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Seismological imaging of the lithosphere – in the light of joint inversion / interpretation

Christian Weidle & Thomas Meier

Overview

- Targets in lithospheric imaging
- Seismic observables in the aspect of joint inversion / interpretation
  - Body wave traveltime tomography
  - Surface wave dispersion, Waveform tomography, wavefield imaging, ambient noise
  - Receiver Functions

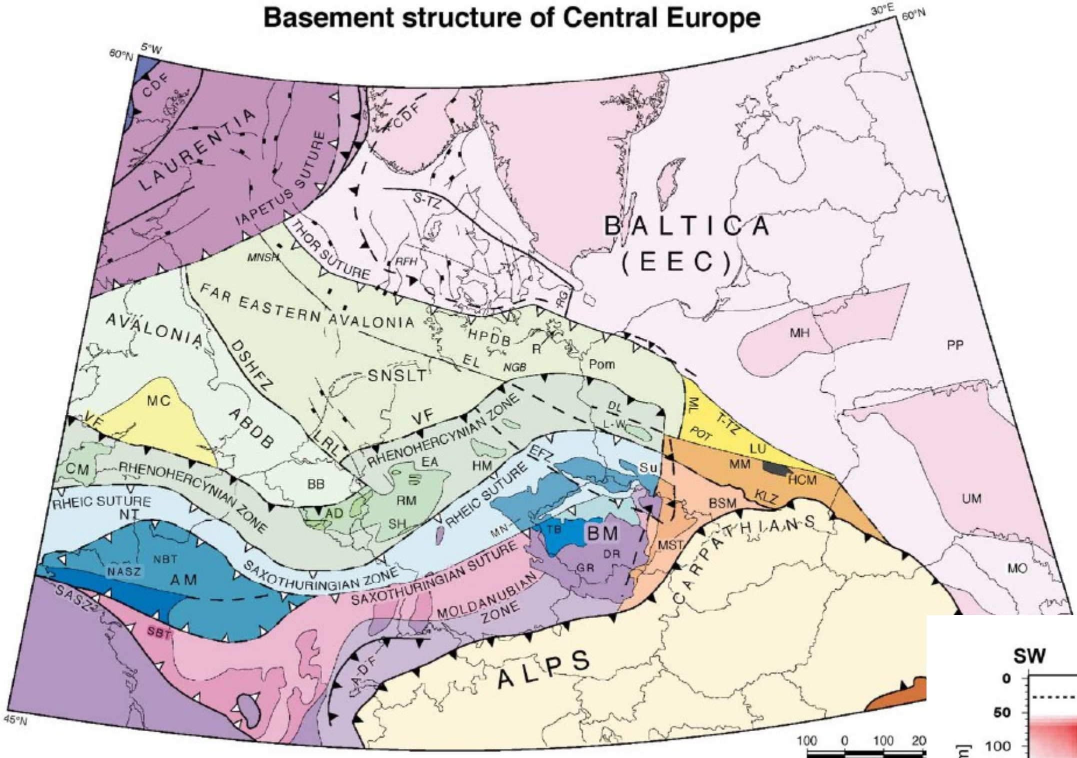
Targets

- Depth-to-...
  - Moho
  - LAB
  - Intra-crustal (depth-to-basement, Conrad)
  - Intra-lithospheric (MLD?)
  - … and their thicknesses (are they sharp?)
- Velocities vp, vs, vp/vs ratio
- Anisotropy
  - Azimuthal
    - Crust: frozen-in, ancient deformation
    - Mantle: current stress regime/mantle flow
  - Radial
    - SH vs. SV

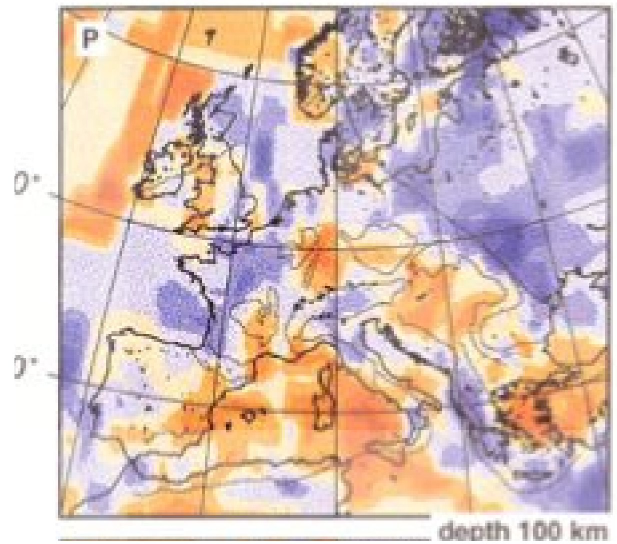
Broad spectrum → requires broad methodology?, is there ONE solution?

Sample case: Southern Norway

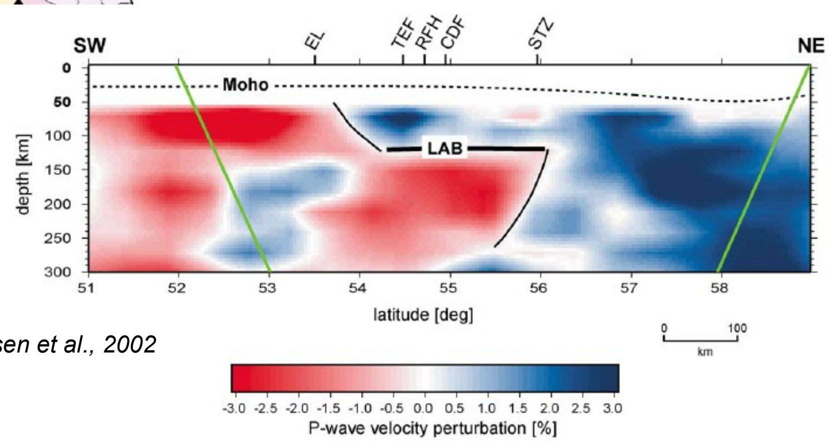
Basement structure of Central Europe



Winchester, 2002



Goes et al., 2000 from Bijwaard et al., 1998



Gregersen et al., 2002

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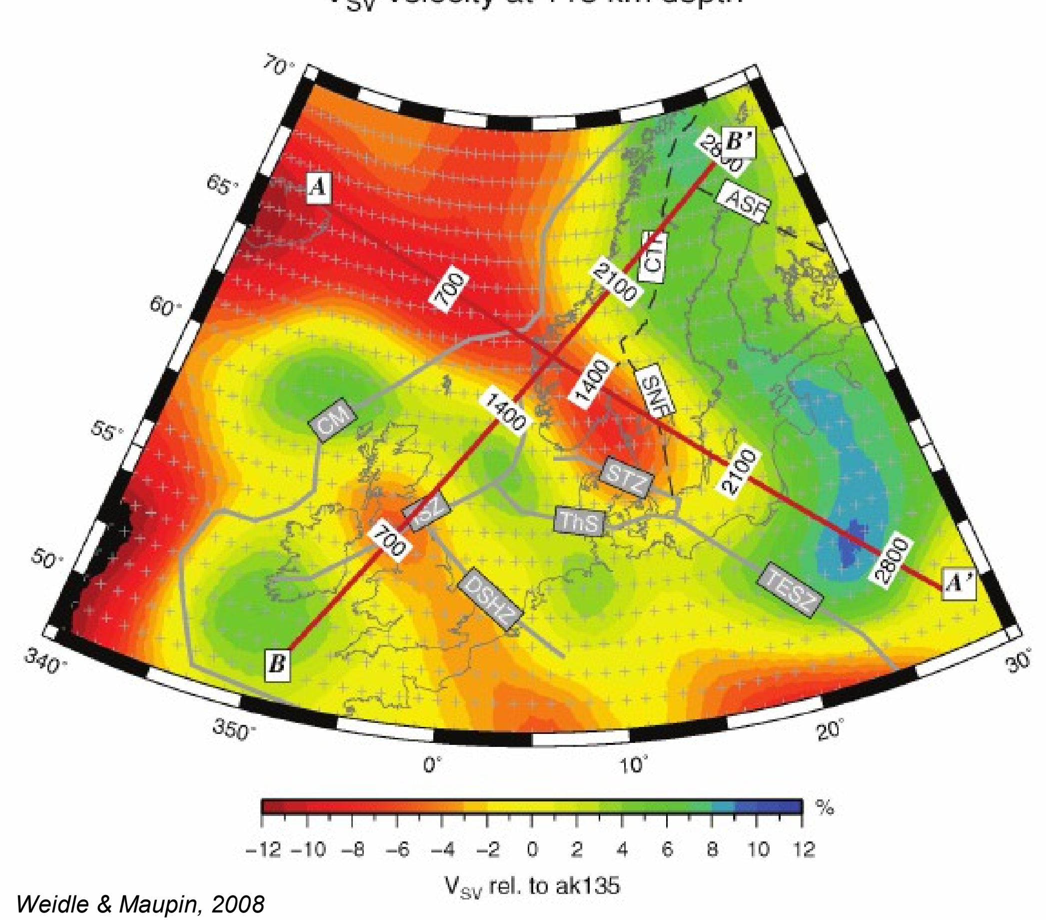
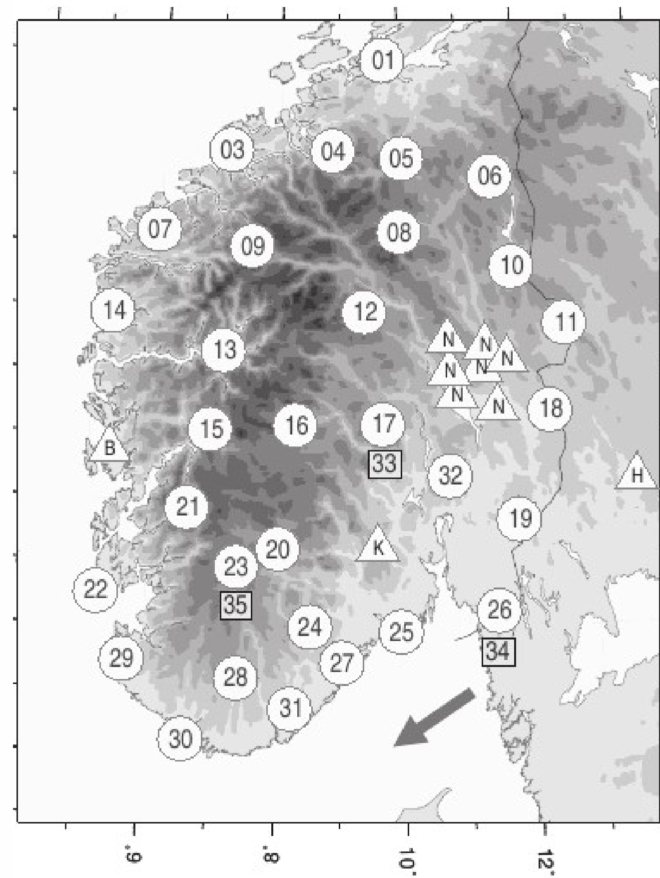
Sample case: Southern Norway



Weidle & Maupin, 2008



Weidle et al., 2010

Seismic observables

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Traveltimes (body waves)

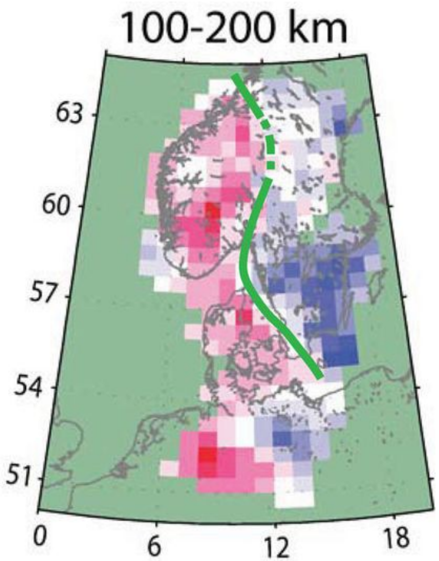
- Useful approximation, simple to implement
  - Ray theory: 3D globally – Finite Frequency: 1D Kernels
- High frequency, short wavelength
- High spatial resolution (station coverage)
- Global (multi-) scale inversions feasible
- Relative / absolute velocity models
- “simple” data error assessment

Problem:

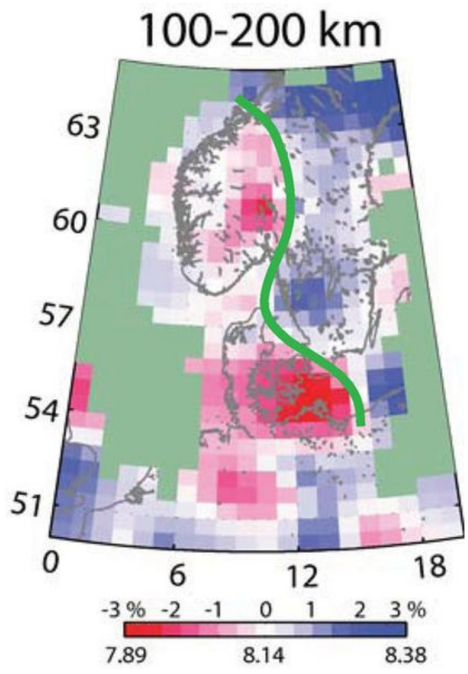
- Anisotropy … possible …
- Consistent determination (manual picks, many data centers, …)
- Useful phases? Depth phases for shallow structure ↔ auto-picking?

