ΣIGMA2

Closing Symposium 2022

On κ & Hard Rock motion

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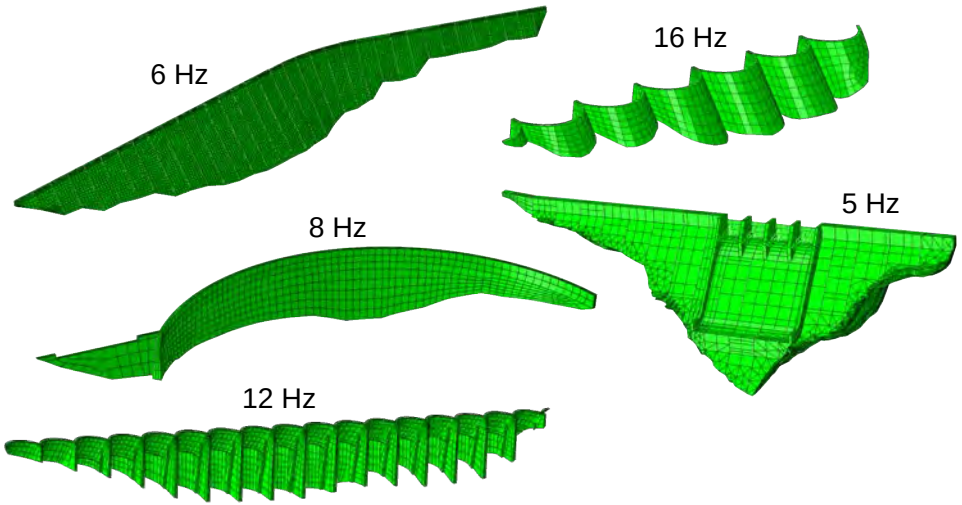
HFs & structures

➔ **Critical facilities**

Safety-related **equipment** is sensitive to ground shaking at frequencies above 10-20 Hz.

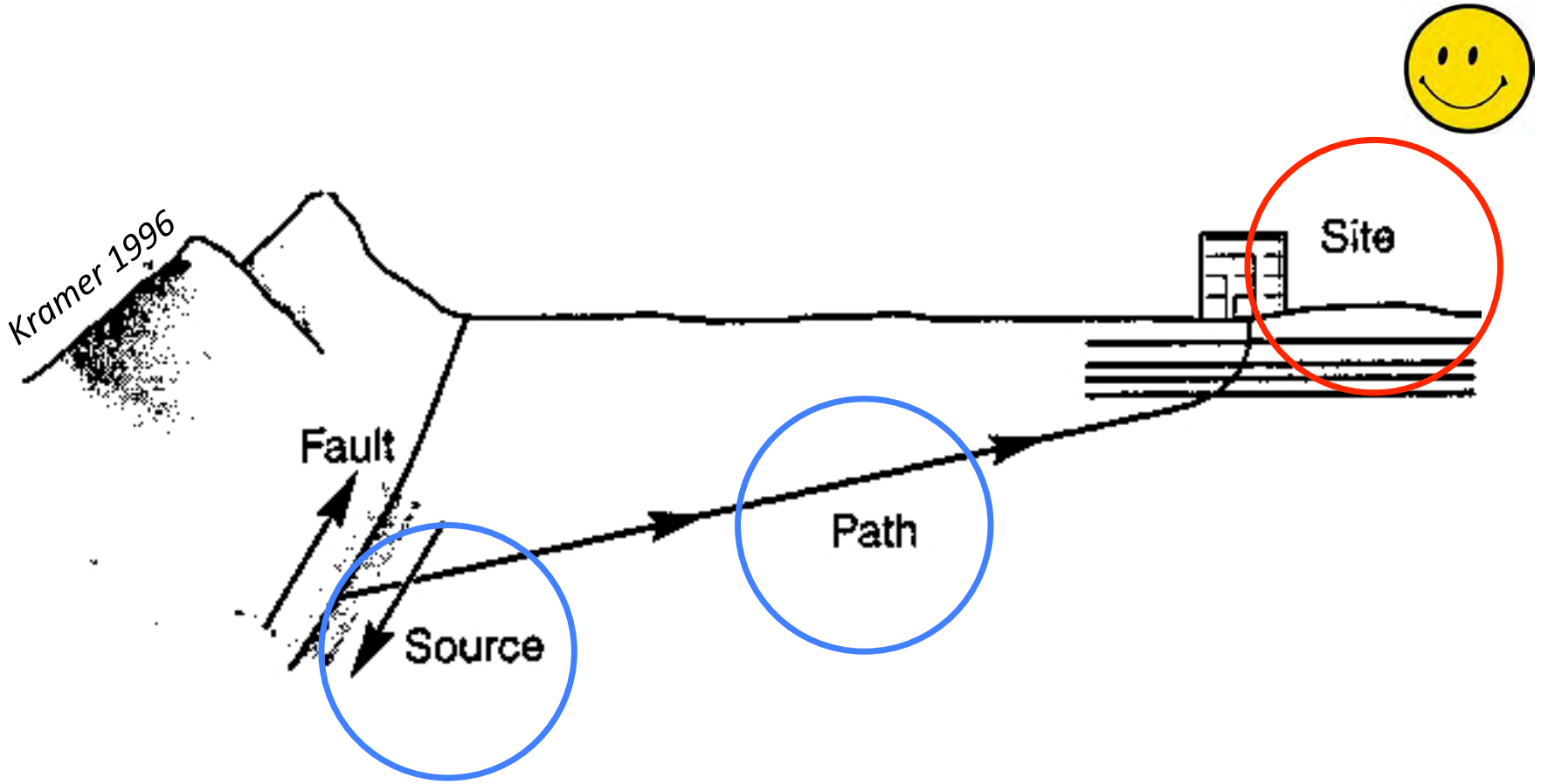
➔ **Dams**:

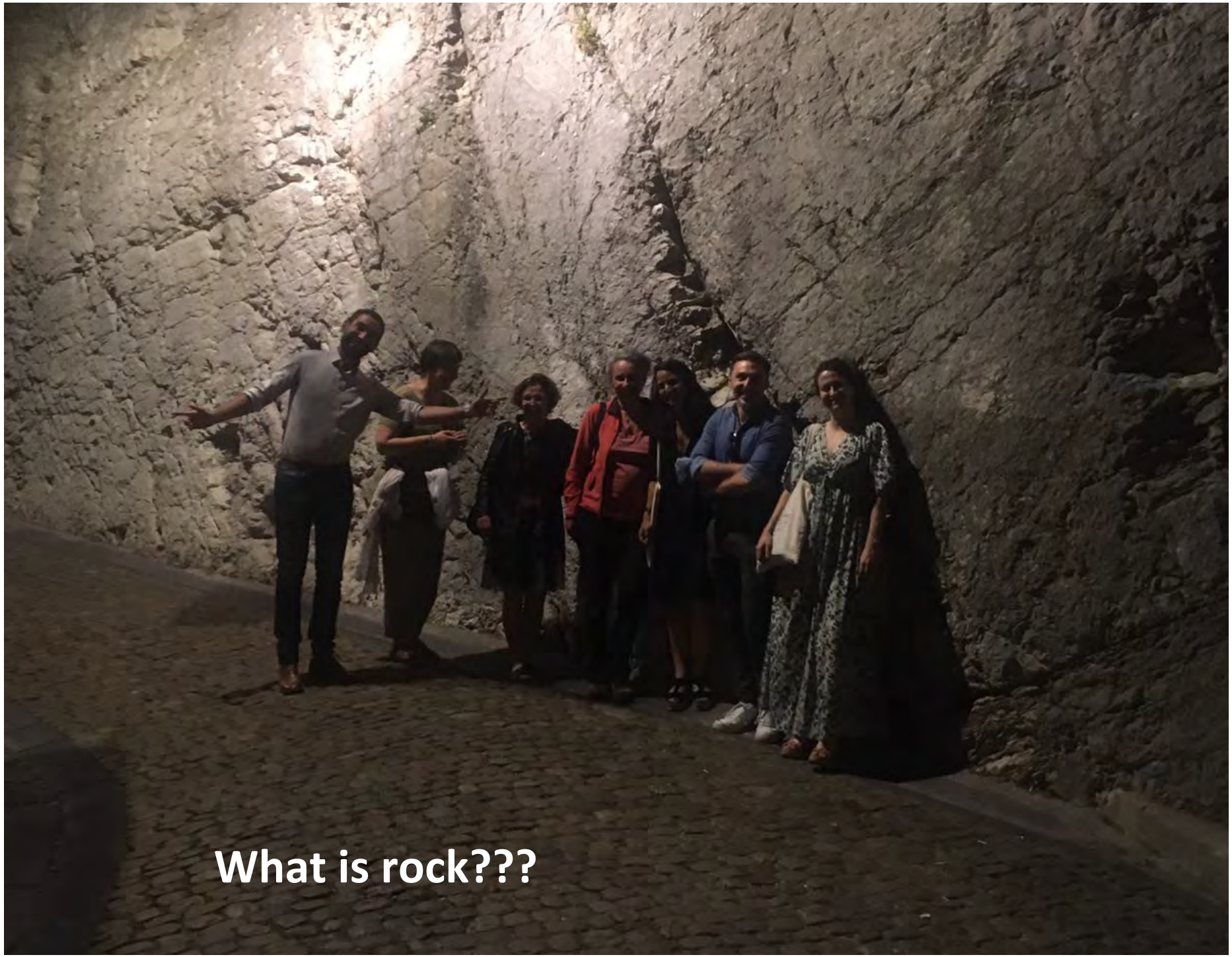
Small, concrete dams have eigenfrequencies
up to 10-16 Hz
Critical components e.g. gates



Courtesy of Matt Muto

Ground motion components

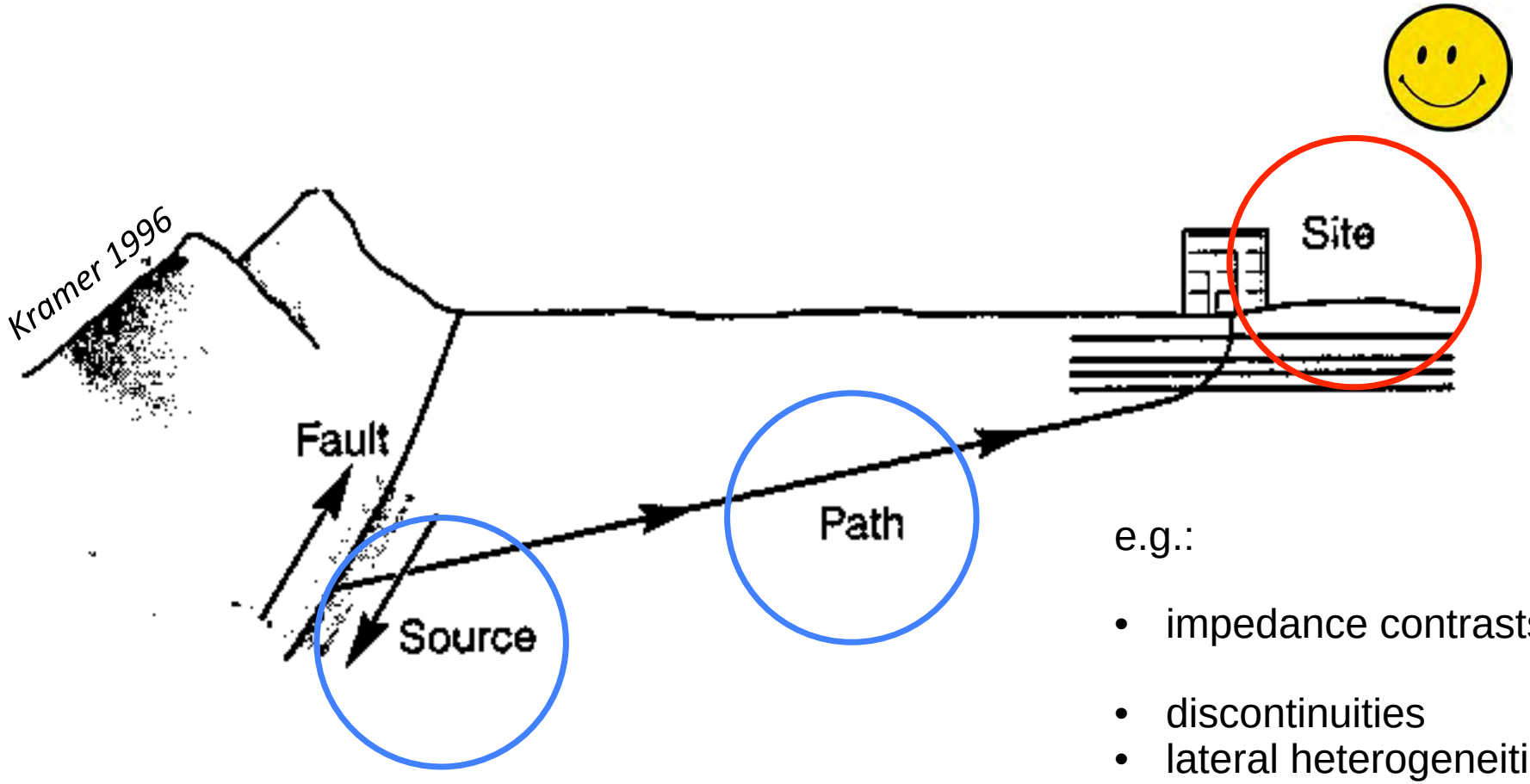



What is rock???

Amplification

(classic)

Ground motion components



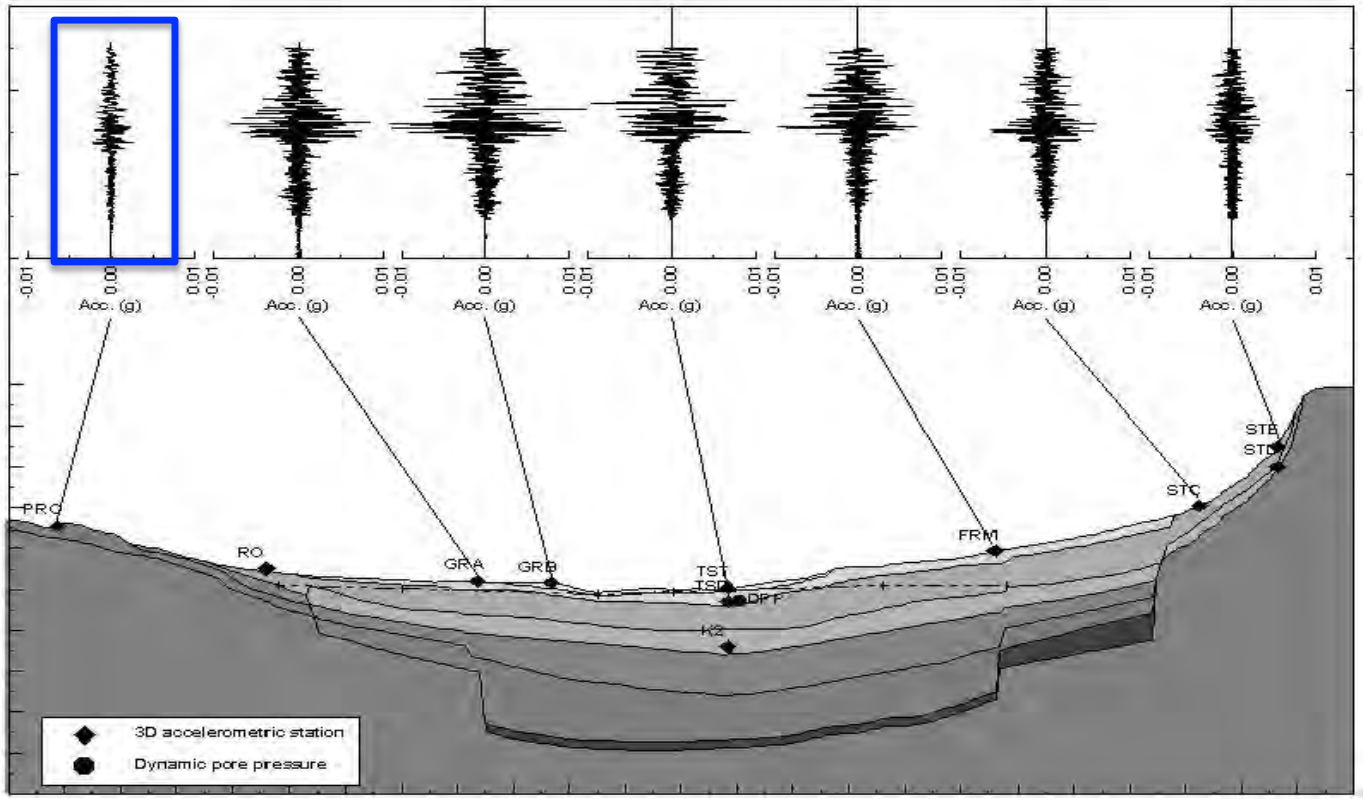
e.g.:

- impedance contrasts

- discontinuities
- lateral heterogeneities
- basins
- topography

- non-linearity

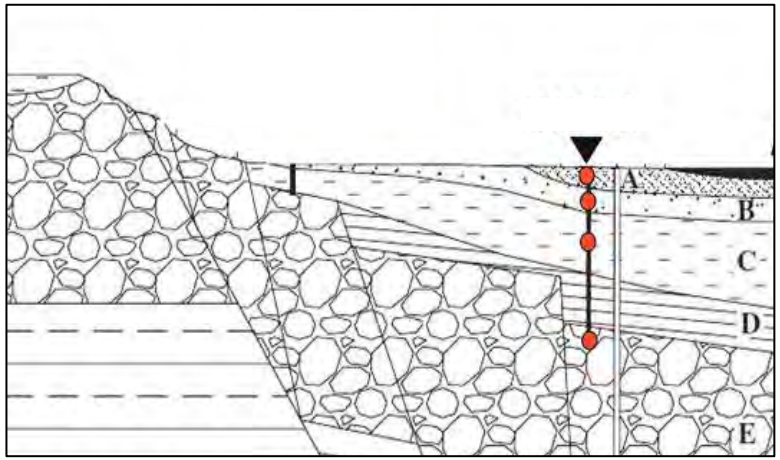
Site (“soil”) effects

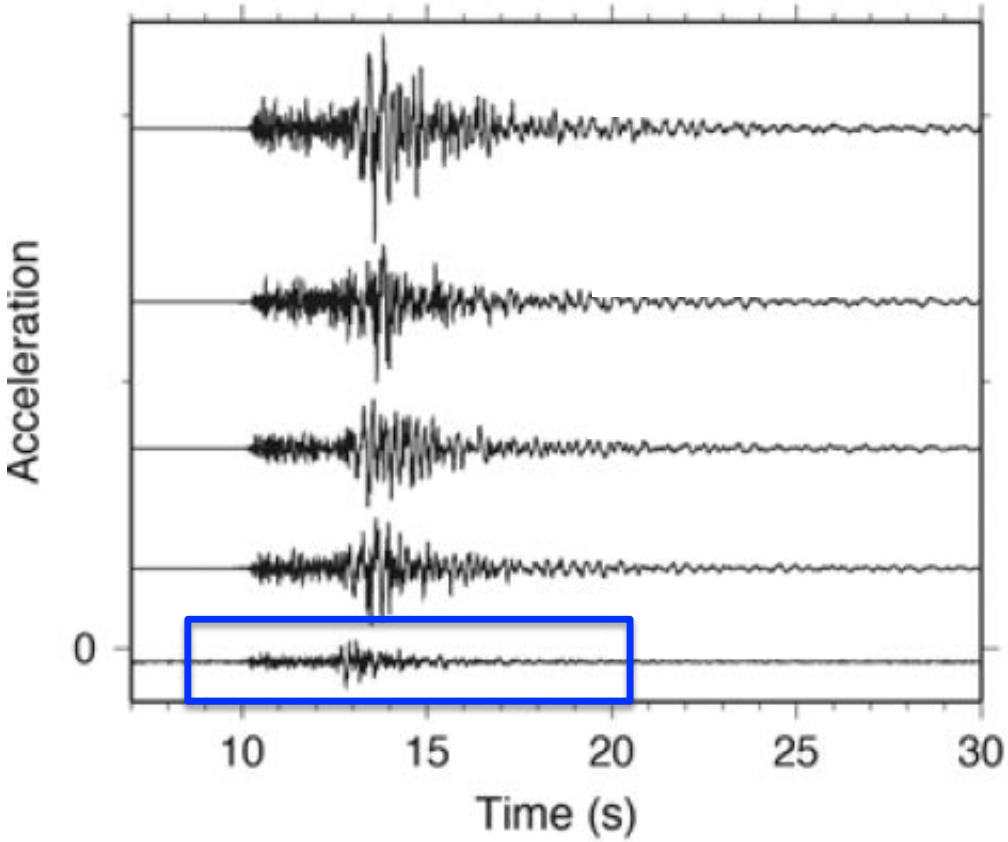


Makra et al 2005

Site effects

Time series

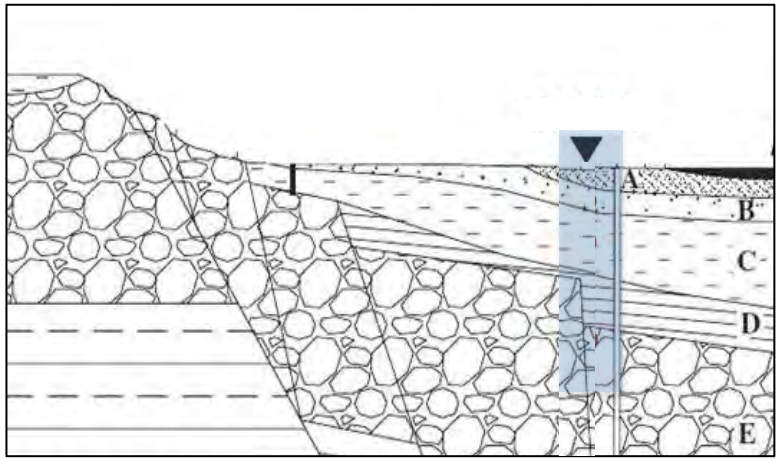


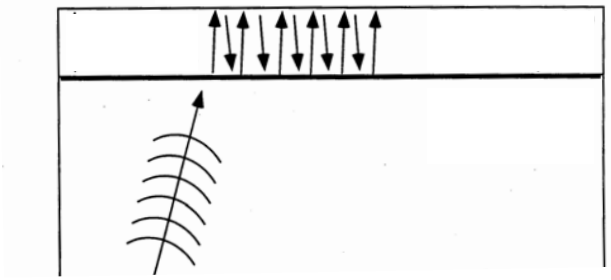


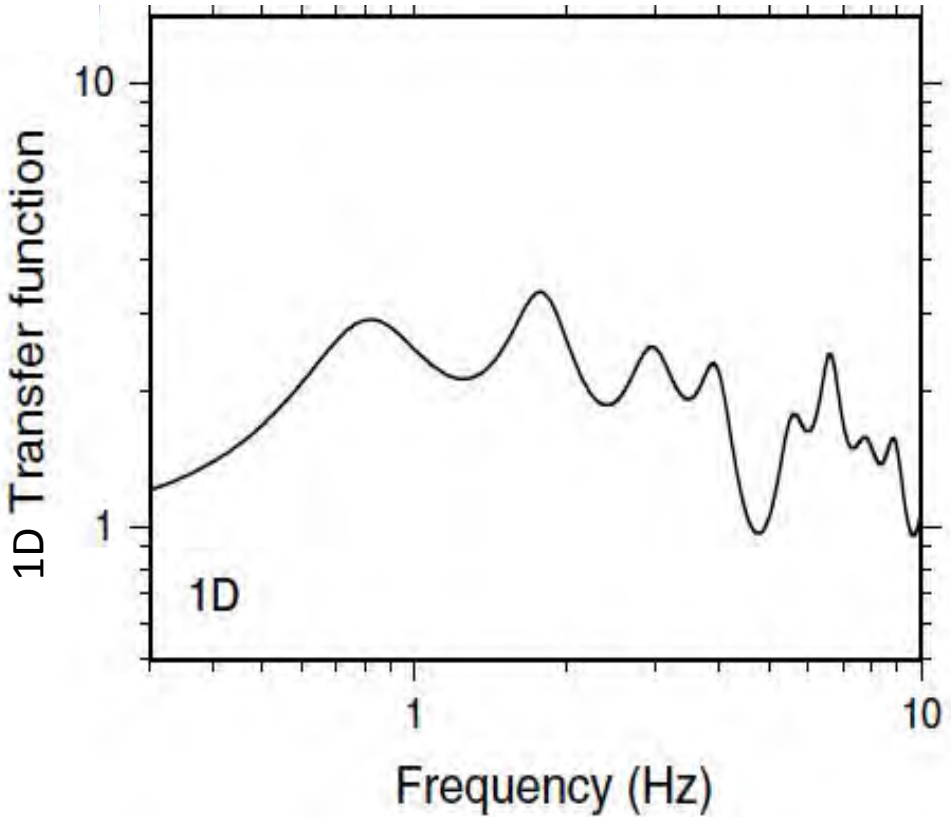
Ktenidou et al 2011

Amplification

1D theoretical model



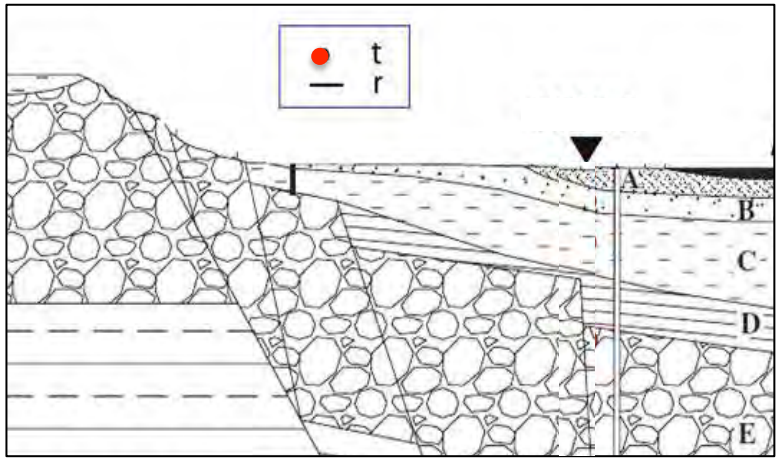


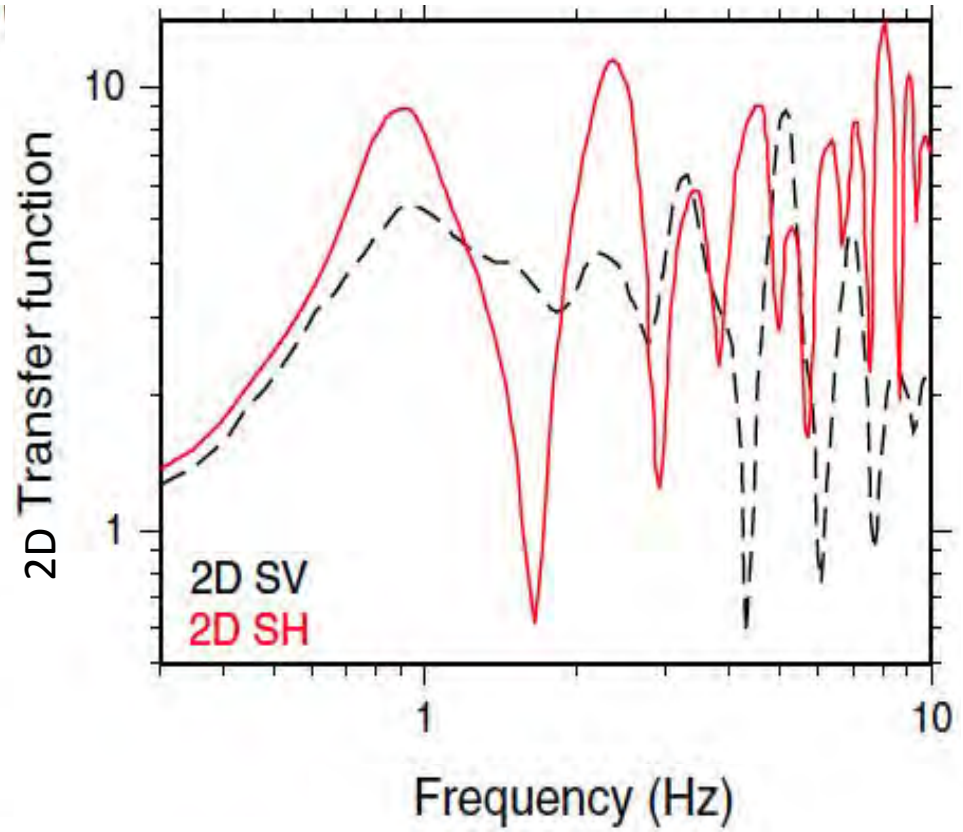


Ktenidou et al 2016

Amplification

2D numerical analysis

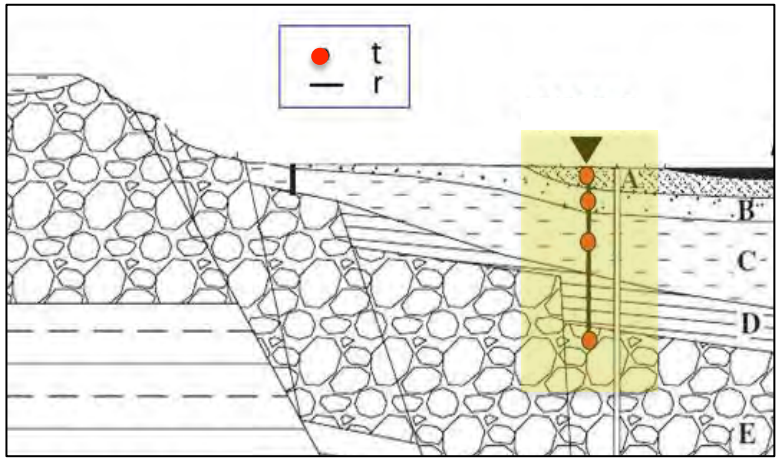


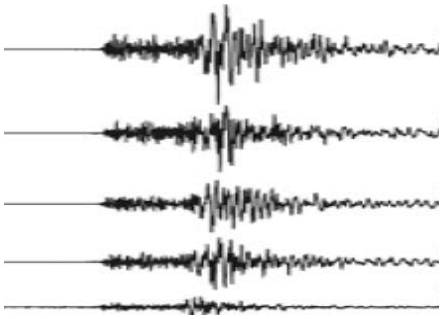


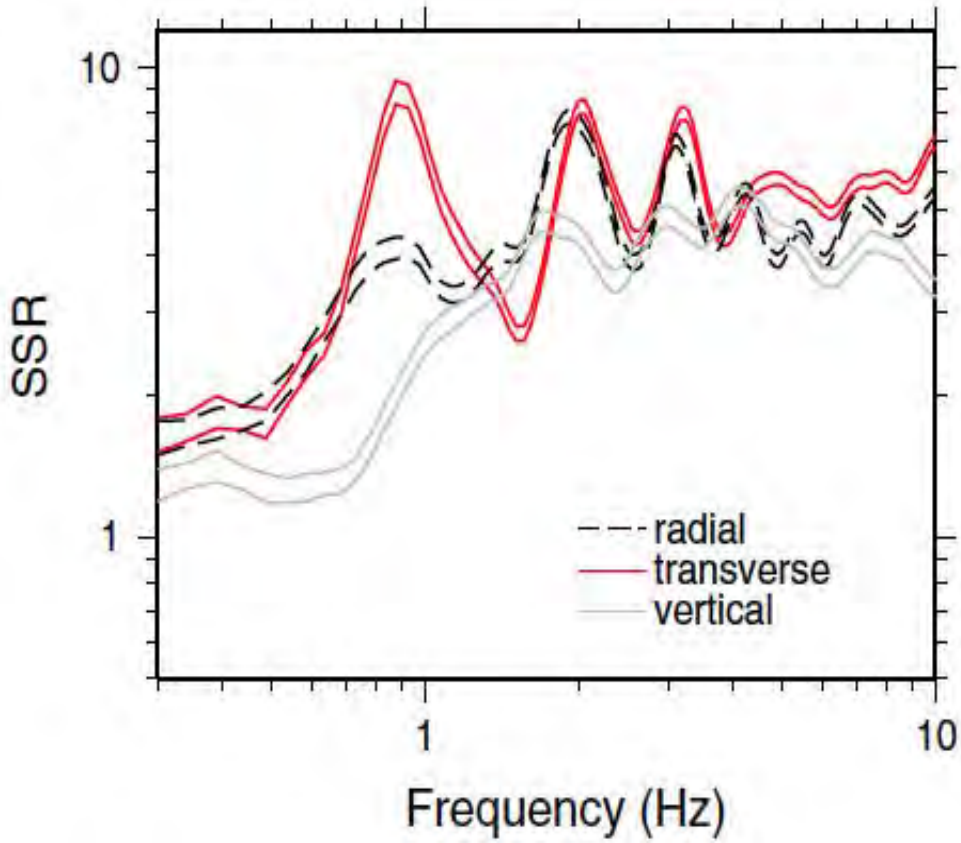
Ktenidou et al 2016

Amplification

Standard spectral ratio





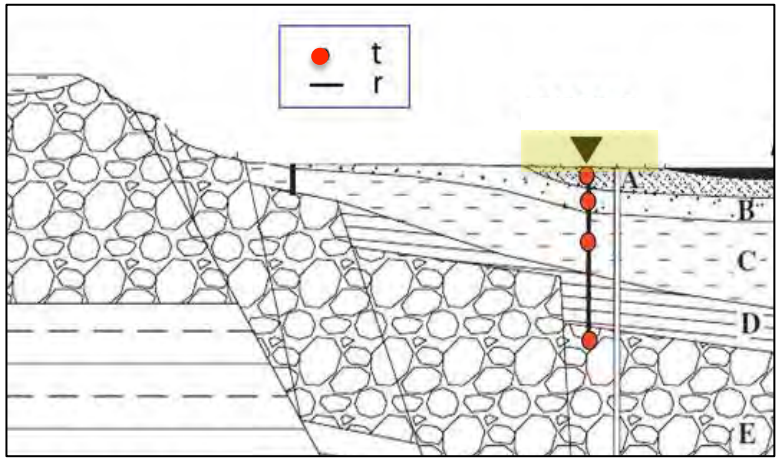


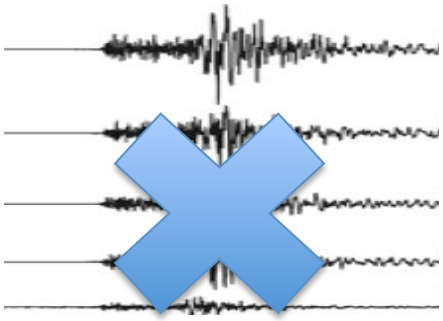
Borcherdt 1970

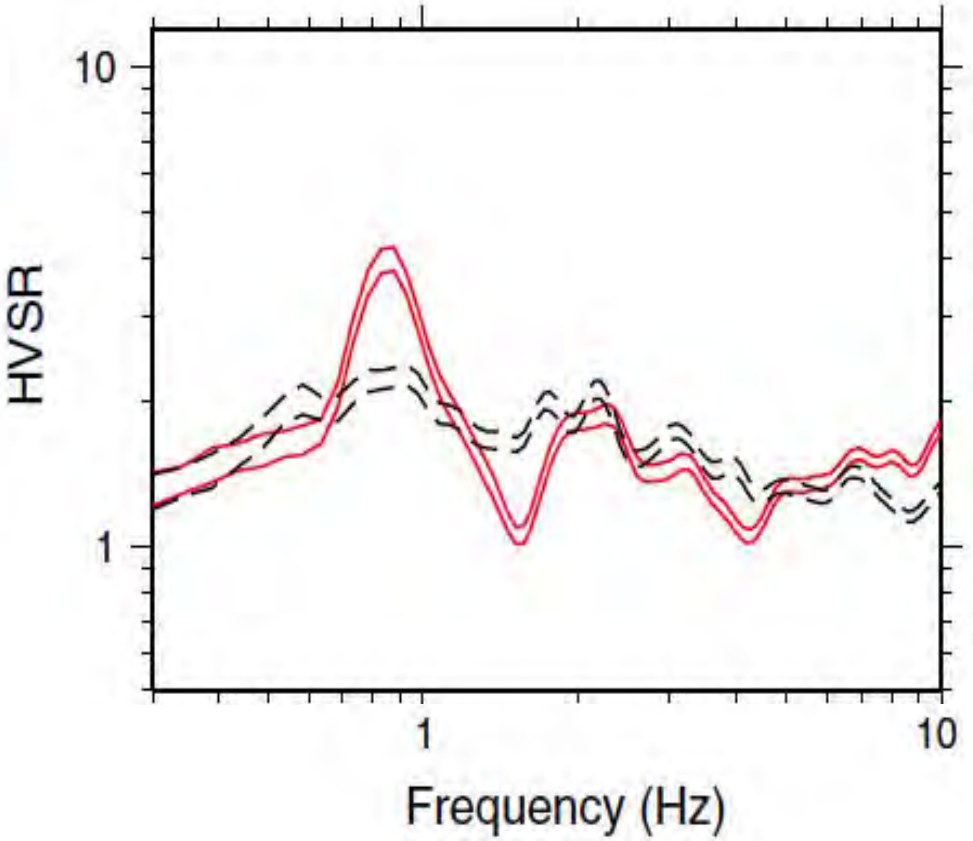
Ktenidou et al 2016

Amplification

Poor relation: H/V spectral ratio



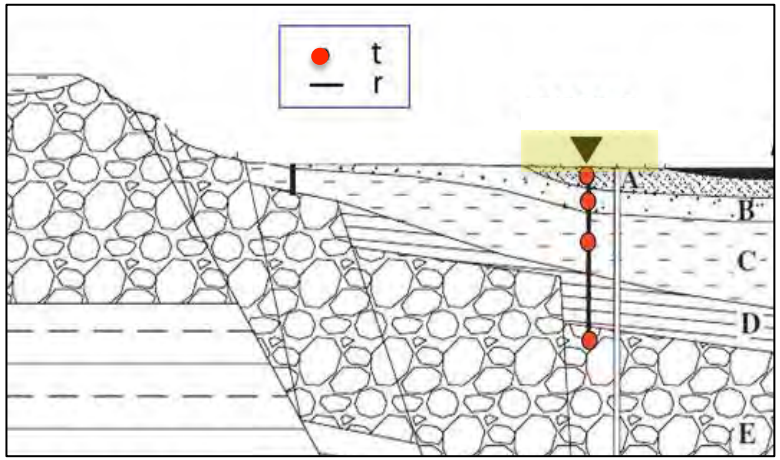


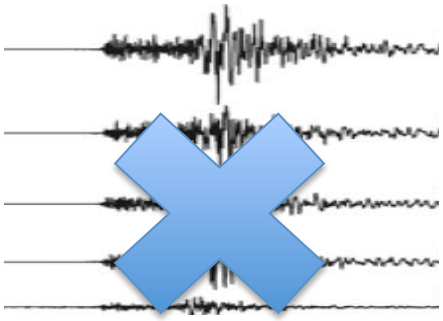


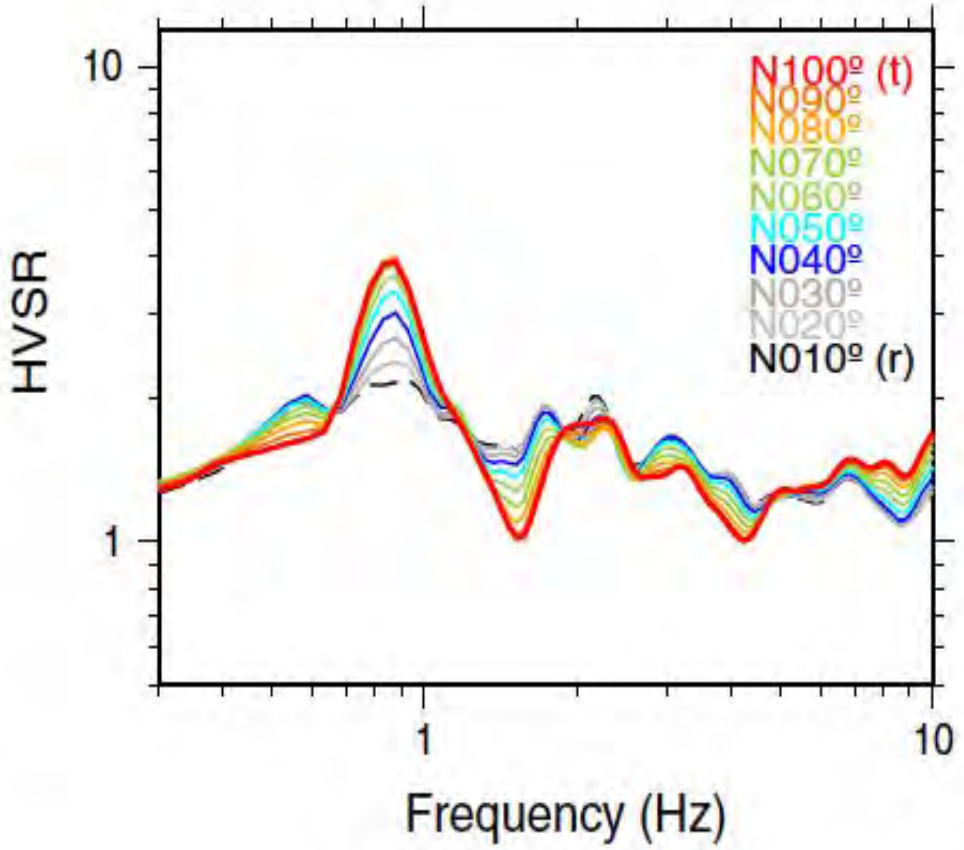
Lermo & Chávez-García 1993
Ktenidou et al 2016

