Università degli Studi di Roma “La Sapienza”
Dipartimento di Ingegneria Civile, Edile e Ambientale

Efficient use of Ambient Vibrations for Site Characterization and Seismic Response Analysis

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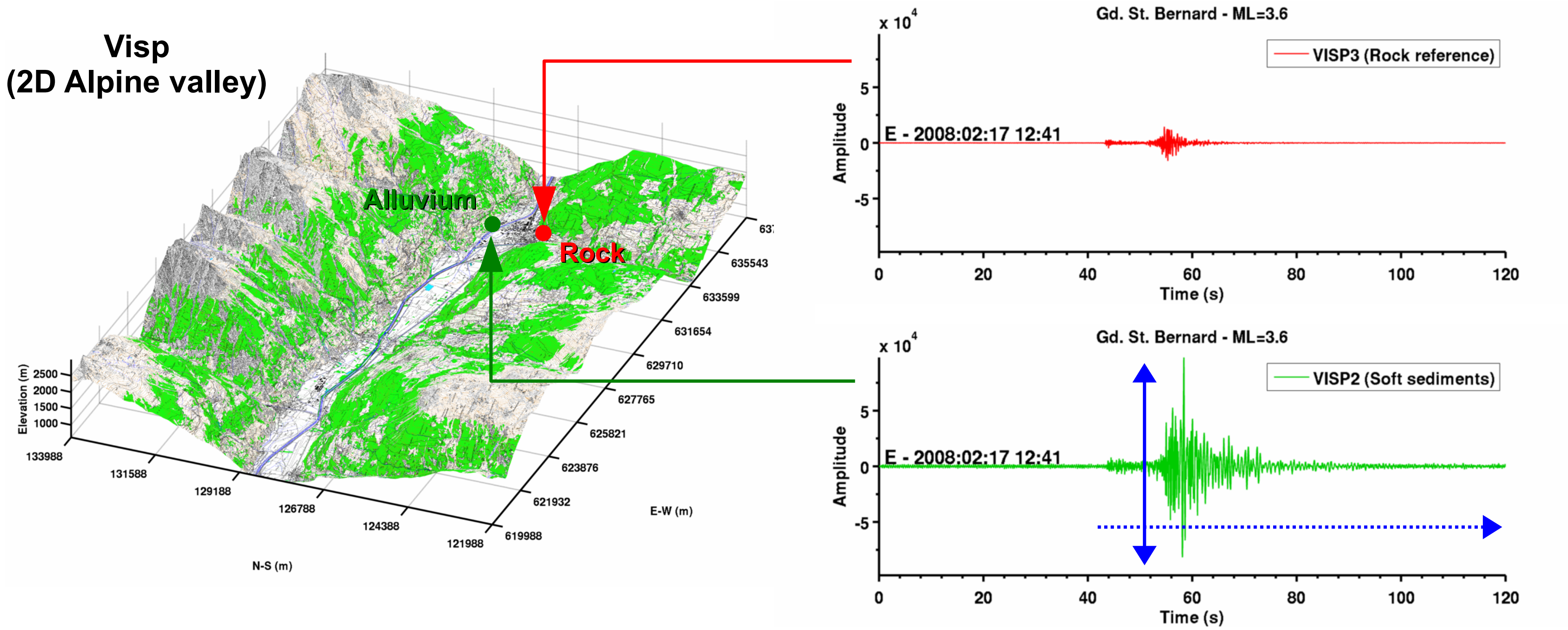
Proc sel n 1 SC 04/A4 SSD GEO/11
Codice bando: 2018RTDB006

Local Seismic Response

- For a particular site, the **amplitude** and **duration** of the ground motion during an earthquake can significantly be modified by the effect of the *local site conditions*
- On **very soft sediments** on top of a rigid bedrock, the ground motion can be **amplified** by more than a factor of 10, with increase in duration of several tens of seconds.
- Additionally, the energy can be non-evenly redistributed over different *frequency bands* of the spectrum, with a chance of matching the dominant **resonant frequencies of buildings**

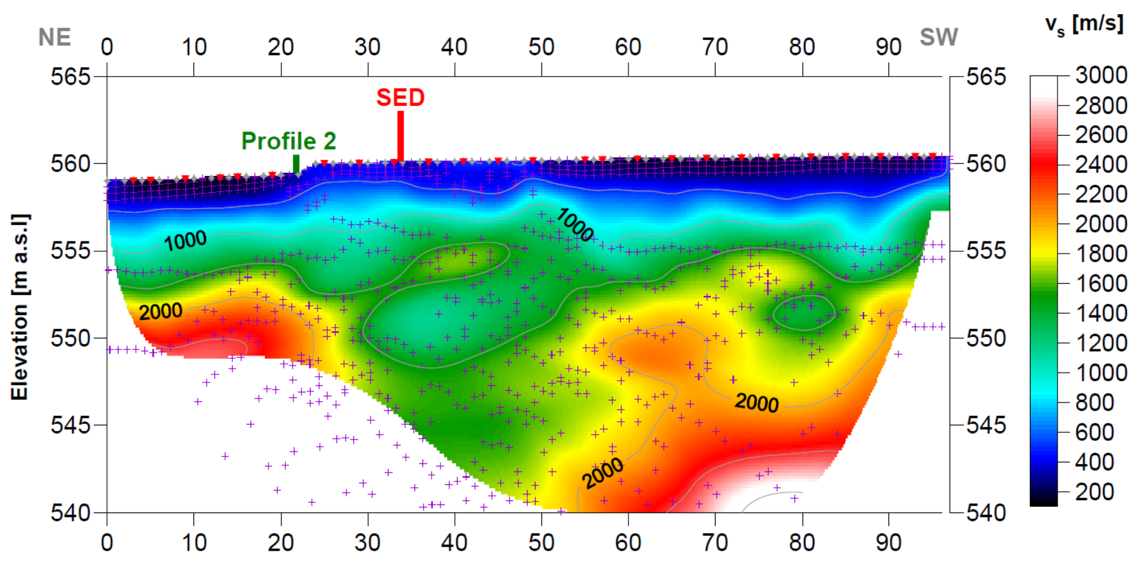


Geophysical Site Characterization

- The ground motion at the surface is highly controlled by the *geophysical properties* (velocity, density, quality factors) of the **first tens to hundreds of meters of the earth structure**, where the larger variability of the geological conditions is present.

- To correctly compute/analyze the seismic response, an adequate *level of knowledge* of the structural characteristics for the site area is necessary.

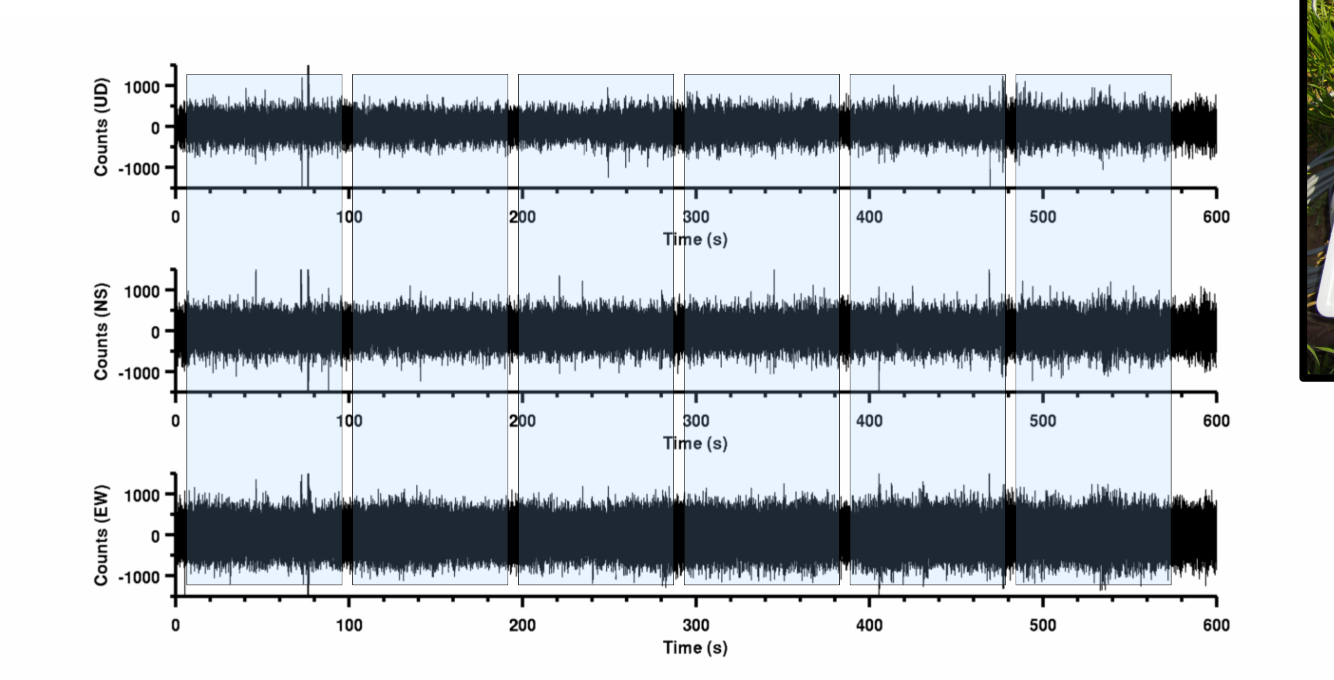
- The available level of knowledge is often insufficient because of the *considerable investments* required for measurements.



SED station SKEH - Vs profile from hybrid seismic survey (PRP Project).

Using Ambient Vibrations

- Ambient vibrations (often improperly called seismic noise) are mircovibrations originated from the interaction of **natural** (wind, rain, ocean) and **anthropogenic sources** with the earth surface.
- The ambient vibration wave-field is largely dominated by **surface waves** (Rayleigh and Love), with a minor although not negligible contribution of **body waves**.
- Due to its **stochastic nature**, amplitude and/or the phase information is analyzed statistically to obtain properties (e.g. polarization, velocity dispersion) which can be used to infer information on the soil structure



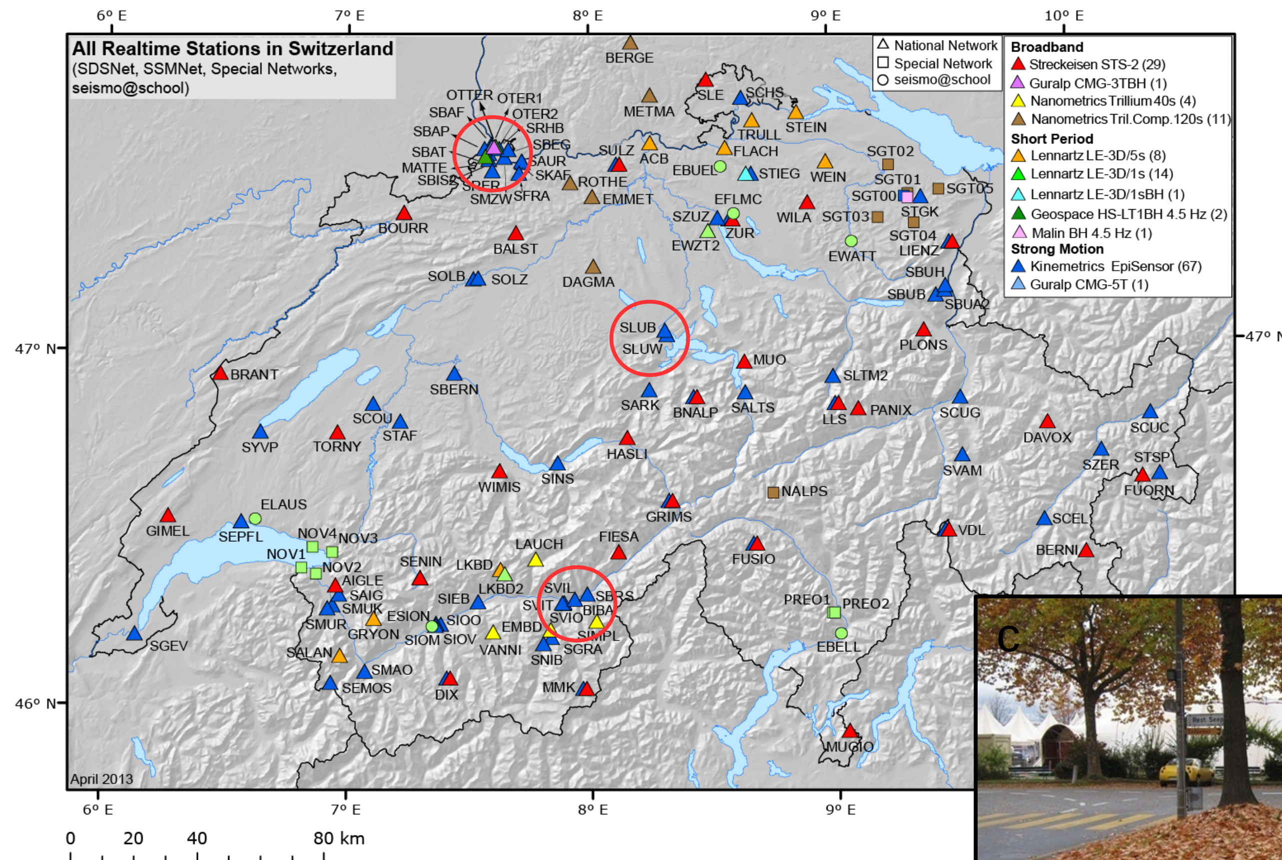
State of the Art (?)

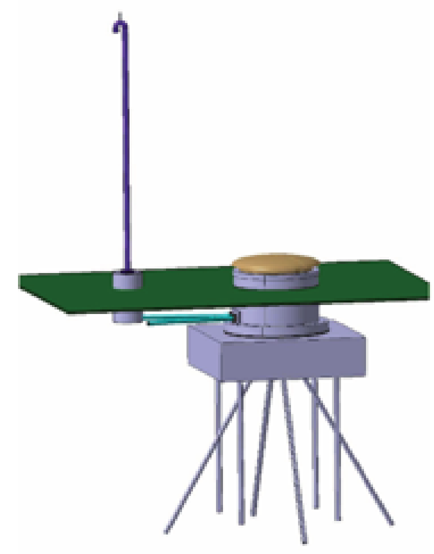
- The number of publications about the use of ambient vibrations has <u>increased considerably</u> during the last decade, due to **simplicity** and **cost-effectiveness** of the method.
- In most cases, however, authors settle using basic processing techniques (e.g. **simple H/V ratios**) without fully exploring the huge potential of such phenomenon.
- Are here presented a few examples of the **advance use of ambient vibrations** for site characterization and seismic response analysis.

SECTION A
Single Site Characterization

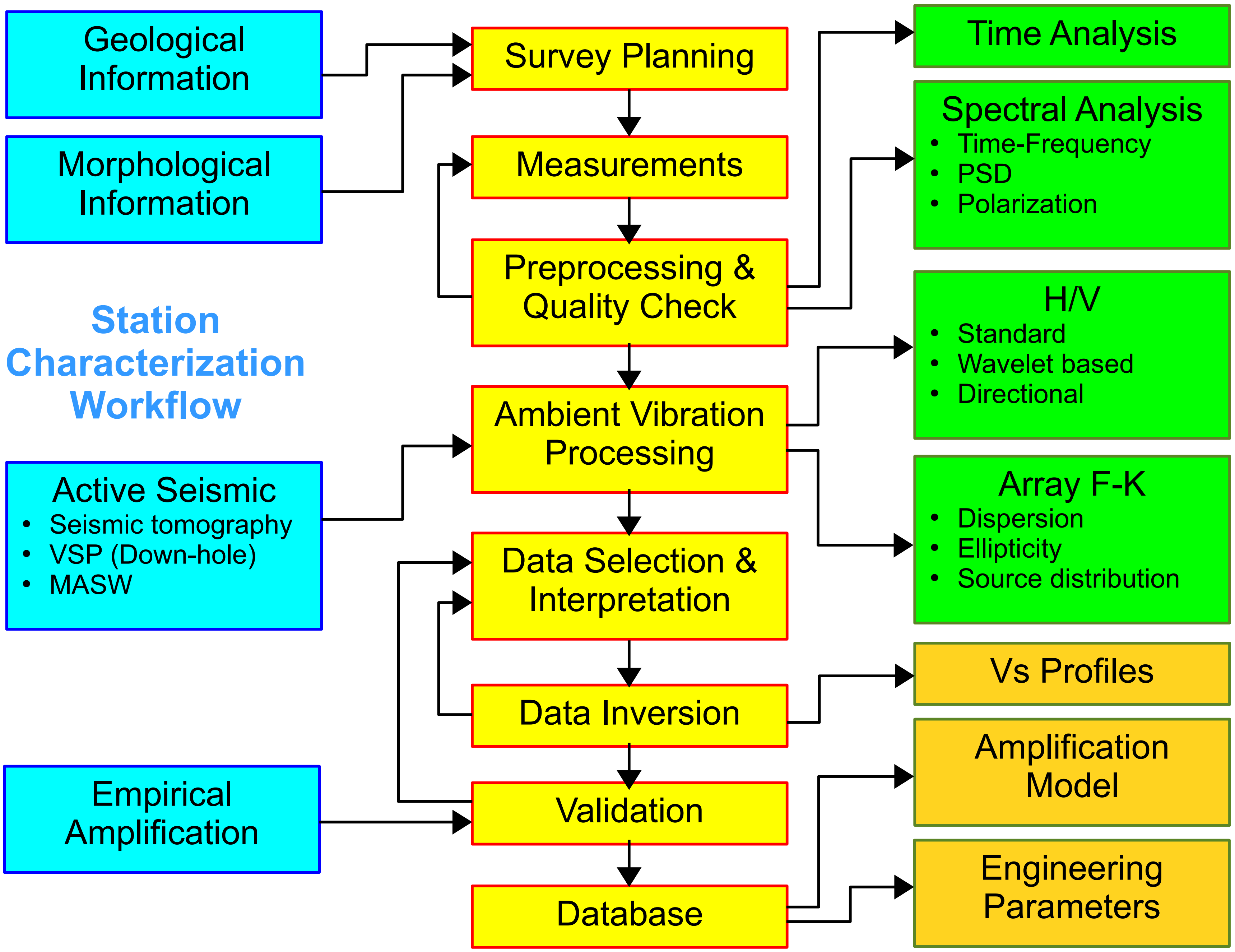
The Swiss Networks (SSMNet, SDSNet)

The **Strong Motion Network** (SSMNet, 55 stations) and the **Swiss Digital Network** (SDSNet, 52 stations) cover a variety of geological conditions in Switzerland, from very hard rock sites to low-velocity sedimentary valleys.