Seismic observables

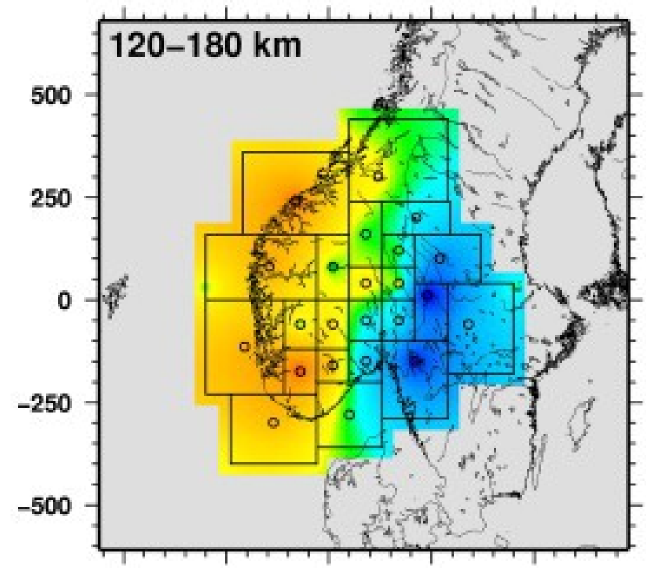
Vp_{rel}



Vp_{abs}



Vs_{rel}



Amplitudes +/- 3%

Medhus et al., 2012

Wawerzinek et al., 2013

The perfect world:

$$\mathbf{G} \bullet \overline{m} = \overline{d}$$

G: Full resolution 3-D seismic wavefield
$\overline{m}$: "mm-scale" model of all physical parameters
$\overline{d}$: error-free data

The *real* world:

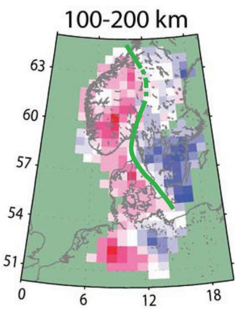
$$(\mathbf{G} * \sigma_{\mathbf{G}}) \bullet (\overline{m} * \sigma_m) = \overline{d} + \sigma_d \qquad \rightarrow \text{regularization}$$

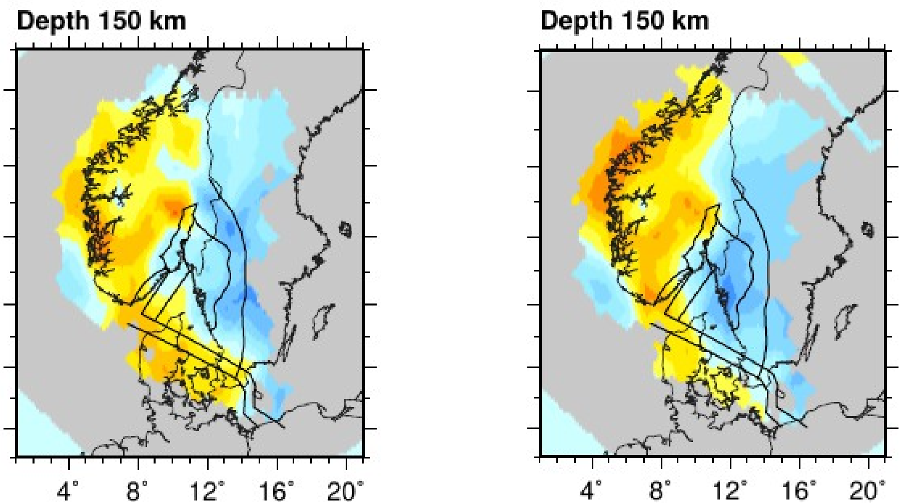
"Filters":
$\sigma_{\mathbf{G}}$: approximation in wave propagation, e.g. ray theory, forward scattering, fundamental modes
σ_m: geometric model parameterization and selection of parameters (e.g. velocity, attenuation)
σ_d: data limitations, e.g. measurement, frequency content, ...

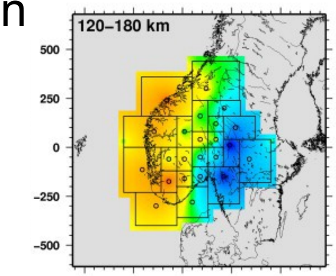
Seismic observables

Vp$_{rel}$ Vs$_{rel}$

Consistently parameterized (not joint) Vp, Vs inversion







Amplitudes +/- 2% +/- 4%

More consistent anomalies in Vp and Vsh

~ 100 events, ~ 3000 – 4000 traveltimes

Medhus et al., 2012 *Kolstrup et al., 2015* *Wawerzinek et al., 2013*

Seismic observables

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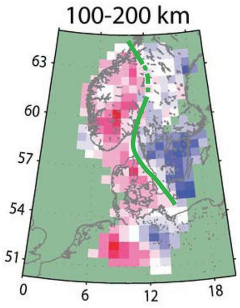
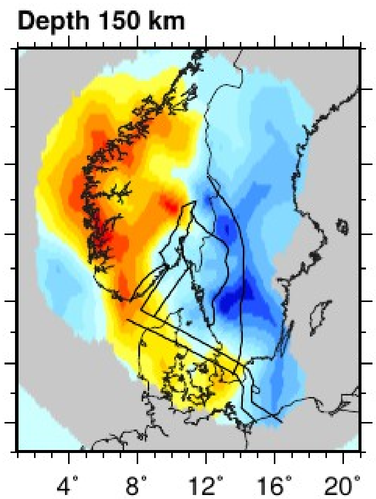
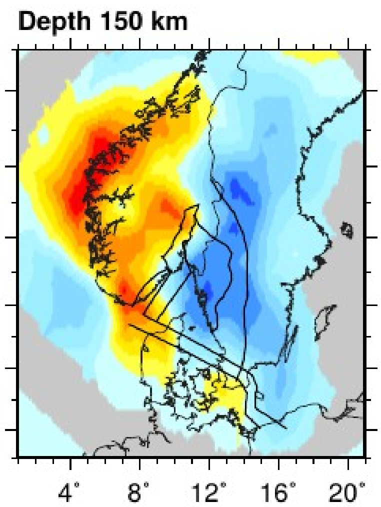
Vp_{rel}



Medhus et al., 2012

Vp, Vs Finite Frequencies inversion





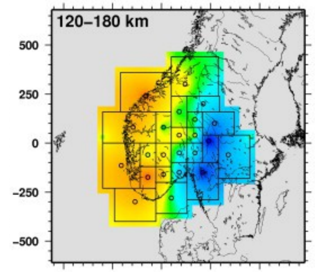
Amplitudes +/- 2.5% +/- 4%

More consistent anomalies in Vp and Vsh

Covers slightly larger region (at depth)

Kolstrup et al., 2015

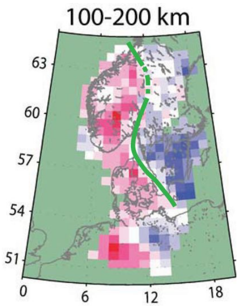
Vs_{rel}

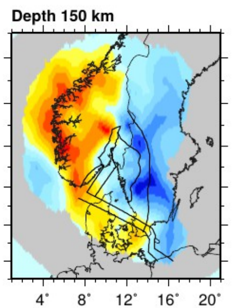


Wawerzinek et al., 2013

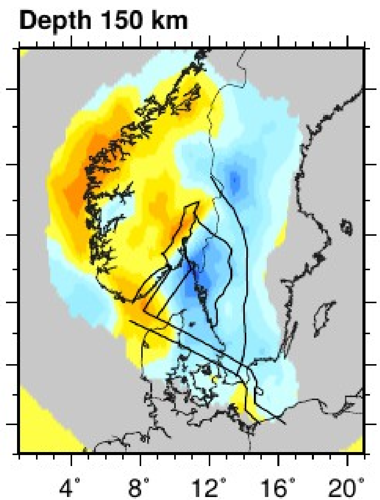
Seismic observables

Vp_{rel}



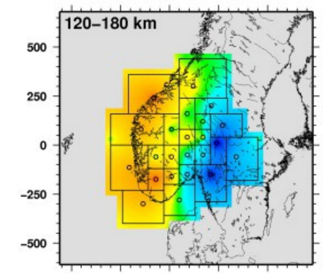


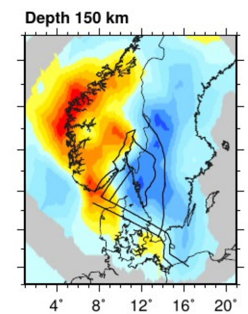
Plausible Vp/Vs model



Variations in lithospheric thickness
+300° temperature S.Norway
Depleted mantle below Sweden

Vs_{rel}





Medhus et al., 2012

Kolstrup et al., 2015

Wawerzinek et al., 2013

Seismic observables

Surface wave dispersion

- Useful parameterization of (fundamental) mode waveforms
- Group velocities
  - Single station, no 2π problem
  - Amplitude measurement, sensitive to interference
- Phase velocities
  - Two-station methods:
    - 2π problem reduced
    - high accuracy ("relative" measurement)
- Broad sensitivity to shear wave velocity with depth
- Strong sensitivity on anisotropy (azimuthal & radial)

Problem:

- Two-step inversion procedures through group-/phase-velocity maps
- Regional-scale resolution
- Error analysis difficult on few data, better on large datasets (automated processing)