Amplification

Directionality



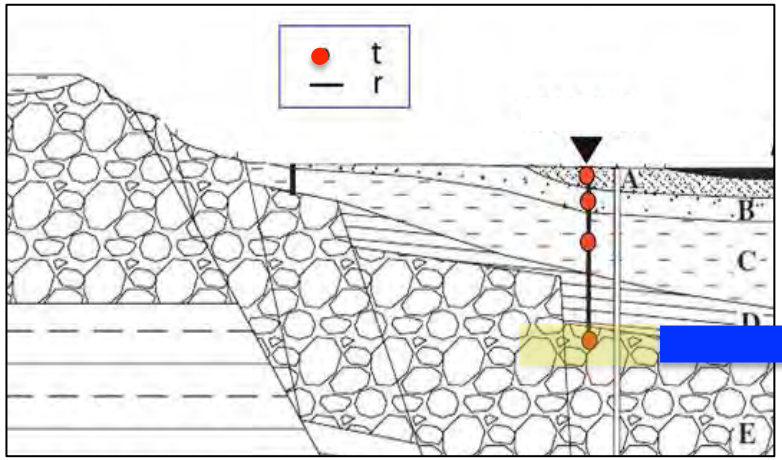


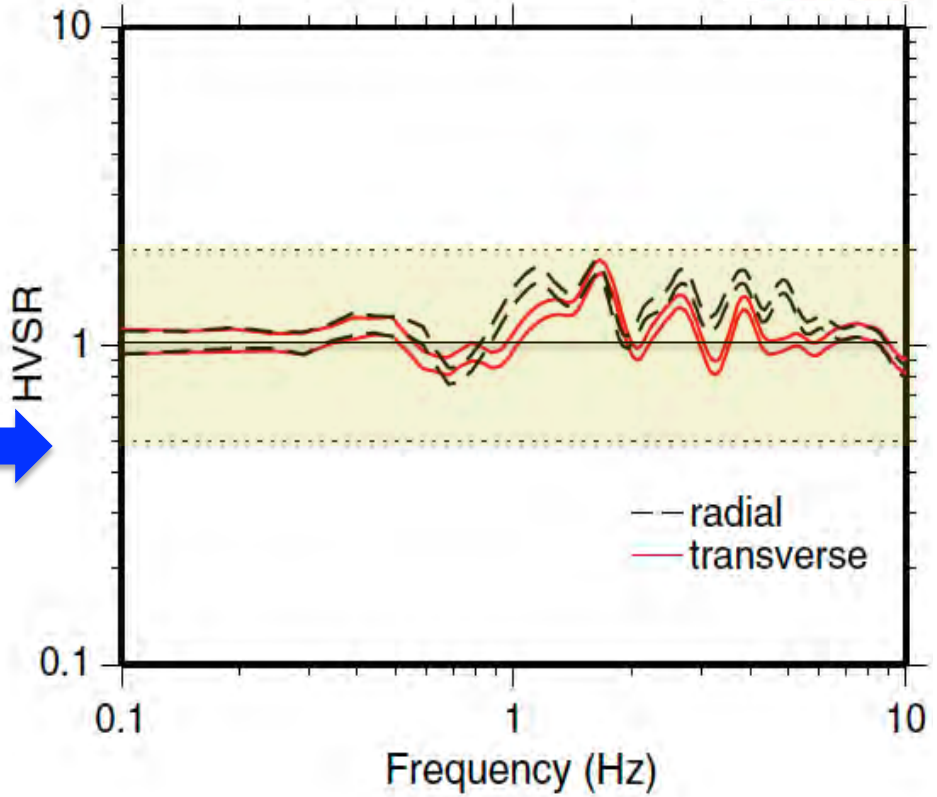


Ktenidou et al 2016

Amplification

Reference conditions





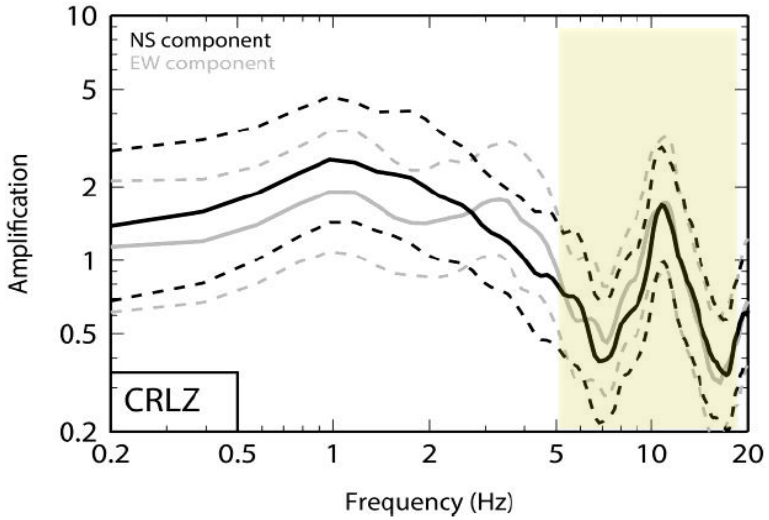
…is it always so??

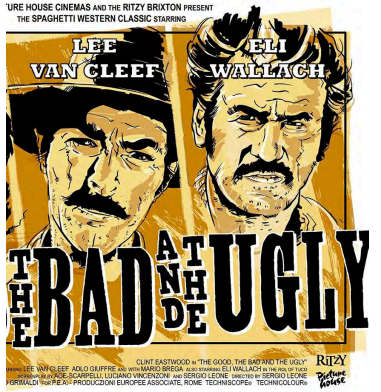
Ktenidou et al 2011

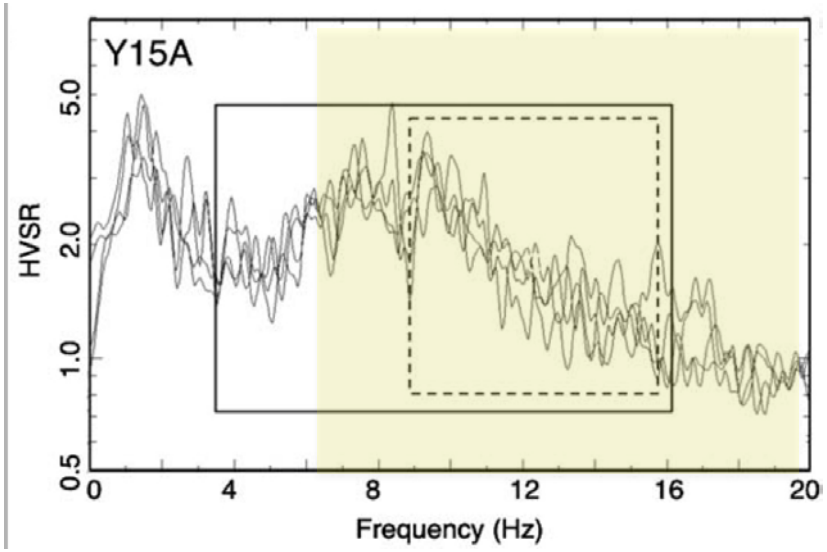
Rock will be rock?

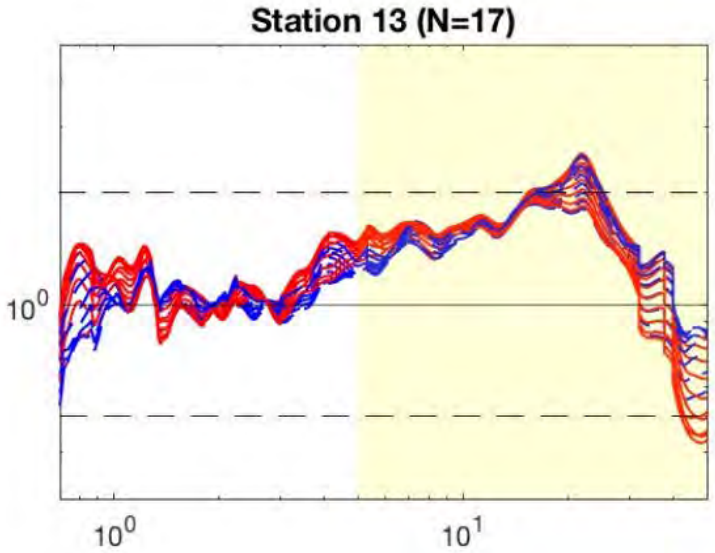
Rock sites, global

Arizona
New Zealand
CENA

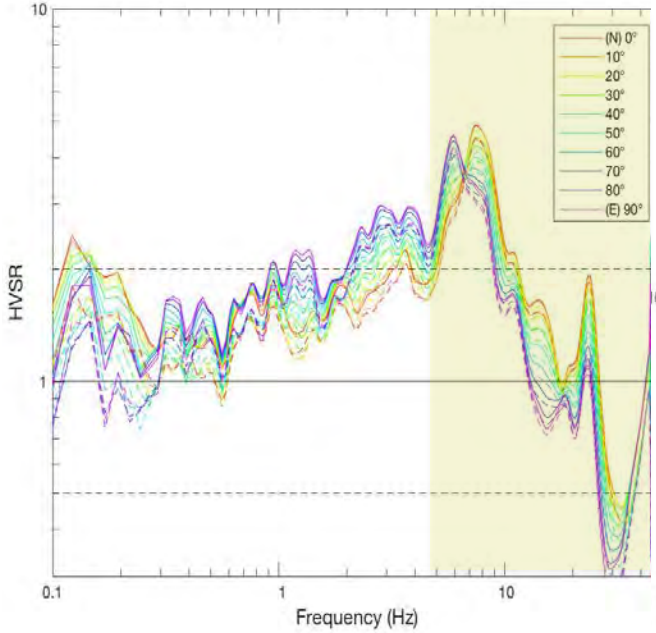


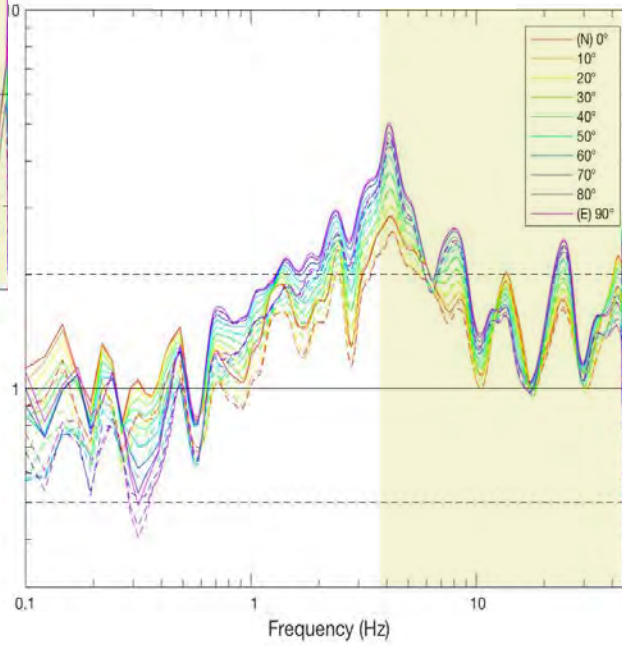


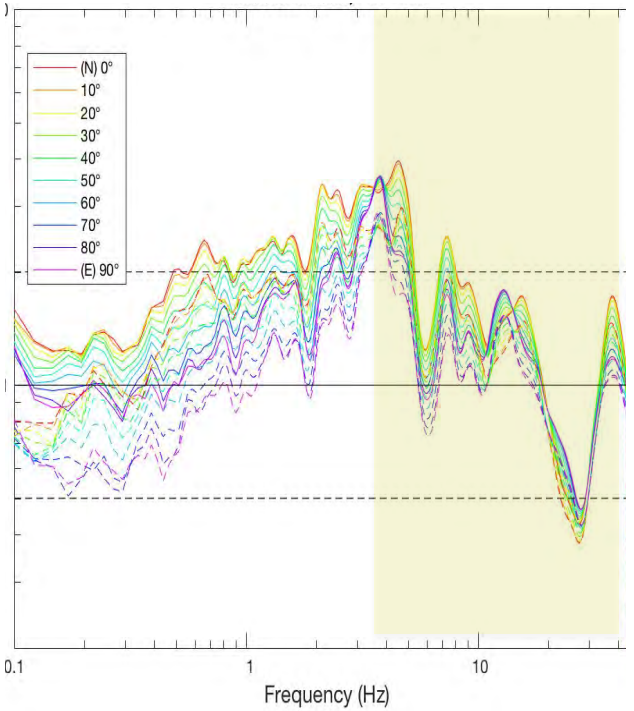


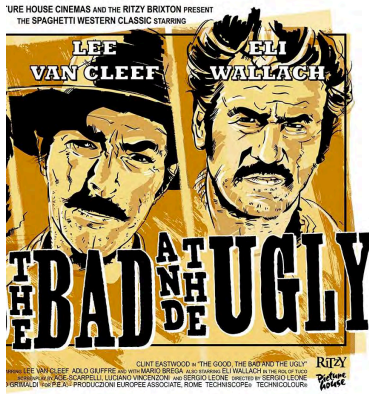


Rock sites, BB









Site classification

Seismic design codes

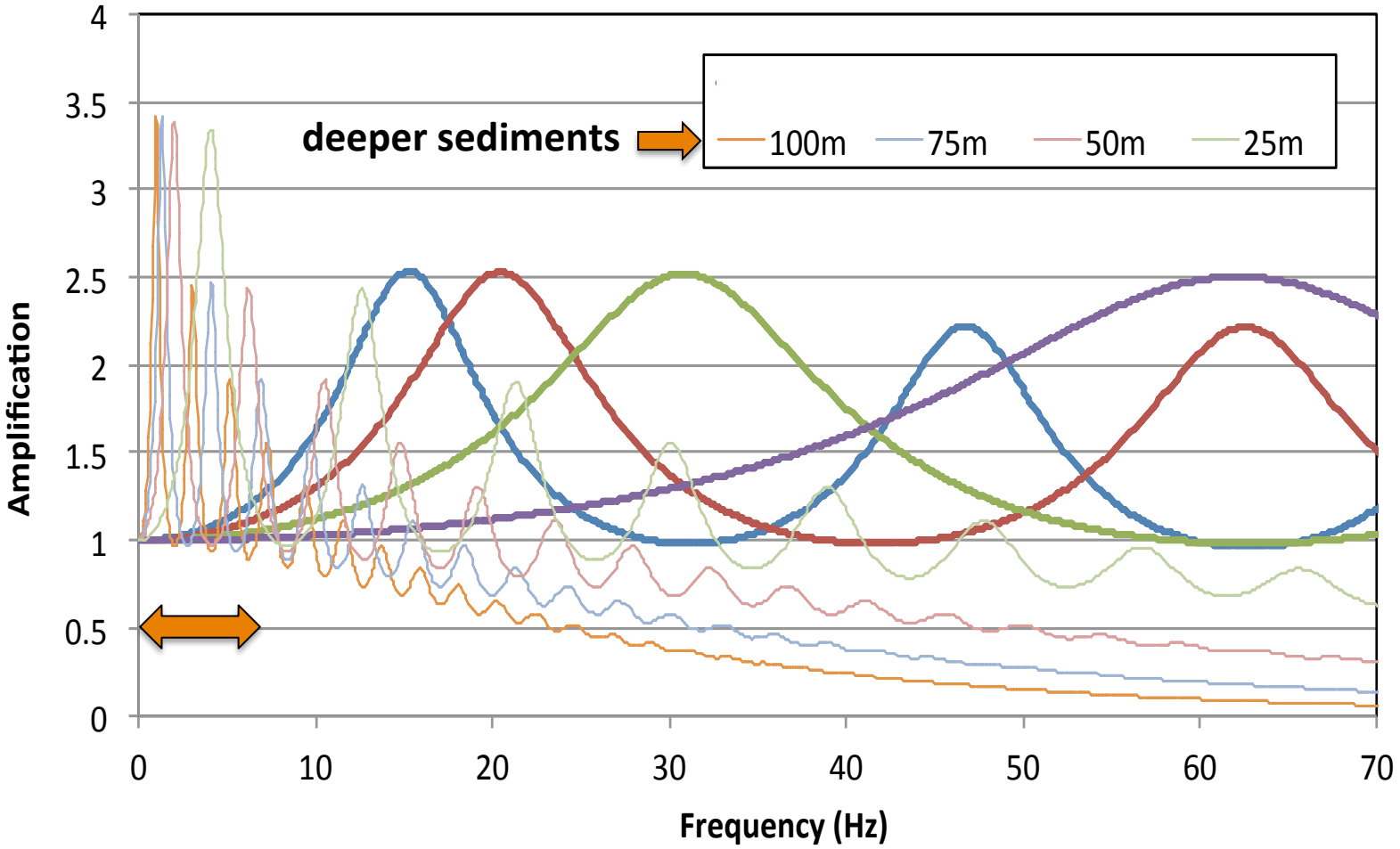
Class		Soil	Vs_{30} (m/s)	
UBC	EC8	General	BSCC	EC8
A	A	Hard rock	> 1500	>800
B		Rock	760- 1500	
C	B	Soft rock & Very dense soil	360- 760	360- 800
D	C	Stiff soil	180- 360	180- 360
E	D	Soft soil	<180	<180
F	E	Special soils		S_1<100 S_2 liq.

Ferucha 2009

Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface.

Resonances

Low (soil) vs. high (rock) resonant frequencies
Effect of weathered layer thickness



Resonances

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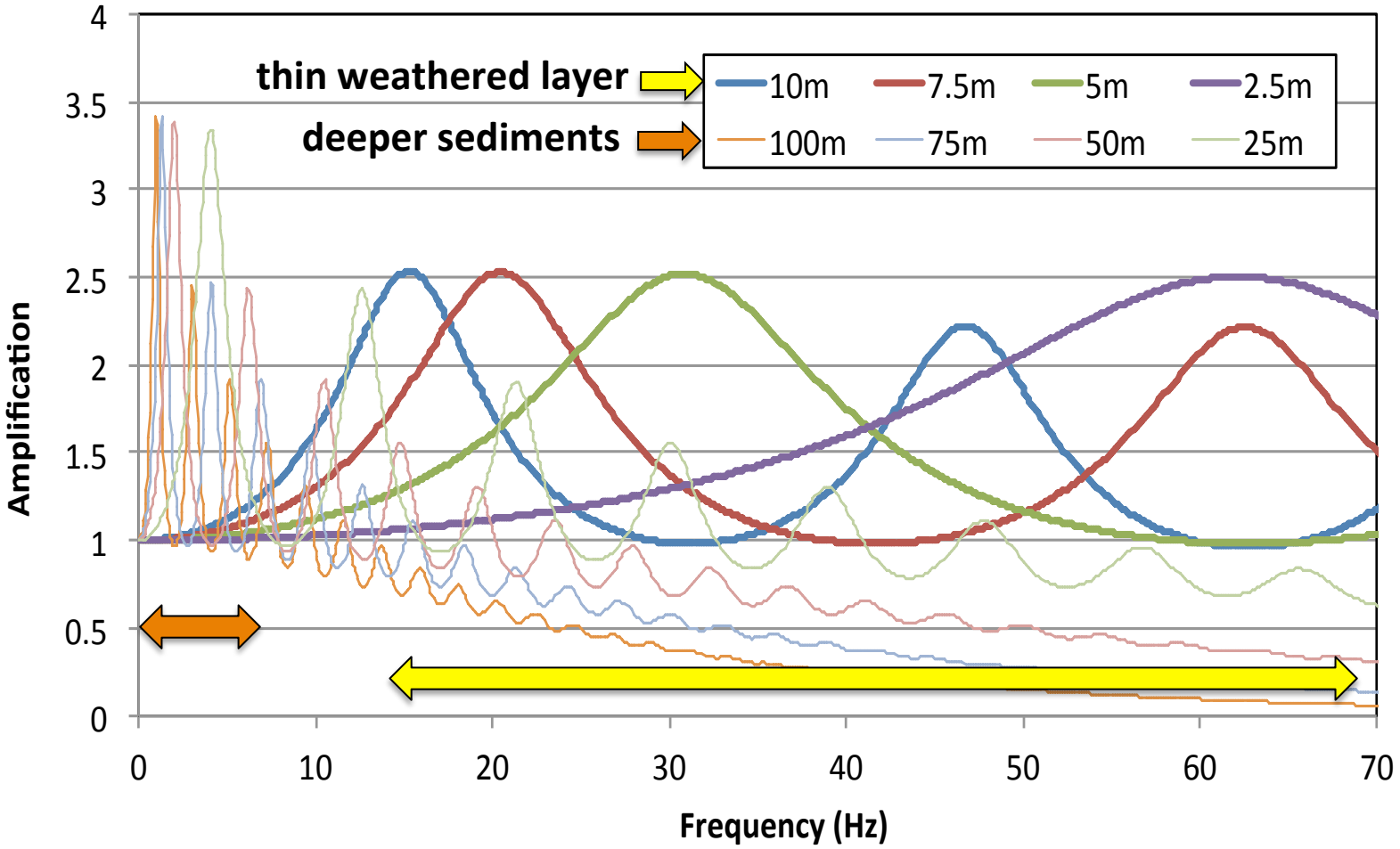

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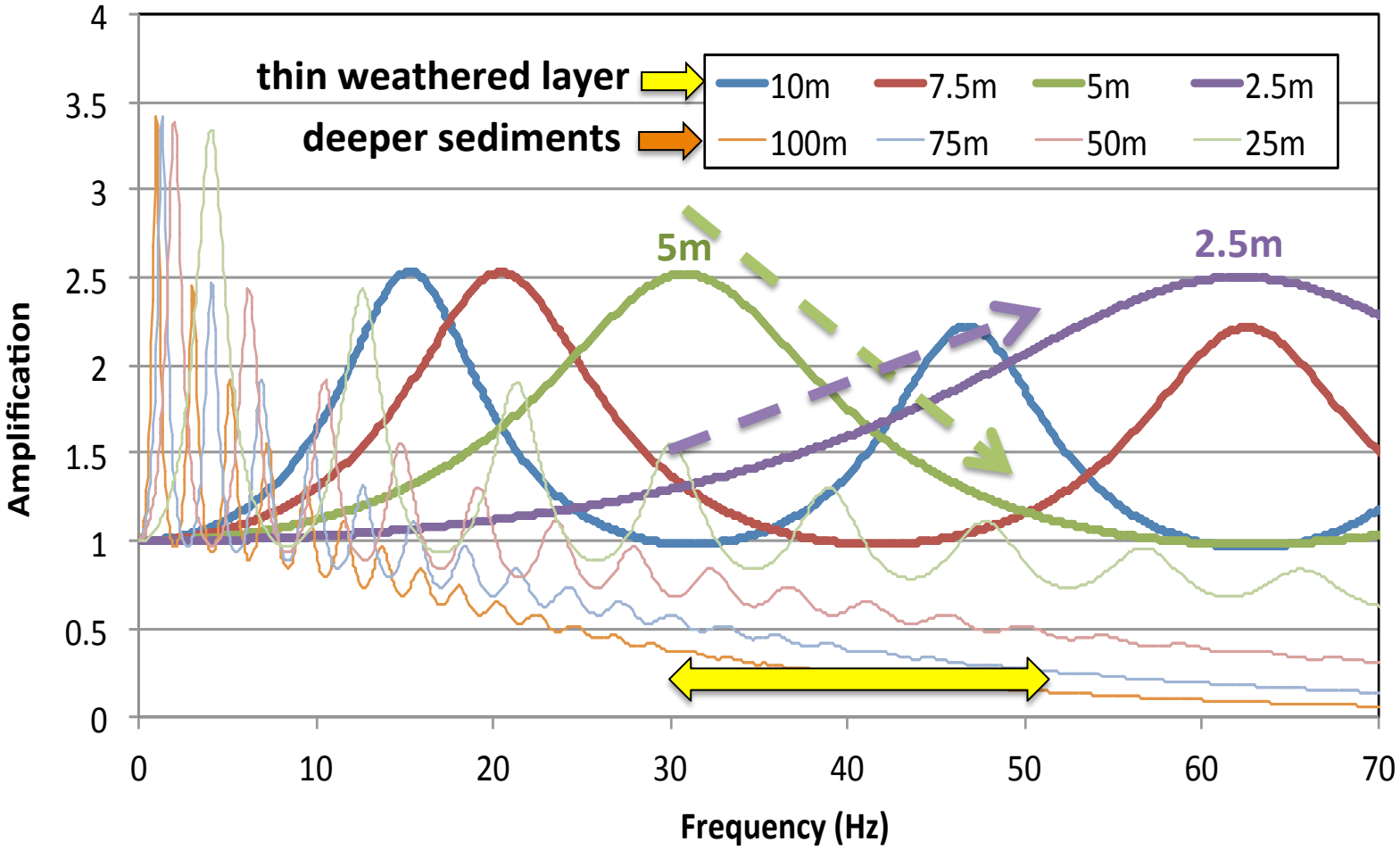
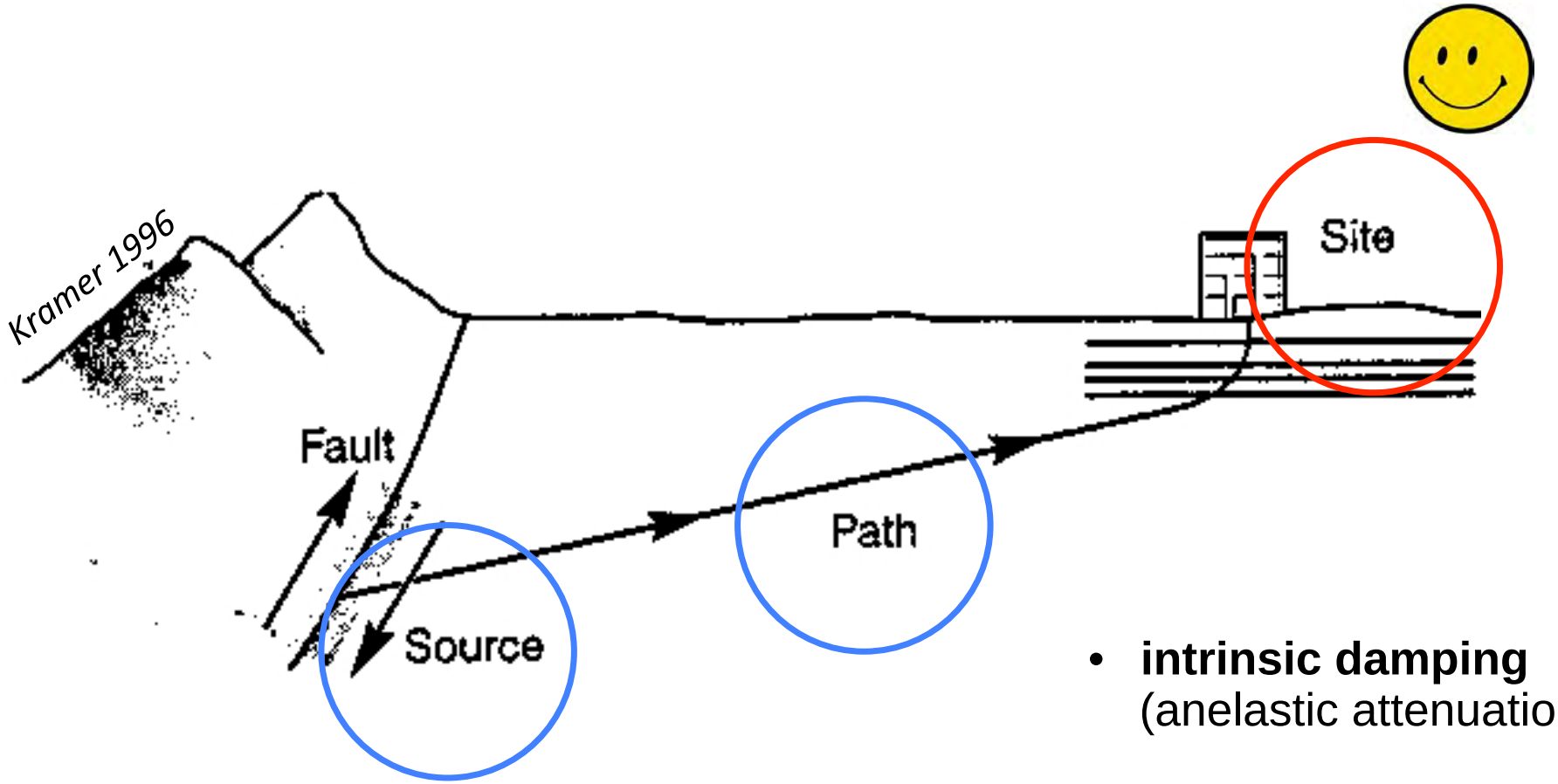


Attenuation

from amplification to attenuation



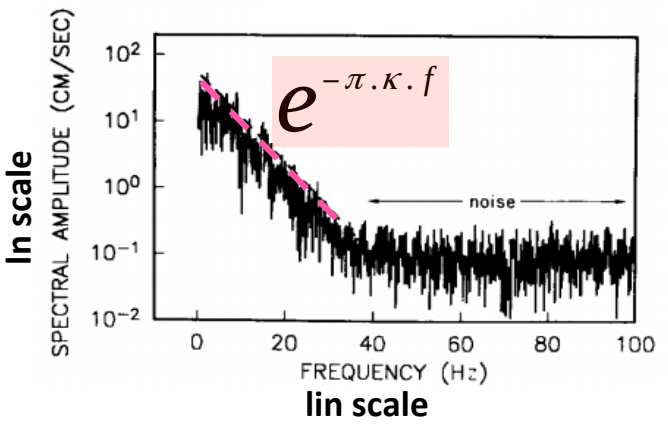
- **intrinsic damping** (anelastic attenuation)
- **frequency-dependent scattering** from small-scale heterogeneities

What is κ

Anderson & Hough (1984)

spectral decay parameter ‘κ’

$$A(f) = A_0 \cdot e^{-\pi \kappa f}, \quad f > f_E$$

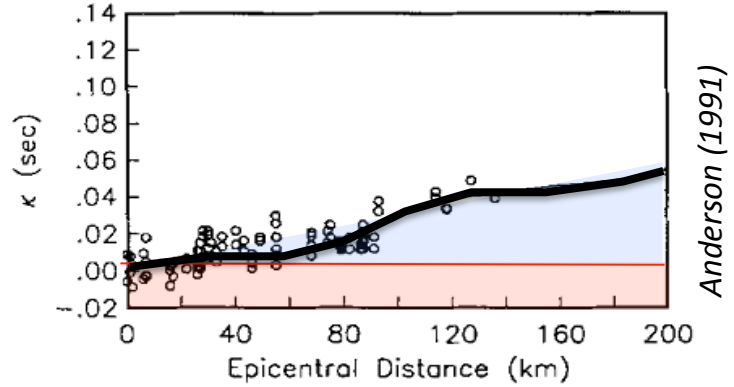


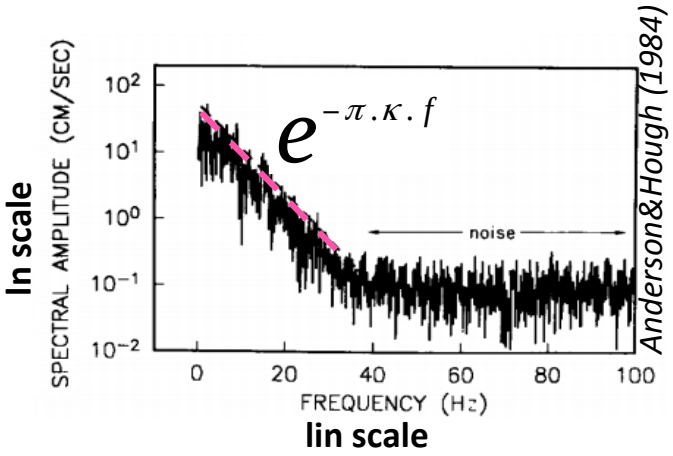
t*

What is κ

Anderson & Hough (1984)
spectral decay parameter 'κ'

$$A(f) = A_0 \cdot e^{-\pi \kappa f}, \quad f > f_E$$

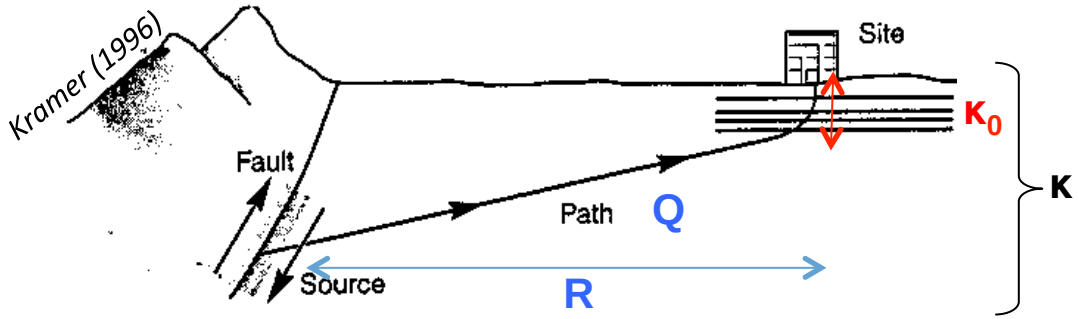




t*

$$\kappa = \kappa_0 + \tilde{\kappa}(R)$$

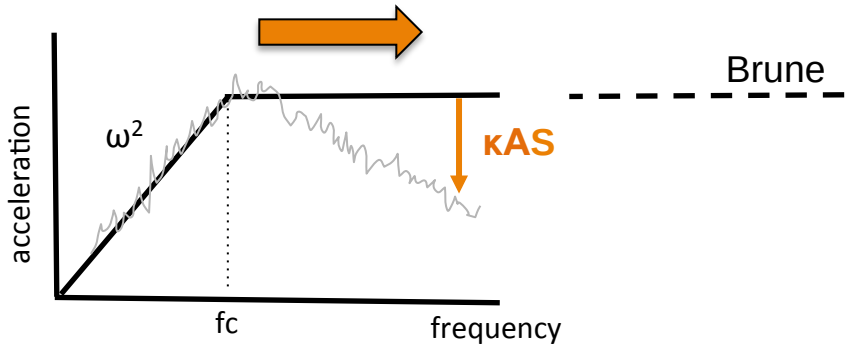
'site' 'régional'



