Surface-Wave Tomography

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Outline

- Properties of surface waves
- Examples of surface-wave tomography:
  - different scales
  - central Europe, Mediterranean, Alpine region
- Conclusions

Surface waves

seismogram

Green‘s function

source

$$\mathbf{u}(\mathbf{r},\omega) = \mathbf{G}(\mathbf{r},\mathbf{r}_s,\omega)\cdot\mathbf{f}(\omega)$$

single force (e.g. hammer blow, ambient noise)

$$\mathbf{u}(\mathbf{r},\omega) = \nabla_s\mathbf{G}(\mathbf{r},\mathbf{r}_s,\omega) : \mathbf{M}(\omega)$$

moment tensor (e.g. earthquake)

frequency domain:

- $\mathbf{u}(\mathbf{r},\omega)$: seismogram at location $\mathbf{r}$
- $\mathbf{f}(\omega)$: time dependent single force
- $\mathbf{M}(\omega)$: time dependent moment tensor
- $\mathbf{G}(\mathbf{r},\mathbf{r}_s,\omega)$: Green's function (transfer function from source location $\mathbf{r}_s$ to location $\mathbf{r}$)

Options for calculation of the Green‘s function

- body waves
- surface waves
- normal modes
- numercial solution of equation of motion

Surface waves

Surface waves result from a factorization ansatz for the solution of the equation of motion**:** separation in an amplitude-depth functions and a propagation factor. Amplitudes of surface wave are decaying with depth. Surface waves propagate along the tension free surface.

In case of limited lateral heterogeneity the Green's function may be expressed as:

propagation factor

Green's function (wavefield)

$$\mathbf{G}(\mathbf{r}, \mathbf{r}_s, \omega) = \sum_{modes} \mathbf{A}_m(z, \omega) P_m(\Delta, \omega)$$

depth dependence

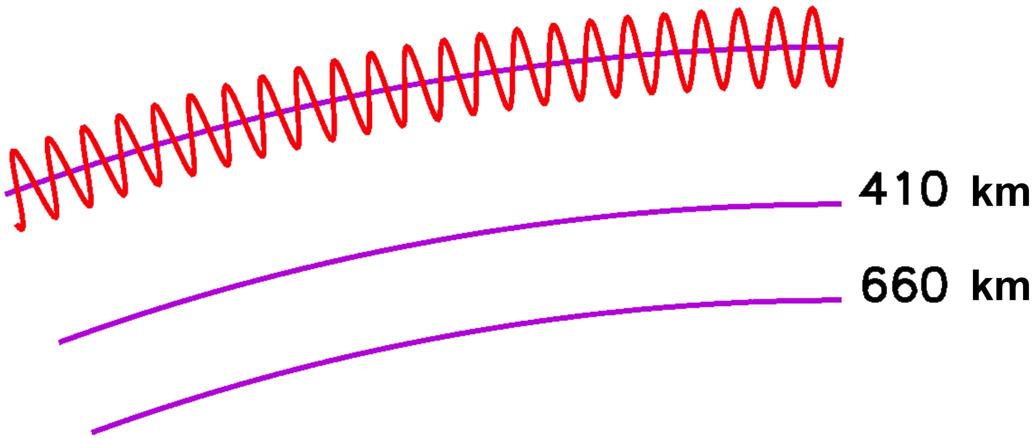
$\mathbf{A}_m(z, \omega)$: amplitude-depth function (eigenfunction) mode m

$P_m(x, \omega)$: propagation factor mode m

Δ: epicentral distance

There are different ansatzes for body waves and normal modes.

Rayleigh fundamental mode: wavelength and amplitude-depth function



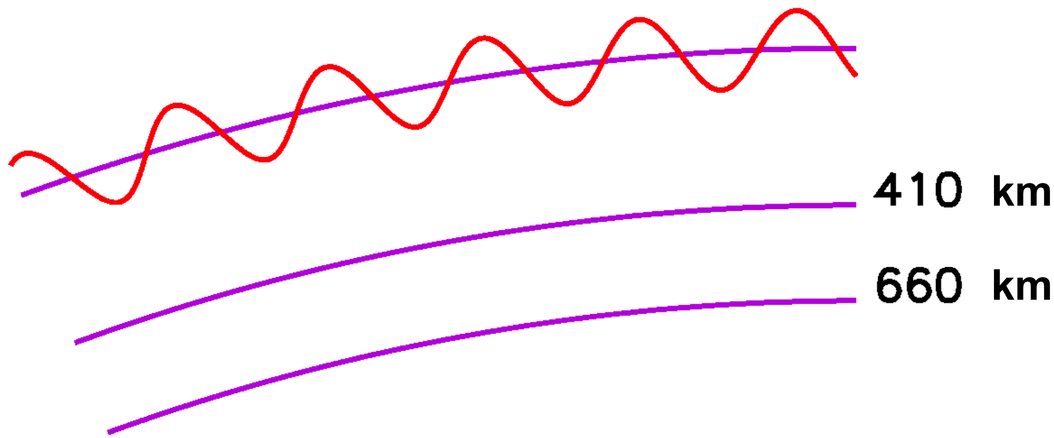
period: 25 s
wavelength: 95 km

amplitude-depth function

vertical displacement (solid)
horizontal displacement (dotted)

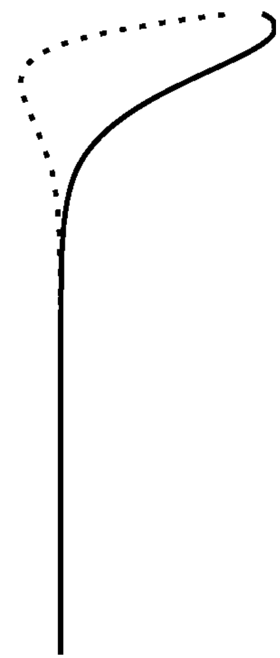
Surface waves

Rayleigh fundamental mode: wavelength and amplitude-depth function



period: 100 s
wavelength: 406 km

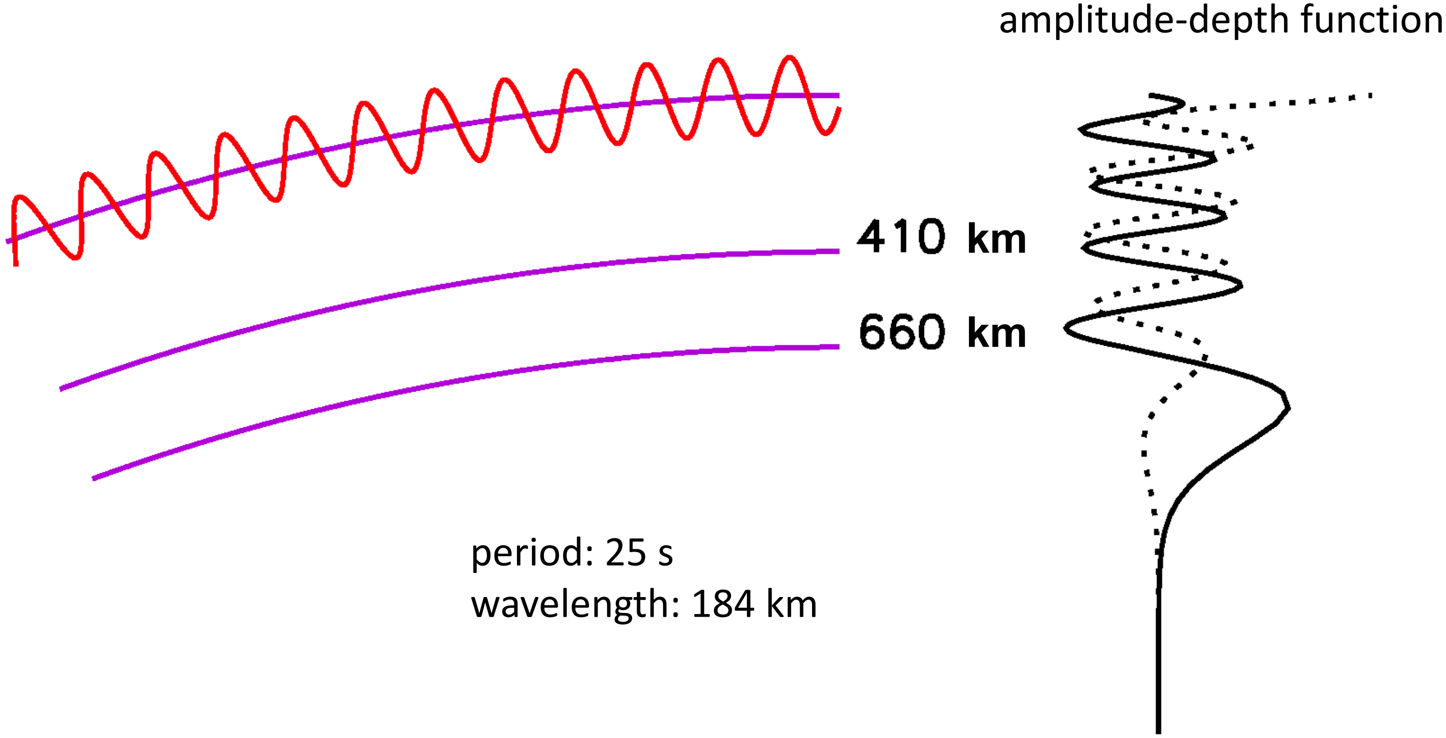
amplitude-depth function



vertical displacement (solid)
horizontal displacement (dotted)

Surface waves

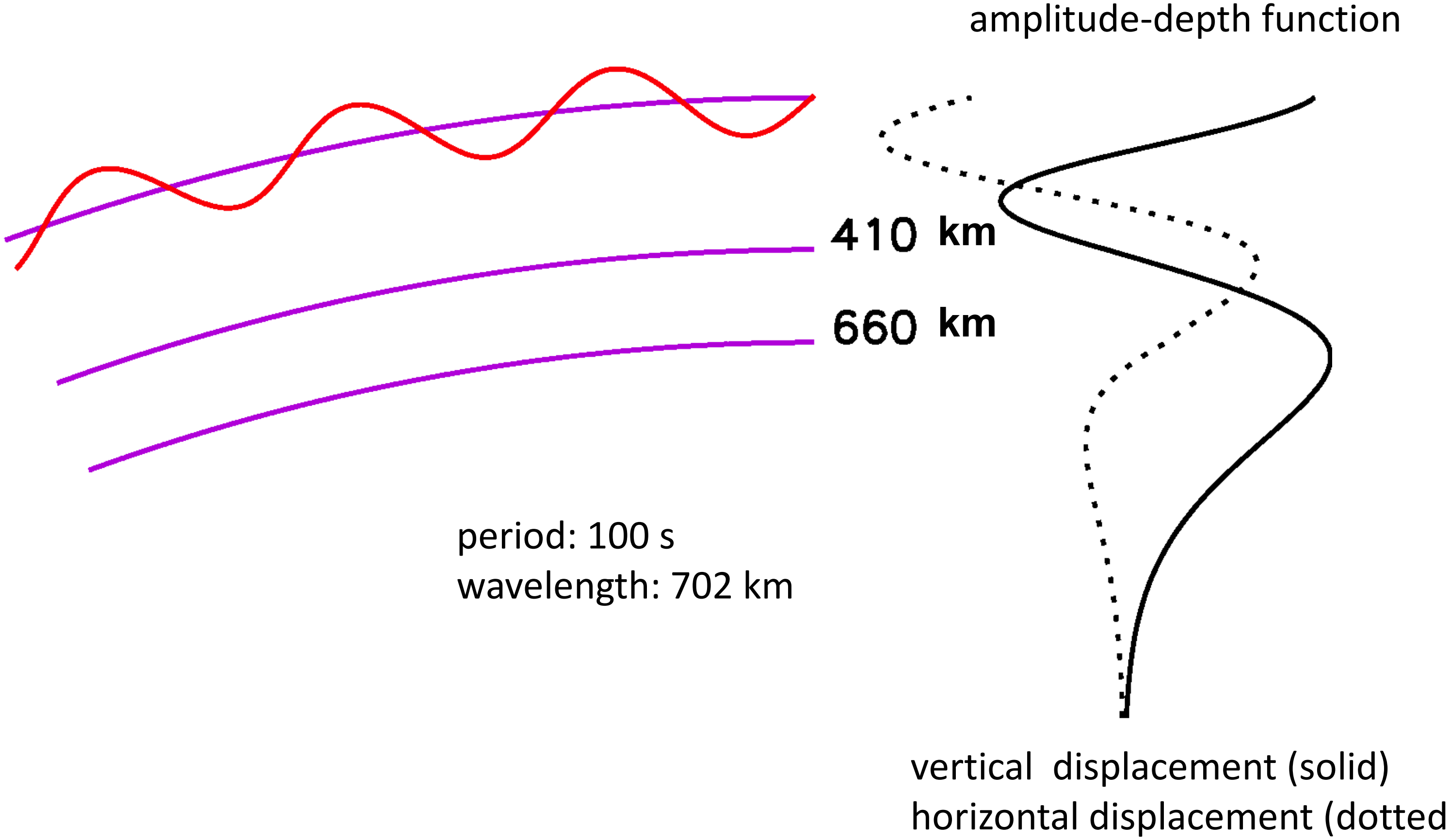
Rayleigh (9. higher mode): wavelength and amplitude-depth function



period: 25 s
wavelength: 184 km

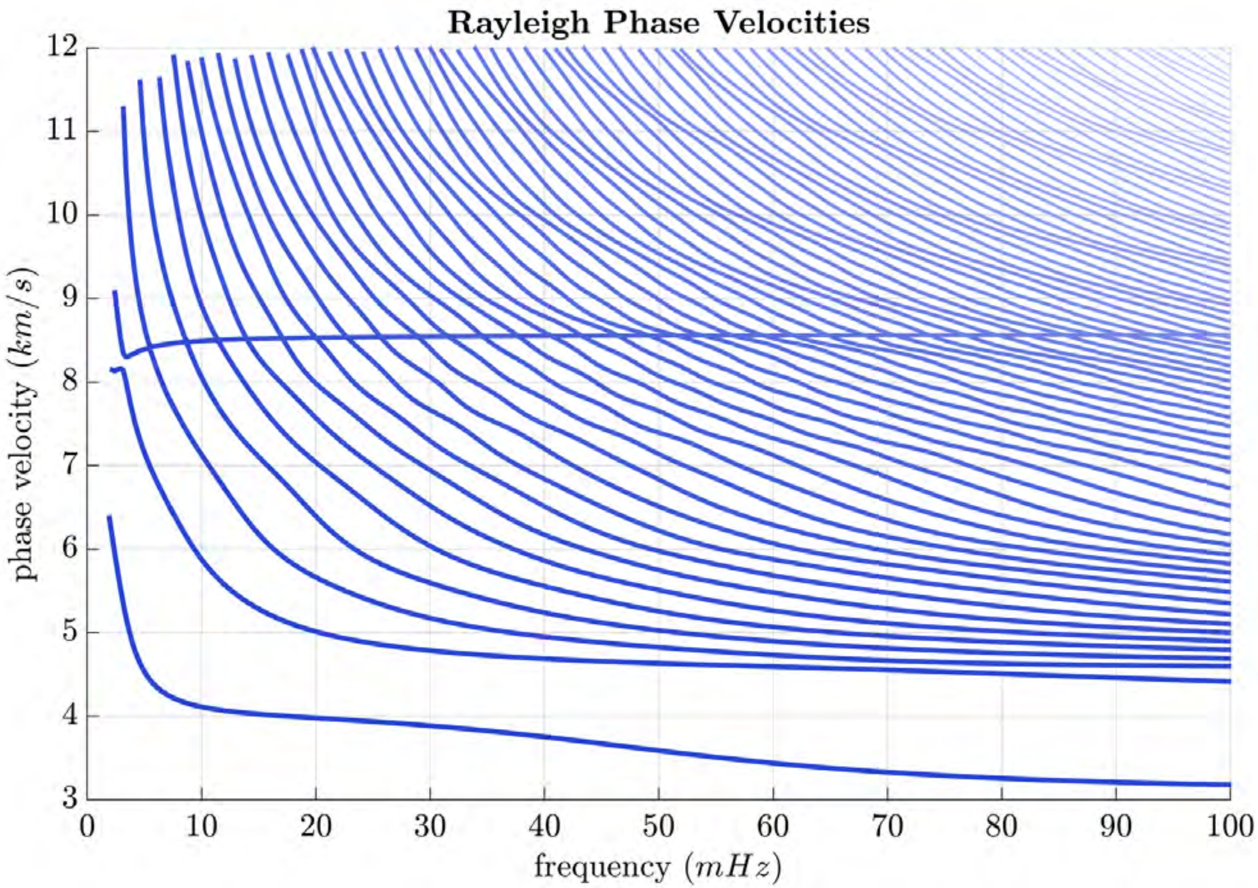
vertical displacement (solid)
horizontal displacement (dotted)