Seismic observables

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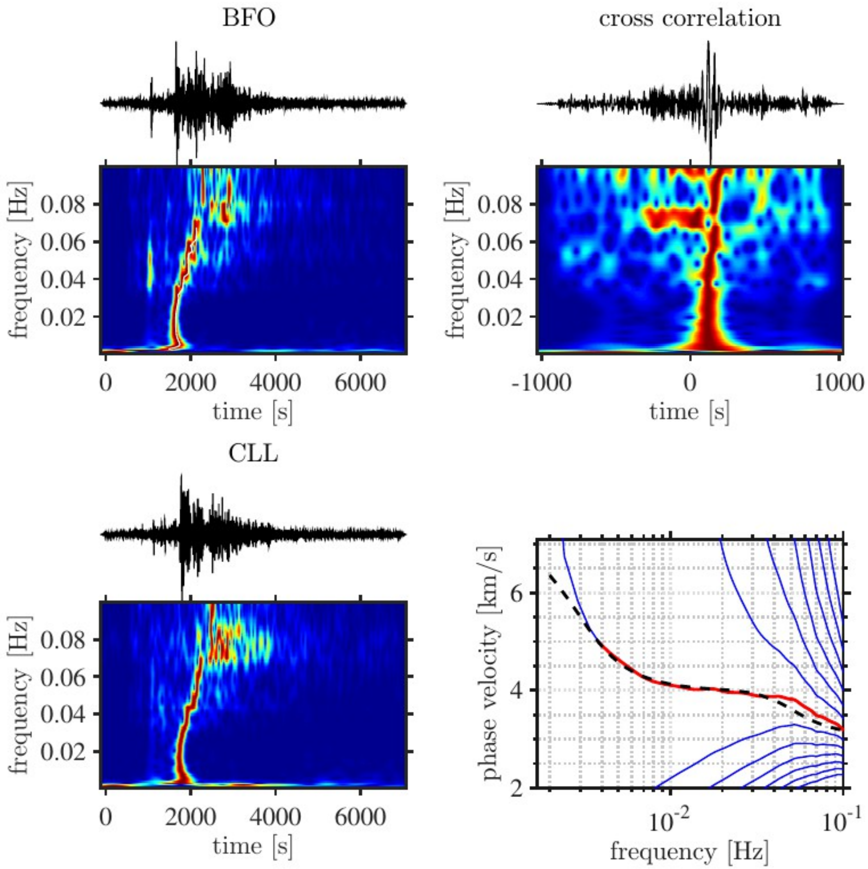
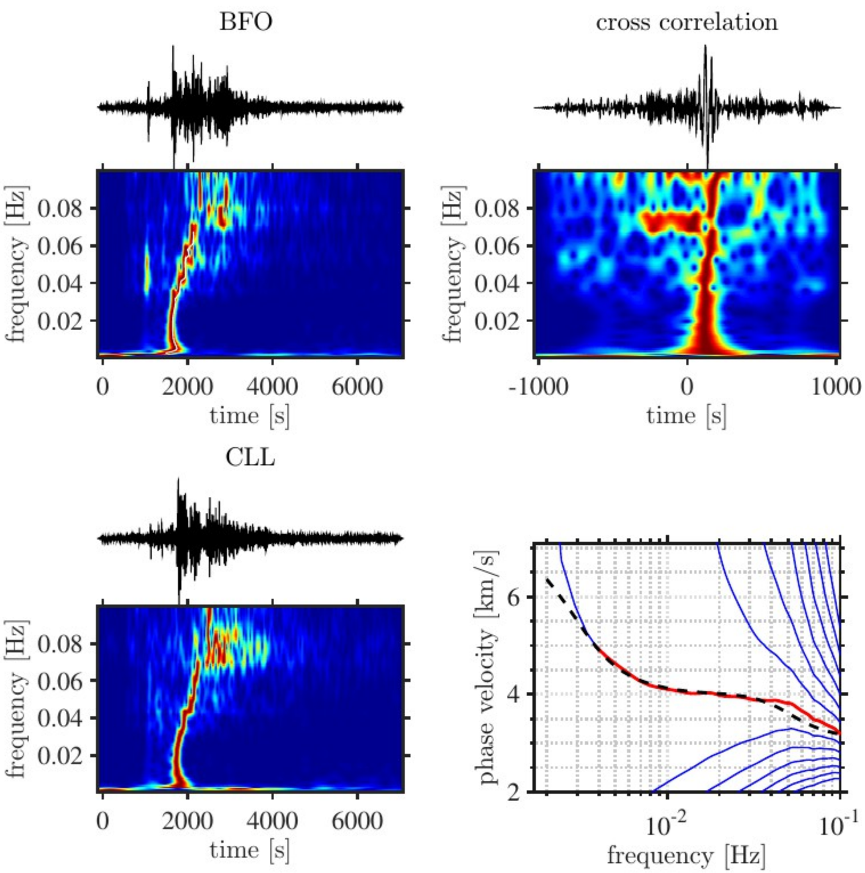
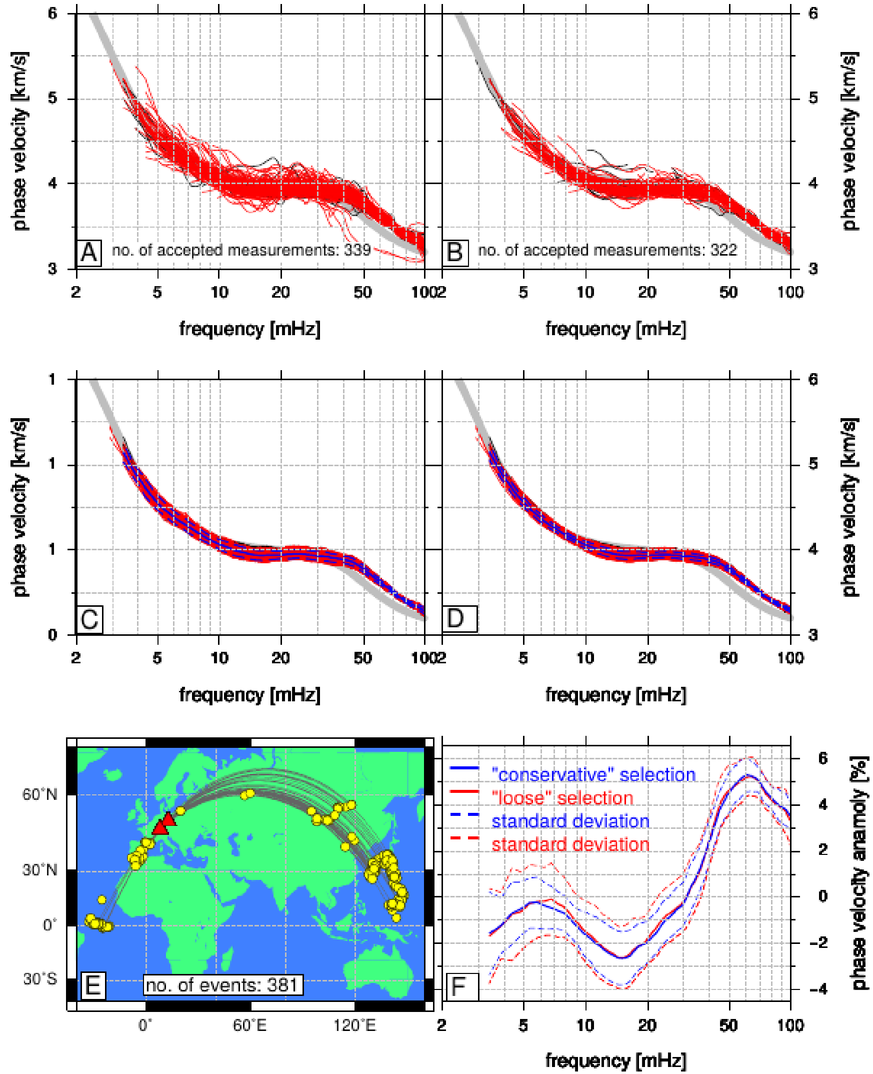


Soomro et al., 2015

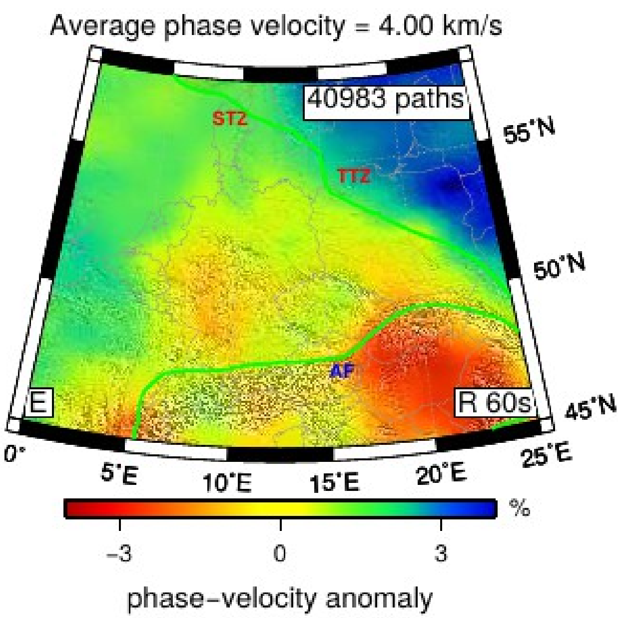
Seismic observables



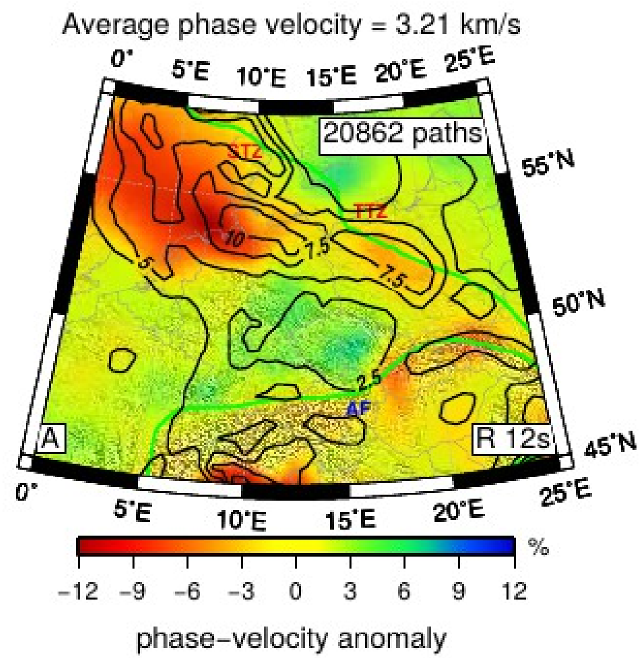
Soomro et al., 2015



Seismic observables



Soomro et al., 2015



- 70 km grid
- Azimuthal anisotropy
- Rayleigh & Love → radially anisotropic inversion possible

Seismic observables

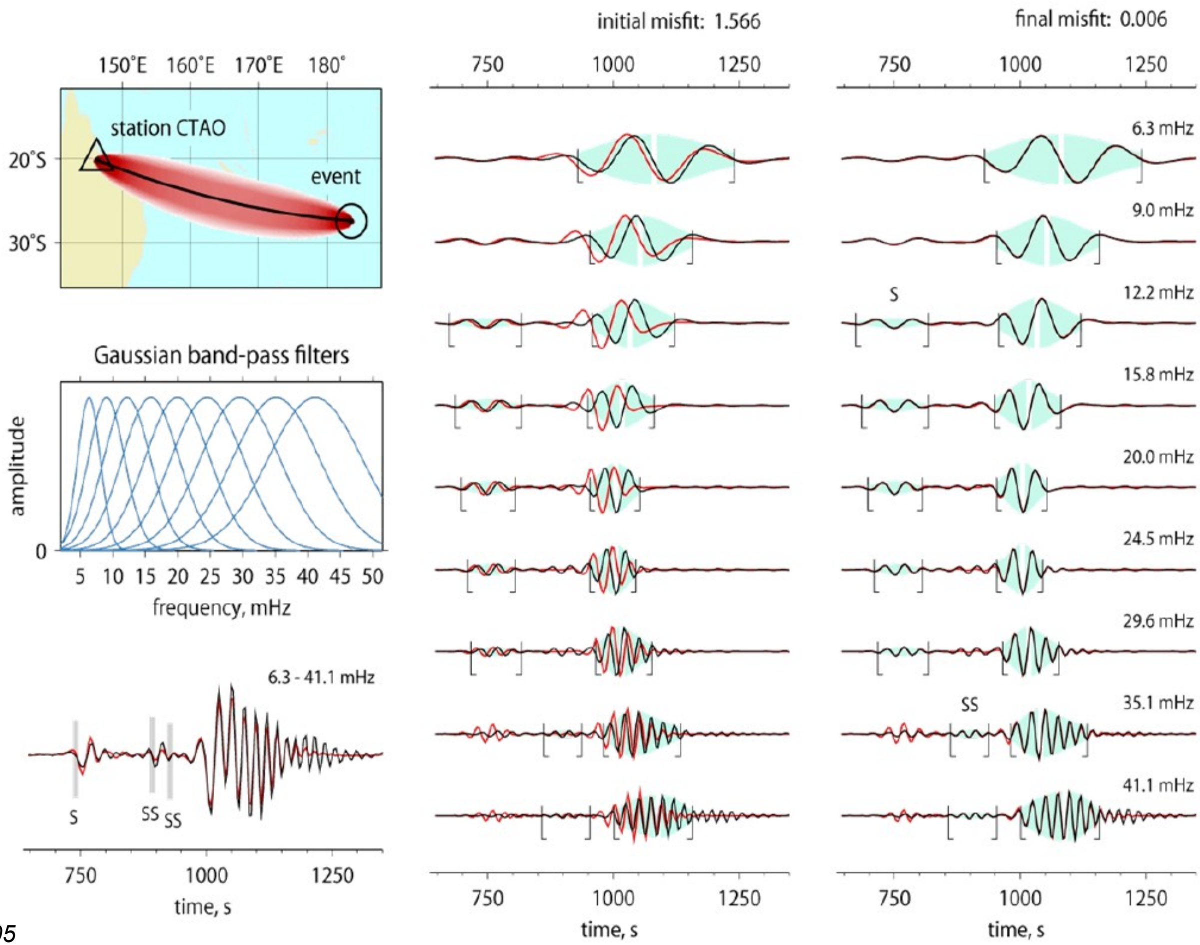
Waveforms

- Fundamental and higher mode waveforms
- Surface and body waves
- Theoretically best approach but in practice limited to long to intermediate periods
- strong cycle skipping, particularly at higher frequencies

Problem:

- calibration of amplitudes in recordings
- Little resolution for crust
- Need good starting model
- Errors strongly varying with frequency