Methods

K_{AS}

large M
small fc
go above



Anderson & Hough (1984)

Methods

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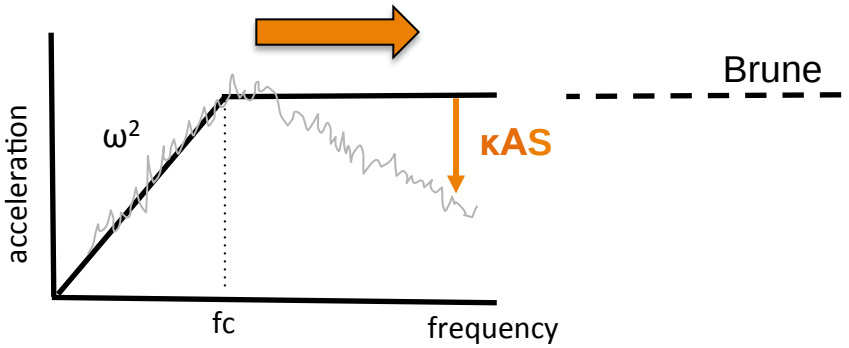
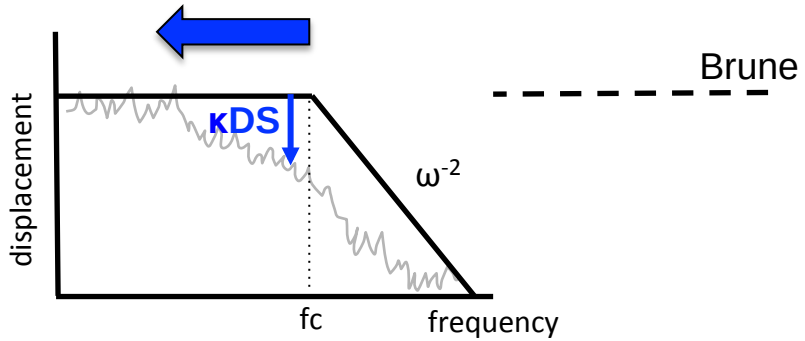


Anderson & Hough (1984)

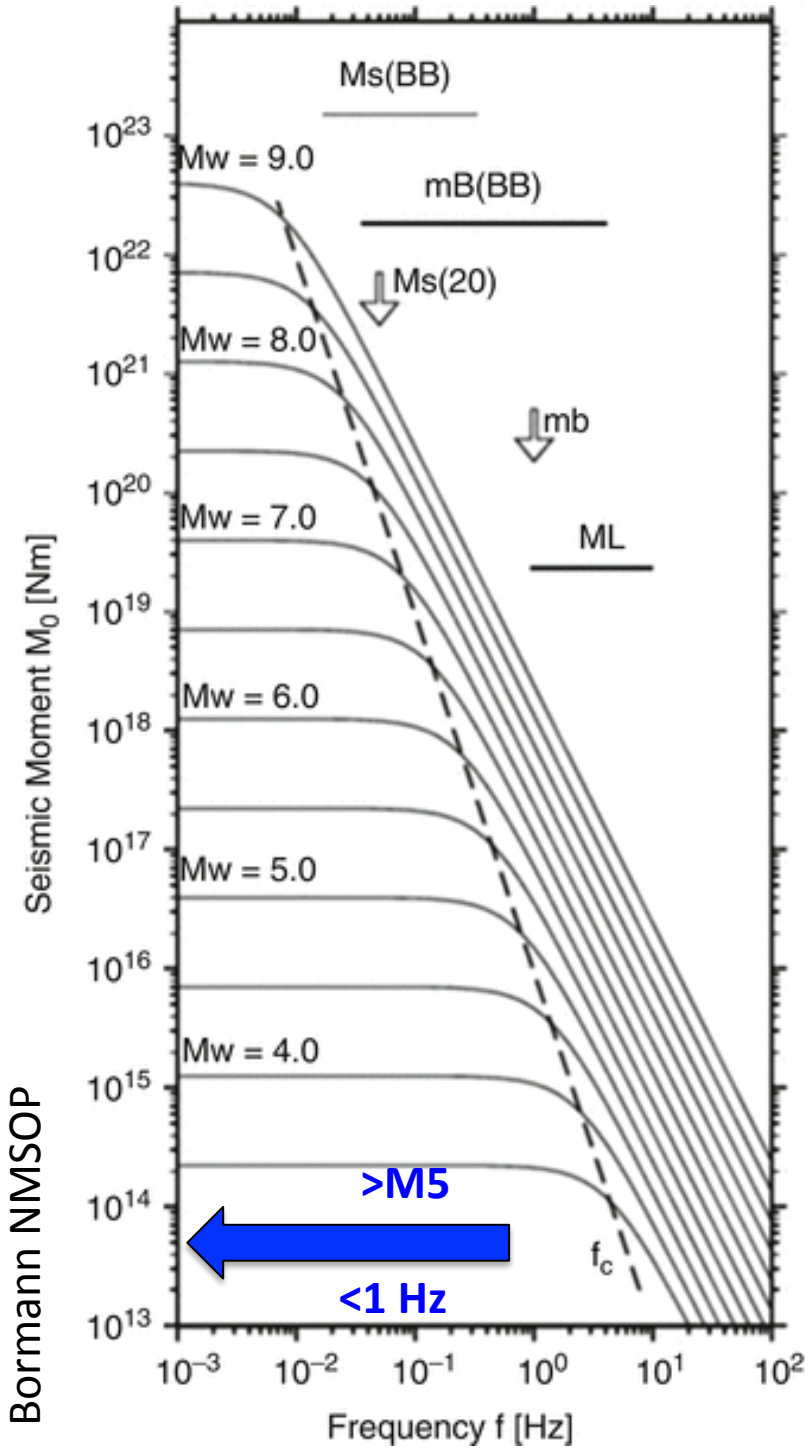
K_{DS}

(K_{mini})

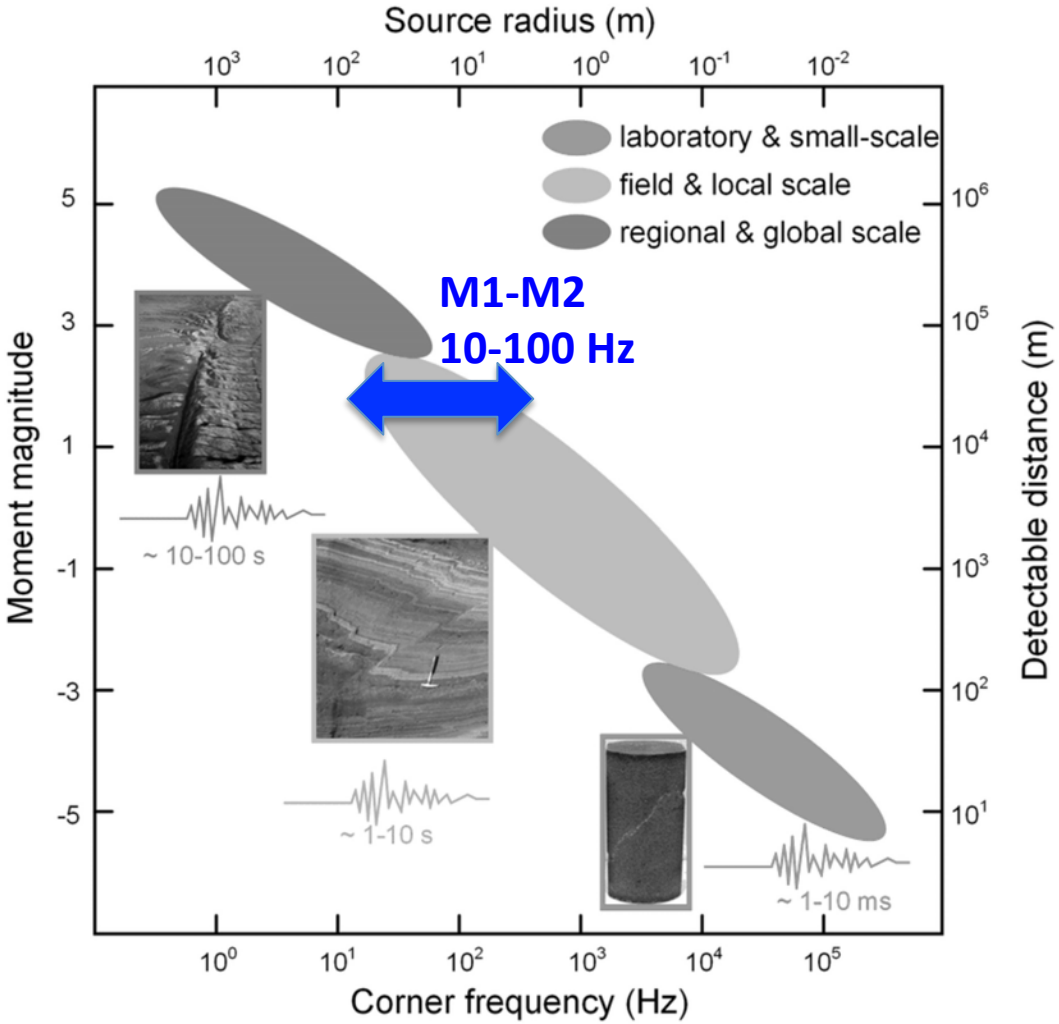
small M
large fc
go below



Biasi & Smith (2001)



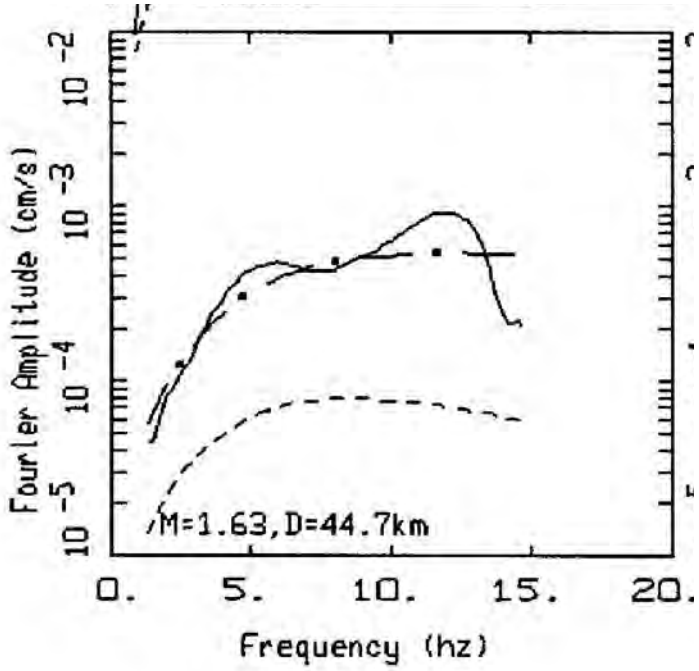
Bormann NMSOP



Li et al. (2020)

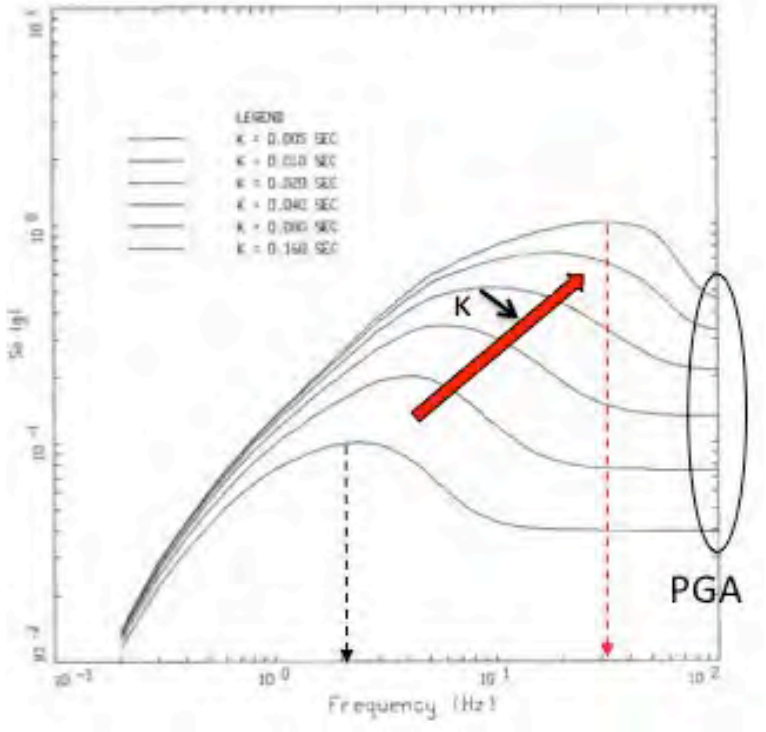
K_{bb}

Anderson & Humphrey (1991), Silva et al. (1996), etc



K_{resp}

Silva & Darragh (1995), Silva et al. (1998)



Kappa-related products: ΣIGMA1 project:

- First GMM with κ predictor variable (Laurendeau et al., 2013; Japan)
- Method taxonomy and Vs30 correlation uncertainty (Ktenidou et al., 2014; review paper)
- Uncertainty refinement in κ due to orientation, instrument/data frequency constraints, excitation level (Van Houtte et al., 2014; New Zealand)
- Conceptual physical model for κo with asymptotic regional values and scattering/damping effects (Ktenidou et al., 2015; Greece)
- κ for low-seismicity areas and trade-offs with Q (Edwards et al., 2015; Switzerland)
- Data processing/selection for large databases (Kishida et al., 2016 & Ktenidou et al., 2016; US/NGA)
- κ for low magnitudes and bandlimited data (Ktenidou et al., 2017; US)

What we think κ indicates

1 Small-strain intrinsic damping / quality factor (from site or lab tests) can be related to κ through Vs and layer thickness:

$$t^* = \int_{\text{path}} \frac{\mathrm{d}r}{V_s(z)Q(z)} = \sum_{i=1}^{N} \frac{H_i}{V_{si}Q_i} = \kappa_0$$

Campbell (2009)

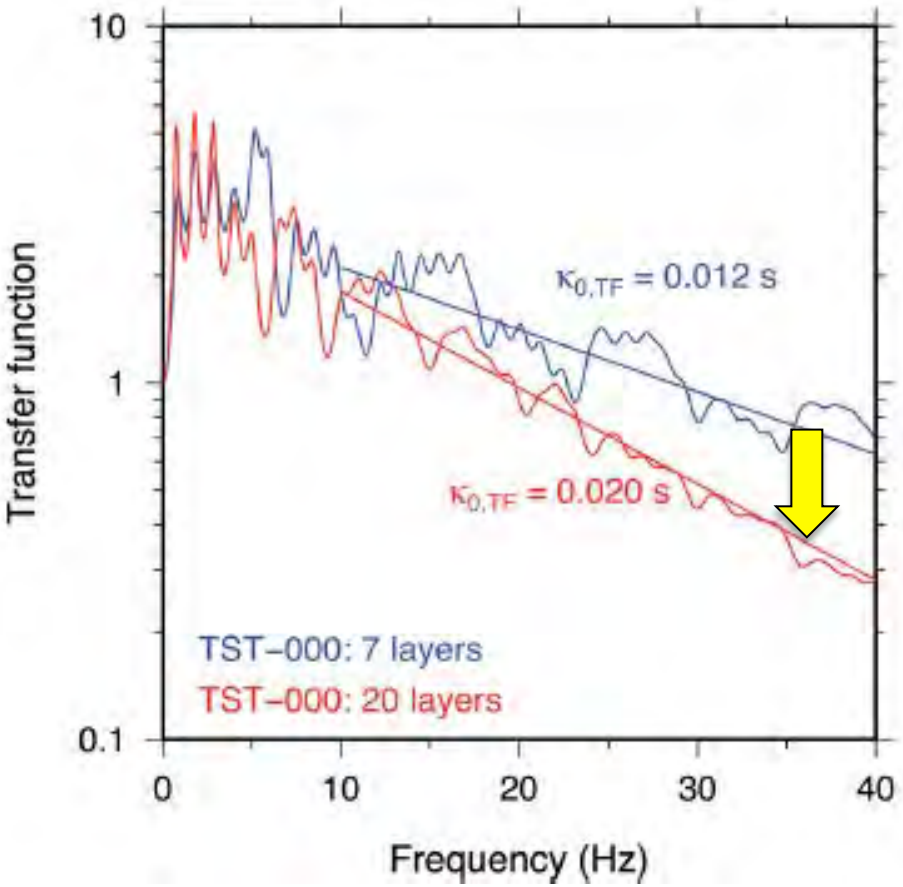
$$Q = \frac{1}{2\xi}$$

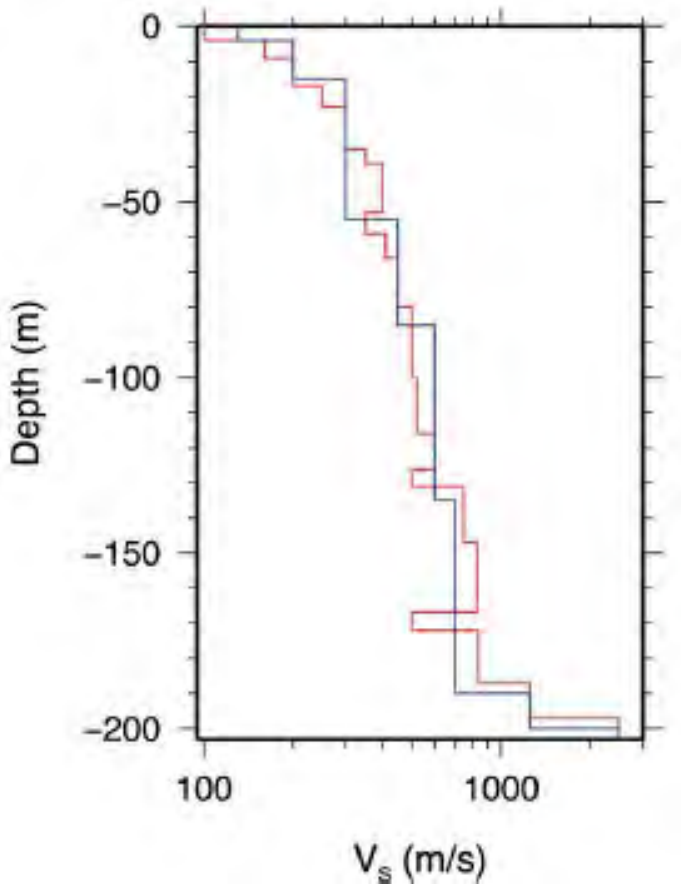
What we think κ indicates

2

Scattering from small-scale fluctuations is an additional source of site att.

adding layers/complexity/reversals to profile:





Ktenidou et al 2015a

What we think κ indicates

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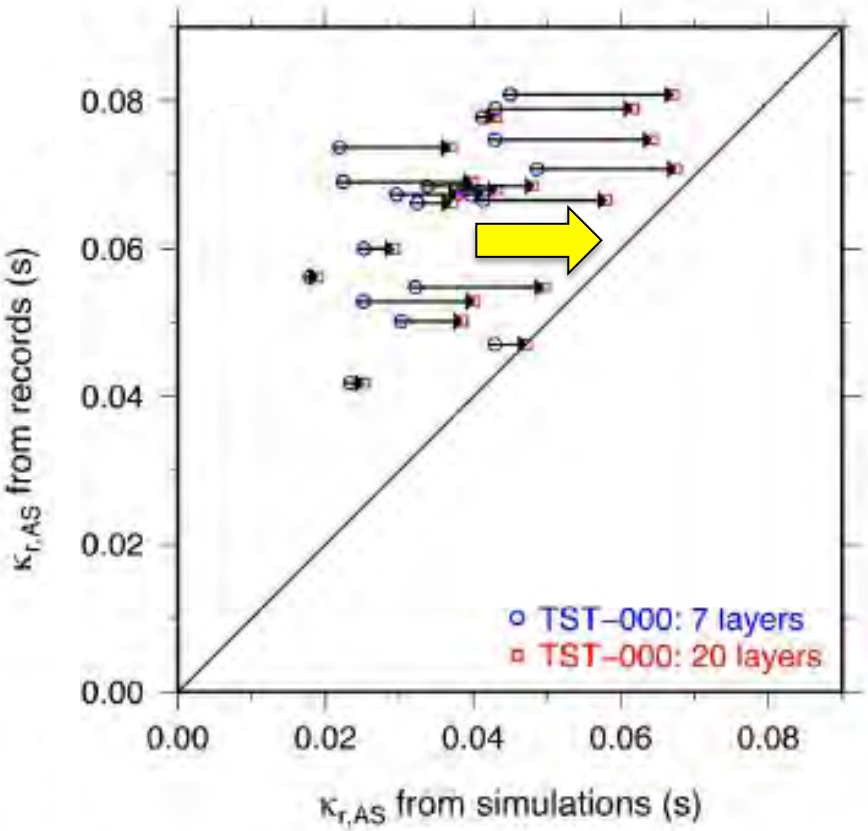
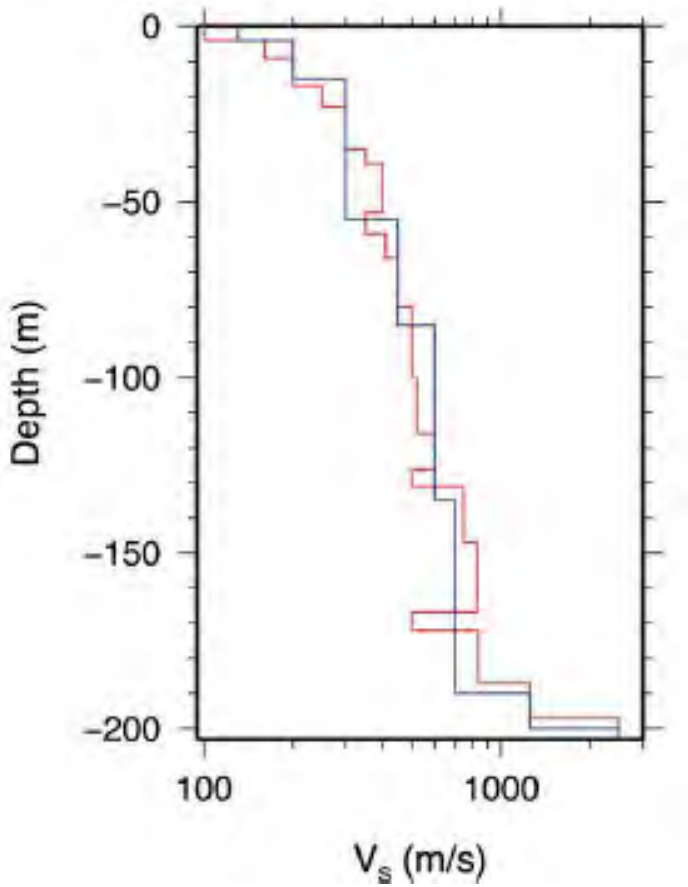
Scattering from small-scale fluctuations is an additional source of site att.

adding layers/complexity/reversals to profile:





Ktenidou et al 2015a

…But!

- S. Mazzotti: Geodesy and present-day deformation in France

"a model, not data!"

"requires expertise and multi-process models!"

What it also includes

Vs: a **material property** - can usually be directly measured to a satisfactory degree for a profile

κ: more intricate - characterizes a profile but is not a property per se! defined and measured as the **deviation from an assumed theoretical model**

'model' may include **source** (ω2), **path** (Q(f)), **site** (amp)

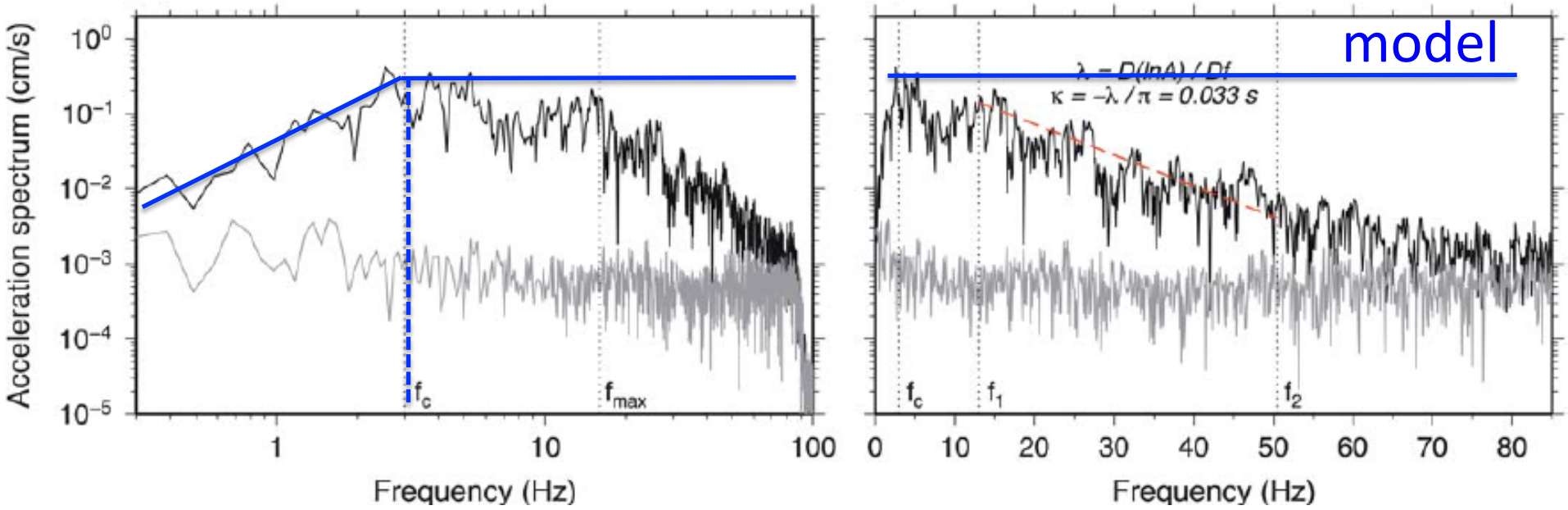


Table 1
The Main Families of Approaches Available for Estimating Site-Specific, Zero-Distance κ_0

Notation	Principle	Main References	Measurement/ Computation	Freq. Range	Q Effect	Zero-Distance?	Site-Specific?	Possible Uses
κ_{r_AS}	High-frequency decay of the *S*-wave Fourier spectrum	Anderson and Hough (1984), Hough and Anderson (1988)	Direct measurement on the *S*-wave Fourier **acceleration spectrum** above f_c, where it is theoretically flat	High (above f_c)	Present	No	No, extrapolate to $R_e = 0$ for κ_{0_AS}	Host-to-target adjustment of GMPEs
κ_{0_TF}	Analogy to high-frequency decay	Frankel *et al.* (1999), Drouet *et al.* (2010)	Direct measurement on the site amplification **transfer function**	High (above resonant peaks)	Removed	Yes	Yes, ready to use	Host-to-target adjustment of GMPEs
κ_{r_SS}	Analogy to high-frequency decay	Margaris and Boore (1998), Oth *et al.* (2011)	Direct measurement on the **source spectrum** (after removal of Q and site amplification effects) and averaging across all spectra recorded at the same site	High (above f_c)	Removed (to 5 km)	Yes	No, average over events for κ_{0_SS}	Host-to-target adjustment of GMPEs
κ_{r_IRVT}	Analogy to high-frequency decay	Al Atik *et al.* (2014)	Direct measurement on the Fourier spectrum derived from **IRVT** as compatible with the GMPE response spectrum	High (above f_{peak})	Ignored (use of small Rs in GMPE)	Yes	No, average over M–R_e scenarios for κ_{0_IRVT}	Host-to-target adjustment of GMPEs (host only)
κ_{0_RESP}	Peak and shape of the normalized acceleration response spectrum	Silva and Darragh (1995), Silva *et al.* (1998)	Fitting of stochastically simulated **response spectra** (where κ_0 is a model input parameter) coupled with site amplification to observed response spectra	Entire band	Removed	Yes	Yes, ready to use	Stochastic simulations
κ_{r_BB}	Inversion of the entire frequency band of the spectrum	Anderson and Humphrey (1991), Humphrey and Anderson (1992), Silva *et al.* (1997), Edwards *et al.* (2011)	**Broadband** inversion of the entire spectrum for source, path and site terms (usually for moment, f_c and κ_0)	Entire band	Present	No	No, extrapolate to $R_e = 0$ for κ_{0_BB}	Stochastic simulations
κ_{r_DS}	Small magnitudes (strong trade-off with source)	Biasi and Smith (2001)	Direct measurement on low-frequency part of the Fourier **displacement spectrum** (much below f_c) where it is theoretically flat	Below f_c	Present	No	No, extrapolate to $R_e = 0$ for κ_{0_DS}	Host-to-target adjustment of GMPEs (target only: measure rather than infer from V_{S30})

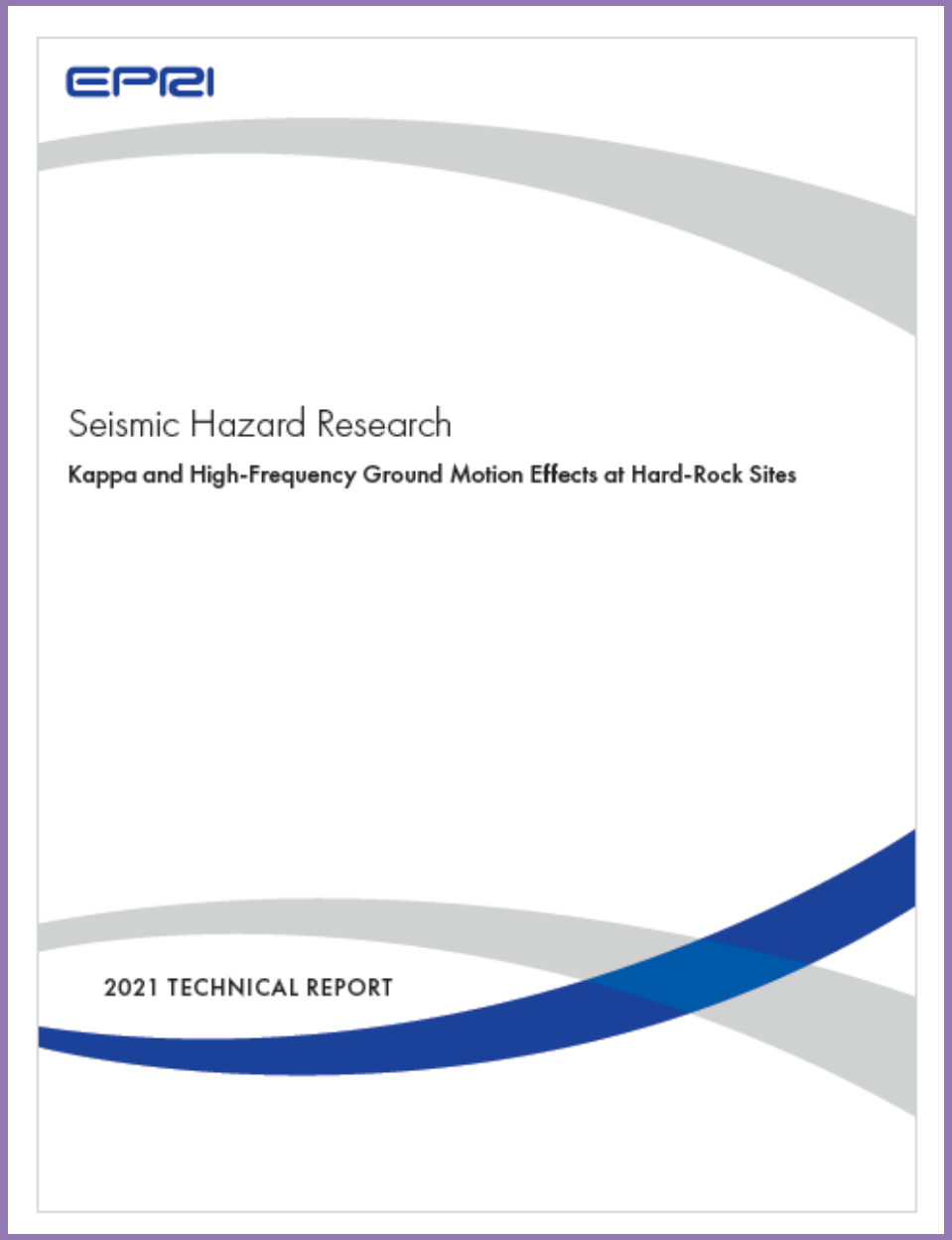
This table summarizes the notation proposed herein for each approach (or family of approaches), its main principle, the main references, a short description of the approach, the frequency range used, how Q and distance are accounted for, and the possible applications, which, in the opinion of the authors, are most compatible with the approach.

Taxonomy

All methods have trade-offs - all methods assume models

Ktenidou et al. (2013)

EPRI/PEER/UCLA/EDF project



Principal Investigators
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Principal Investigator
Y. Bozorgnia

Magic number?

