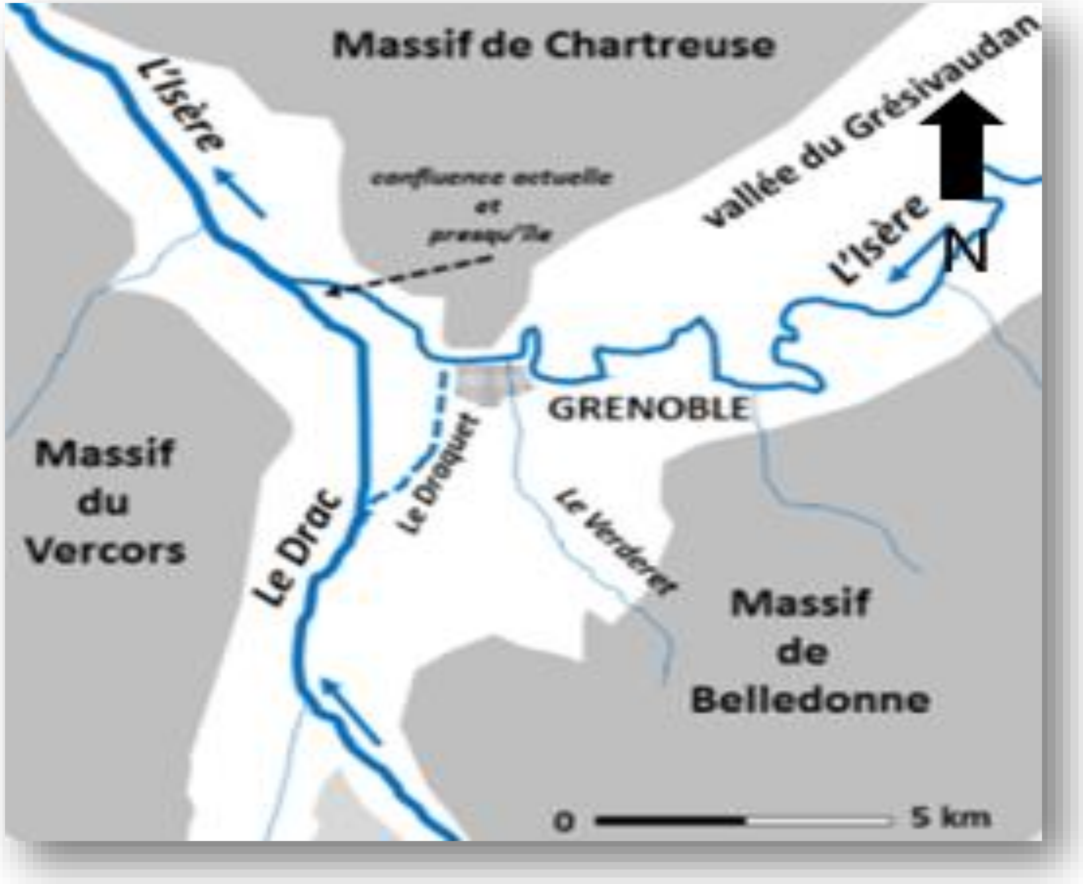
$\Rightarrow$ Example of dense arrays in Europe

$\Rightarrow$? Possible extension using seismic noise wavefield ?