Seismic observables



after Lebedev et al., 2005

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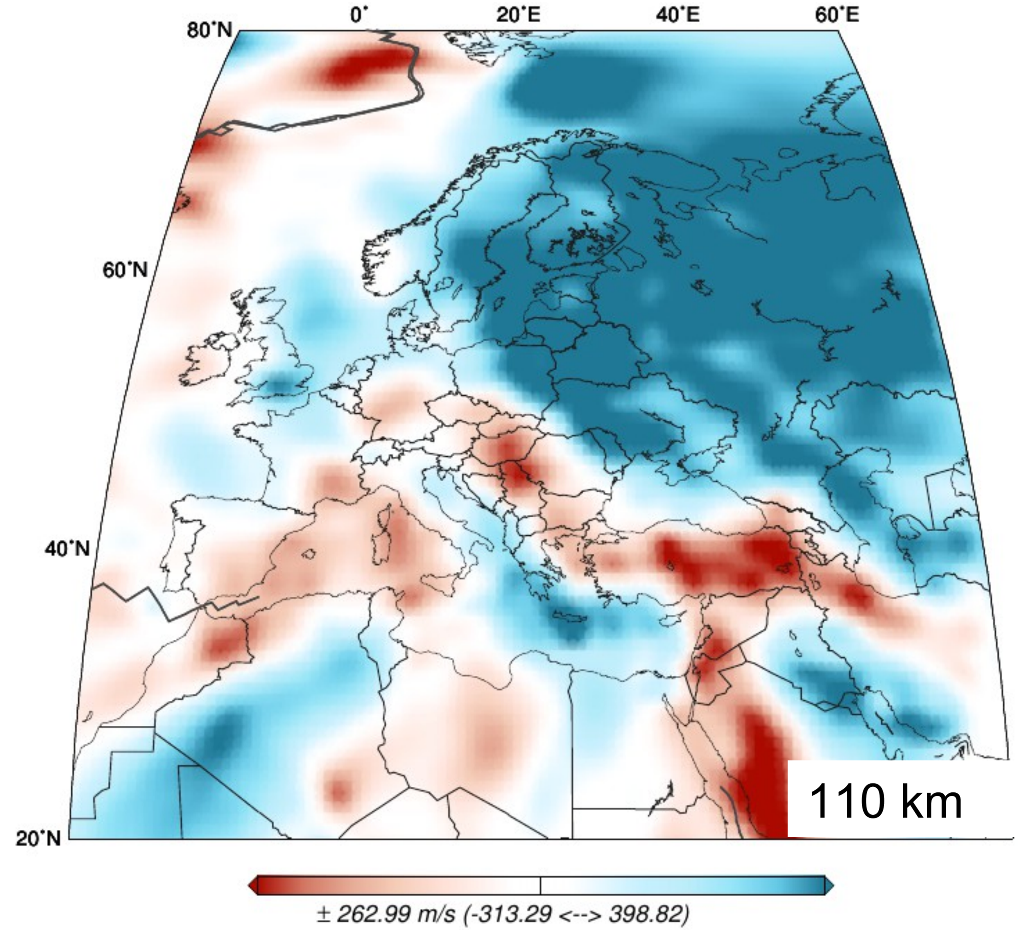
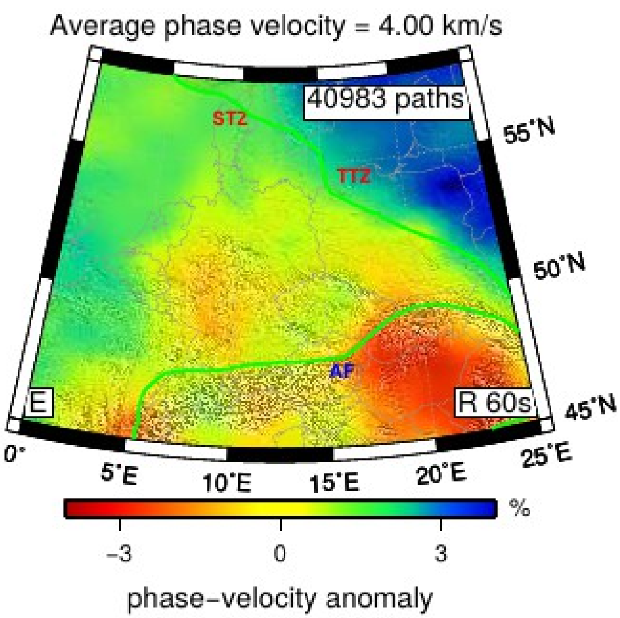
Seismic observables

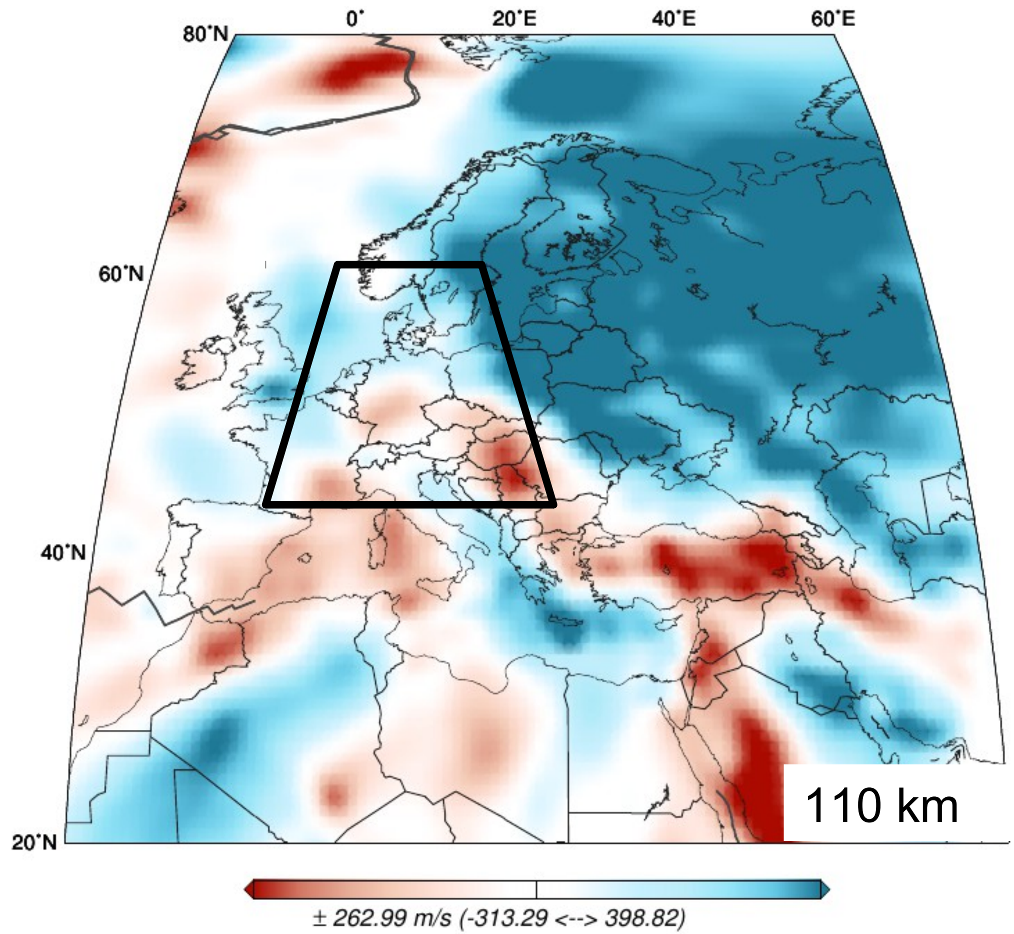


Schaeffer & Lebedev, 2013

Seismic observables



Soomro et al., 2015



Schaeffer & Lebedev, 2013

Waveforms vs. dispersion:
- Periods: >20s – >8s
- node spacing: 280km – 70km
- model depth: CMB – upper mantle

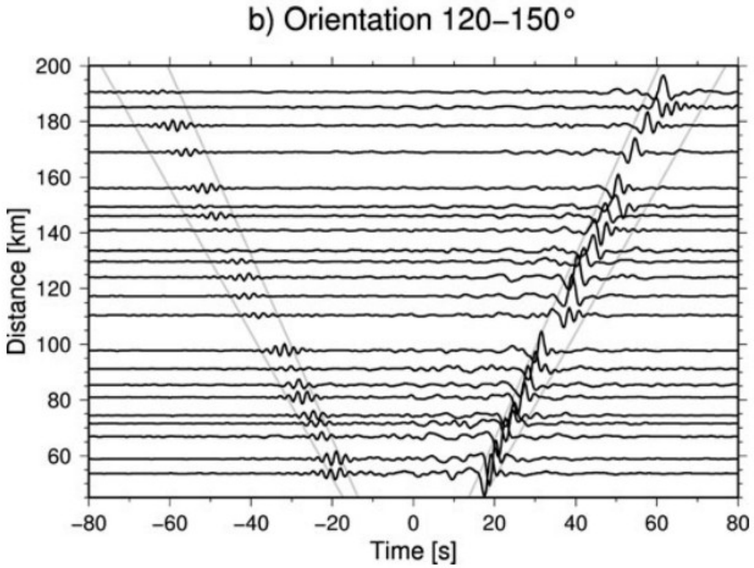
Ambient noise

- Surface and body wave observables
- Strong sensitivity for crust
- Know-how from established methods (e.g. surface wave tomography) applicable

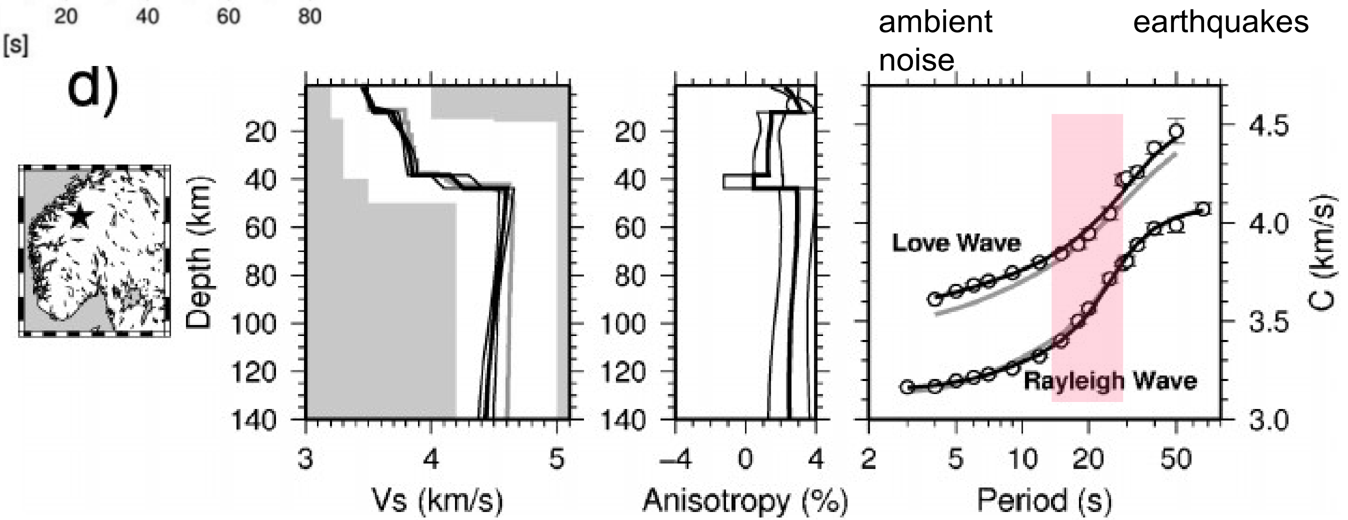
Problem:

- Qualitative error analysis
- Amplitudes

Seismic observables



- Cross correlation of > 12 months of ambient noise recorded at two stations
- Emergence of Greens Function along interstation path
- Surface wave part can be measured as for surface waves



Köhler et al., 2012

Array observables – wavefield imaging

- Source independent
- Interpolating phase observations at dense network
- "parameter-free" Eikonal / Helmholtz "tomography"

Problem:

- Aperture and density of network ↔ frequencies
- Typical edge effects of velocity maps
- Classical inversion for velocity-depth

