The use of Rayleigh wave ellipticity for site-specific hazard assessment

Application to the city of Lucerne, Switzerland

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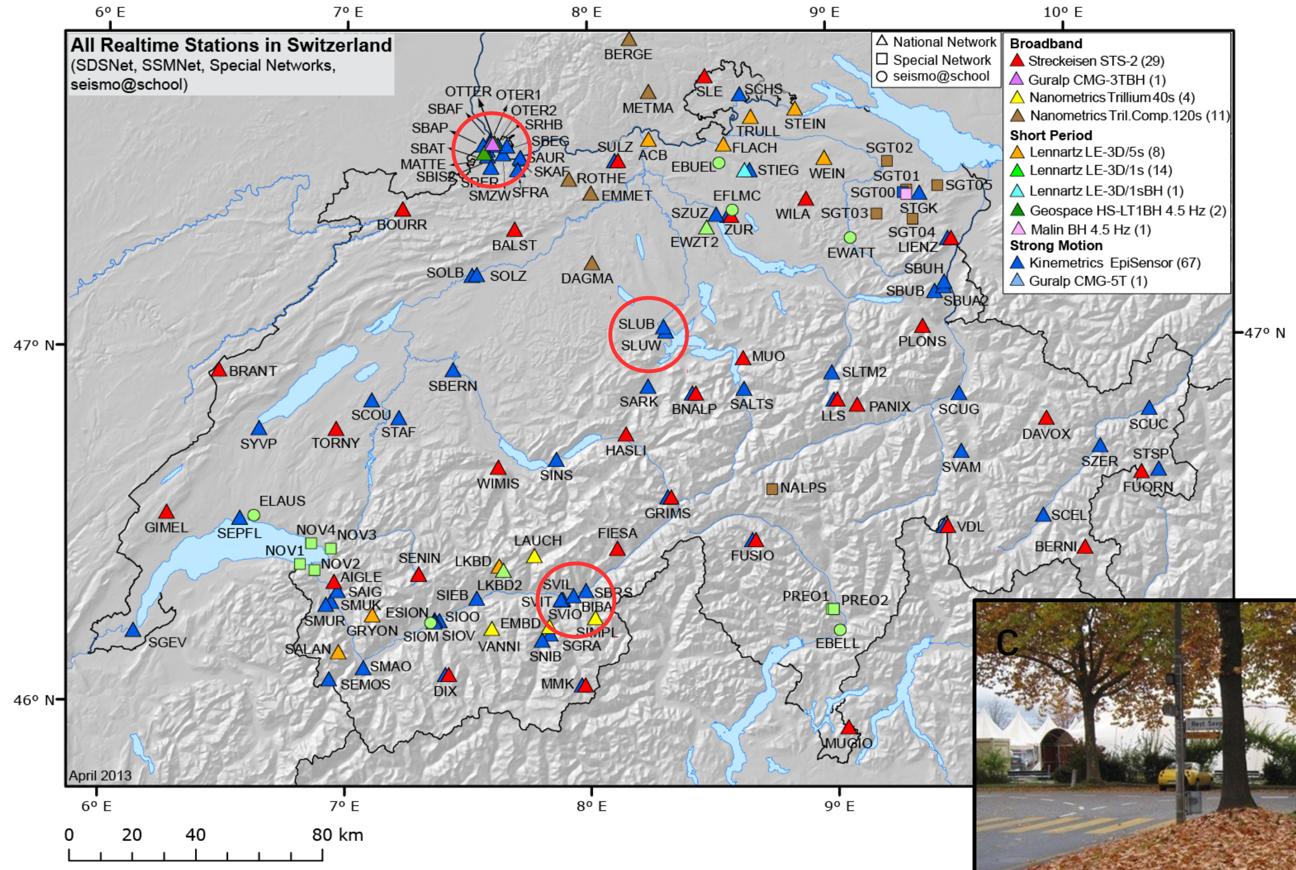
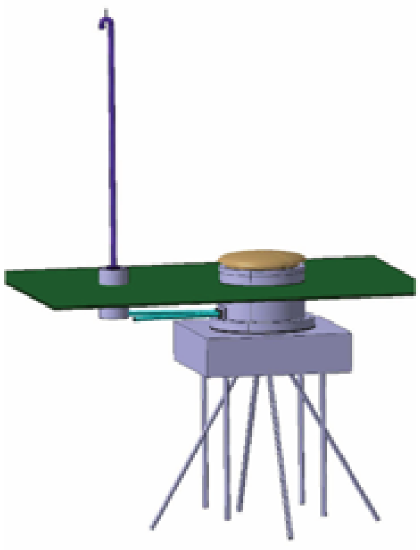
INGV Milano, 2017, February 13

The Swiss Networks (SSMNet, SDSNet)

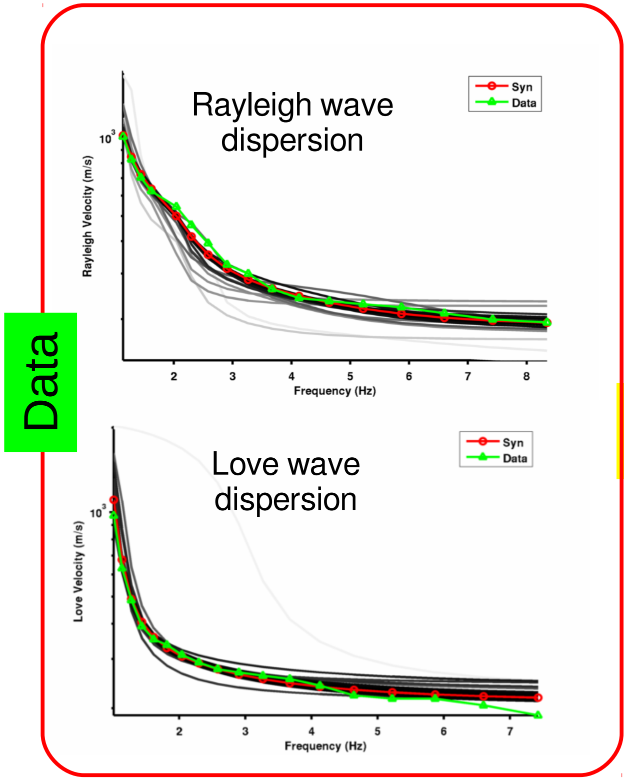
The Strong Motion Network (SSMNet, 55 stations) and the Swiss Digital Network (SDSNet, 52 stations) cover a variety of geological conditions in Switzerland, from very hard rock sites to low-velocity sedimentary valleys.

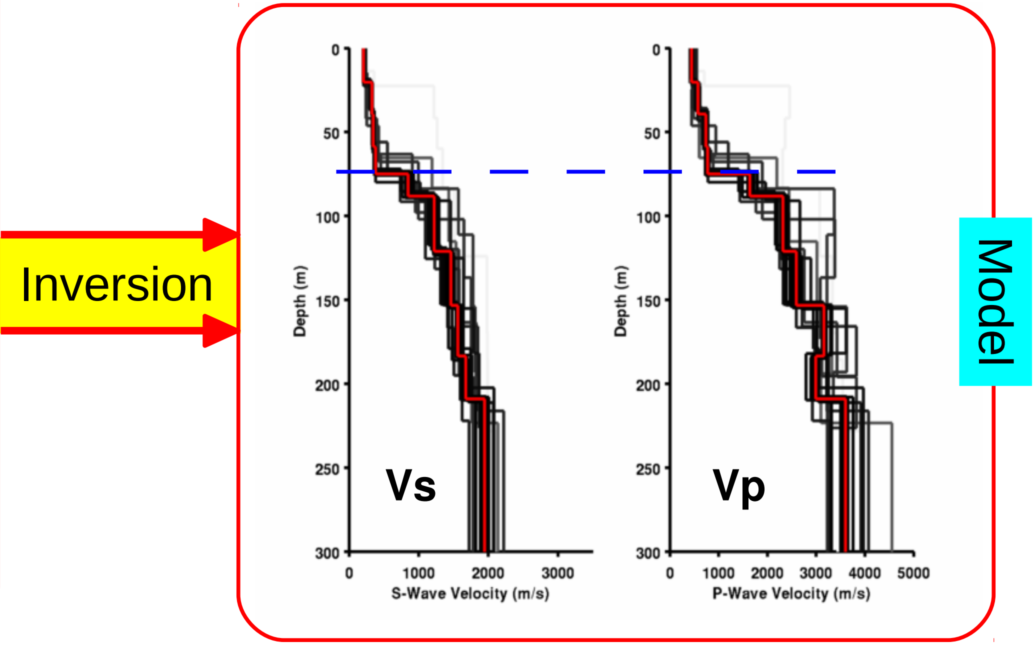




Site characterization using surface wave analysis

- *Cost efficient methods* to estimate soil parameters are one of the major issues in local seismic response evaluation and site-specific seismic hazard assessment
- *Surface wave analysis* techniques (**passive** and **active**) suit this purpose, because of their simplicity and reliability
- The *dispersion* features of the surface waves are *optimal constraints* for non-linear inversion of the seismic velocities.





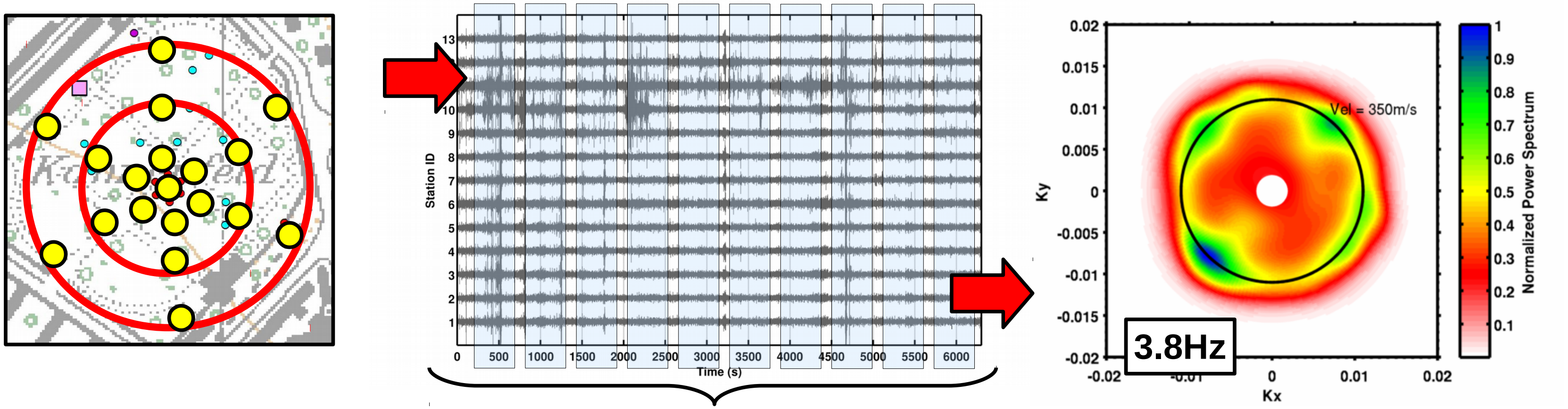
Ambient vibration seismology

(Array analysis)