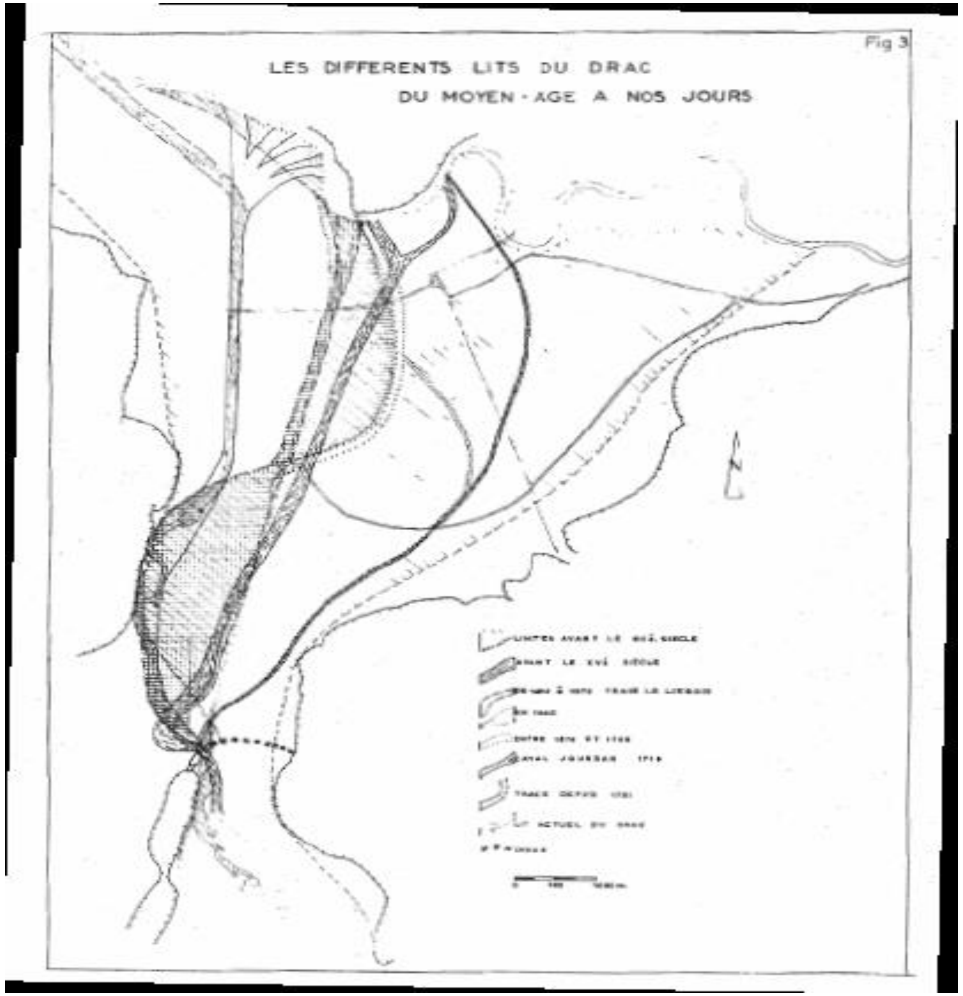
Grenoble basin

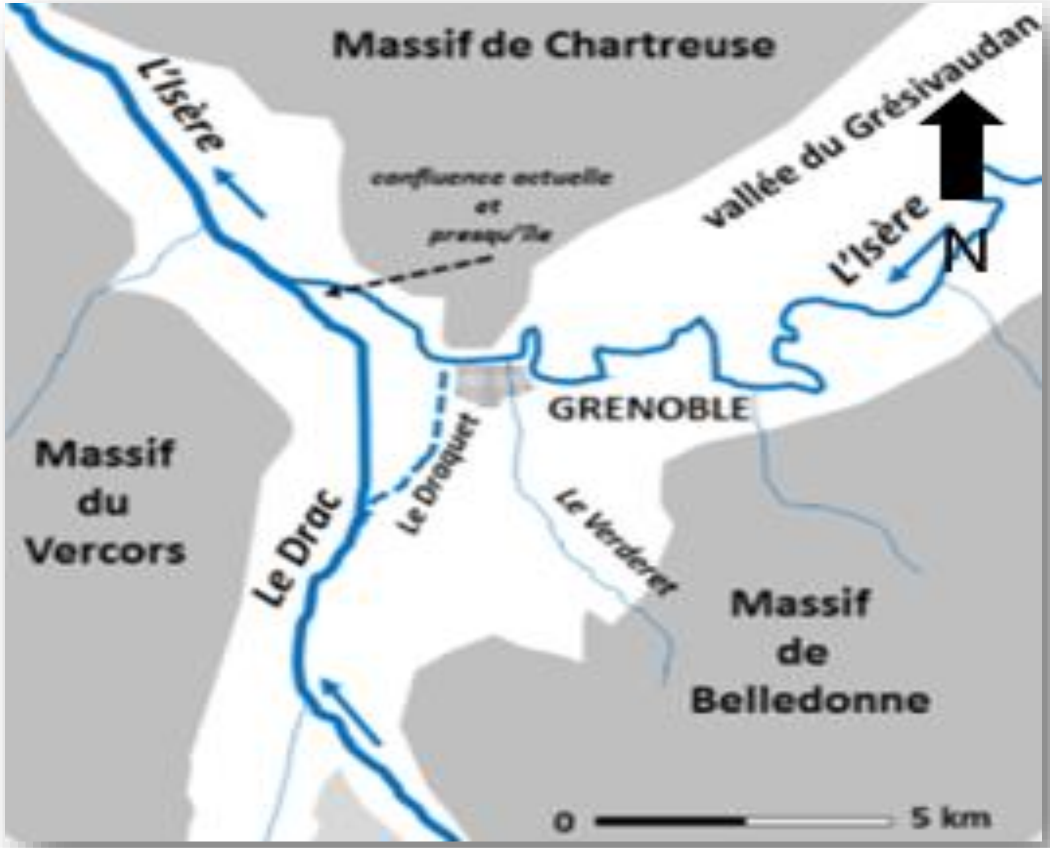


bedrock topography
Chaljub et al., 2006



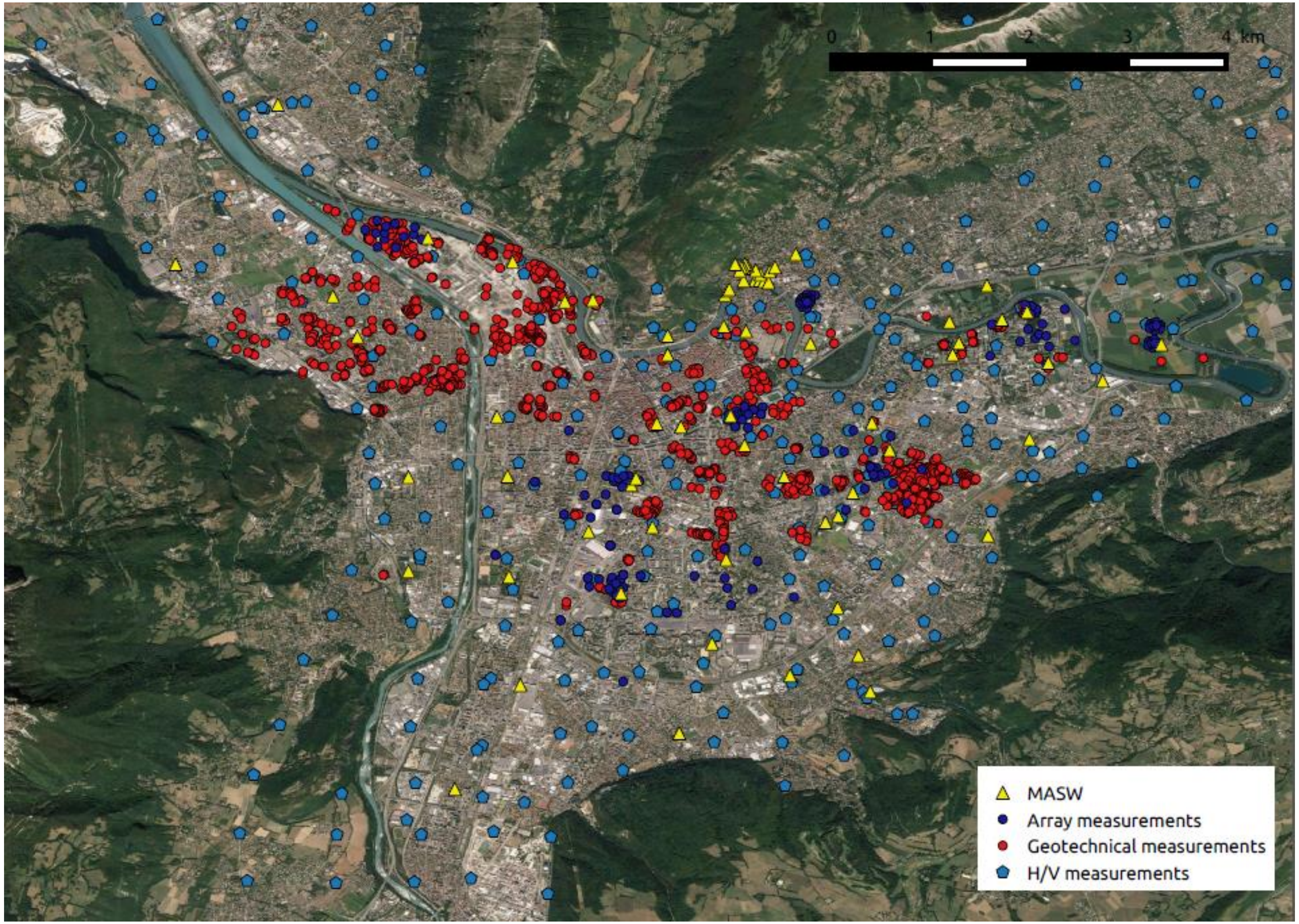
Grenoble basin





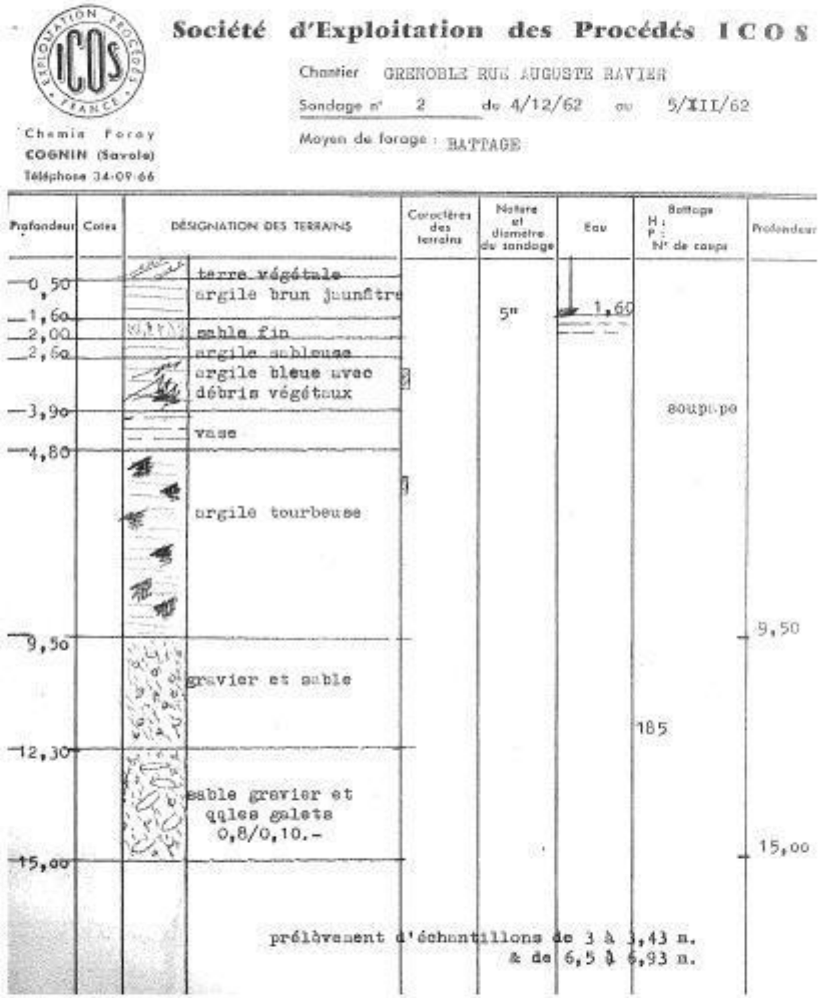
Lacroix, 1970

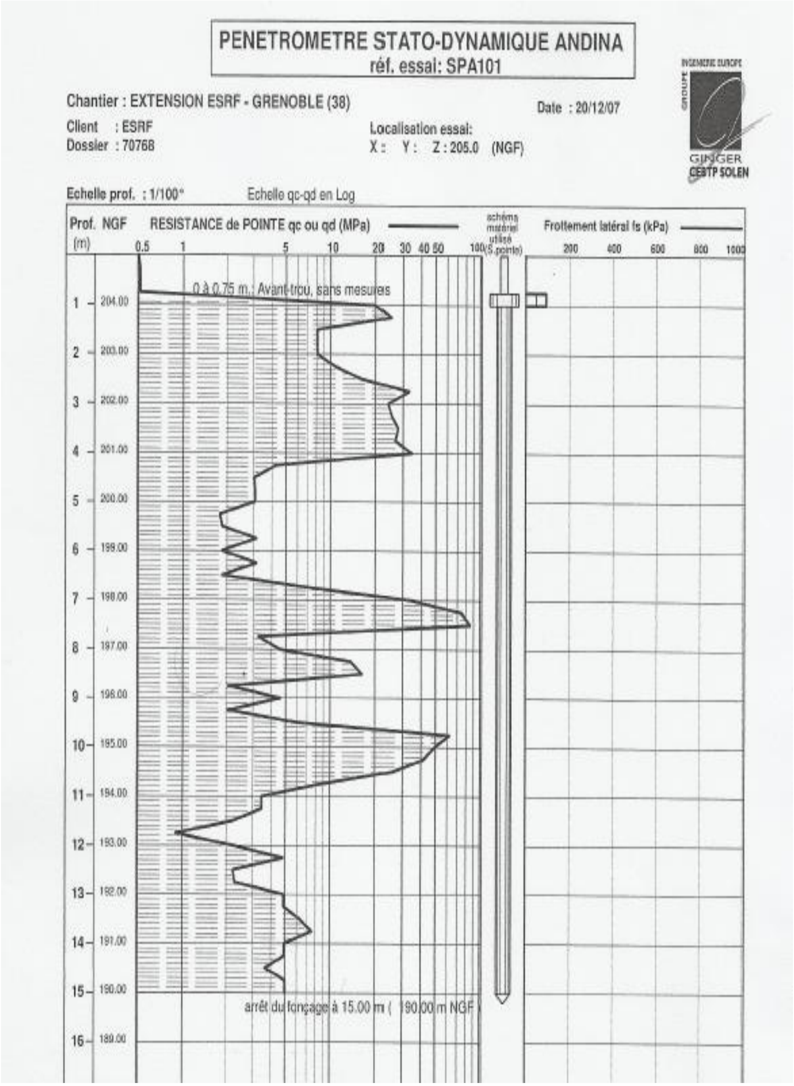
Geophysical and geotechnical/borehole data



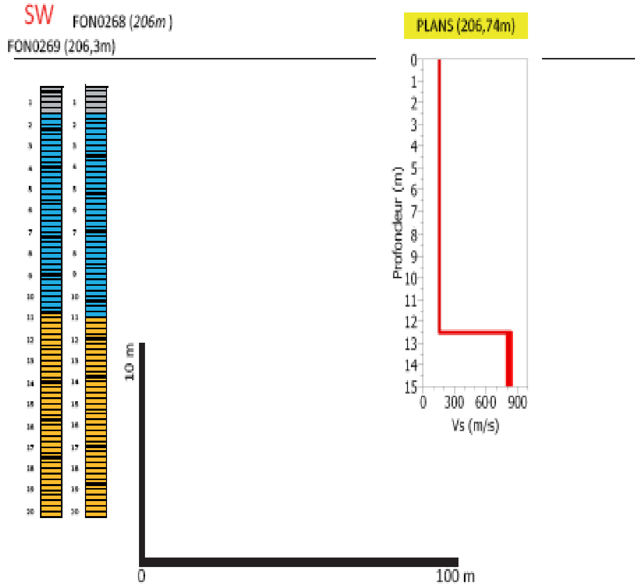
Geotechnical / borehole data

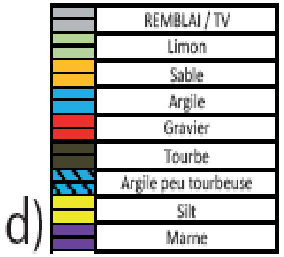
A) Andina penetrometer test (modern penetrogram format); B) Destructive drilling description log (ancient format); C) Pressuremeter test with geological interpretation; D) Electrical resistivity results



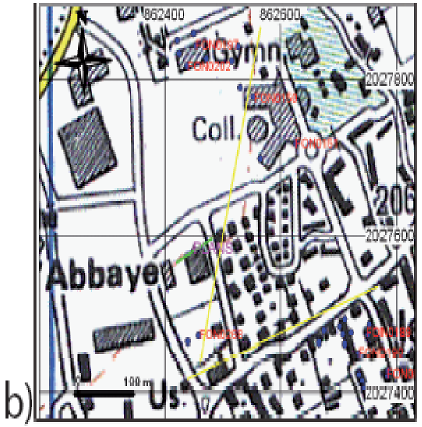


Correlation between geological facies and Vs





a) Profile with geotechnic wells near PLANS seismic stations. Shear wave velocity profiles derived from MASW measurements included in profile. Wells start level are NGF altitudes (with interpolated values in Italics). b) Orientation of well profile is displayed in the map. c)Measured (± standard deviation) dispersion curve (red dots) and inverted dispersion curves (gray lines). d) Geological legend.