Rayleigh (2. higher mode): wavelength and amplitude-depth function



Surface waves

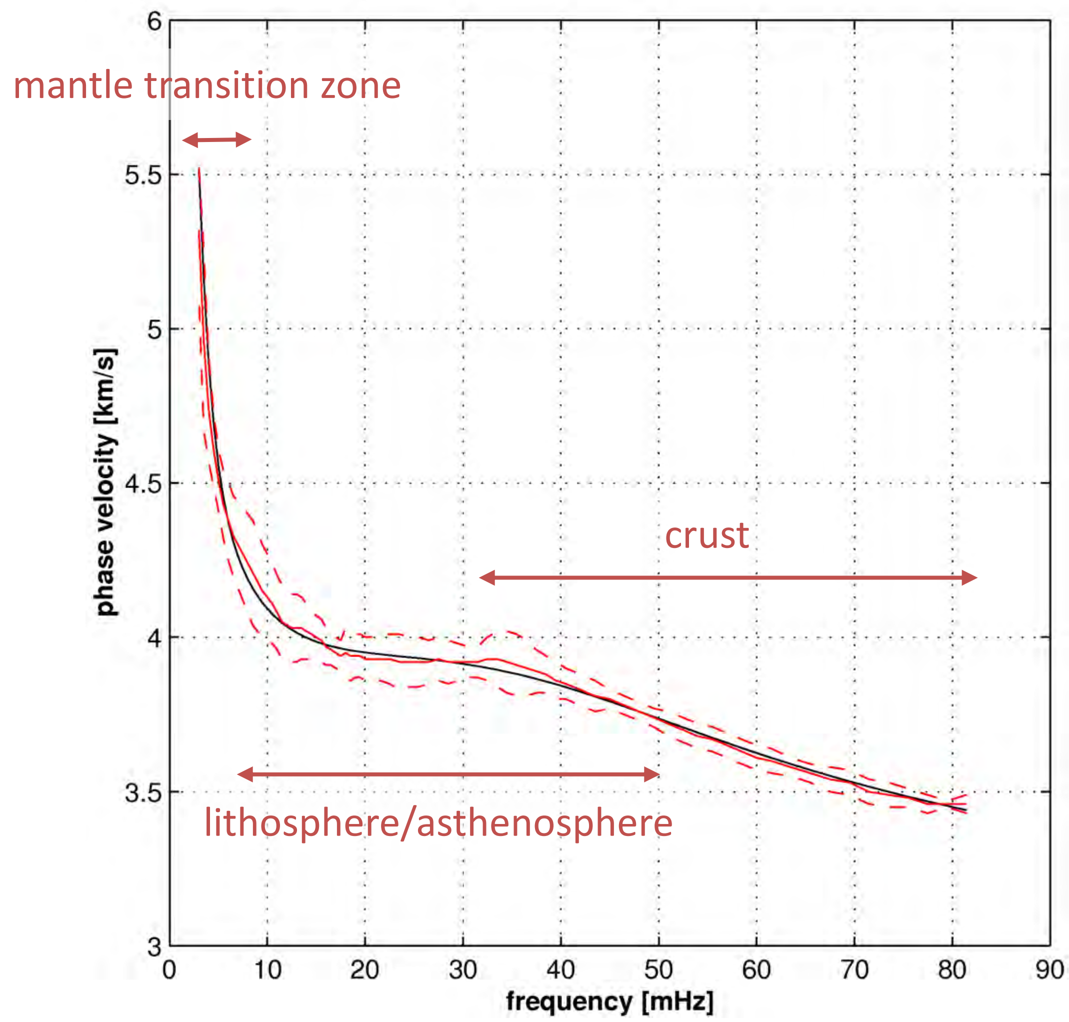
Rayleigh wave phase velocities (ca. 50 modes):
determines phase delay in the frequency domain



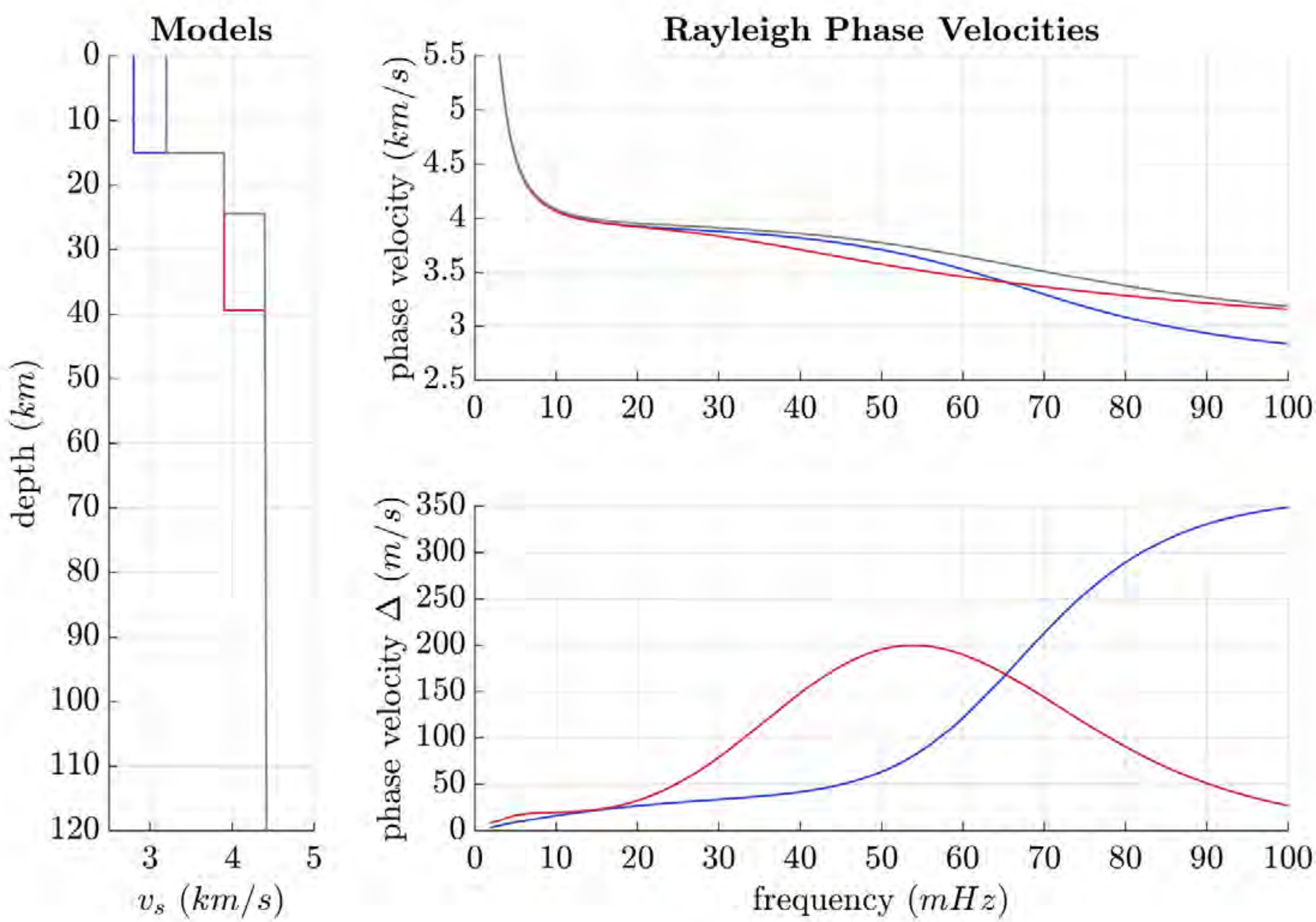
fundamental mode

M. Tesch

Rayleigh wave fundamental mode: sensitivity to Earth structure



Rayleigh wave fundamental mode: sensitivity to sediments and Moho depth



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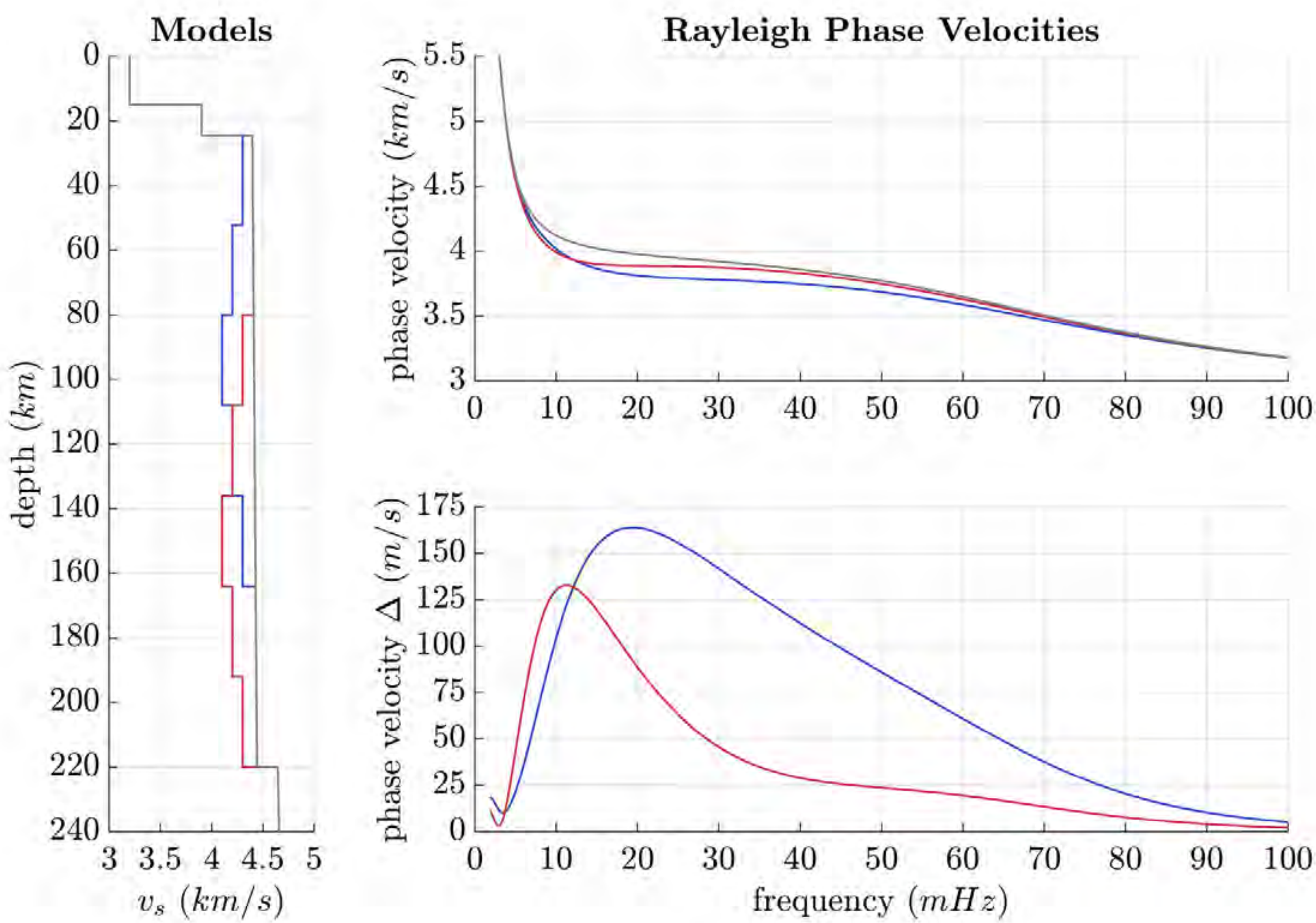
Rayleigh wave fundamental mode: sensitivity to mantle lithosphere and asthenosphere



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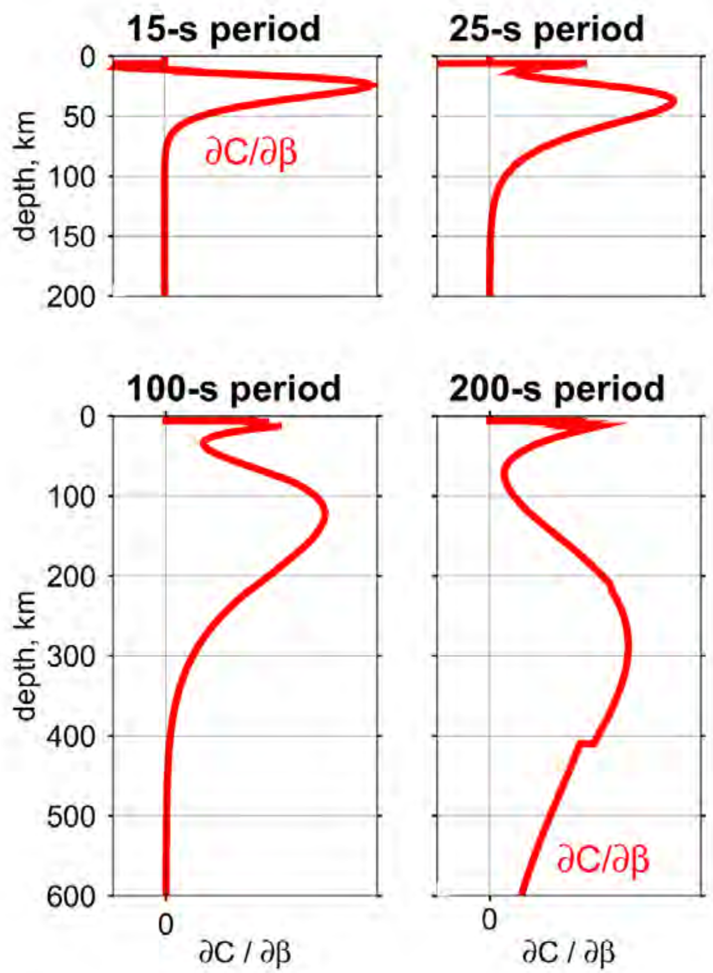
Rayleigh wave fundamental mode: sensitivity to Earth structure

lower crust
(15 km – 35 km)

mantle lithosphere
(25 km – 60 km)



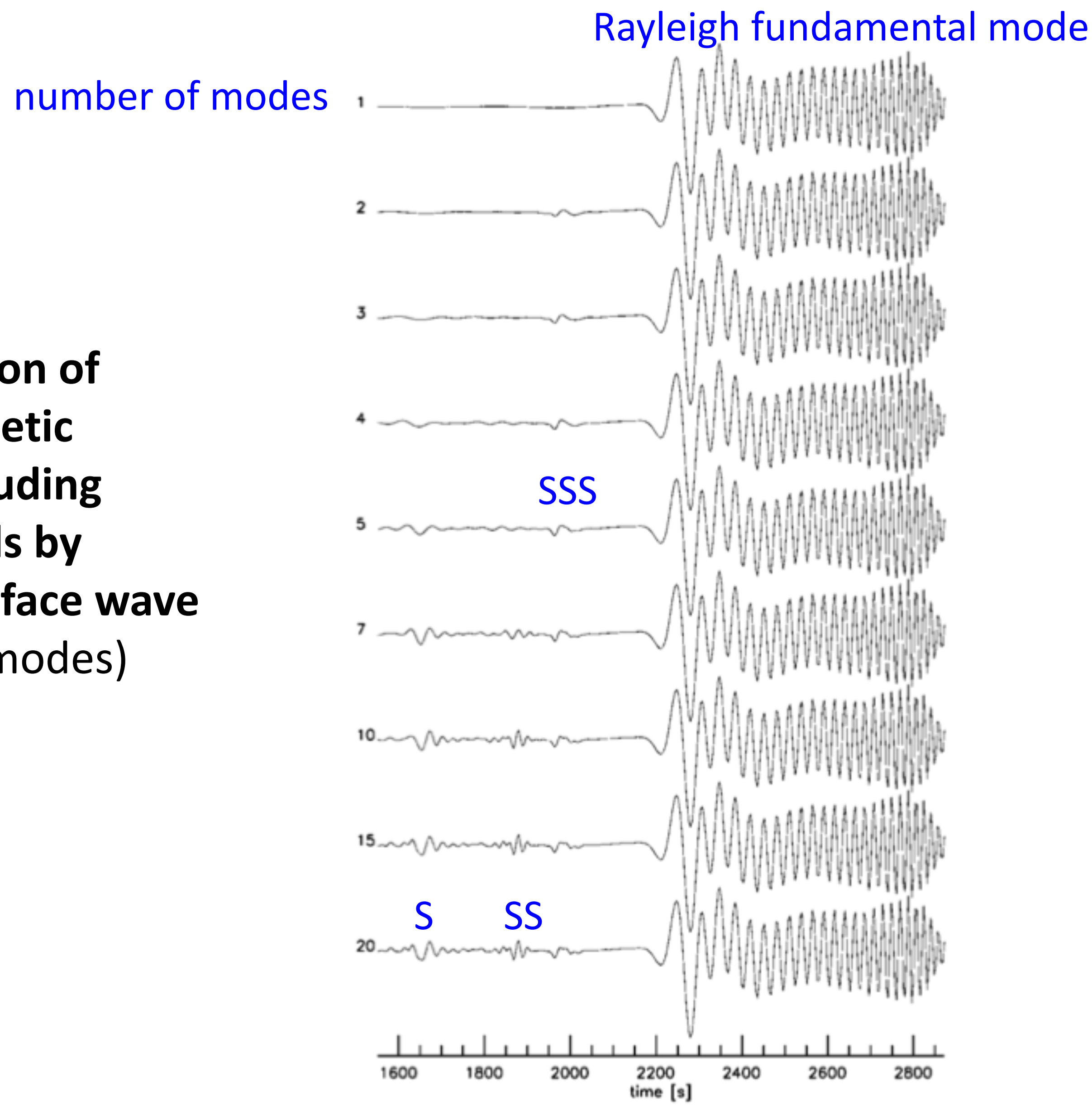
lithosphere-
asthenophere
boundary (LAB)
(80 km – 200 km)

asthenosphere
(150 km – 400 km)