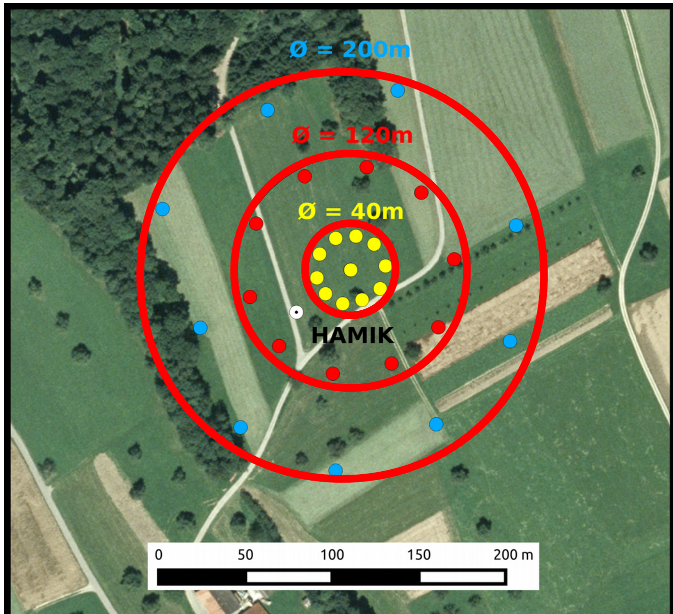


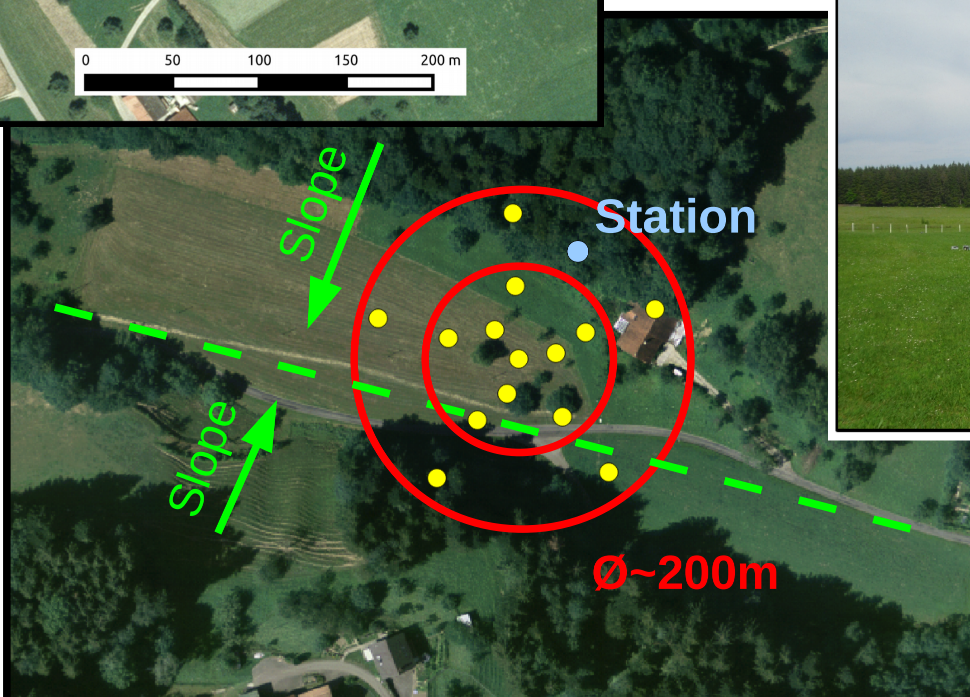


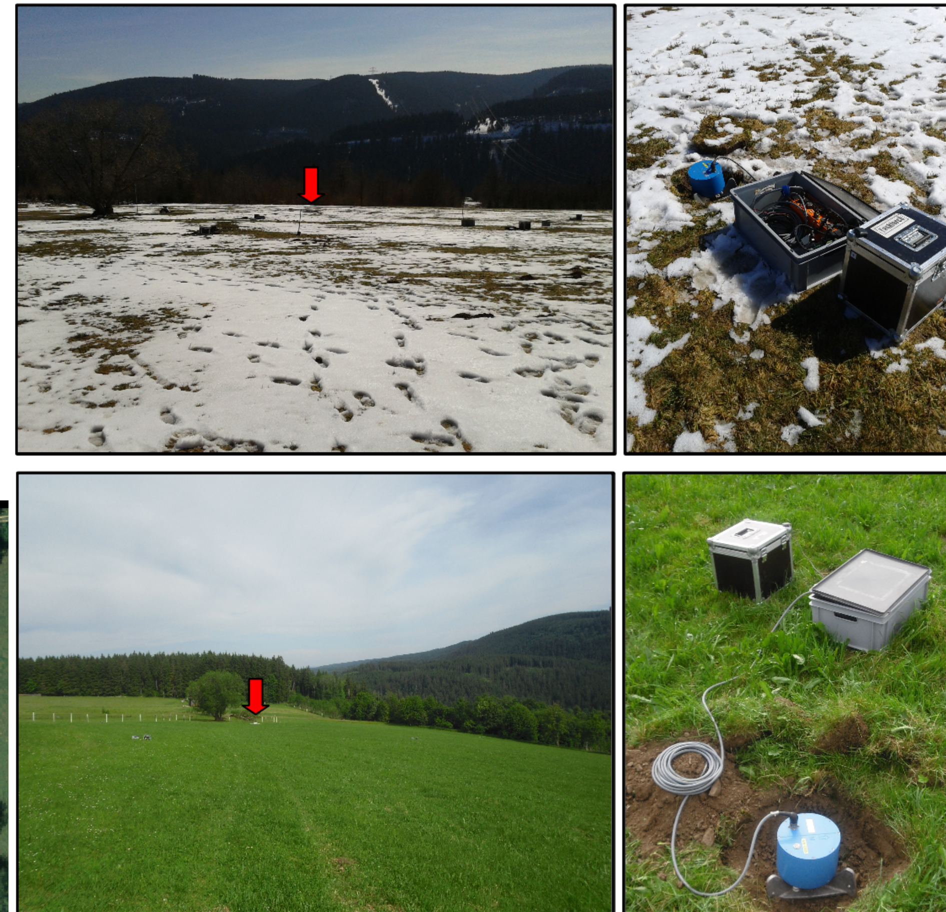
Underestimation of the local response introduces **errors** and **uncertainties** in ground motion analysis (e.g calibration of GMPEs, location solutions...)


Geological Information
Morphological Information
Station Characterization Workflow
Active Seismic
• Seismic tomography
• VSP (Down-hole)
• MASW
Empirical Amplification
Survey Planning
Measurements
Preprocessing & Quality Check
Ambient Vibration Processing
Data Selection & Interpretation
Data Inversion
Validation
Database
Time Analysis
Spectral Analysis
• Time-Frequency
• PSD
• Polarization
H/V
• Standard
• Wavelet based
• Directional
Array F-K
• Dispersion
• Ellipticity
• Source distribution
Vs Profiles
Amplification Model
Engineering Parameters

Ambient Vibration Measurements



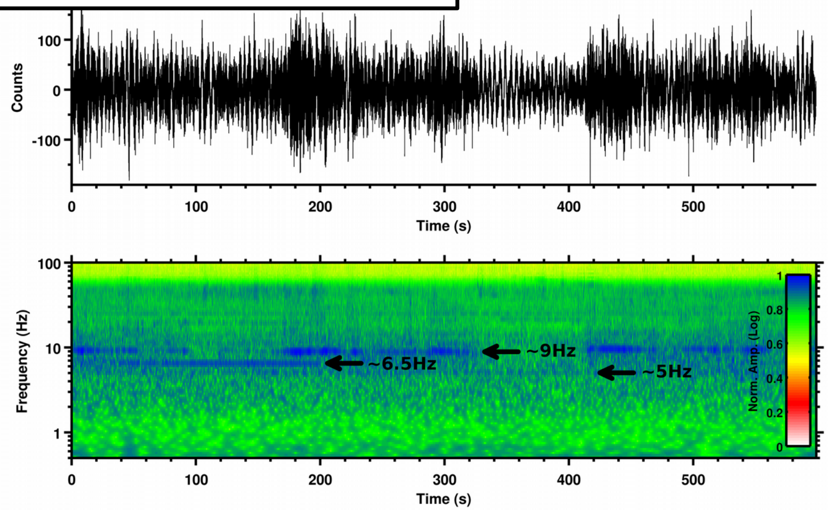




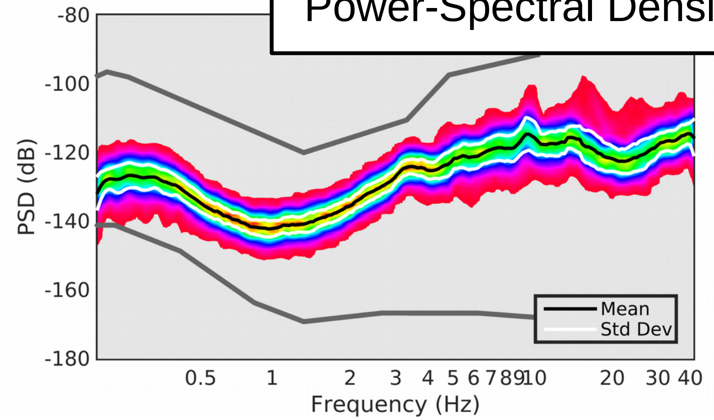
Equipment
Lennartz 3D (5s)
Quanterra Q330 (32Bit @ 200Hz)
Leica Viva Differential GPS

Preliminary Quality Assessment

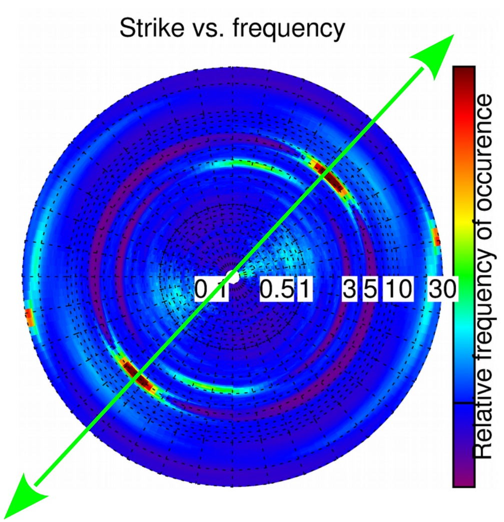
Time-Frequency Analysis

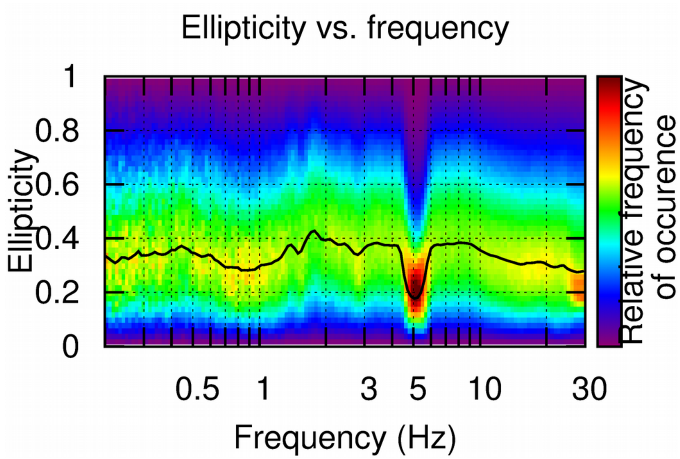


Power-Spectral Density



Polarization Analysis

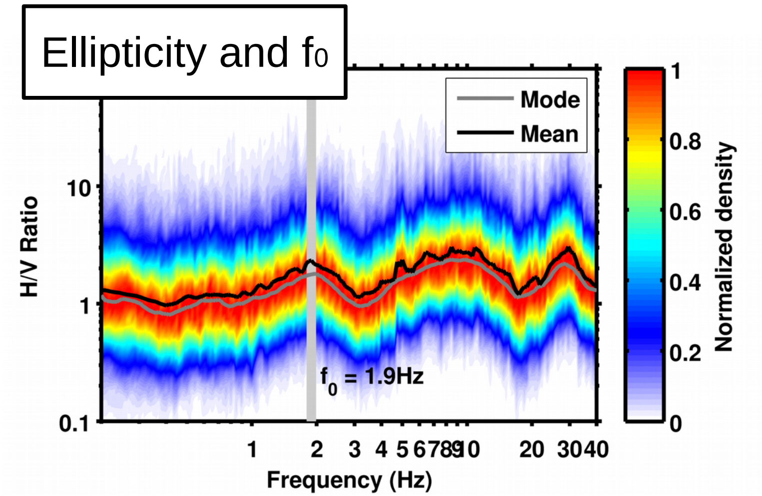




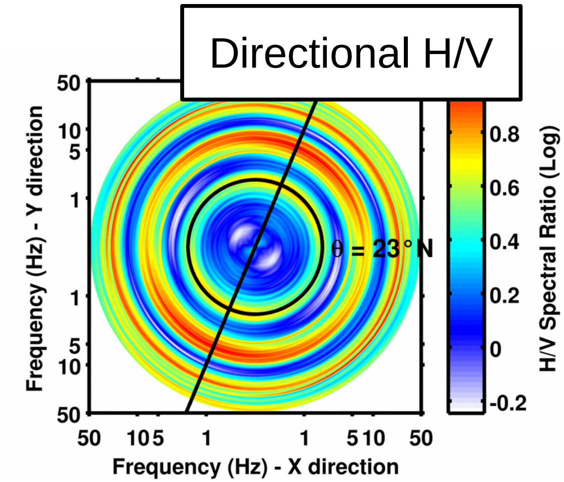
Target

- Anthropogenic Signals
- Coherence & Stationarity
- Energy level
- Anisotropy

Single-Station Analysis

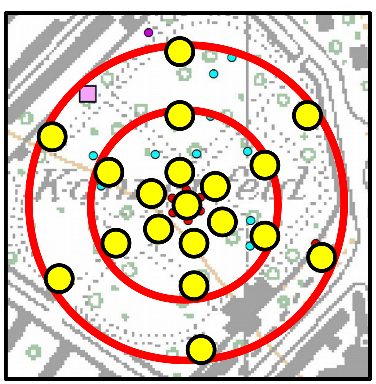


- Standard H/V
- Wavelet H/V
- RayDec

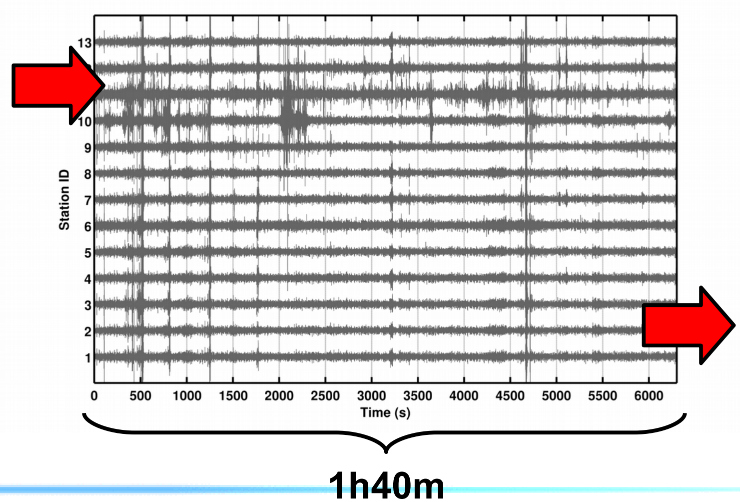


Surface Wave Array Analysis

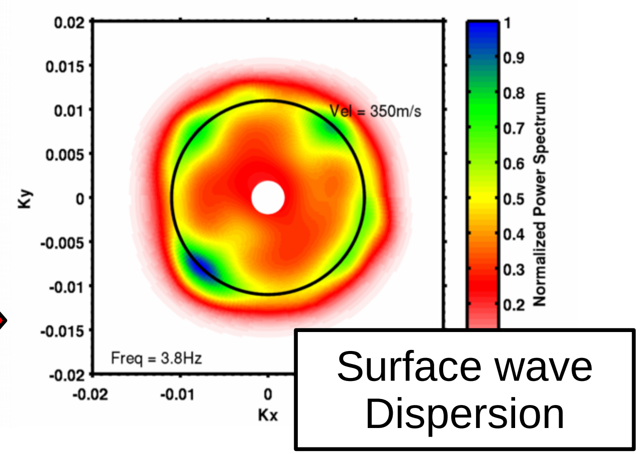
Array deployment



Noise recording

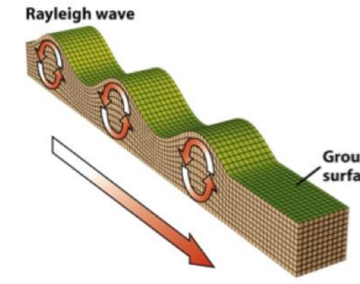


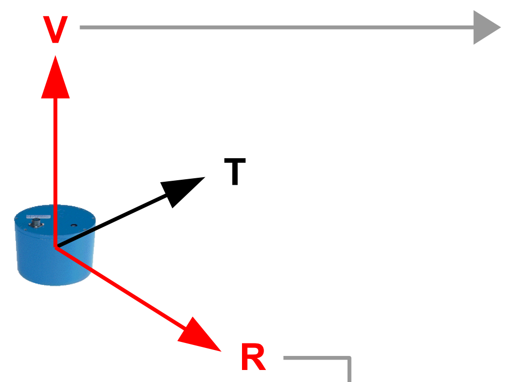
f-k analysis



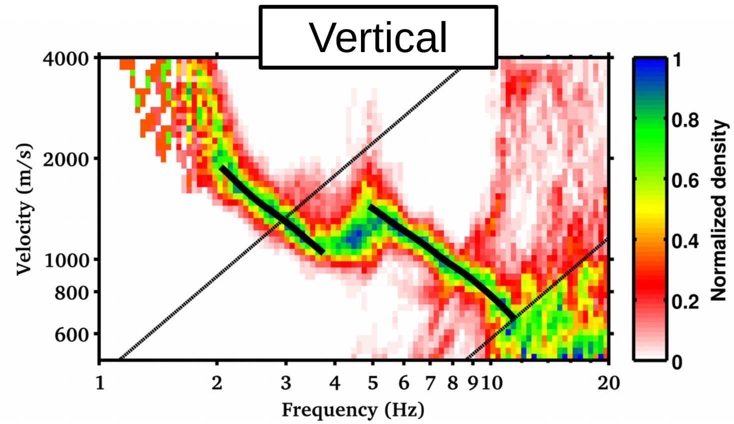
3C F-K Array Processing

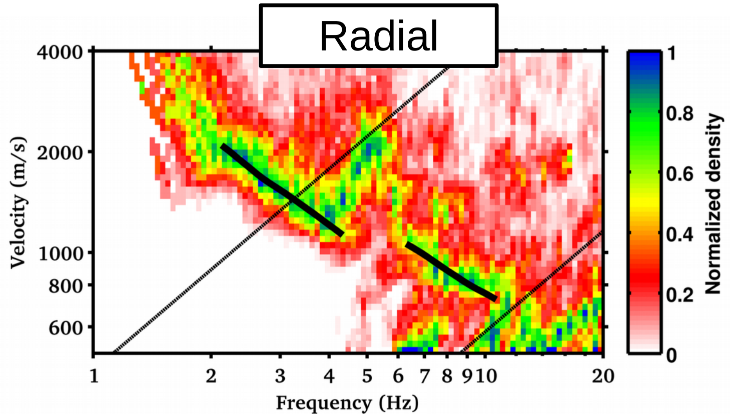
Three-component f-k analysis extends the original high-resolution algorithm of **Capon (1969)** to estimate the f-k power-spectrum for the horizontal components.