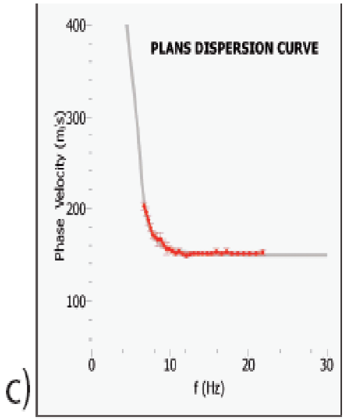
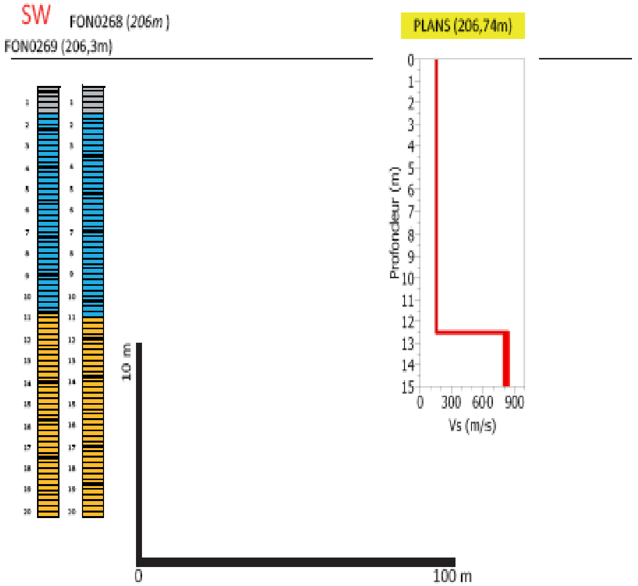


Tableau 2 : Range of shear-wave velocities at various depth ranges.

Station Name	Layer or transition zone	Shear-waves velocity values (m/s)	Depth Interval (m)	Remarks
ILL	Shalow layer	230 - 250	0 - 2.5	
	Transition zone		2.5 - 2.7	
	Lower layer	370 - 380	2.7 – 9.1	
ILL_01	Shalow layer	200 - 230	0 - 2.5	clear transition in Vs profile as a consequence of clear inflexion of the dispersion curve at about 40 Hz
	Transition zone		2.5 - 3.2	
	Lower layer	360 - 430	3.2 – 8.7	
ILL_02	Shalow layer	250 - 270	0 - 1.6	
	Transition zone		1.6 - 1.9	
	Lower layer	420 - 475	1.9 – 6.9	
ILL_03	Shalow layer	110 - 385	0 - 1	High uncertainty over the entire Vs profile as a consequence of a very limited measured wavelength range
	Transition zone		1 - 3	
	Lower layer	280 - 520	3 - 8	
ILL_04	Shalow layer	240 - 275	0 - 2.4	clear transition in Vs profile as a consequence of clear inflexion of the dispersion curve at about 40 Hz
	Transition zone		2.4 - 2.75	
	Lower layer	410 - 435	2.75 – 9.6	
ILL_05	Shalow layer	280 - 375	0 - 1	Uncertainty at shallow depth
	Transition zone		1 - 1.9	
	Lower layer	400 - 420	1.9 - 10	
ILL_06	Shalow layer	275 - 300	0 - 2.5	
	Transition zone		2.5 - 3.2	
	Lower layer	345 - 400	3.2 – 5.4	
ESPLANADE	Shalow layer	125 - 310	0 - 1	Limited frequency range /Uncertainty at shallow depth due to large standard deviation on the dispersion curves
	Transition zone		1 - 4	
	Lower layer	250 - 350	4 - 10	
G 15	Shalow layer	90 - 160	0 - 2	clear velocity gradient
	Transition zone			
	Lower layer			
GEVES	Shalow layer	425 - 550	0 - 1	Topmost high velocity layer
	Intermediate layer			
	Lower layer	100 - 150	1 - 13.9	
	Shalow layer	190 - 270	0 - 1.5	

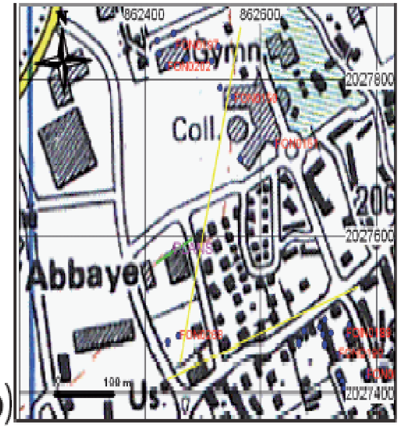
Correlation between geological facies and Vs



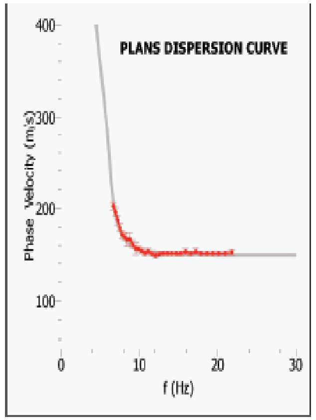
d)

a) Profile with geotechnic wells near PLANS seismic stations. Shear wave velocity profiles derived from MASW measurements included in profile. Wells start level are NGF altitudes (with interpolated values in Italics). b) Orientation of well profile is displayed in the map. c)Measured (± standard deviation) dispersion curve (red dots) and inverted dispersion curves (gray lines). d) Geological legend.

b)



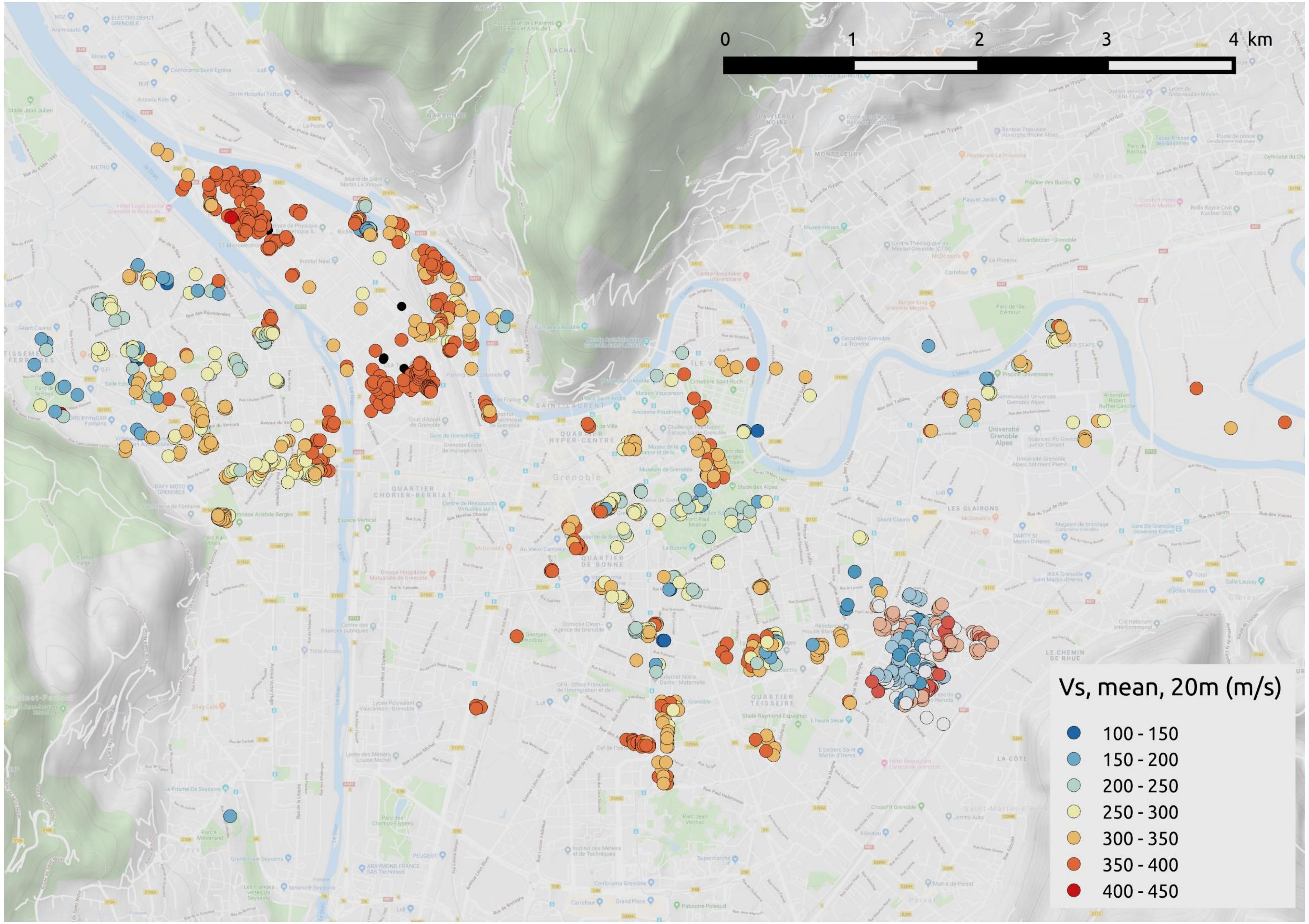
c)