Array deployment

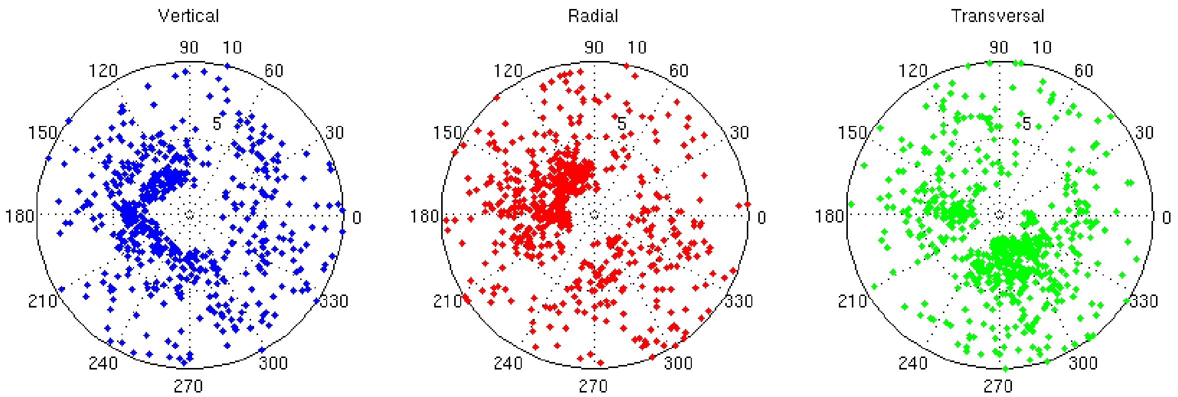
Noise recording

f-k analysis



3.8Hz

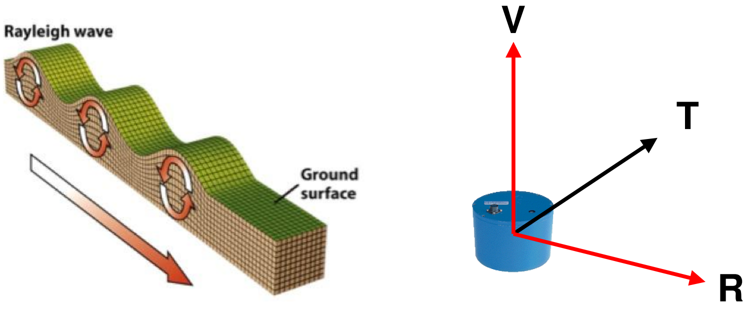
1h40m


Vertical

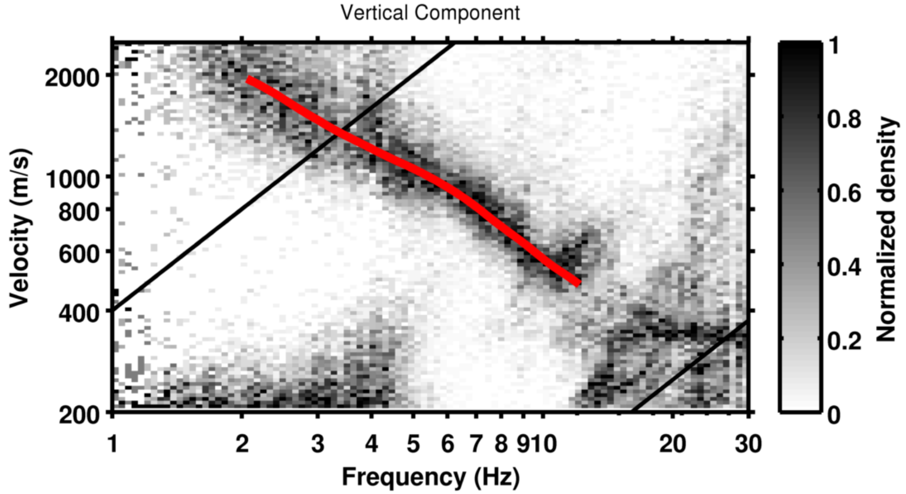
Radial

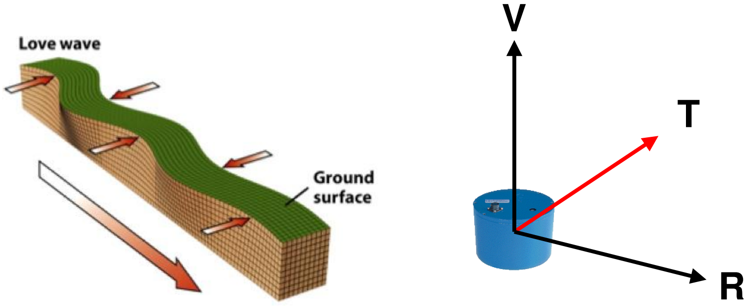
Transversal

Three-component high-resolution f-k analysis

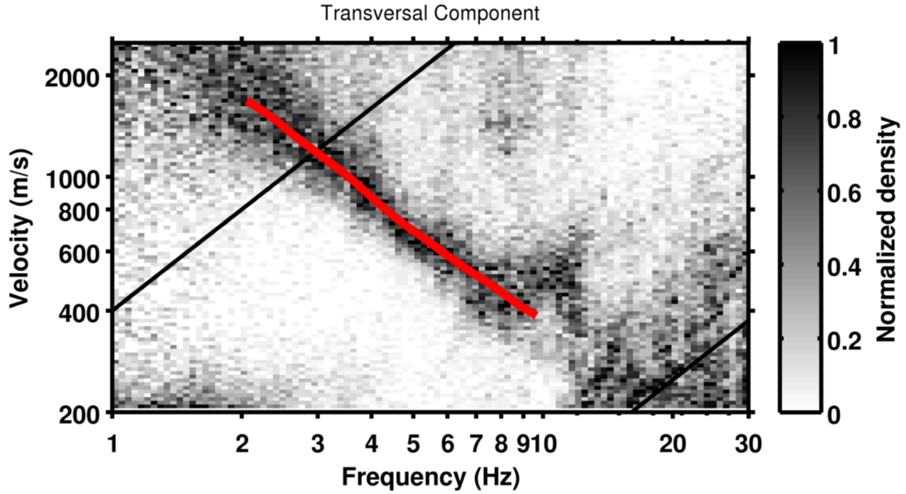


Rayleigh wave dispersion





Love wave dispersion

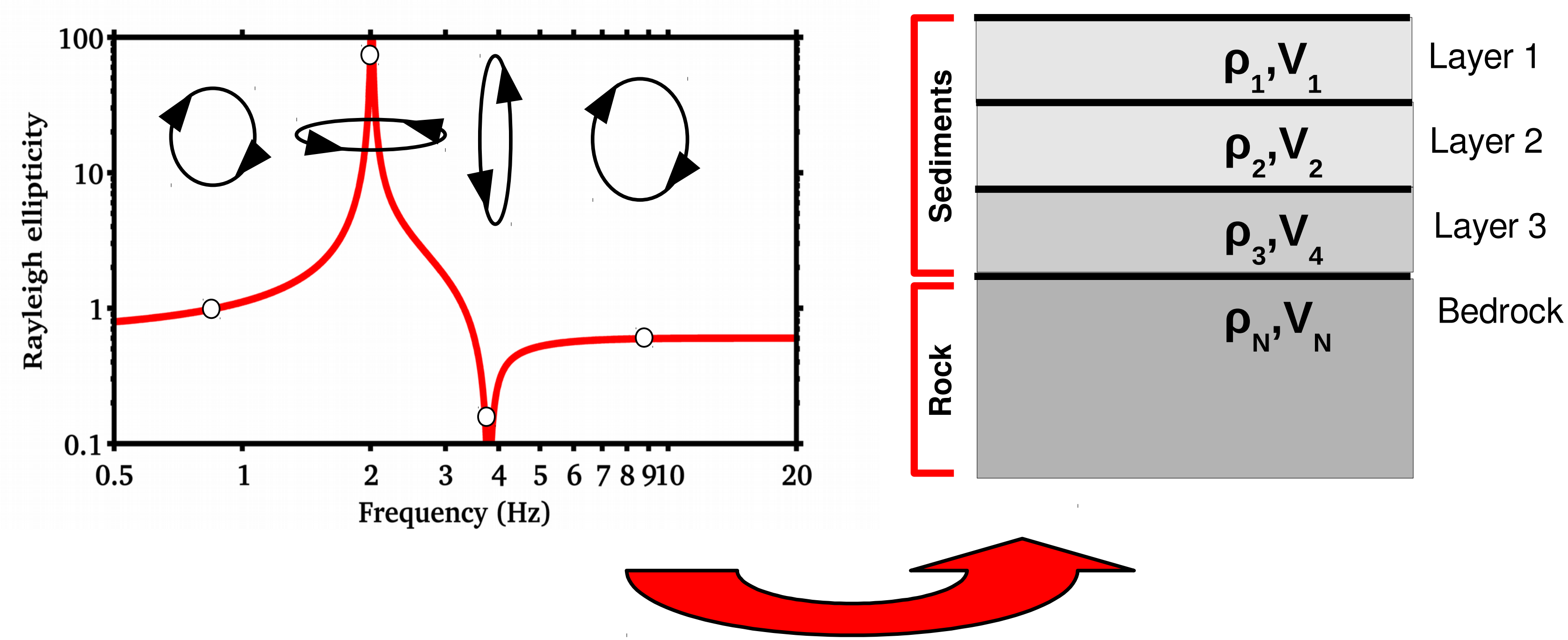


Rayleigh wave elliptical motion

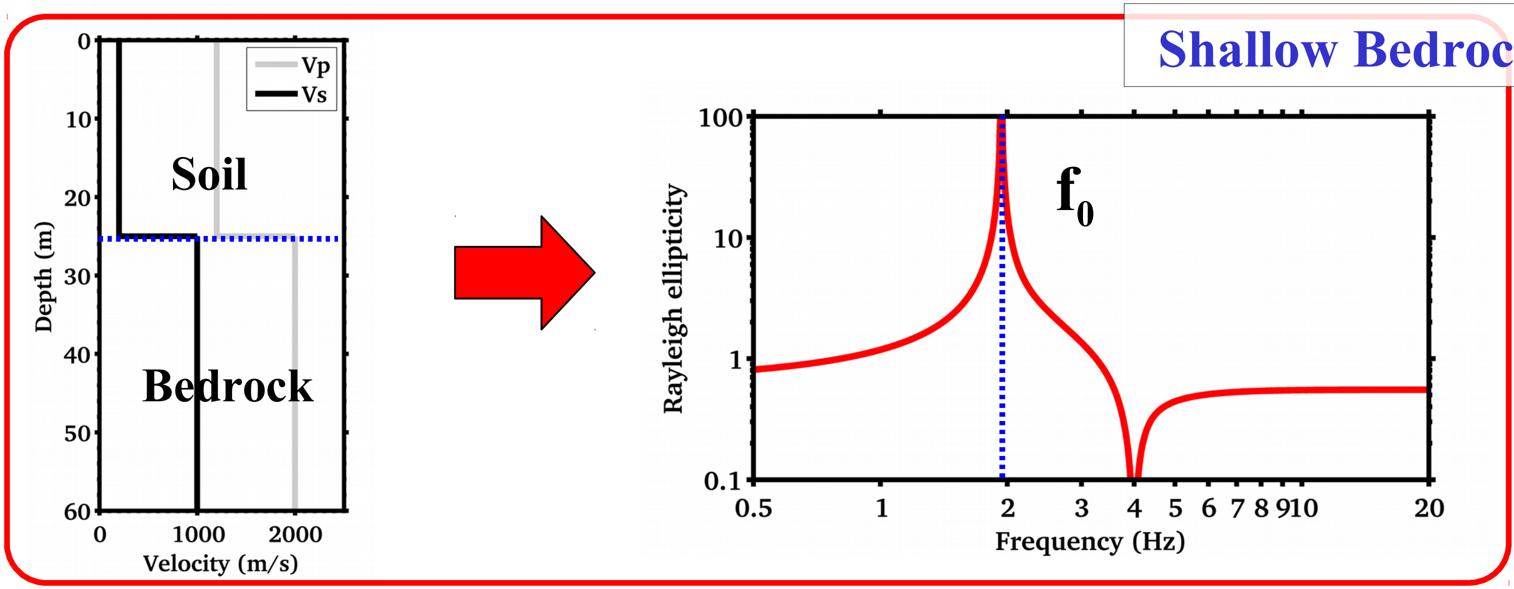
1) Rayleigh wave ground motion is elliptical. It can be described by two orthogonal components (horizontal and vertical) oscillating in phase in a plain perpendicular to the free surface, which contains the direction of propagation

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

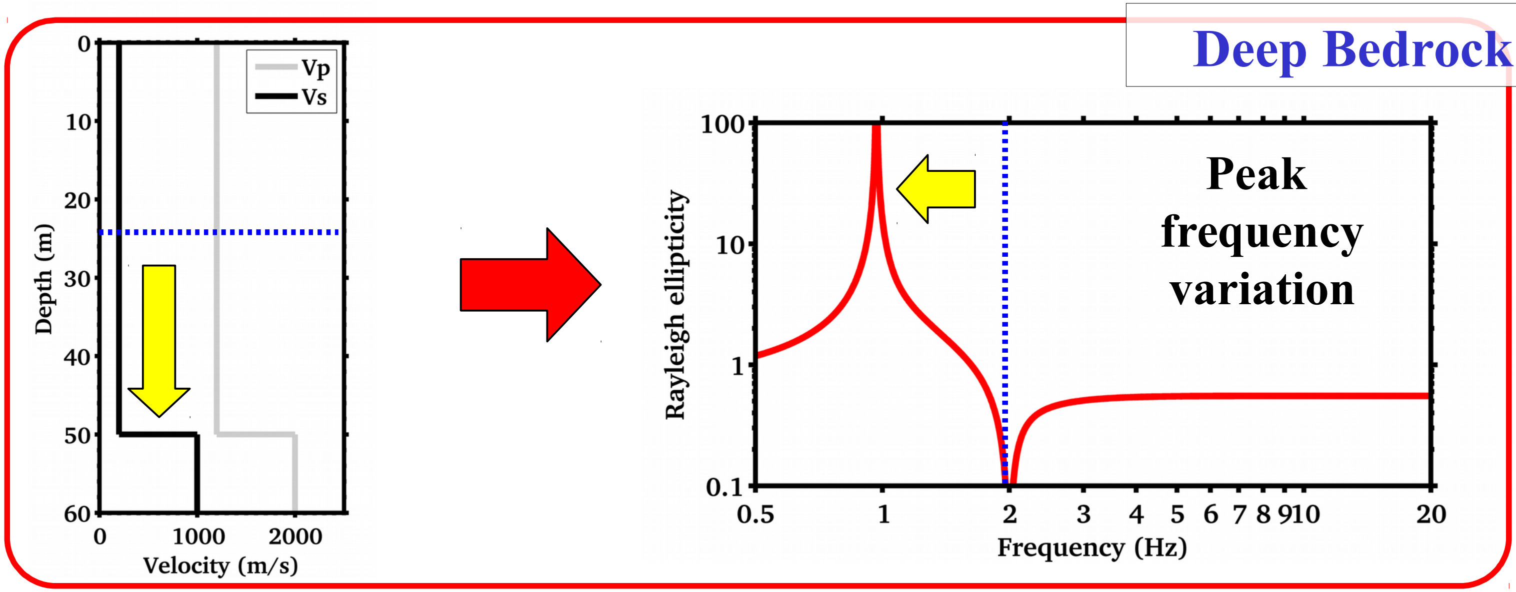
3) Rayleigh wave ellipticity is site specific and could be used in principle to retrieve the properties (Vp, Vs, density) of the ground by inversion procedure