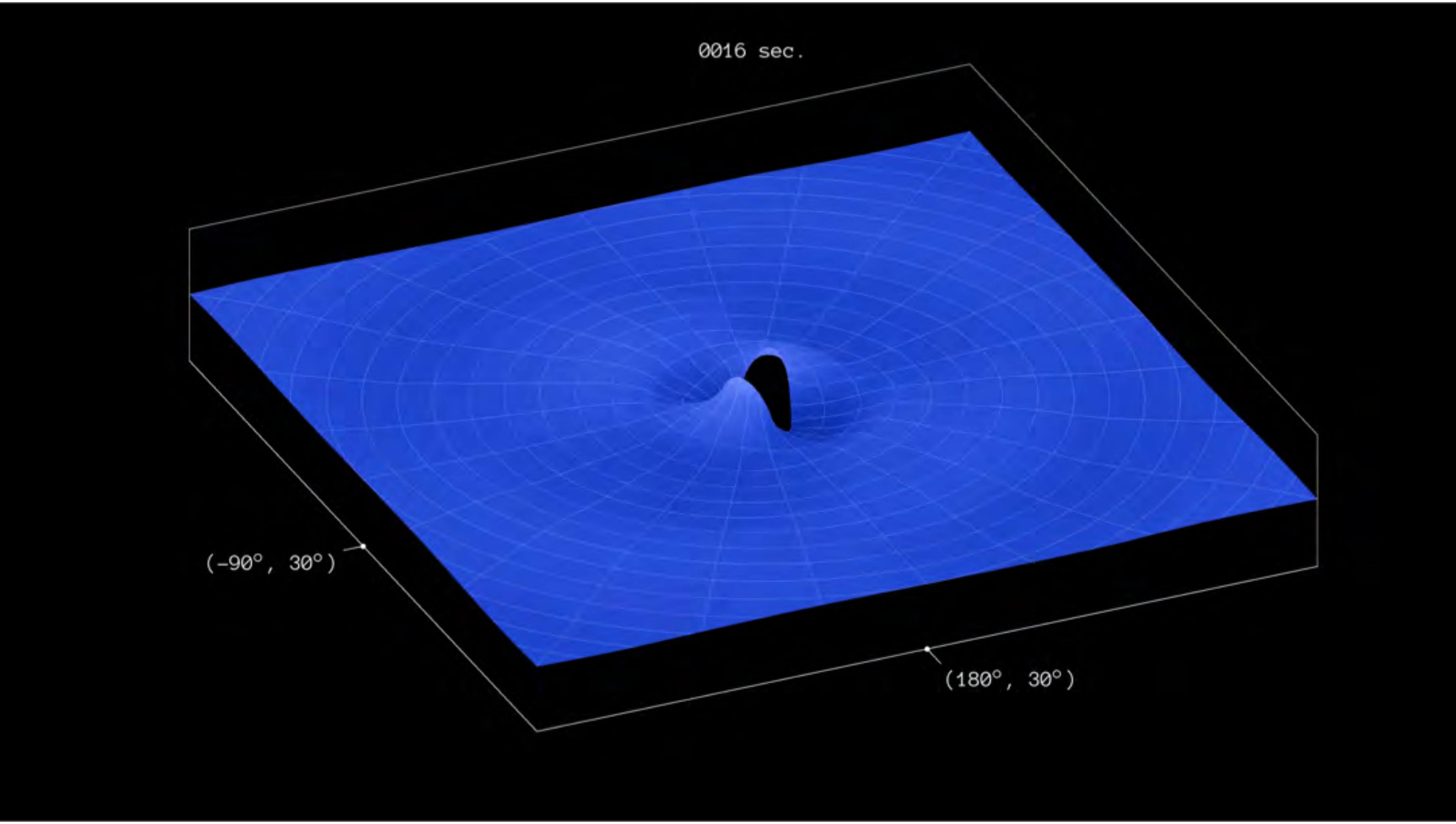
S. Lebedev

Surface waves

Effecitve calculation of long-period synthetic seismograms including body wave arrivals by summation of surface wave modes (up to 20 modes)



Central Italy — 18 January 2017



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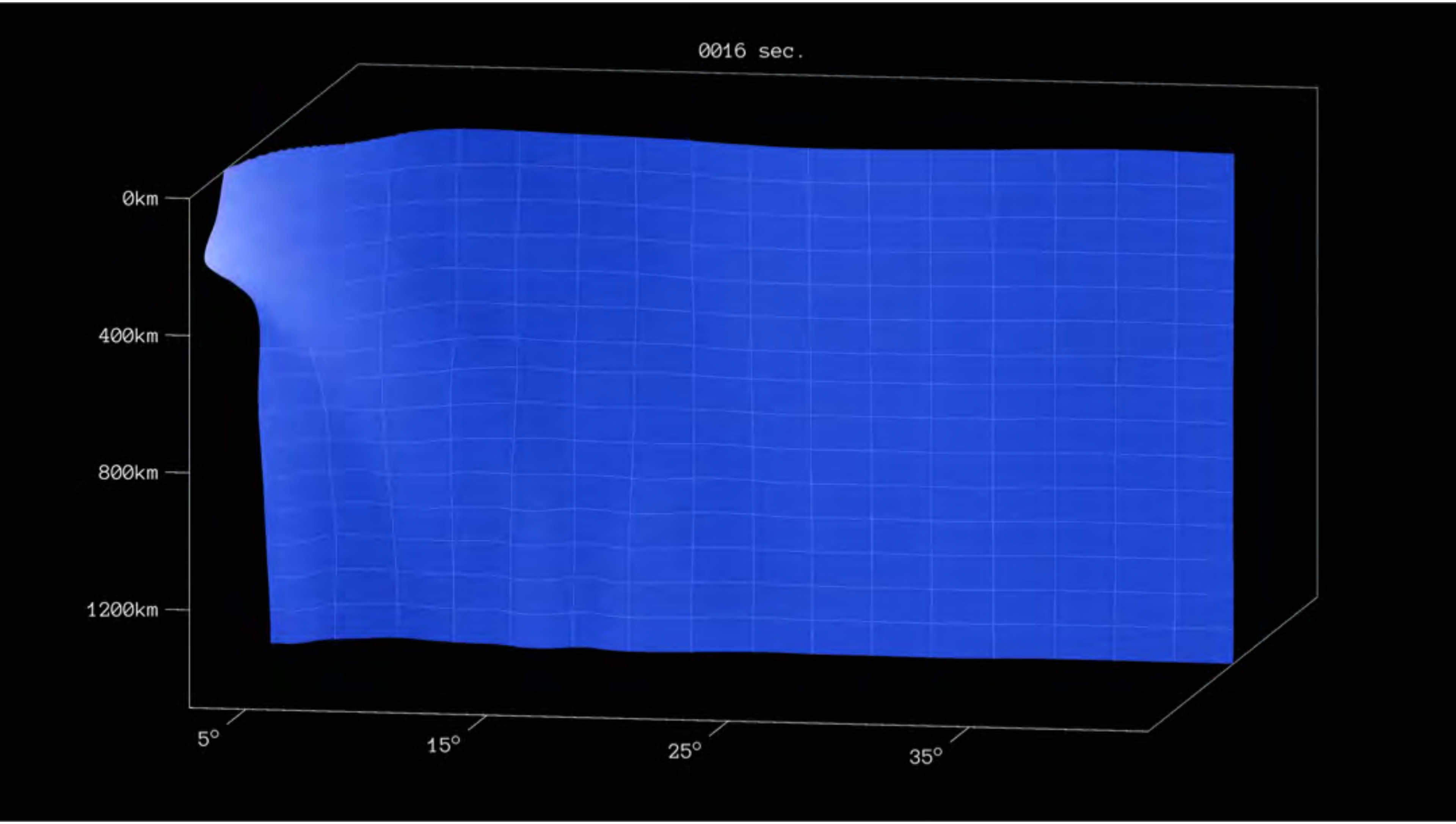
Central Italy — 18 January 2017



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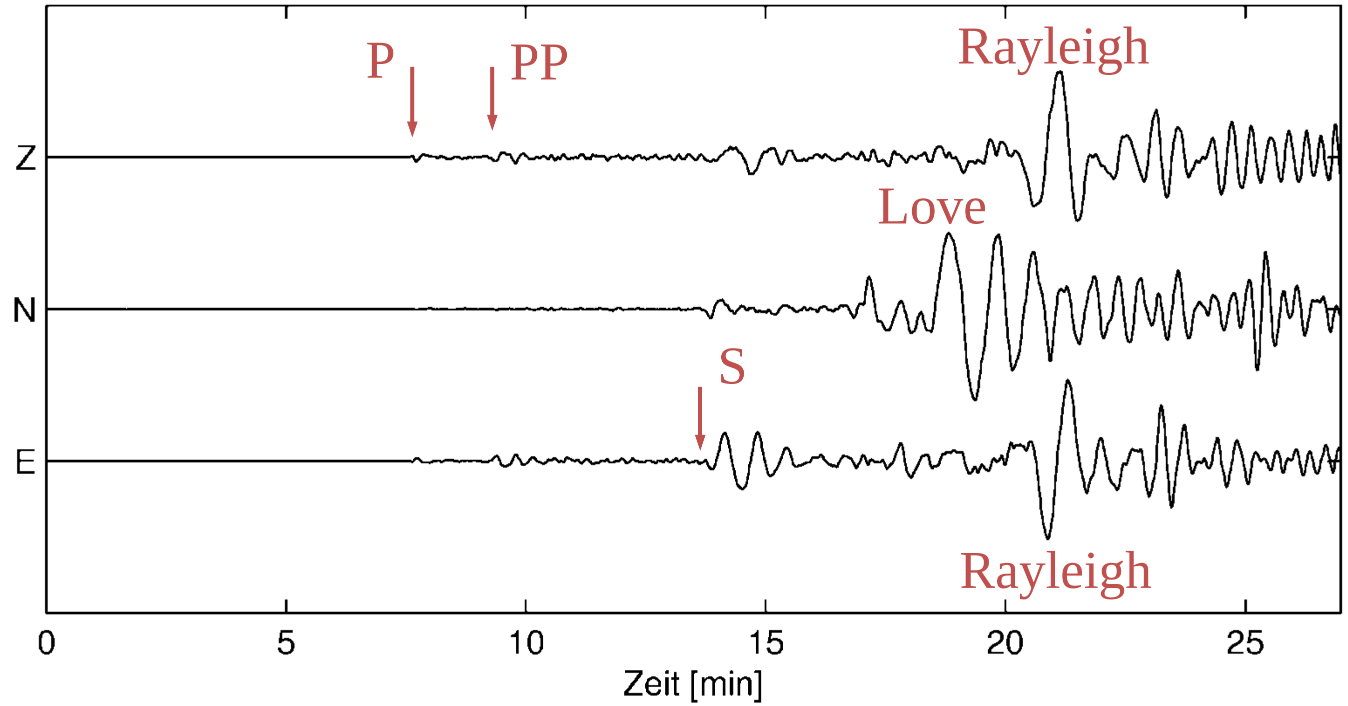
Surface waves

Waveform example: Iran 26.12.2005, magnitude 6.4, station BFO



Surface waves

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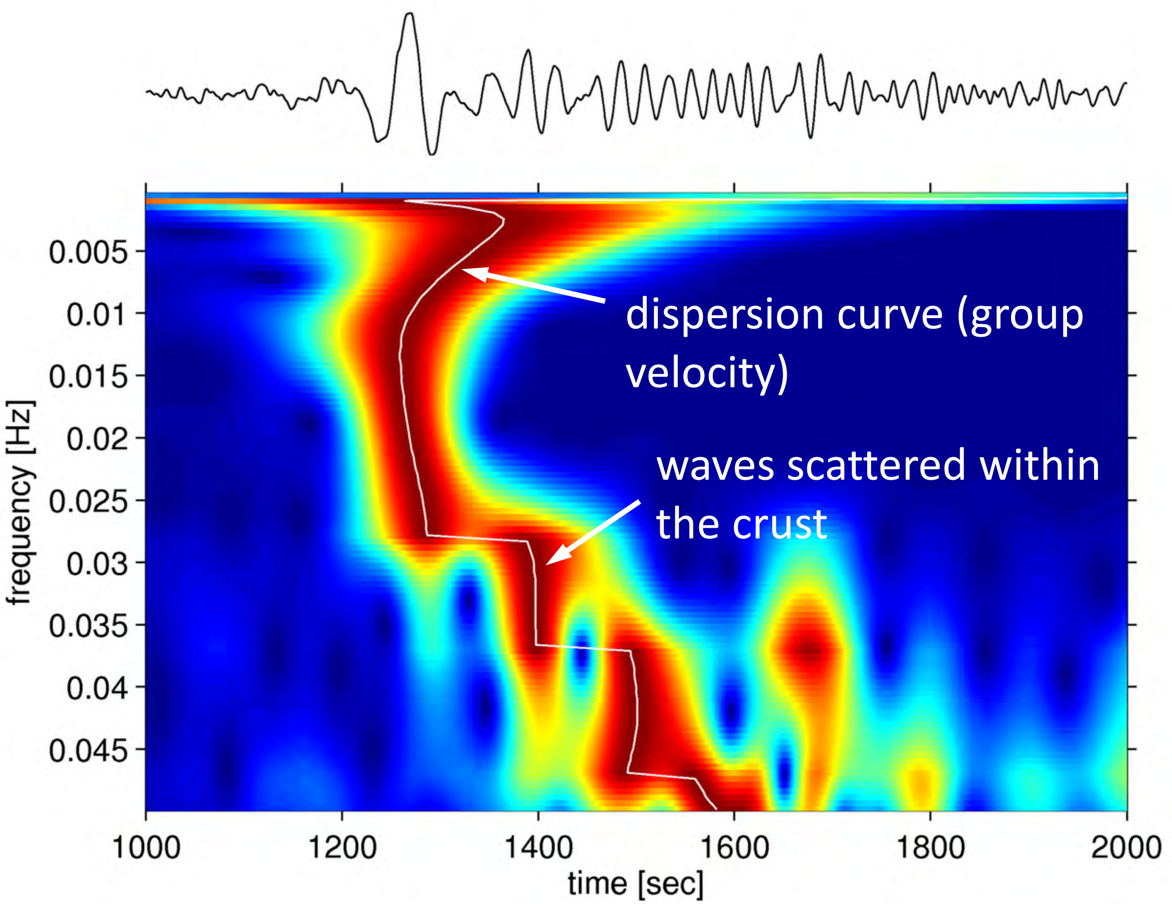
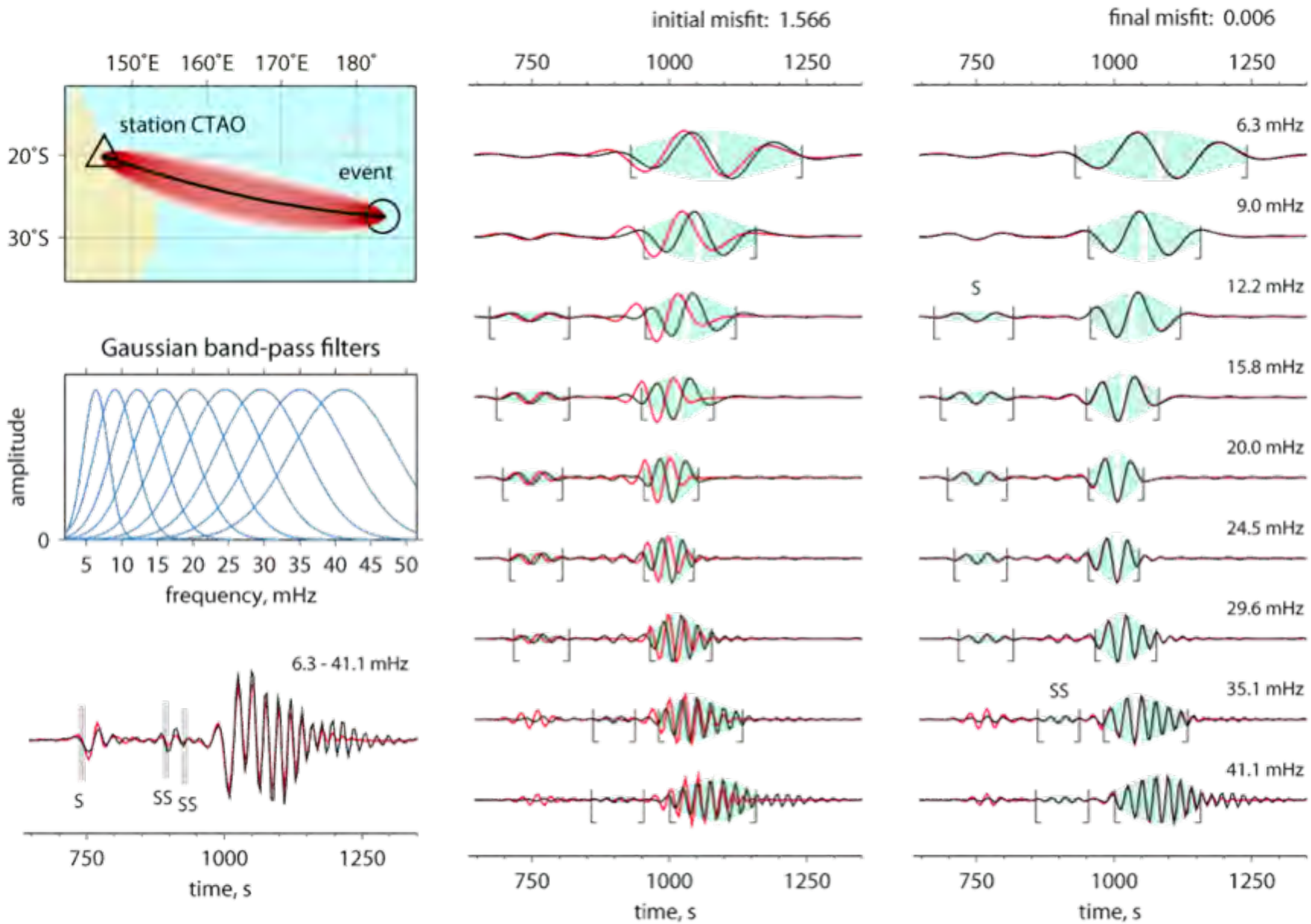