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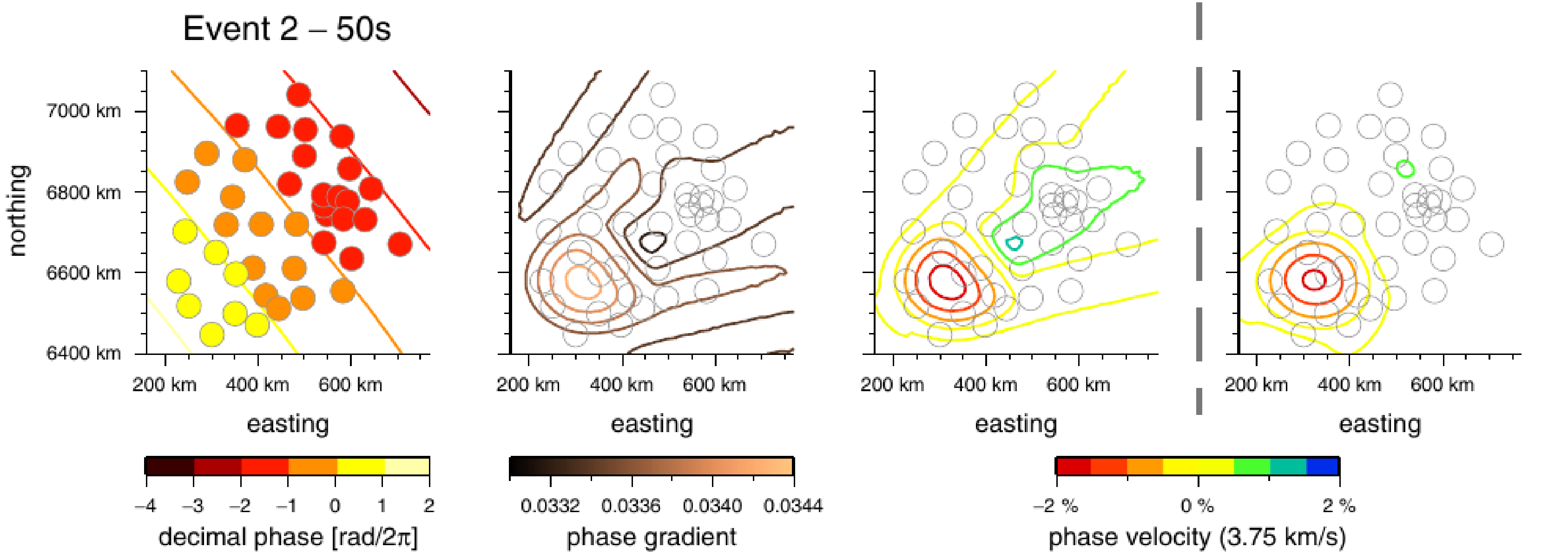
Synthetic experiment $c = 2\pi / (T * |\nabla\varphi|)$



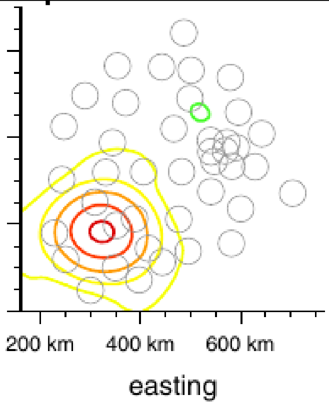
- Anomaly at 70 km depth causes perturbation (scattering) in phase and amplitude of the wavefield
- Stacking of many events from different azimuths (Eikonal tomography)
- Correction of the "dynamic" phase velocity with amplitude term (Helmholtz tomography)

Weidle, 2012

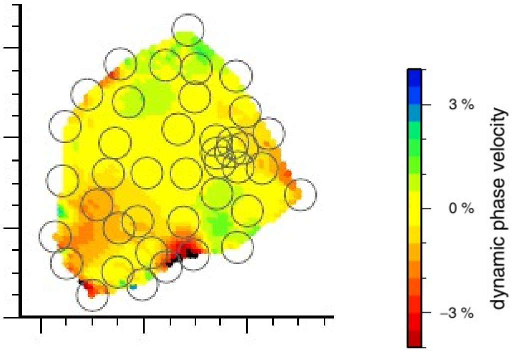
Seismic observables

Synthetic experiment – stacking of 12 (noisy) events

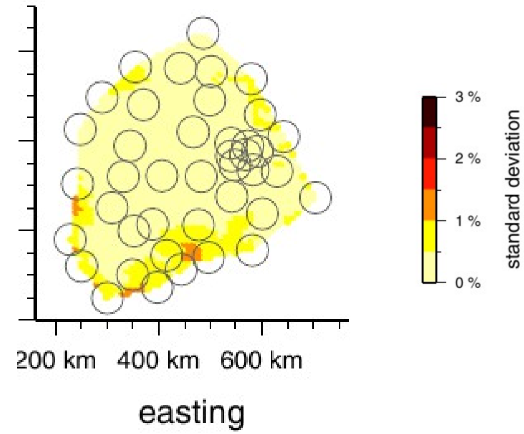
Model



Result



Error



Promising, inversion-free approach
Applicable to dense networks

Weidle, 2012

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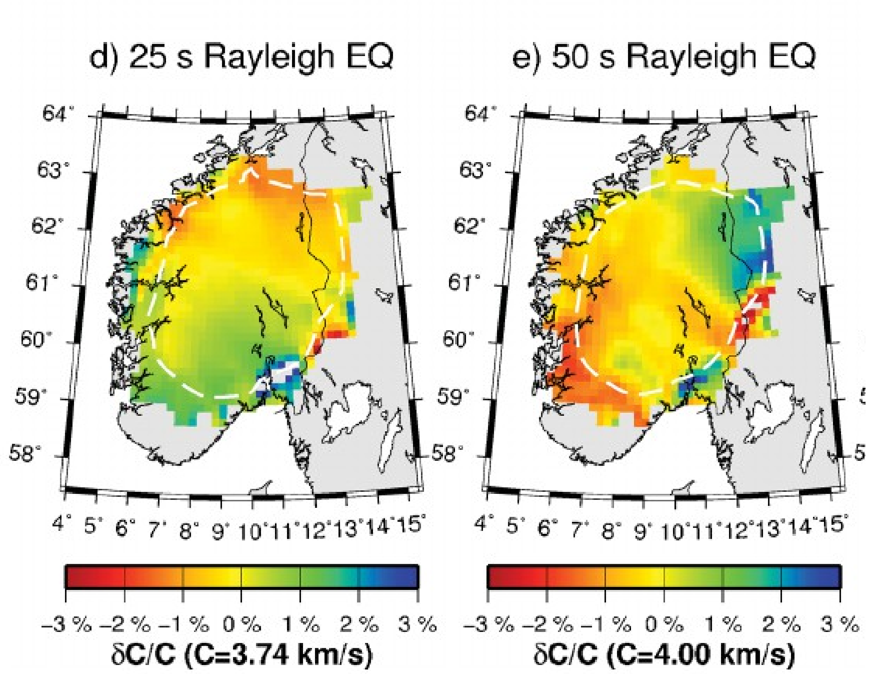
Application to real data

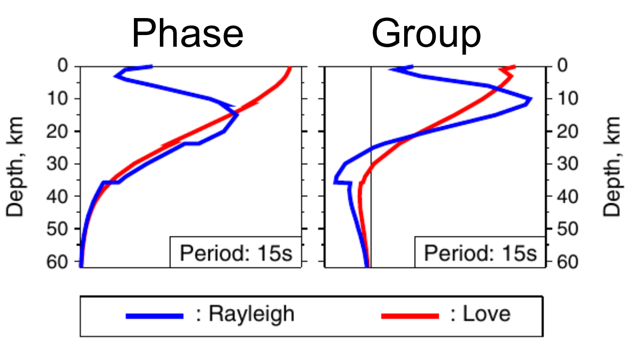


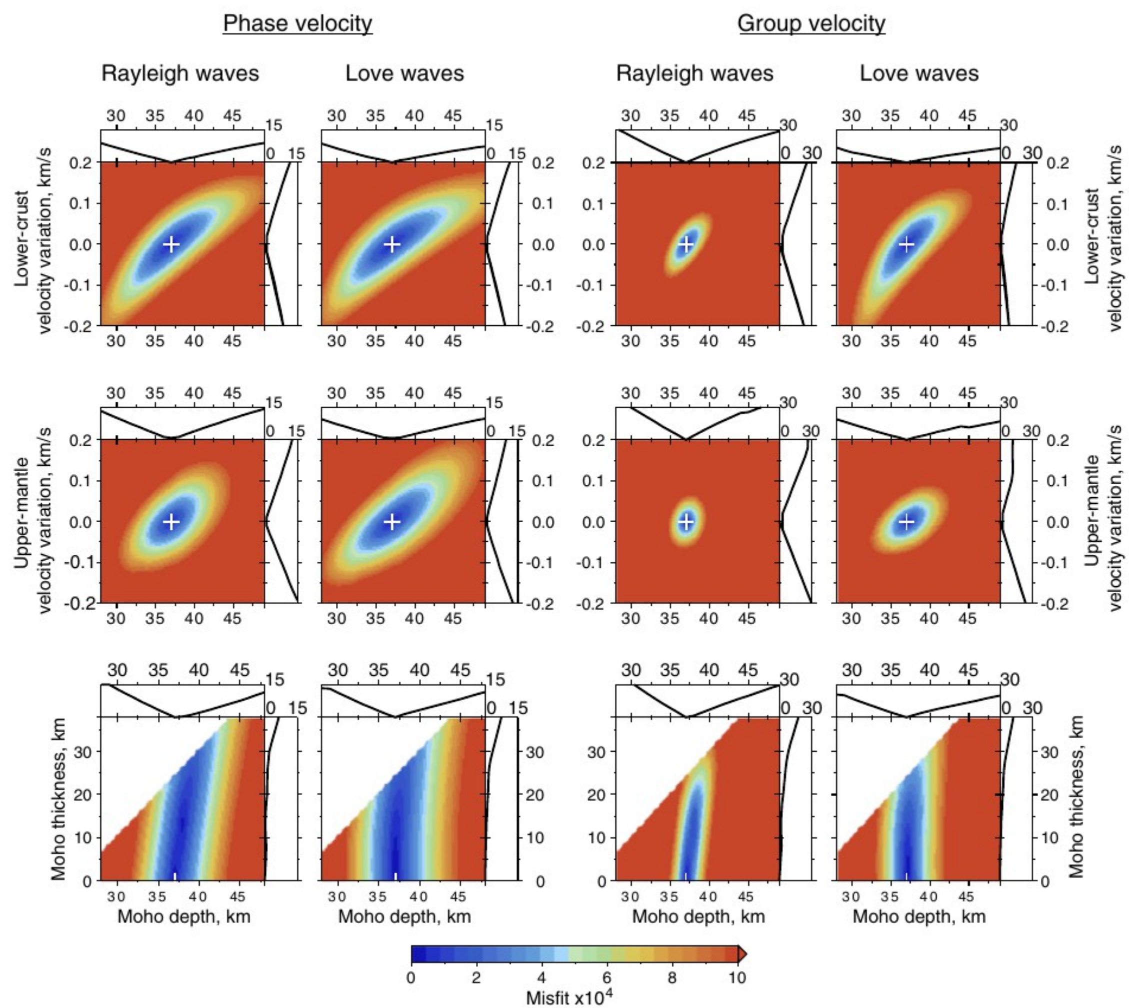
~ Moho ~ 100km

Köhler et al., 2012

Sensitivity of surface waves to Moho depth and thickness

Depth sensitivity





→ surface waves don't see contrasts very well!

Lebedev et al., 2013

Receiver Functions

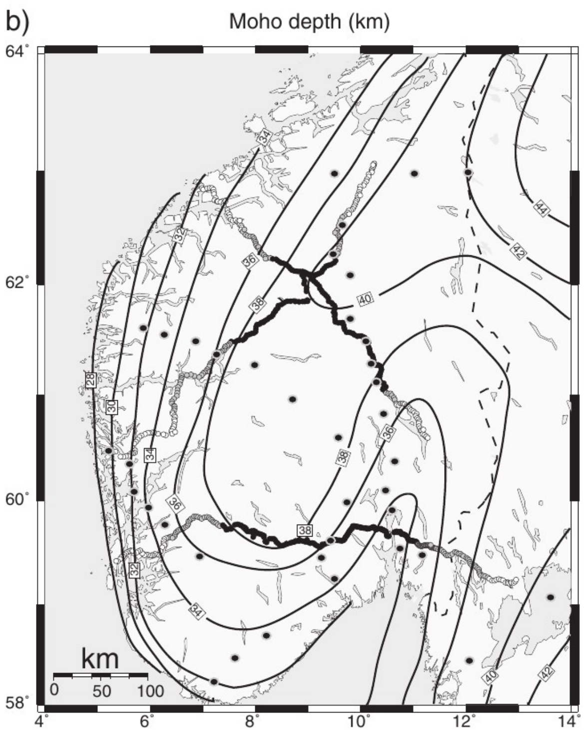
- Single station method
- Best(?) method to determine depths to discontinuities
- Image velocity/impedance contrast

Problem:

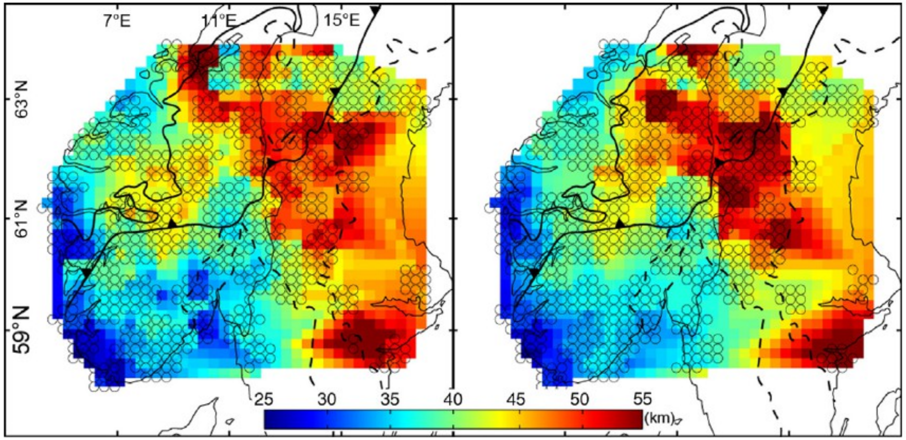
- Trade-off velocity ↔ depth ↔ contrast
- … influences error estimate (→ also filtering)
- qualitative “mismatch” of Moho depths with wide-angle seismics
- Gradual Moho (→ need for joint inv!)
- LAB “100 km” problem → Mid-lithospheric discontinuity