~ 0.006 ± 0.002 s

Reference rock conditions (Vs>2800 m/s)

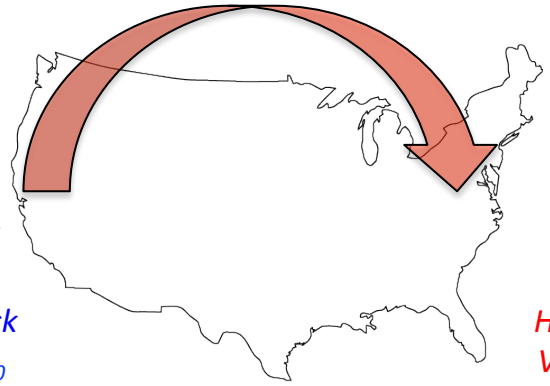
Table 1 **Summary of hard-rock site kappa (κ_0) estimates in CENA.**

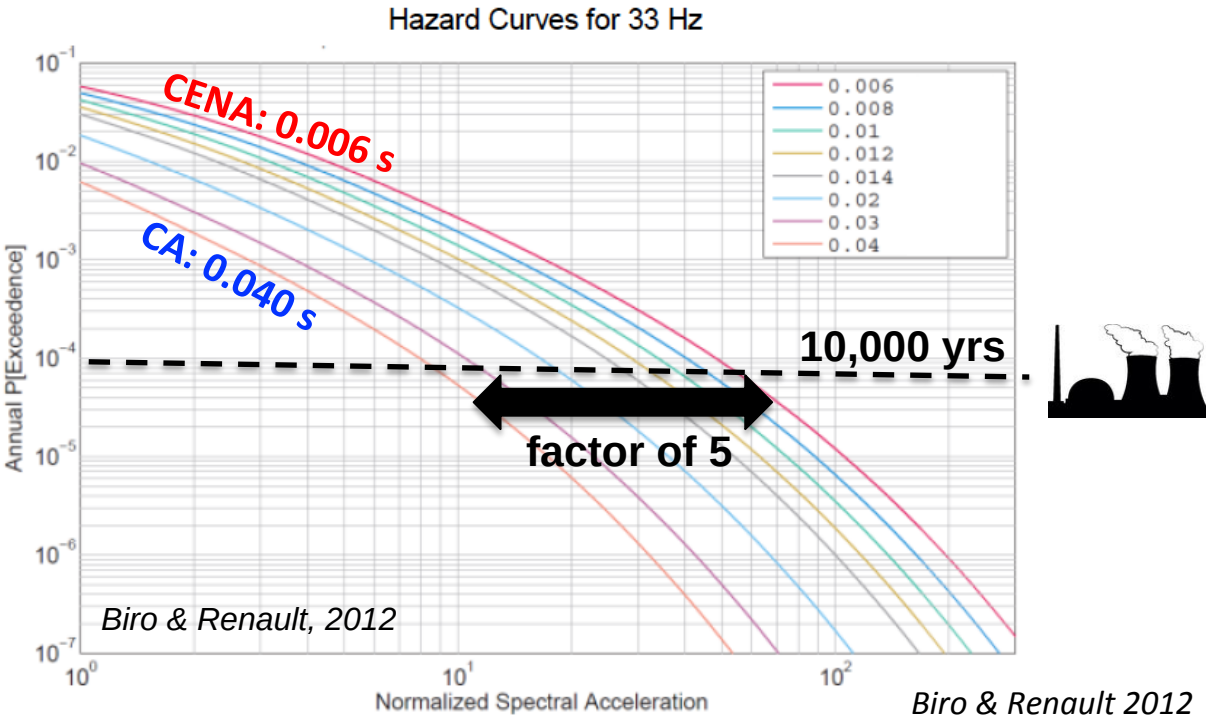
Source	Mean (sec)	Range (sec)	Comments
Atkinson [1984]	0.006	–	Based on $f_{max} = 50$ Hz
Atkinson [1984]	0.009	–	Based on $f_{max} = 35$ Hz
Toro and McGuire [1987]	0.008	–	Based on $f_{max} = 40$ Hz
Darragh et al. [1989]	0.006	–	–
Silva and Darragh [1995]	0.007	0.004 – 0.016	Including Monticello Res.
Silva and Darragh [1995]	0.006	0.004 – 0.008	Excluding Monticello Res.
Atkinson [1996]	0.002	0 – 0.004	4 – 30 Hz
Chapman et al. [2003]	0.009	0 – 0.018	Monticello Reservoir
Campbell [2009]	0.004	0 – 0.007	12 – 22 Hz [Atkinson 1996]
Atkinson and Boore [2006]	0.005	0 – 0.01	Data from Atkinson [2004]

Campbell et al., 2014 (PEER)

Effect on hazard

adjusting **soft to hard rock**



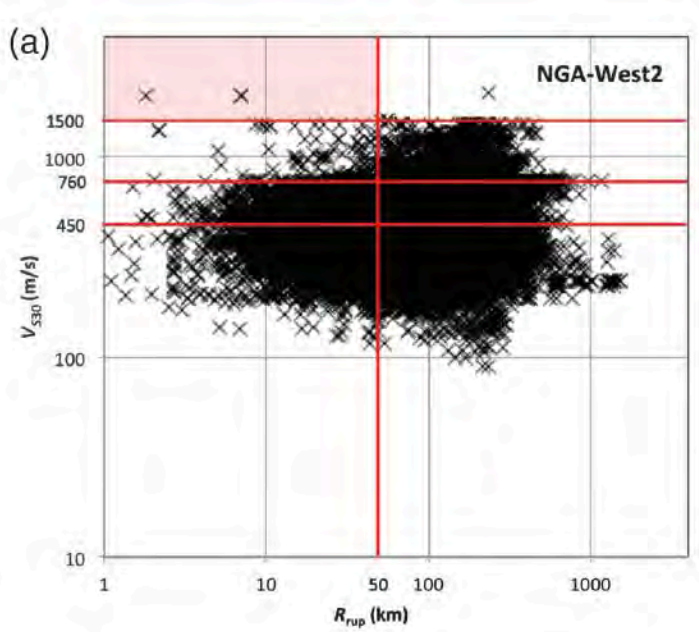


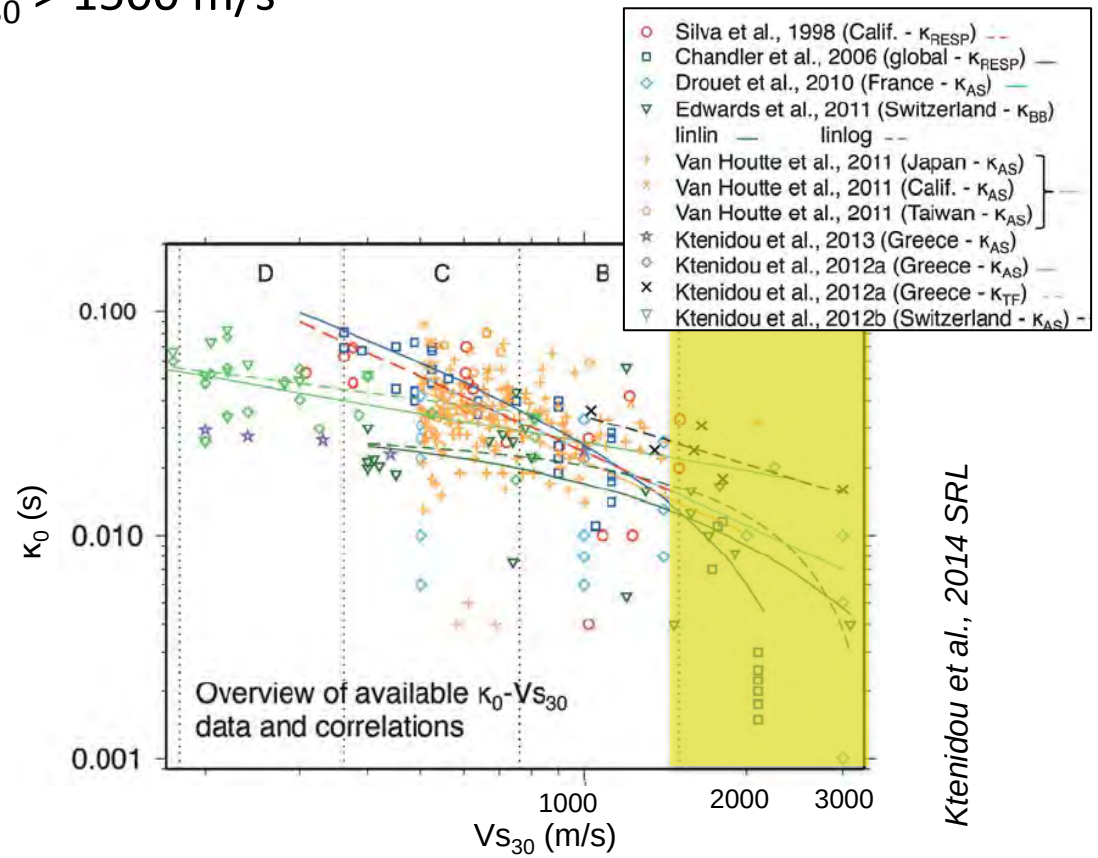
Biro & Renault 2012

Problem 1

Typical HR κ_0 values are mostly from literature (analytical)
Not enough hard-rock data in typical global databases

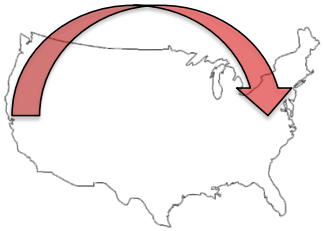
Large scatter & few data for Vs_{30} > 1500 m/s





Ktenidou et al., 2014 SRL

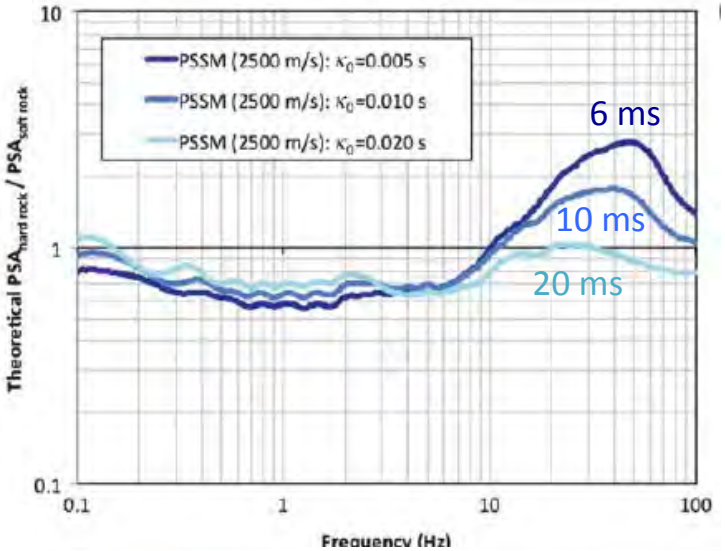
Problem 2

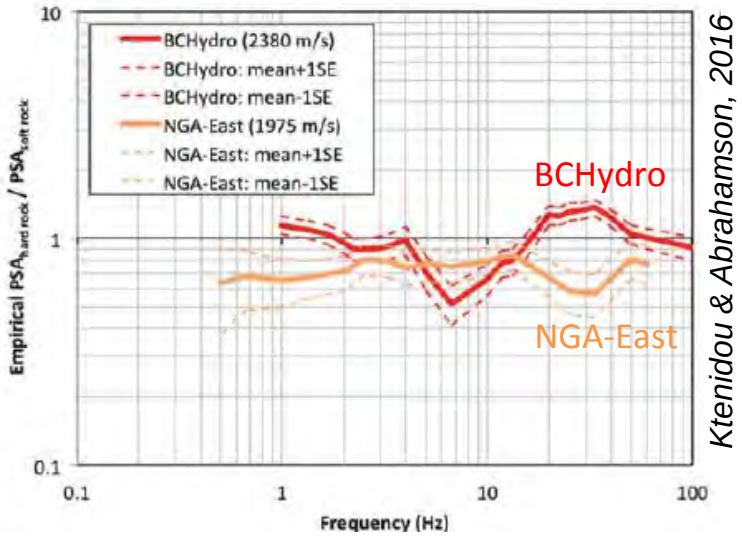


>10 Hz, scaling factors for PSA show discrepancy between analytical models and data

Predicted GM amplification is larger at HFs than what is observed

Is κ all damping? (no)





Ktenidou & Abrahamson, 2016

models typically assume small κ

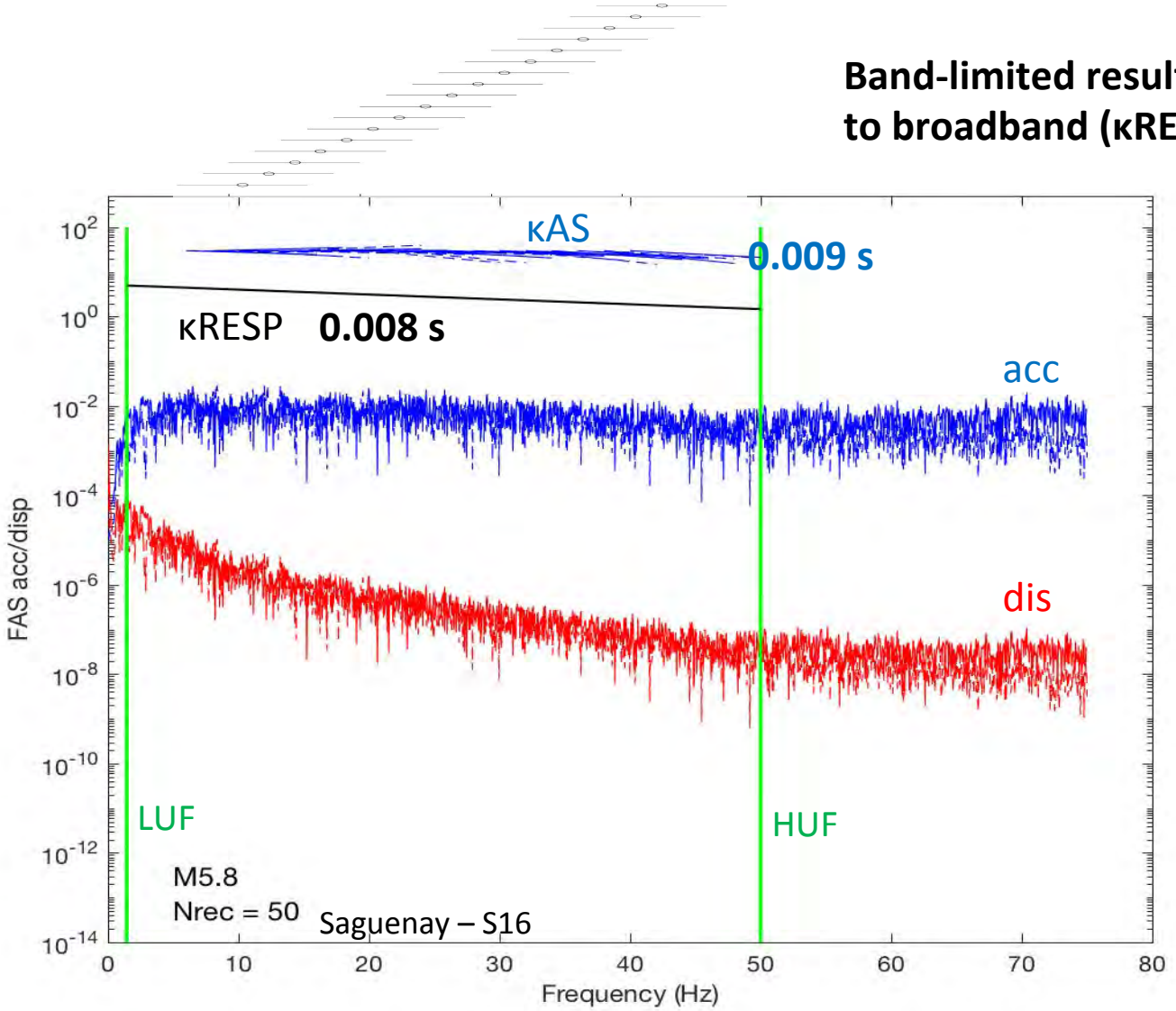
data imply larger κ

Stage 1

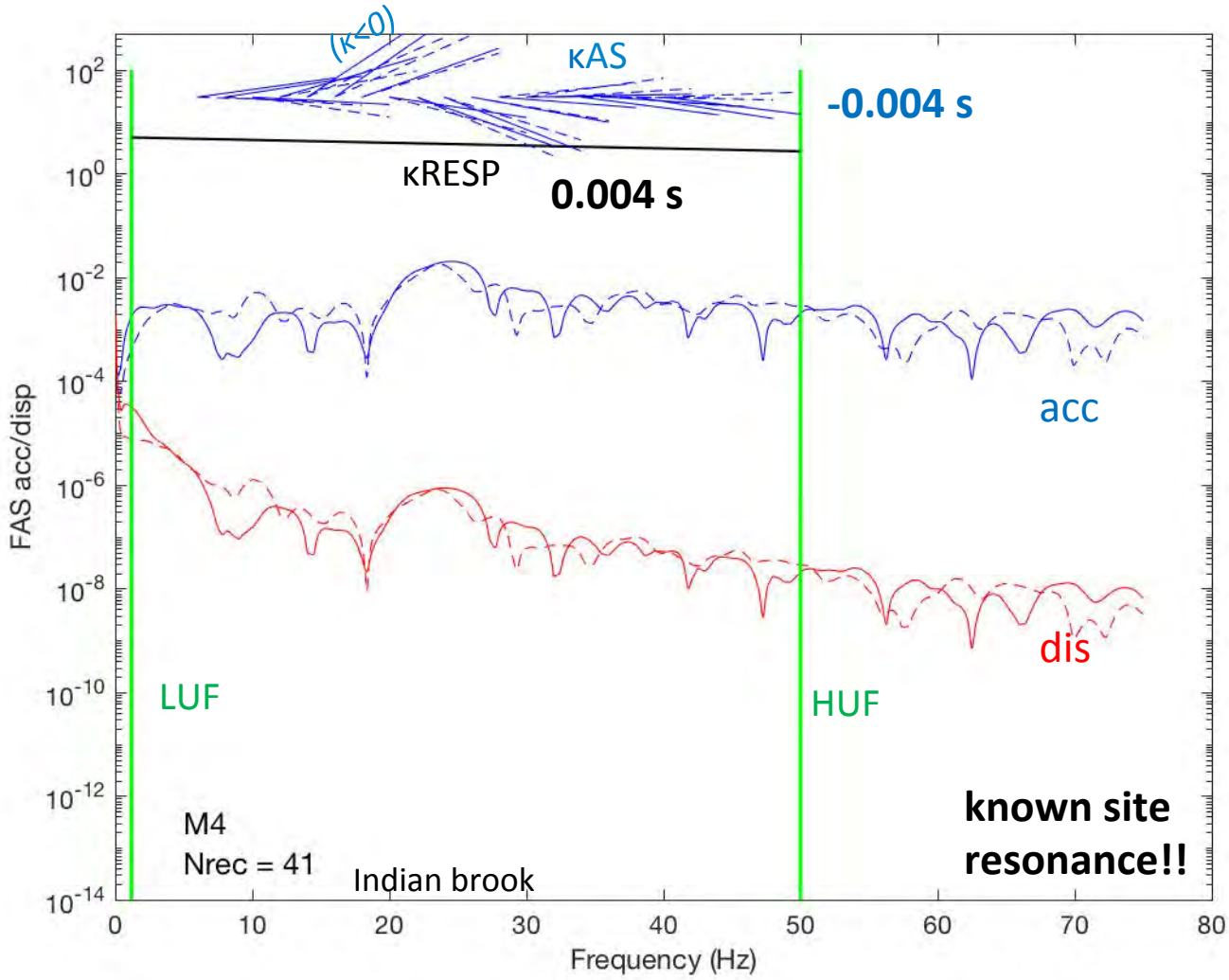
EPRI 1995 revisit

E.g. of **low κAS variability** with moving window

Band-limited result (κAS) similar to broadband (κRESP) result



E.g. of **high κAS variability** with moving window

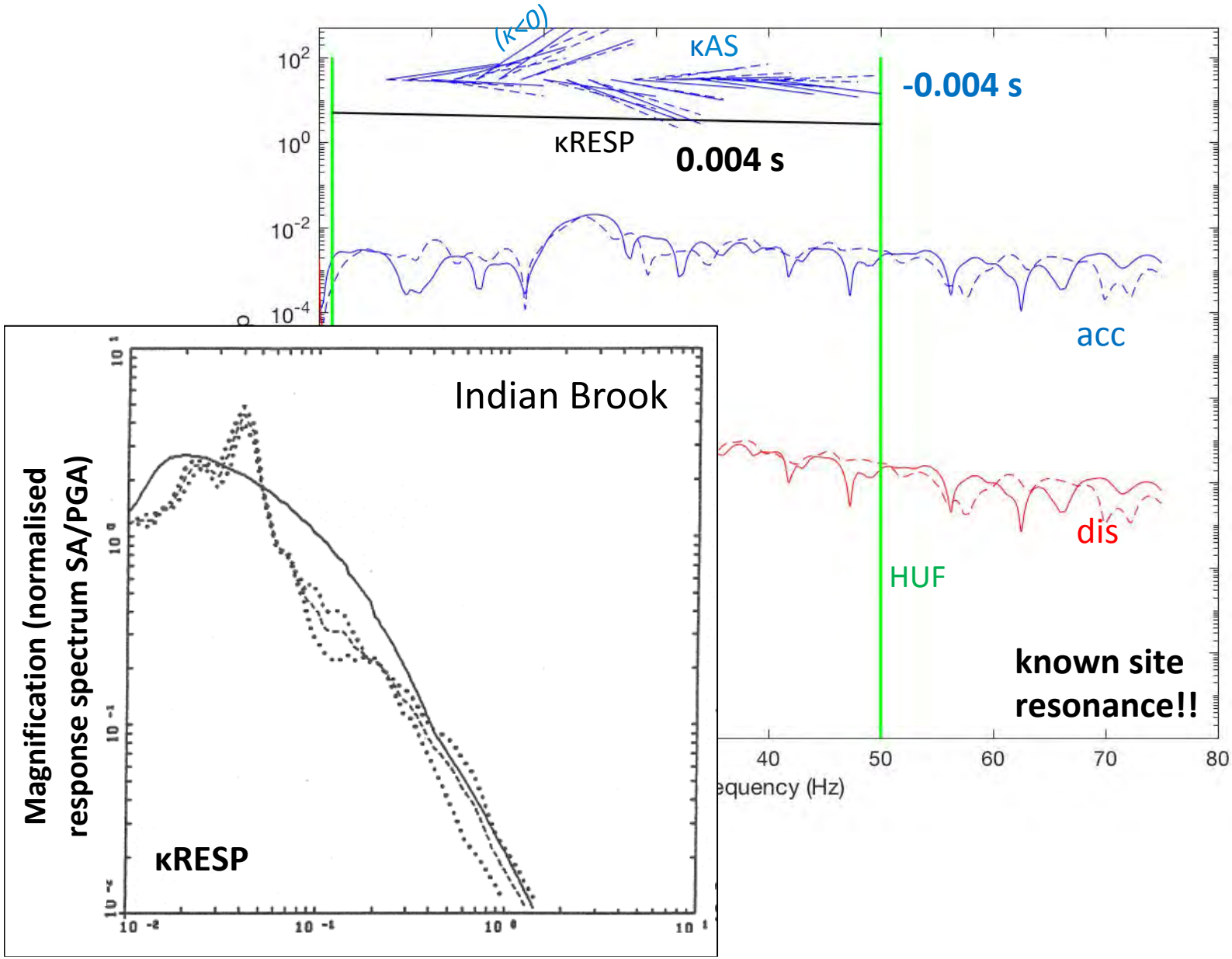


amp vs. damp!

➔ ***Resonance known to affect κ (Parolai & Bindi, 2004)***

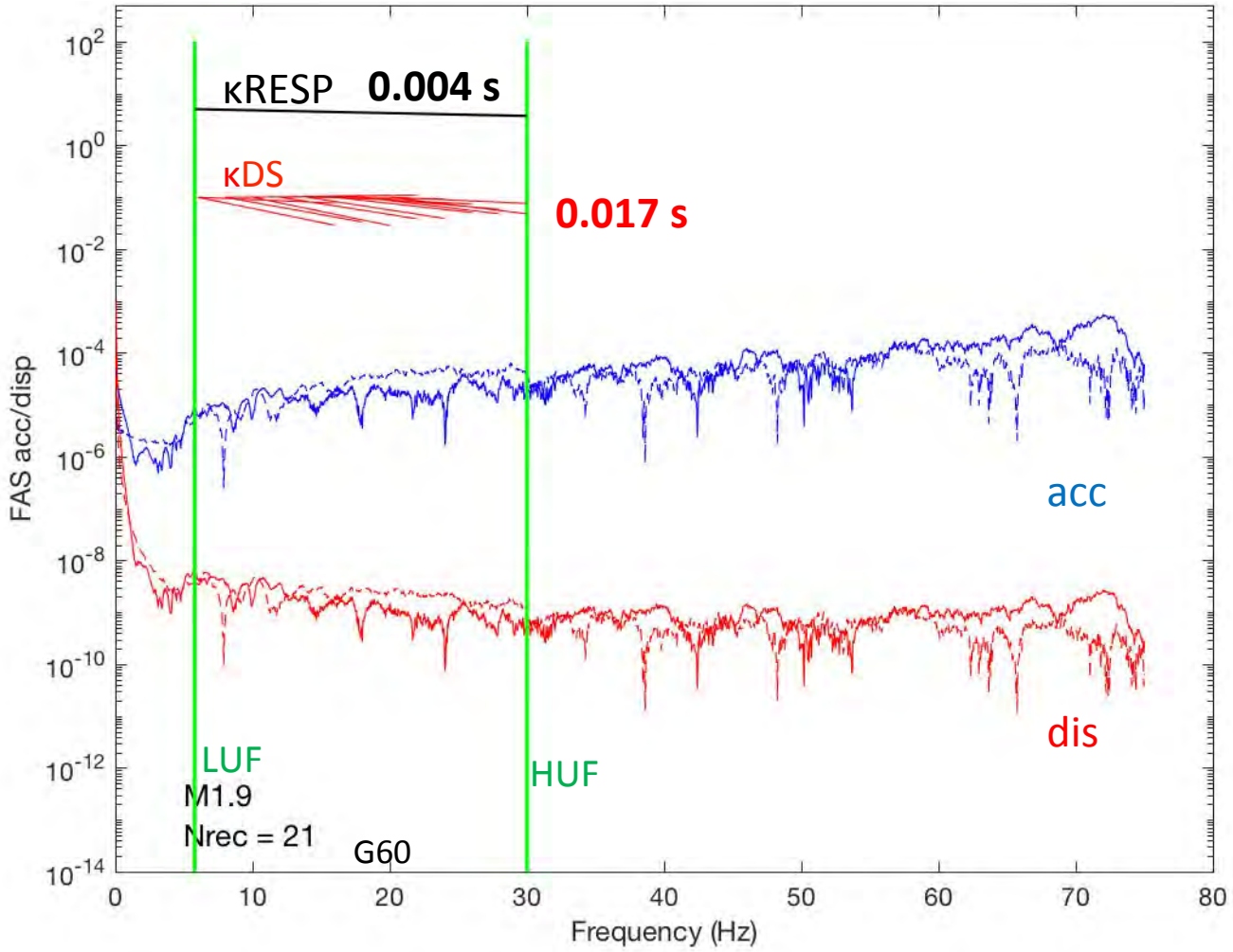
➔ ***To achieve stability: site response needs to be resolved (site characterisation)***

E.g. of **high κAS variability** with moving window

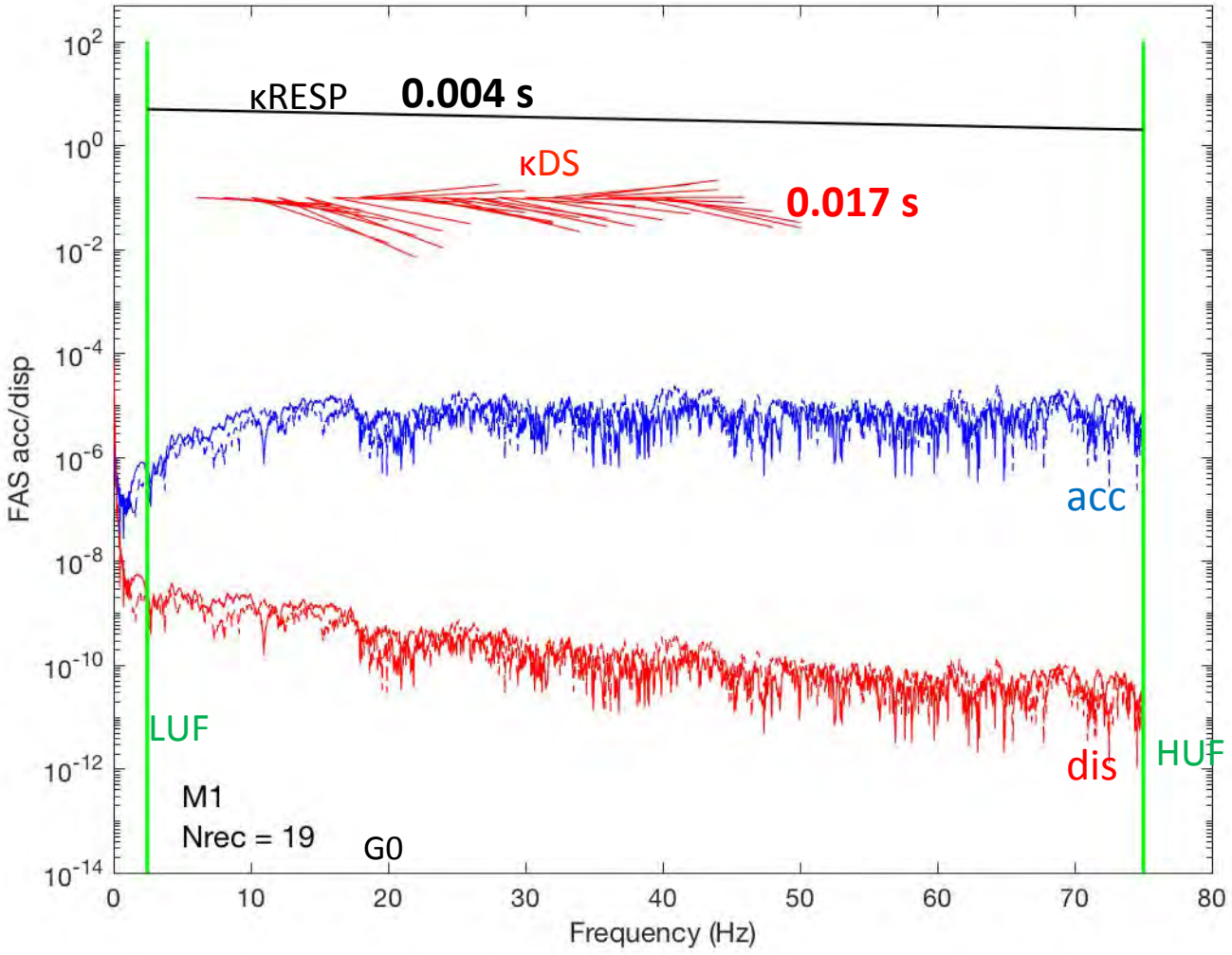


amp vs. damp!

E.g. of **low κDS variability** with moving window

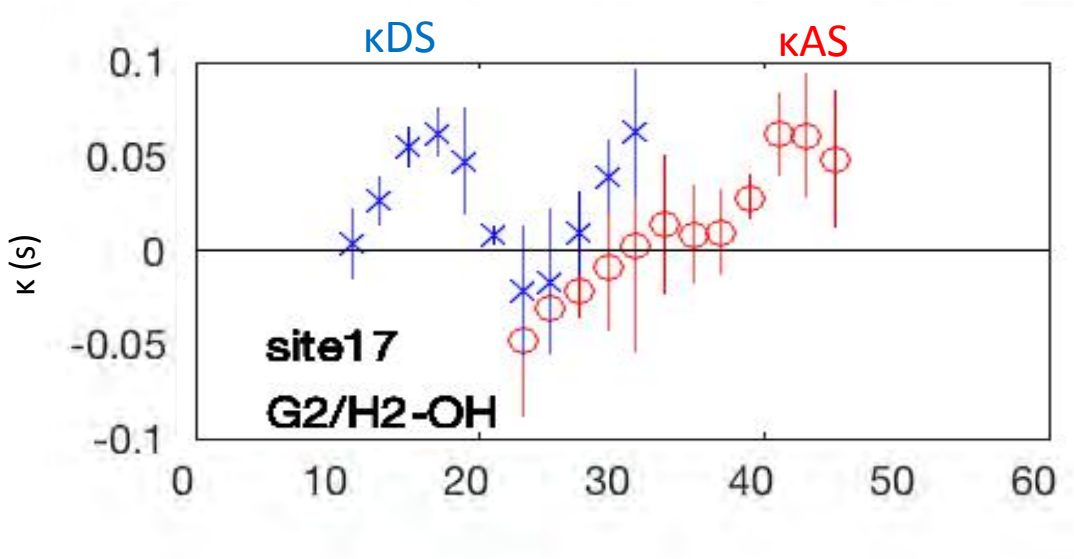


E.g. of **high κDS variability** with moving window

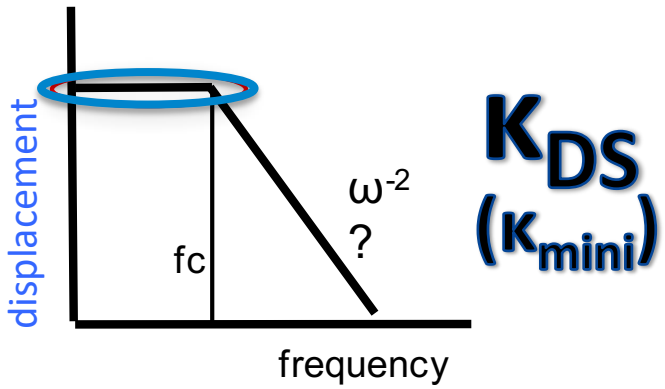


➔ ***Both A sites, same κDS, vastly different variability + dependence on freq. band***

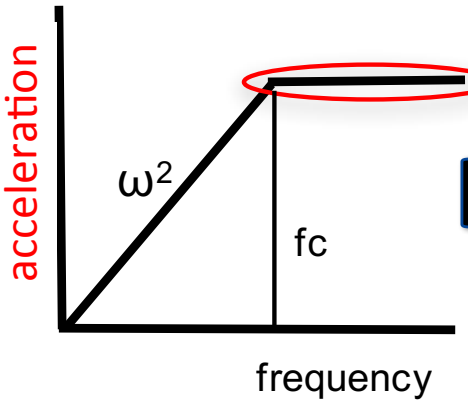
Combining approaches



AS
DS

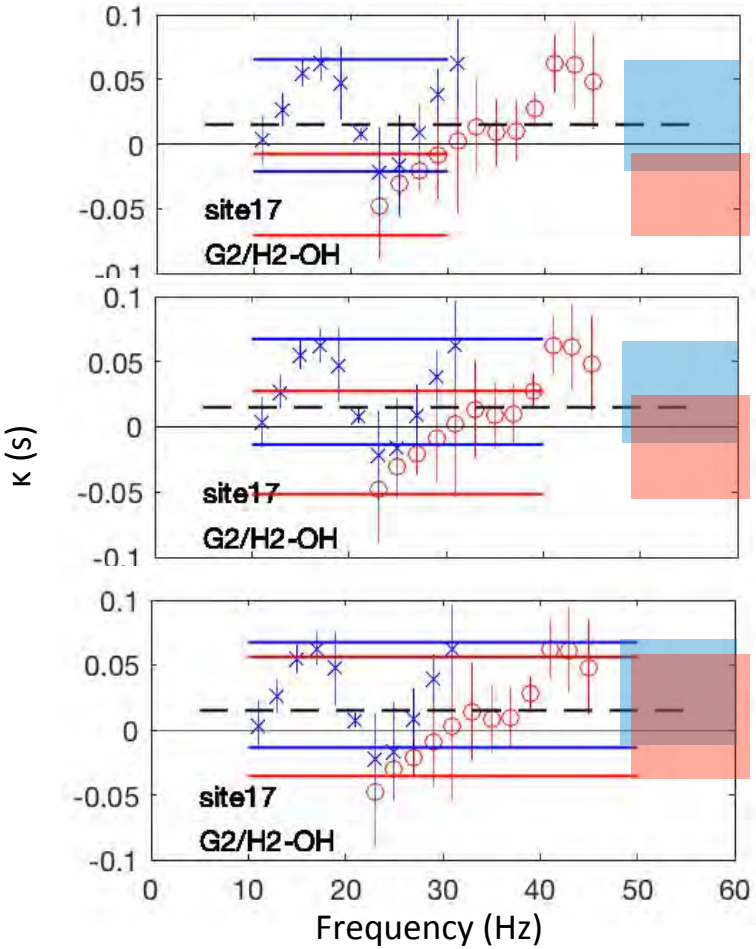


K_{DS} (κ_{mini})



K_{AS}

Combining approaches



Averaging **up to 30 Hz**

Averaging **up to 40 Hz**

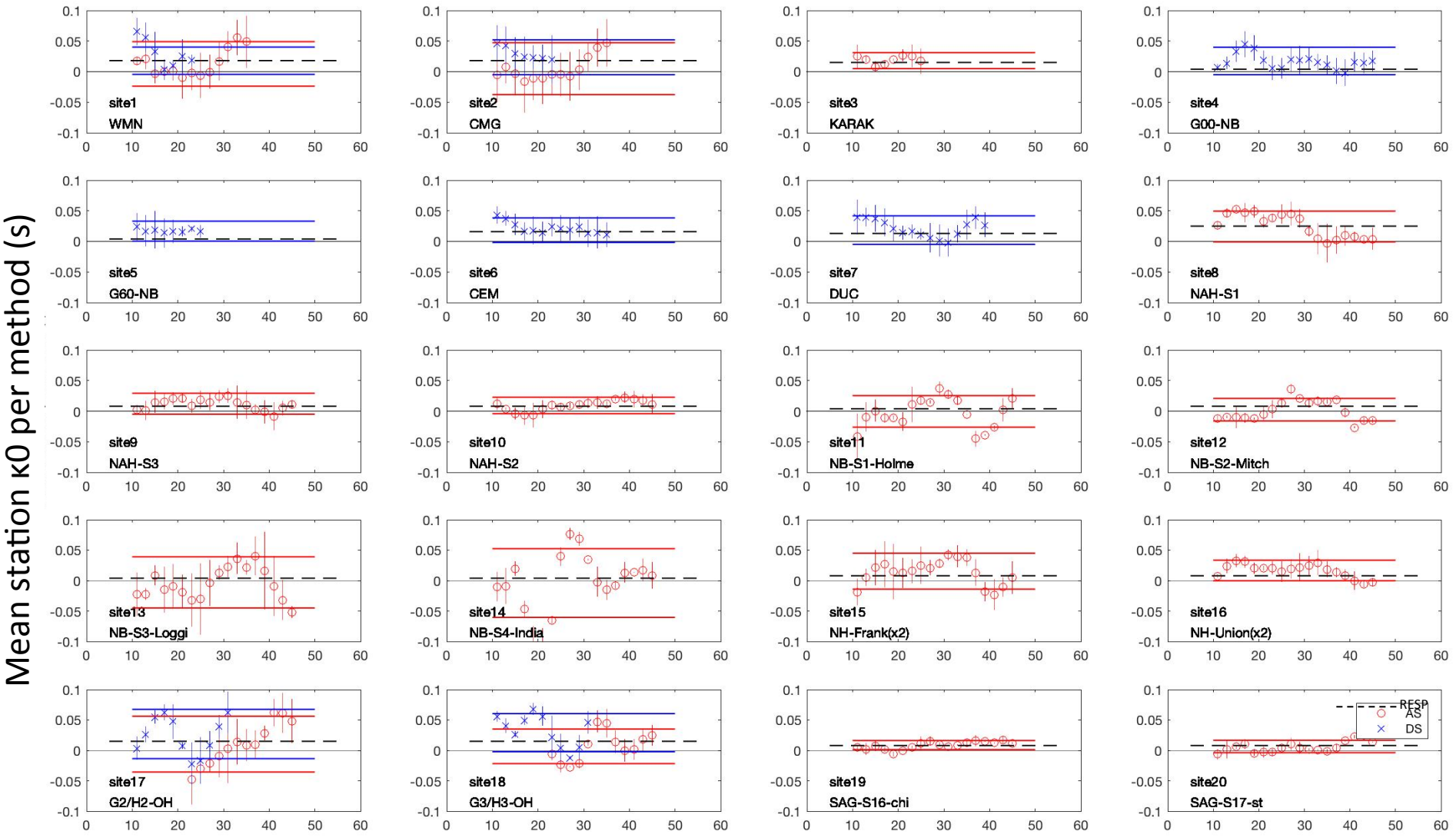
Averaging **up to 50 Hz**

AS
DS
RESP

As frequency range increases:

- κAS and κDS come together
- Band-limited estimates come closer to broadband κRESP

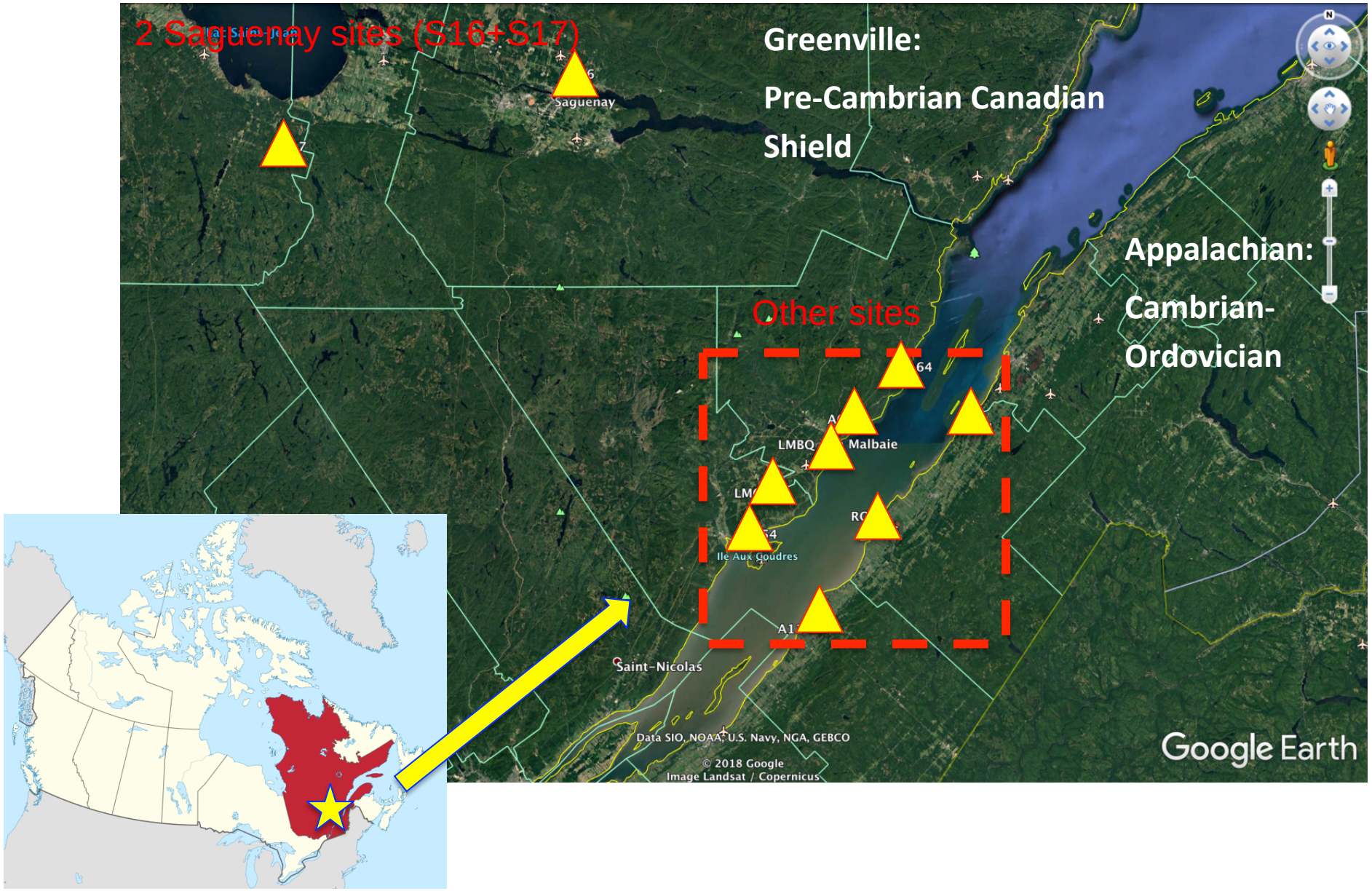
All sites


Mean station κ0 per method (s)
site1
WMN
site2
CMG
site3
KARAK
site4
G00-NB
site5
G60-NB
site6
CEM
site7
DUC
site8
NAH-S1
site9
NAH-S3
site10
NAH-S2
site11
NB-S1-Holme
site12
NB-S2-Mitch
site13
NB-S3-Loggi
site14
NB-S4-India
site15
NH-Frank(x2)
site16
NH-Union(x2)
site17
G2/H2-OH
site18
G3/H3-OH
site19
SAG-S16-chi
site20
SAG-S17-st
RESP
AS
DS
Mean center frequency of moving window (Hz)
AS DS RESP

Stage 2

New hard rock data
& station characterisation

Quebec stations



Shear Wave Velocity Profiling Using the SASW Method with "Raptor" as the Active Seismic Source in Quebec, Canada

for

University of California at Los Angeles

Kenneth H. Stokoe, II, Ph.D., PE., D.GE, Dist. M.ASCE, NAE
Gunwoong Kim, M.S.C.E.
Sungmoon Hwang, Ph.D.