Surface waves

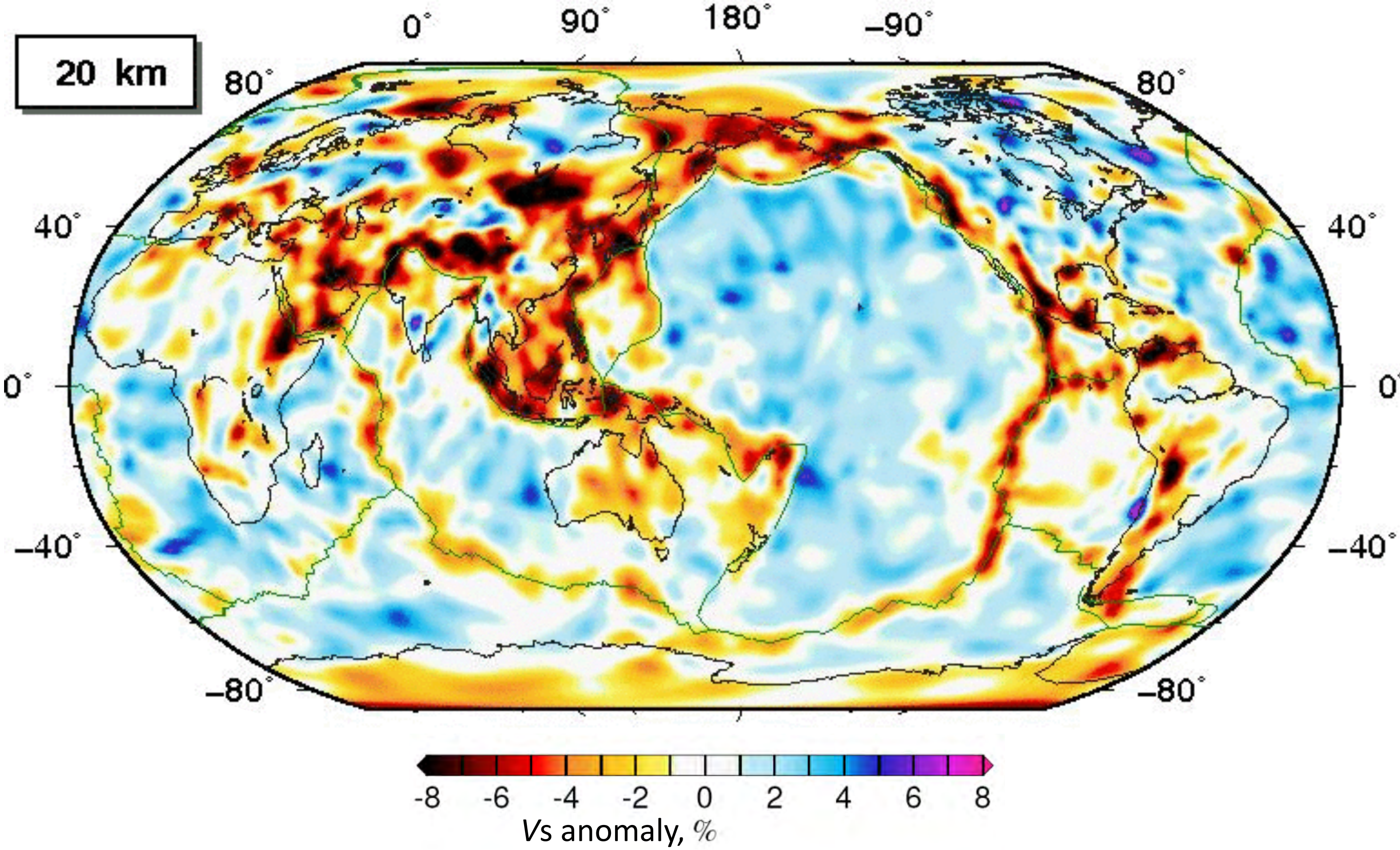
- Rayleigh and Love wave modes (fundamental modes + higher modes)
- fundamental modes: large amplitudes for shallow sources
- surface wave velocities are frequency dependent (dispersive) and are strongly sensitive to the Earth‘s structure (mainly Vs, isotropic + anisotropic; short periods: crust, long periods: down to mantle transition zone)
- synthetic waveforms may be calculated by surface wave mode summation
- surface waves are radiated by active sources, pressure changes (ambient noise) and earthquakes

Surface-wave tomography: Automated Multimode Inversion



Lebedev, Meier, Nolet, van der Hilst (2005); Lebedev, van der Hilst (2008)

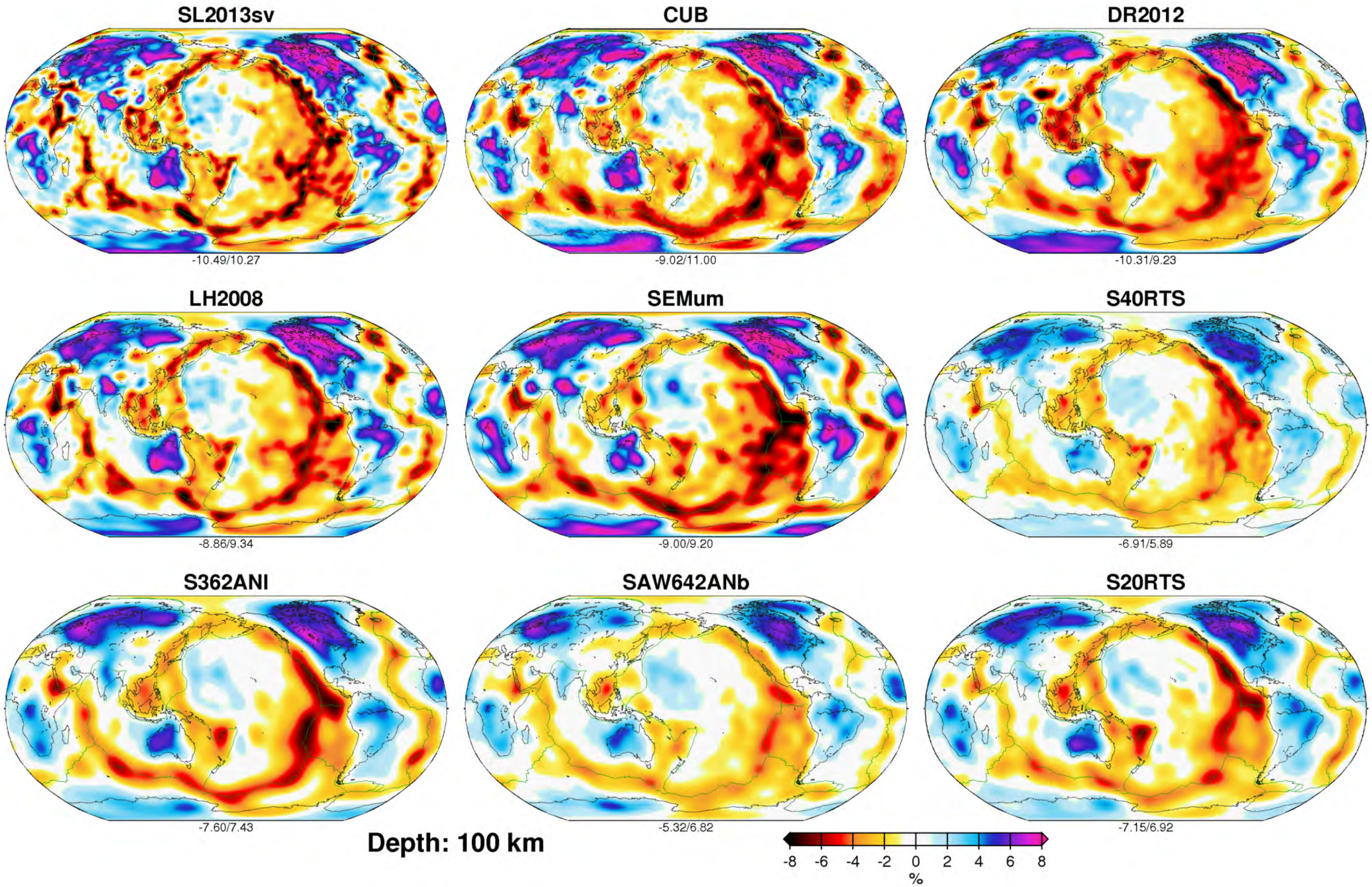
Surface-wave tomography: Automated Multimode Inversion



Schaeffer & Lebedev, 2013, 2015

global scale, lateral resolution ca. 400 km

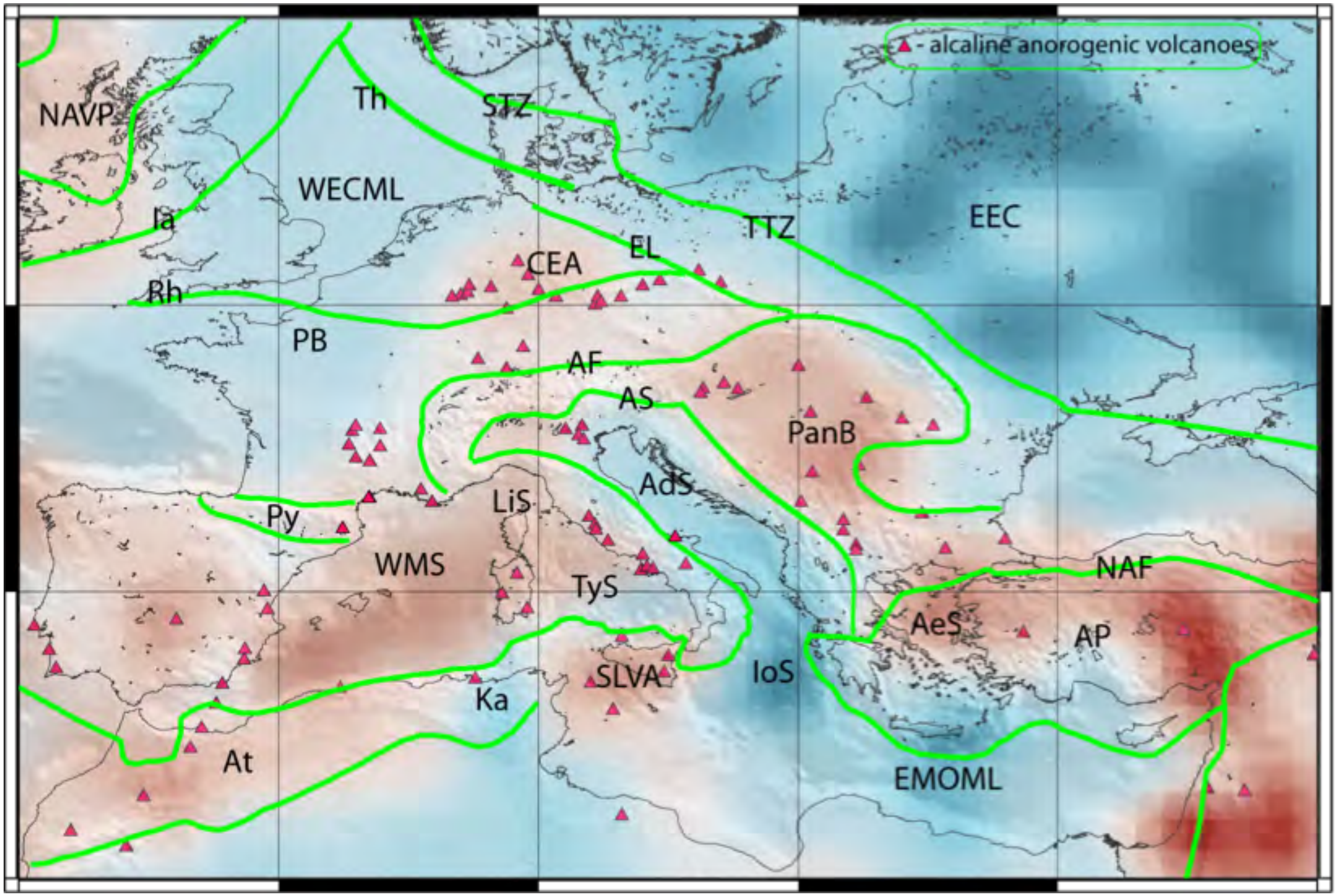
Surface-wave tomography: Automated Multimode Inversion



Schaeffer & Lebedev, 2013, 2015

Surface-wave tomography: Automated Multimode Inversion

Vs at 110 km depth + anorogenic Cenozoic volcanism

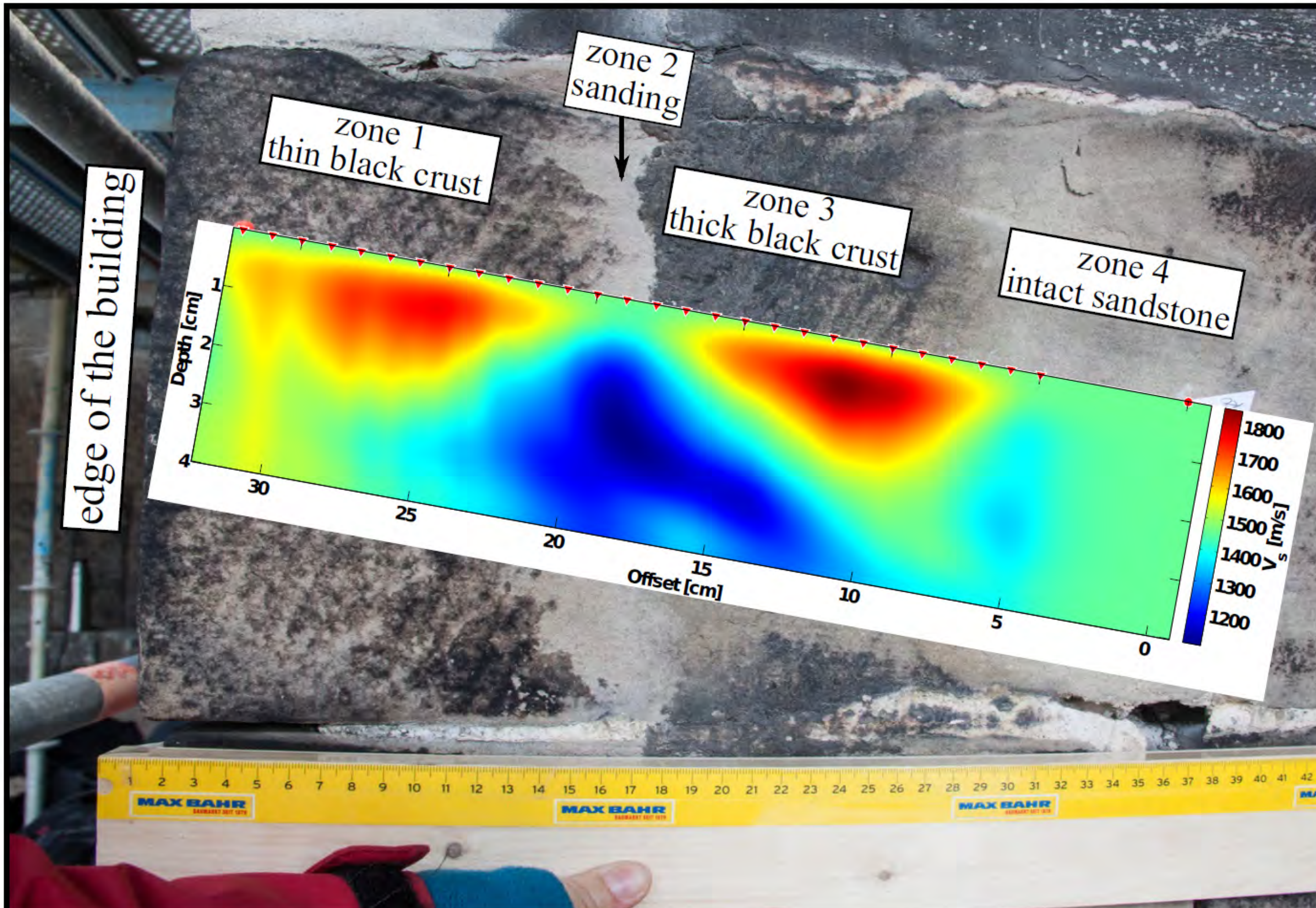


Legendre et al. (2012)

regional scale, lateral resolution ca. 200 km

Surface-wave tomography: ultrasonic measurements

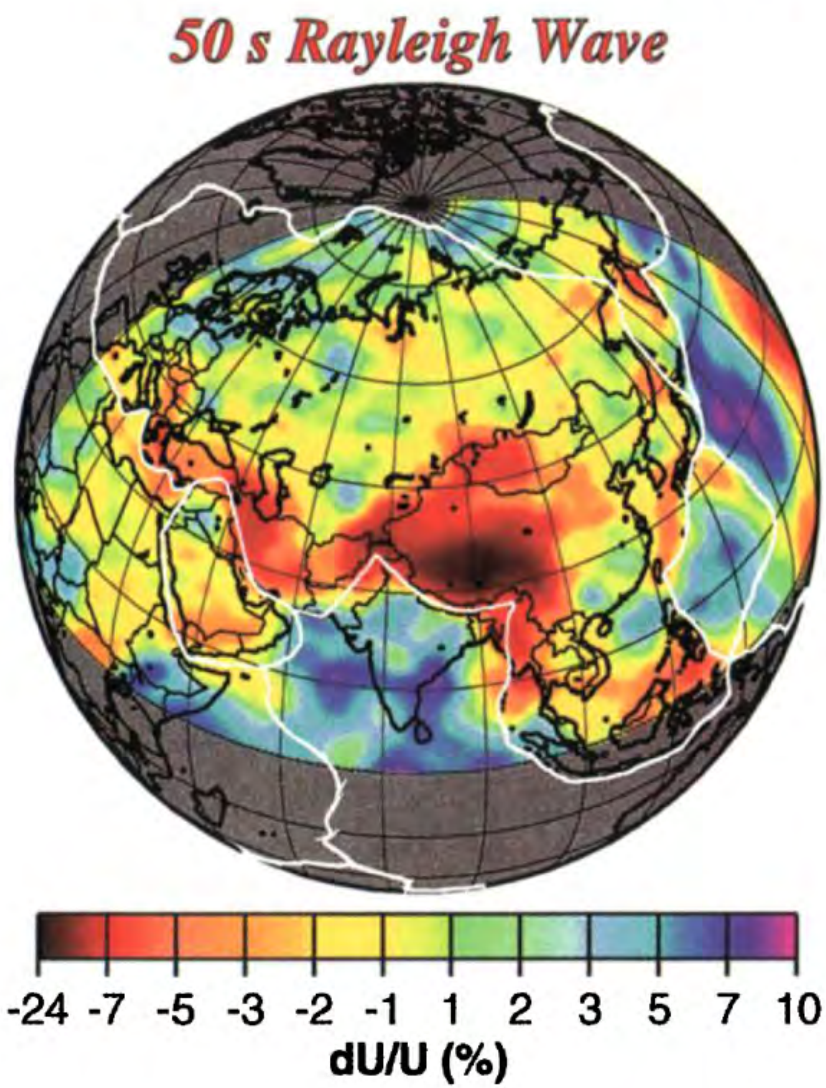
analysis of surficial alterations (Porta Nigra Trier, sandstone)



decimeter scale, lateral resolution ca. 4 cm

Köhn et al. (2016)