Sensitivity to layer's interface depth



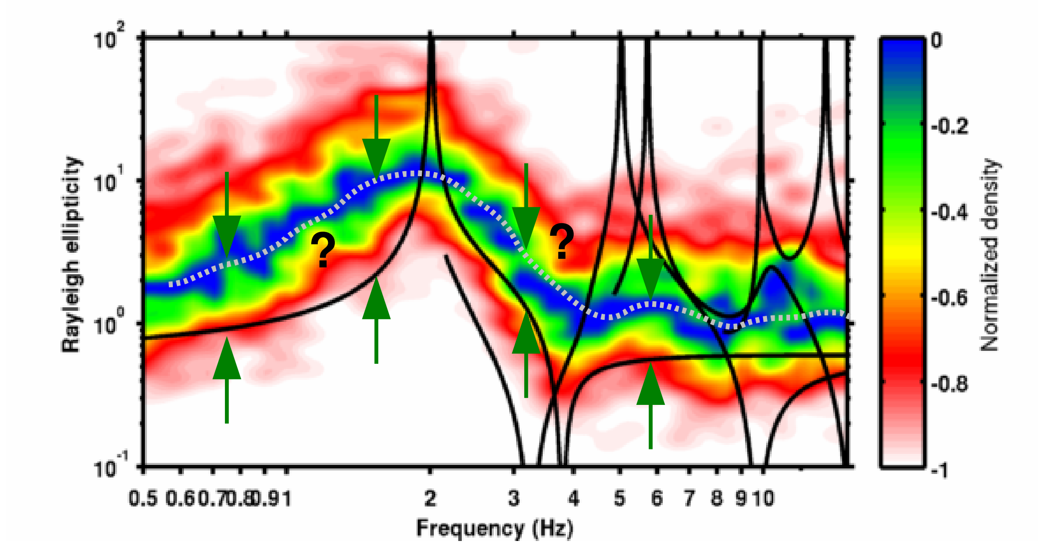
Shallow Bedrock



Deep Bedrock

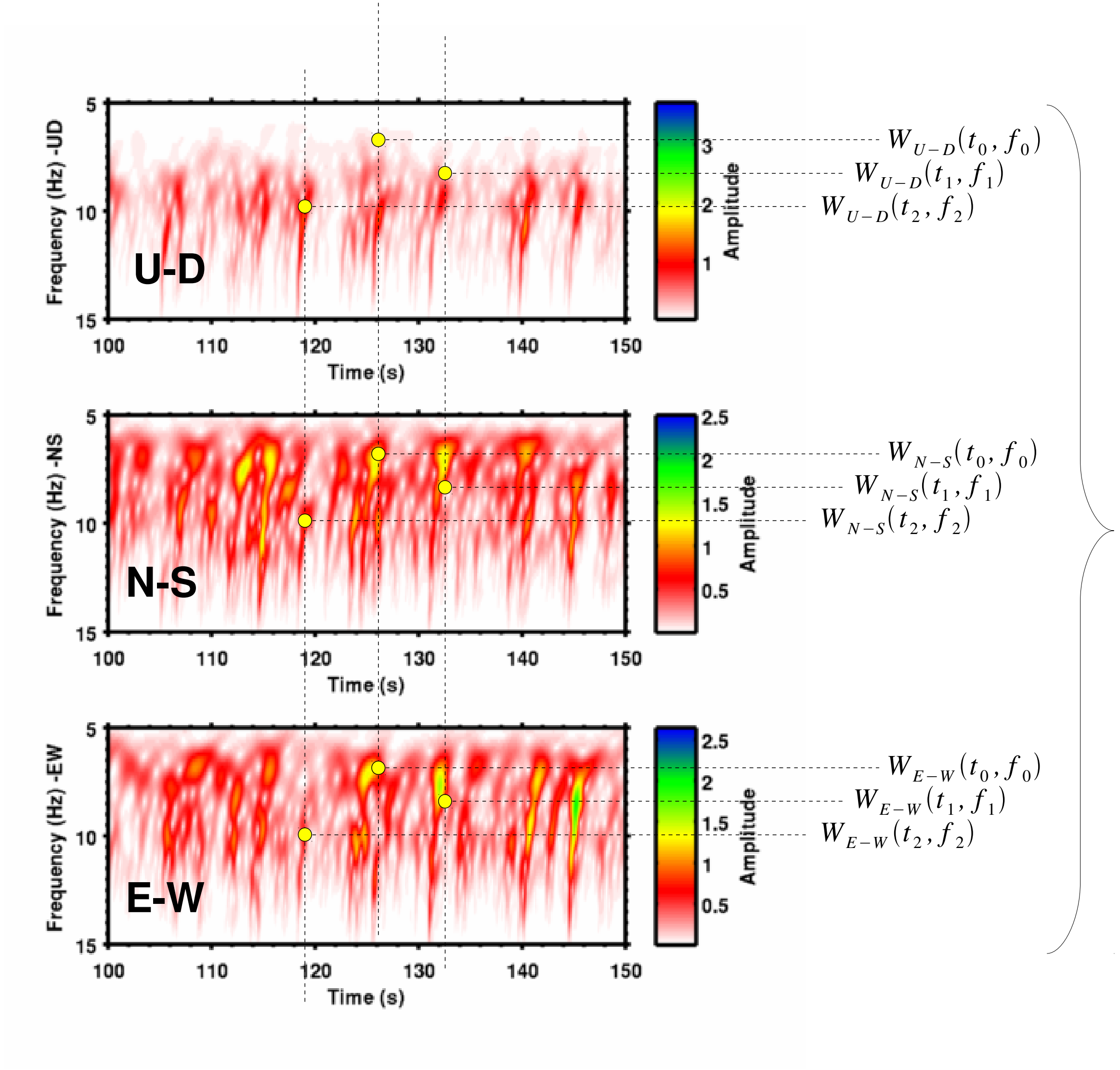
Rayleigh wave ellipticity from ambient vibrations

- Inversion of dispersion curves is a highly non-linear and non-unique problem and may require additional constraints or some *“a priori” knowledge*.
- Combined inversion using *ambient vibration H/V spectral ratios* can be used, assuming these curves are directly related to the Rayleigh wave ellipticity function.



...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

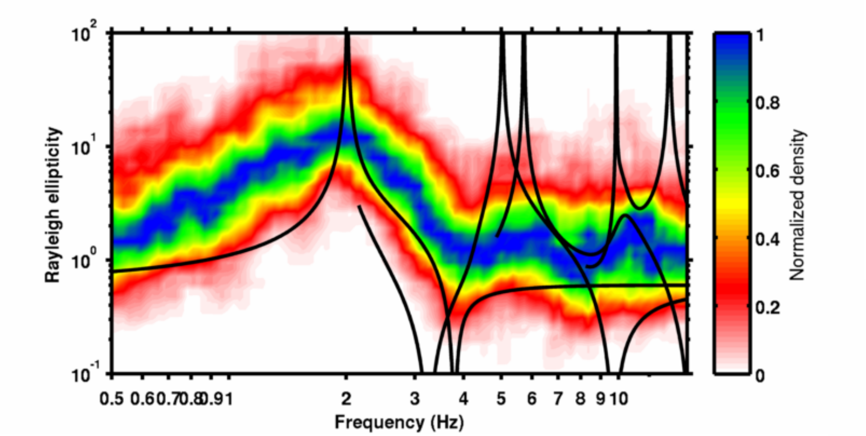


$$Ell_R(t,s)=\frac{\sqrt{W_{N-S}^2+W_{E-W}^2}}{W_{U-D}^2}$$

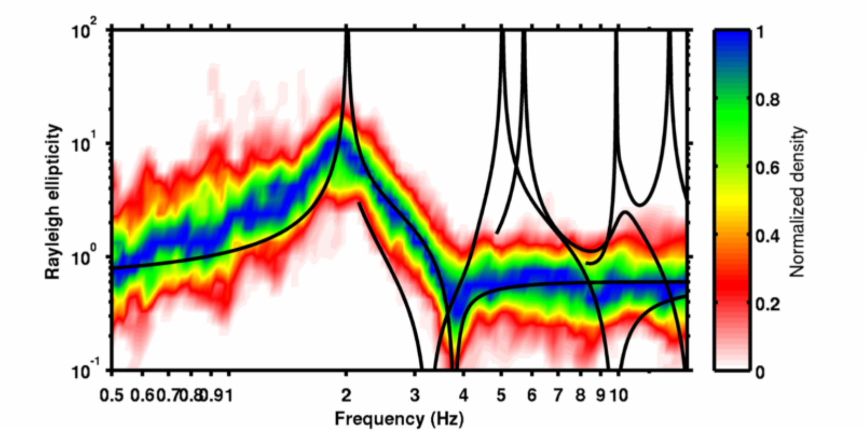
H/V spectral ratio using wavelets

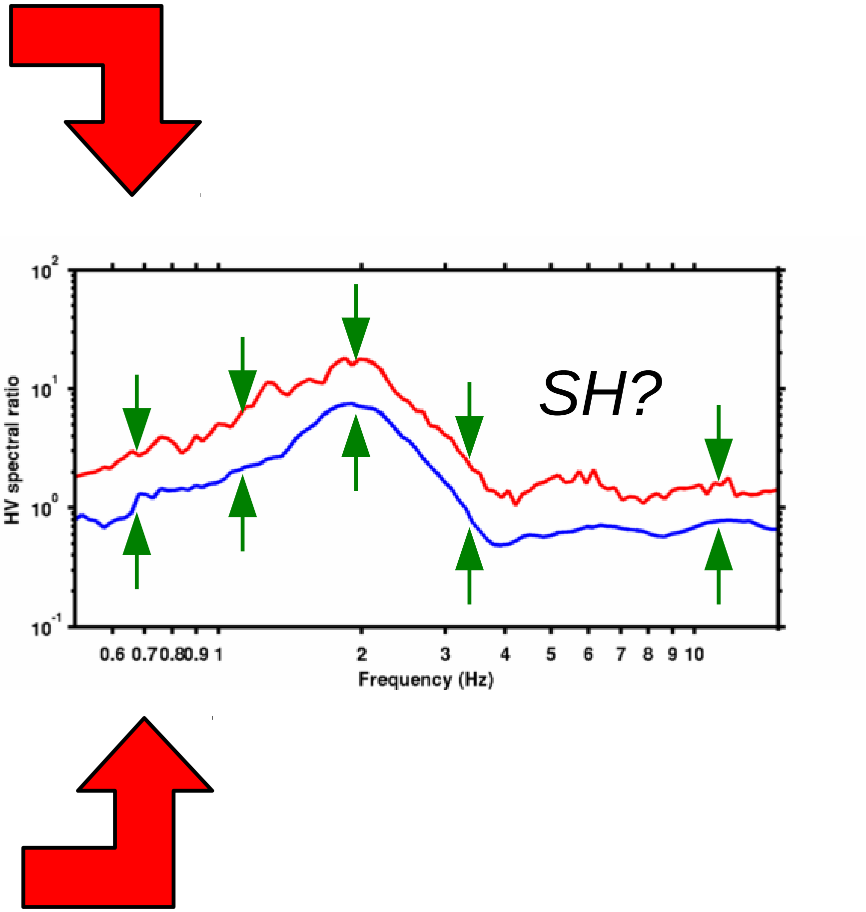
Compared to classical H/V, the FTAN method helps in minimizing the effect of Love (and SH) wave contribution, particularly for the fundamental mode.

Classic H/V



Wavelet H/V

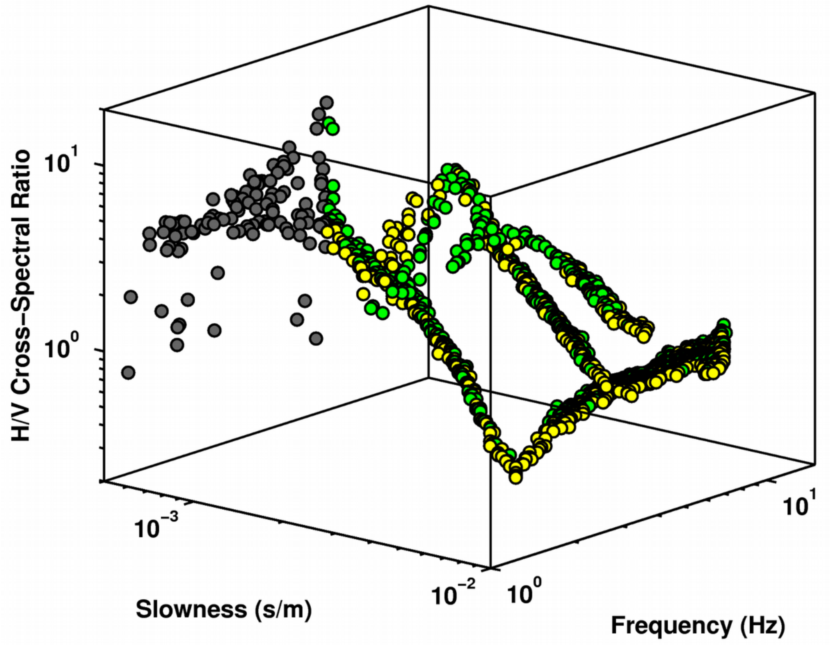




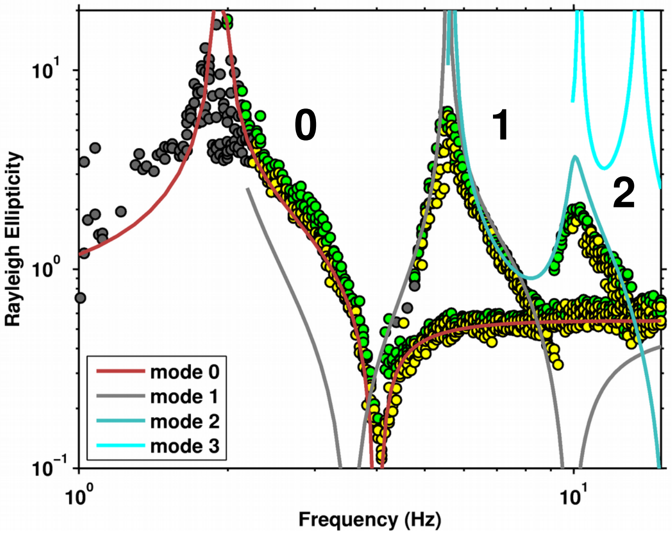
SH?