Seismic observables

CSS Moho



RF Moho



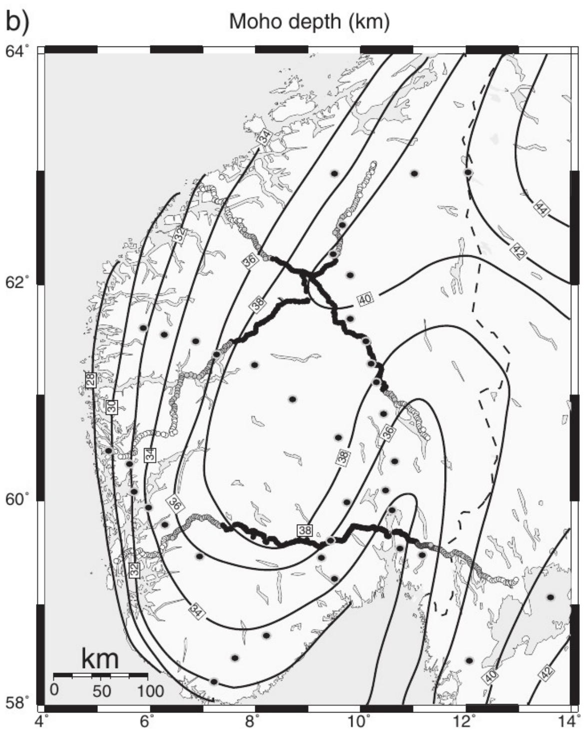
Different filters in deconvolution

Stratford et al., 2011

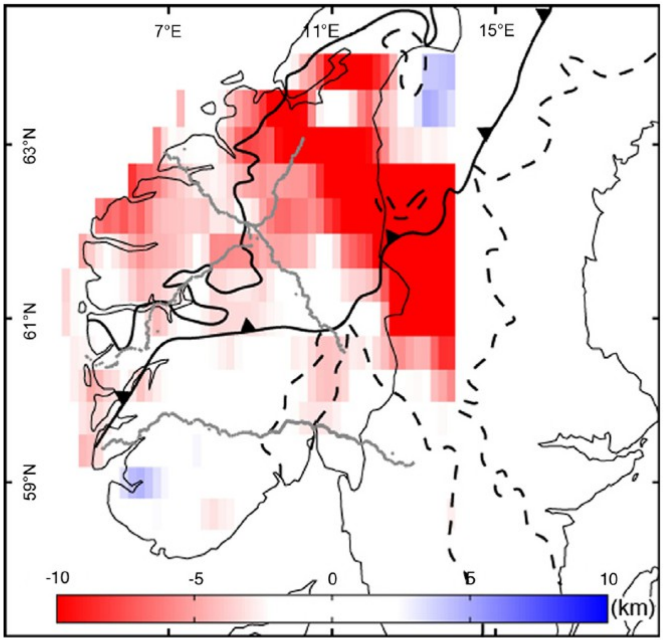
Frassetto & Thybo, 2013

Seismic observables

CSS Moho



RF Moho

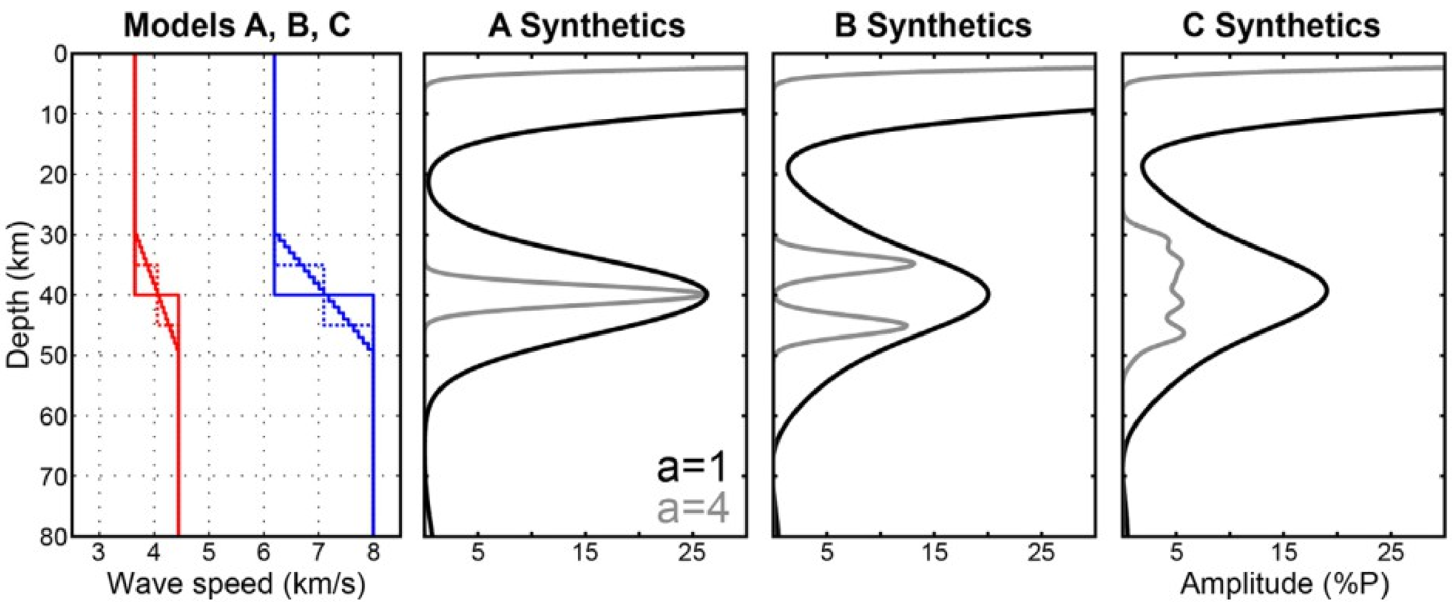


Difference to CSS
→ decrease in conversion amplitude in NE
→ gradual Moho

Stratford et al., 2011

Frassetto & Thybo, 2013

Seismic observables

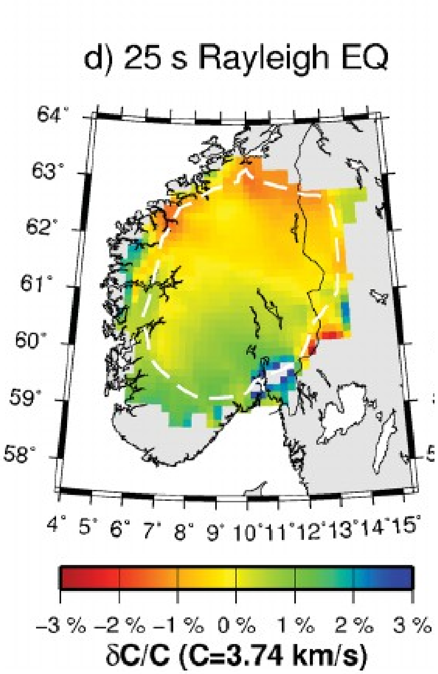


Frassetto & Thybo, 2013

- Joint inversion of surface wave dispersion and Receiver Functions
  - Established approach, resolves
  - … Vs structure with SW
  - … depth of discontinuities with RF

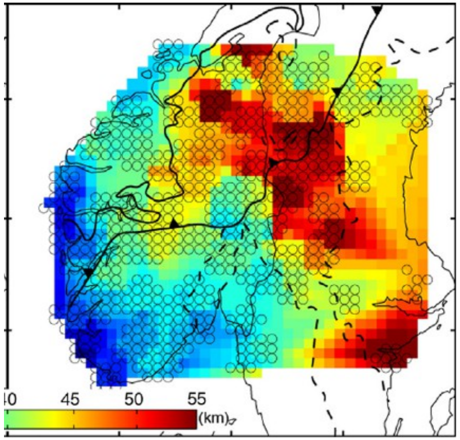
Moho, RF & Surface waves

SW dispersion



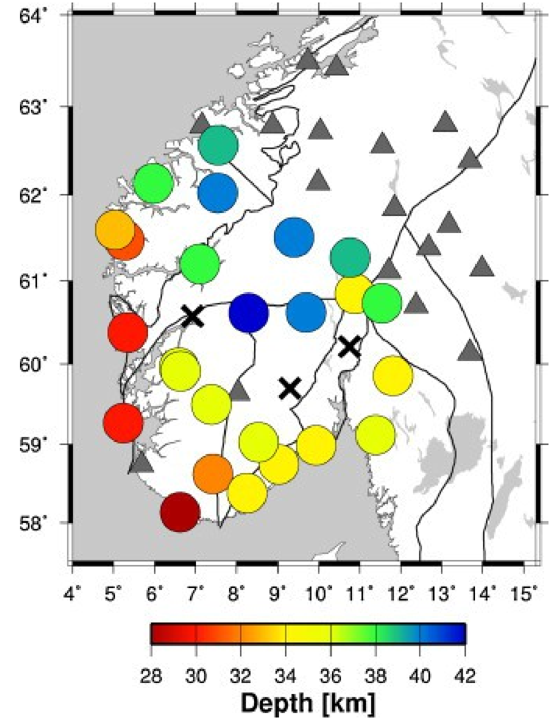
Köhler et al., 2012

RF Moho



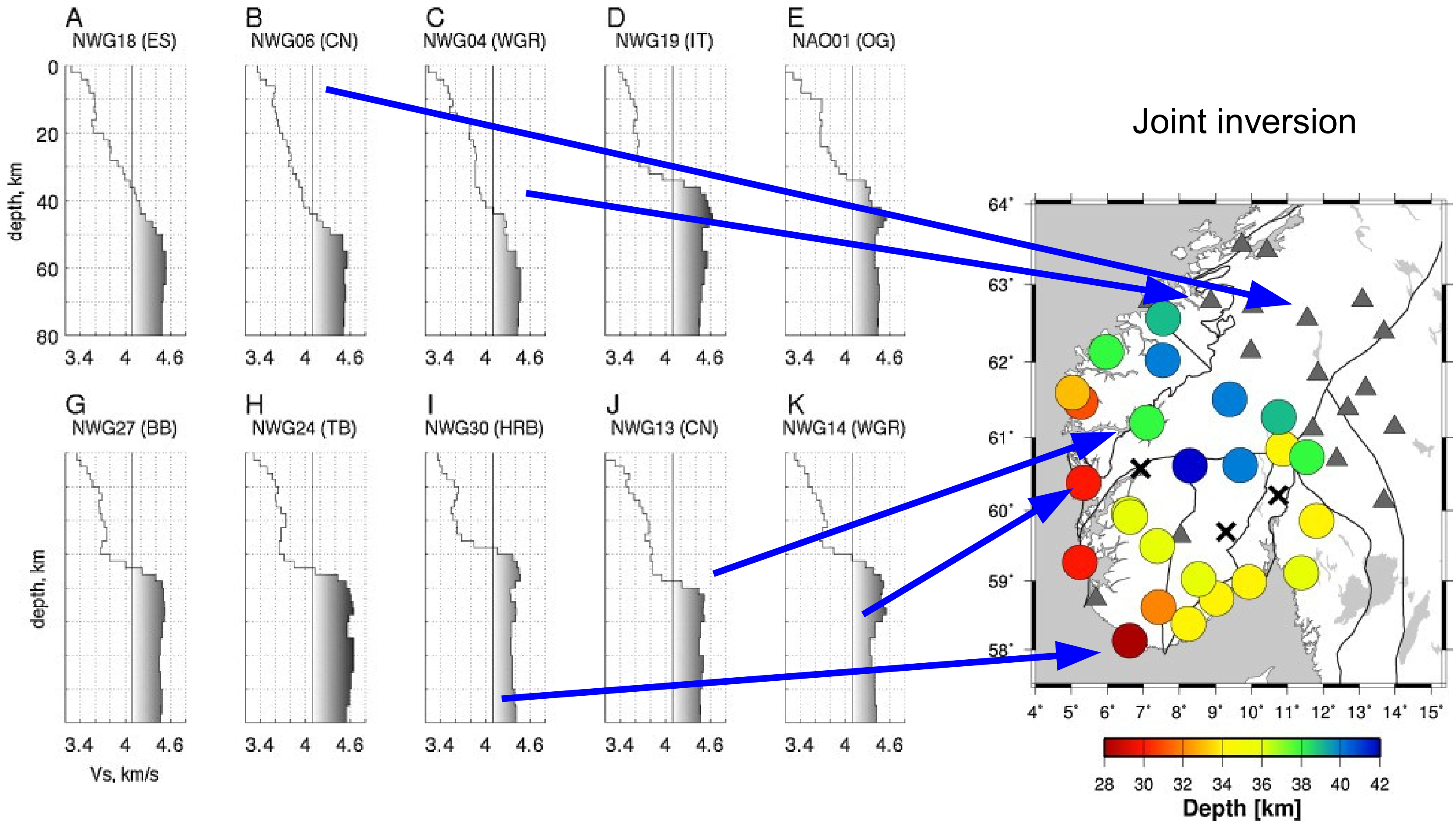
Frassetto & Thybo, 2013

Joint inversion



Kolstrup & Maupin, 2013

Moho, RF & Surface waves



Kolstrup & Maupin, 2013

Receiver Functions

- Single station method
- Best(?) method to determine depths to discontinuities
- Image velocity/impedance contrast