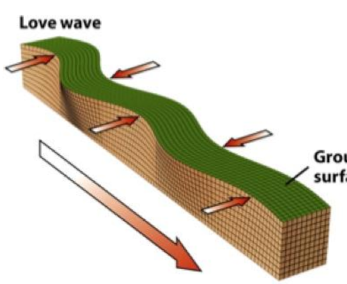


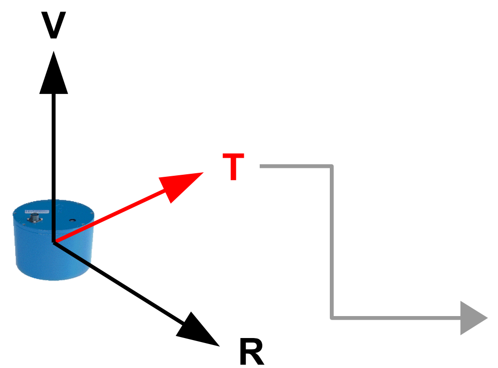


Rayleigh wave dispersion

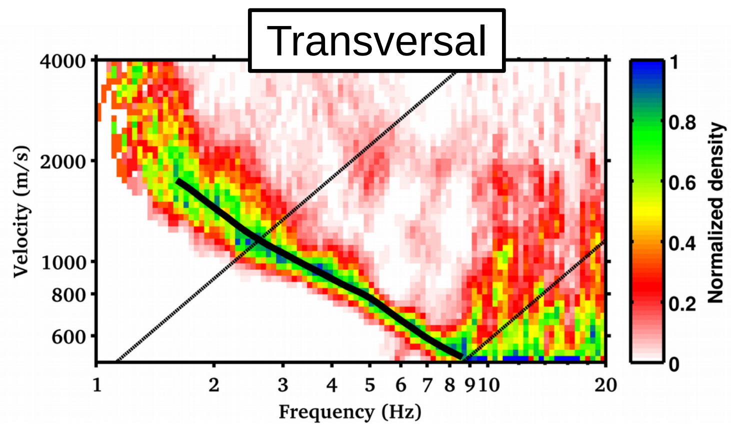




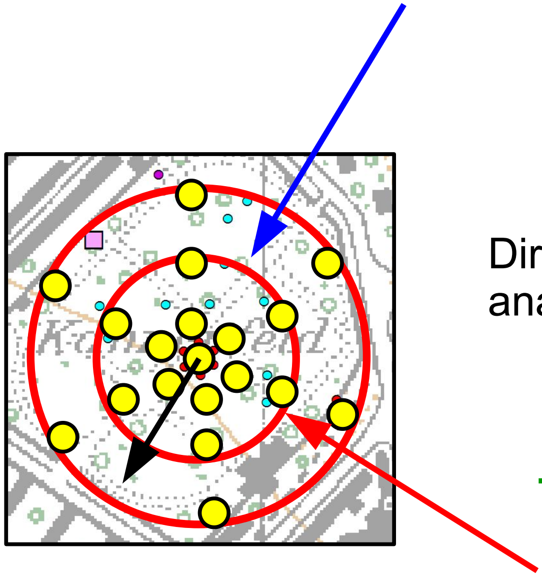




Love wave dispersion



Radial/Transversal Decomposition



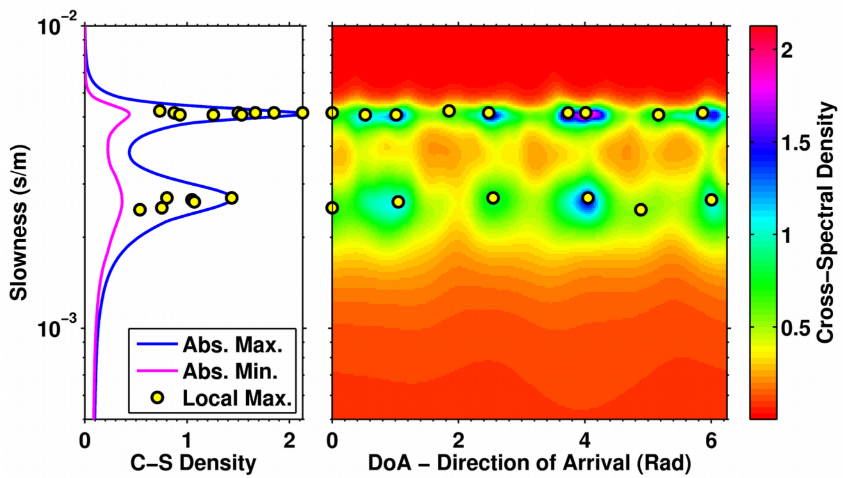
Rayleigh DoP
Love DoP
Particle motion (R&T)

Direction of Arrival (DoP) ambiguity can be solved by array analysis using vector composition of the horizontal wave-field:

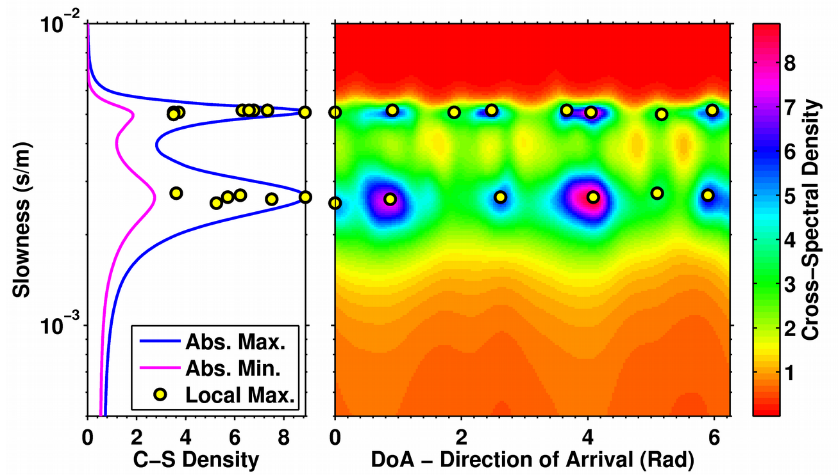
Radial (Rayleigh) → $U^R = U^{N\text{-}S} \cdot \cos(\vartheta) + U^{E\text{-}W} \cdot \sin(\vartheta)$

Transversal (Love) → $U^T = U^{N\text{-}S} \cdot \cos(\vartheta + \pi/2) + U^{E\text{-}W} \cdot \sin(\vartheta + \pi/2)$

f-k Vertical spectrum



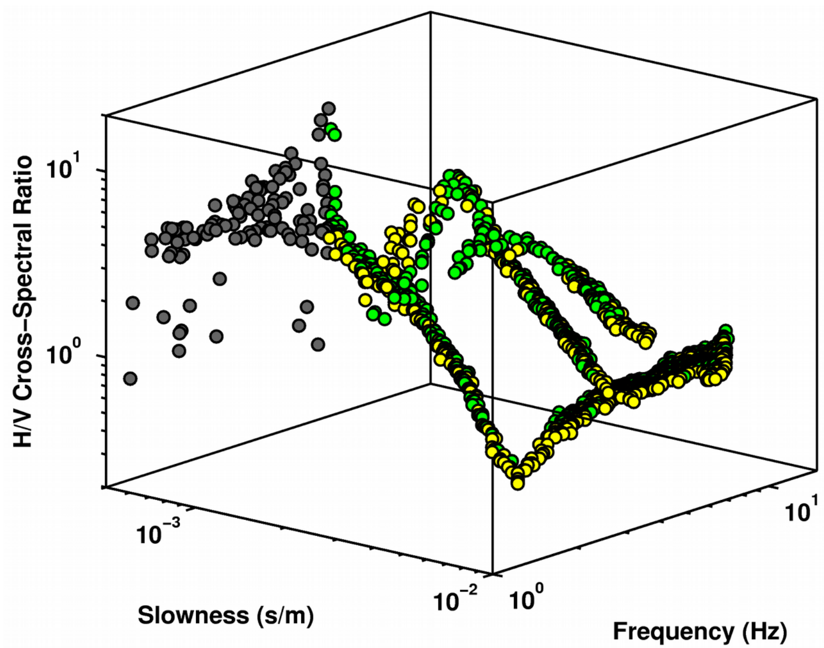
f-k Radial spectrum



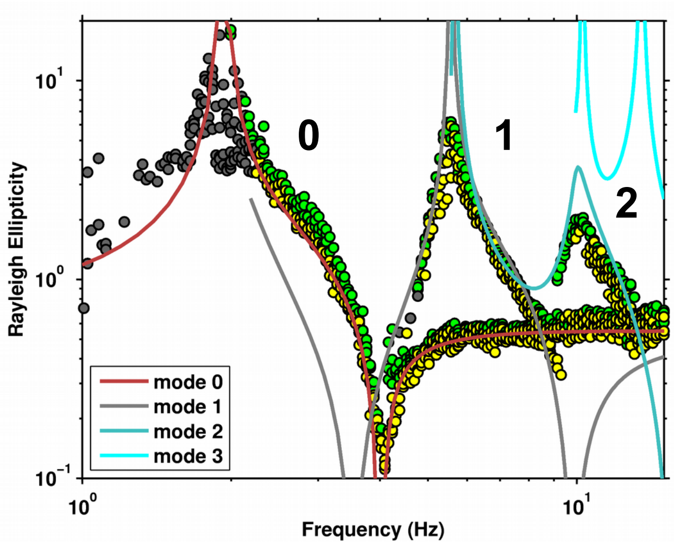
Cross-Spectral Rayleigh Ellipticity

- If a Rayleigh wave mode is identified on the f-k planes, the <u>amplitude ratio between the horizontal-radial and the vertical f-k power-spectra</u> will represent its **ellipticity**.

- Thus, if several modes of propagation are identified in the f-k planes, then the Rayleigh ellipticity function can be extracted *<u>for each mode separately</u>*.



SESAME Dataset M2.1



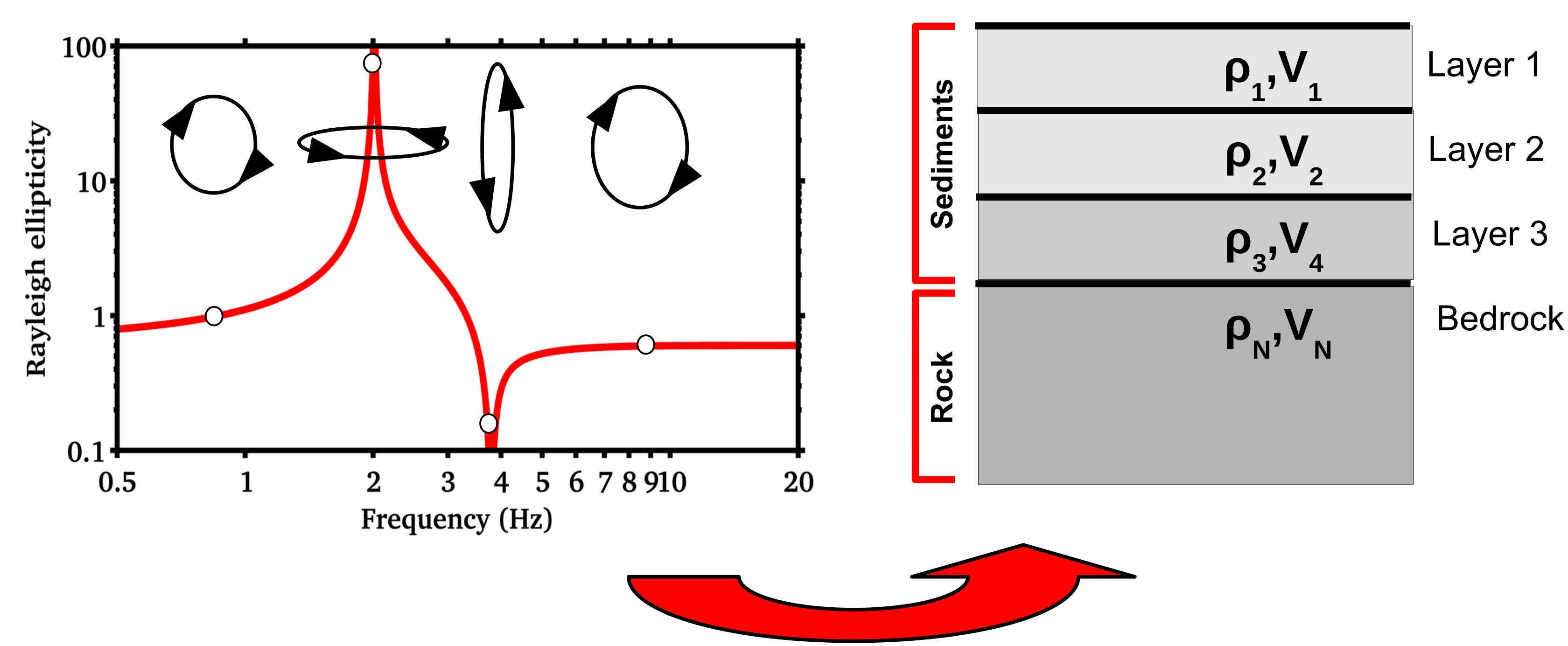
Picking from vertical component
Picking from radial component
Outside resolution limits

Rayleigh wave elliptical motion

1) Rayleigh wave ground motion is **elliptical**. It can be described by **two orthogonal components** (horizontal and vertical) oscillating in phase in a plain perpendicular to the free surface, which contains the direction of propagation

2) As for velocity dispersion, the ellipticity of the Rayleigh wave ground motion is **frequency dependent**

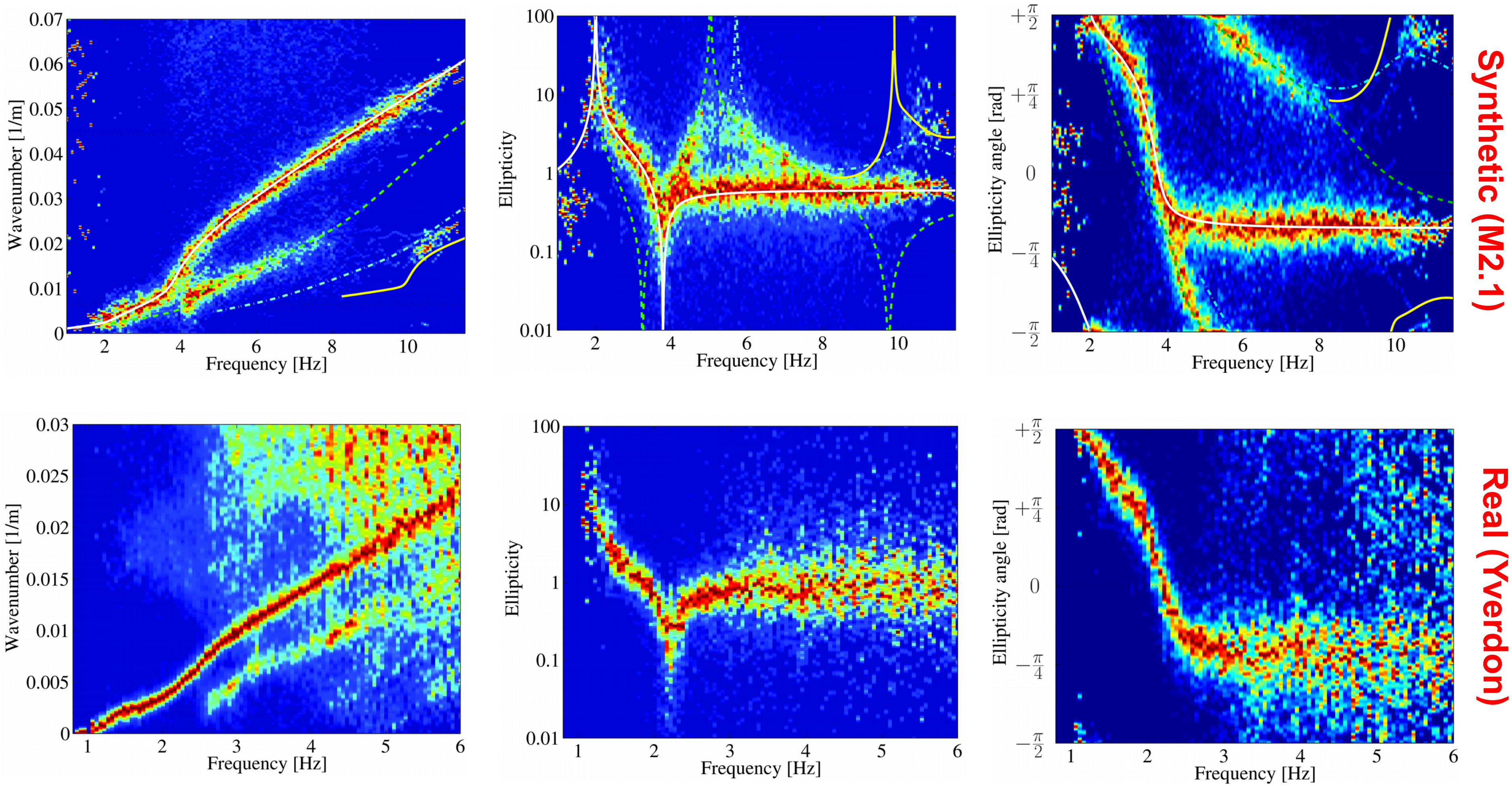
3) Rayleigh wave ellipticity is site specific and could be used in principle to retrieve the properties (Vp, Vs, density) of the ground by **inversion procedure**