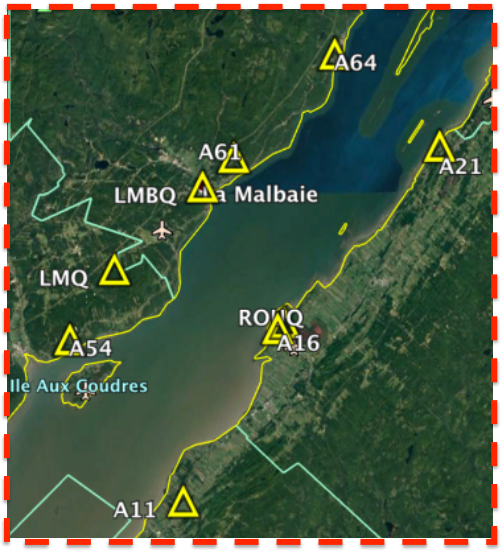
February, 2020

Geotechnical Engineering Report GR20-03
Geotechnical Engineering Center
Civil Engineering Department
The University of Texas at Austin

Vs + geology

the ‘2000 m/s’ sites

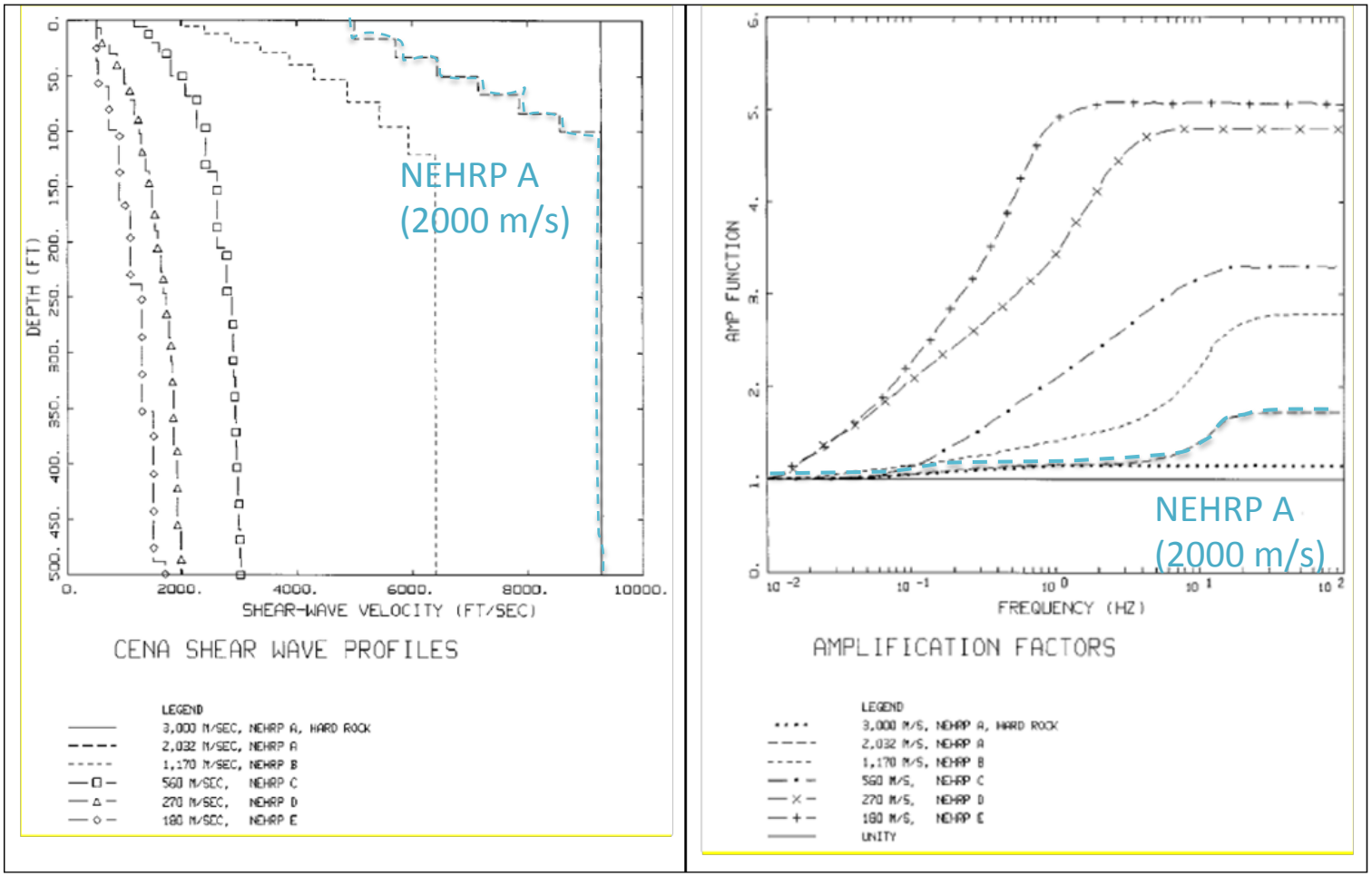
Greenville Province

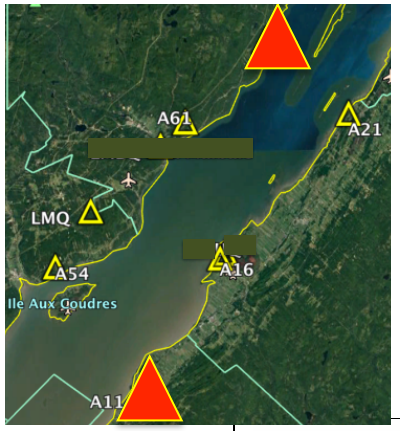


Appalachian Province

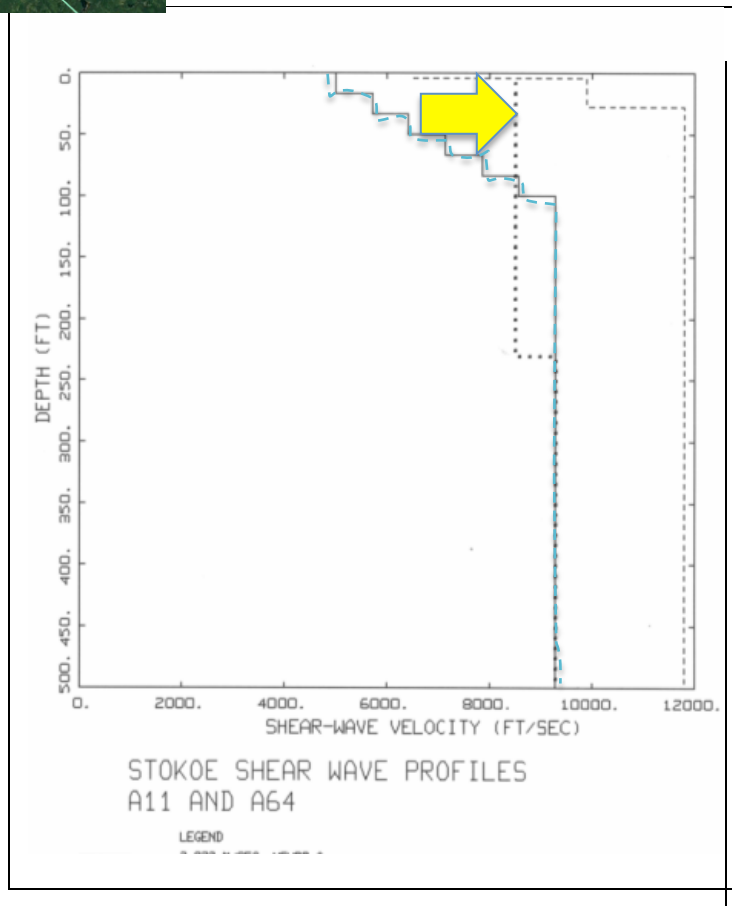
Station Name	Vs30 (Stokoe et al. 2020) (m/s)	Station on Whale back (Stokoe et al. 2020)	Surface Geology (Palmer et al. 2018 and Stokoe et al. 2020)	Bedrock Geology Age (Palmer and Atkinson, 2020)
Sites: South-east of the St. Lawrence Seaway: Appalachian Province				
A11: St. Roch des Aulnaies	2590 (Hard)	Yes	Granite	Cambrian-Ordovician
A16: Riviere-Ouelle	2000 (Hard)	Yes	Hard-rock	Cambrian-Ordovician
A21: St. Andre	1655 (Hard)	Yes	Rock (granite)	Cambrian-Ordovician
Sites: North-west of the St. Lawrence Seaway: Grenville Province				
A54: Misere	1160	No	Weathered Rock	Pre-Cambrian Canadian Shield
A61: Ste. Mathilde	1105	No	Very stiff till over rock	Pre-Cambrian Canadian Shield
A64: St. Simeon	3340 (Hard)	No	Hard-rock	Pre-Cambrian Canadian Shield
LMQ: La Malbaie	930	No	Stiff soil	Pre-Cambrian Canadian Shield

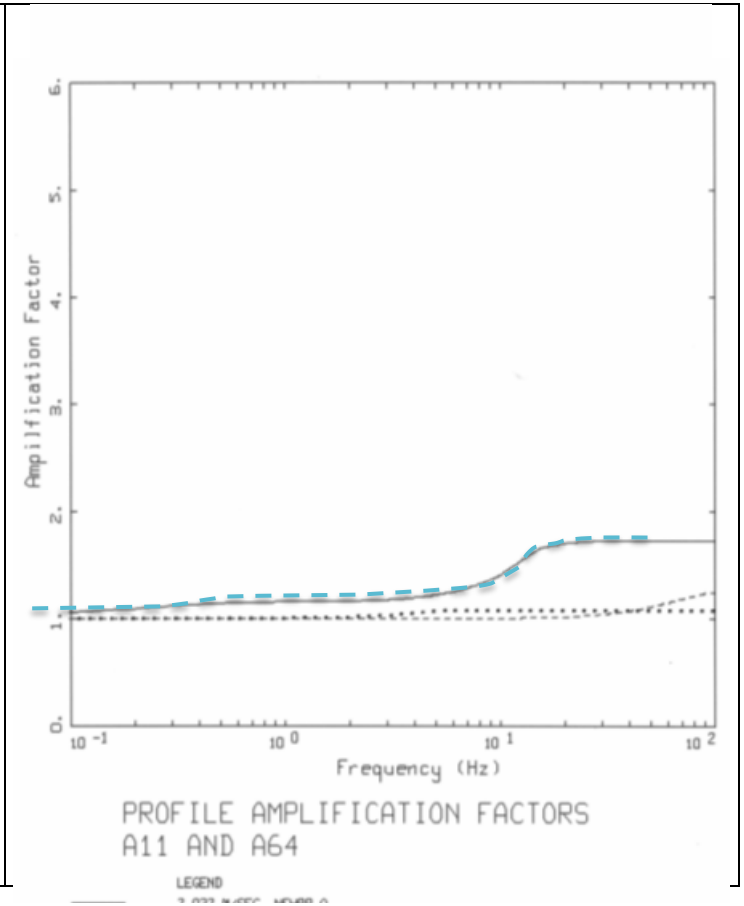
CENA generic Vs Profiles and Linear-elastic Crustal Amplifications (Darragh et al. 2015)



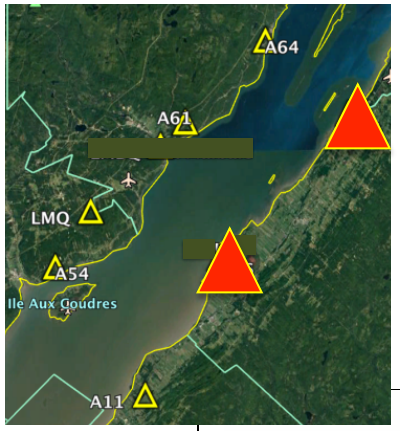


Vs Profiles for A11 and A64 (constructed from Stokoe et al. 2020) and Linear-elastic Site-specific Crustal Amplifications

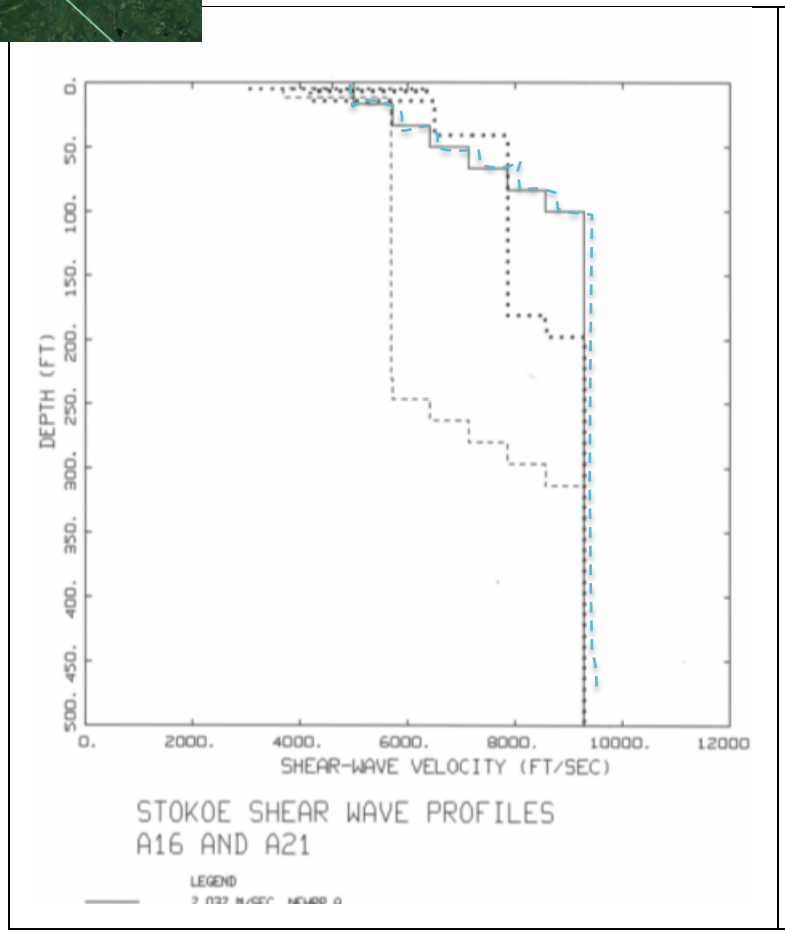


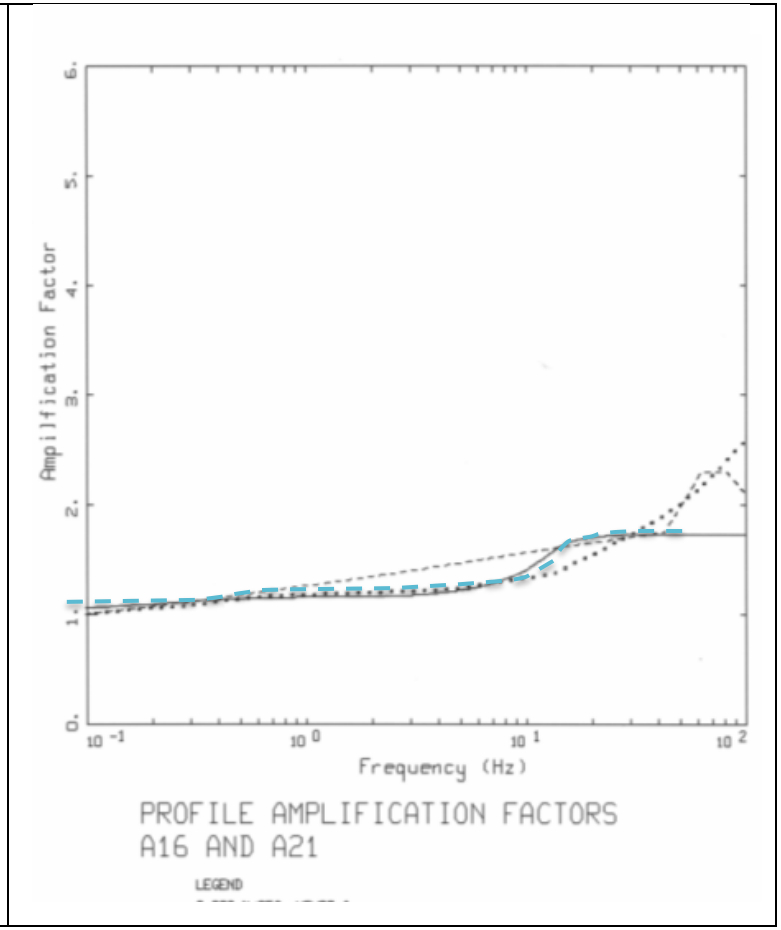


FASTER: Site-specific amps less than Generic CENA amps

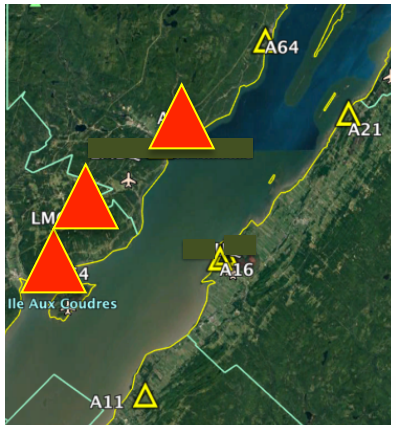


Vs Profiles for A16 and A21 (constructed from Stokoe et al. 2020) and Linear-elastic Site-specific Crustal Amplifications

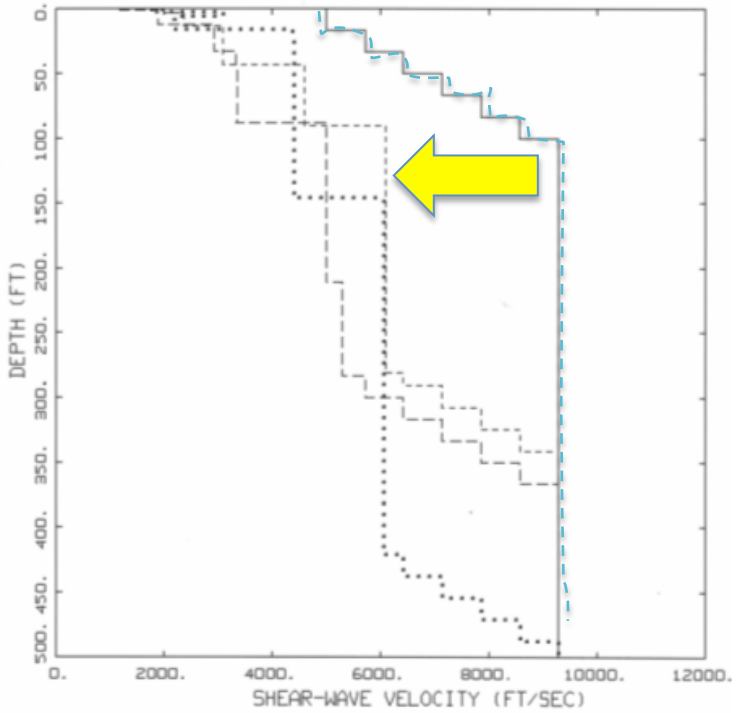


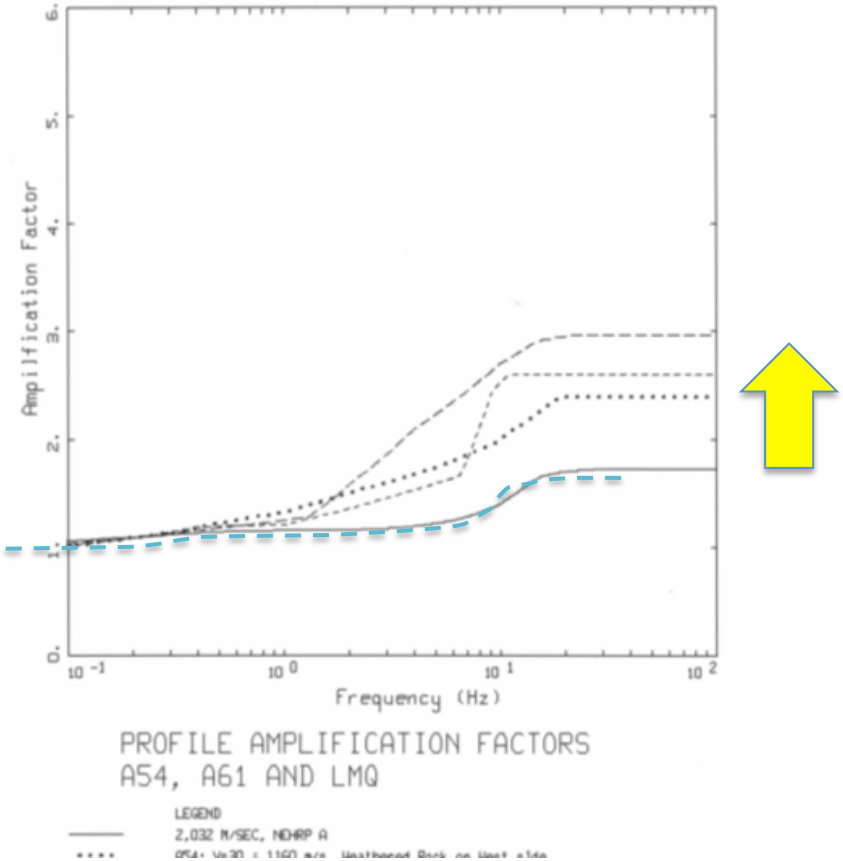


SIMILAR: Site-specific amps similar to Generic CENA to ~ 40 Hz

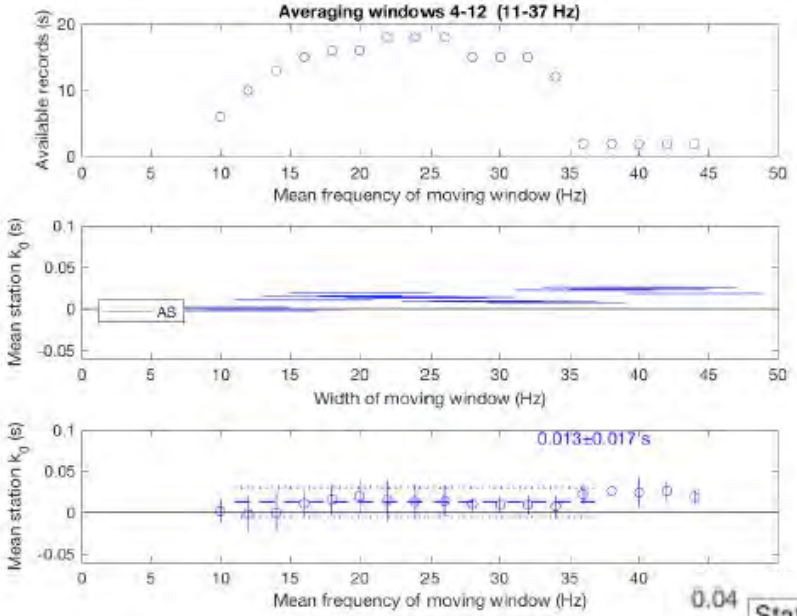


Vs Profiles for A54, A61 and LMQ (constructed from Stokoe et al. 2020) and Linear-elastic **Site-specific** Crustal Amplifications





SLOWER: Site-specific amps greater than Generic CENA > ~2 Hz


Averaging windows 4-12 (11-37 Hz)
Available records (s)
Mean frequency of moving window (Hz)
Mean station k_0 (s)
AS
Width of moving window (Hz)
0.013±0.017's
Mean frequency of moving window (Hz)

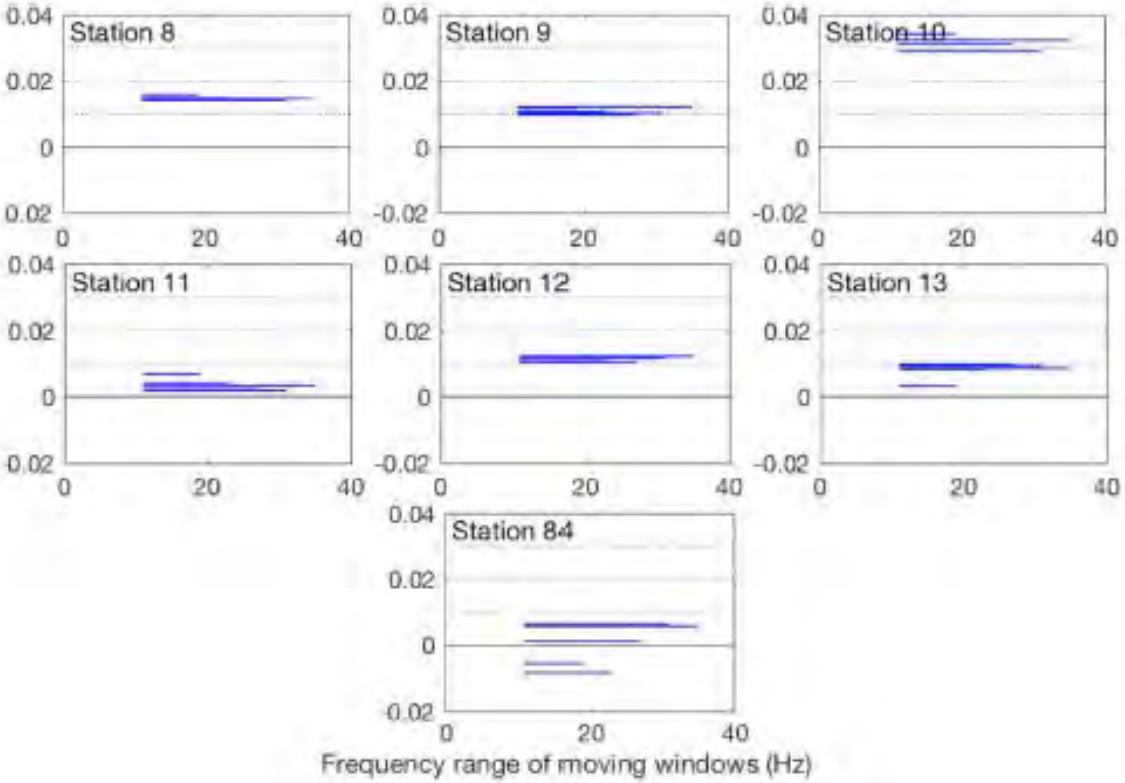
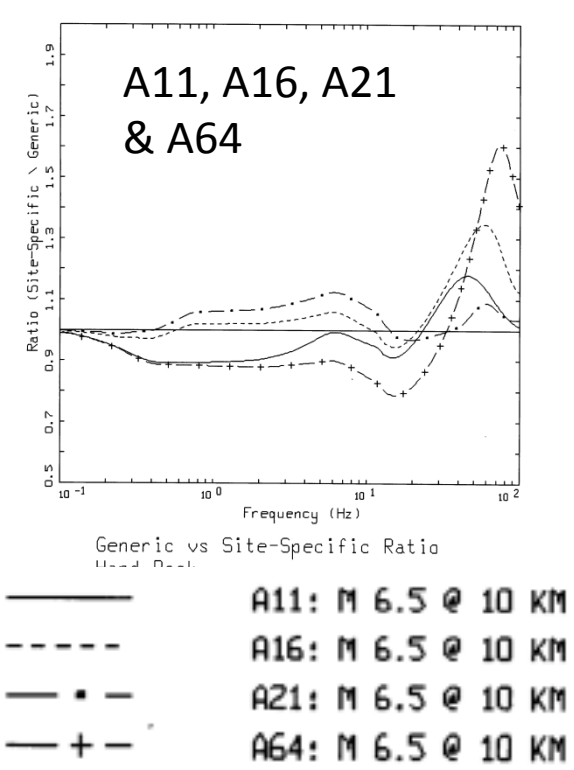

Station 8
Station 9
Station 10
Station 11
Station 12
Station 13
Station 84
Frequency range of moving windows (Hz)

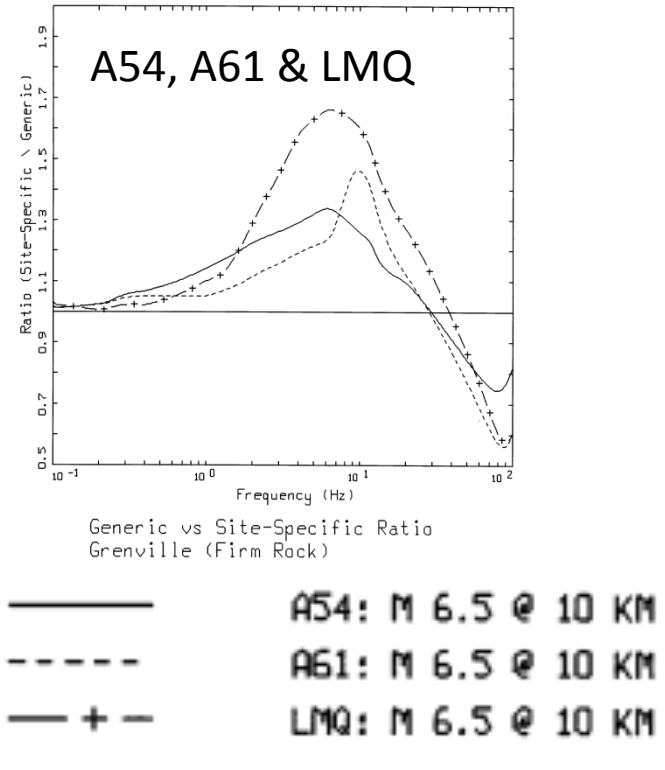
Table 8-2
Kappa at Sites in Quebec, Eastern Canada: Current Analyses

Station Name	Vs30 Profile [10]	Generic Profile (2032 m/s assumed) → Site-Specific Profile (measured near-surface Vs)	
		κBB (sec)	κAS (sec)
Sites: South-east of the St. Lawrence Seaway: Appalachian Province			
A11: St. Roch des Aulnaies	2590	0.021 → 0.014	0.014 ± 0.018 → 0.013 ± 0.018
A16: Riviere-Ouelle	2000	0.013 → 0.011	0.010 ± 0.017 → 0.013 ± 0.017
A21: St. Andre	1655	0.015 → 0.015	0.031 ± 0.014 → 0.031 ± 0.014
Sites: North-west of the St. Lawrence Seaway: Grenville Province			
A54: Misere	1160	0.007 → 0.011	0.002 ± 0.016 → 0.002 ± 0.016
A61: Ste. Mathilde	1105	0.004 → 0.009	0.011 ± 0.015 → 0.010 ± 0.015
A64: St. Simeon	3340	0.005 → 0.0, constrained	0.010 ± 0.021 → 0.010 ± 0.022
LMQ: La Malbaie	930	0.003 → 0.008	0.001 ± 0.043 → 0.001 ± 0.043

Hard versus Stiff Soil and Weathered Firm-Rock

- Hard Rock (N=4)
- Stiff-soil & Weathered



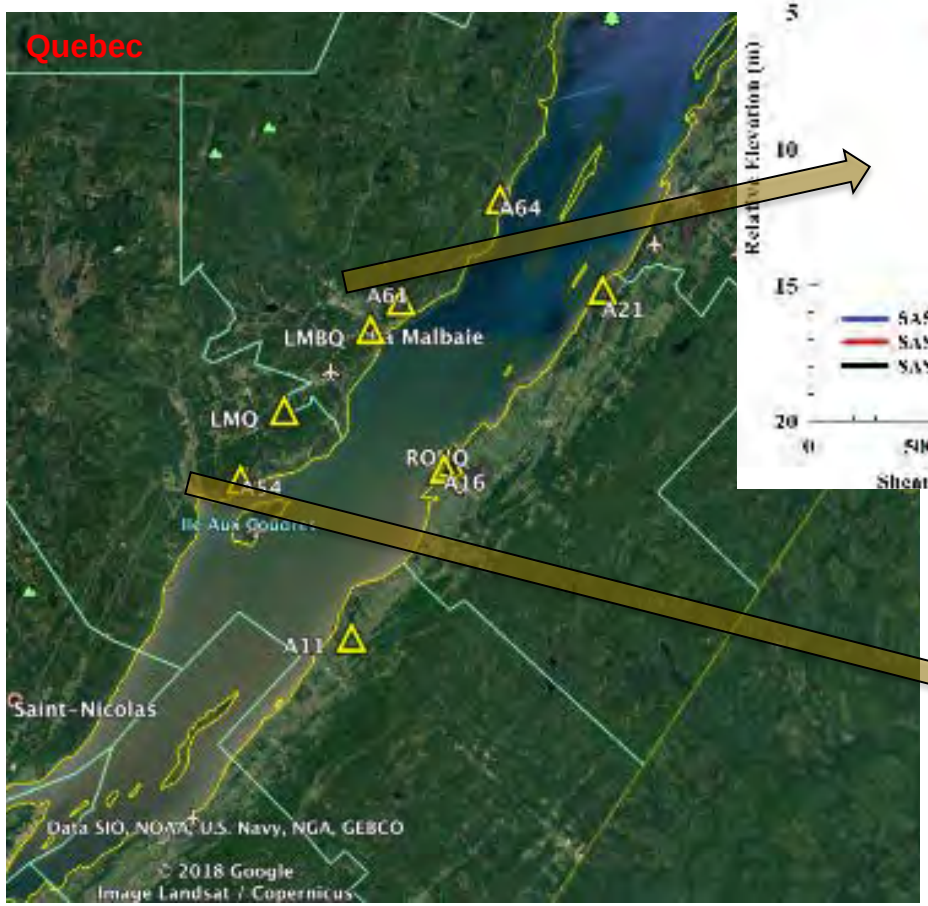


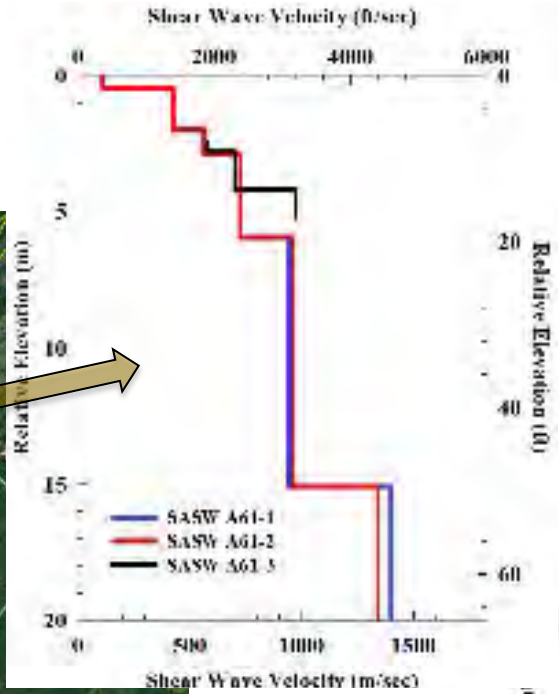
Ratio of site-specific/generic amplification