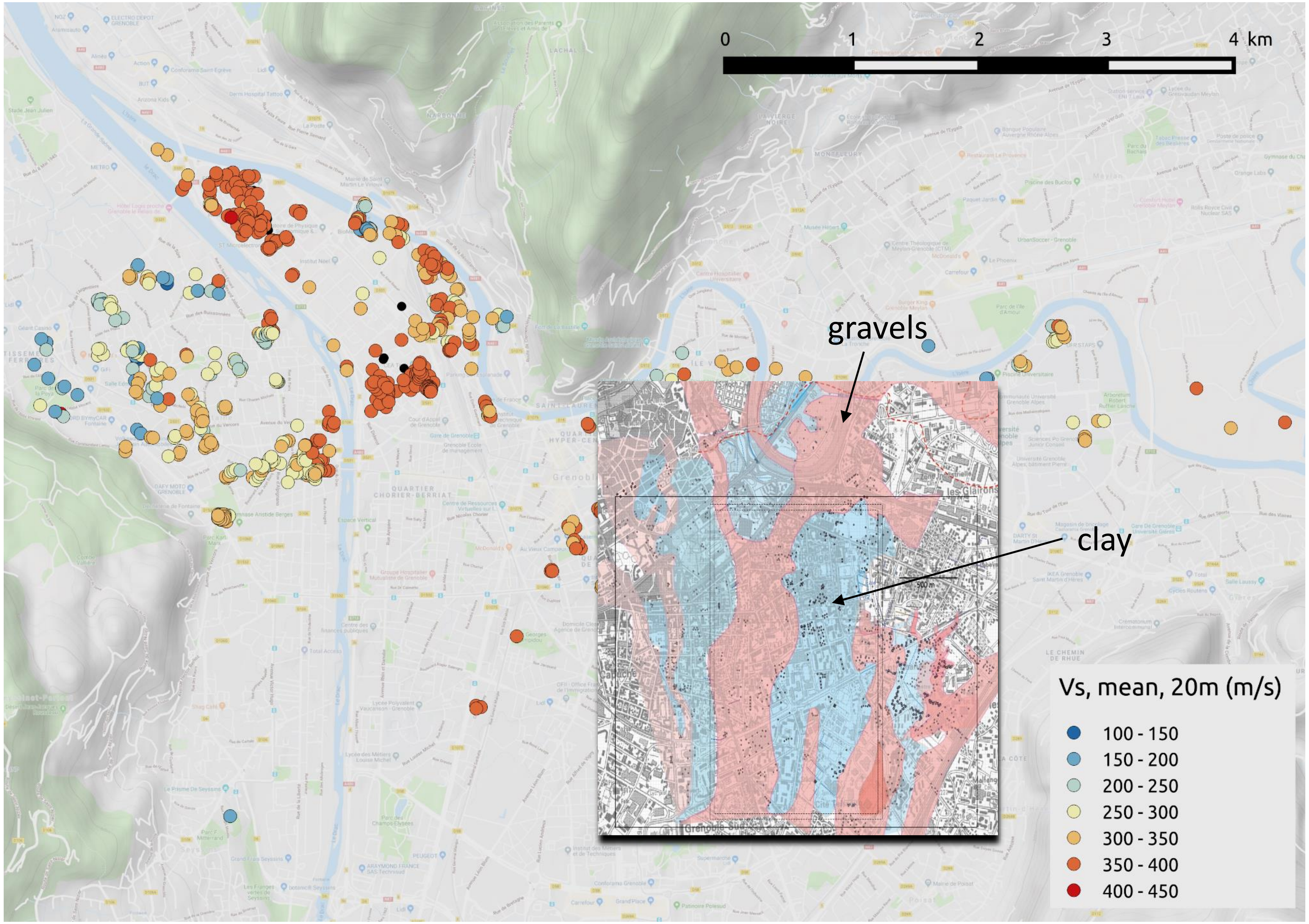
Entité	Vs [m/s]	Prof [m]
Terre	250	/
Remblai	250	/
Béton	1000	/
Limon	150	/
Gravier	400	/
Sable	400	/
Argile	150	≤20m
Argile	200	>20m
Tourbe	100	/
Marne	150	/
Galet	400	/
Enrobé	1000	/
Bloc Gravier	400	/
Bloc calcaire	1000	/
Troncs	100	/