Subsequent Developments

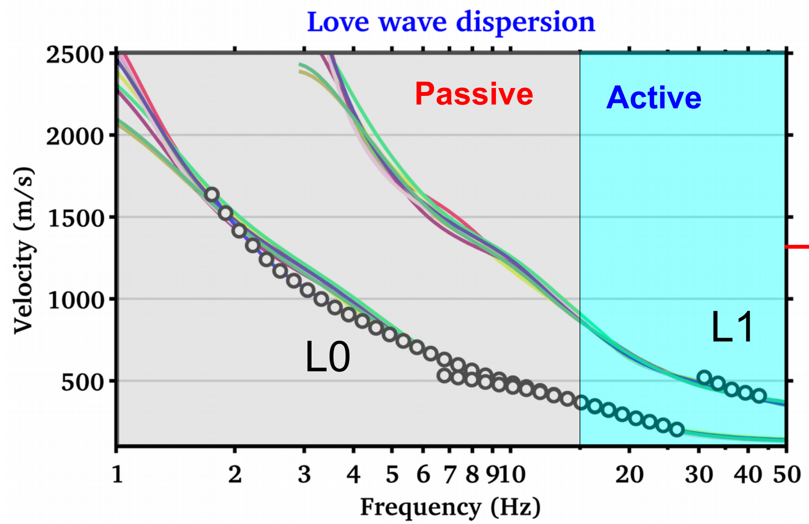
Factor-graph decomposition of ambient vibration wave-field

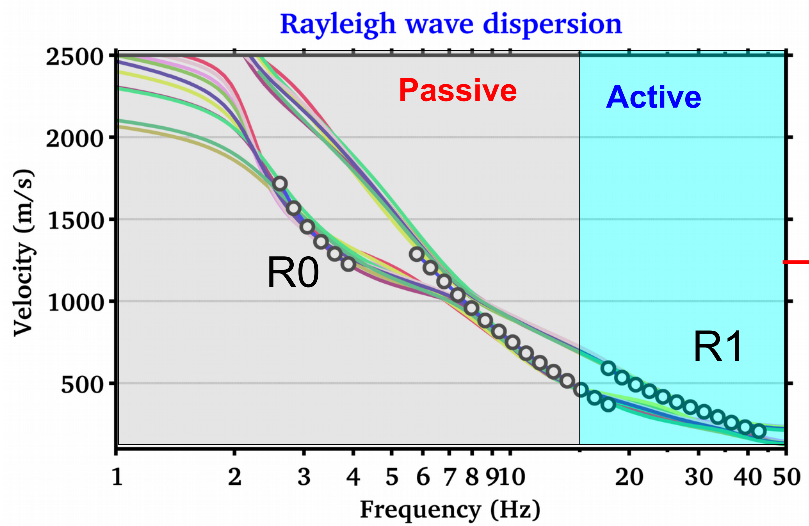
Dispersion | Ellipticity | Ellipticity angle

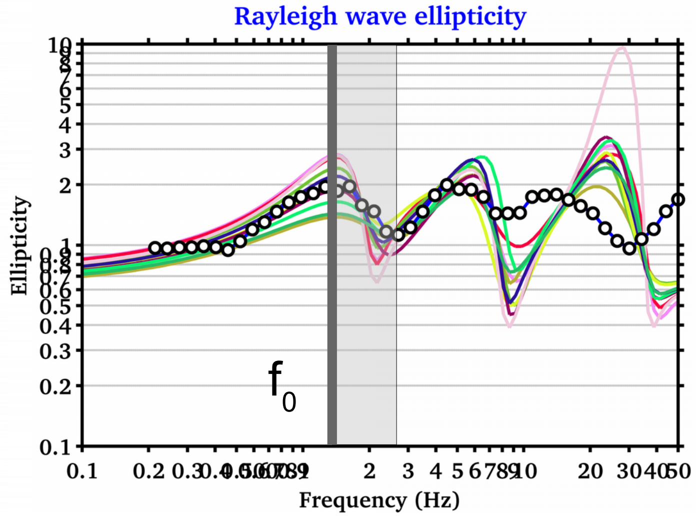


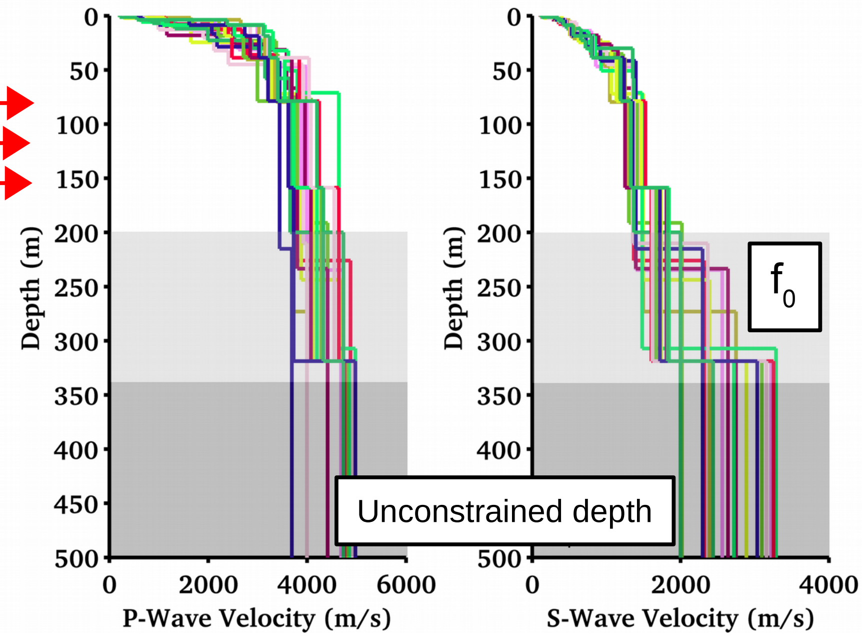
Marano' et al., 2013

Combined Inversion of Multiple datasets





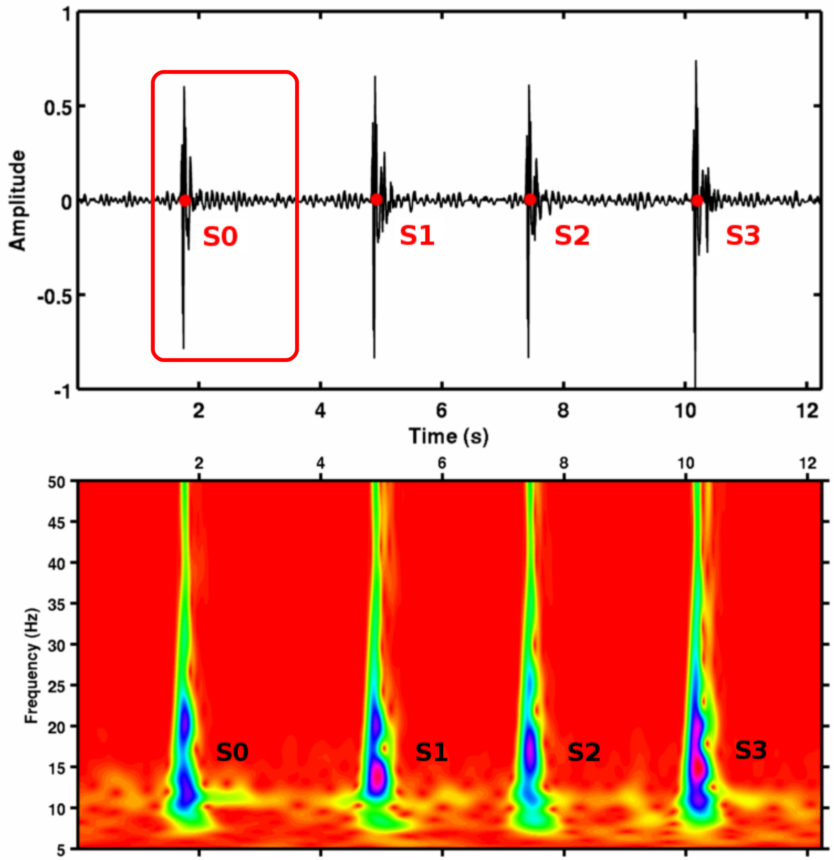




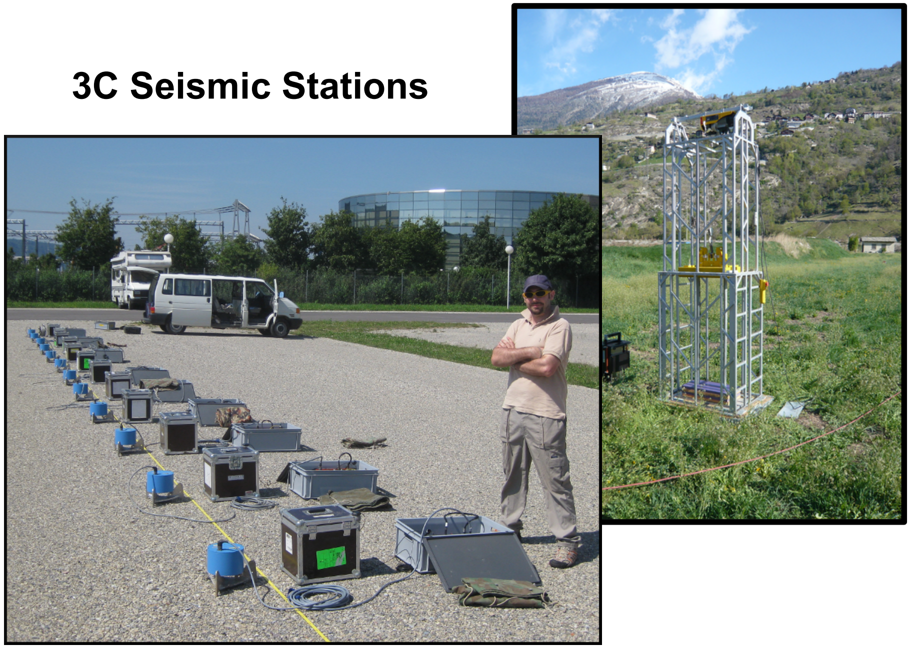
Active Seismic on Continuous Recordings

Reference time is defined on the continuous recordings using the Hilbert transform.

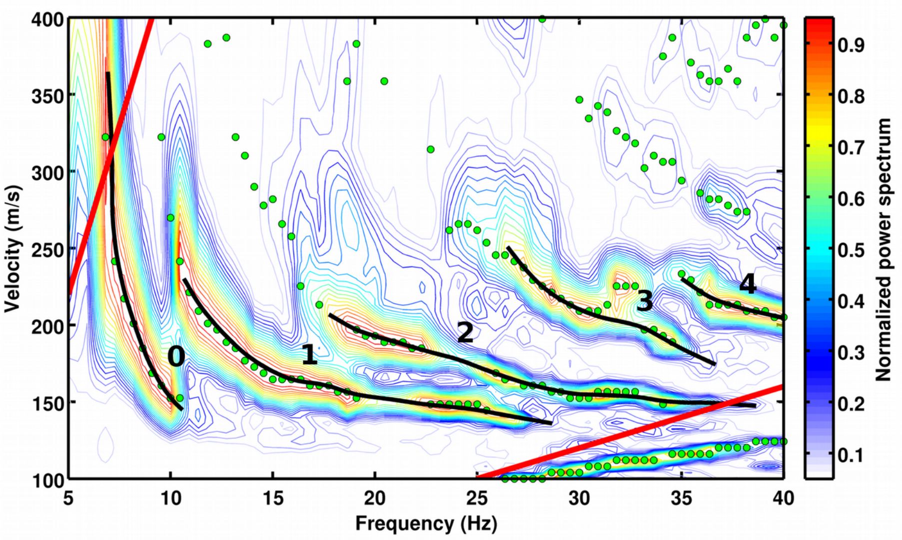
The wave-field is then decomposed using the *continuous (complex) wavelet transform*.



3C Seismic Stations

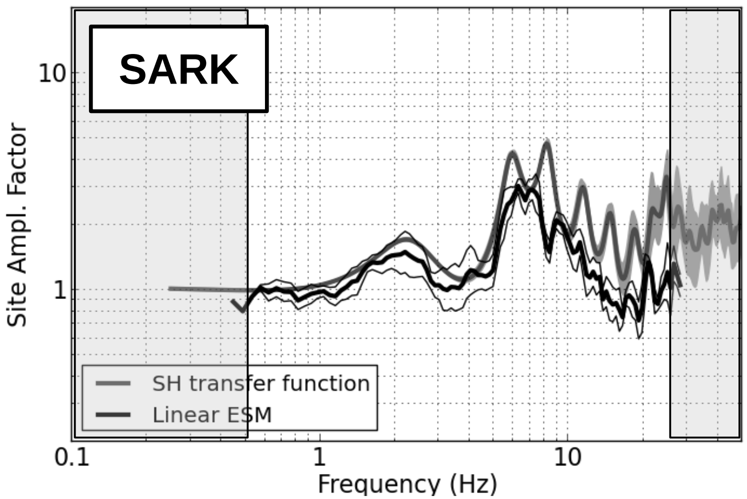


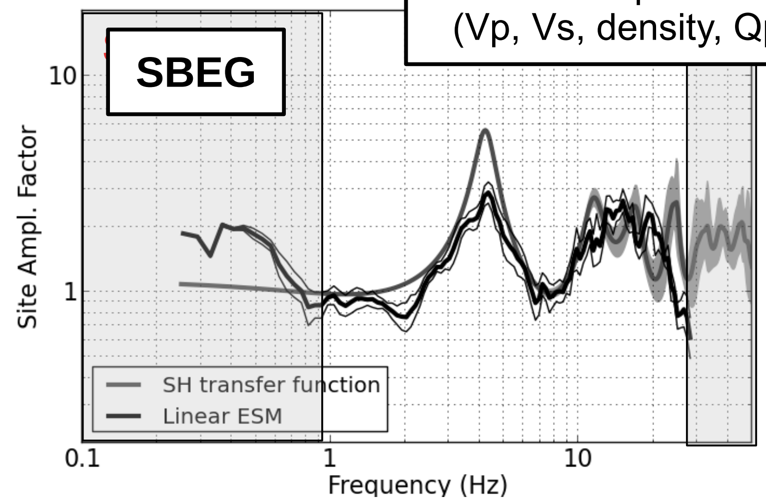
Rayleigh Wave Radial & Vertical

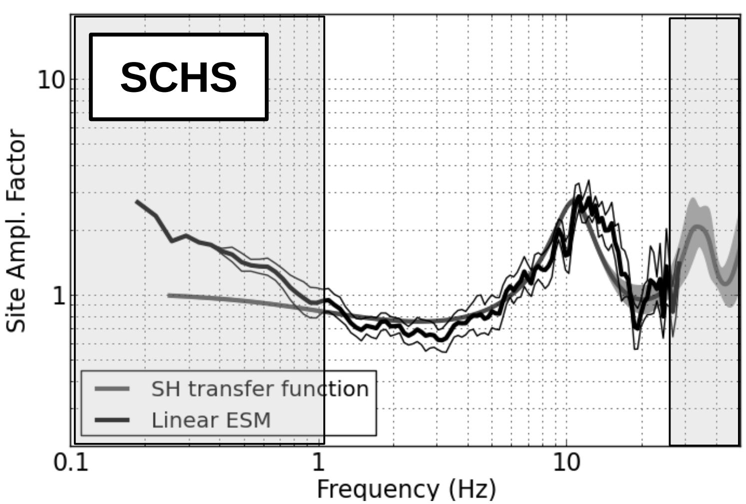


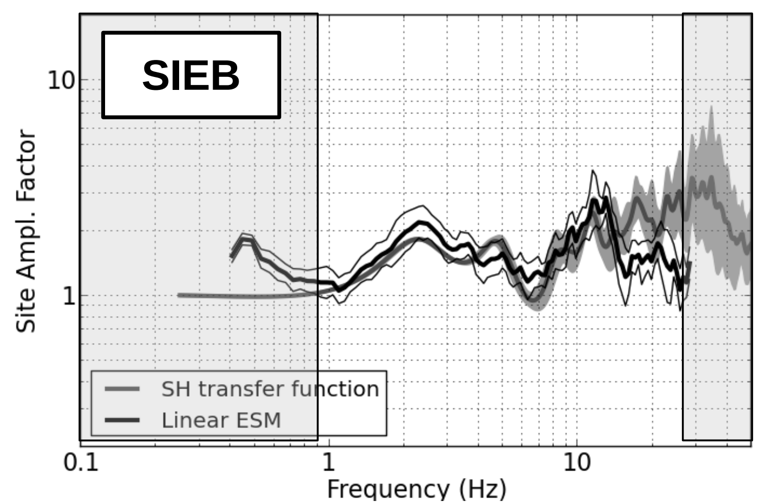
Amplification Model Validation

Require accurate knowledge of soil parameters (Vp, Vs, density, Qp, Qs...)