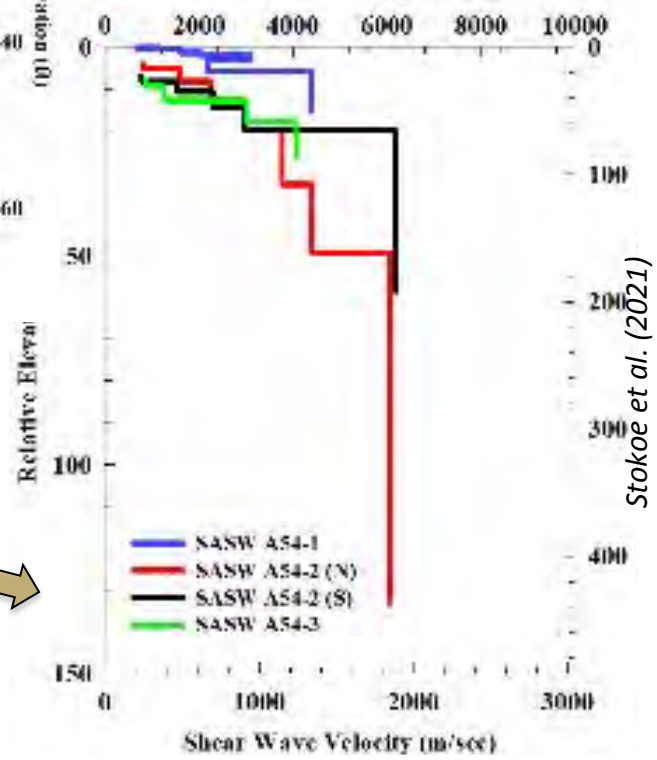
Rock peculiarities

Difficulties in getting Vs & variability

‘ 2000 m/s’



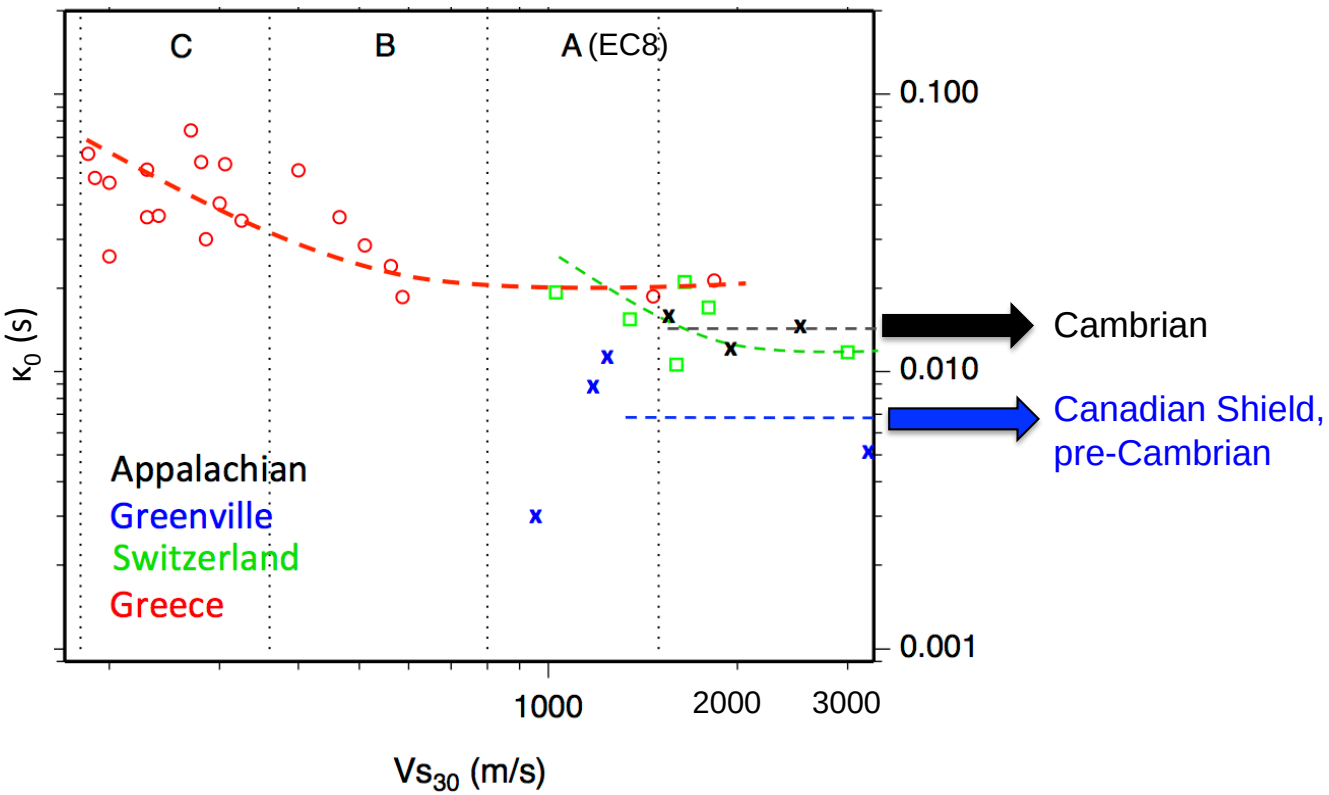


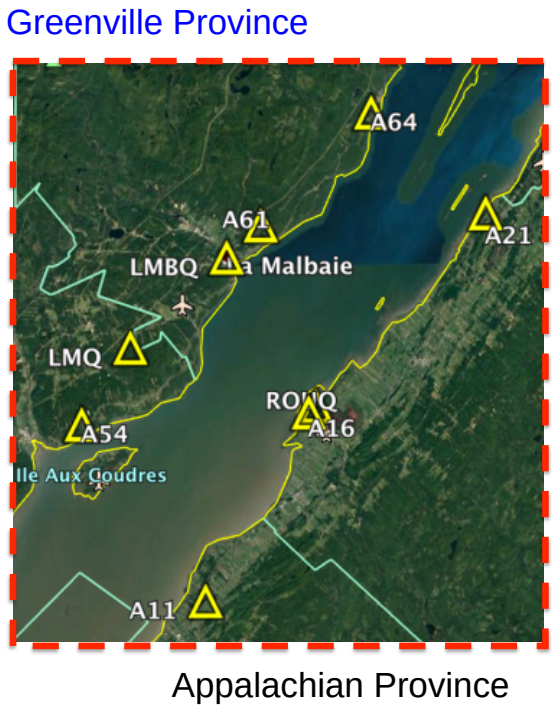


Stokoe et al. (2021)

Is stiffness an indicator of damping?

- after correcting for crustal/near-surface amp, κ seems to have deeper roots
- Some of the epistemic uncertainty in kappa may have been masquerading as aleatory variability





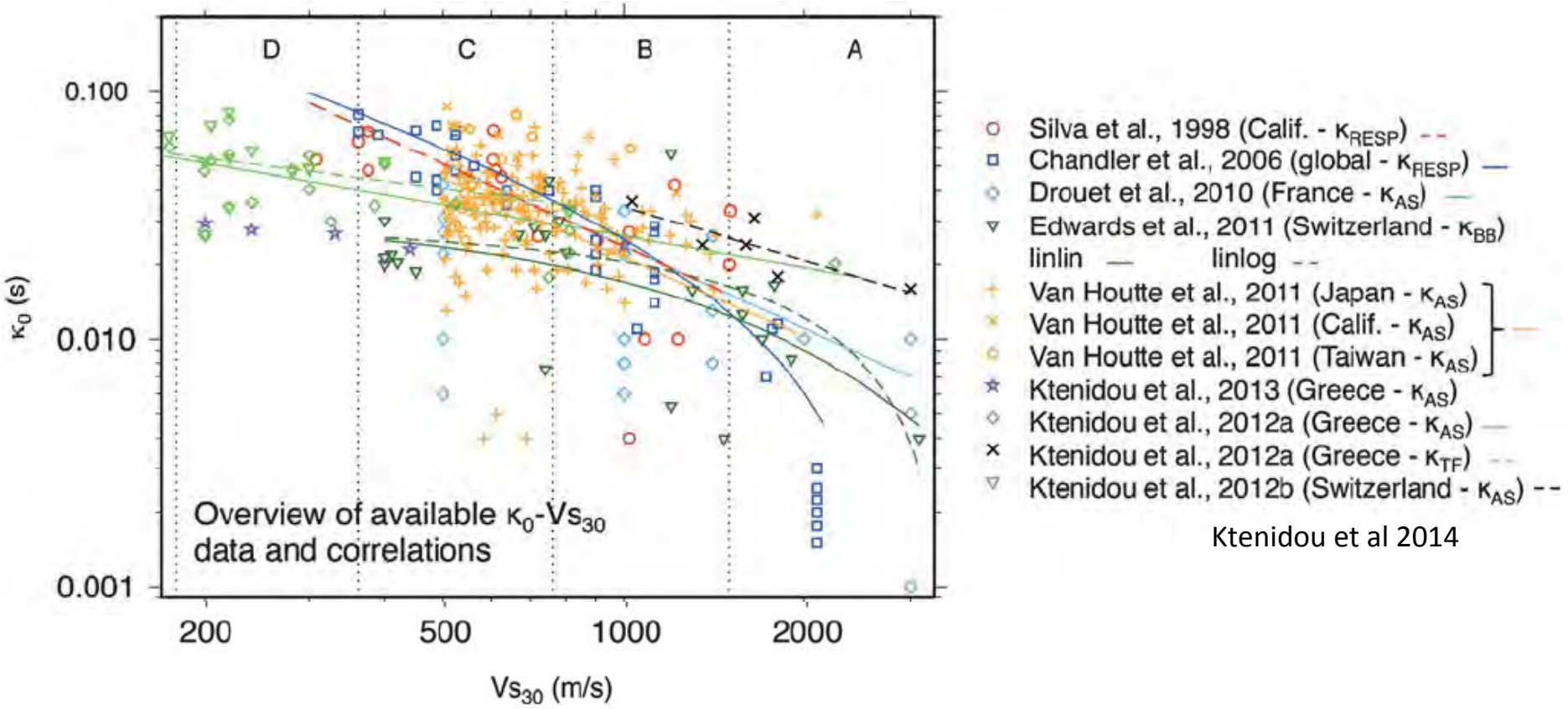
When we have no data?

- N. Abrahamson: Non-ergodic ground-motion models, uncertainty propagation

"..if you don't give me numbers from data,
I'll make them up!"

When there are no seismic (or geotechnical) data?
…empirical correlations

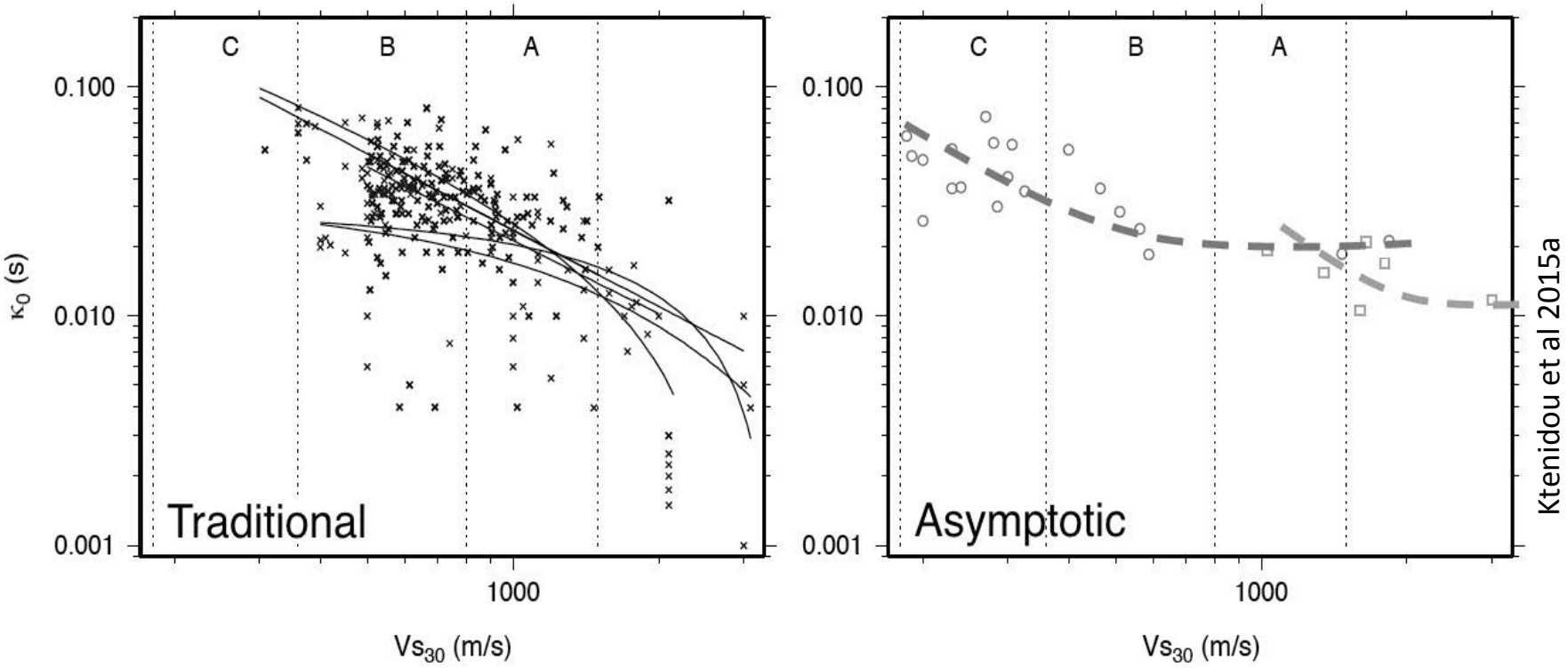
(Vs and other factors, incl. f0, Hbed)



Ktenidou et al 2014

…but:

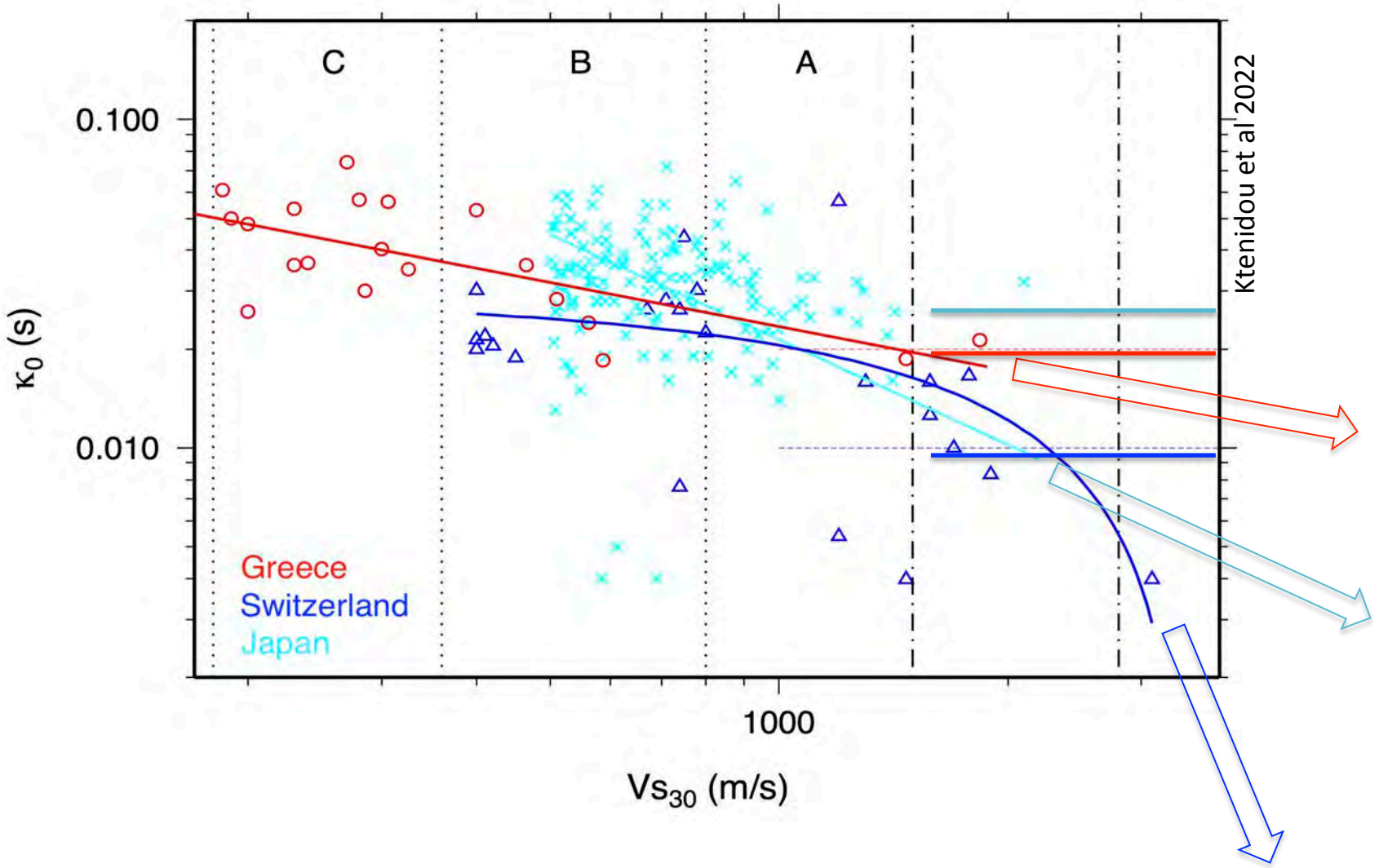
- practically: large scatter, low R2, few data
- theoretically: can attenuation go on decreasing forever???



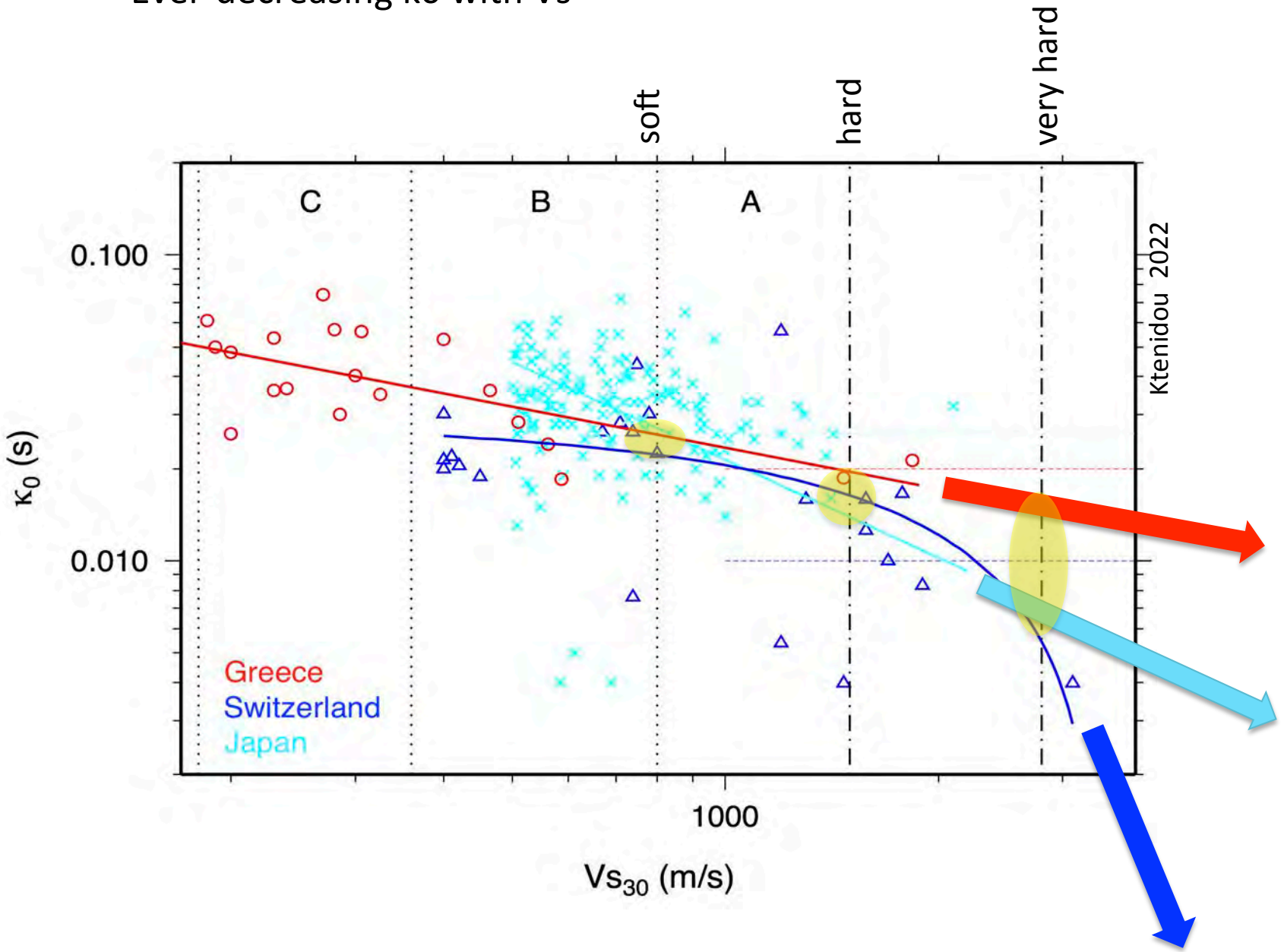
…regionally-bound minimum values for hard rock

…but:

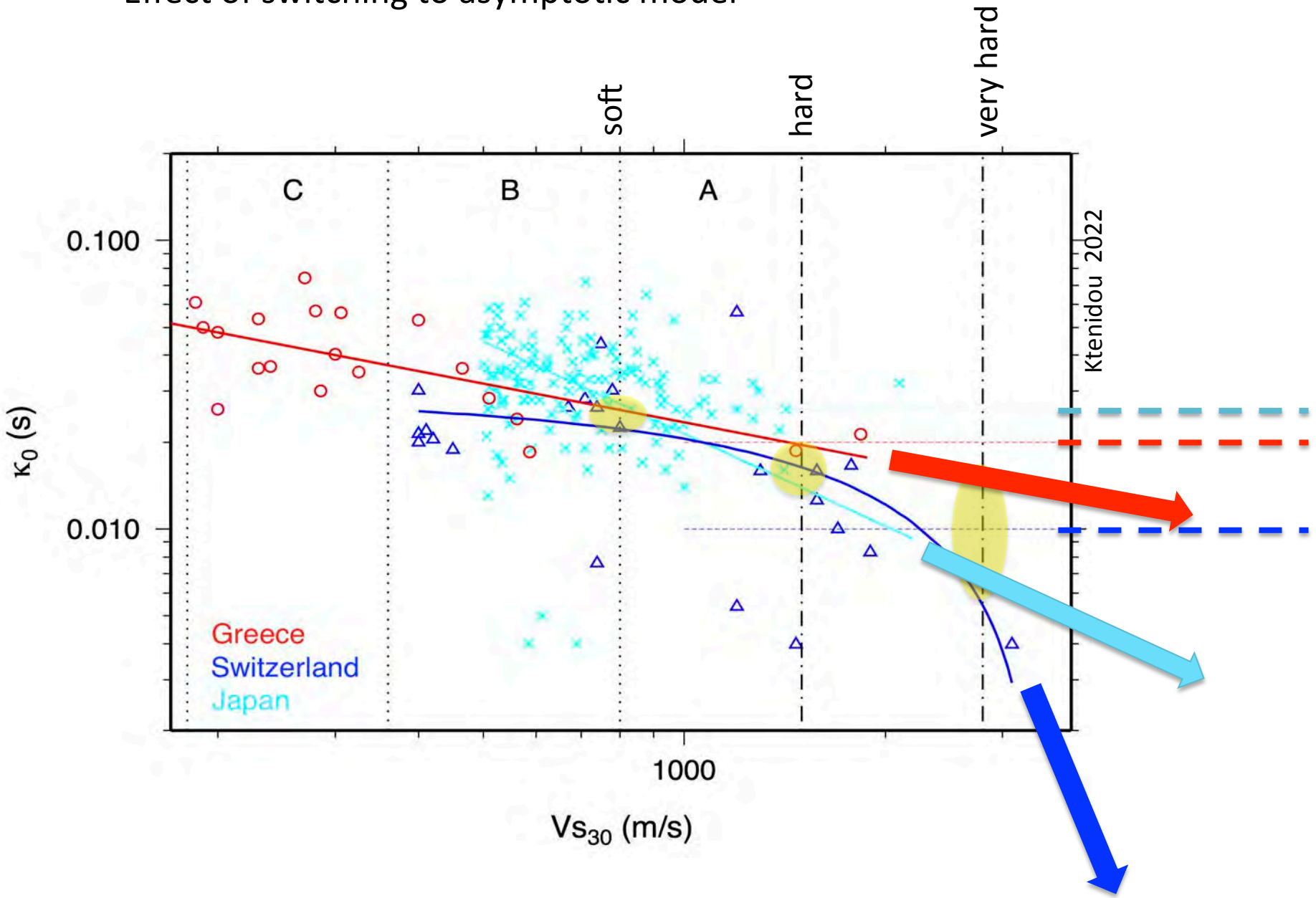
- practically: large scatter, low R2, few data
- theoretically: can attenuation go on decreasing forever???



Ever-decreasing κ0 with Vs



Effect of switching to asymptotic model



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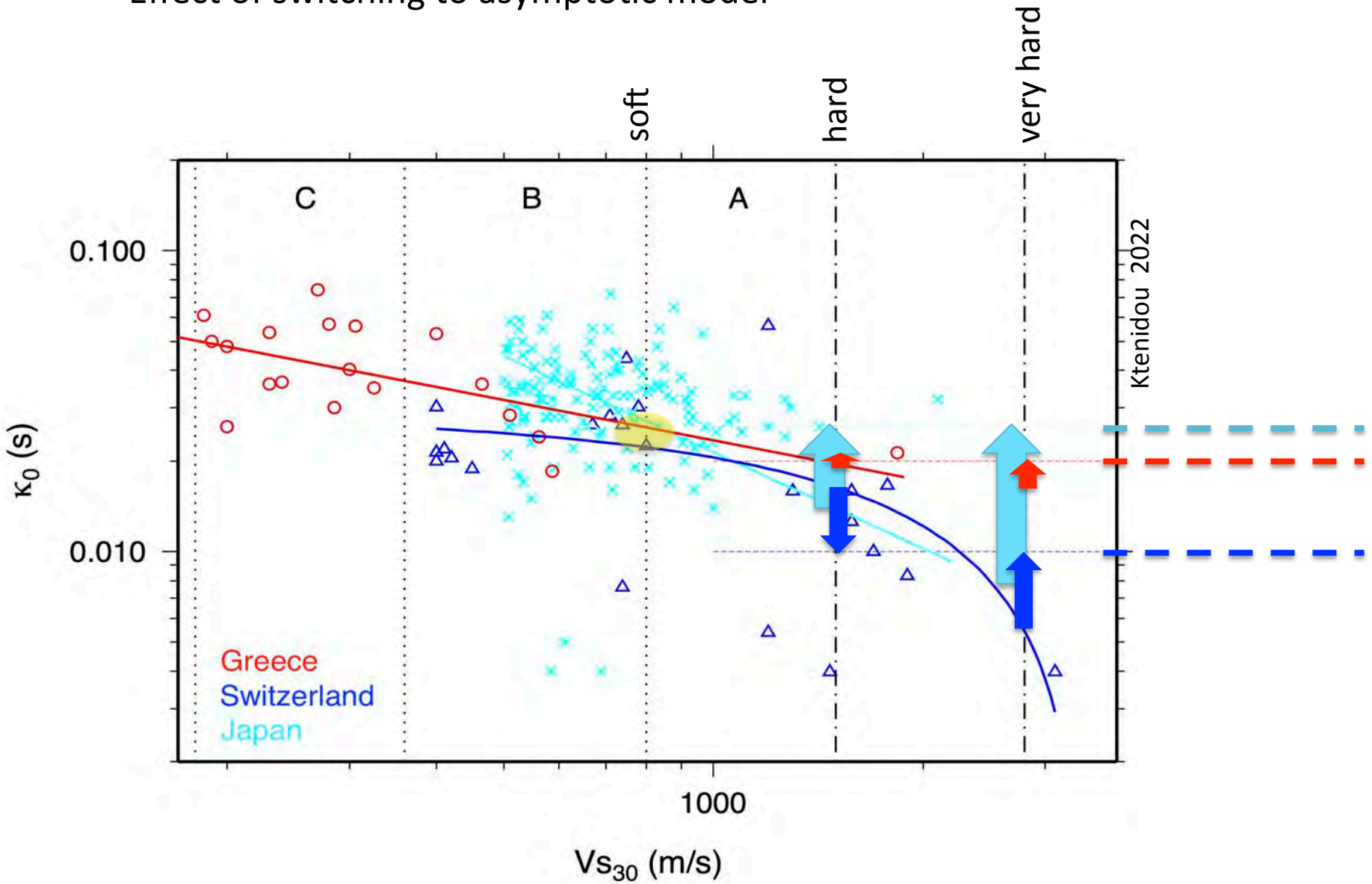
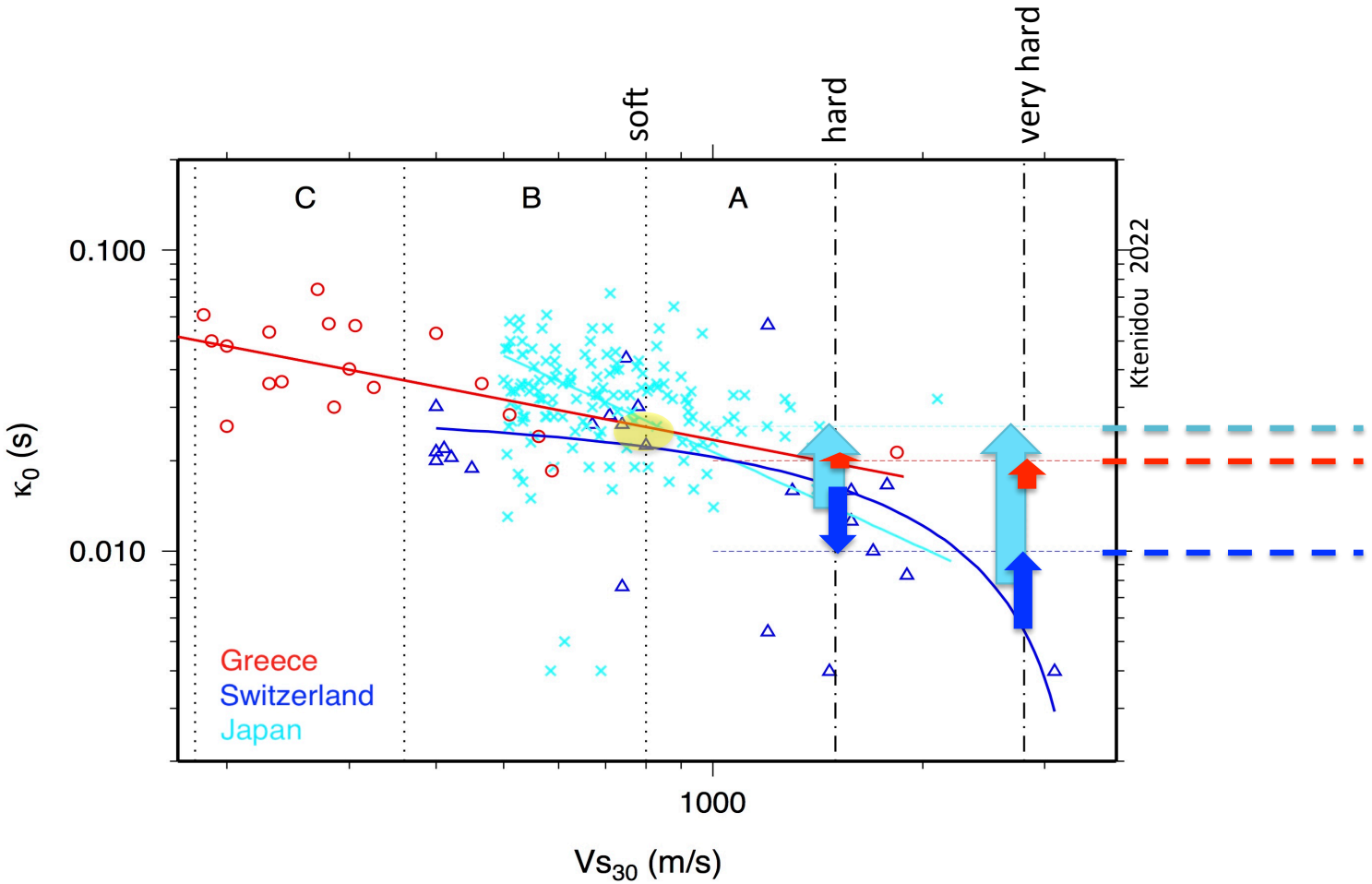


Effect of switching to asymptotic model

Author	Region	κ_0 [s] (800/1500/2800 m/s)	κ_0 [s] (asymptotic)
Ktenidou et al. (2015)	Greece	0.026 / 0.019 / 0.015	0.020
Edwards et al. (2015)	Switzerland	0.022 / 0.016 / 0.005	0.010
Van Houtte et al. (2011)	Japan	0.027 / 0.014 / 0.007	0.026



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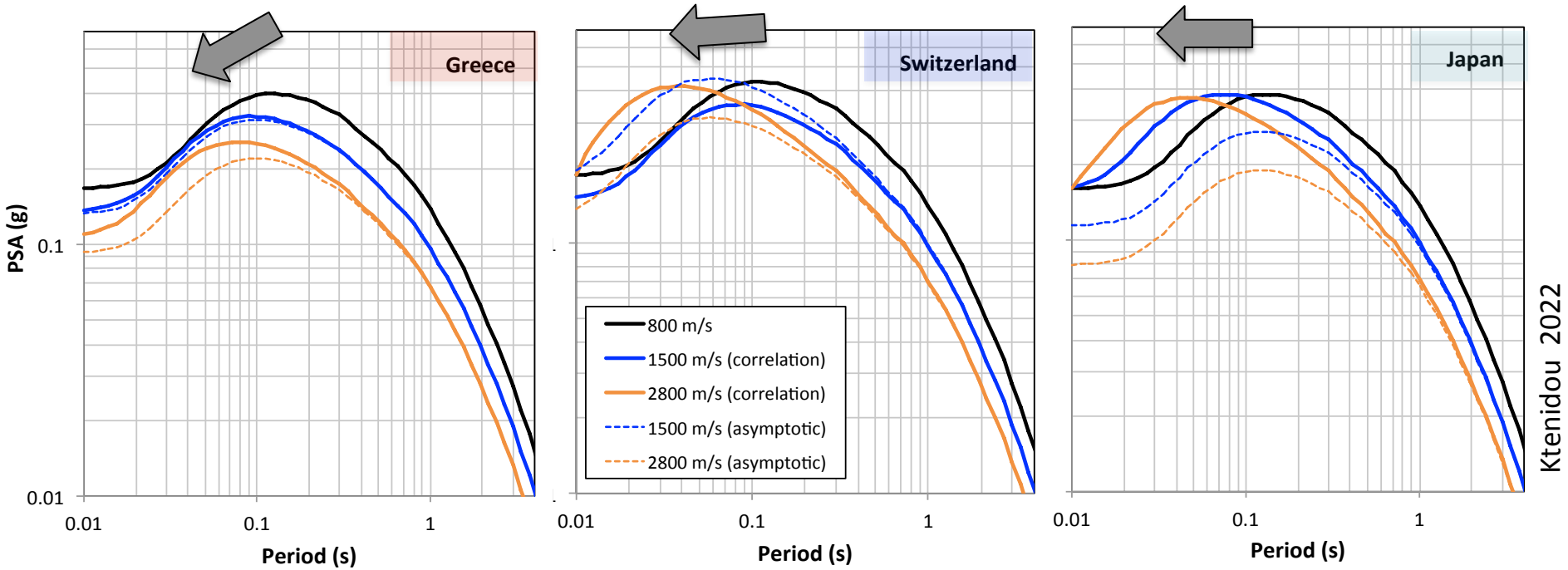
M6 @ 20 km