Uncertainty on Vs : 20 %

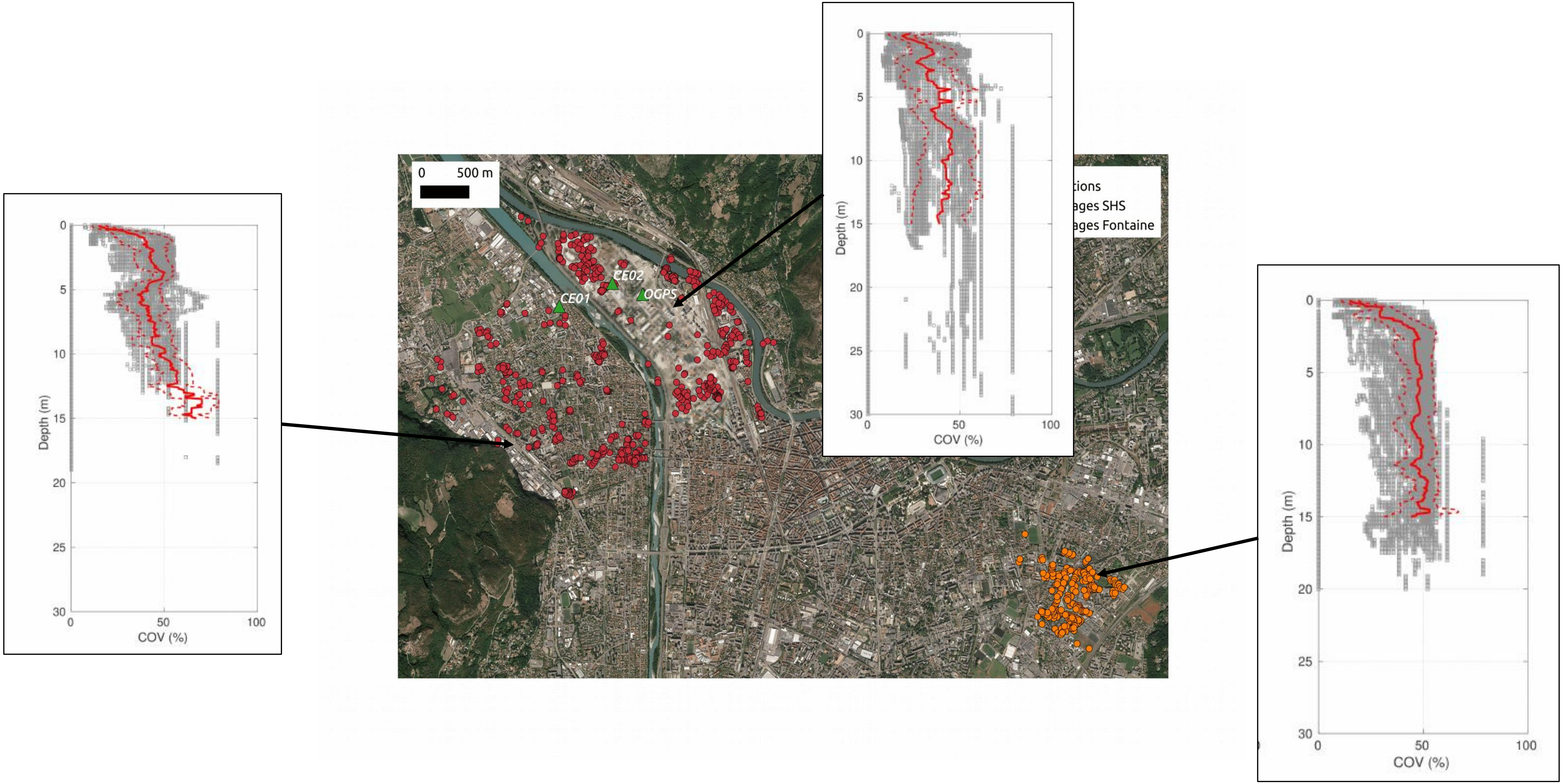
Average Vs from 0 to 20 m depth



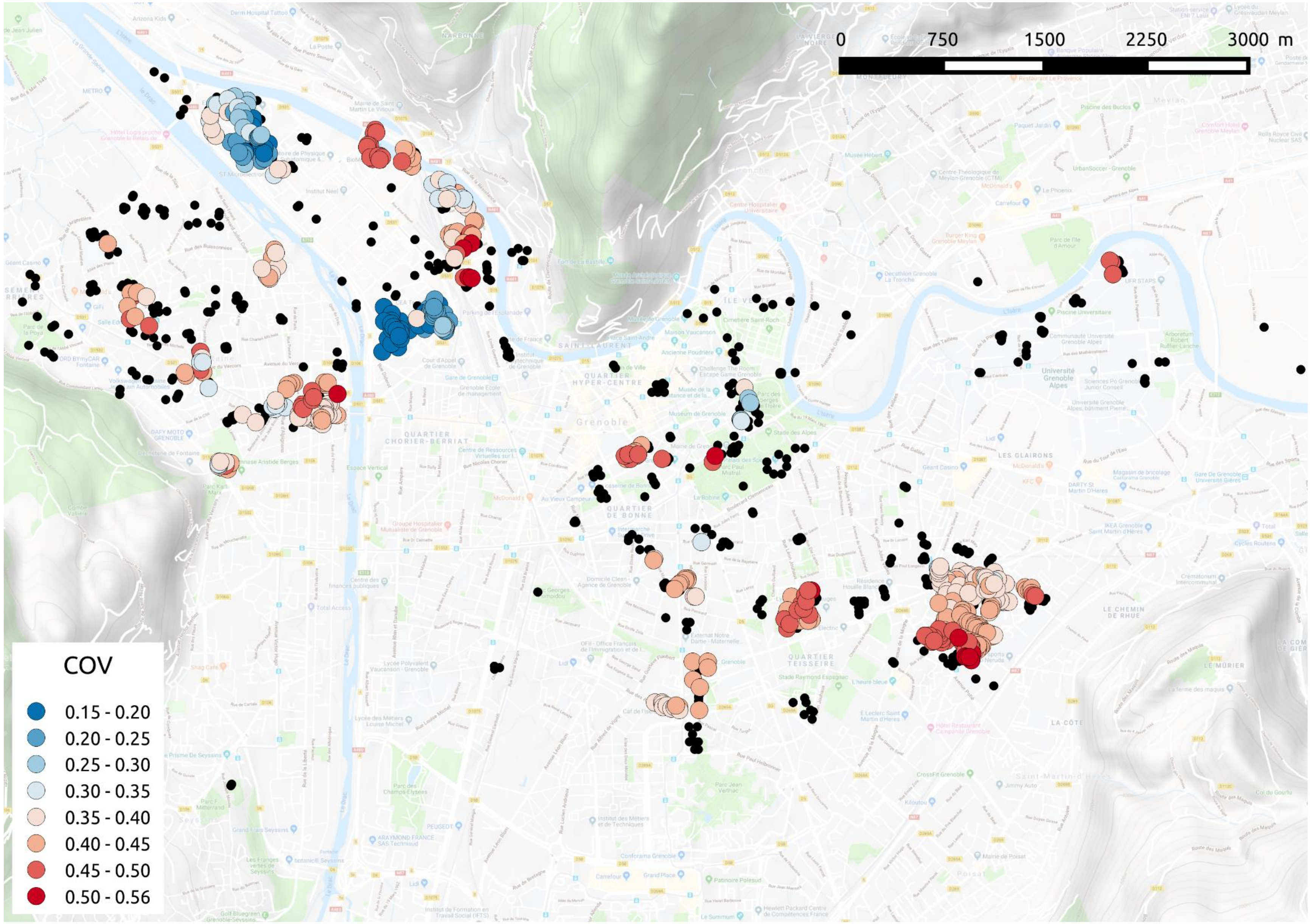
Average Vs from 0 to 20 m depth



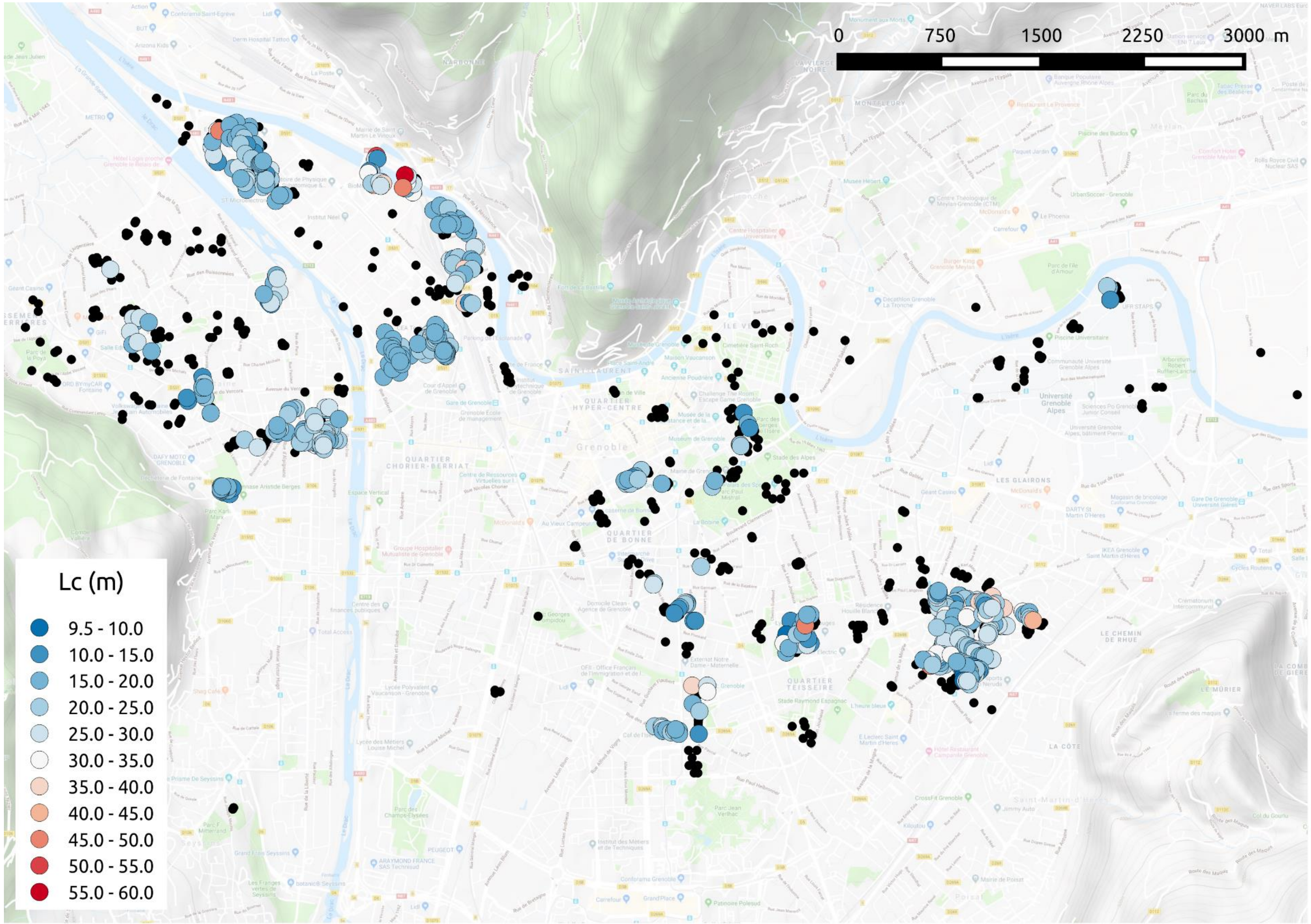
CoV Vs for each geological zone



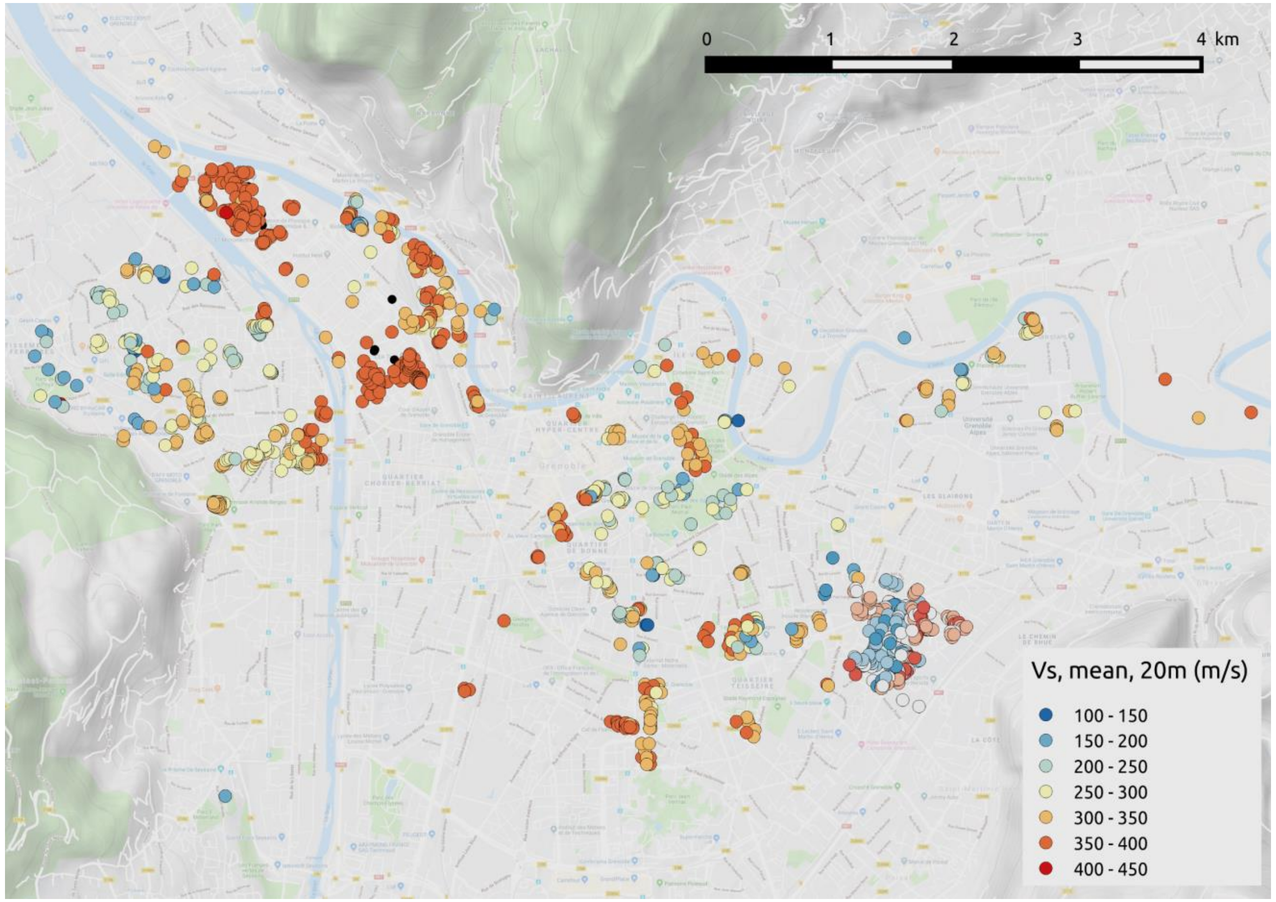
Average CoV Vs from 0 to 20 m depth accounting for borehole data within 200 m radius