The cross-spectral H/V spectral ratio

- If a Rayleigh wave mode is identified on the f-k planes, the amplitude ratio between the horizontal-radial and the vertical f-k power-spectra 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 *for each mode separately*.

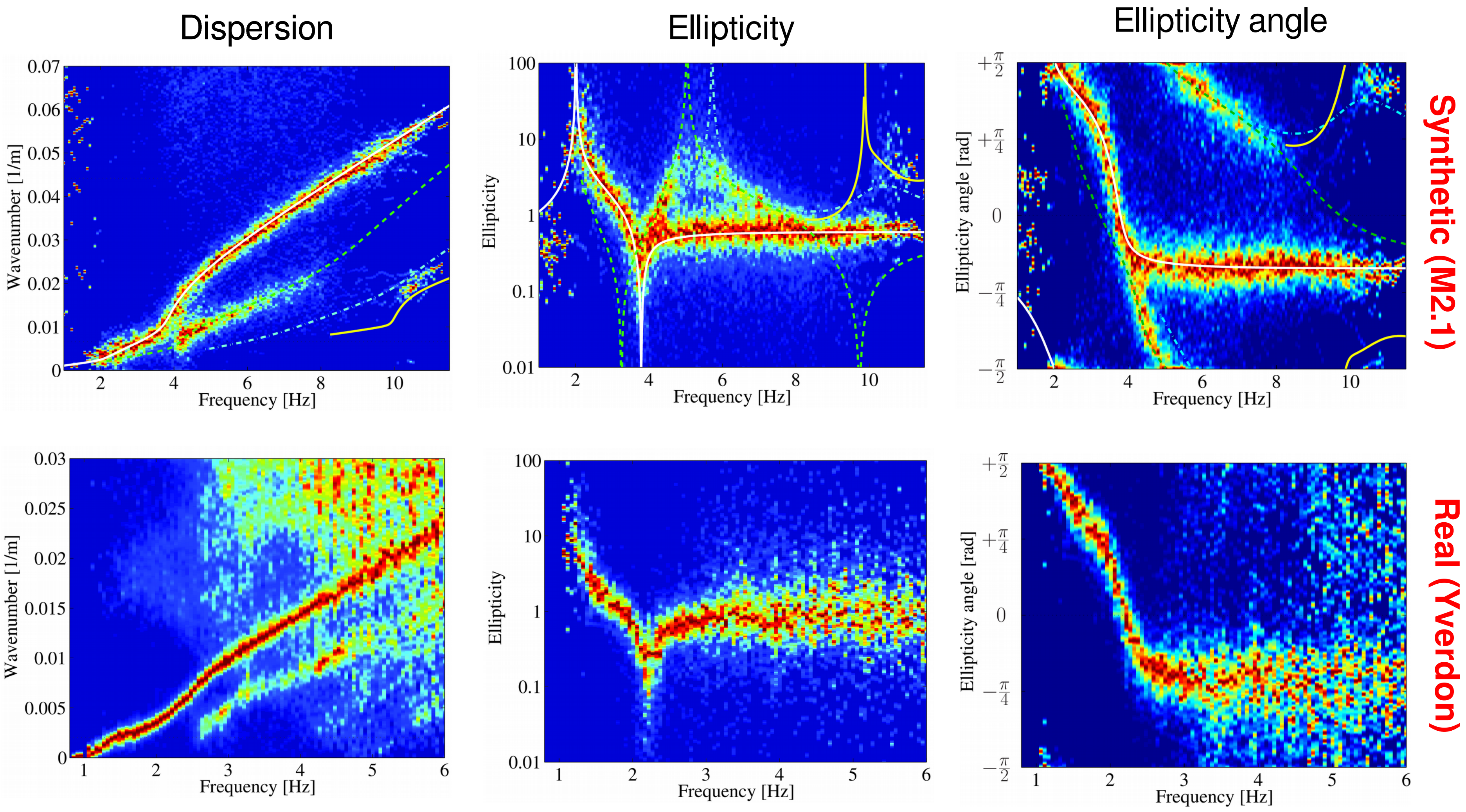


SESAME Dataset M2.1



● *Picking from vertical component*
● *Picking from radial component*
● *Outside resolution limits*

Factor-graph decomposition of ambient vibration wave-field



Dispersion

Ellipticity

Ellipticity angle

Synthetic (M2.1)

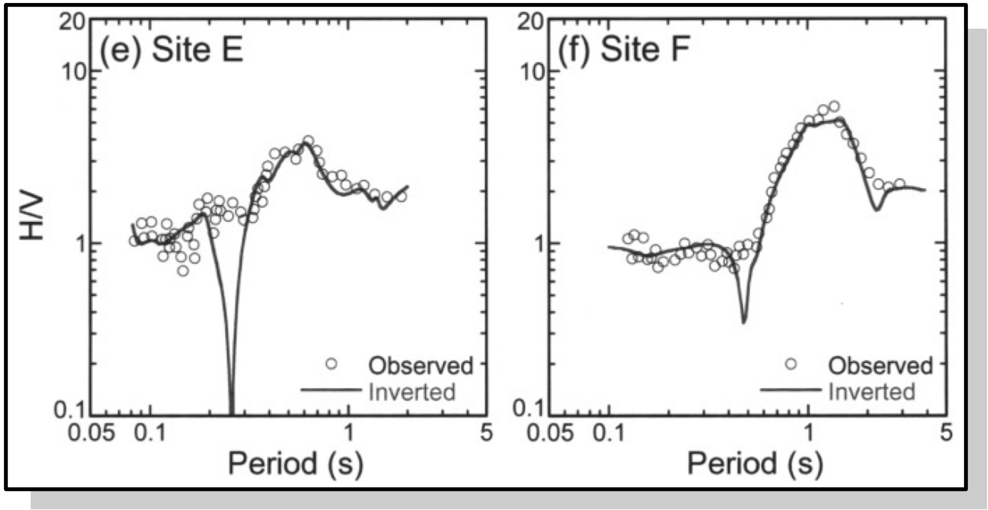
Real (Yverdon)

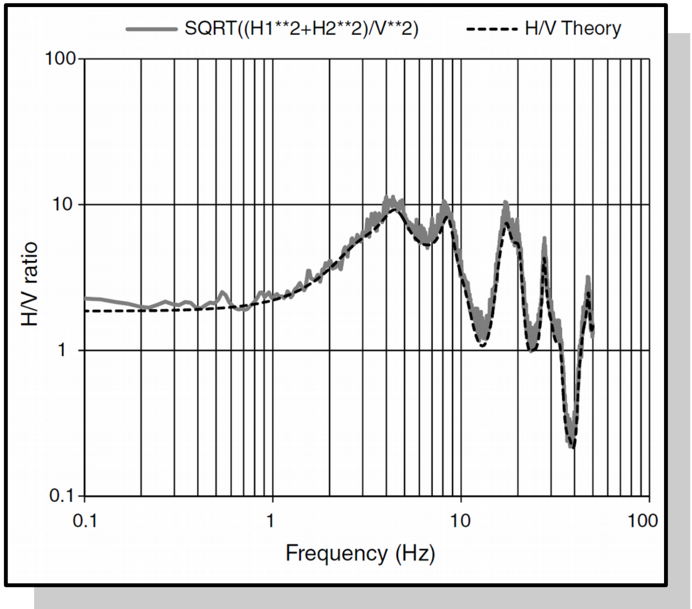
Alternative modeling/inversion approaches

To model H/V ratios directly, different approaches are available, for example:

1) analytical solution and sum of the different wave contributions (Love, Rayleigh, higher modes) → Aray and Tokimatsu, 2004, Lunedei & Albarello 2010.

2) Numerical modeling of the three-component Green functions (1D/3D approach) → Sanchez-Sesma et al. 2010, Kawase et al. 2011.





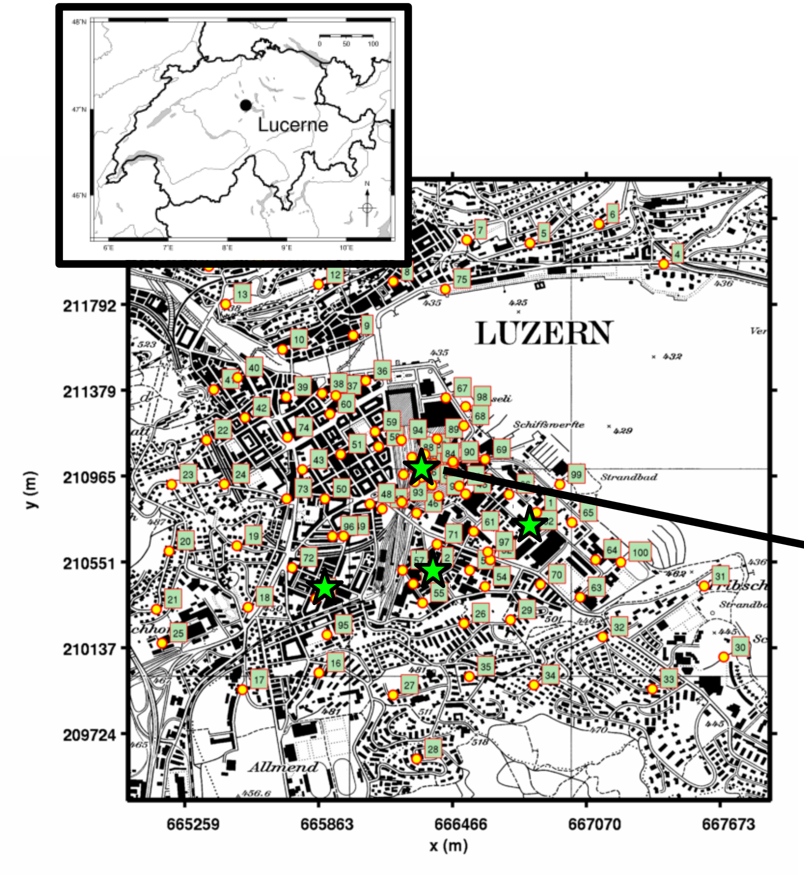
A seismic site response model for Lucerne

1) The *low-velocity sediments* underlying the city of Lucerne, have the potential to produce strong amplification of the seismic wave-field.

2) We combine different methodologies based on *surface wave analysis* to obtain a reliable estimation of the subsoil structure.

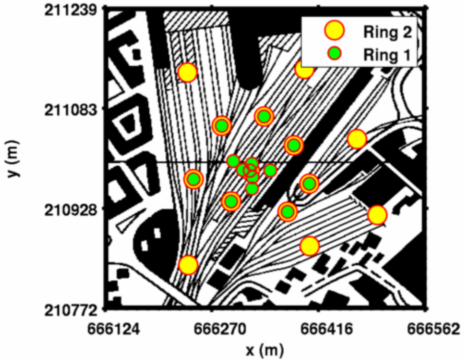
3) We focus on optimizing the use of Rayleigh-wave ellipticity information to enhance the resolution of the *bedrock geometry*.

Ambient vibration measurement survey



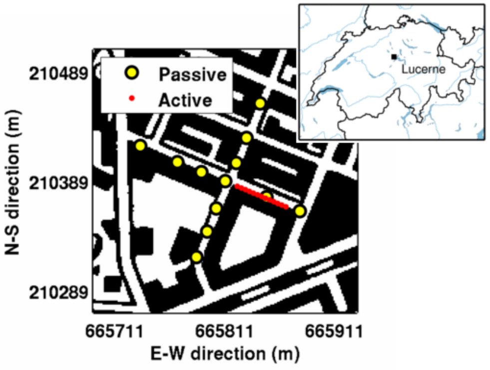
● > 100 single station measurements

★ 4 array installations

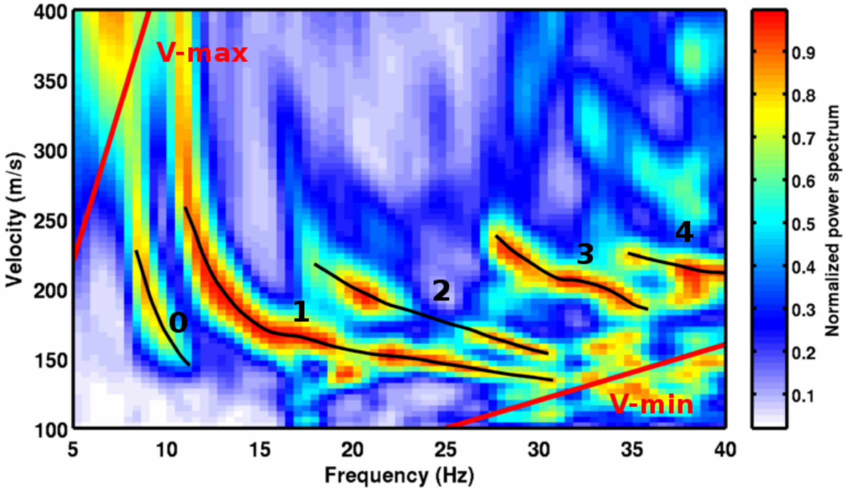


Main array (~350m ∅)

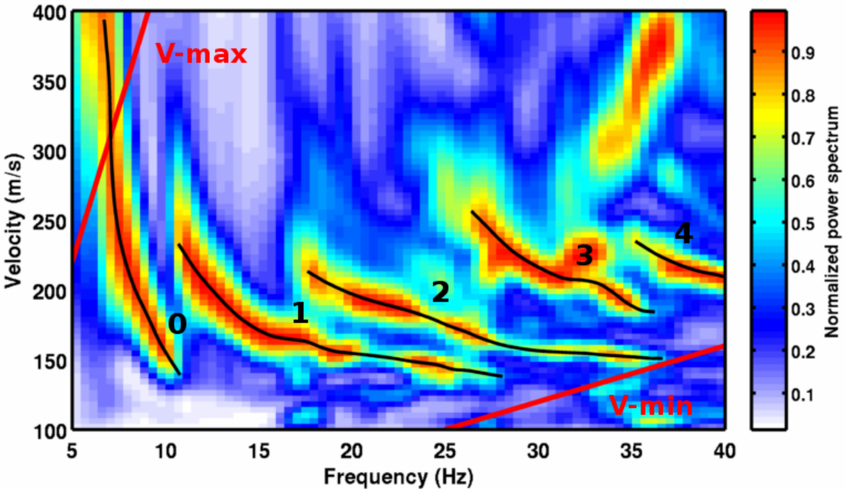
Active seismic on continuous seismic recordings