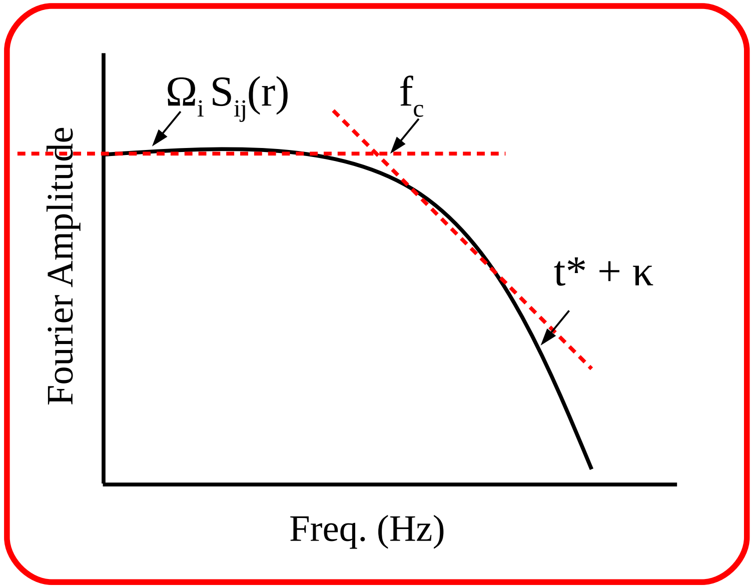


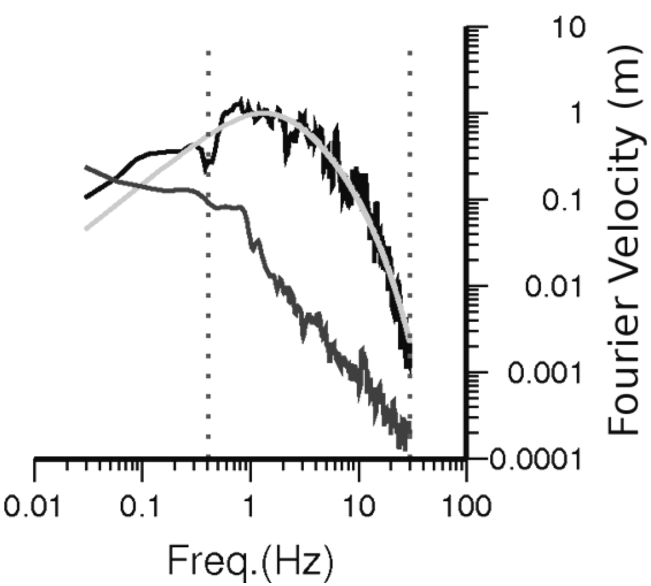


Empirical Amplification from Spectral Modeling

Here GMPE terms are **analytical solutions** of a given physical model, whose complexity can be increased with the availability of new information

$$\Omega_{ij}(f,r) = \underbrace{\omega \cdot \Omega_i \cdot f_c^{\gamma}/(f_c^{\gamma} + f^{\gamma})}_{\text{Source Spectrum}} \cdot \underbrace{S_{ij}(r) \cdot \exp(-\pi \cdot f^{1-\alpha} \cdot t_{ij}^*)}_{\text{Path Effects}} \cdot \underbrace{A_j(f) \cdot \exp(-\pi \cdot f^{1-\alpha} \cdot K_j)}_{\text{Site Effects}}$$

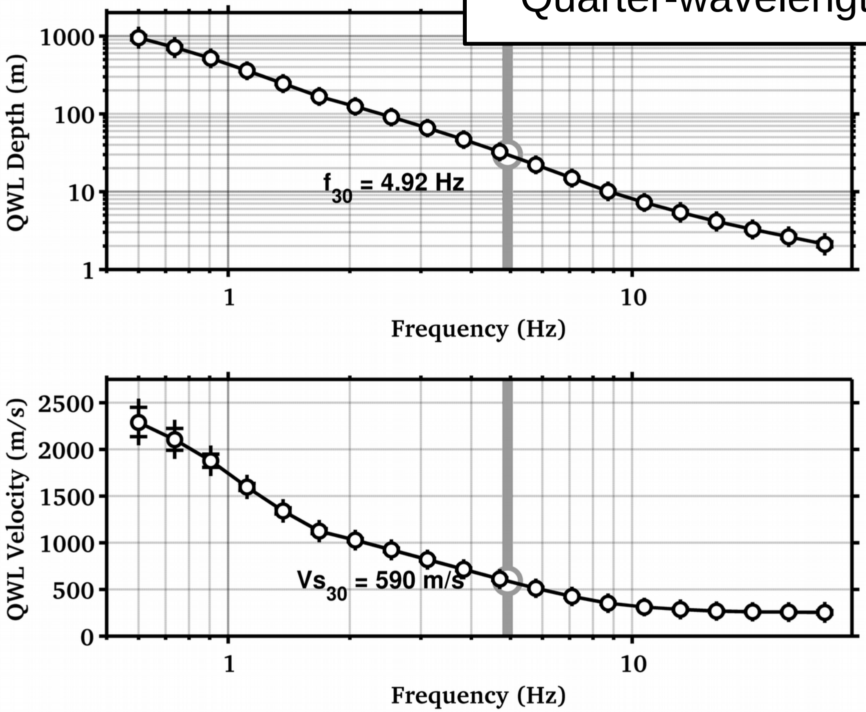




Engineering Parameters

- Travel-time average velocities (Vs-Z)
- Quarter-wavelength parameters (Vs and IC)
- Soil classification (SIA261)
- SH amplification functions and f_0

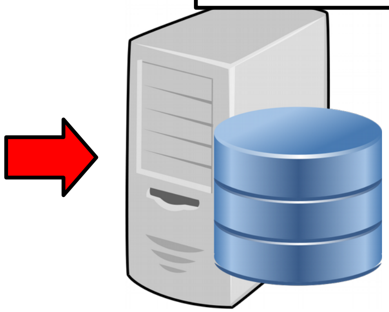
Quarter-wavelength



Vs-Z

	Averaging Depth (m)							
	5	10	20	30	40	50	100	200
STIEG	229.55	292.77	382.21	453.01	500.99	556.49	786.21	1105.71
BERGE	1356.45	1416.48	1514.8	1703.22	1833.41	1939.84	2204.53	2371.5
DAGMA	701.25	729.08	823.92	913.7	982.23	1051.84	1263.87	1515.05
METMA	336.62	442.72	640.81	817.94	969.04	1098.2	1602.18	2124.63
ROTHE	611.92	665.97	843.89	954.4	1024.6	1074.3	1202.77	1294.47
HAMIK	238.33	314.41	407.08	487.58	552.09	616.4	834.86	1060.17
BOBI	279.96	350.94	486.23	590.02	668.27	736	955.85	1212.99
WALHA	397.93	464.16	642.18	766.06	851.3	933.78	1165.62	1380.97
EMING	220.99	306.21	489.82	659.08	803.27	932	1392.32	1895.09
EMMET	468.12	571.58	672.68	800.73	892.53	960.55	1140.8	1316.13

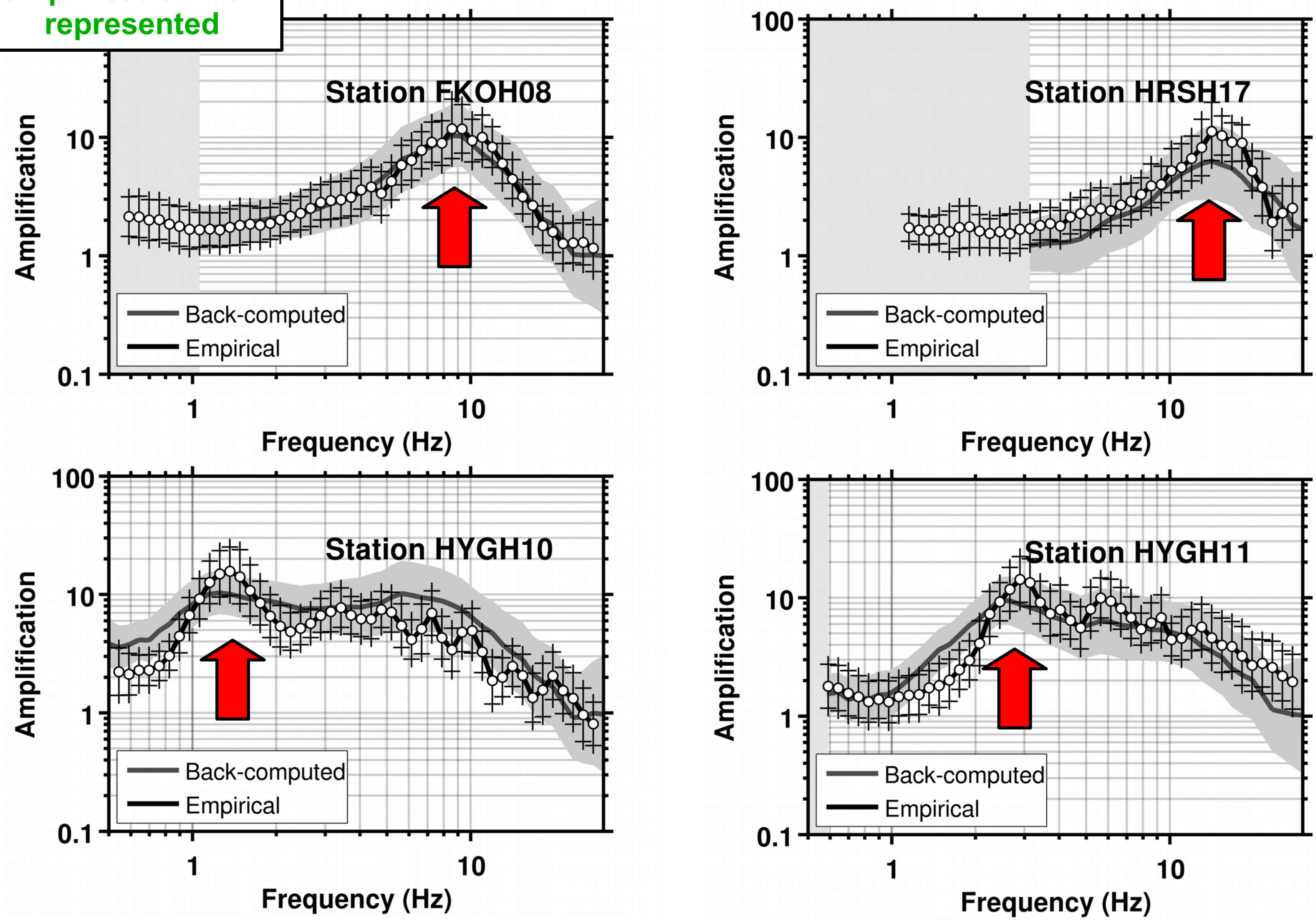
Database



Empirical Models for Amplification Prediction

$$\ln[T(A,f,K)] = \ln(A^{DC} A^{K}) + \ln(A^{L}) = a\ln(Vs^{Qwl}) + b\ln(IC^{Qwl}) + c$$

Resonance amplification well represented



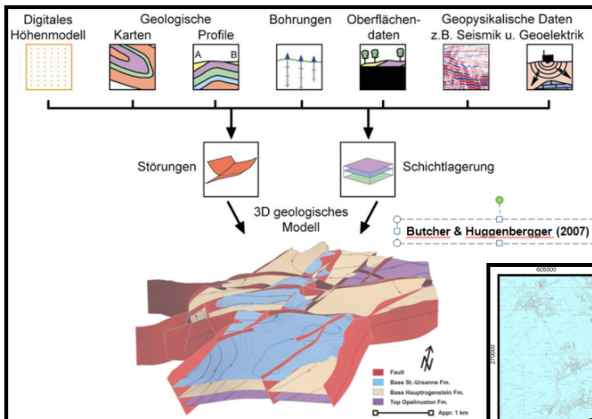
SECTION B
Basin Analysis and Microzonation Studies

Seismic Microzonation and Site-Response Analysis

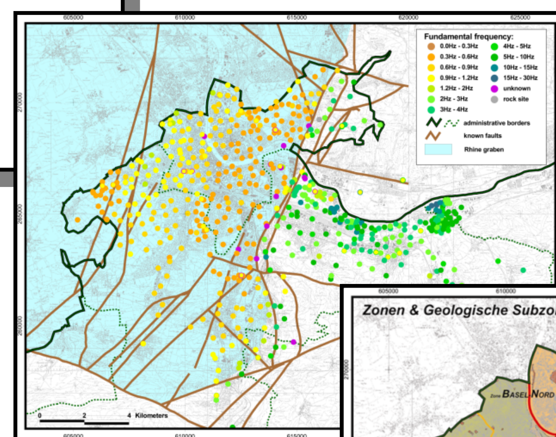
Microzonation is the **seismic hazard assessment at local scale**, accounting for both:

❶ the modification of the ground motion (amplitude, duration)

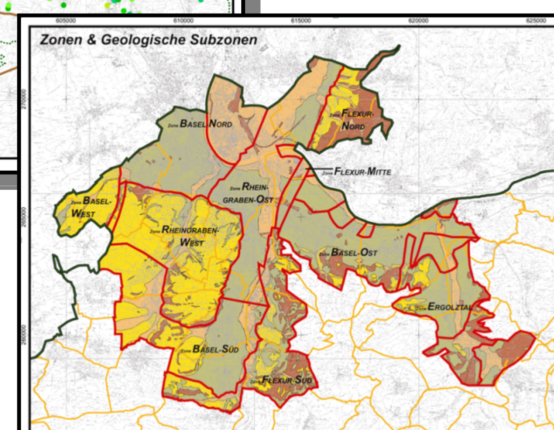
❷ earthquake induced phenomena



Geological Model



Direct Investigations

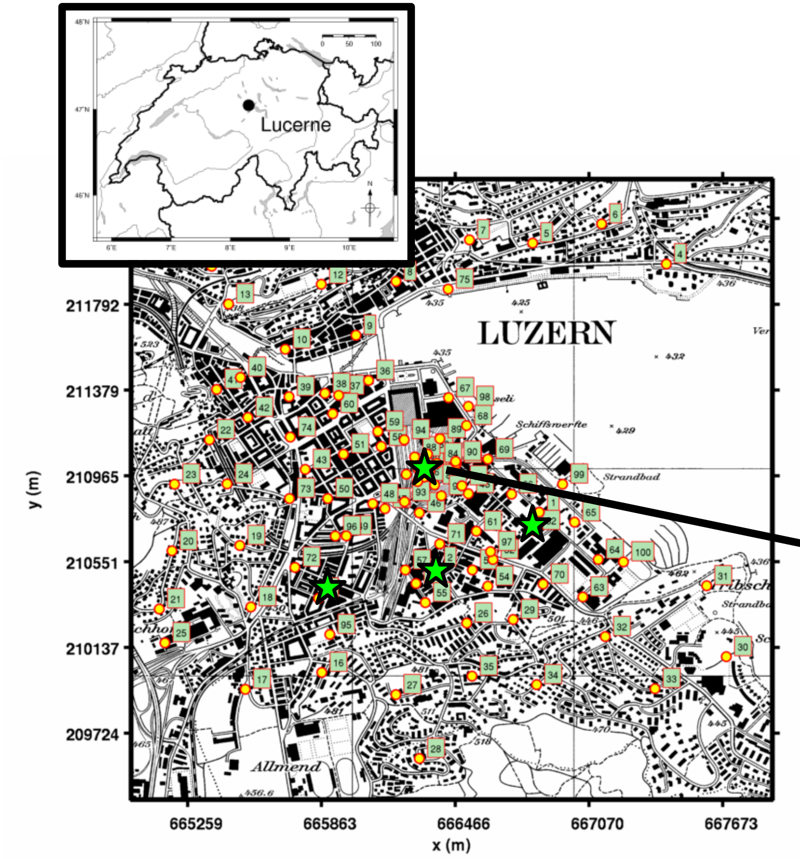


Interpretation & Zonation

Microzonation is aimed to (but not only):

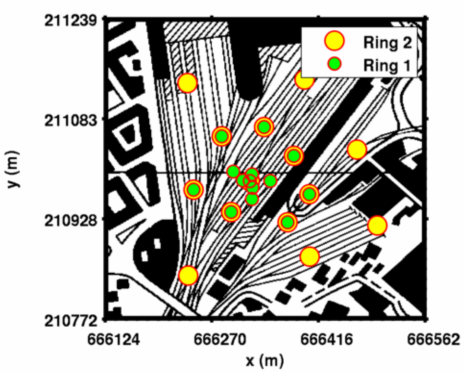
- ✔ **Mitigation of damage** through preventive land and urban planning
- ✔ **Building code** provisions
- ✔ Assistance to **emergency intervention** after catastrophic events
- ✔ Setting priorities for **retrofitting**

Ambient Vibration Measurement Survey



> 100 single station measurements

4 array installations

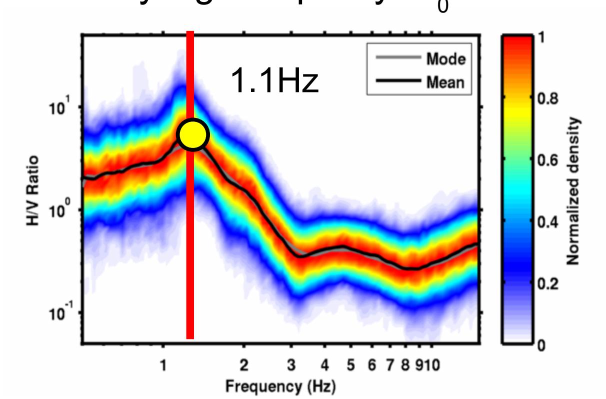


Main array (~350m ⌀)

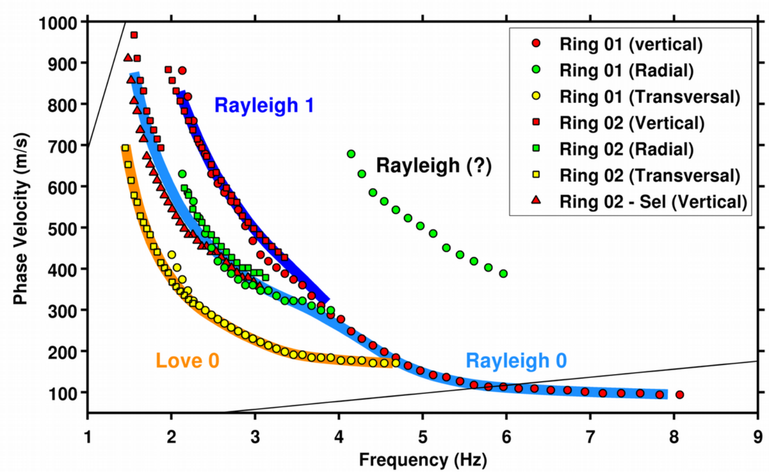
Building the Reference 1D Velocity Model