Problem:

- Trade-off velocity ↔ depth ↔ contrast
- … plus filters → influences error estimate
- qualitative "mismatch" of Moho depths with wide-angle seismics
- gradual Moho (→ find better method)
- LAB "100 km" problem → Mid-lithospheric discontinuity

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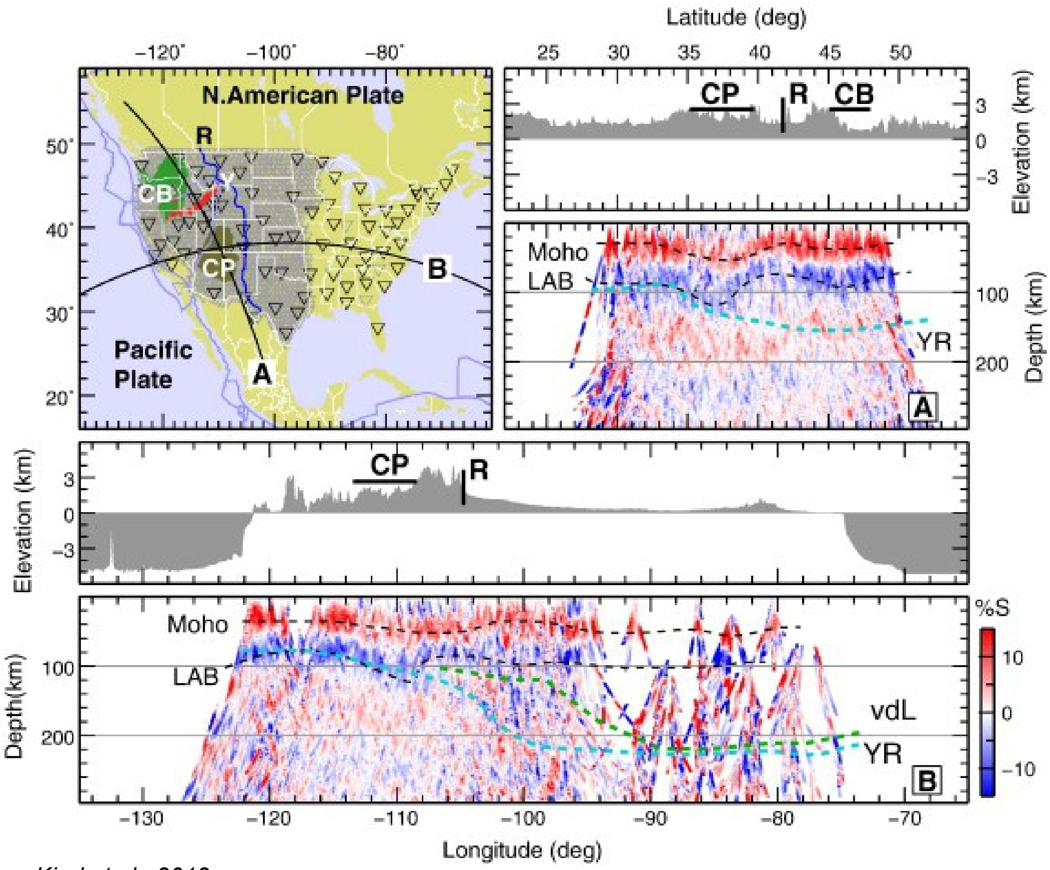
RF LAB "problem"

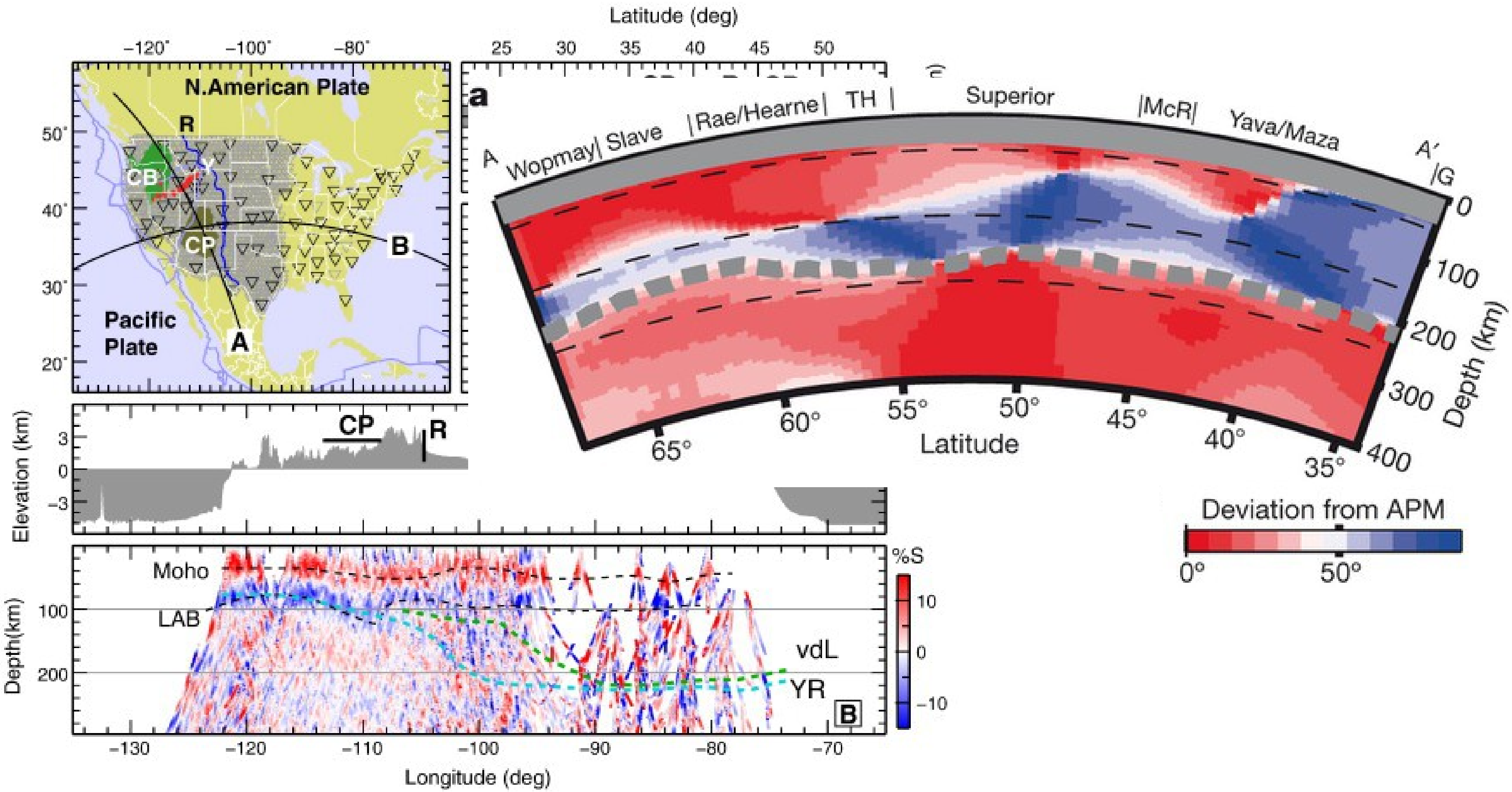


Kind et al., 2012

Seismic observables

RF LAB “problem”

Anisotropy from surface waves



Kind et al., 2012

Yuan & Romanowicz, 2010

Seismic observables

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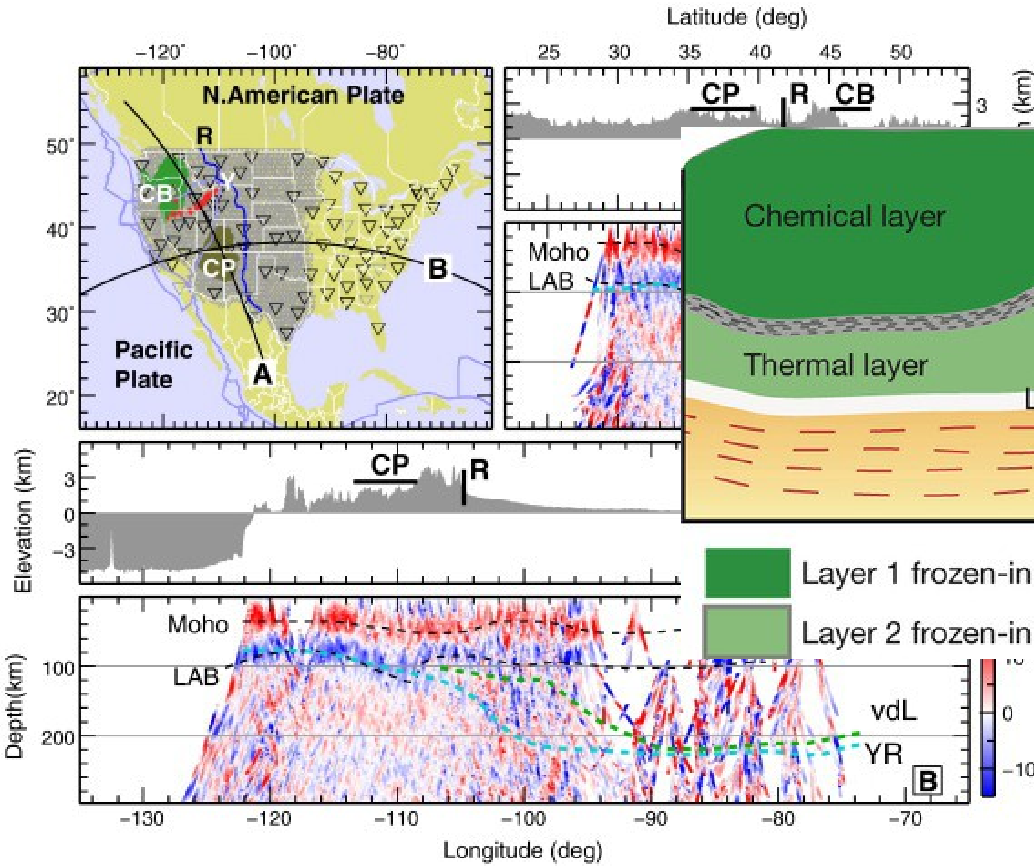
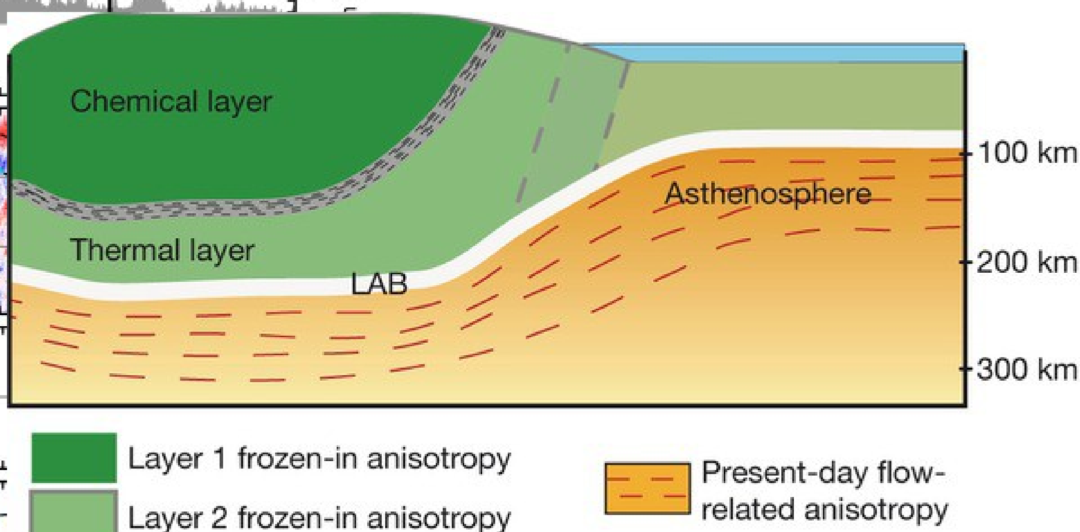
RF LAB "problem"