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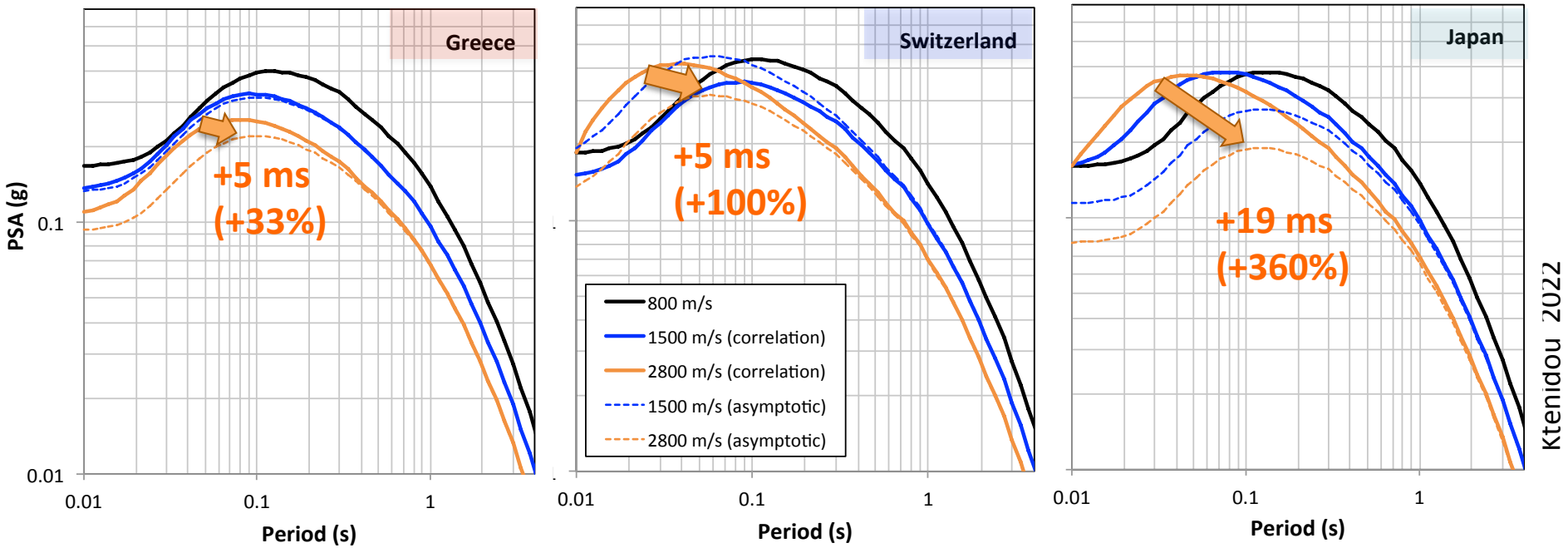
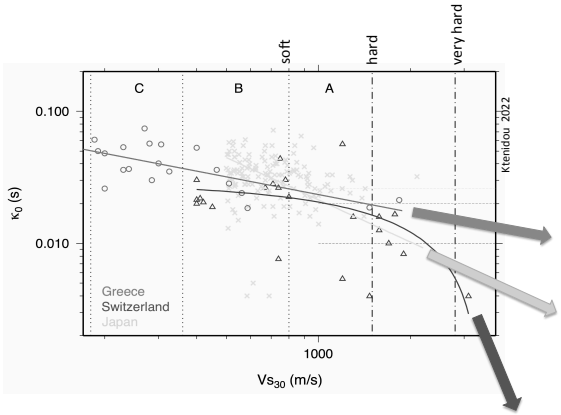
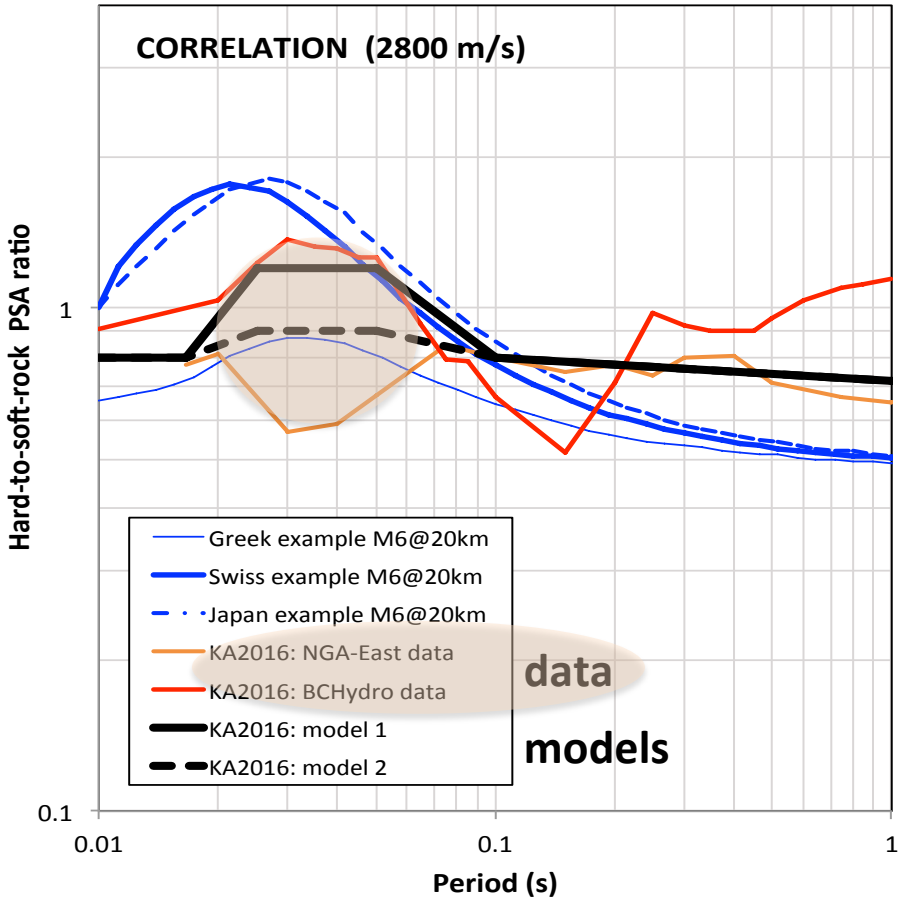
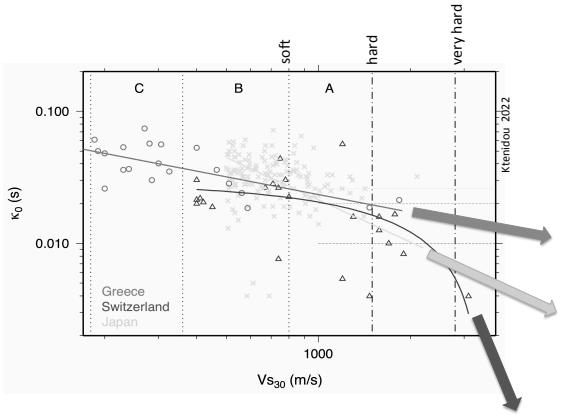



soft
hard
very hard
C
B
A
0.100
0.010
κ_0 (s)
Greece
Switzerland
Japan
1000
Vs_{30} (m/s)
Ktenidou 2022


CORRELATION (2800 m/s)
Hard-to-soft-rock PSA ratio
1
0.1
0.01
0.1
1
Period (s)
Greek example M6@20km
Swiss example M6@20km
Japan example M6@20km
KA2016: NGA-East data
KA2016: BCHydro data
KA2016: model 1
KA2016: model 2
data
models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κ_0 (s)
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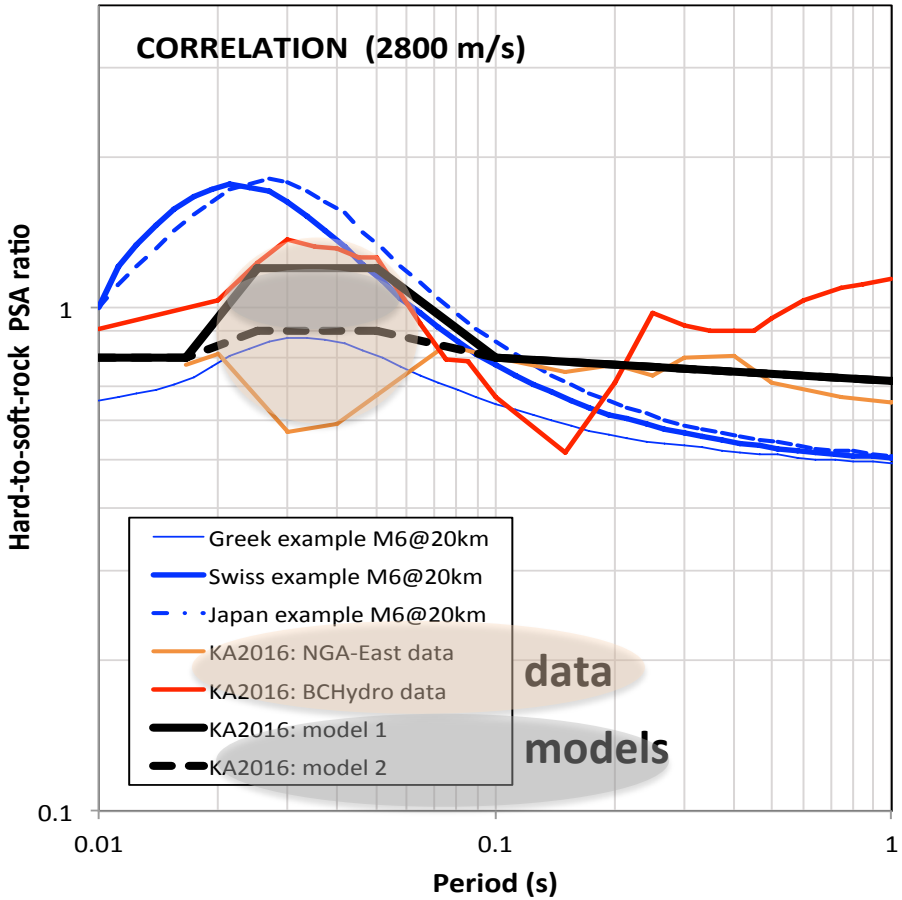
Ktenidou 2022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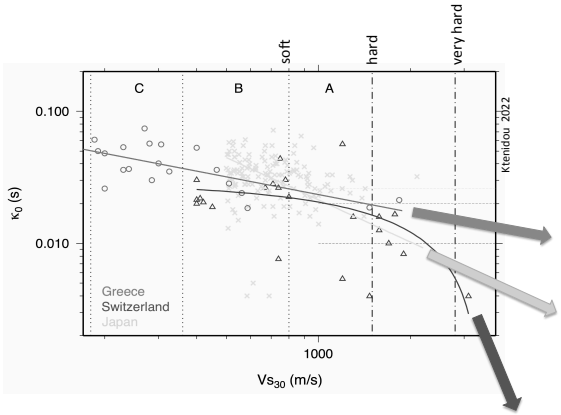
soft
hard
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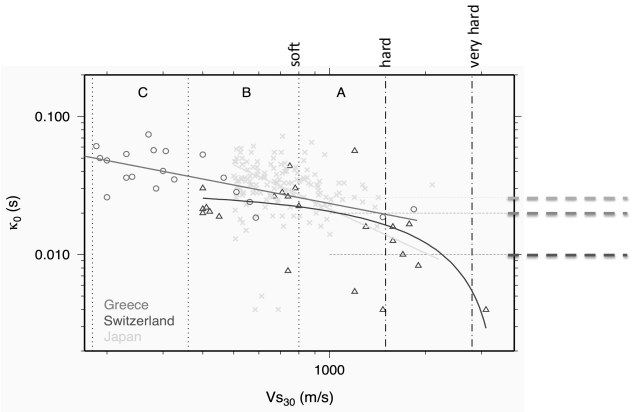
1000
Vs_{30} (m/s)
Ktenidou 2022


soft
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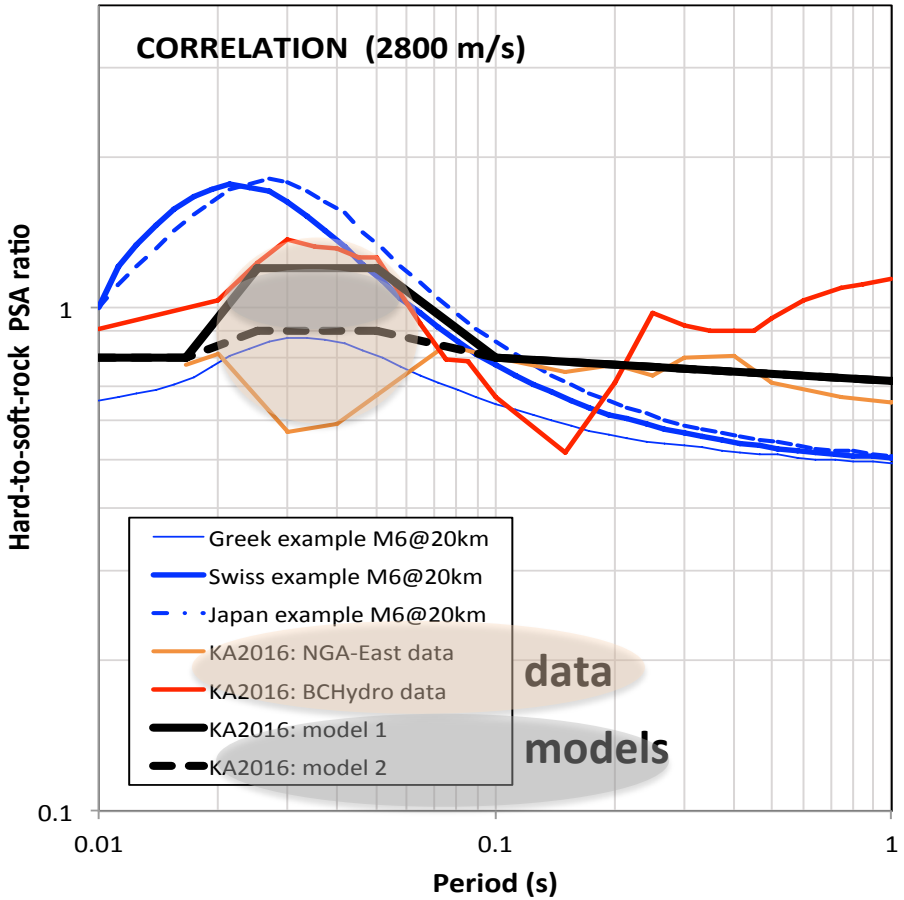
Vs_{30} (m/s)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0.01
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Greek example M6@20km
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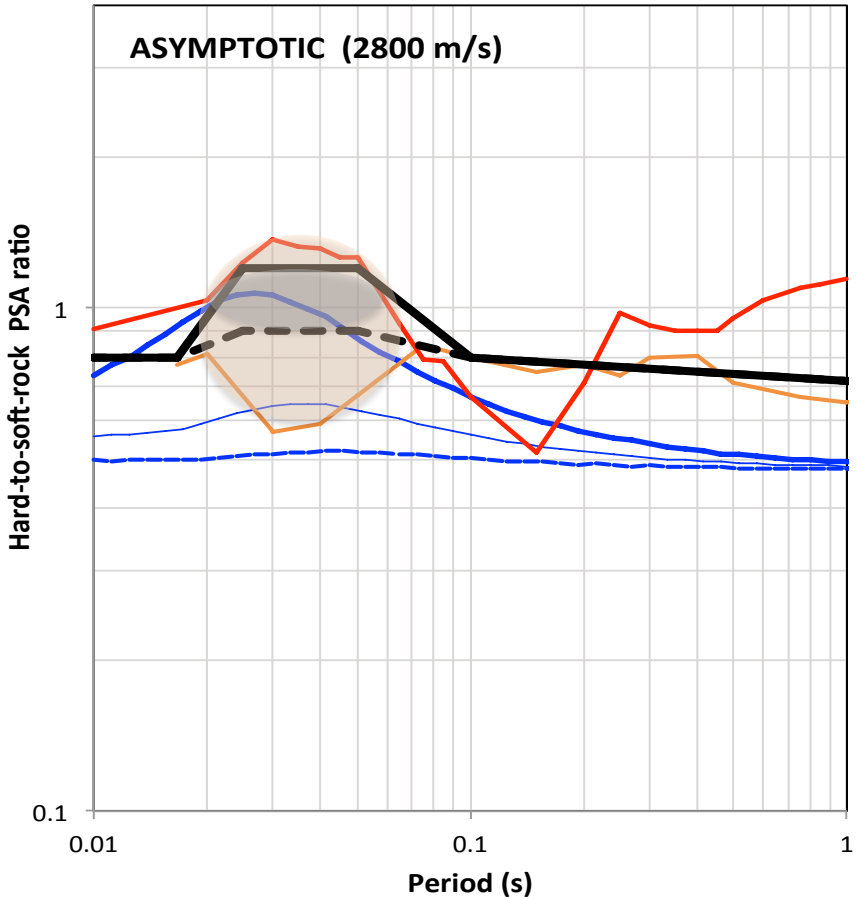
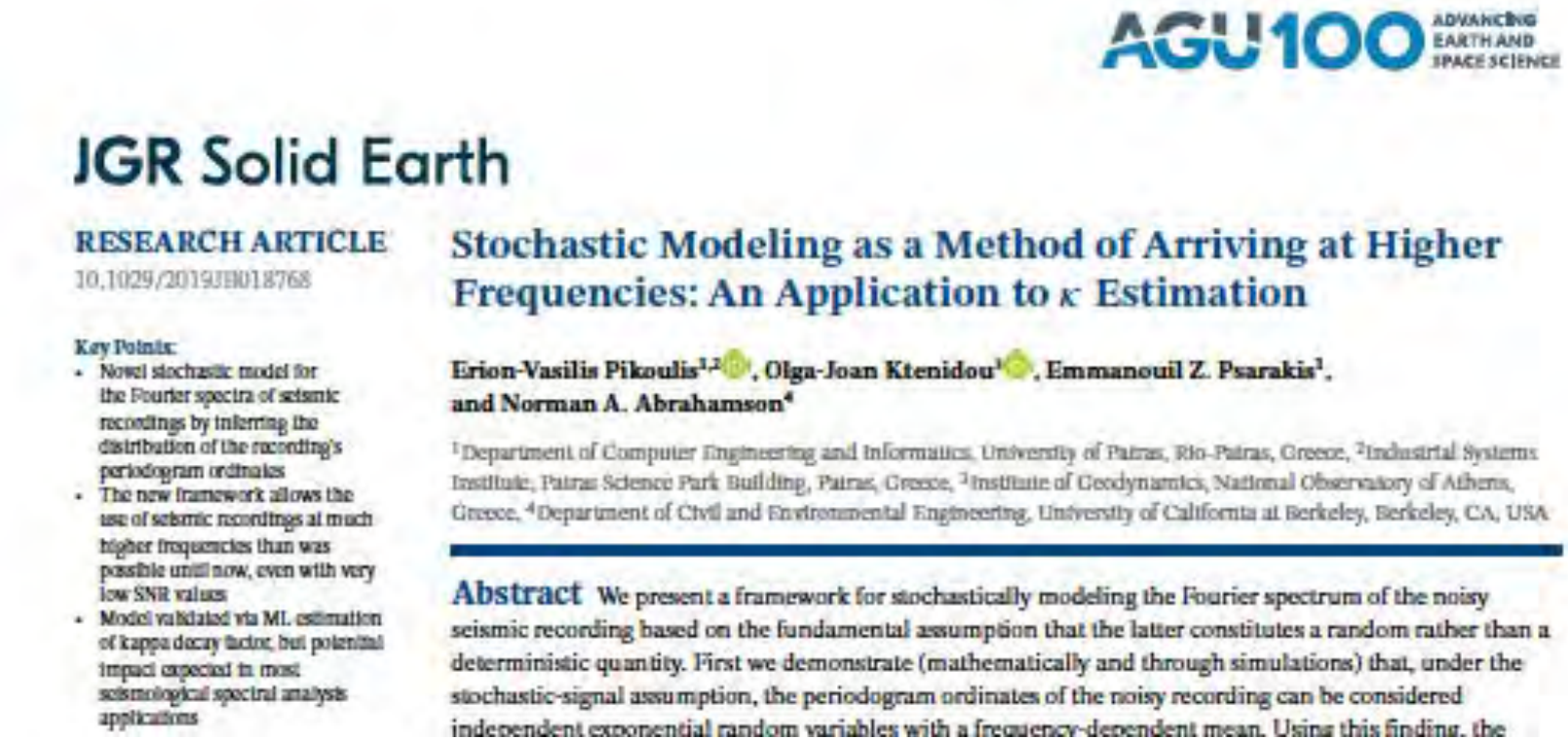

ASYMPTOTIC (2800 m/s)
Hard-to-soft-rock PSA ratio
1
0.1
0.01
0.1
1
Period (s)
Ktenidou 2022

Moving forward – Noise modelling

The idea

- **Model + correct rather than avoid noise** to allow more robust estimation of spectral parameters?



AGU100 ADVANCING EARTH AND SPACE SCIENCE

JGR Solid Earth

RESEARCH ARTICLE
10.1029/2019JB018768

Key Points:
- Novel stochastic model for the Fourier spectra of seismic recordings by inferring the distribution of the recording's periodogram ordinates
- The new framework allows the use of seismic recordings at much higher frequencies than was possible until now, even with very low SNR values
- Model validated via ML estimation of kappa decay factor, but potential impact expected in most seismological spectral analysis applications

Stochastic Modeling as a Method of Arriving at Higher Frequencies: An Application to κ Estimation

Erion-Vasilis Pikoulis[1,2], Olga-Joan Ktenidou[3], Emmanouil Z. Psarakis[1], and Norman A. Abrahamson[4]

[1]Department of Computer Engineering and Informatics, University of Patras, Rio-Patras, Greece, [2]Industrial Systems Institute, Patras Science Park Building, Patras, Greece, [3]Institute of Geodynamics, National Observatory of Athens, Greece, [4]Department of Civil and Environmental Engineering, University of California at Berkeley, Berkeley, CA, USA

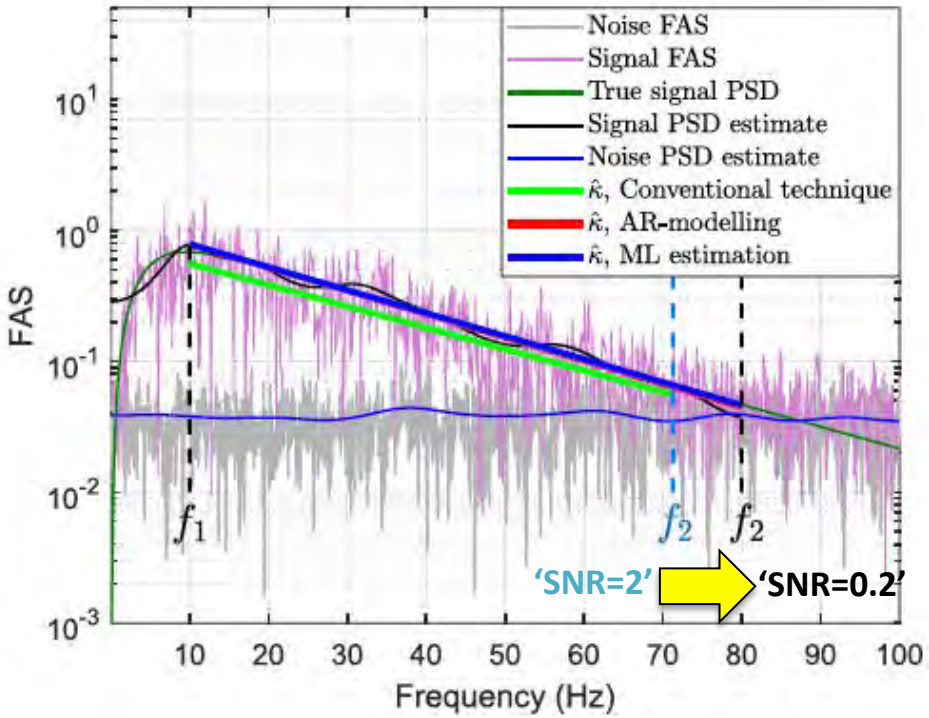
Abstract We present a framework for stochastically modeling the Fourier spectrum of the noisy seismic recording based on the fundamental assumption that the latter constitutes a random rather than a deterministic quantity. First we demonstrate (mathematically and through simulations) that, under the stochastic-signal assumption, the periodogram ordinates of the noisy recording can be considered independent exponential random variables with a frequency-dependent mean. Using this finding, the

https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JB018768

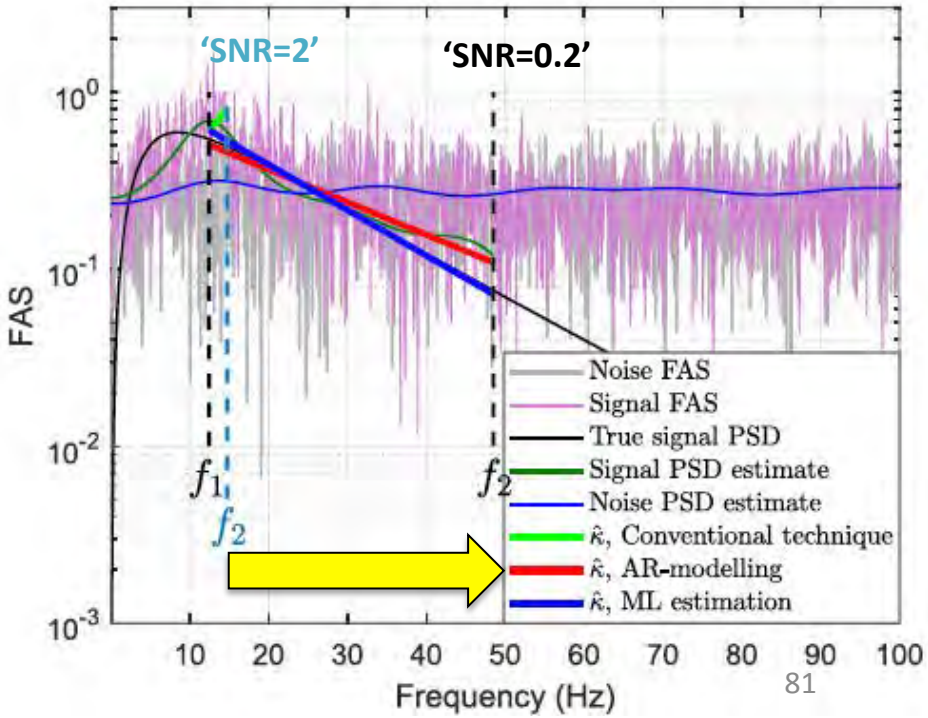
Demonstration on synthetics

- By noise **modelling** instead of noise **avoidance,** we can retrieve κ even from a FAS drowning in up to -3 dB noise

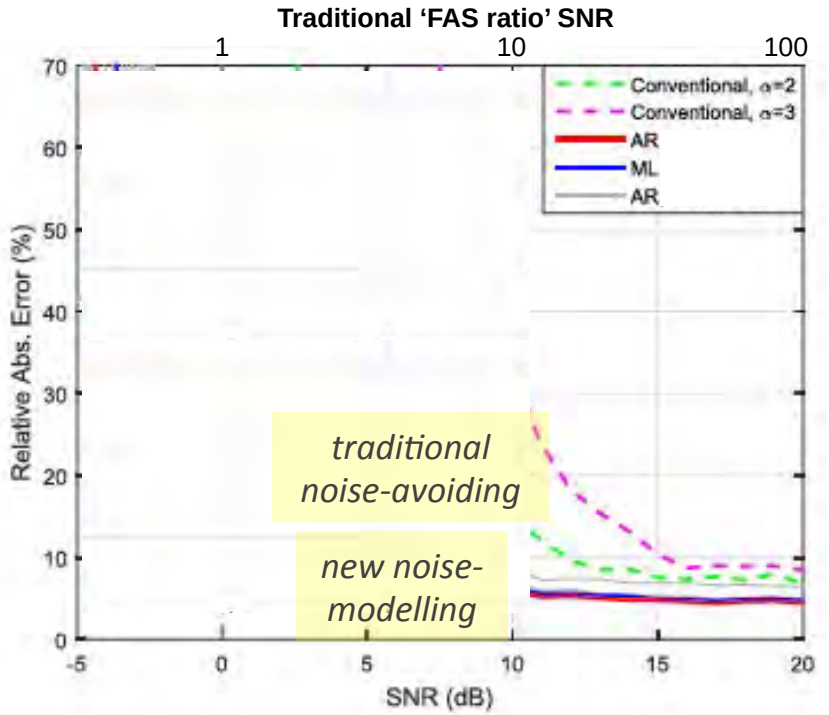
very clean simulated signal



simulated signal 'drowning' in noise

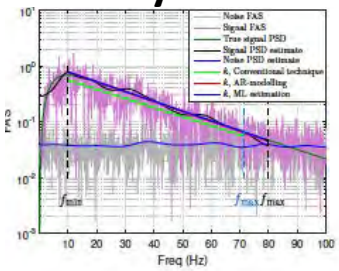


Demonstration on synthetics



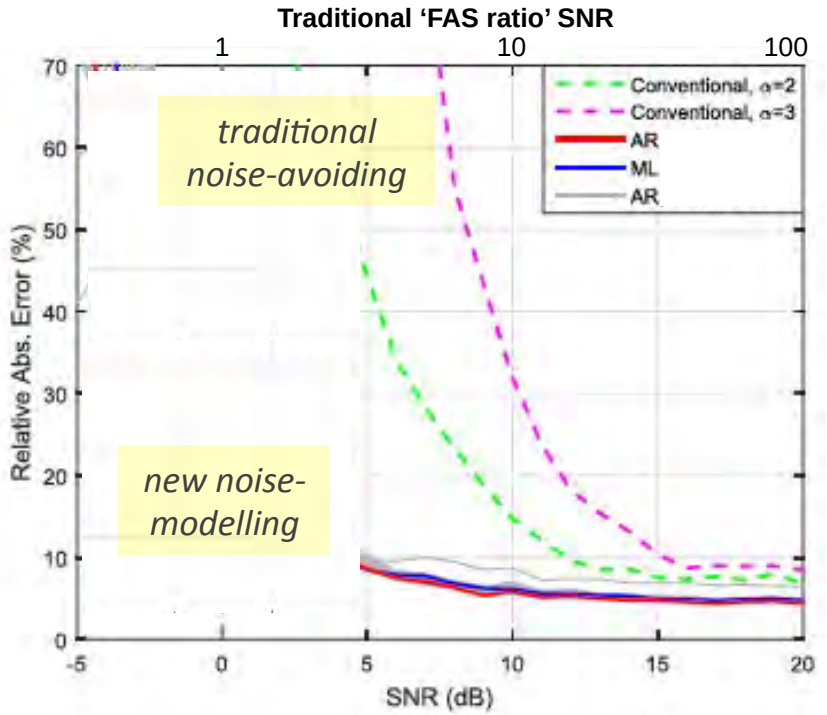
relative error
vs. noise level

very clean



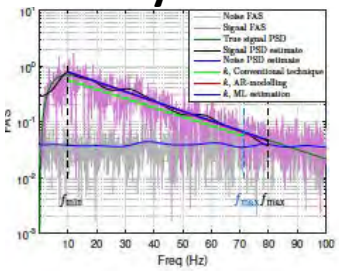
- all methods are acceptable for very clean signals (SNR=30)

Demonstration on synthetics



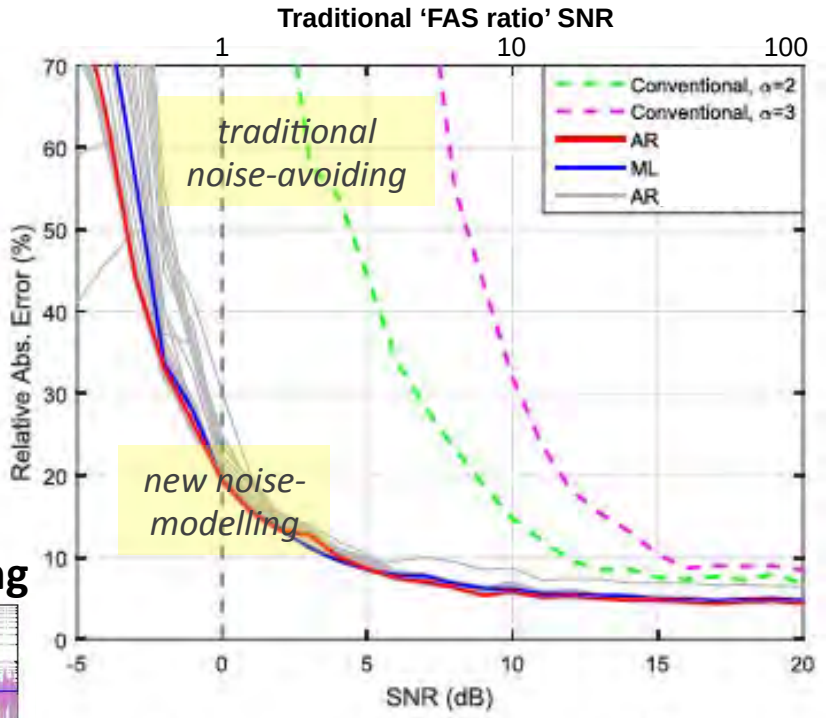
relative error
vs. noise level

very clean



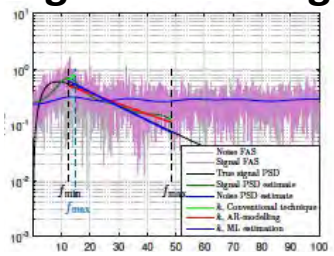
- as noise increases, traditional threshold approaches **start to diverge strongly** from the true solution

Demonstration on synthetics

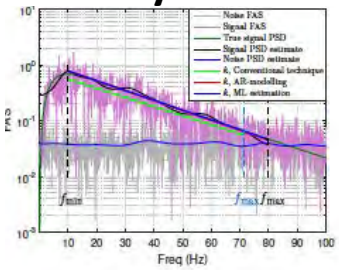


relative error
vs. noise level

signal drowning

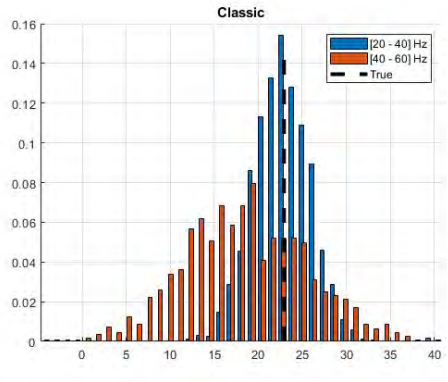


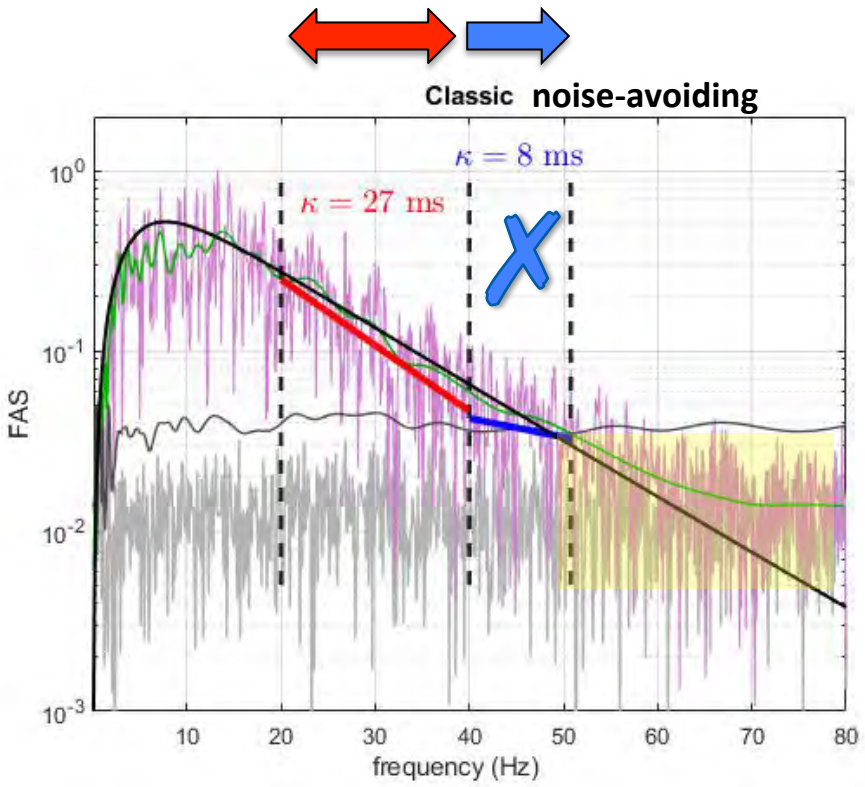
very clean



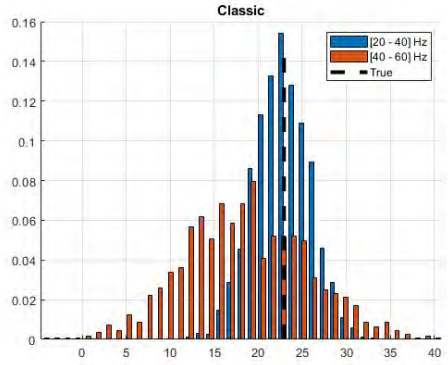
- **only ML holds up** for very poor signals (0 dB / **SNR=1 or less**)