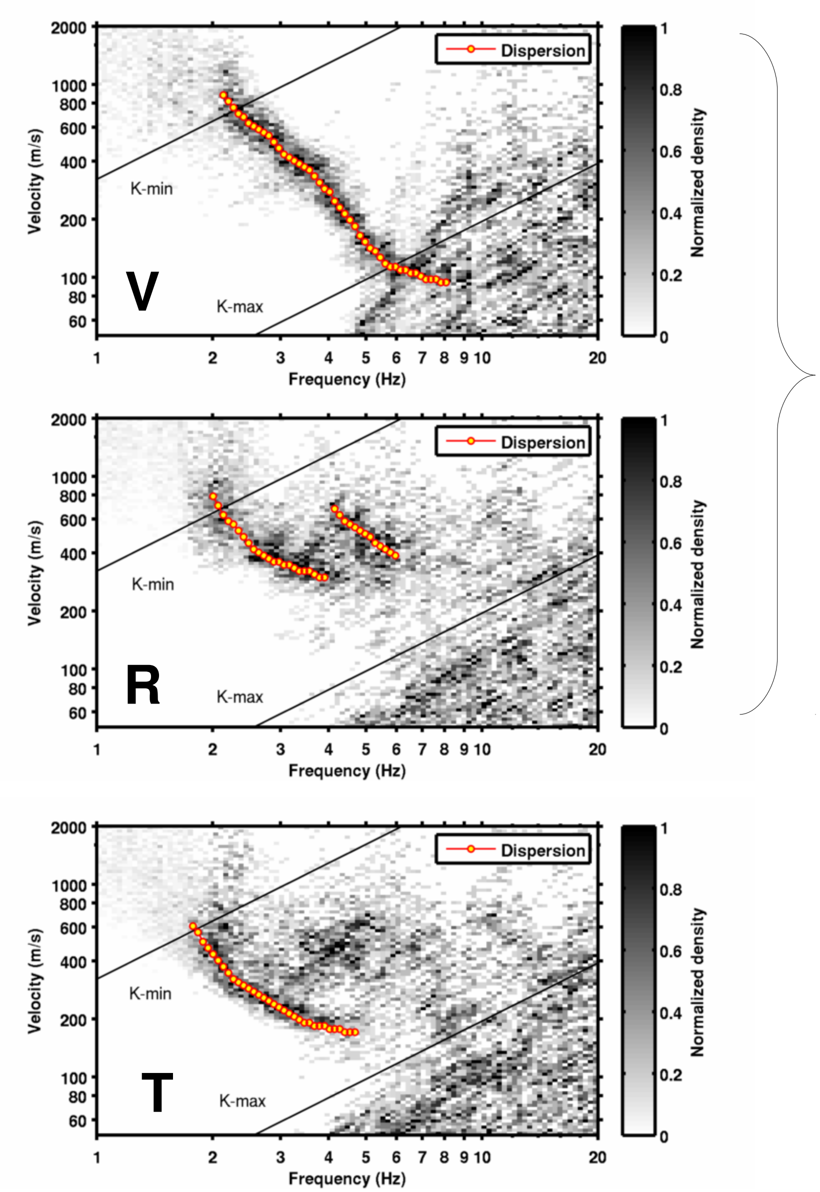
Rayleigh Wave Vertical

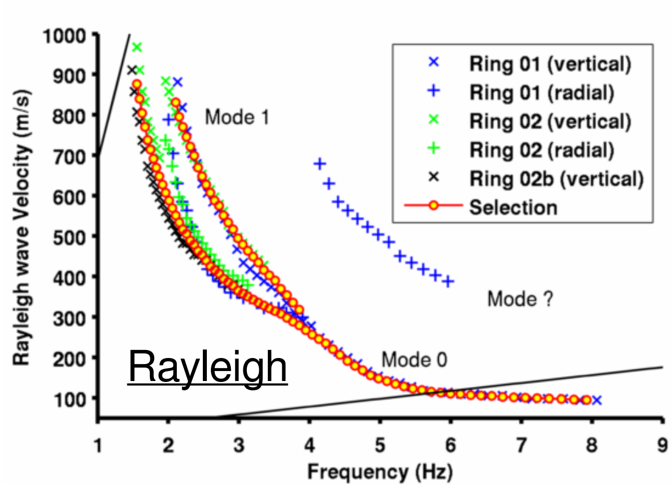


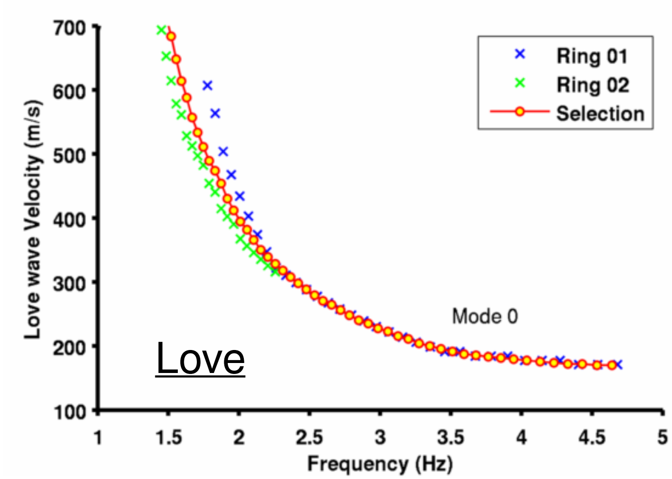
Rayleigh Wave Radial



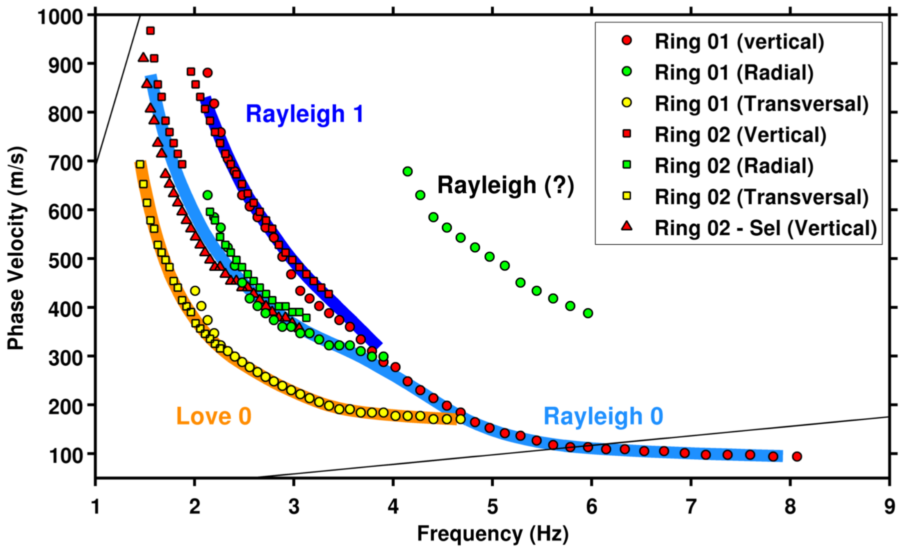
High-resolution 3-components f-k analysis





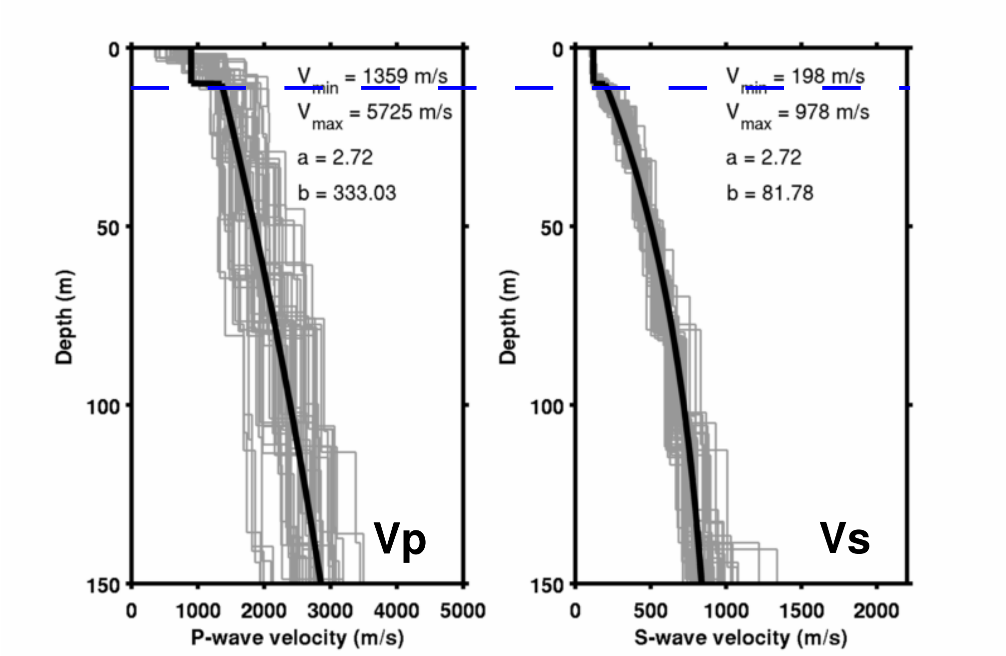


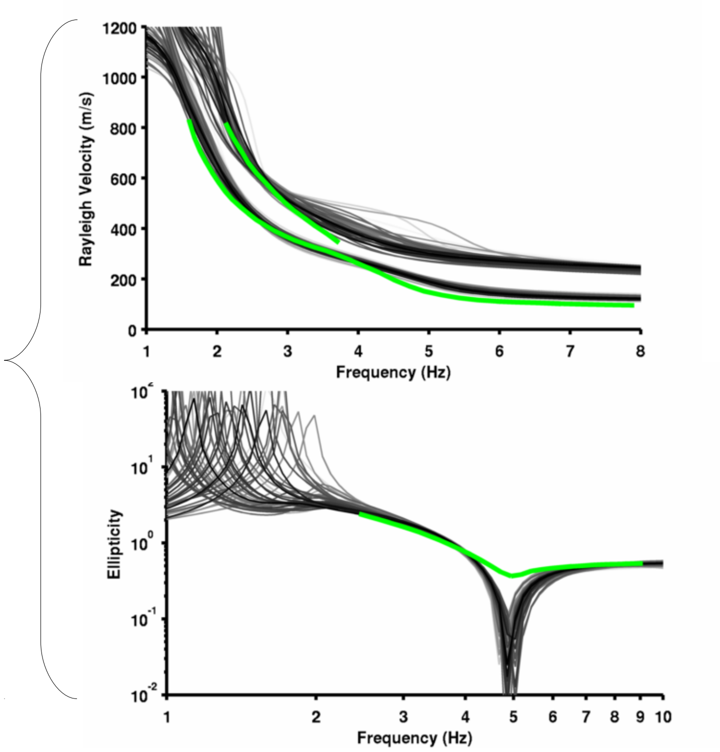
Combined inversion



To invert for the velocity structure we use a global optimization approach based on adaptive Monte Carlo sampling.

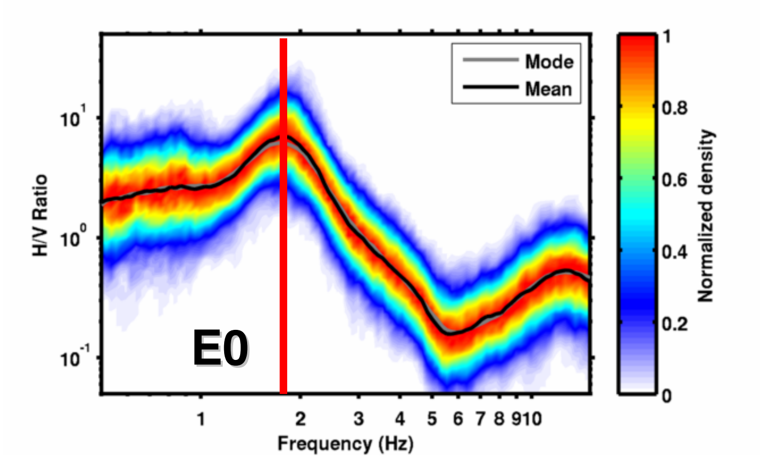
To generalize the velocity structure of the basin, a *simplified piecewise gradient model* is used.