Surface-wave tomography: dispersion analysis fundamental mode

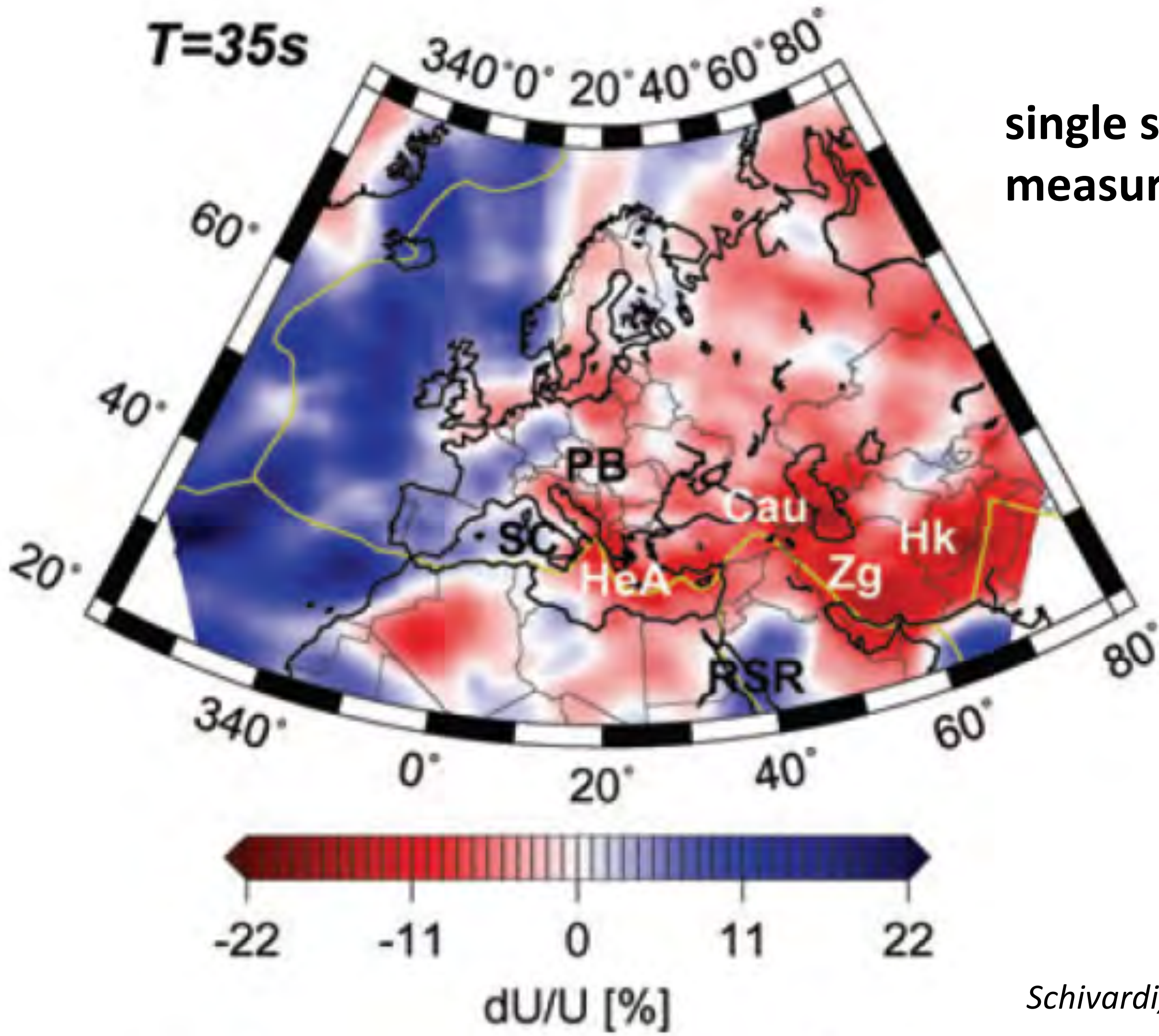


single station group velocity measurements (Eurasia)

Ritzwoller, Levshin (1998)

continental scale, lateral resolution ca. 500 km

Surface-wave tomography: dispersion analysis fundamental mode



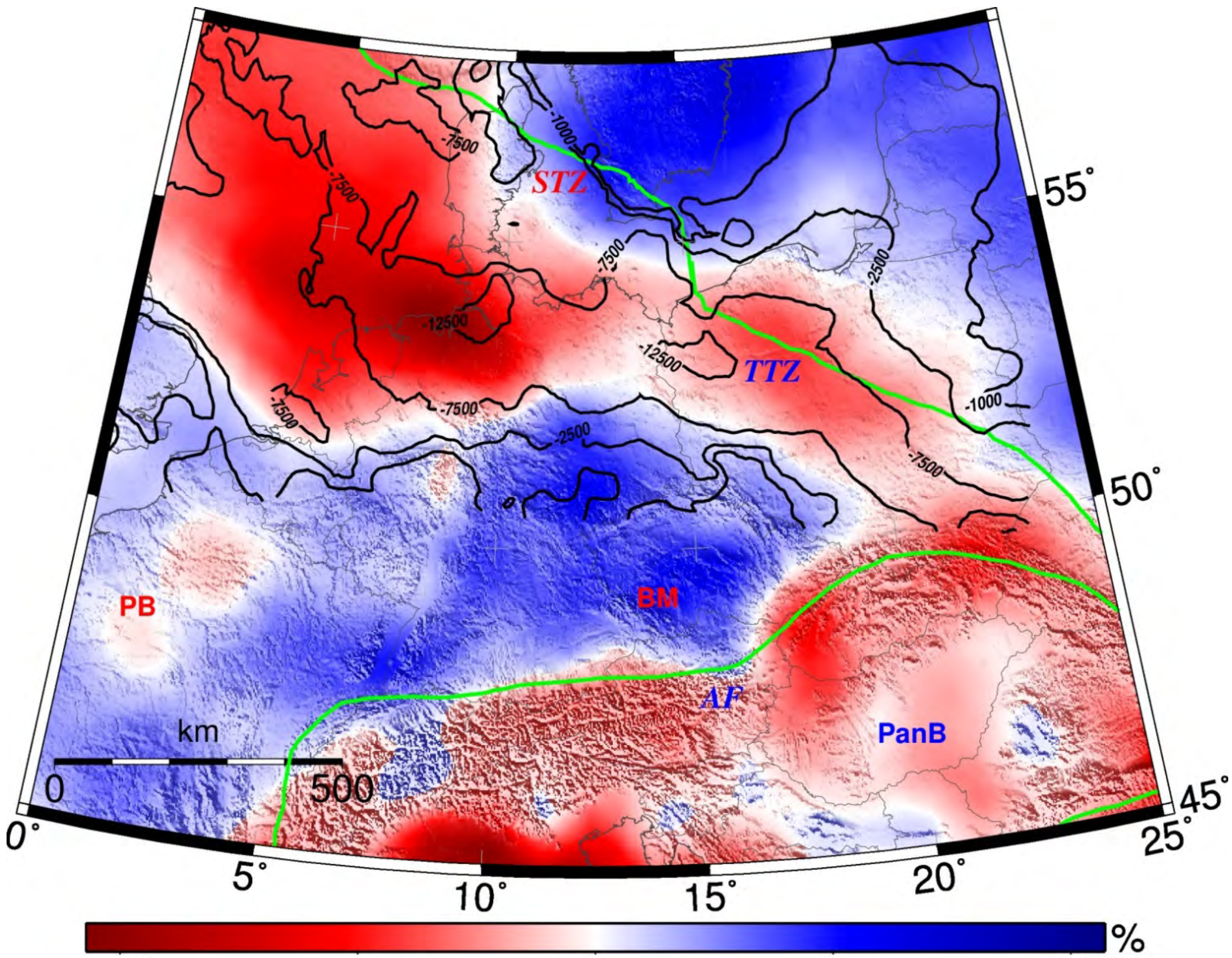
single station group velocity measurements (Europe)

Schivardi, Morelli (2009)

continental scale, lateral resolution ca. 500 km

Surface-wave tomography: dispersion analysis fundamental mode

phase velocity 12 s: upper to mid crustal structure (central Europe)

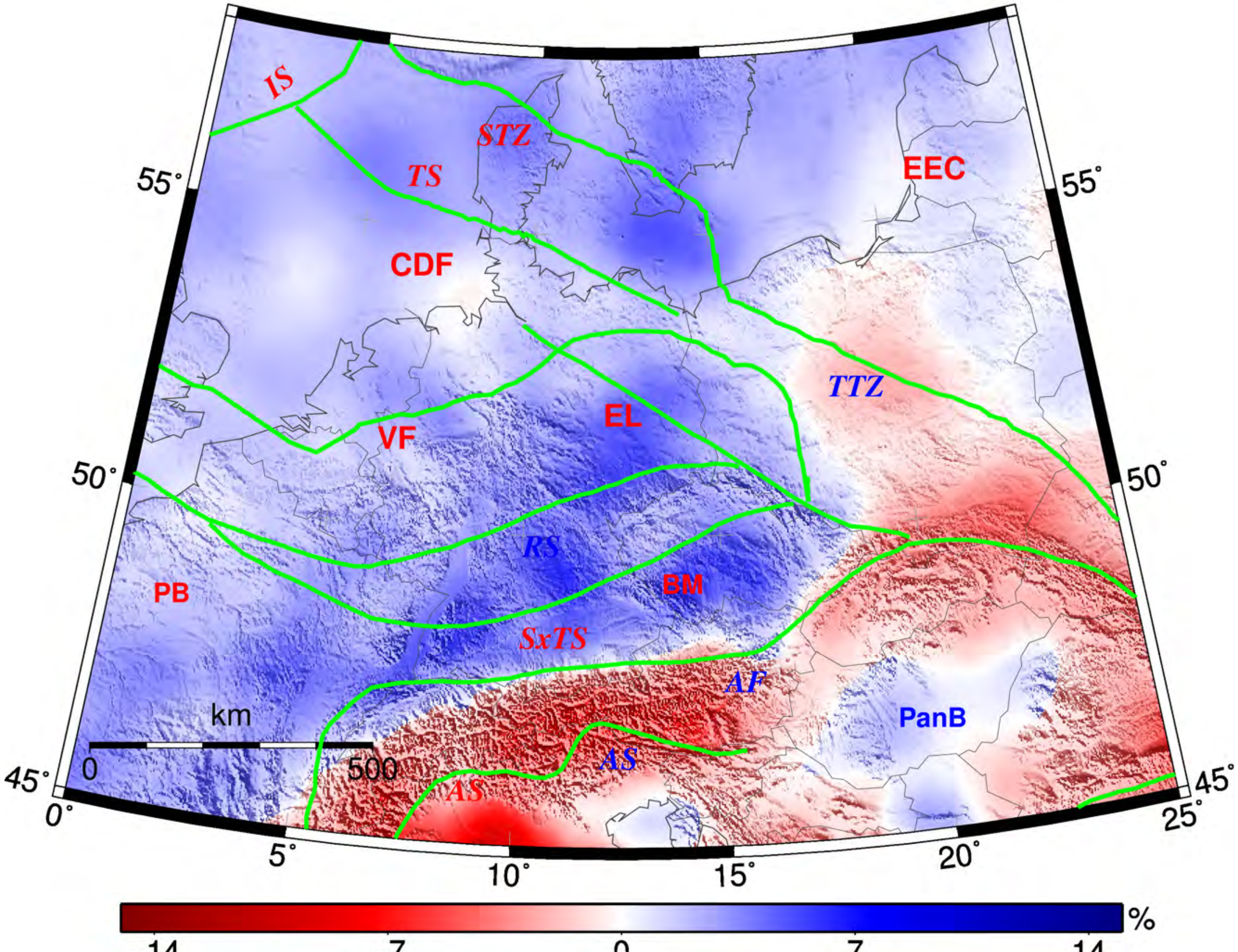


regional scale,
lateral resolution partly < 100 km

Scheck-Wenderoth and Lamarche (2005); Soomro et al. (2016); Meier et al. (2016)

Surface-wave tomography: dispersion analysis fundamental mode

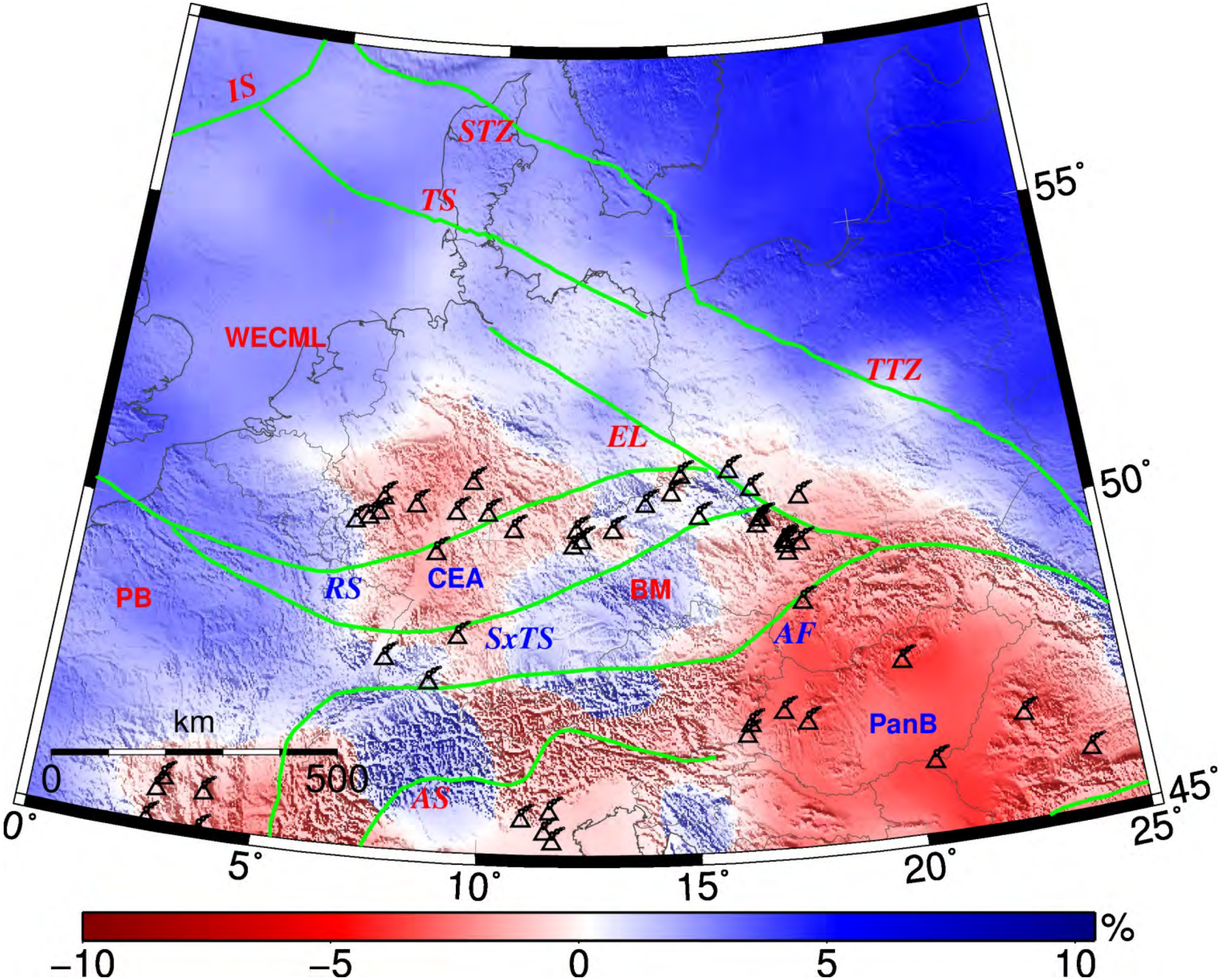
phase velocity 25 s: crustal roots + subMoho structure



Soomro et al. (2016); Meier et al. (2016)

Surface-wave tomography: dispersion analysis fundamental mode

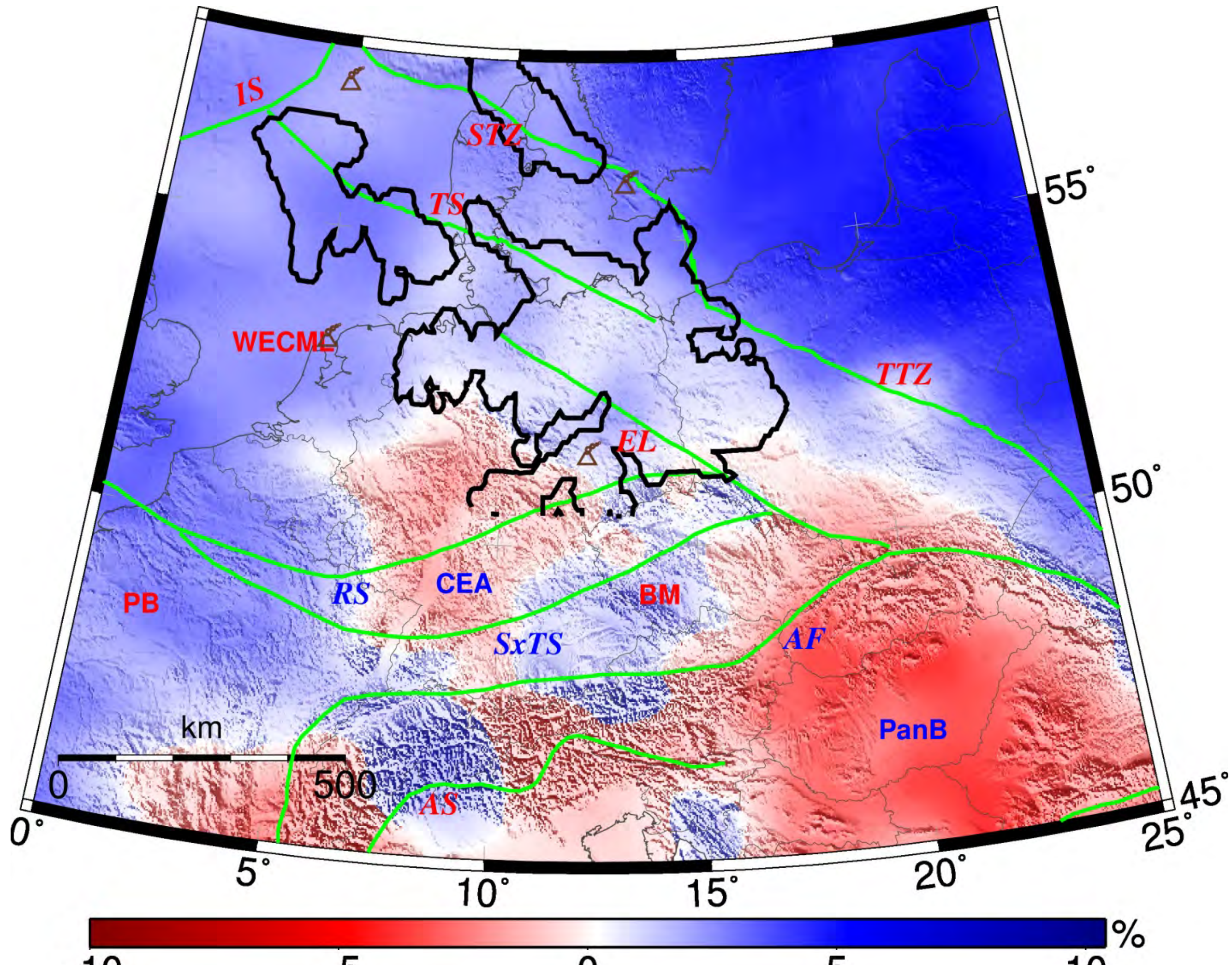
phase velocity 55 s: LAB topography + Cenozoic intraplate volcanism