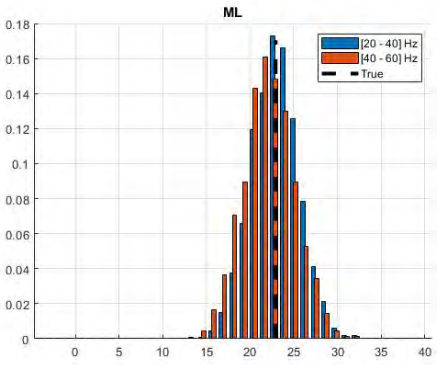
Demonstration on synthetics

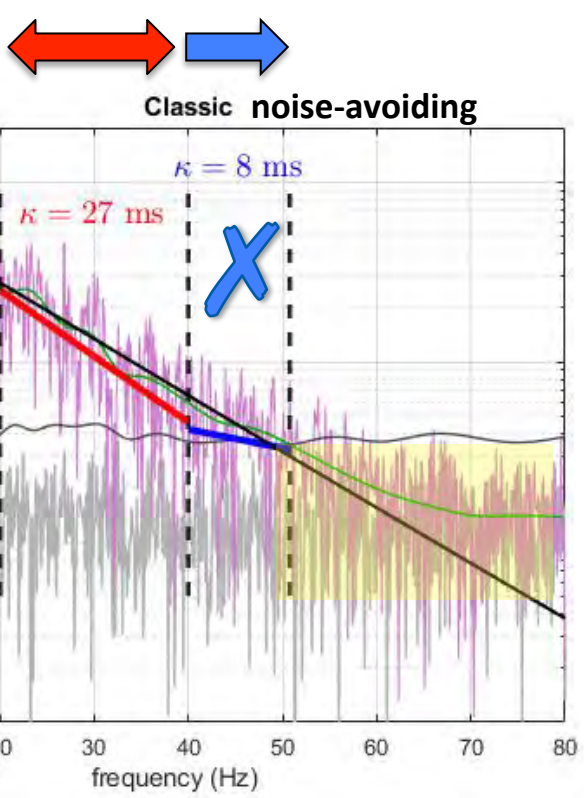


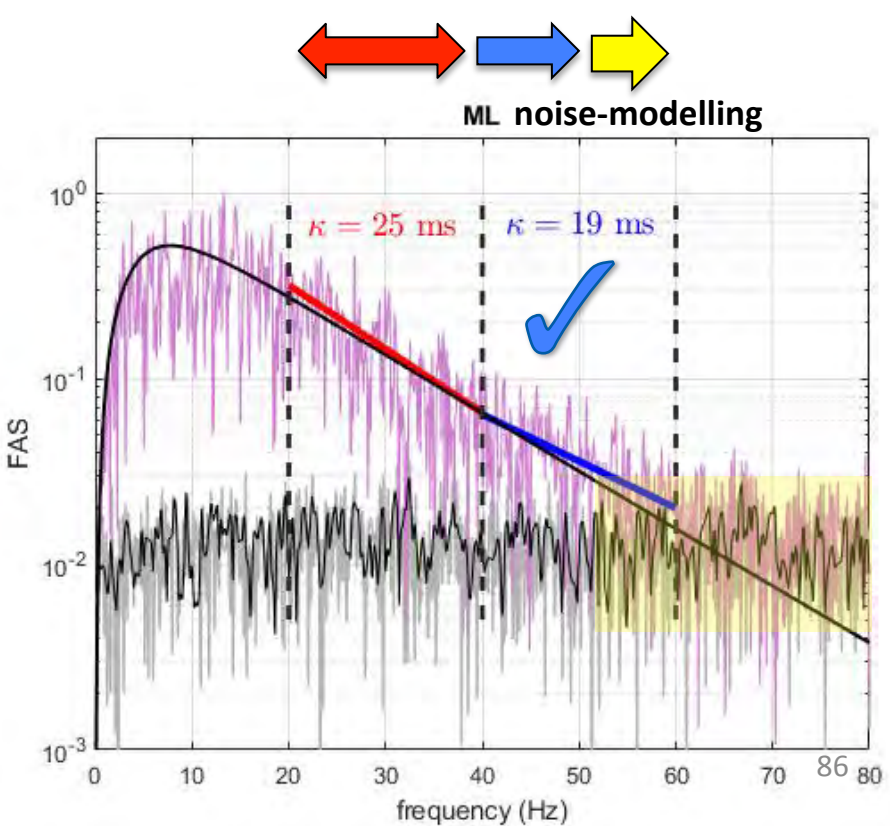


Demonstration on synthetics



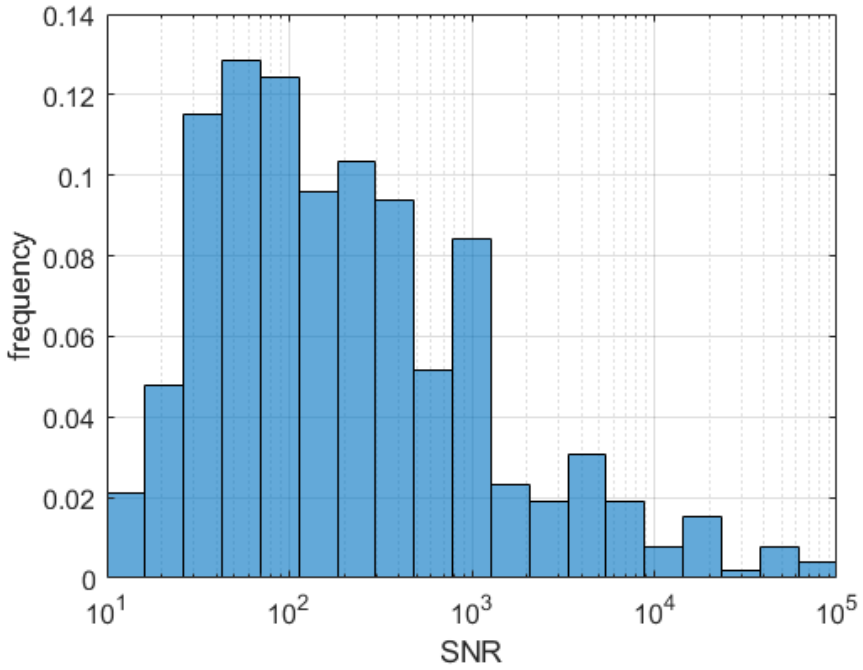




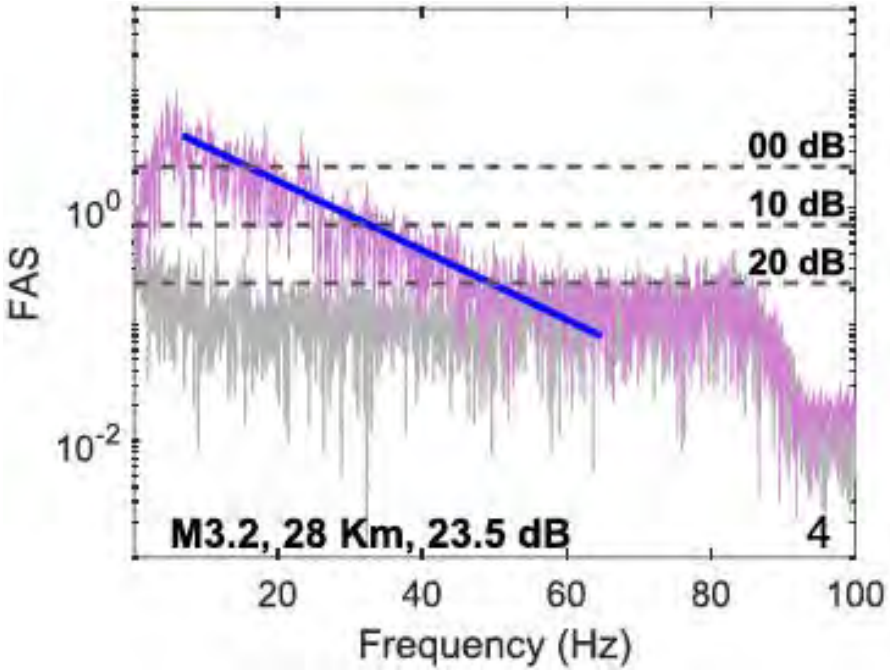


Data application 1

180 m in downhole
very quiet, « ideal »

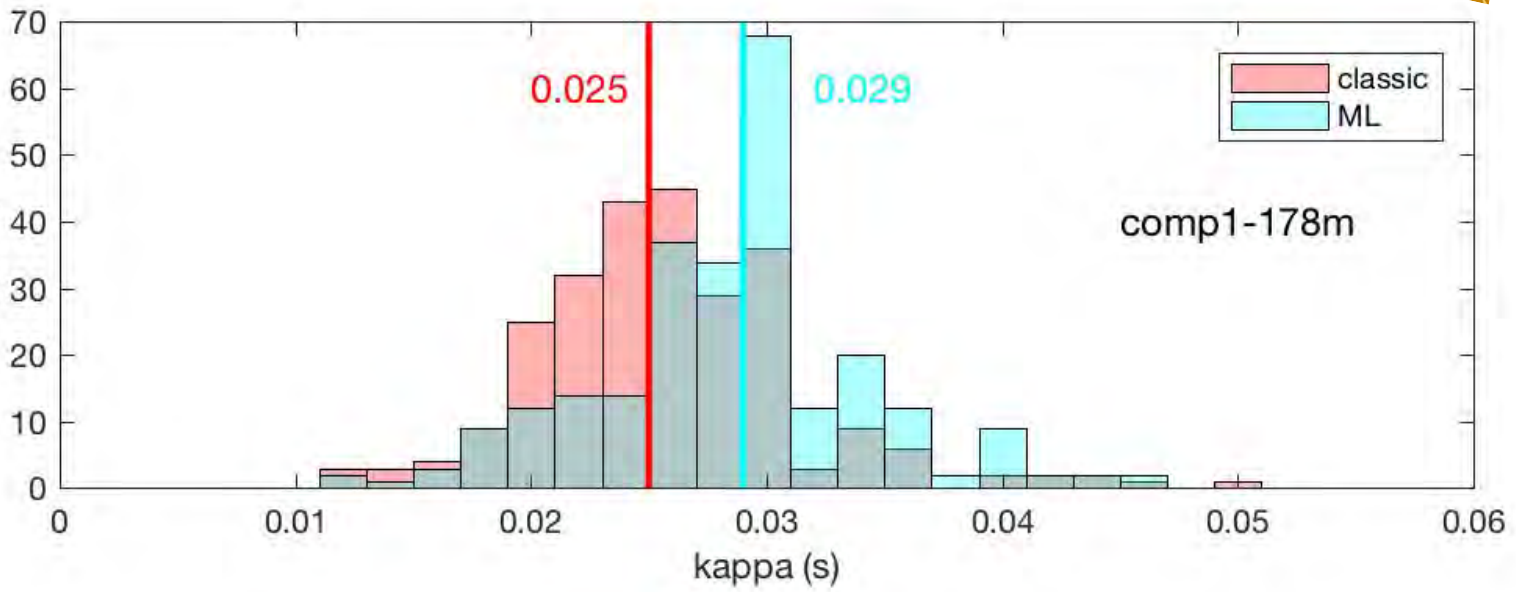


SNR=200



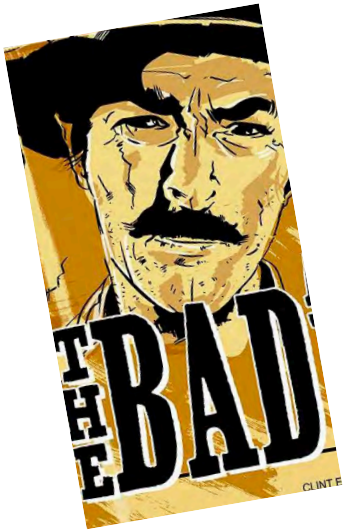
Data application 1

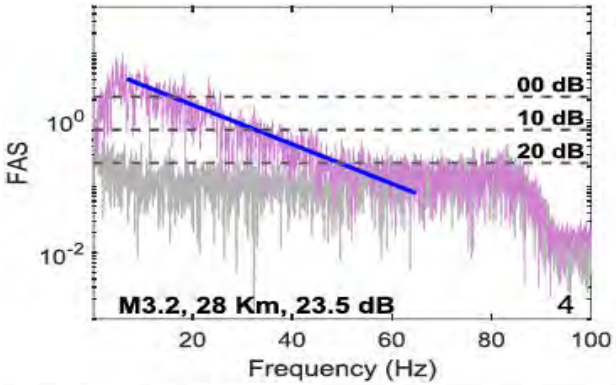
250 near-source recordings
small shift in median κ

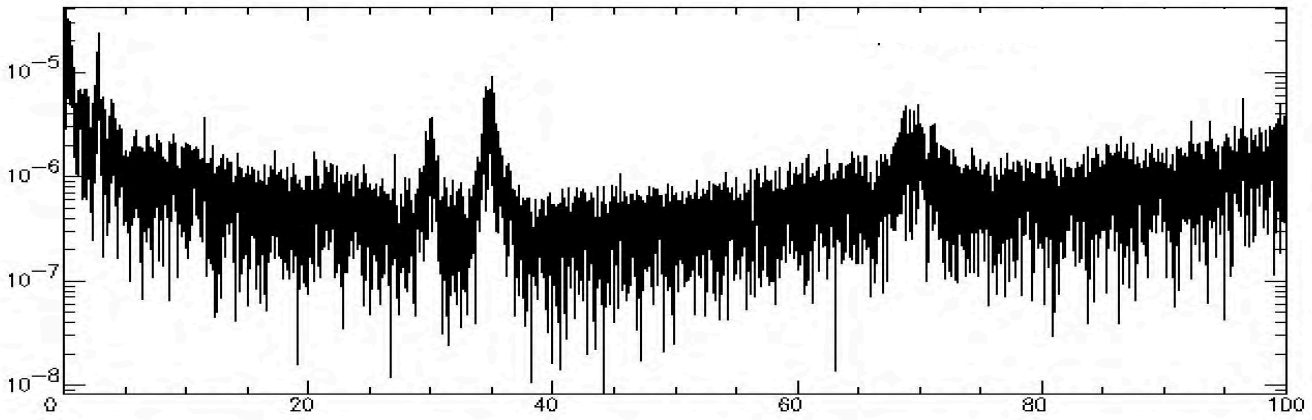


Data application 2

tested on unfavorable noise conditions
(spectral peaks / monochromatic noise)



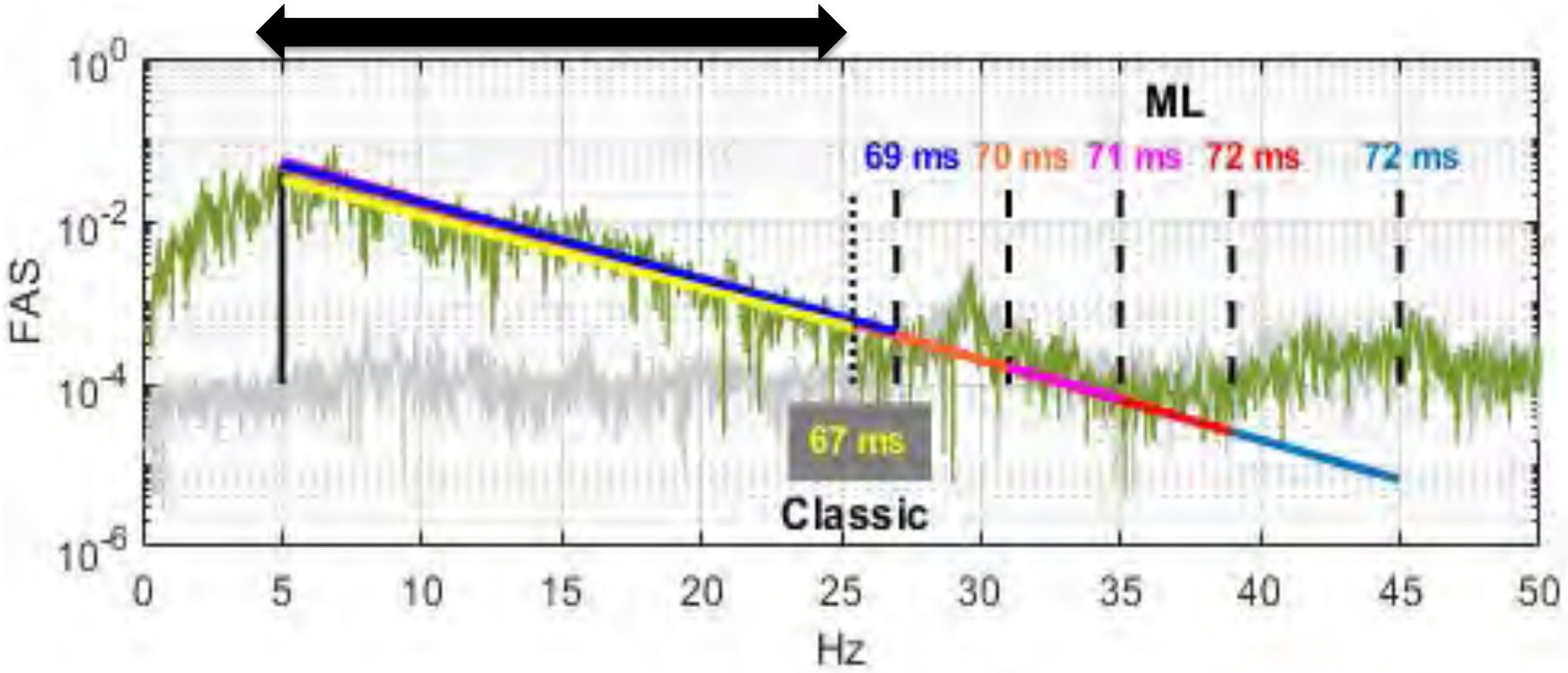




Data application 3

example 1:

strongest recording, very adequate Df (calibration record)
ML method can go beyond spectral peak and well into noise with consistent results ➔ resilience

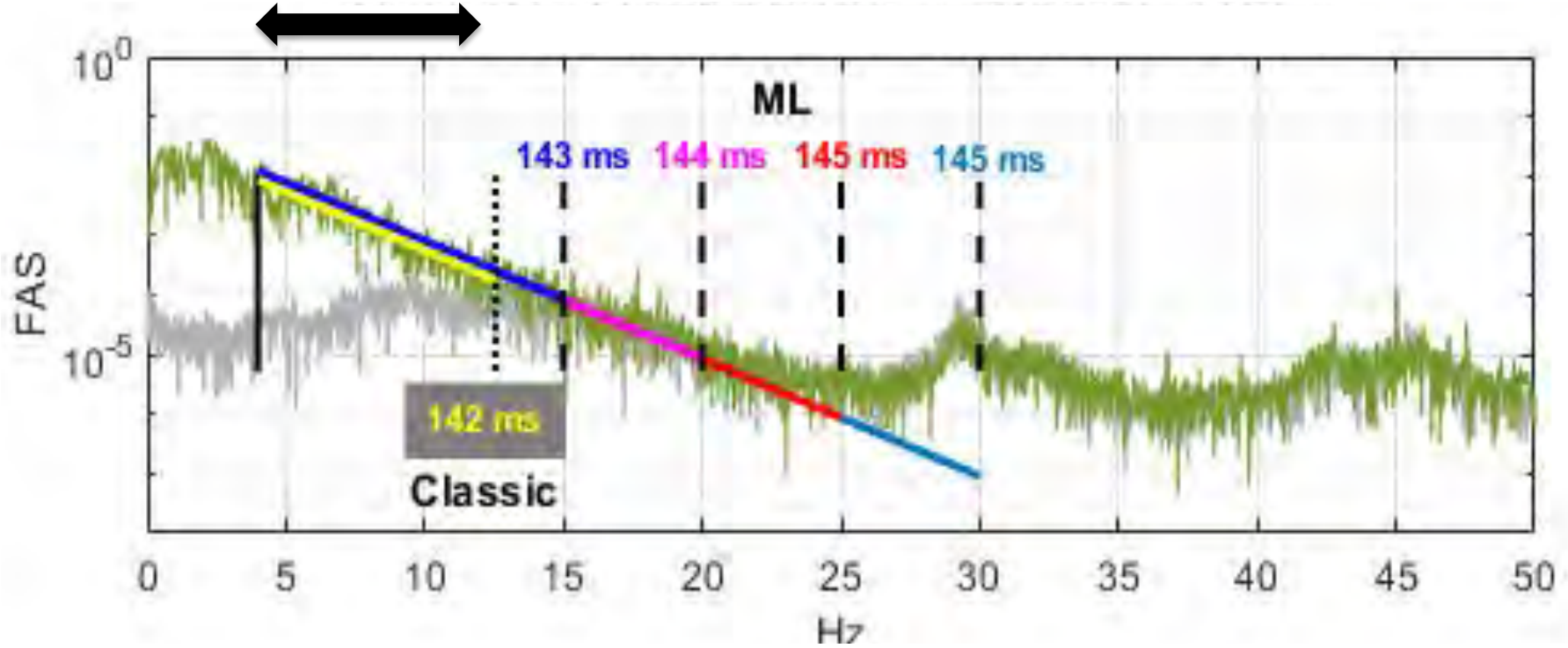


Data application 3

example 2:

weak recording, very short 'legitimate' Df

ML method increases usable bandwidth allowing for more confidence in spectral slope despite spike

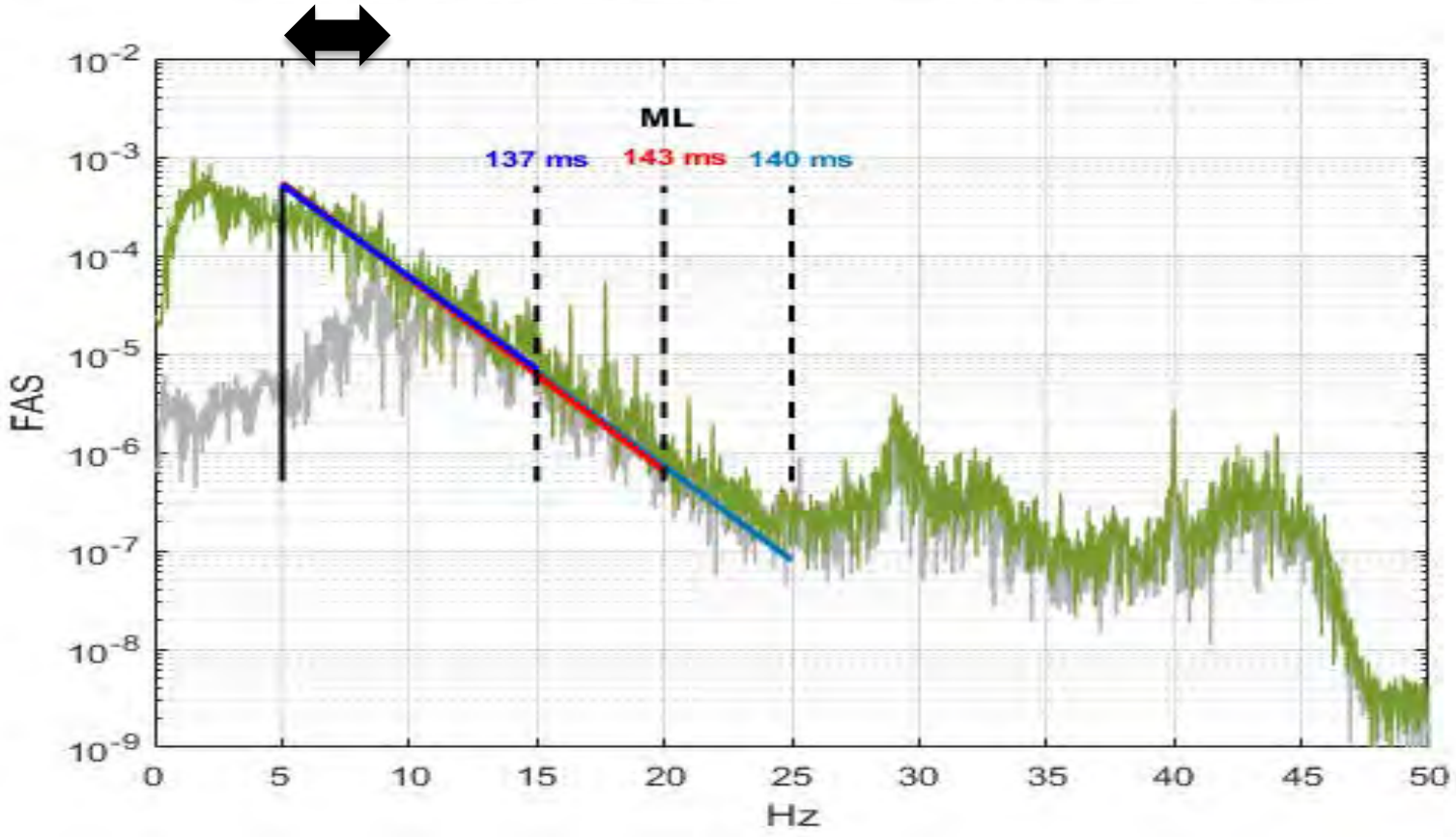


Data application 3

example 3:

very weak recording, no ‘legitimate’ Df whatsoever

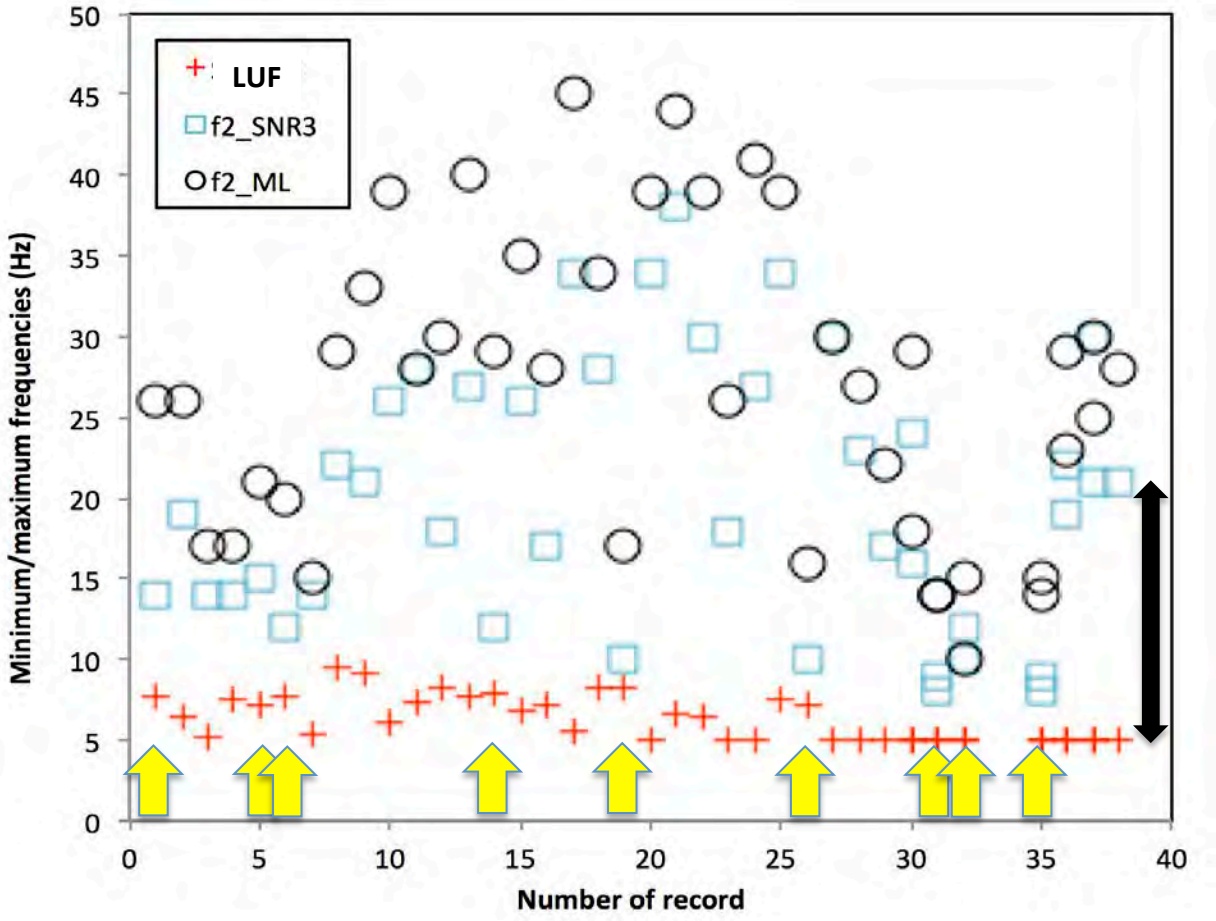
ML method provides the necessary usable bandwidth



Data application 3

bandwidth gained by ML method:

25% hitherto unusable events taken out of the trash can



Take home

Take home

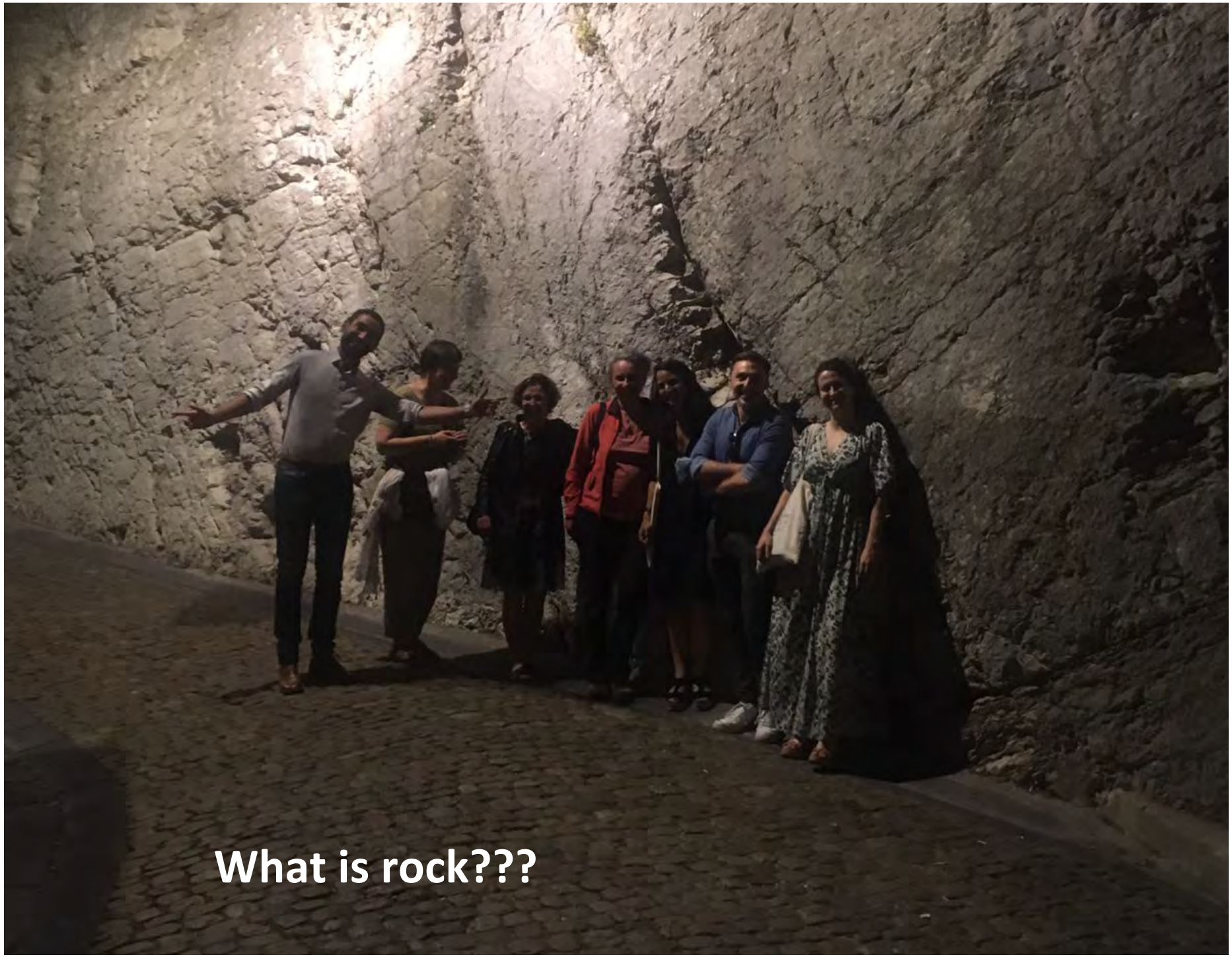
- Great variability
- Geological units, code classes, and stiffness/Vs_{30}s do not suffice

- κ is deviation from model
- 'Apparent' damping includes amplification, path, source, noise assumptions

- Need to understand & decouple effects

- Need more rock recordings & station characterisation

- Noise-modeling extends Df & exploits poor data


What is rock???

Visit to discuss more!

Acknowledging…

- Norm Abrahamson
- Walt Silva
- Bob Darragh
- many others

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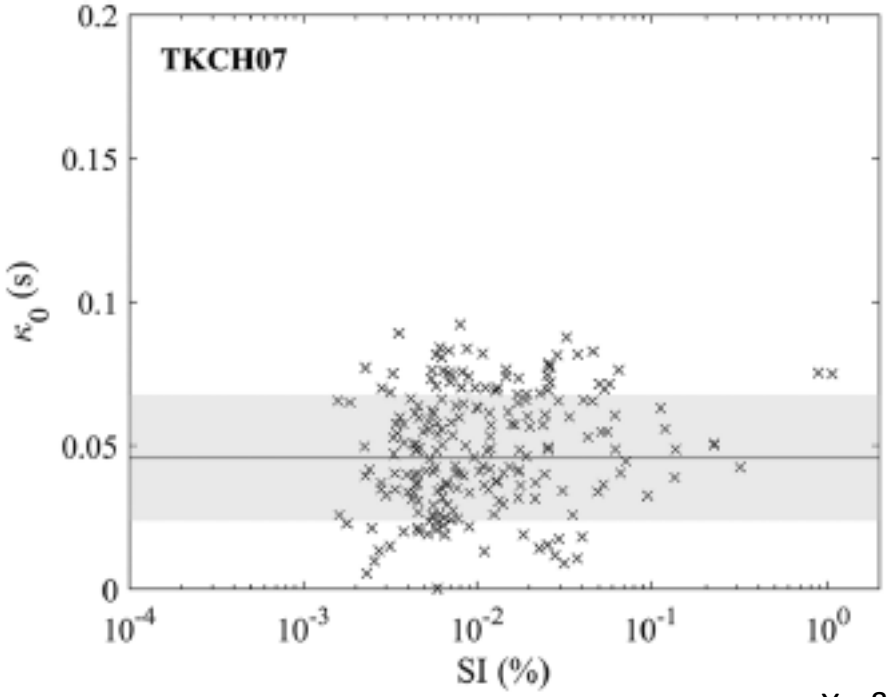
extra slides

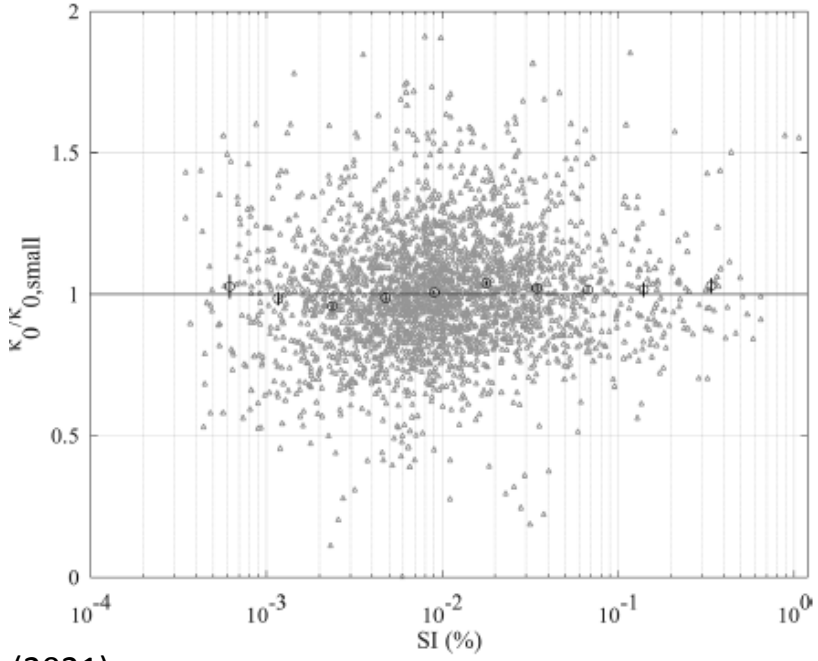
Limitation: higher-strain damping?

- Dimitriu (2001) showed κ increasing with ground shaking level (consistent with G-γ-D soil dynamics curves)

- Van Houtte et al. (2014) found the opposite result – perhaps due to PGA indicating not shaking level but rate of shearing

- Xu & Rathje (2021) used a larger dataset to study nonlinearity ad hoc. They find no correlation of κ0 with strain index $(\mathrm{SI} = \mathrm{PGV}_{surf}/V_{smin})$.





Xu & Rathje (2021)