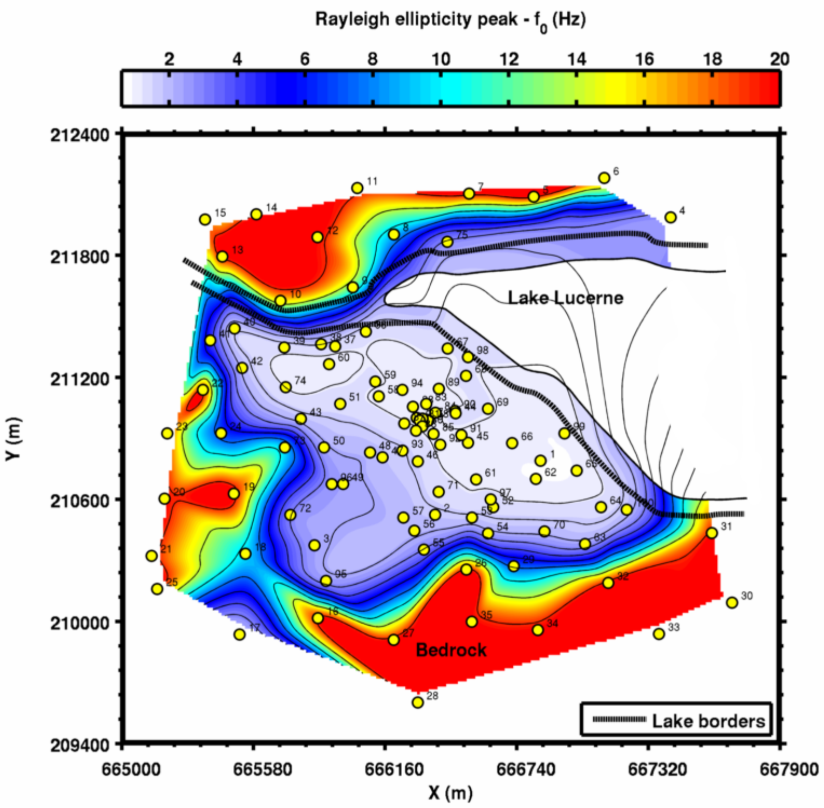




The ellipticity peak (E0) map

Ellipticity peaks (E0) from single station measurements are extracted using *wavelet time-frequency analysis* (NERIES WP4). A map is then produced using cubic interpolation between contiguous stations.



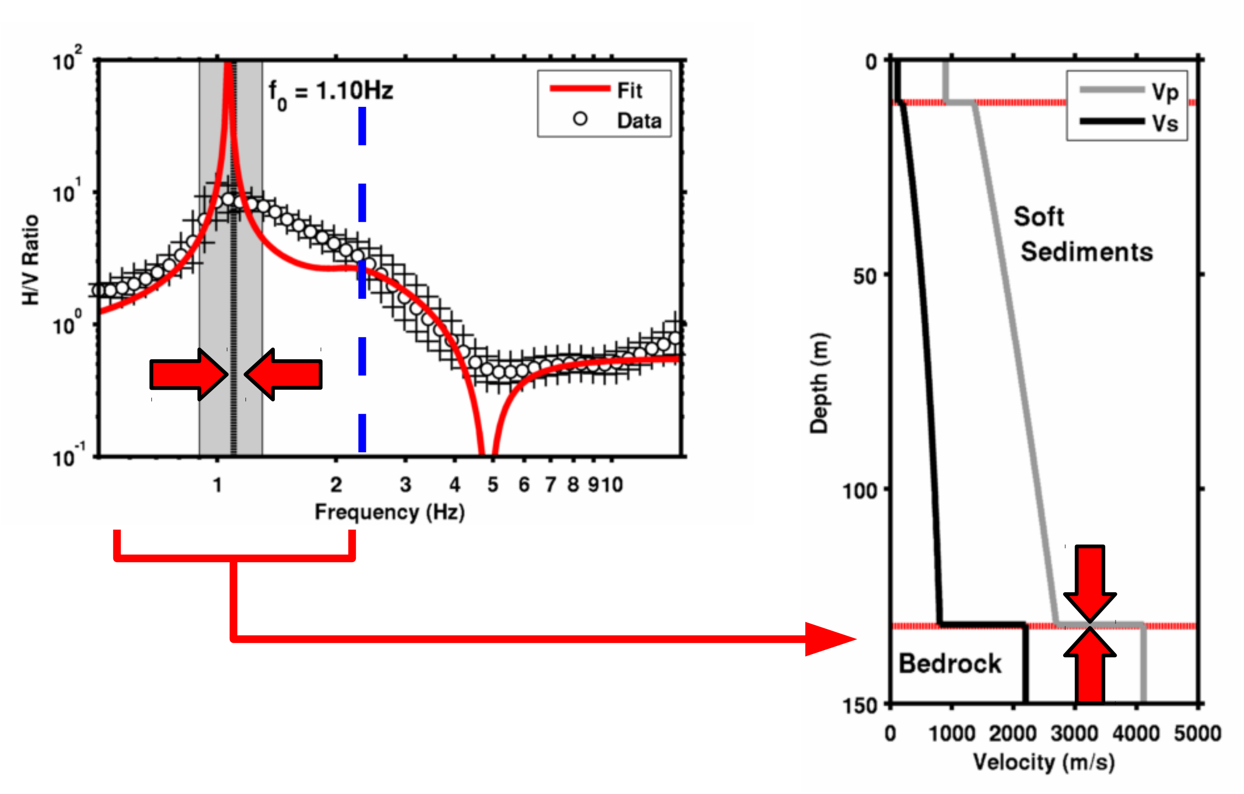


The peak at E0 is due to a strong velocity contrast at the bedrock interface.

Constrain bedrock depth and velocity

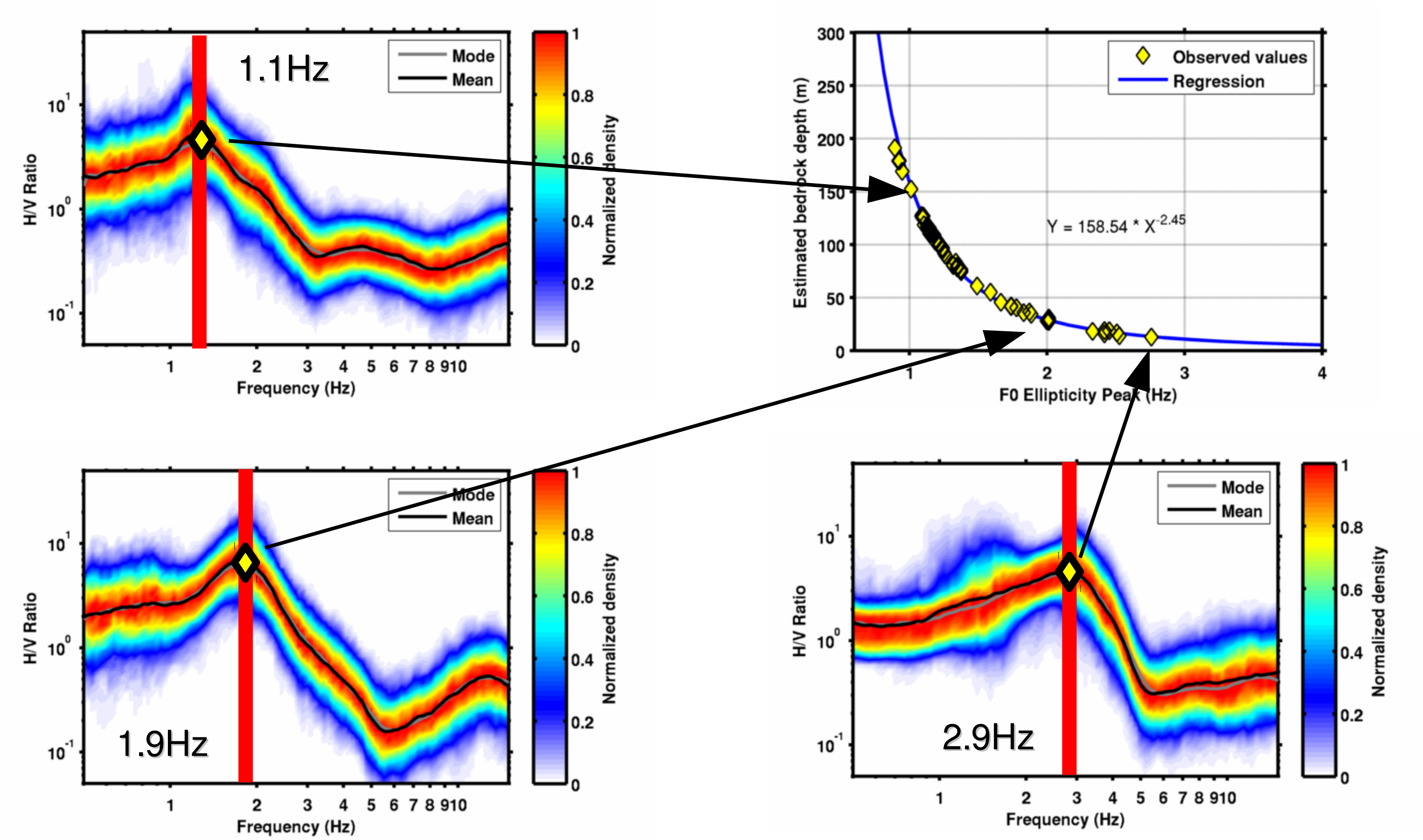
- Combined inversion of ellipticity and dispersion is not always capable to correctly resolve the bedrock location at depth. We therefore use a two-step procedure.

- Once the upper part of the model is constrained, *low frequency ellipticity* and *E0* are inverted separately to resolve bedrock properties.



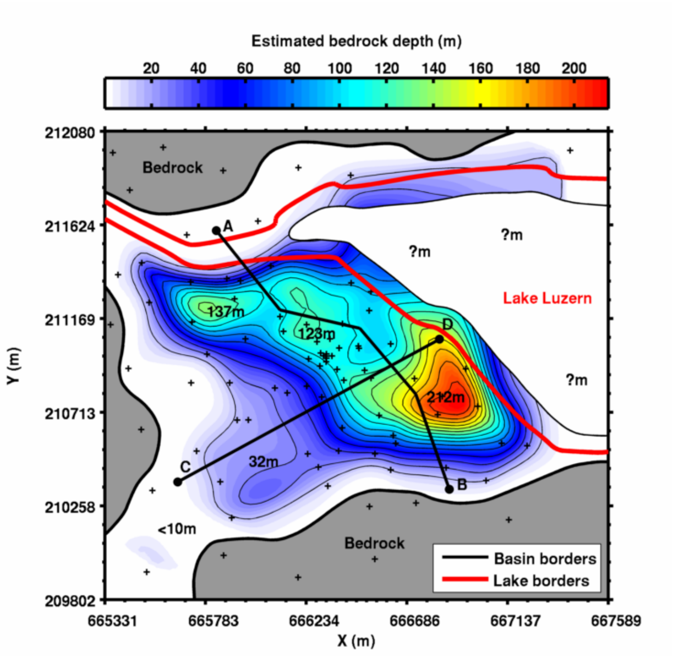
Global inversion of single station measurements

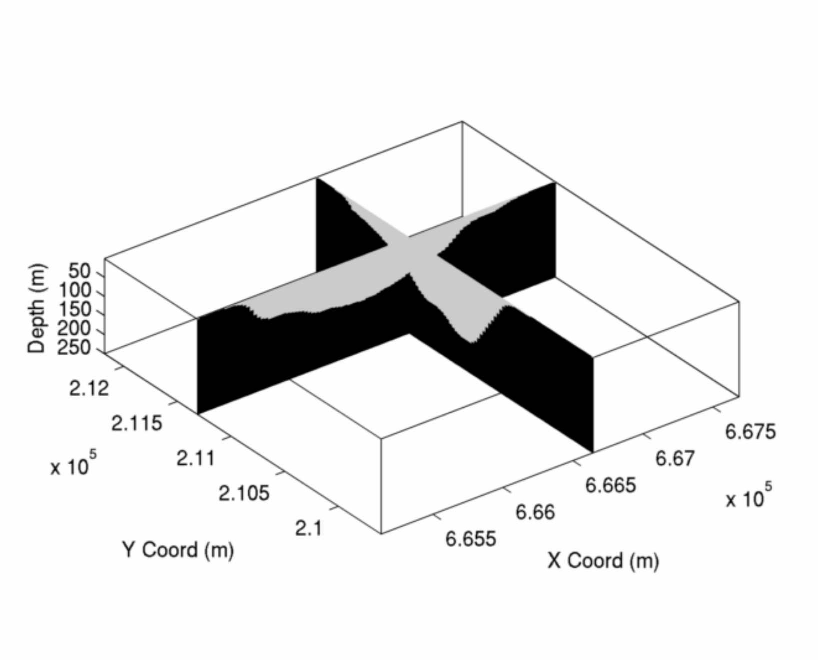
- Globally inverting the ellipticity peaks (E0) from wavelet-based H/V ratios minimizes the uncertainties introduced by the inversion procedure.
- An *exponential regression* is used to describe the relation between the frequency values and inverted depths.



3D bedrock model from ellipticity

Coefficients from the regression of inverted E0 values are used to reconstruct the bedrock geometry under the basin.