Horizontal Lc from 0 to 20 m depth



Conclusions on Grenoble basin

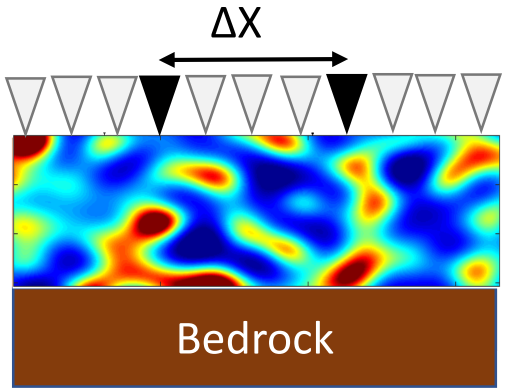


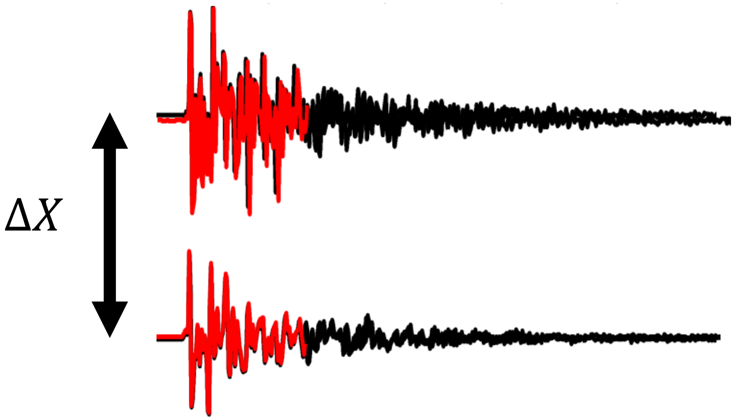
- Test of the robustness of results (uncertainty on Vs, depth variation, …)
- Lateral variation of Vs over short distance (up to 40%)
- CoV Vs about 15-20% in geological unit dominated by gravels
- CoV Vs about 40-50% in geological unit showing alternance of gravel and sands
- Lc is ranging between 15 and 30 m whatever the geological unit

What can be extracted from earthquakes ?

Spatial correlation : variation of engineering indicators (Arias intensity, duration, Fourier amplitude spectrum, etc.) as a function of inter-station distance

$$\Delta AI(\Delta X) = Avg\ (|AI(i + \Delta X) - AI(i)|)$$



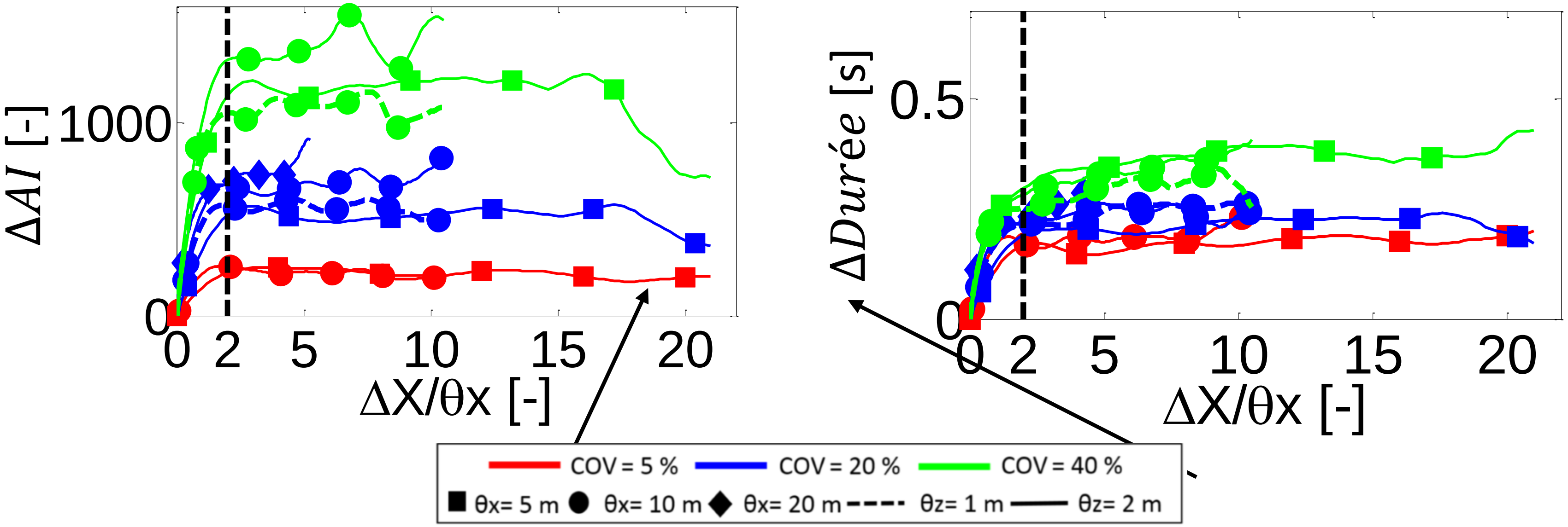


Synthetics:
- One layer over halfspace
- SV plane wave
- FLAC2D code
- Frequency range : 1 – 25 Hz

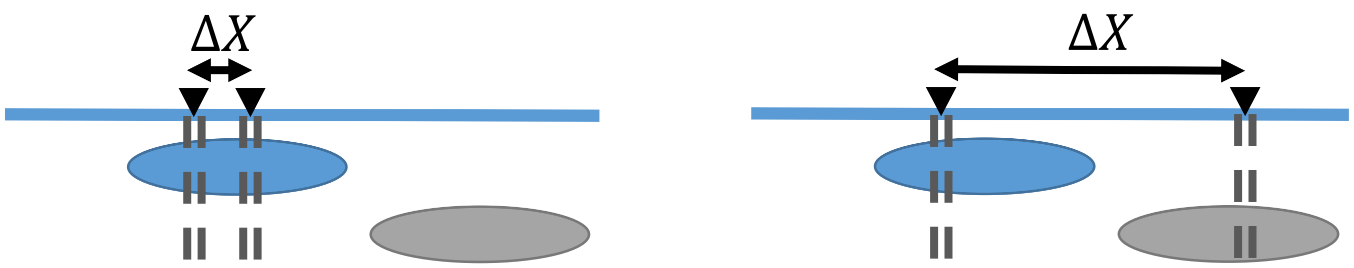
Seismic phase:
- «S-wave»

El Haber et al. (2019)

What can be extracted from earthquakes ?



El Haber et al. (2019)



Simple interpretation : spatial correlation of the « S-wave » is mainly controled by wave propagation within the 1D soil underneath the observation site

=> θx could be easily inferred from threshold distance (D) of spatial correlation (D=2θx)

Spatial correlation of seismic ground motions of very dense seismic arrays in Europe

Koufoudi et al. (2019) - submitted

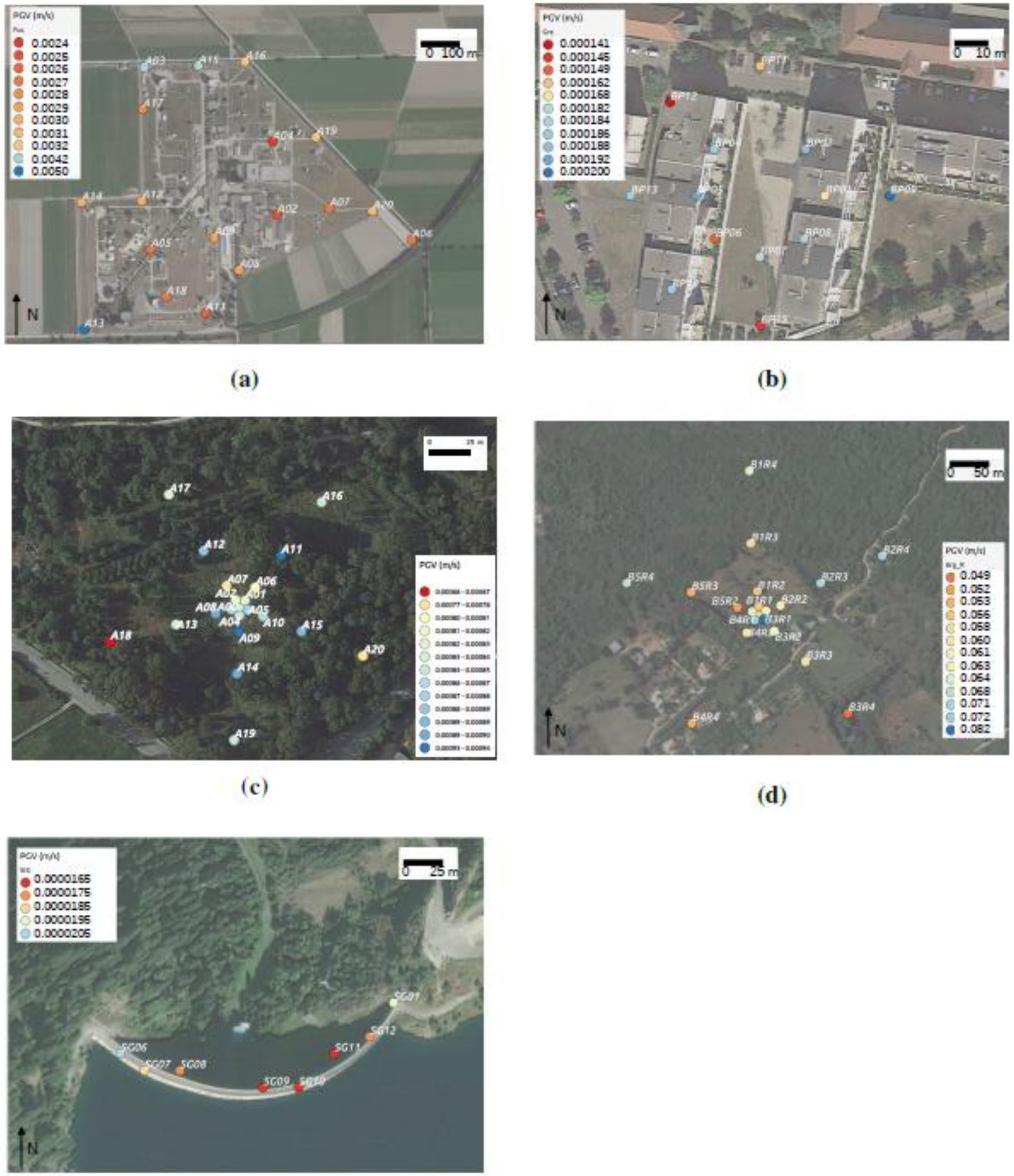


Table 2. Geological characteristics of the European dense seismological arrays.