Soomro et al. (2016), Meier et al. (2016)

Surface-wave tomography: dispersion analysis fundamental mode

phase velocity 55 s: LAB topography + Rotliegend volcanics (NGB)



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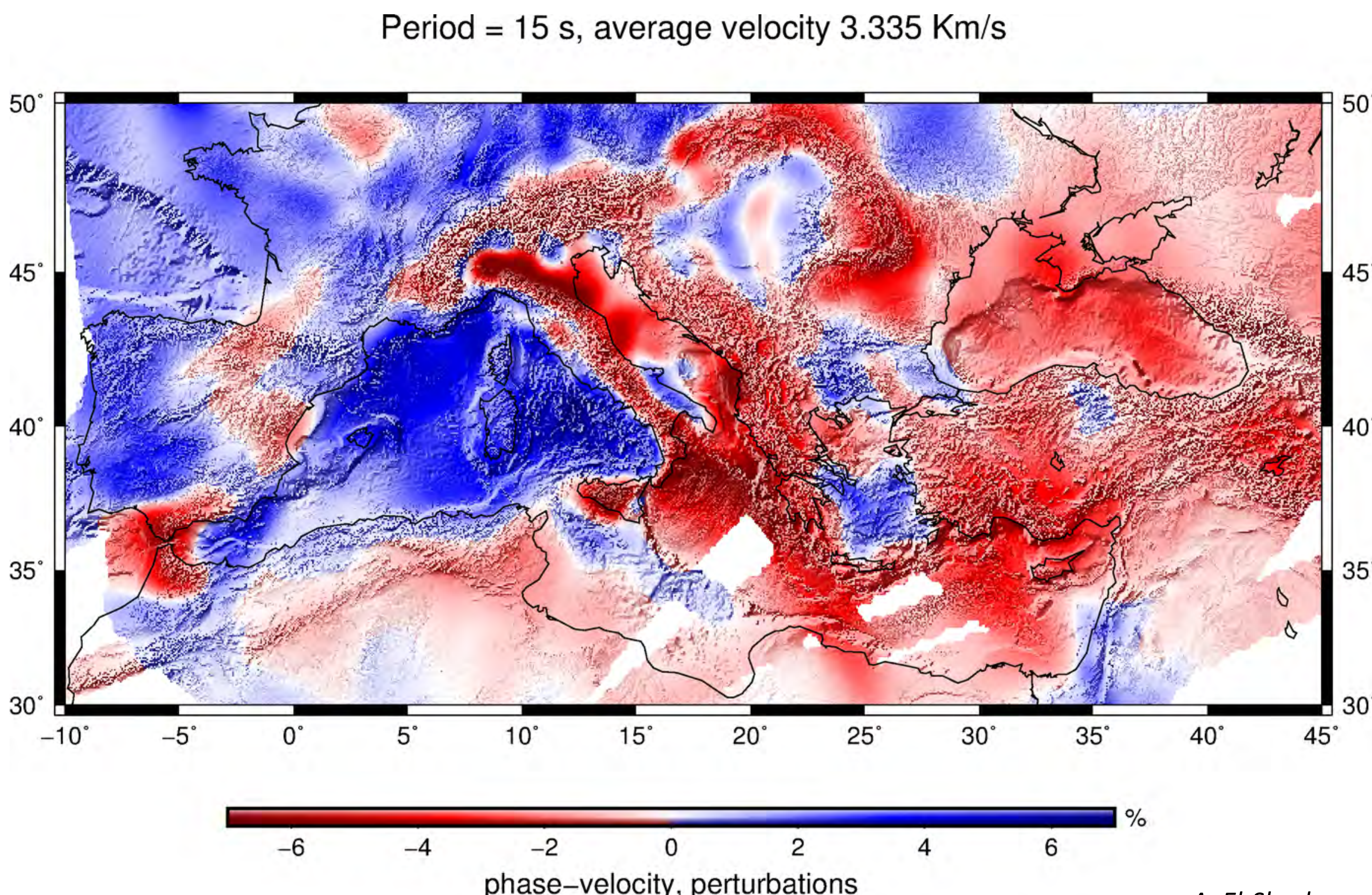
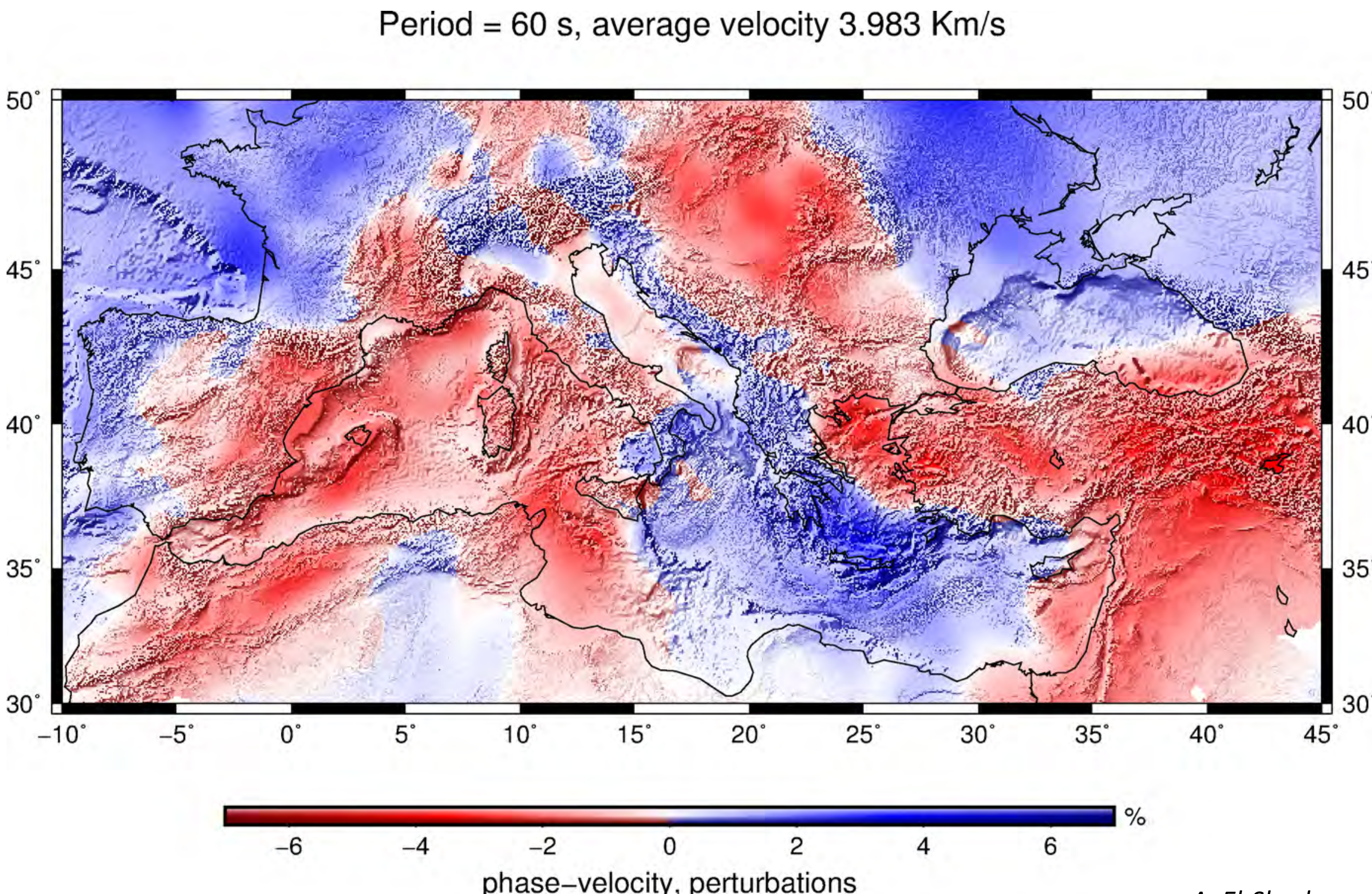


A. El-Sharkawy

regional scale, lateral resolution partly < 100 km

Surface-wave tomography: dispersion analysis fundamental mode



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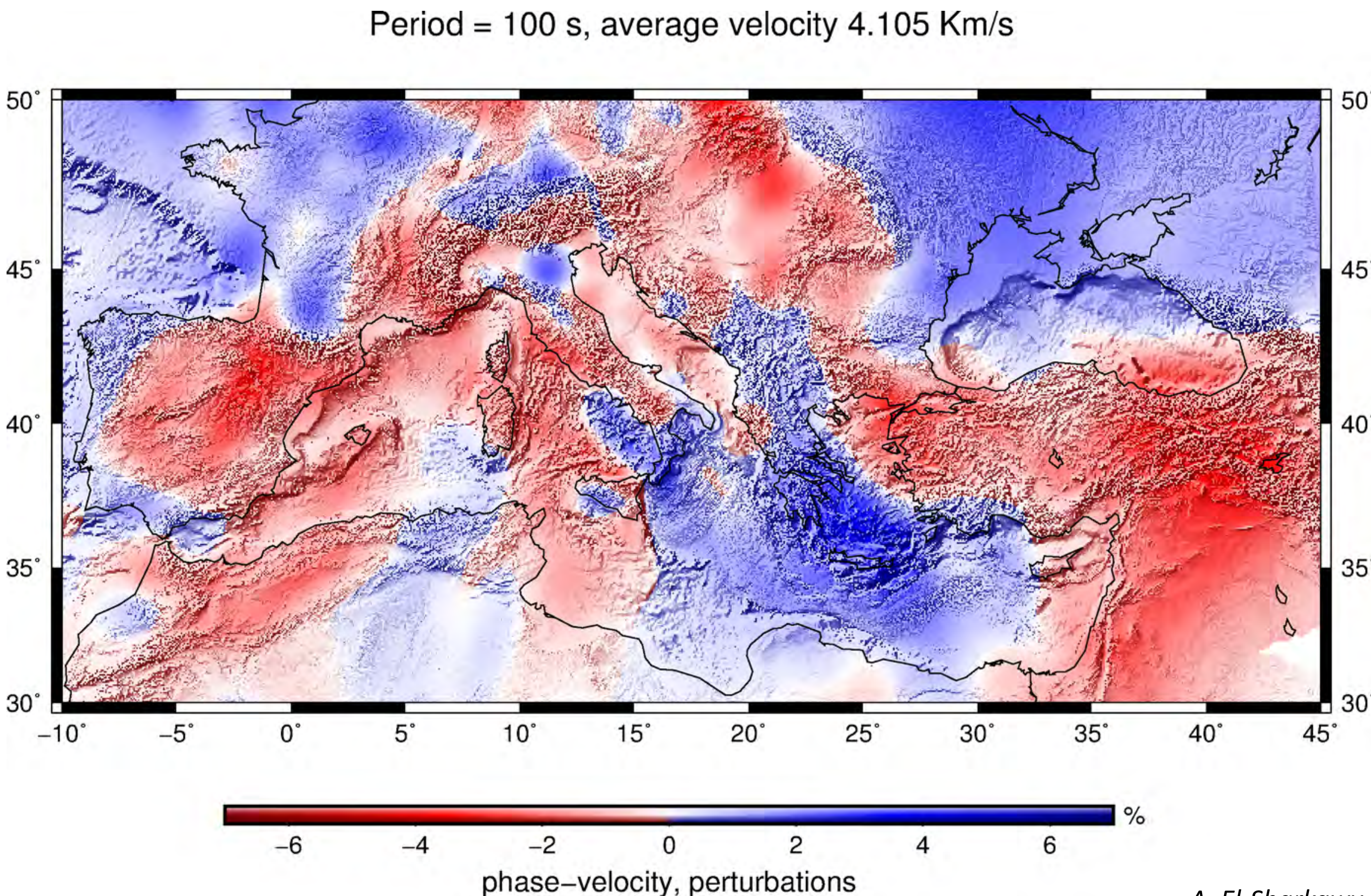
Surface-wave tomography: dispersion analysis fundamental mode



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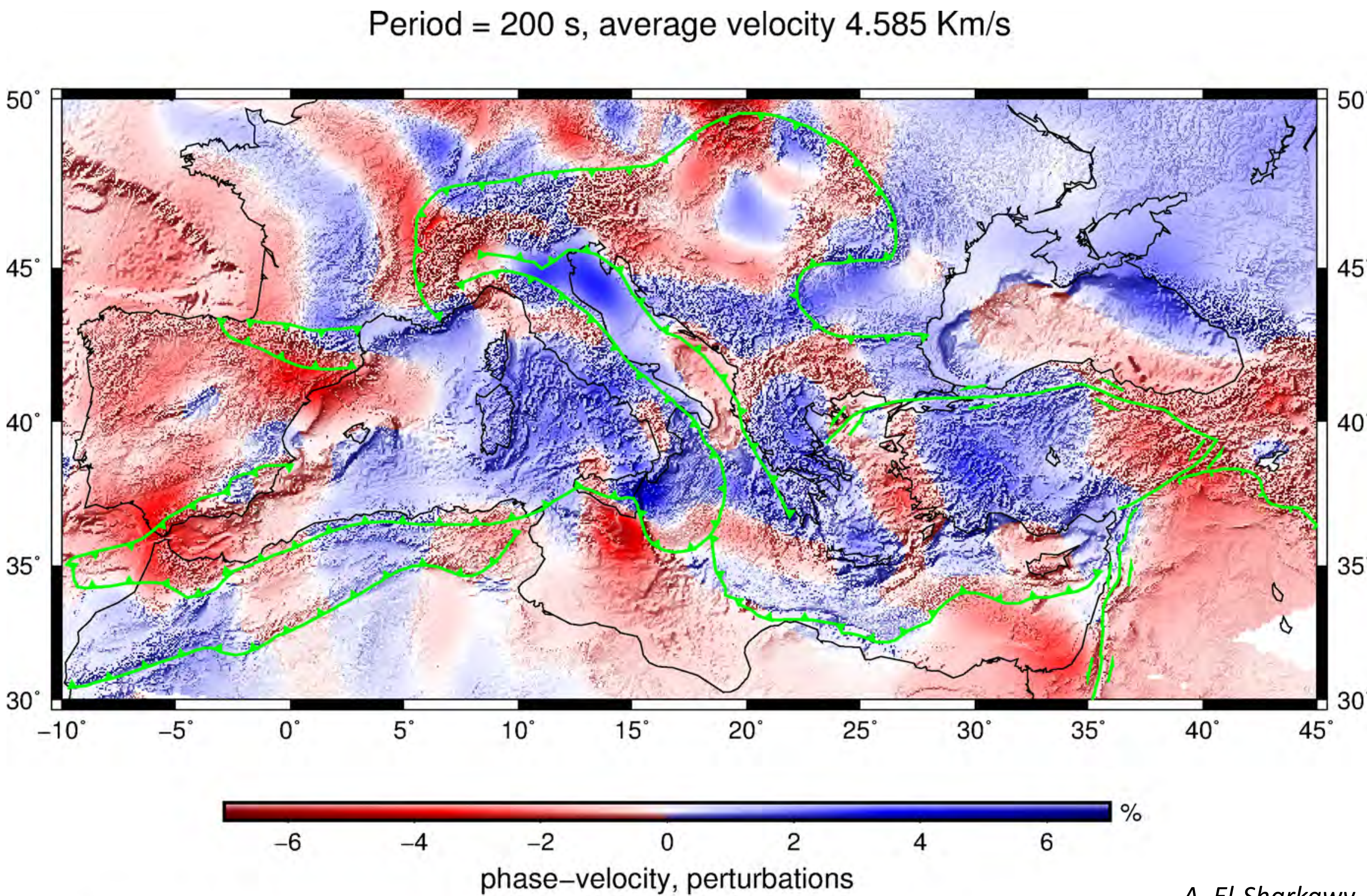
Surface-wave tomography: dispersion analysis fundamental mode