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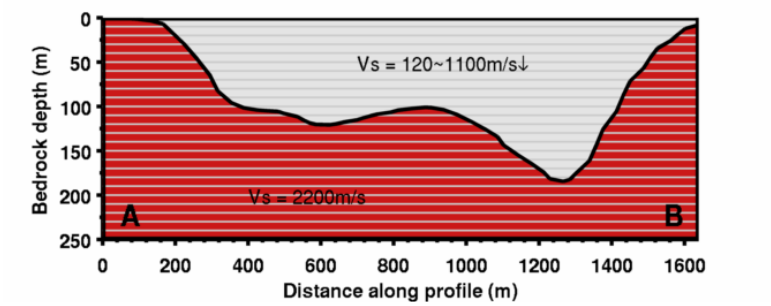
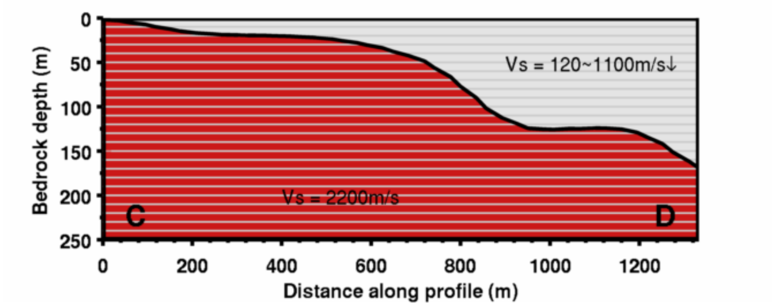
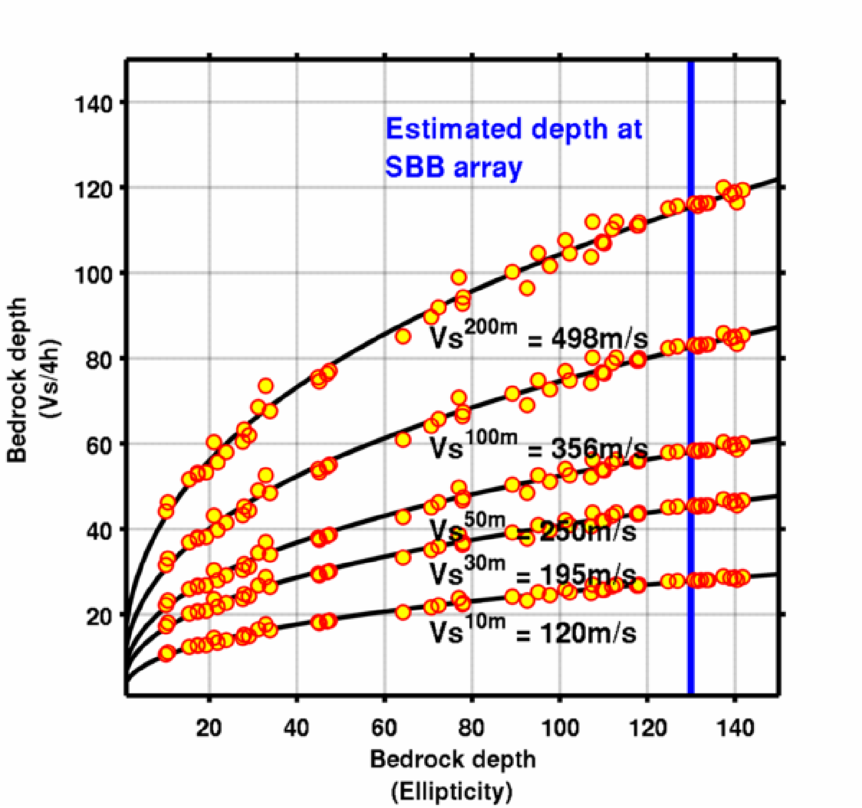


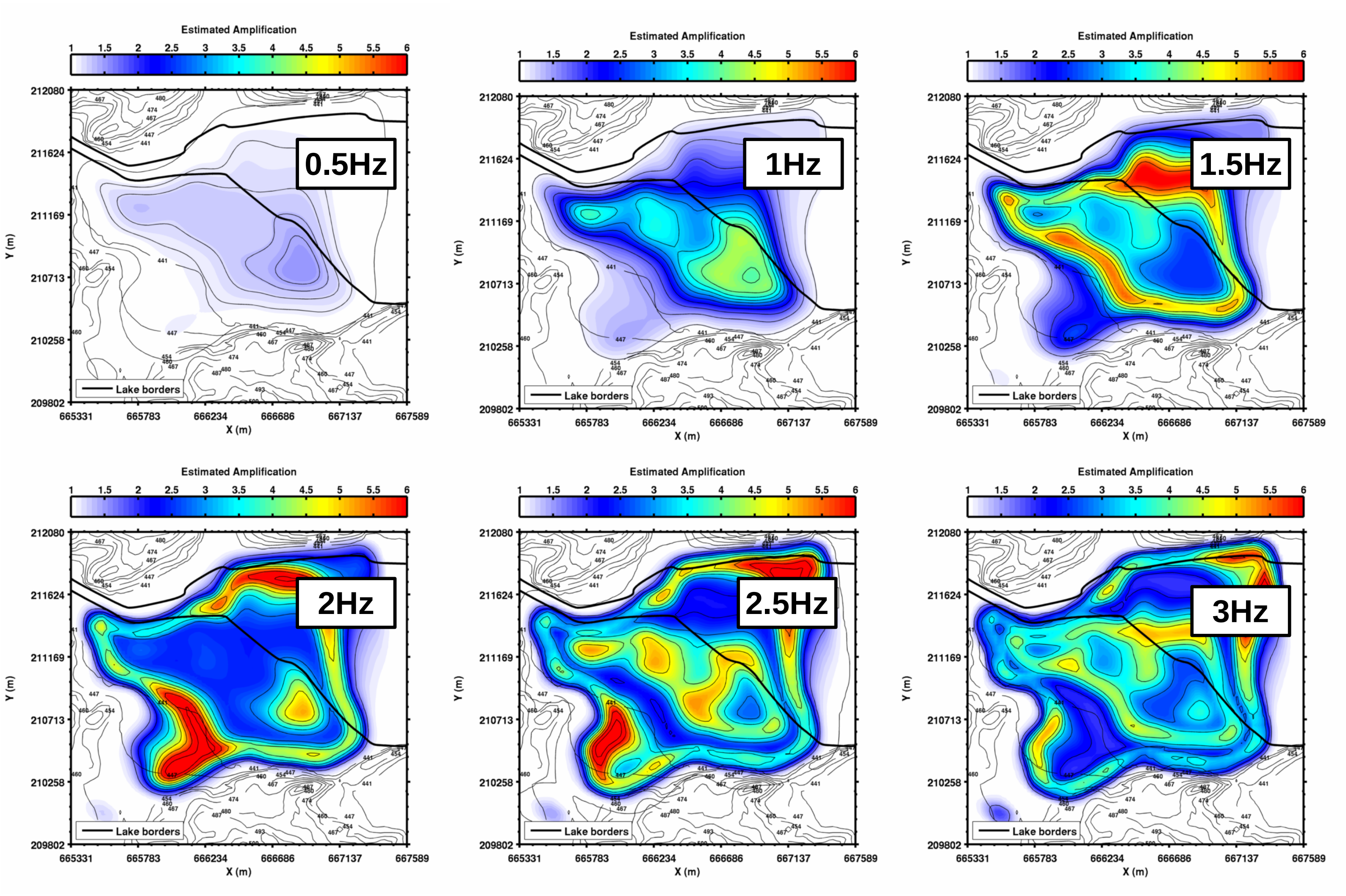


Comparison with the simplified Vs/4h method



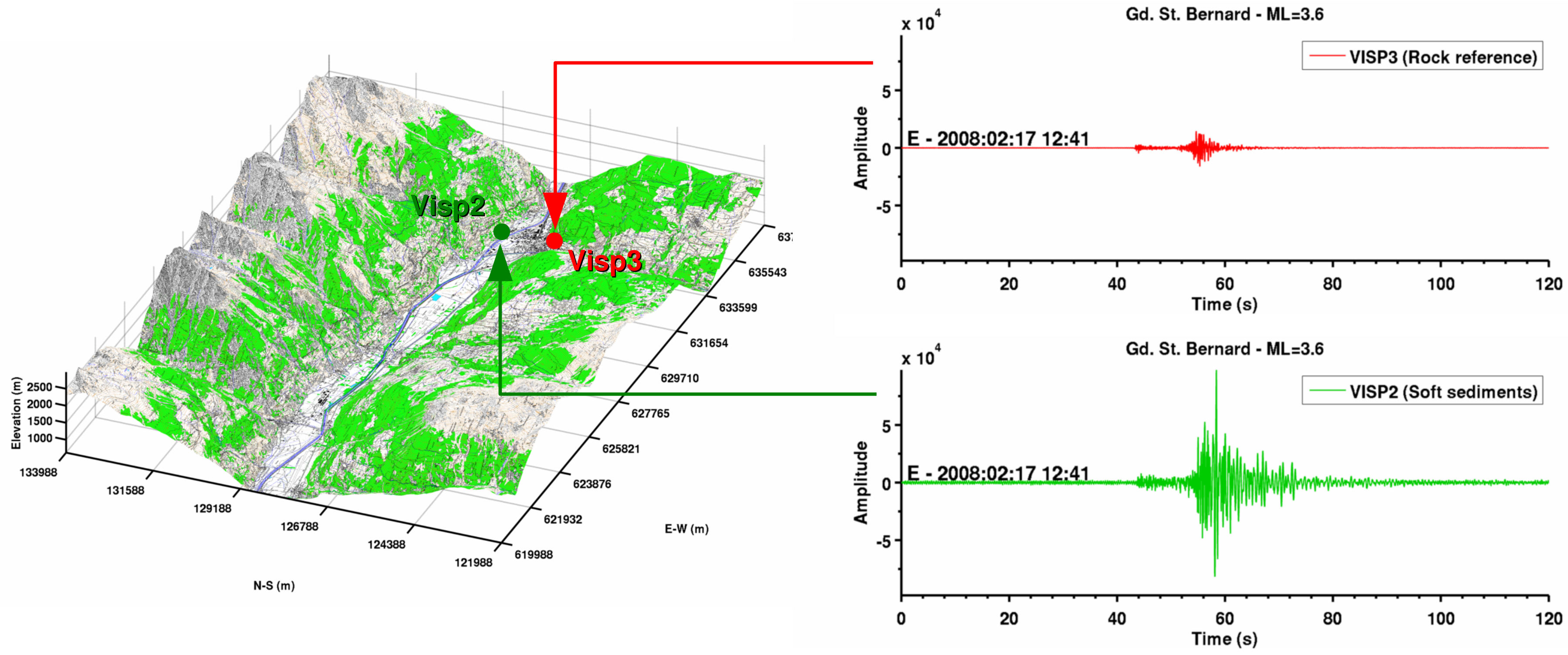
Mapping the SH-wave amplification

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



EXTRA SLIDES

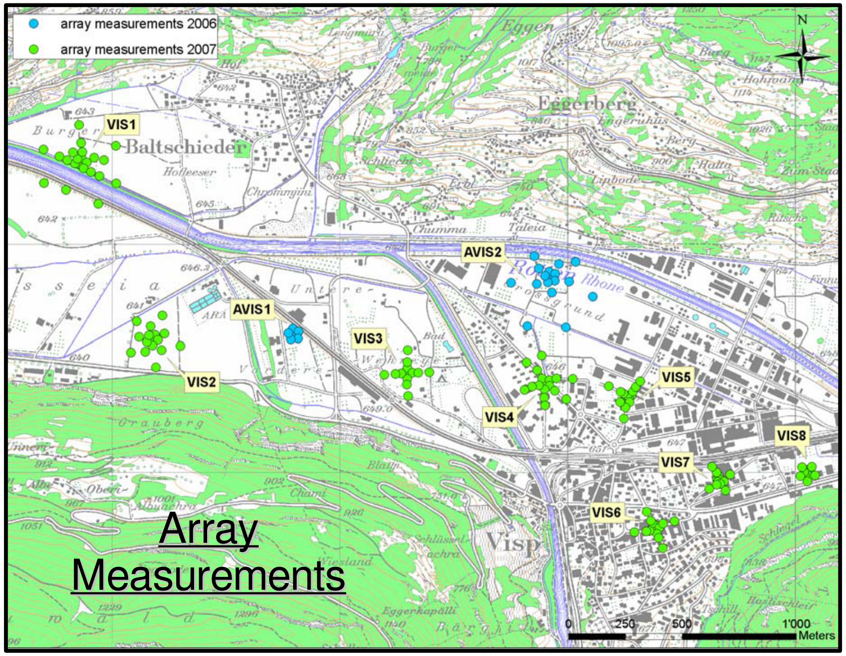
Seismic site response of Visp, Switzerland



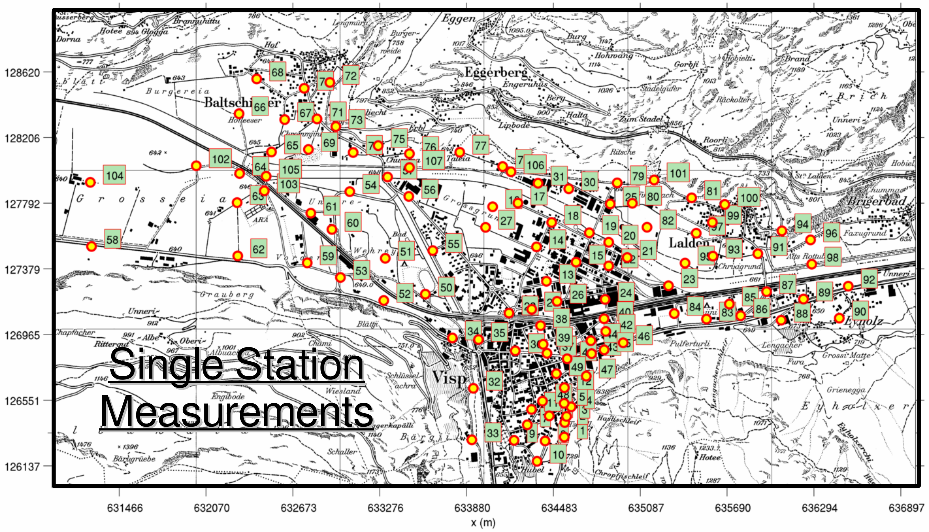
Ambient noise measurement survey

During these last two years, a considerable number of ambient noise measurements (array and single stations) were performed in Visp and its surroundings areas.

Results from the analysis of these measurements has been collected to produce a "preliminary" 3d model of the underlaying basin structure.