Ambient Vibration Data

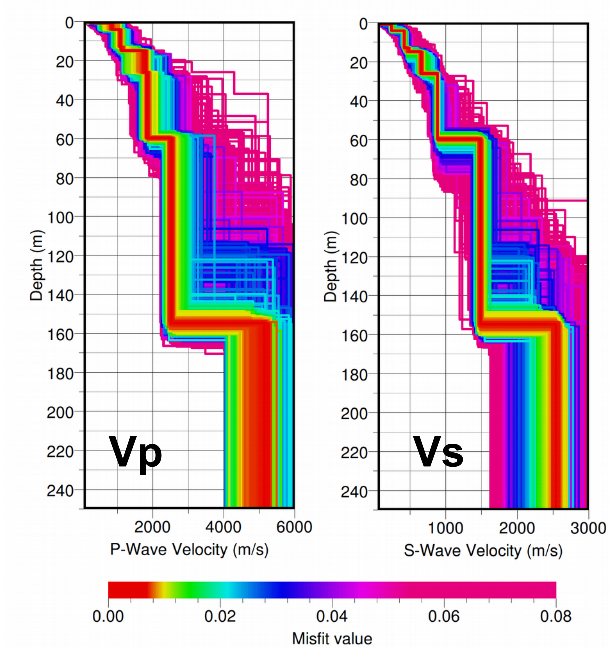
Rayleigh Ellipticity - f_0



Surface Wave Dispersion



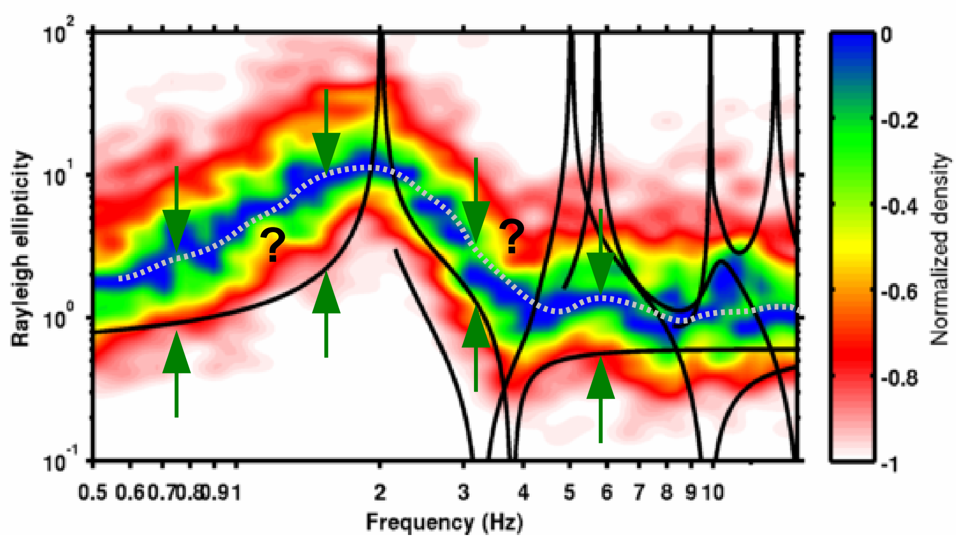
Inversion



Velocity Model

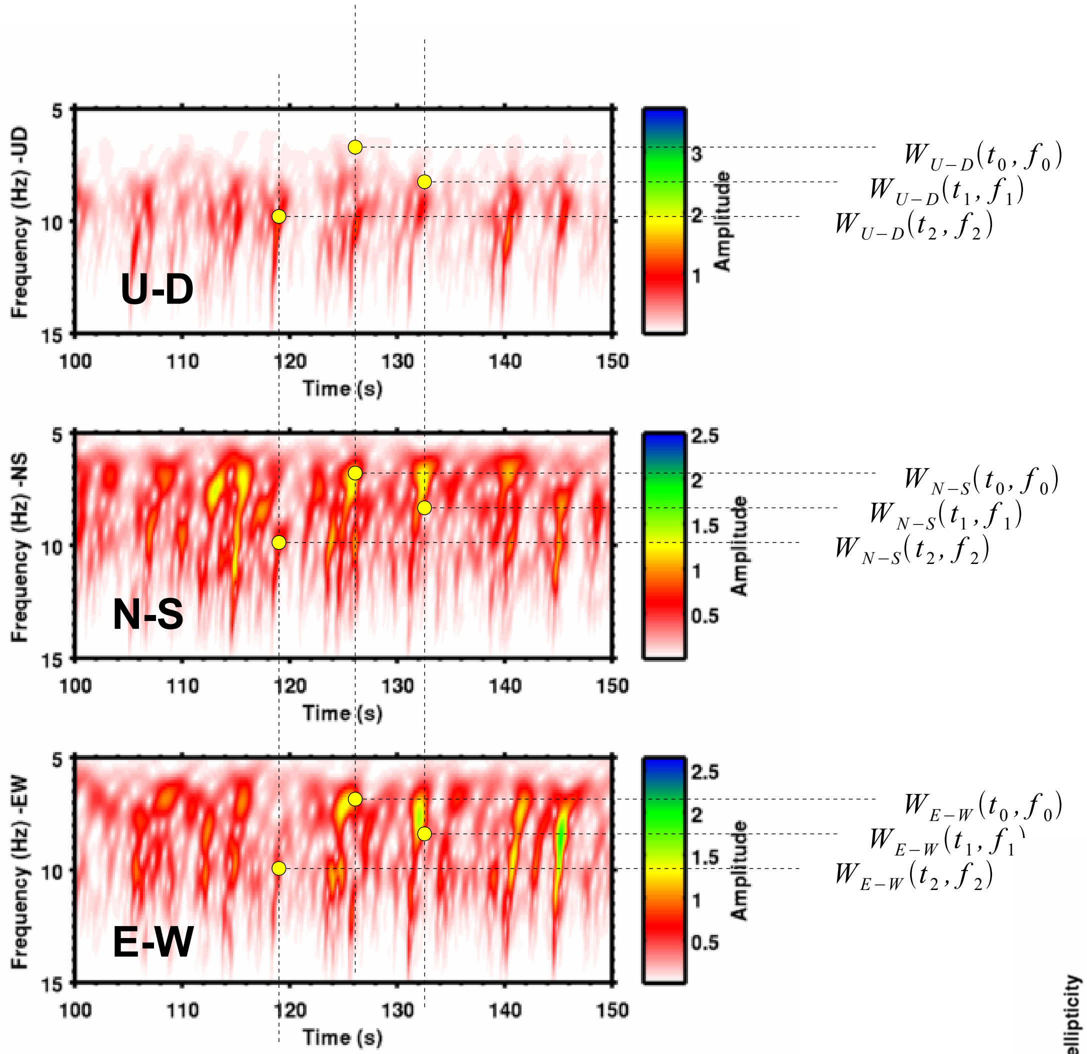
Rayleigh Wave Ellipticity From Single Station Measurements

- Inversion of just ellipticity curves is a highly **non-linear** and **non-unique problem** and may require additional constraints or some *“a priori” knowledge*
- It is however advantageous in that it efficiently constrains the **deepest portion of the velocity model**
- Unfortunately, ellipticity information is hided into single station H/V ratios and extraction is not a trivial task.



...how to correct for body and Love wave contributions?
...how to identify and separate out the contribution of higher modes?

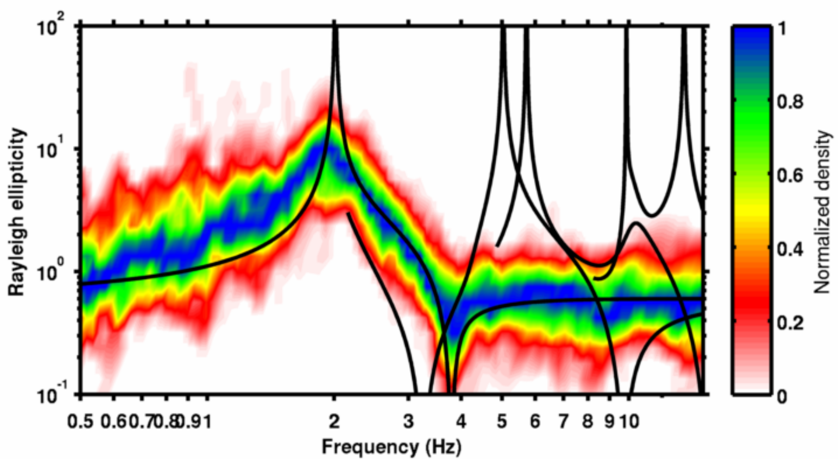
H/V Ratios Using Wavelet F-T Analysis



Compared to classical H/V, the FTAN method helps in minimizing the effect of Love (and SH) wave contribution, particularly for the **fundamental mode**

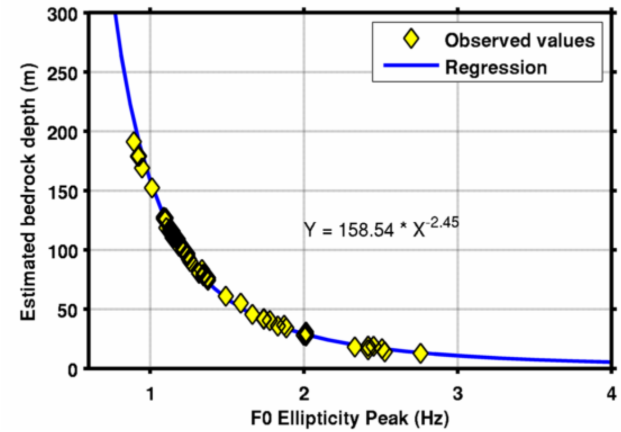
The resulting ellipticity can be directly used for inversion

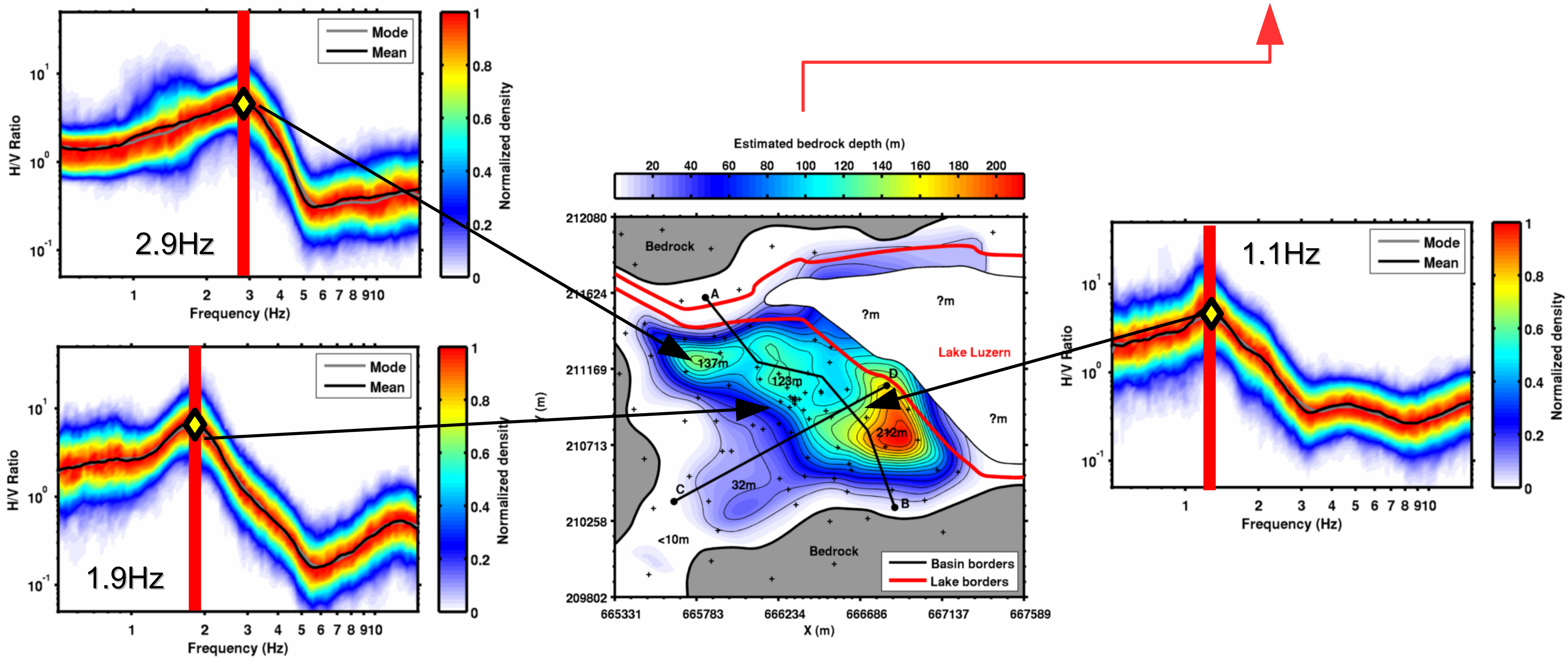
$$\boxed{Ell_R(t,s)=\frac{\sqrt{W_{N-S}^2+W_{E-W}^2}}{W_{U-D}^2}}$$



Ellipticity Inversion

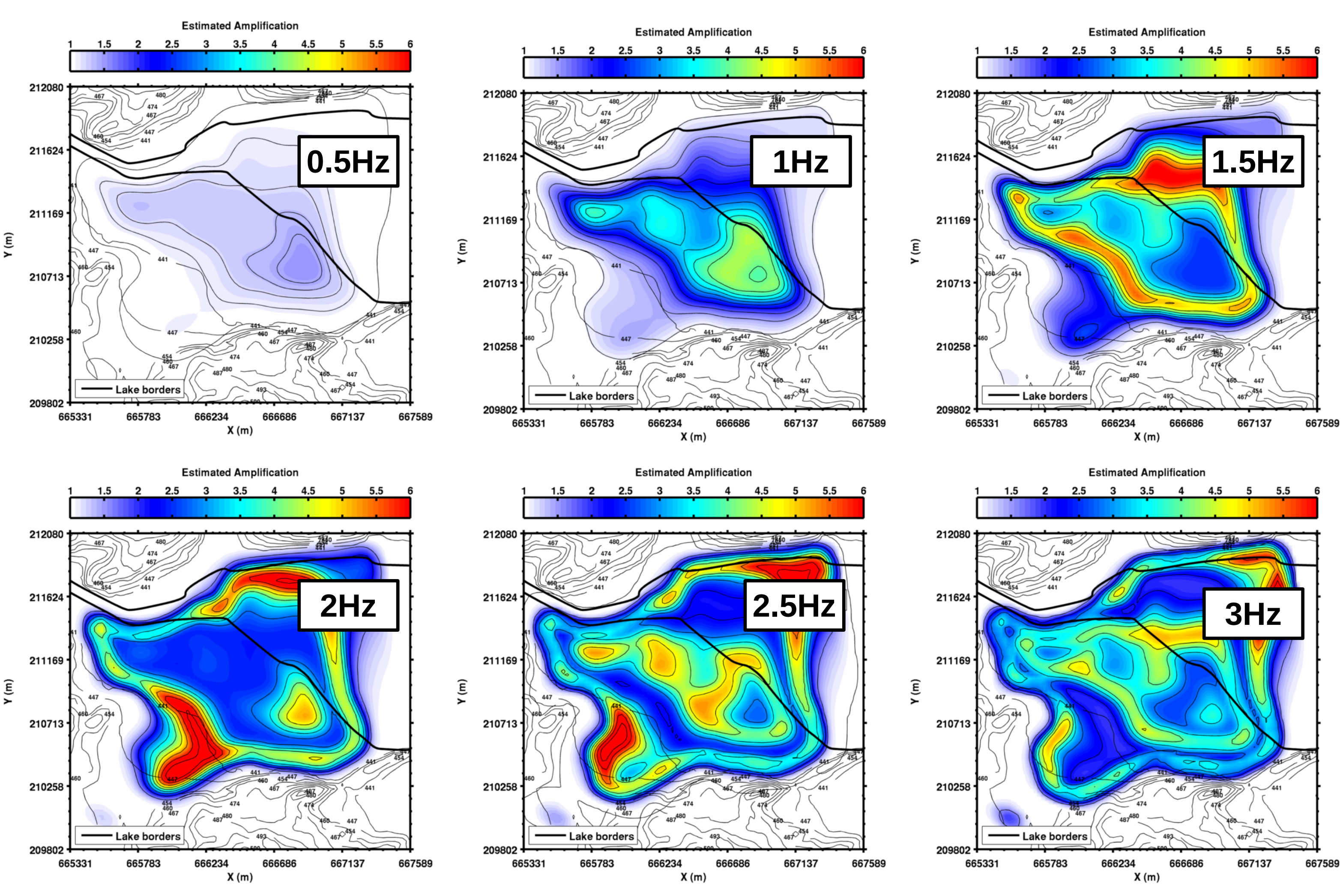
- Bedrock geometry is derived from inversion of the ellipticity information extracted from each individual station
- An *exponential regression* is used to describe the relation between the ellipticity peaks (E0) and inverted depths





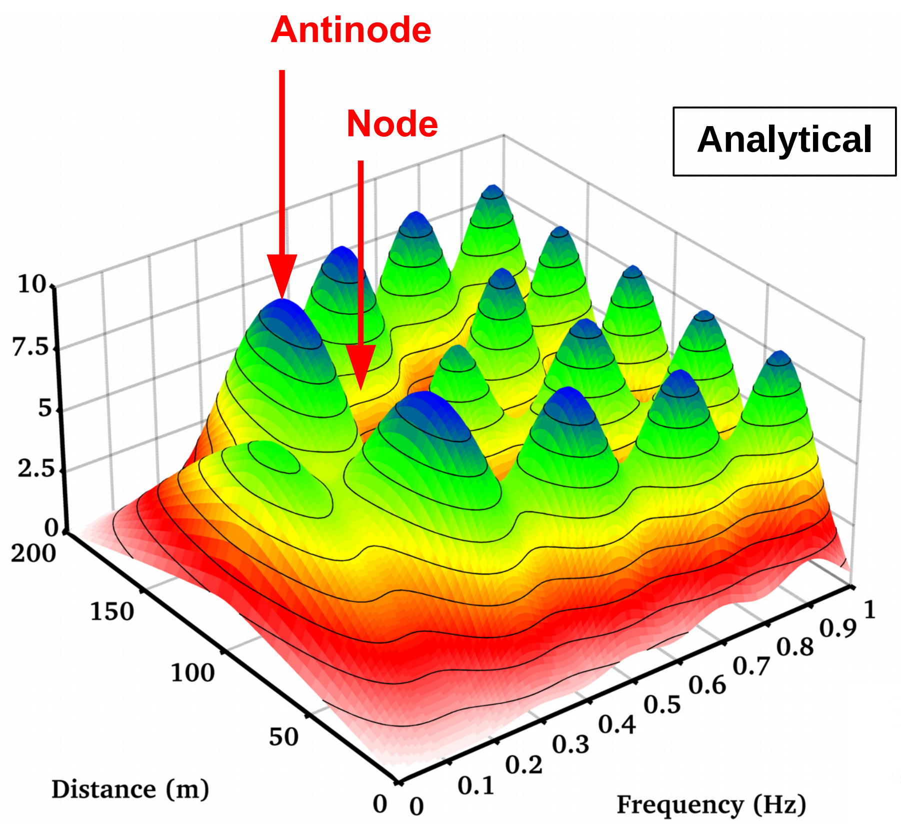
Pseudo 3D SH-Wave Amplification

The 3d model consists of a horizontal grid of 100x100 soil columns
For each cell, a 1D **anelastic SH-wave transfer function** is computed