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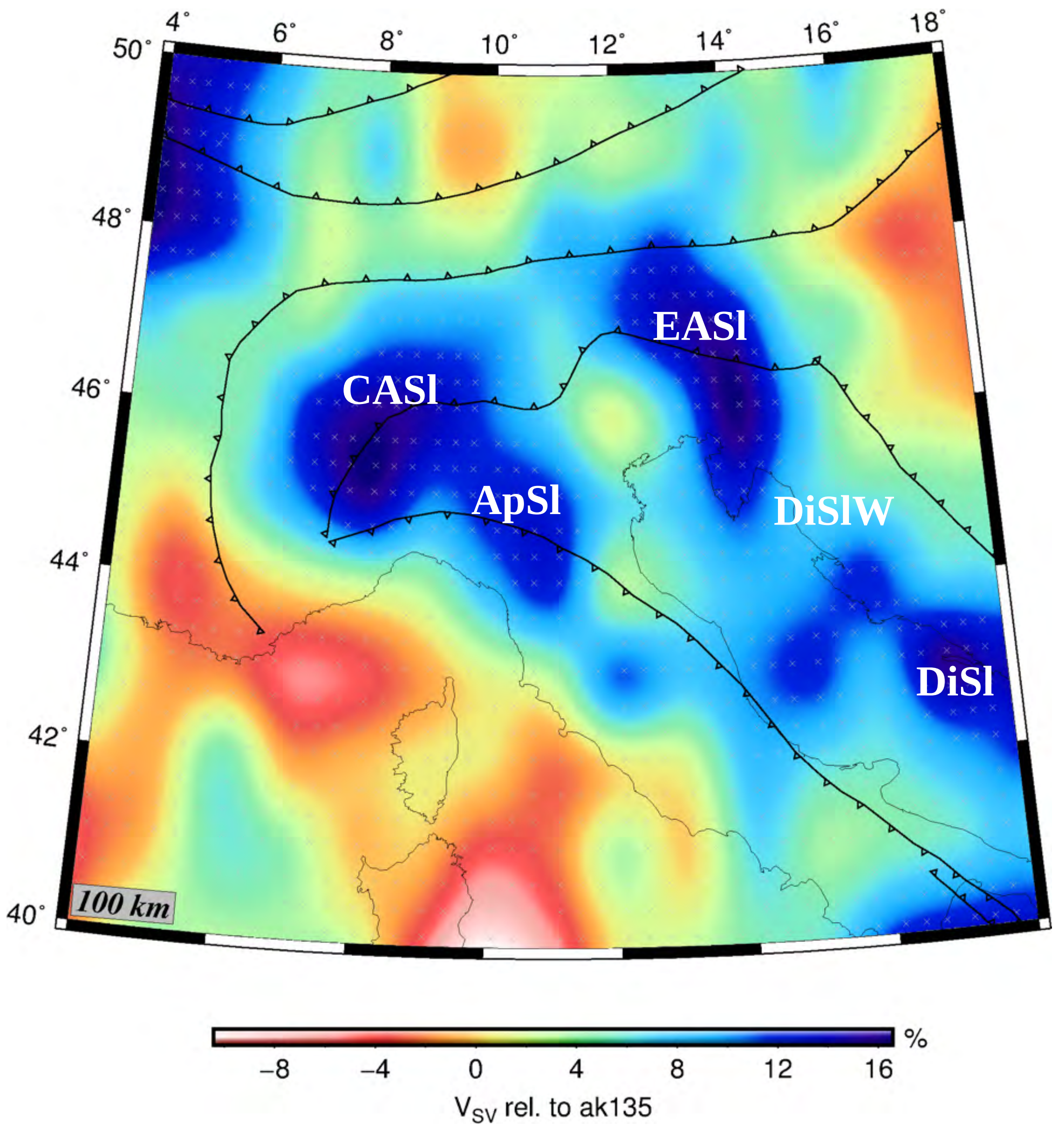
Surface-wave tomography: the Alpine region

- first inversion test
- Pre-AlpArray data only



ApSl: Apenninic Slab
CASl: Central Alpine Slab
DiSl: Dinaridic Slab
DiSlW: Dinaridic Slab Window
EASl: Eastern Alpine Slab

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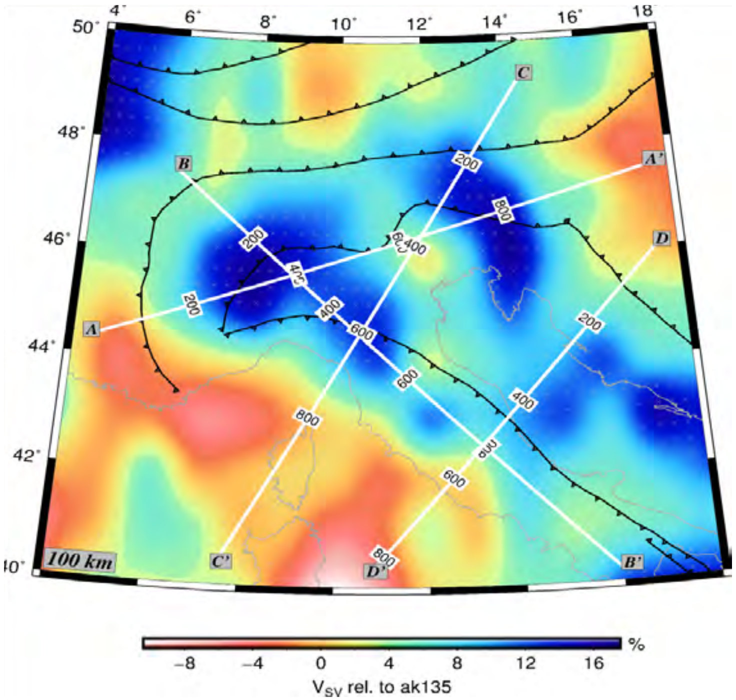
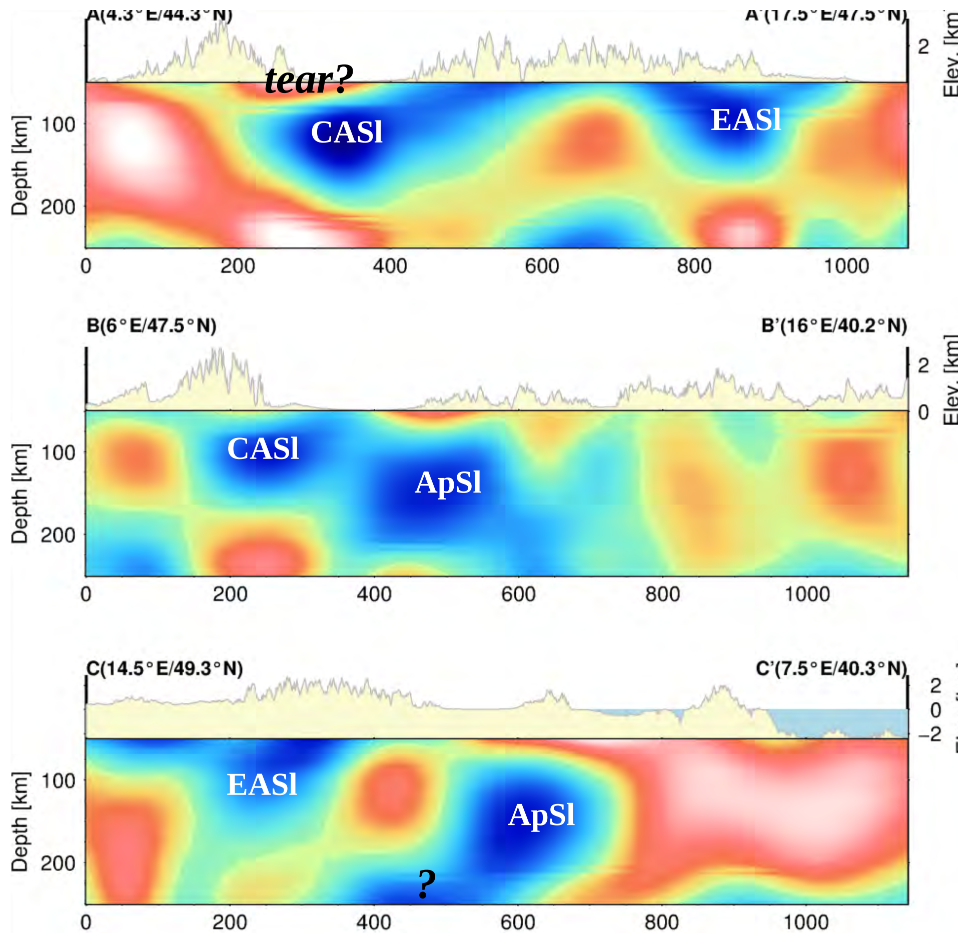
Surface-wave tomography: the Alpine region





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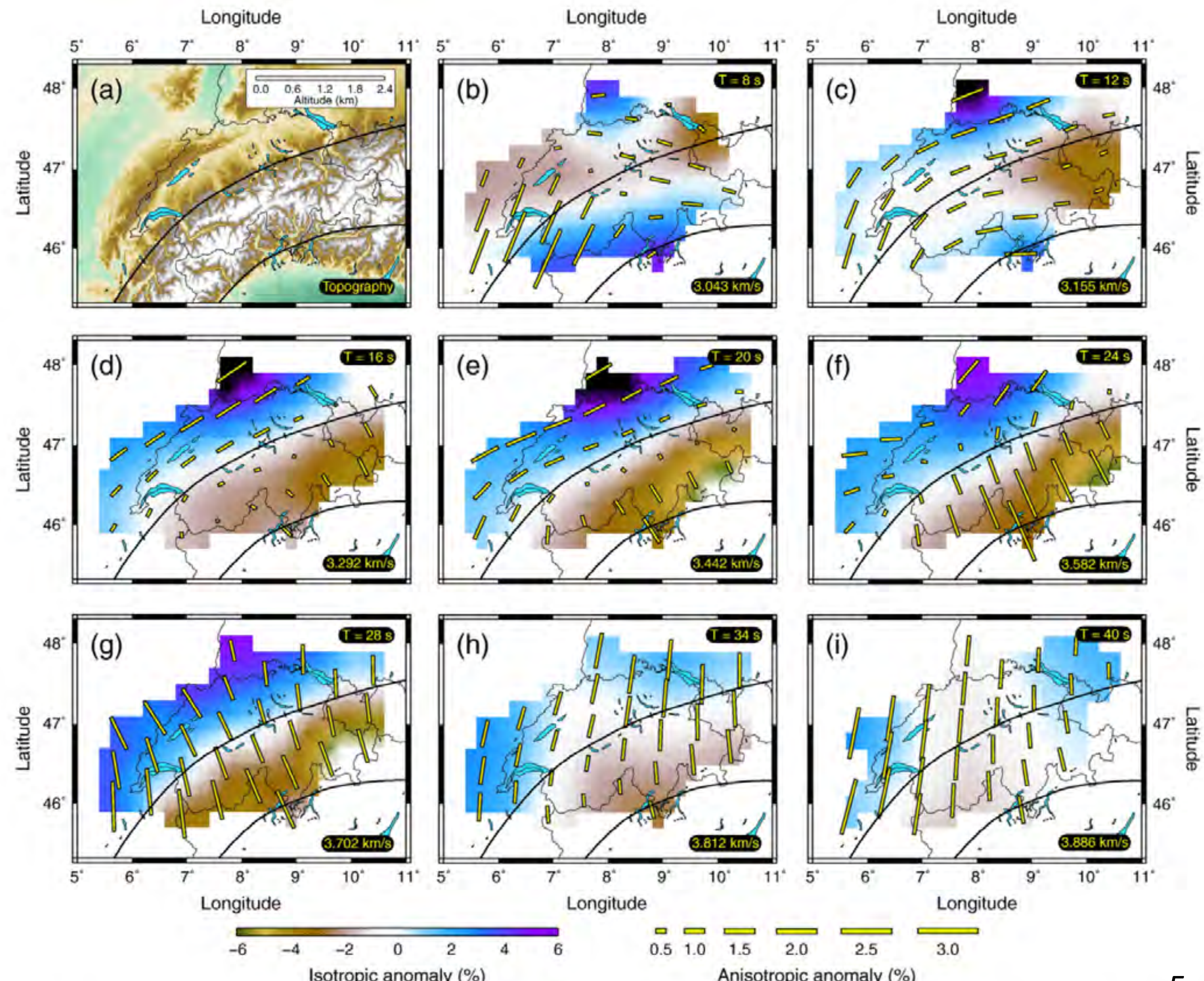
A. El-Sharkawy

Surface-wave tomography: the Alpine region

azimuthal anisotropy

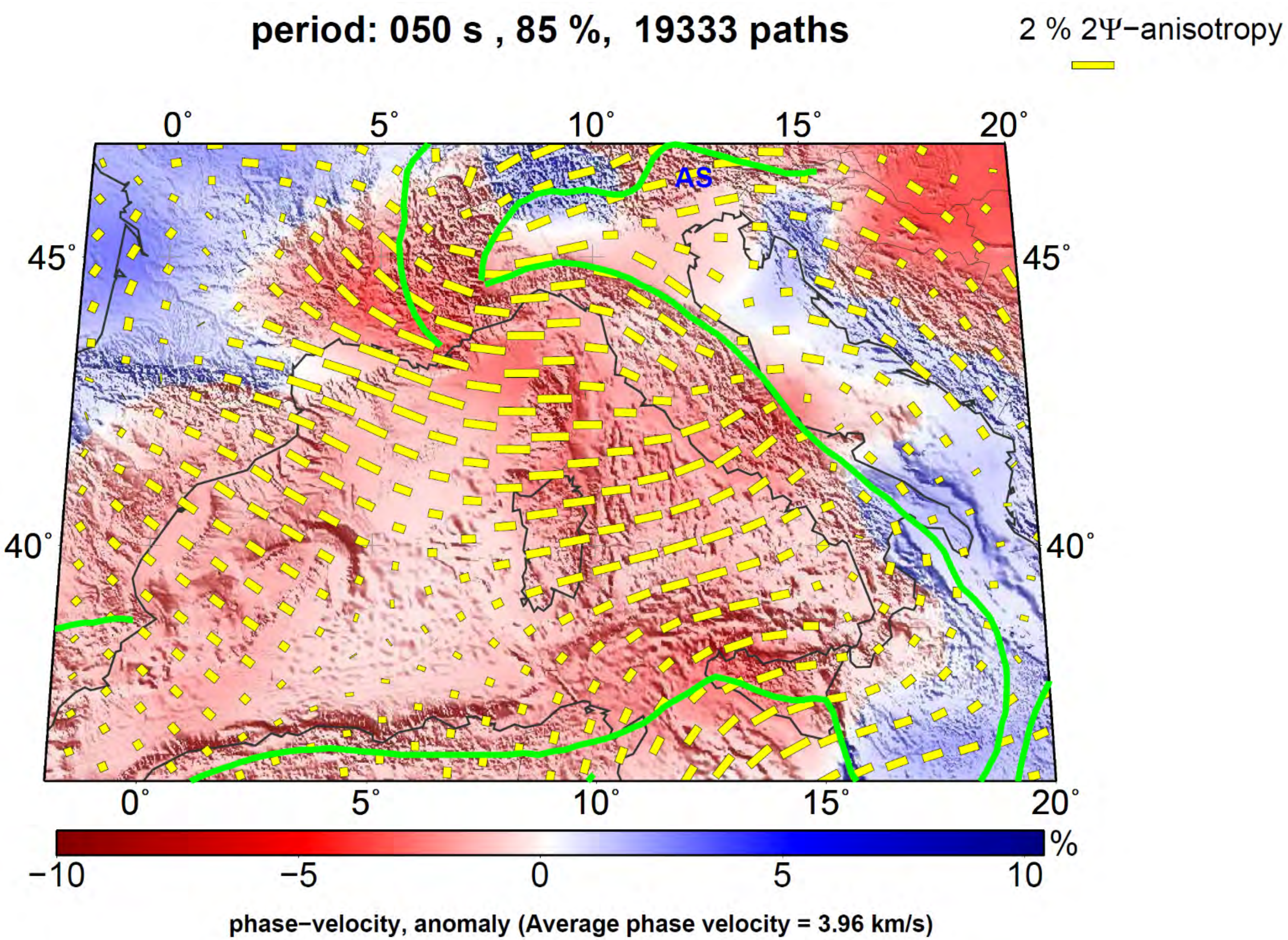


Fry et al. (2010)

local scale, lateral resolution ca. 150 km

Surface-wave tomography: the Alpine region

azimuthal anisotropy

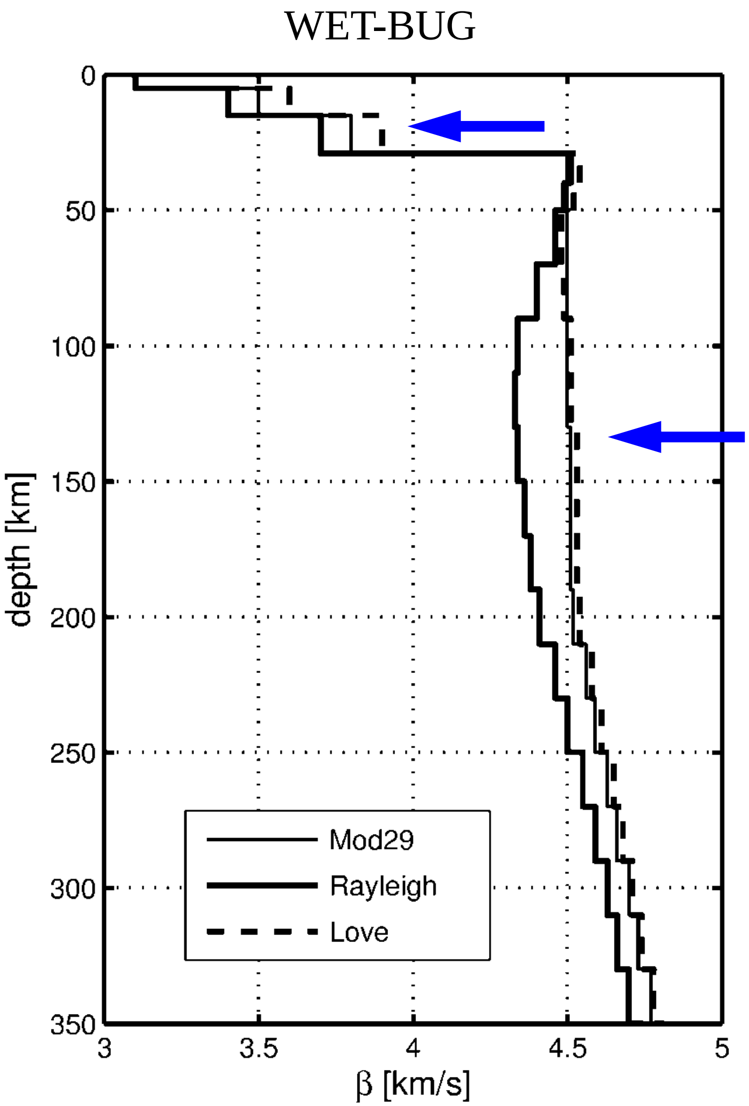


R. Soomro

regional scale, lateral resolution ca. 150 km

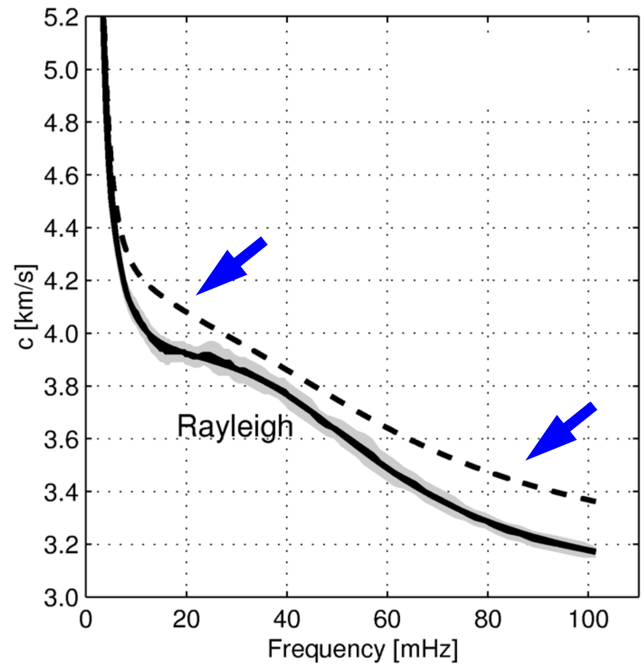
Surface-wave tomography: radial anisotropy