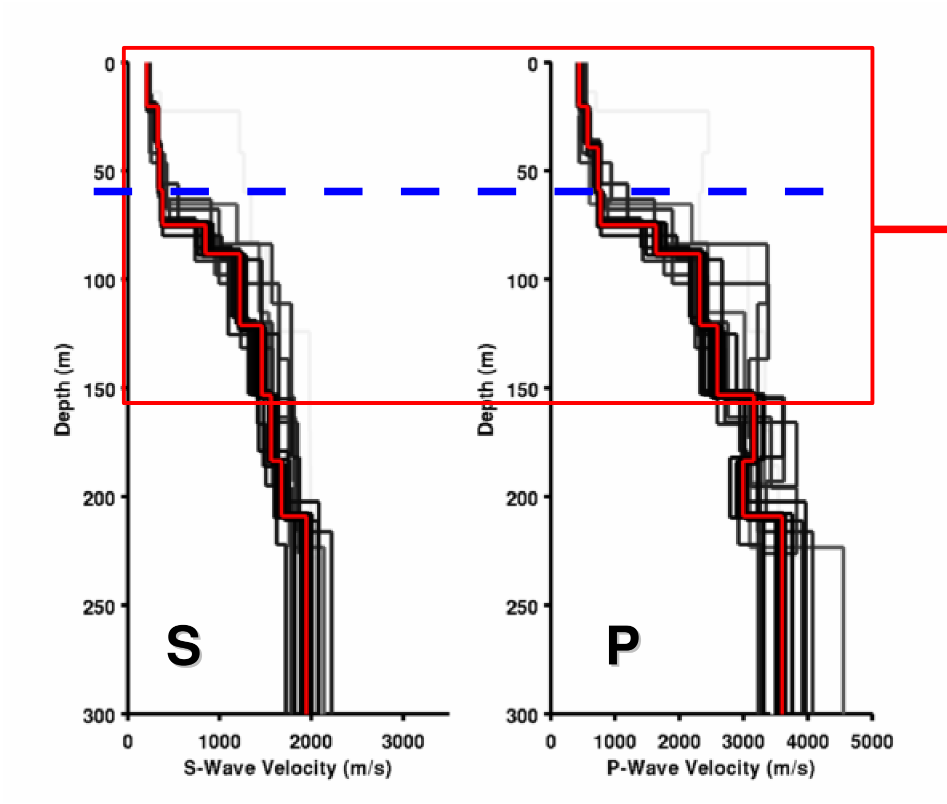
Array Measurements

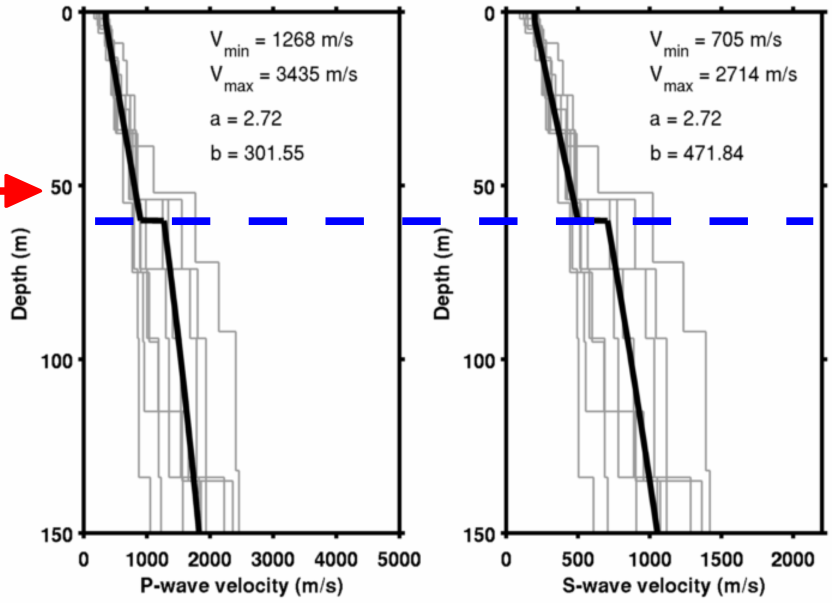


Single Station Measurements

Defining the generic gradient model

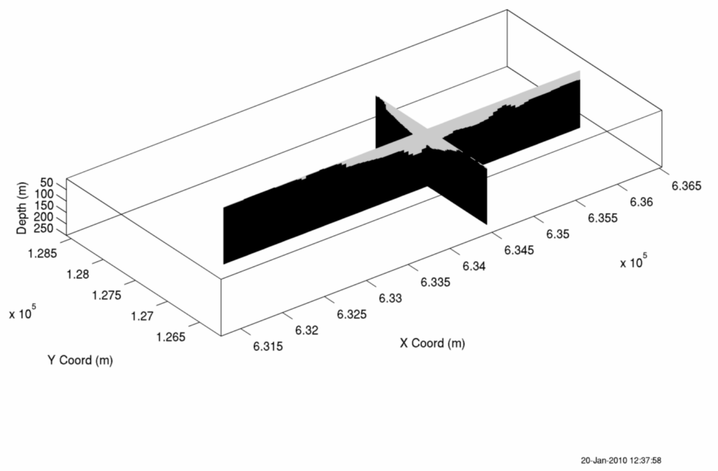
To generalize the velocity structure of the basin, then, a simplified piecewise gradient model based on the previous inversion results is defined.

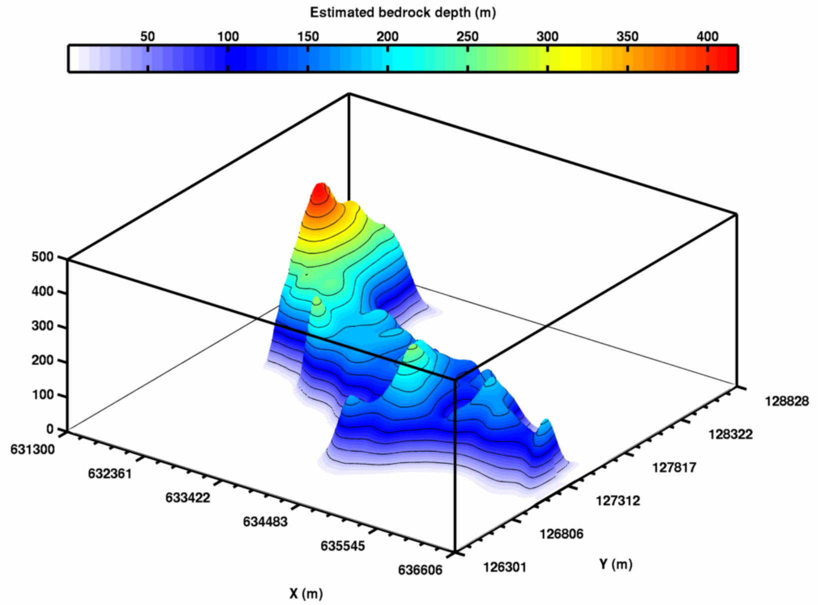




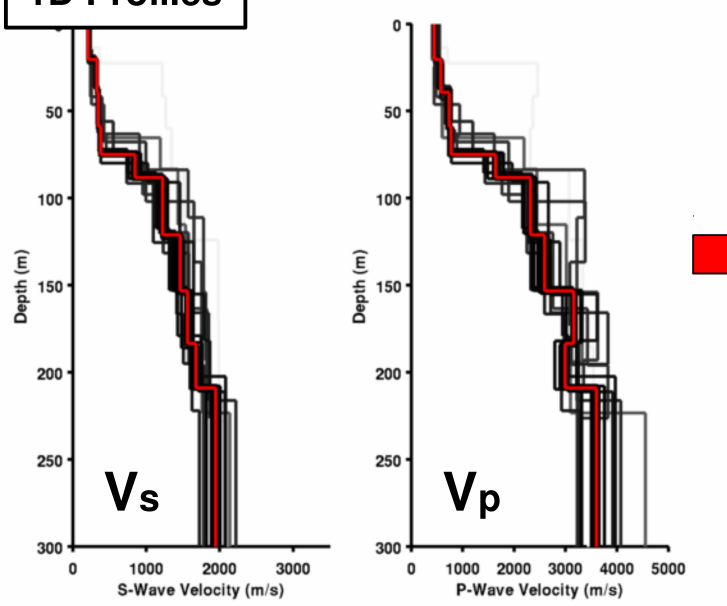
$$V(Z) = (V_{max} - V_{min})\left[1 - a^{\left(\frac{Z_{top} - Z}{b}\right)}\right] + V_{min}$$

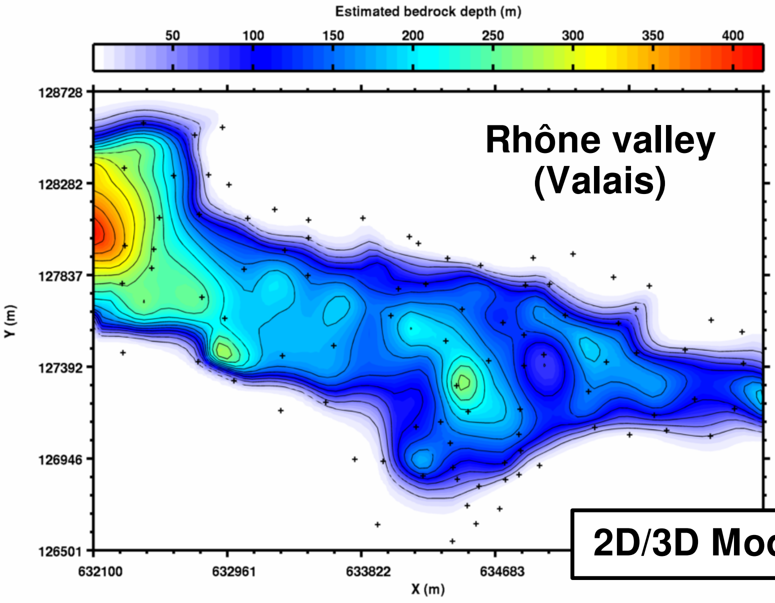
3D velocity model





1D Profiles





Rhône valley (Valais)

2D/3D Models

Mapping the SH-wave amplification

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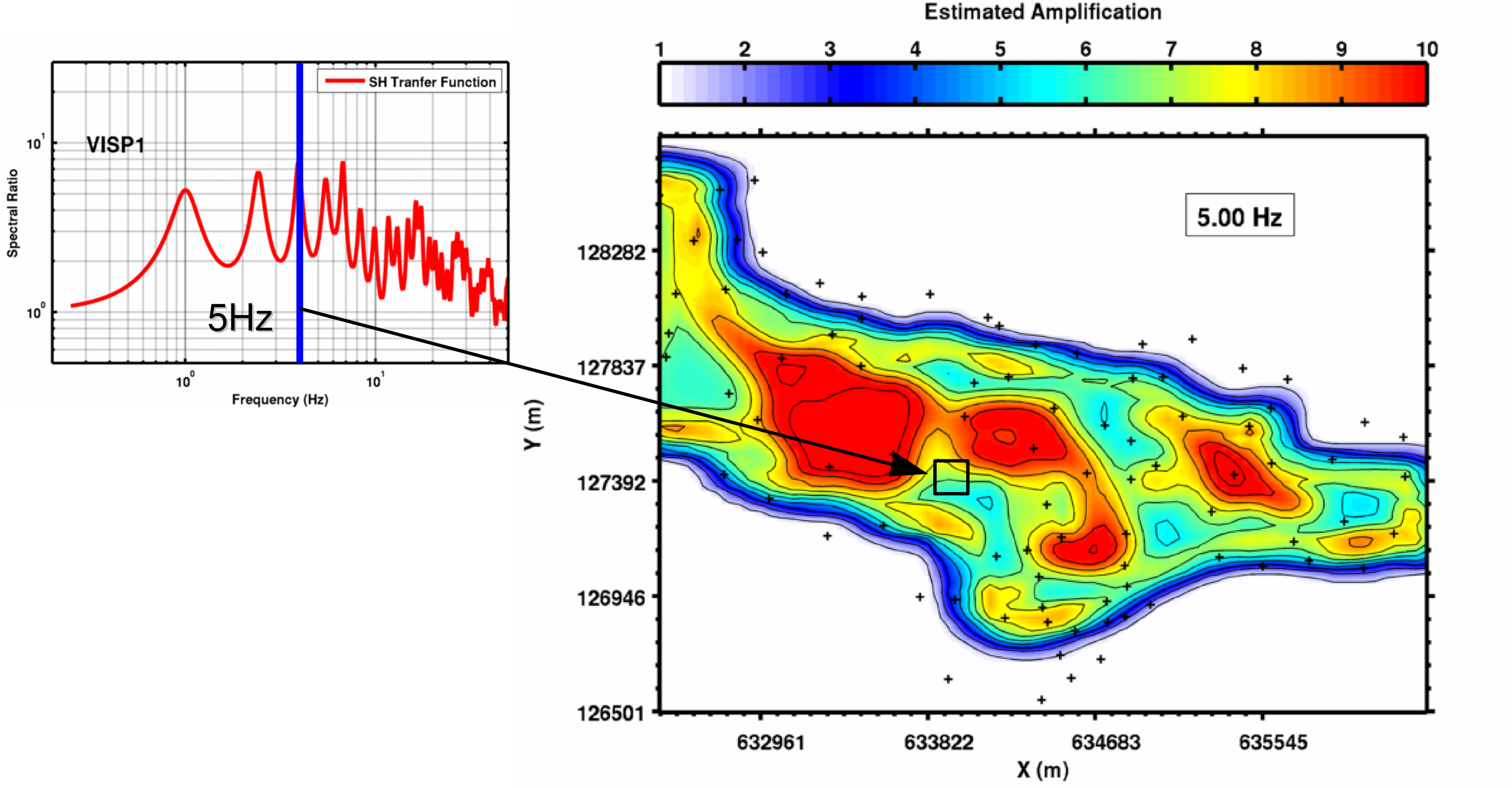

Summary comparison of amplification functions from all methods