SECTION C
2D/3D Basin Response Analysis

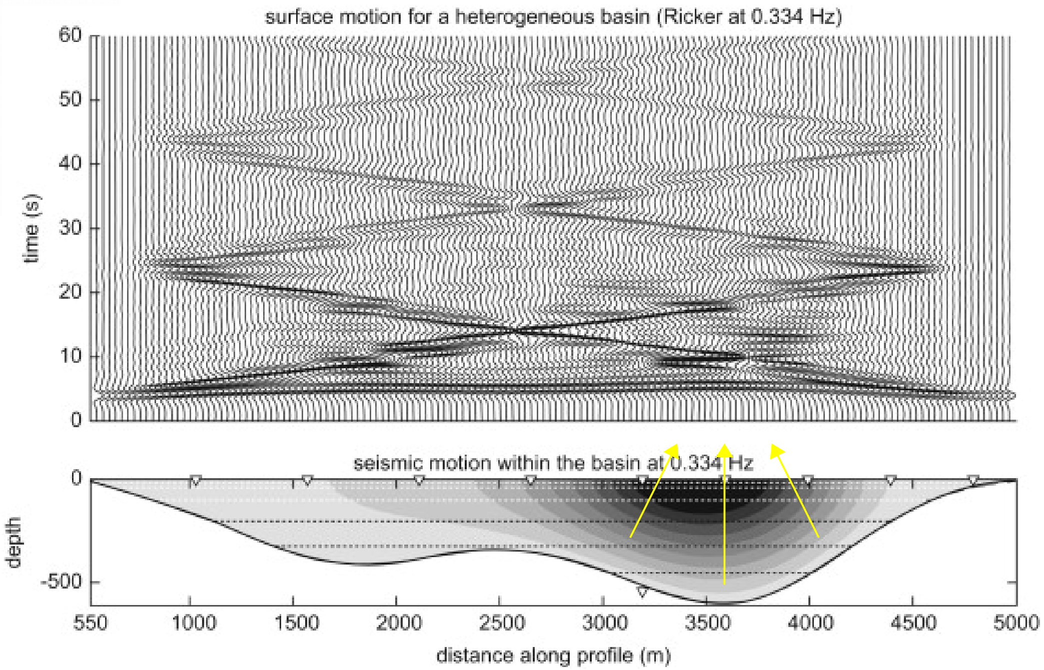
2D/3D Resonance Amplification



In case of **2D/3D resonance**, the effect on the ground motion can be severe, but well localized in delimited areas of the basin (**anti-nodal points**), while nearby areas might be only marginally affected (**nodal points**)

Numerical

Delépinea and Semblat., SDEE, 2012



Quantifying resonance amplification is not easy:

⇨ Analytical solutions (nearly) impossible

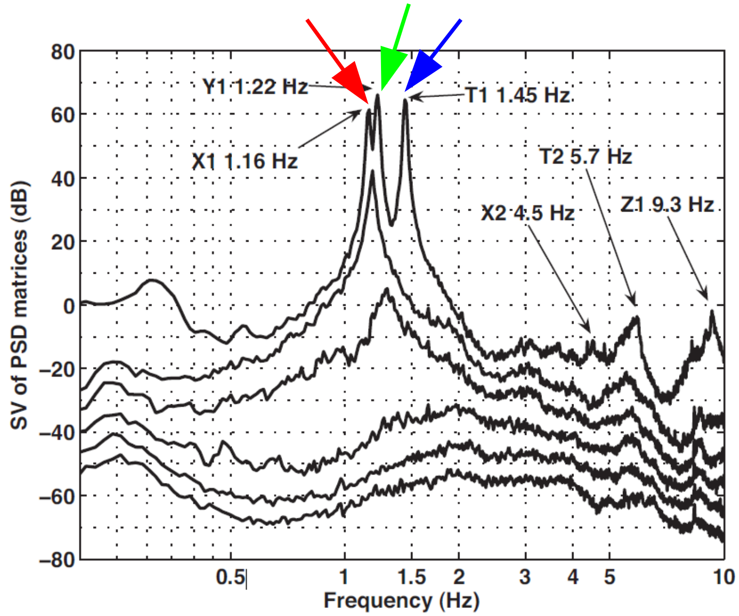
⇨ Numerical analysis very complex

⇨ Empirical estimation problematic....

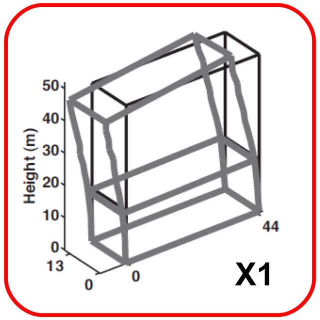
Frequency Domain Decomposition

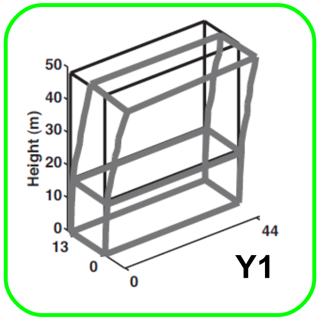
The **Frequency Domain Decomposition** (FDD, Brincker et al., 2001) is a popular seismic array techniques used in civil engineering for system response analysis

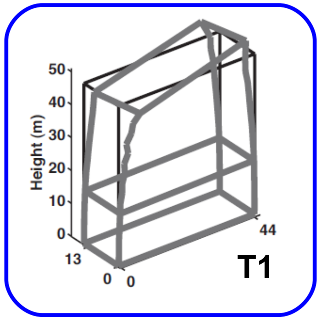
It basically relies on **singular value decomposition** of the signal's cross-power spectral density matrix to retrieve the eigenfunctions of the system (**the modal shapes**)



Michel et al., 2010

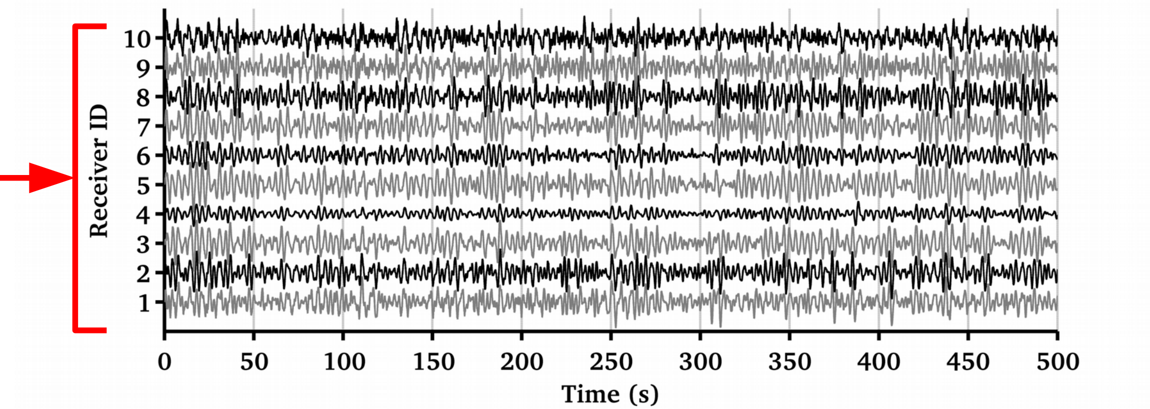


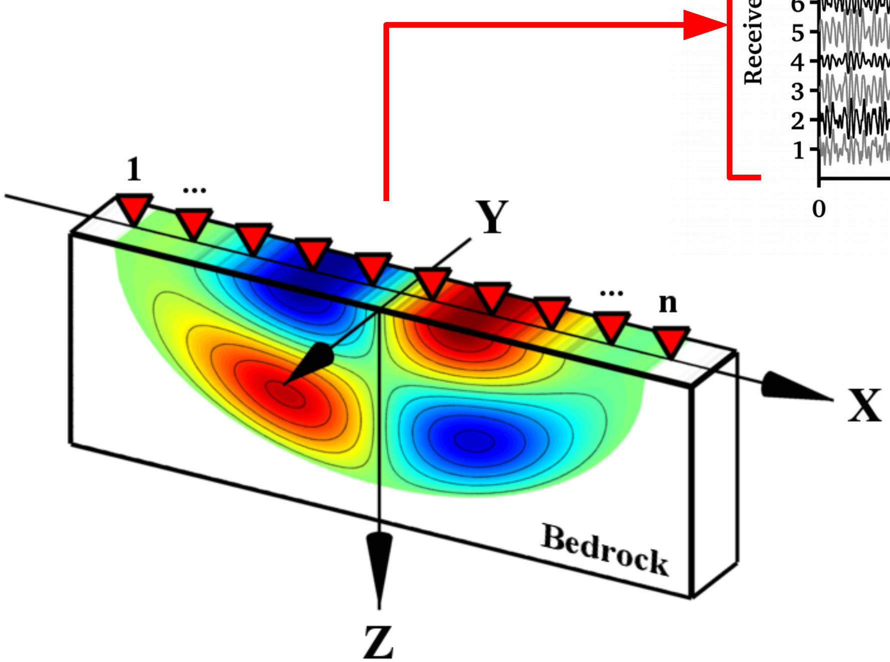




Using FDD in a 2D sedimentary basin

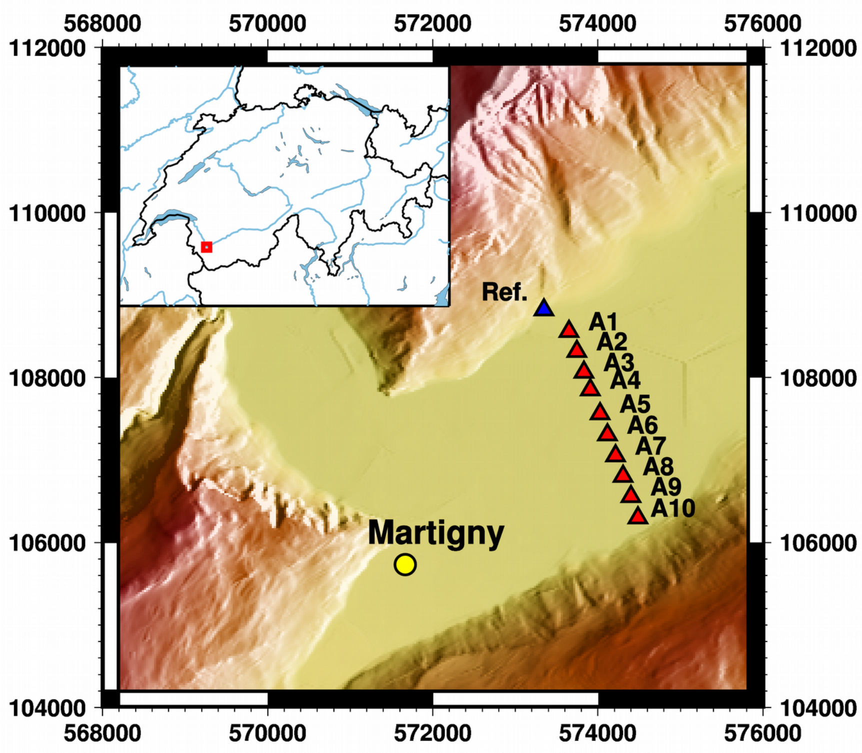
We apply the FDD method to **synchronous recordings of ambient vibration** from a linear array of **three-component seismometers** deployed along the transversal section of the basin





The goal is to retrieve the **2D resonance frequencies** of the basin and their corresponding **modal shapes**

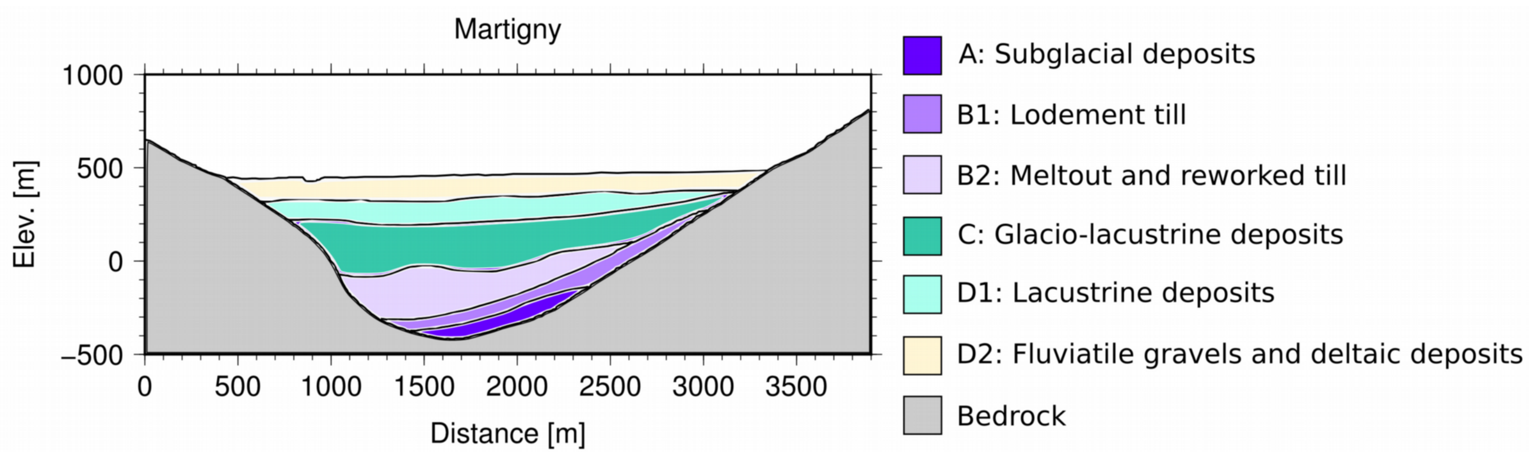
In this study we focus on the only horizontal-axial (**SH**) direction of motion



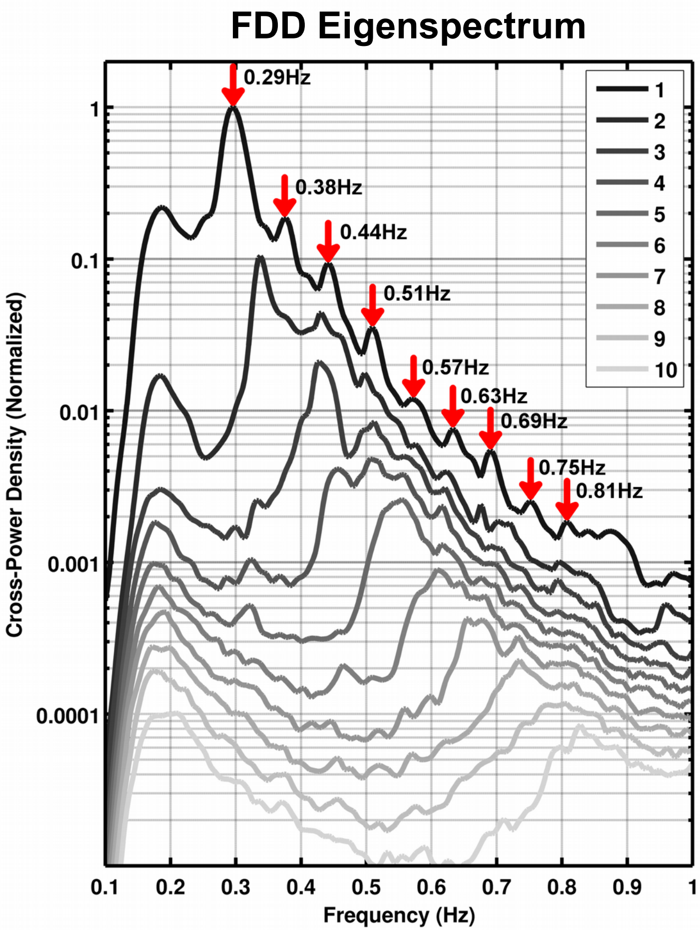
Martigny's Linear Array

Previous analysis of ambient vibration and seismic investigations are available from literature (e.g. Roten and Fäh, 2007)

We use **1h50m** of clean three-component ambient vibration recordings from a linear array of about **2.5km** length



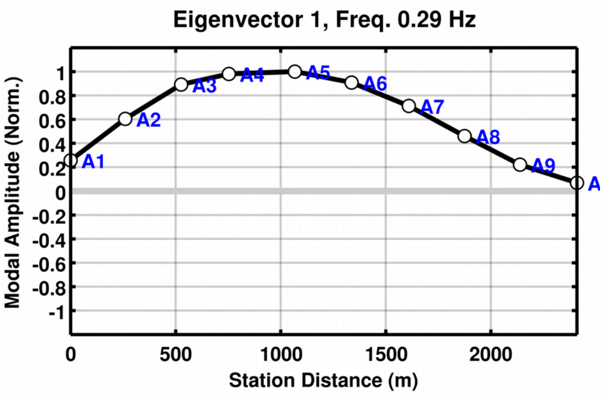
(modified from Pfiffner et al., 1997)

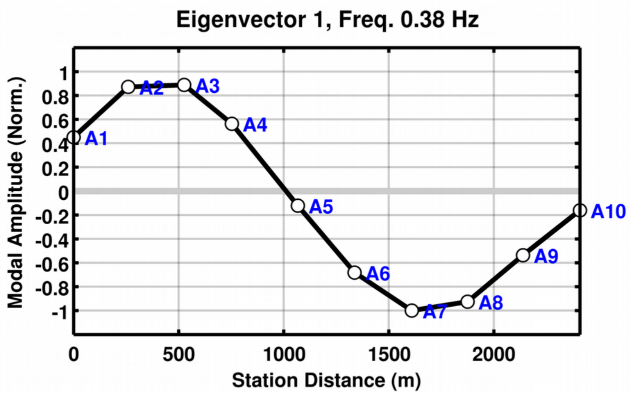


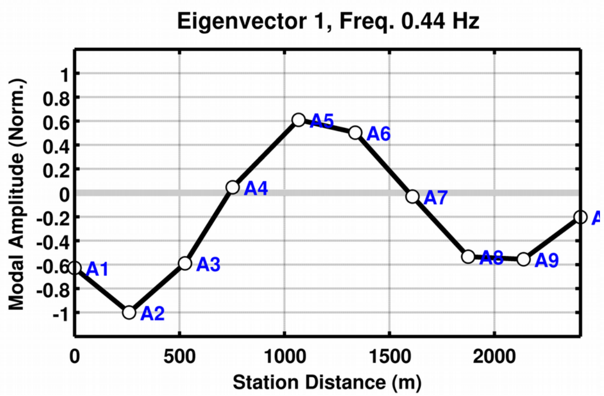
Identification of Resonance Modes Using FDD