radial anisotropy: indicative for horizontal or vertical flow



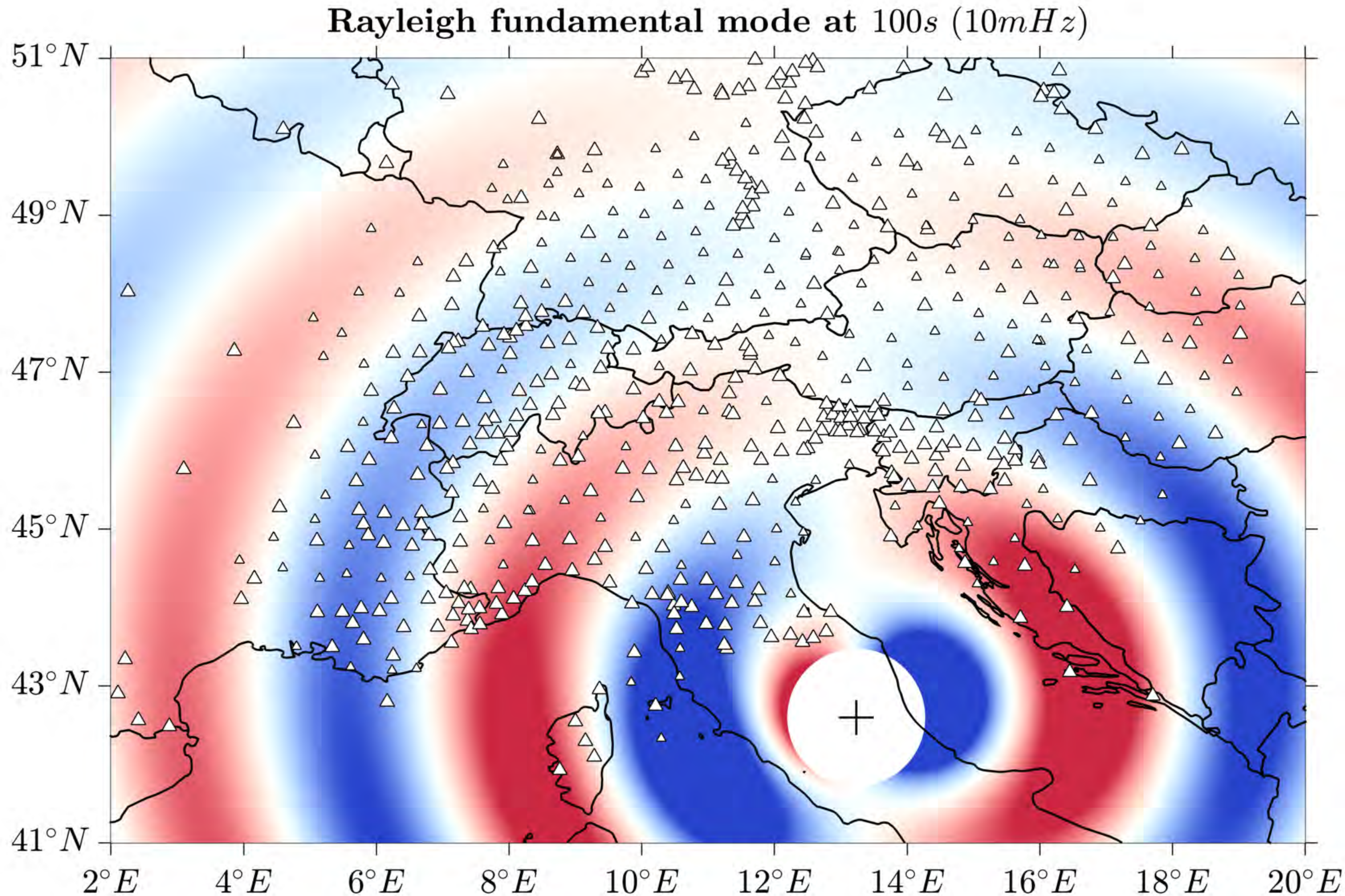
Vs-vertical from Rayleigh waves (solid)
Vs -horizontal from Love waves (dashed)

Love-Rayleigh discrepancy: Rayleigh wave velocity from Love wave model (dashed)



Bischoff et al. (2004), Roux et al. (2011)

Surface-wave tomography: analysis of wavefields



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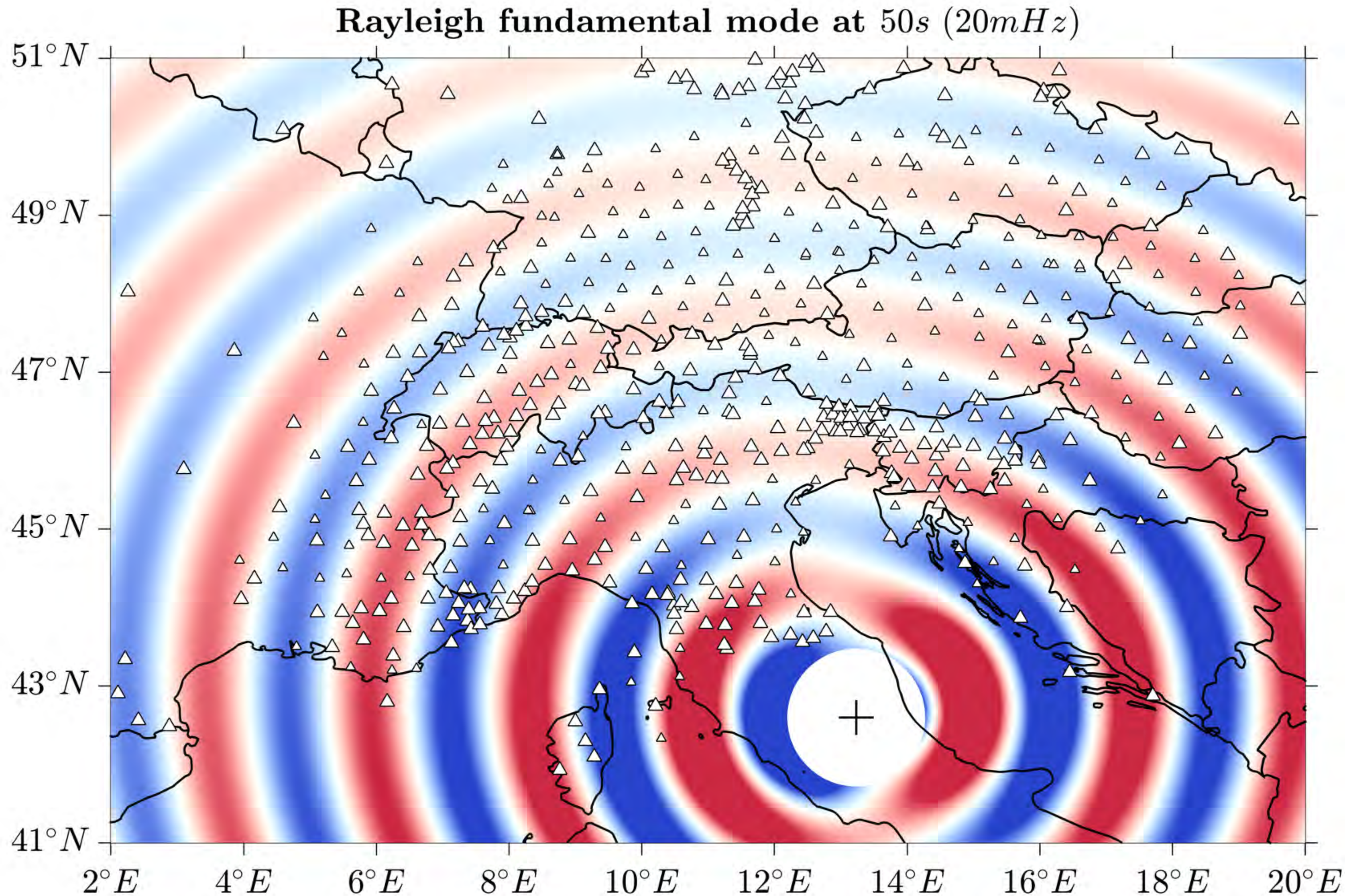
Surface-wave tomography: analysis of wavefields



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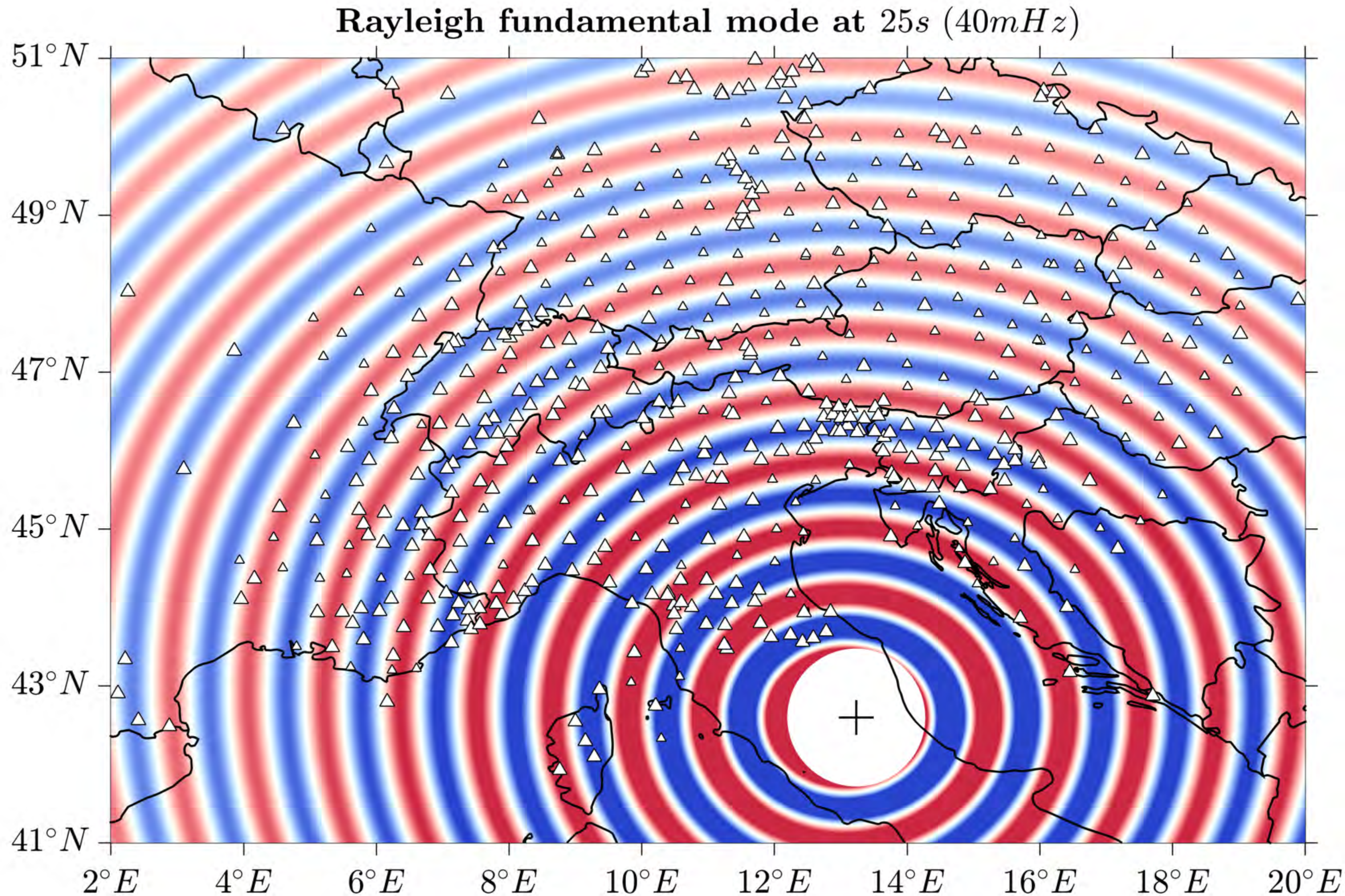
Surface-wave tomography: analysis of wavefields



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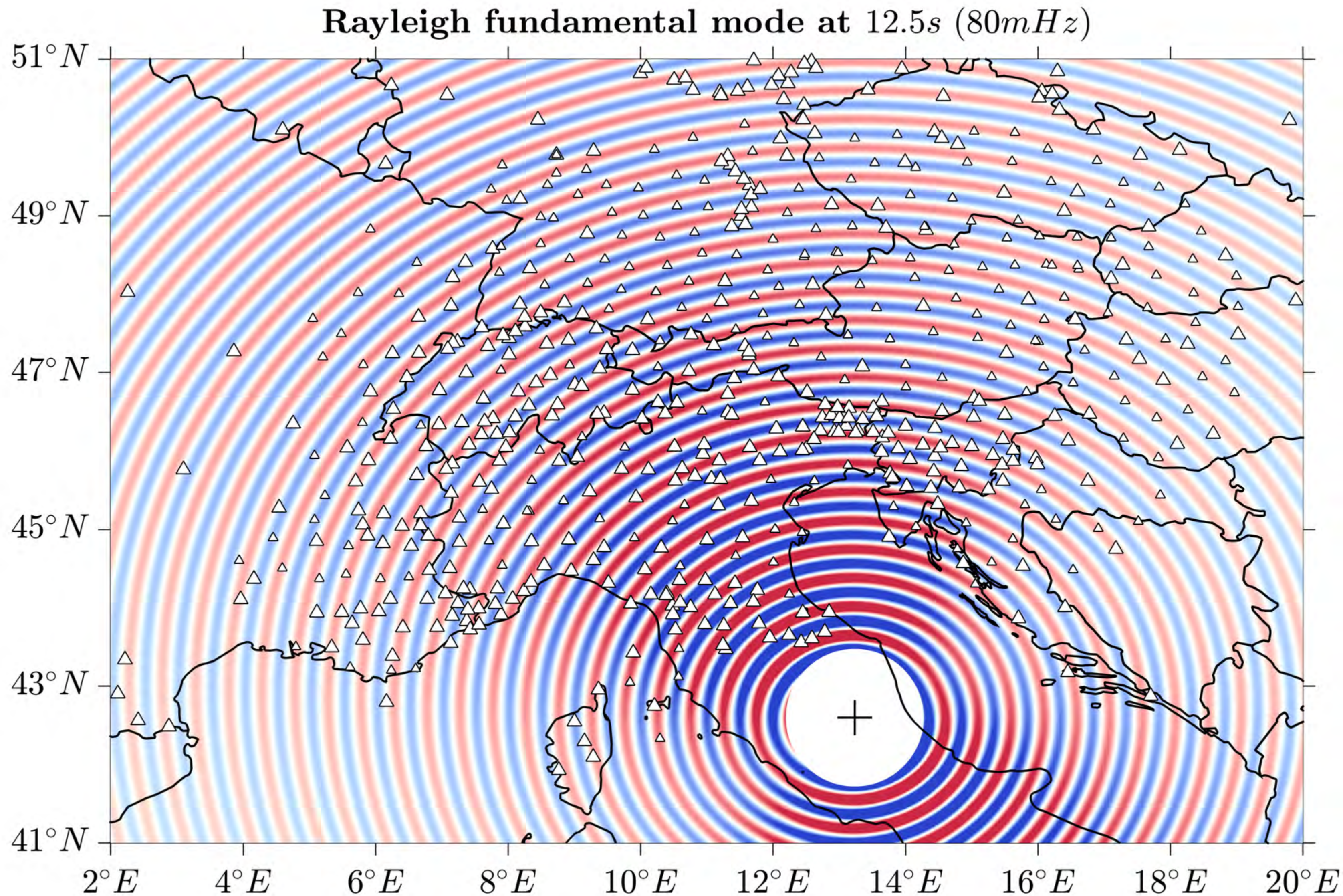
Surface-wave tomography: analysis of wavefields



M. Tesch

Conclusions

surface-wave tomography:

- applicable to a wide range of scales (global to centimeter)
- waveform tomography + analysis of Rayleigh and Love wave phase velocities
- yields 3D models of isotropic Vs + radial + azimuthal anisotropy
- strong sensitivity for crust, Moho, mantle lithosphere, LAB, asthenosphere
- seismic anisotropy: lithospheric deformation + asthenospheric flow

advantages:

- **crucial for resolution of mantle lithosphere + asthenosphere**
- effective data processing -> automated analysis of all available data
- effective data quality control
- effective testing of influence of inversion parameters

disadvantage:

- semianalytic – underlying assumptions have to be tested

Conclusions

-> The resolution limit of surface wave tomography hasn't been reached yet!
-> Resolution is steadily increasing because of methodical developments and new data!

Targets of surface wave tomography within AlpArray:
-> resolving slab segments, slab gaps and tears (down to about 300 km depth)
-> imaging lithospheric deformation and asthenospheric flow

- application of different seismological imaging techniques will result in different models
- interpretations of tomographic models need to take scales and spatially varying resolution into account
- need for consistent models: joint inversion (RF + SKS + traveltimes + phase velocities + waveforms + gravity) in second phase of the SPP?

-> Need for interdisciplinary interpretations!

Looking forward to it!