Array	Site Class	Topography	$V_{s,30}$ (m/sec)	Thickness (m)
Fuccino	Soil	Flat	150	20
Grenoble	Soil	Flat	250	40
Argostoli Soil	Soil	Flat	250	60
Argostoli Rock	Soft Rock	Flat	830	-
St. Guérin	Hard Rock	Mountains	~1400	-

Table 1. Characteristics of the European dense seismological arrays.

Array	Loc.	Number of stat.	Min spacing (m)	Max spacing (m)
Fuccino	Italy	20	100	900
Grenoble	France	15	15	80
Argostoli Soil	Greece	21	~5	~150
Argostoli Rock	Greece	21	~9	~350
St. Guérin	France	9	~20	~210

Grenoble 30% of PGV variation

Argostoli rock 40% of PGV variation

Spatial correlation of seismic ground motions of very dense seismic arrays in Europe

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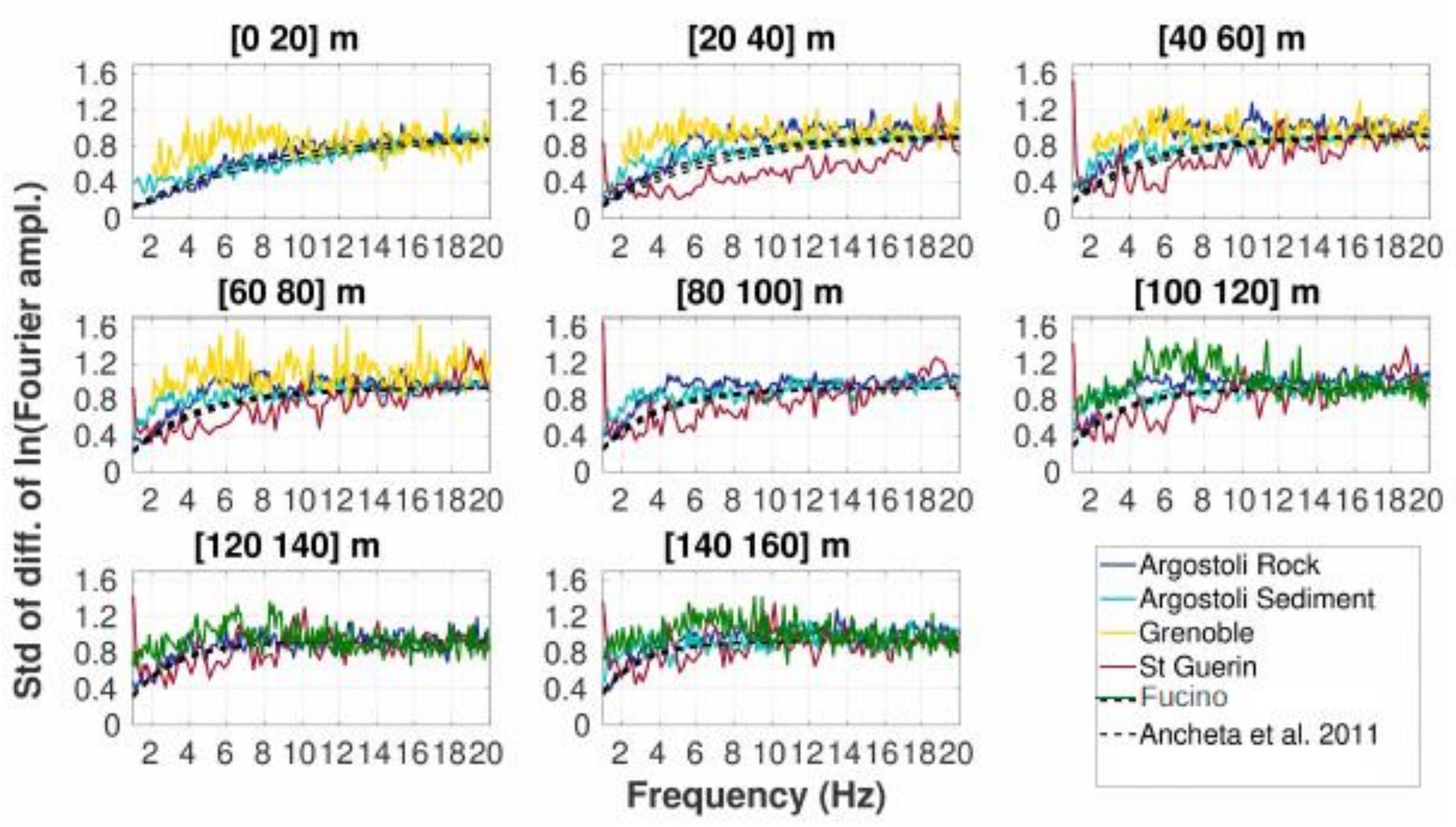


S-wave portion of signals (AI criteria; Abrahamson, 2007)

Plateau at about 0.9
=> Differences of amplitude are uncorrelated

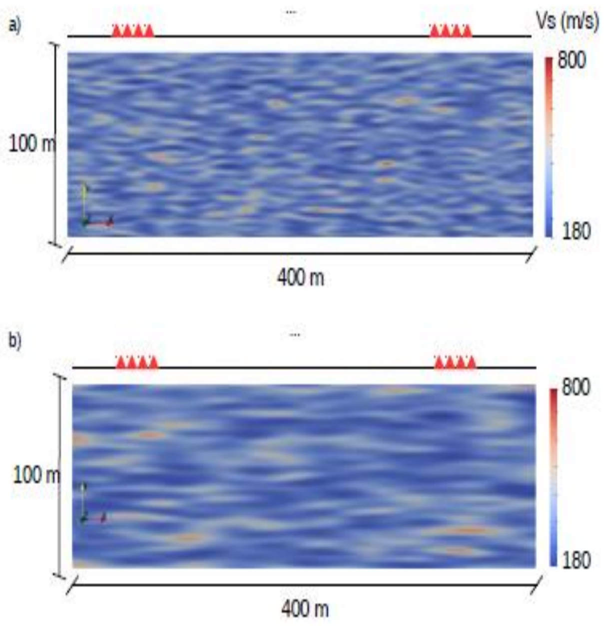
Plateau reached for freq. > 6-9 Hz whatever site condition (and continents)

Higher spatial variability for Grenoble at low frequency

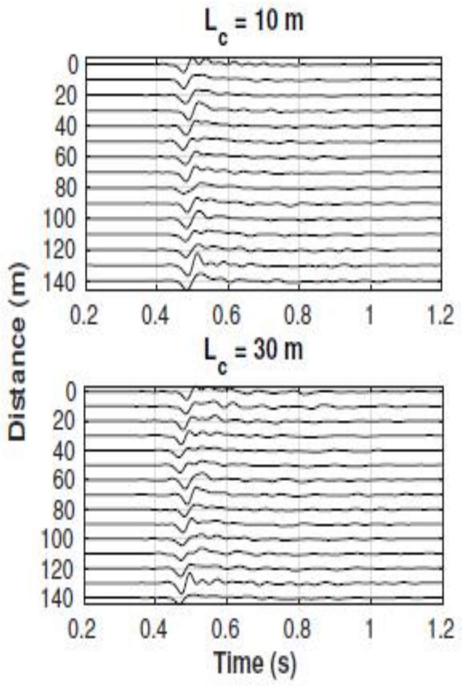
Argostoli rock and soil arrays exhibit similar variability

Spatial correlation of seismic ground motions of very dense seismic arrays in Europe

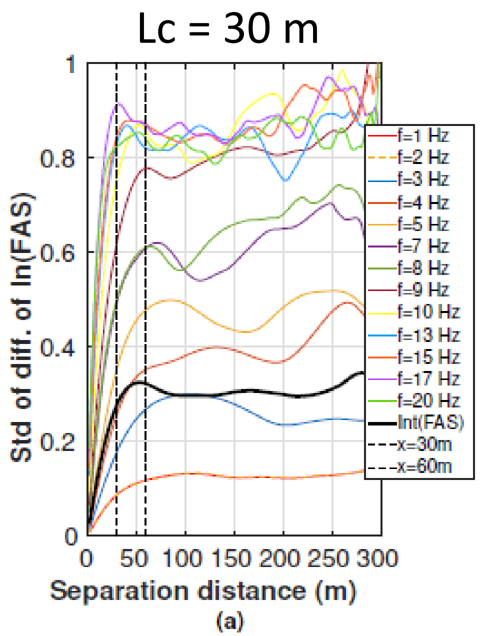
Simulation in random media (no layering)
Code Aster
SV plane wave; delta-like source time function
Frequency range: 1-20 Hz
CoV=20%; mean_Vs = 400 m/s; θz = θx/10
Θx = Lc



(a)



(b)