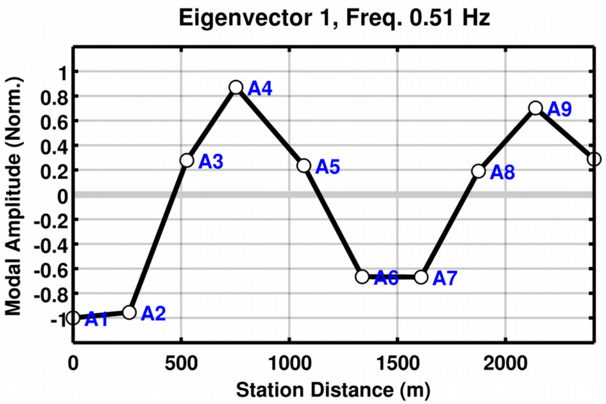
We then apply Frequency Domain Decomposition analysis in the frequency range (0.1-1Hz)

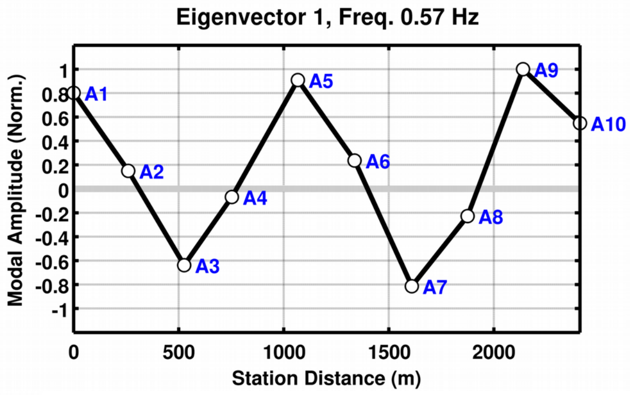
<u>Nine separate SH resonance modes</u> can be identified from the **eigenspectrum**





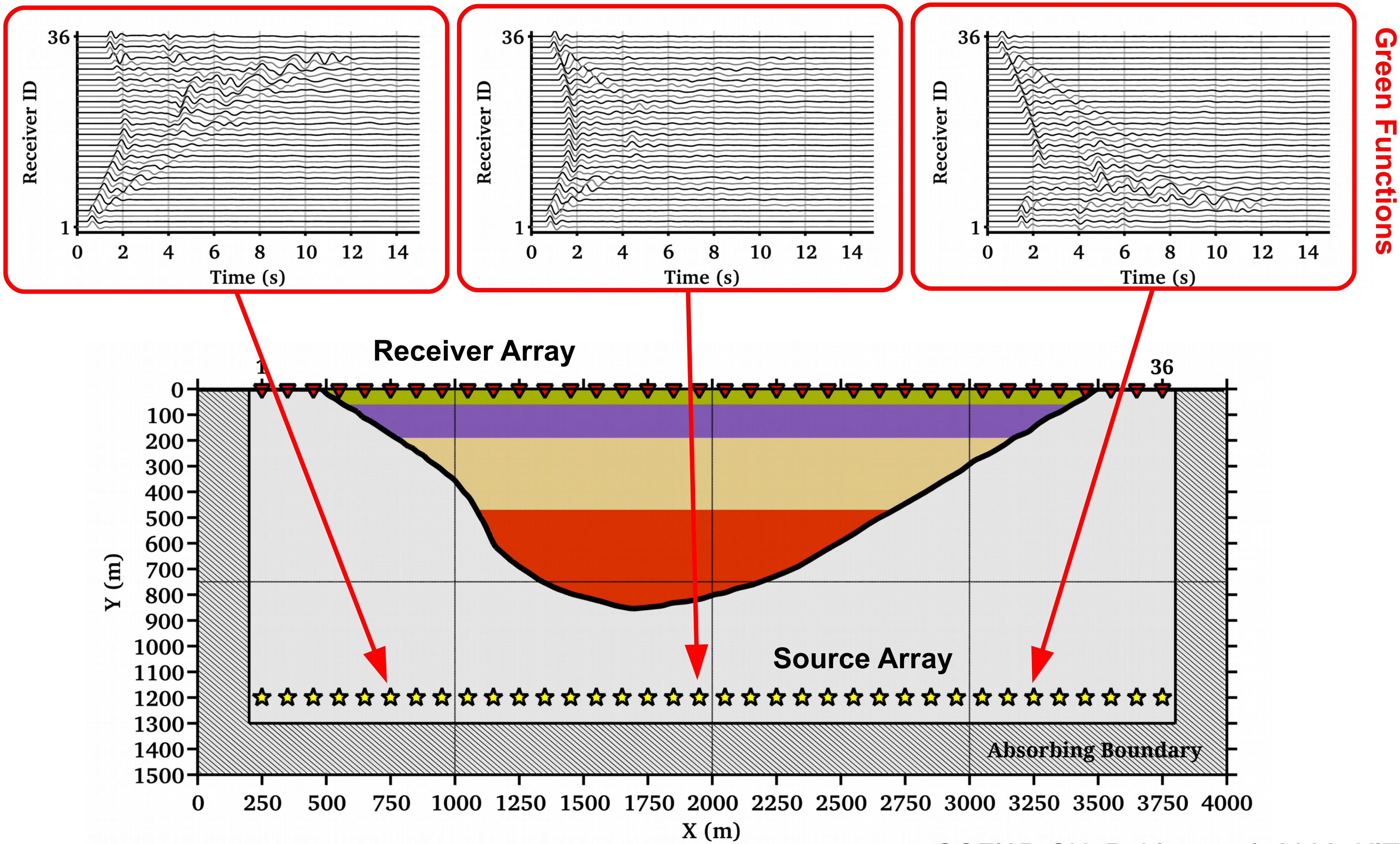






The Numerical Model of Martigny

36 wave propagation simulations are computed for an array of point sources at **fixed depth**

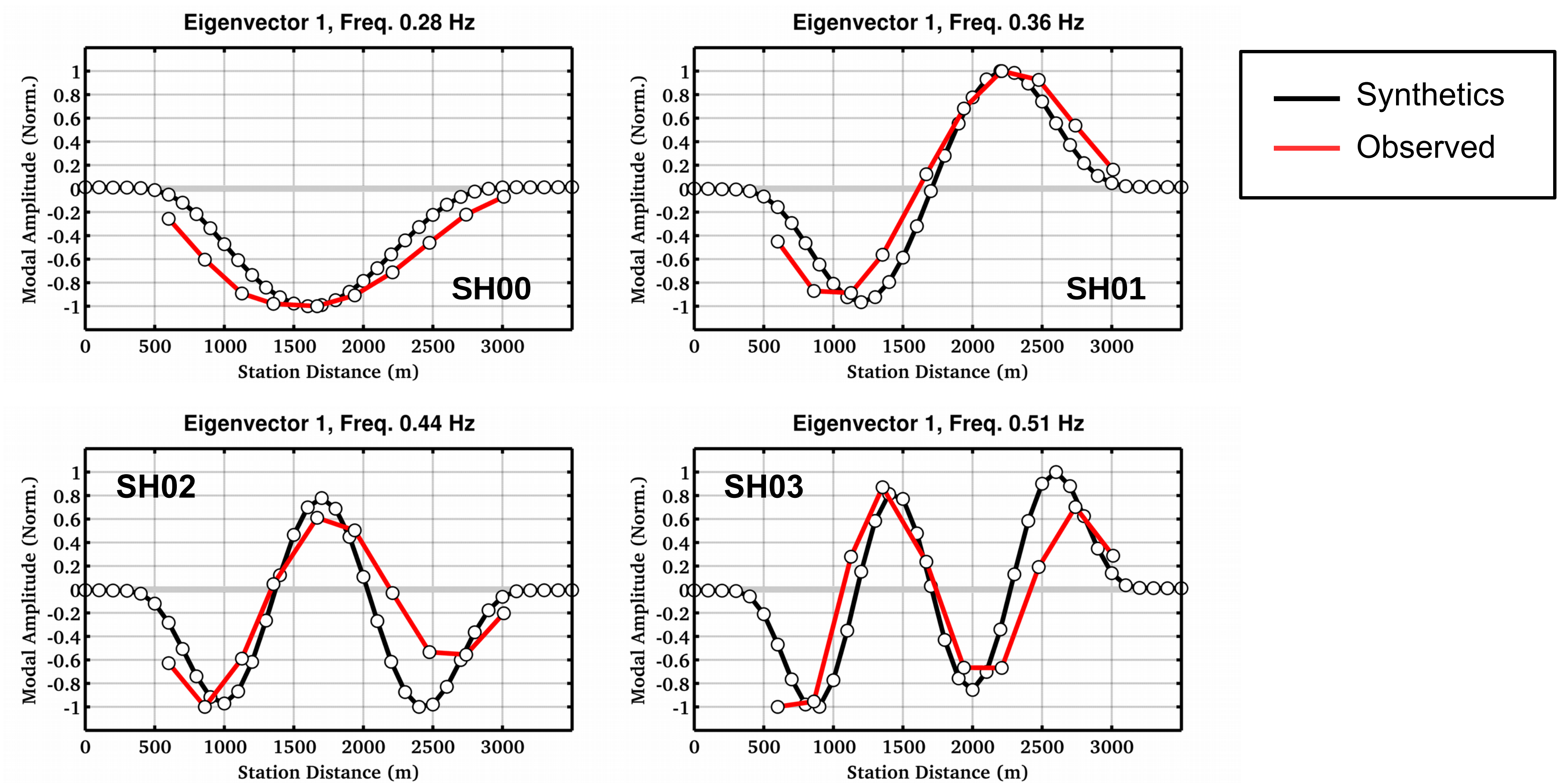


SOFI2D-SH, Bohlen et al. 2002, KIT

Modal Shapes from FDD Analysis

Ambient vibration synthetics are also analyzed using FDD

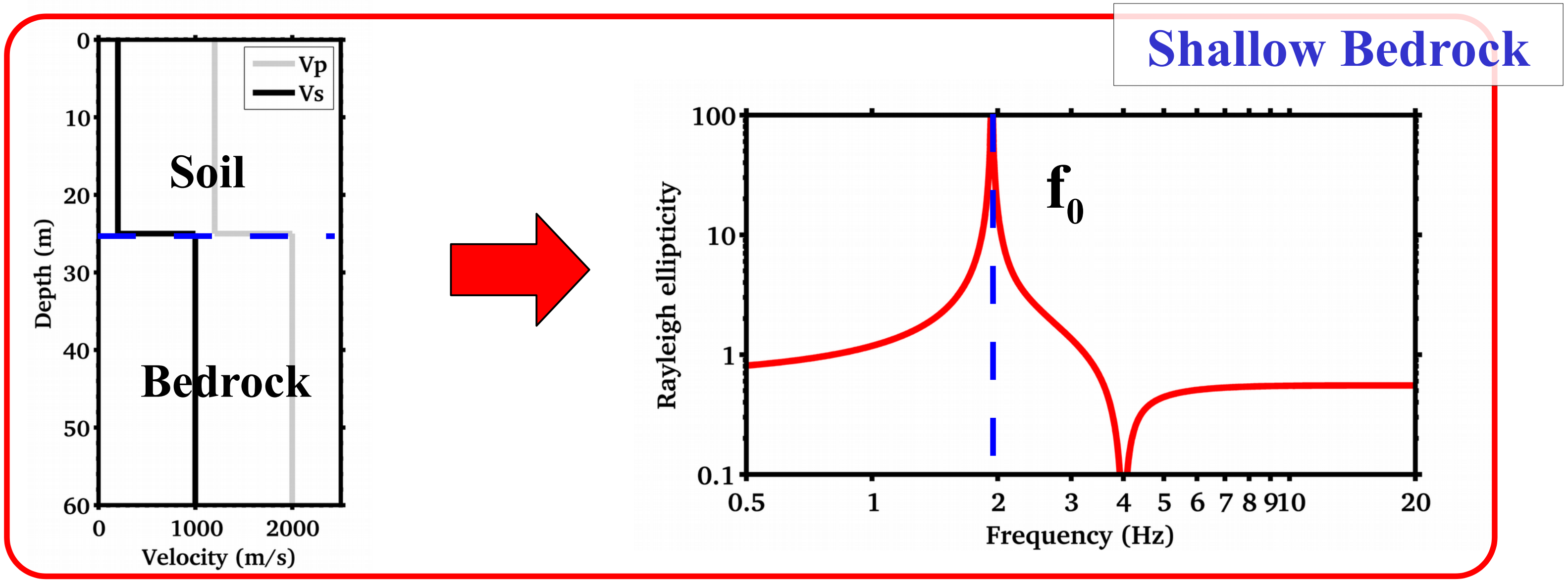
For each resonance mode, modal analysis provides a realistic estimate of the **modal shapes**, including the location of the **nodal and anti-nodal points**, compatible with the **direct observations**

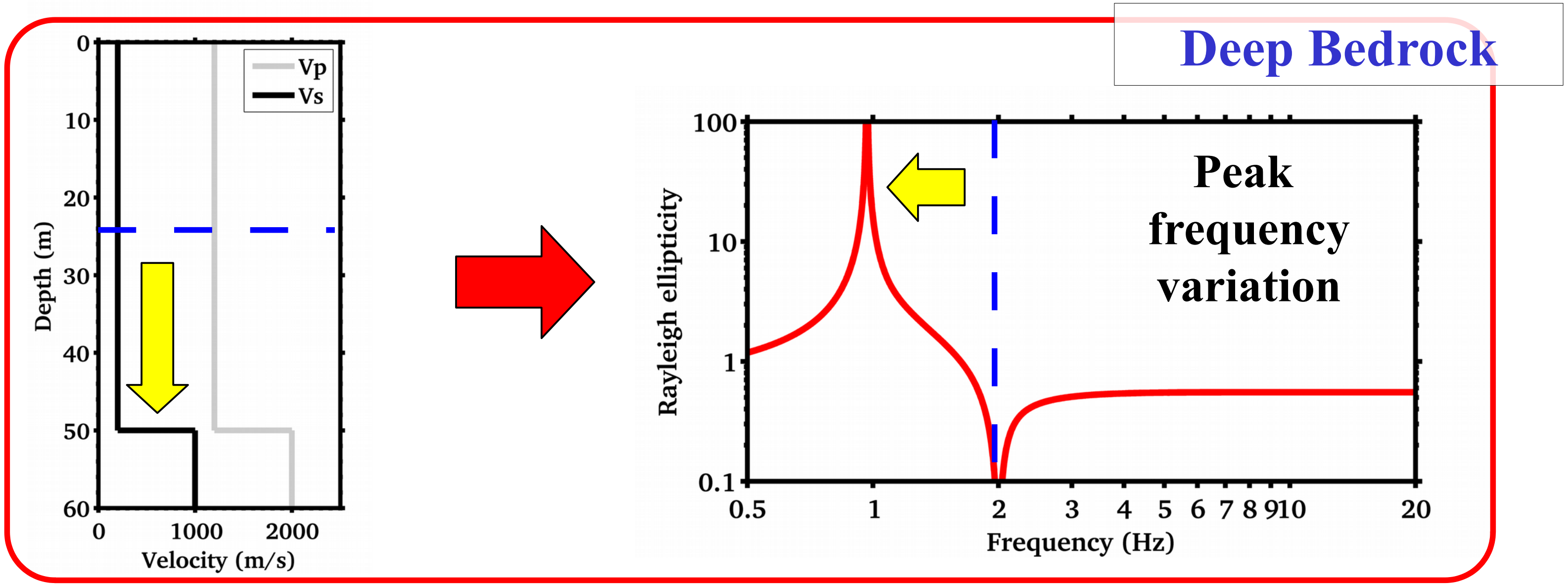


Conclusions….?

EXTRA SLIDES

Sensitivity to layer's interface depth





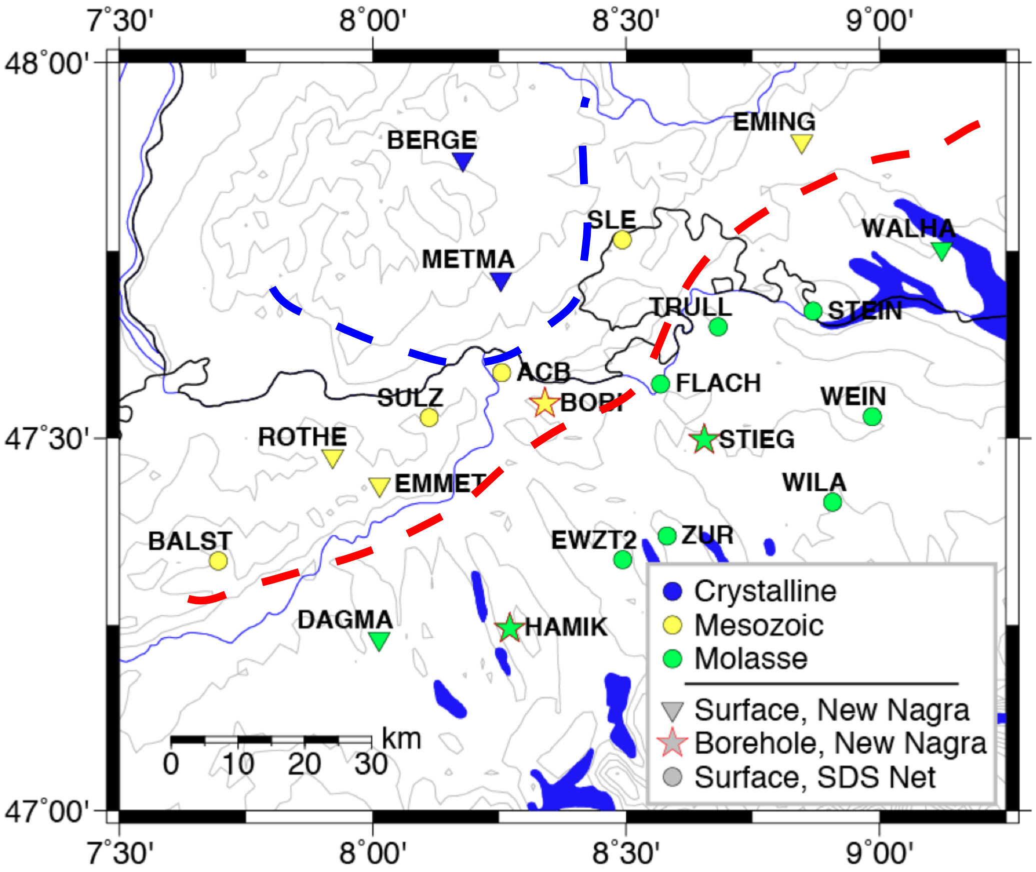
NAGRA-Net

Berge

Bobi

Borehole

Dagma



Walha

Stieg

Borehole

Rothe

Eming

Emmet

Hamik

Borehole

Metma