Kind et al., 2012

Anisotropy from surface waves



Yuan & Romanowicz, 2010

Theory light

The perfect world:

$$\mathbf{G} \bullet \overline{m} = \overline{d}$$

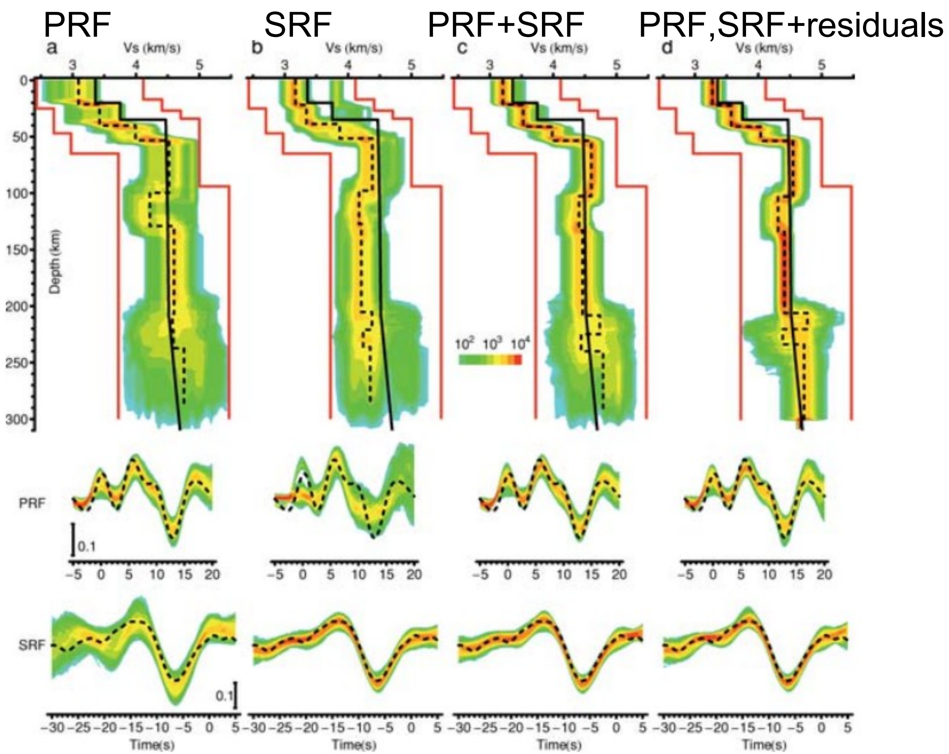
$\underline{\mathbf{G}}$: Full resolution 3-D seismic wavefield
$\overline{m}$: “mm-scale” model of physical parameters
$\overline{d}$: error-free data

The *real* world:

$$(\mathbf{G} * \sigma_{\mathbf{G}}) \bullet (\overline{m} * \sigma_m) = \overline{d} + \sigma_d \qquad \rightarrow \text{regularization}$$

“Filters”:
$\sigma_{\mathbf{G}}$: approximation in wave propagation, e.g. ray theory, forward scattering, fundamental modes
σ_m: model parameterization, geometric and selection of parameters (e.g. velocity, attenuation)
σ_d: data limitations, e.g. measurement, frequency content, ...

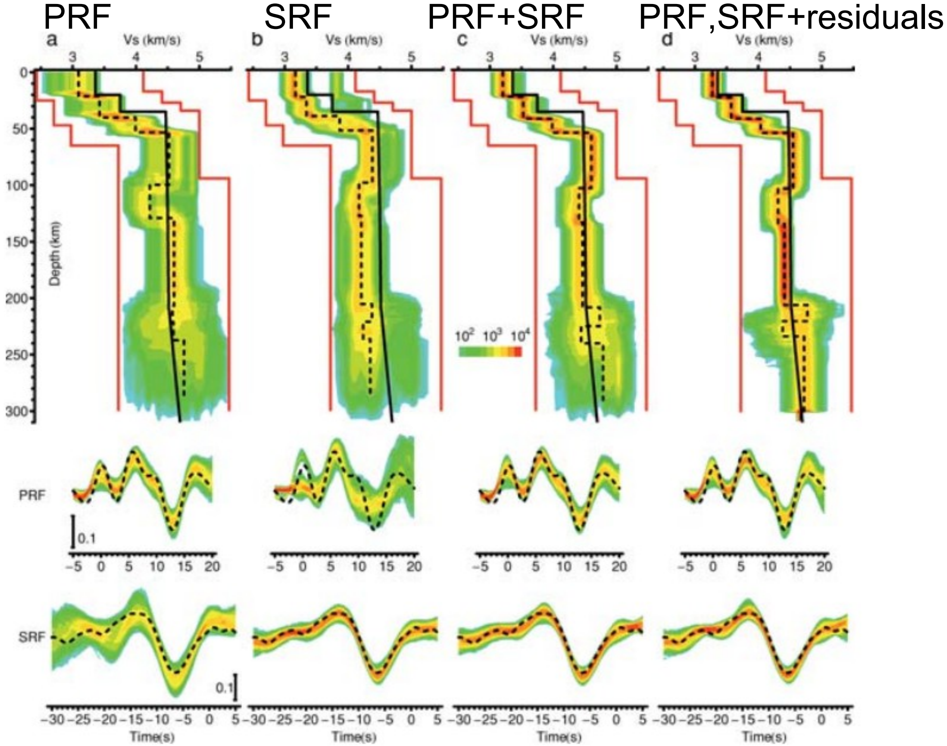
- Joint P & S Receiver Functions
  - Plus P & S traveltime residuals → vp, vs, vp/vs models

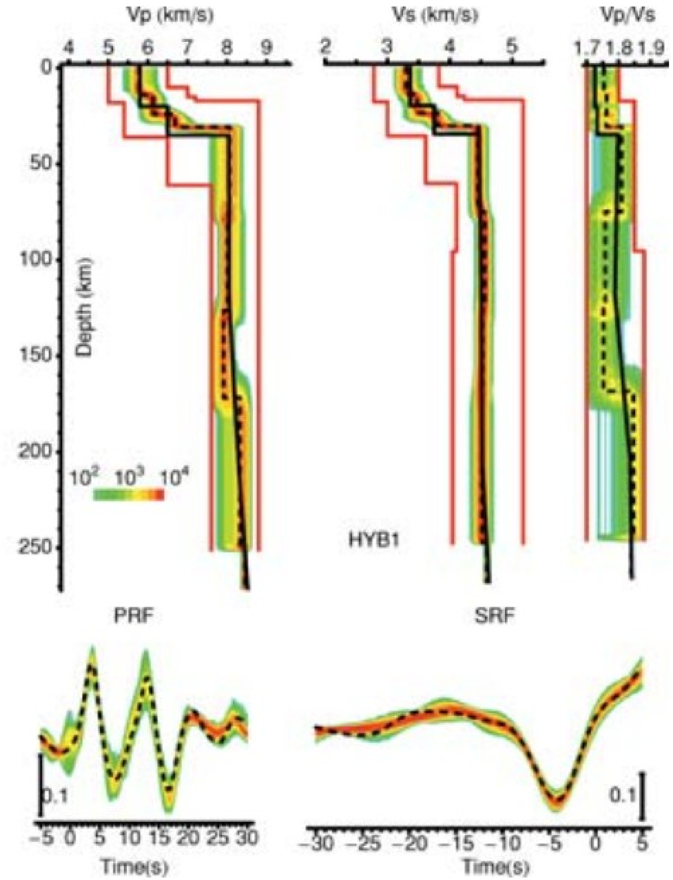


Kiselev et al., 2008

Promising examples

- Joint P & S Receiver Functions
  - Plus P & S traveltime residuals → vp, vs, vp/vs models
  - Propagation of errors into weakest parameter → vp/vs

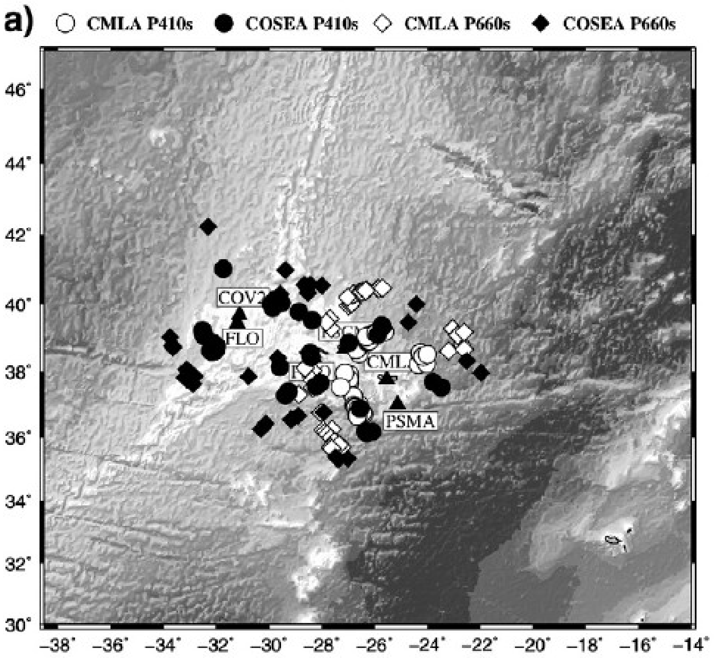


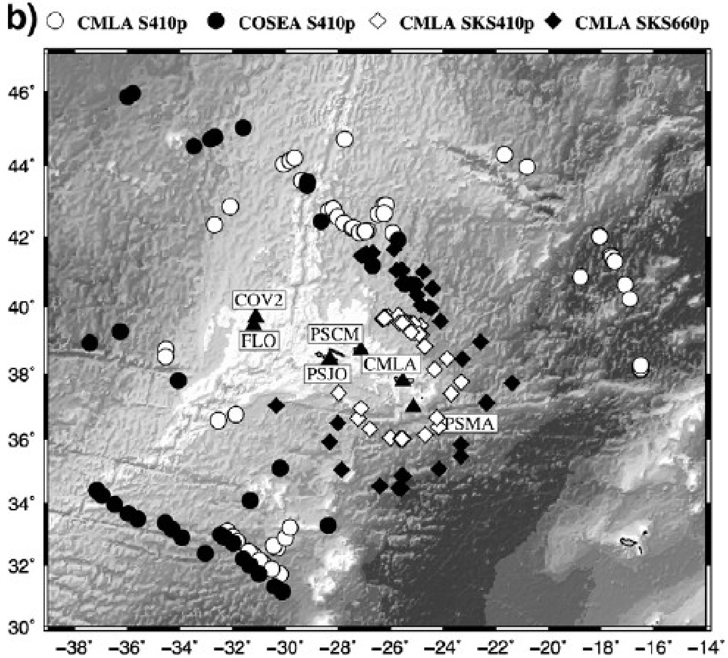


Kiselev et al., 2008

Promising examples

- Joint P & S Receiver Functions
  - Plus P & S traveltime residuals → vp, vs, vp/vs models
  - Propagation of errors into weakest parameter → vp/vs





Silveira et al., 2010

Summary

- Methods:
  - Body wave traveltimes: robust, large-scale, high-resolution (onshore), joint inversion (P&S) feasible
  - Receiver Functions: image depth to discontinuities, tradeoff to velocities, interpretation with other methods, highly suited for joint inversion
  - Surface wave dispersion: robust, large-scale, frequencies for entire lithosphere, strong sensitivity for anisotropy (azimuthal and radial)
  - Waveforms: robust at long to intermediate periods, deeper lithosphere, needs good starting model to converge
  - Wavefield imaging: no inversion, dense networks, tradeoff network geometry – frequencies, high (crustal) frequencies challenging
  - Ambient noise: stable, high frequency extension of earthquake based surface wave observations (→ upper crust)

Summary

- Targets:
  - (upper) crust: ambient noise, Pg/Sg traveltimes
  - Crust & Moho depth: Pn/Sn traveltimes, ambient noise + surface waves, Receiver Functions
    - Anisotropy: surface waves (+ambient noise)
  - Mantle lithosphere: body & surface wave tomography, waveforms, wavefields, Receiver Functions
    - Anisotropy: surface waves (EQ based), SKS splitting

Summary

- Joint inversion and interpretations:

$$(\mathbf{G} * \sigma_{\mathbf{G}}) \bullet (\overline{m} * \sigma_m) = \overline{d} + \sigma_d$$

  - Keep problem in all terms as consistent as possible → merge results from different methods
  - Consistent parameterization often already a big step forward
  - Need for consistent data sets
  - Consistent uncertainties
  - Still there are different sensitivities ...