Propagating wavelengths > Lc

Propagating wavelengths < Lc

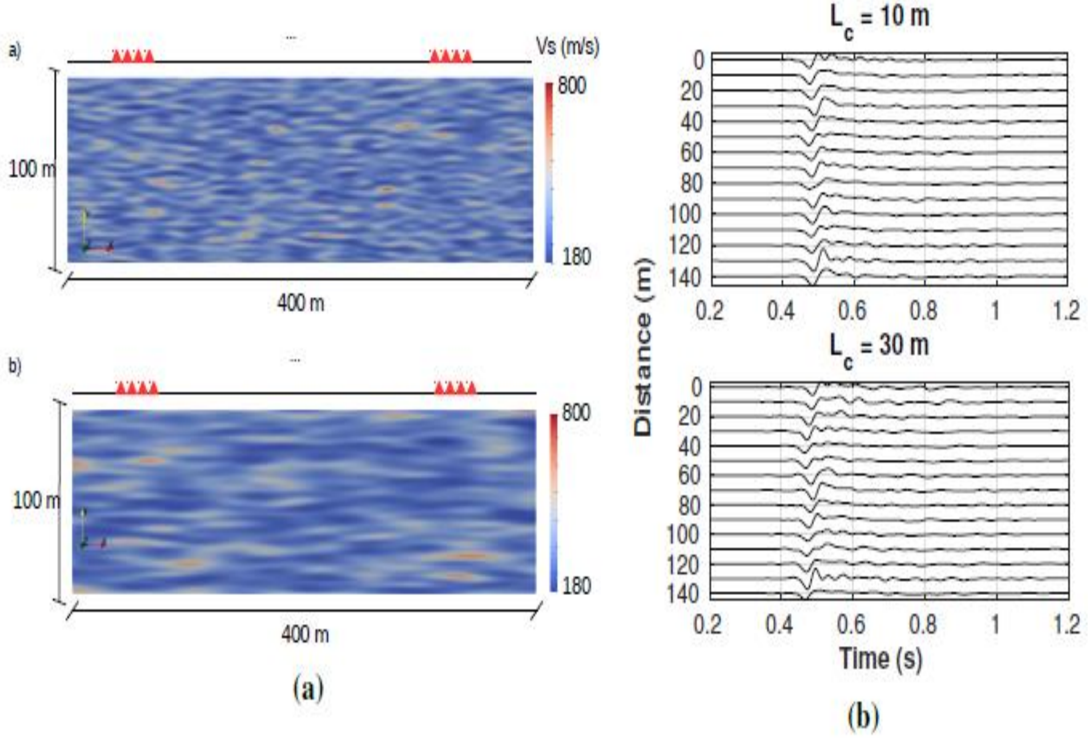
Threshold distance (D)

- Varies with frequency/wavelength
- Occurs beween Lc and 2Lc

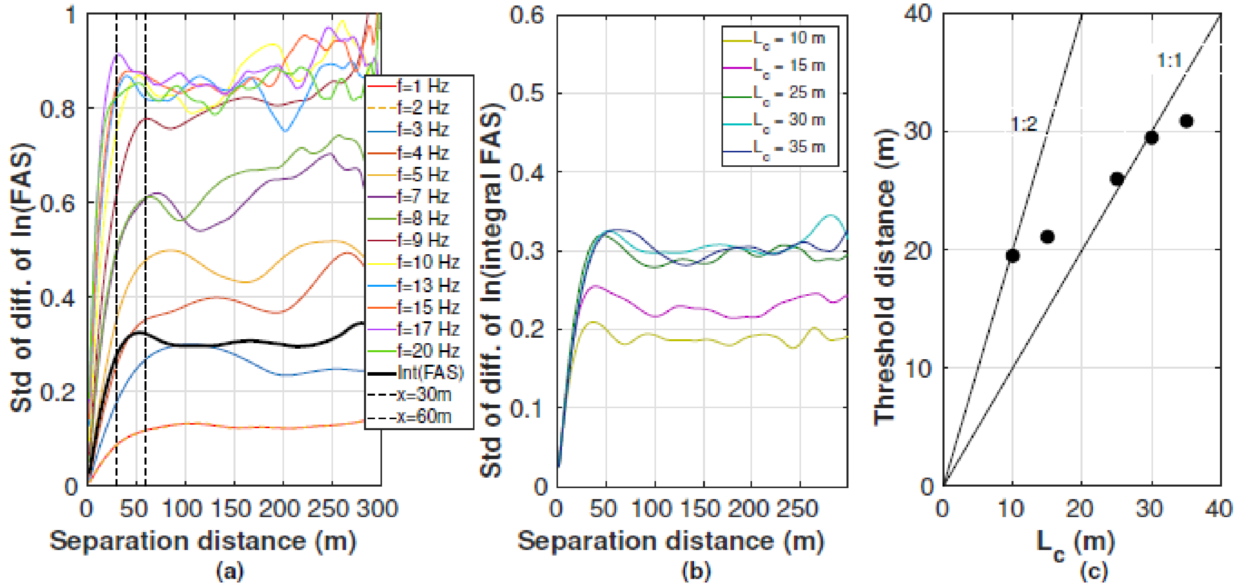
For application to real sites, use of Integral (FAS)

Spatial correlation of seismic ground motions of very dense seismic arrays in Europe

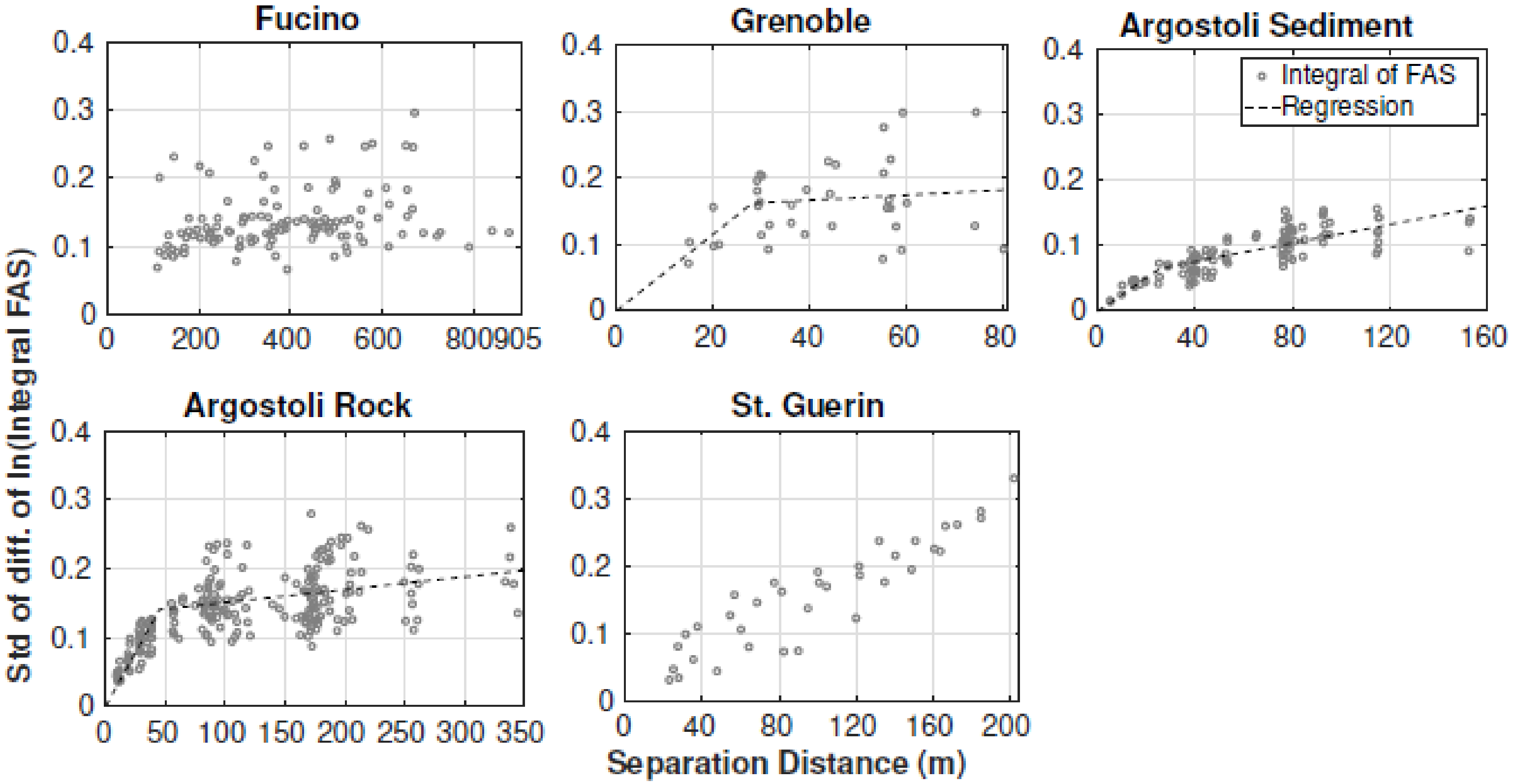
Simulation in random media (no layering)
Code Aster
SV plane wave; delta-like source time function
Frequency range: 1-20 Hz
CoV=20%; mean_Vs = 400 m/s; θz = θx/10
Θx = Lc



Lc = 30 m



Spatial correlation of seismic ground motions of very dense seismic arrays in Europe



Fucino : Lc < 200 m

St Guérin : no weathering / hard rock

Argostoli soil : Lc [13 26 m]

Argostoli rock : Lc [22 42 m]
=> consistent with Svay et al. (2017)
Lc = 30 m

Grenoble: Lc [14 28 m]
=> Consitent with borehole analysis

Learnings / Next steps

Spatial correlation from earthquakes

- Analysis of earthquake recordings at dense array is promising to extract horizontal autocorrelation distance
  - $\Rightarrow$ Can we use seismic noise wavefield instead ?
- Ground motion amplitude is not any more spatially correlated for frequencies > 6-9 Hz whatever the site
  - $\Rightarrow$ Why ? Related to frequency bandwidth and typical frequency content of earthquake recordings ?
  - $\Rightarrow$ simulation of spatially variable ground motion at small spatial scale (application: PSHA for lifelines, shake-maps in urban environement)
- Estimation of CoV from spatial coherence (El Haber, 2018)

Near surface heteregeneities from boreholes

- Time consuming
- Vertical autocorrelation distance range seems to be quite well constrained, typically from 1 to 5 m