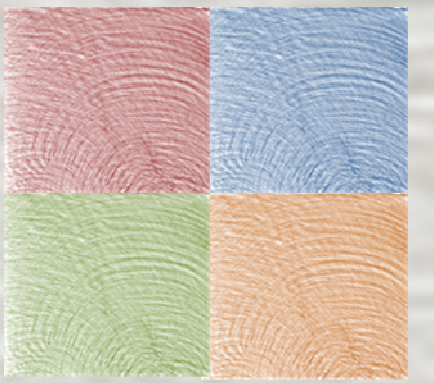
Teleseismic Interferometry

Measurement and model-space-map inversion of very-broadband dispersion of surface waves



Sergei Lebedev, Thomas Meier

Dublin Institute for Advanced Studies
Christian Albrechts University of Kiel

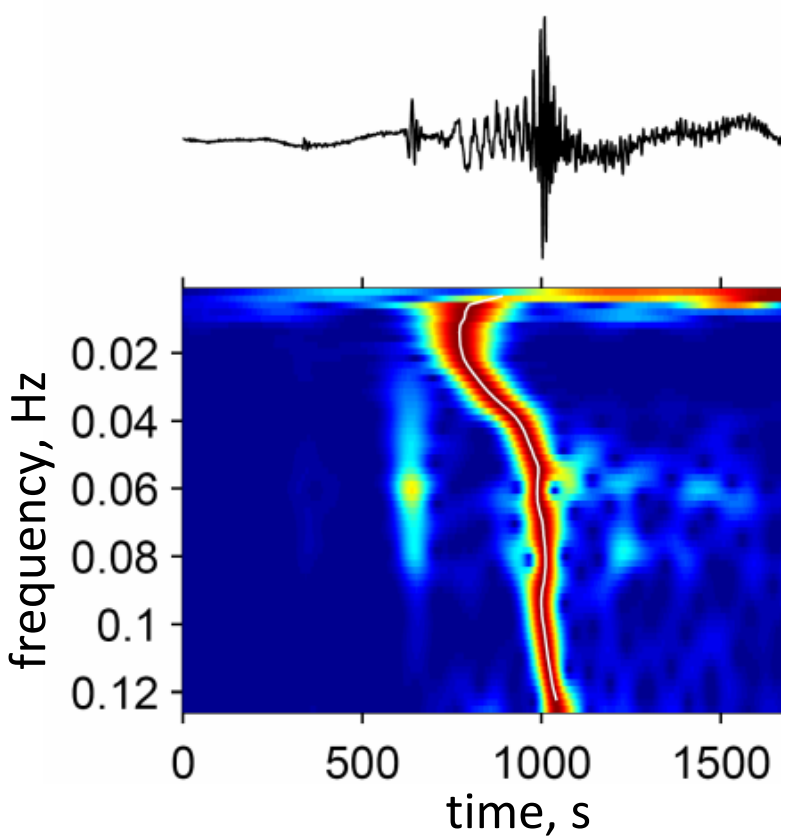
Surface waves

Oldham (1899):

- Rayleigh waves identified on seismic recordings.

Wiechert (1899):

- velocities of the “main waves” could be used to study the properties of the outer shells of the Earth, by measuring phase differences between signals at nearby stations.



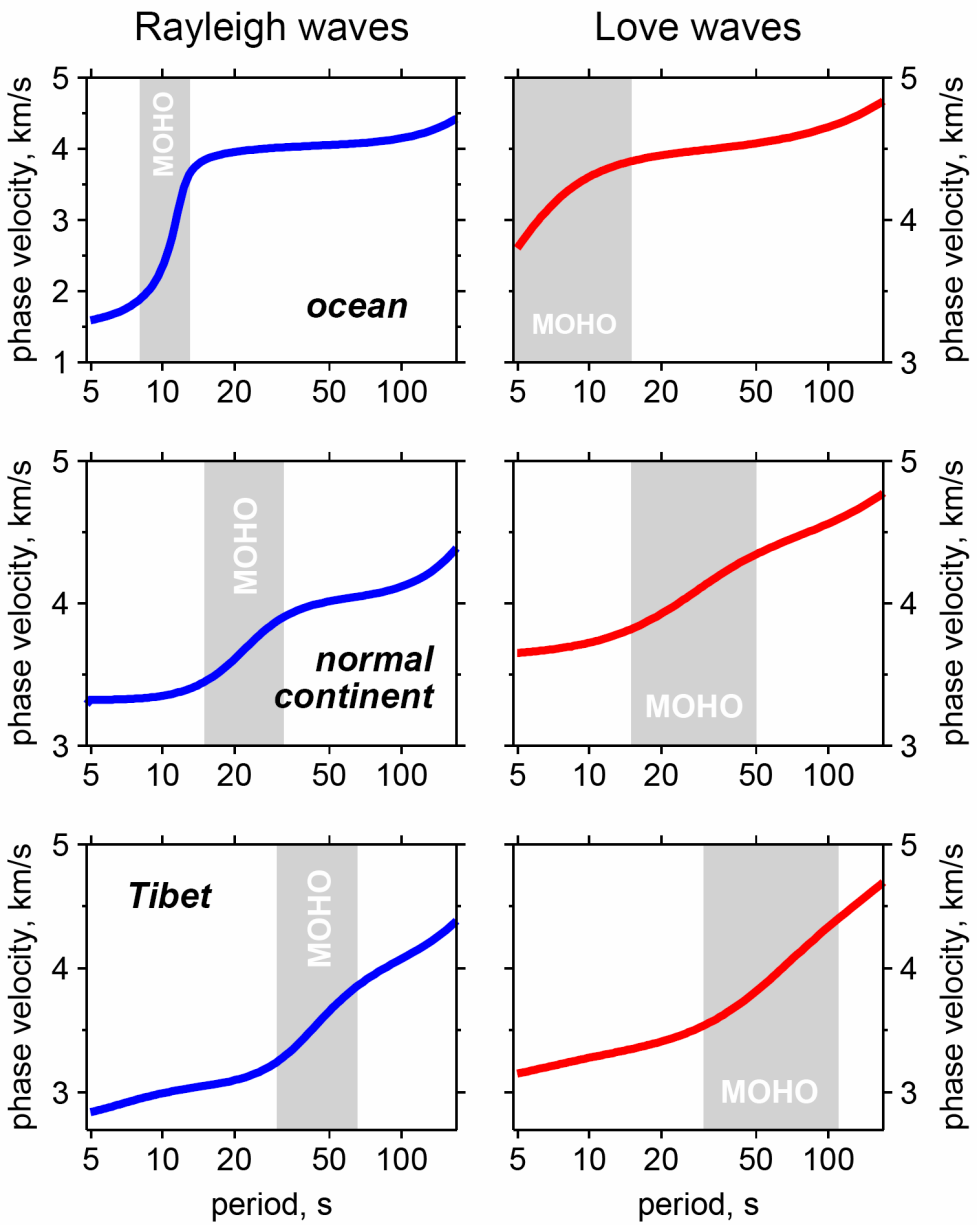
Surface waves

Oldham (1899):

- Rayleigh waves identified on seismic recordings.

Wiechert (1899):

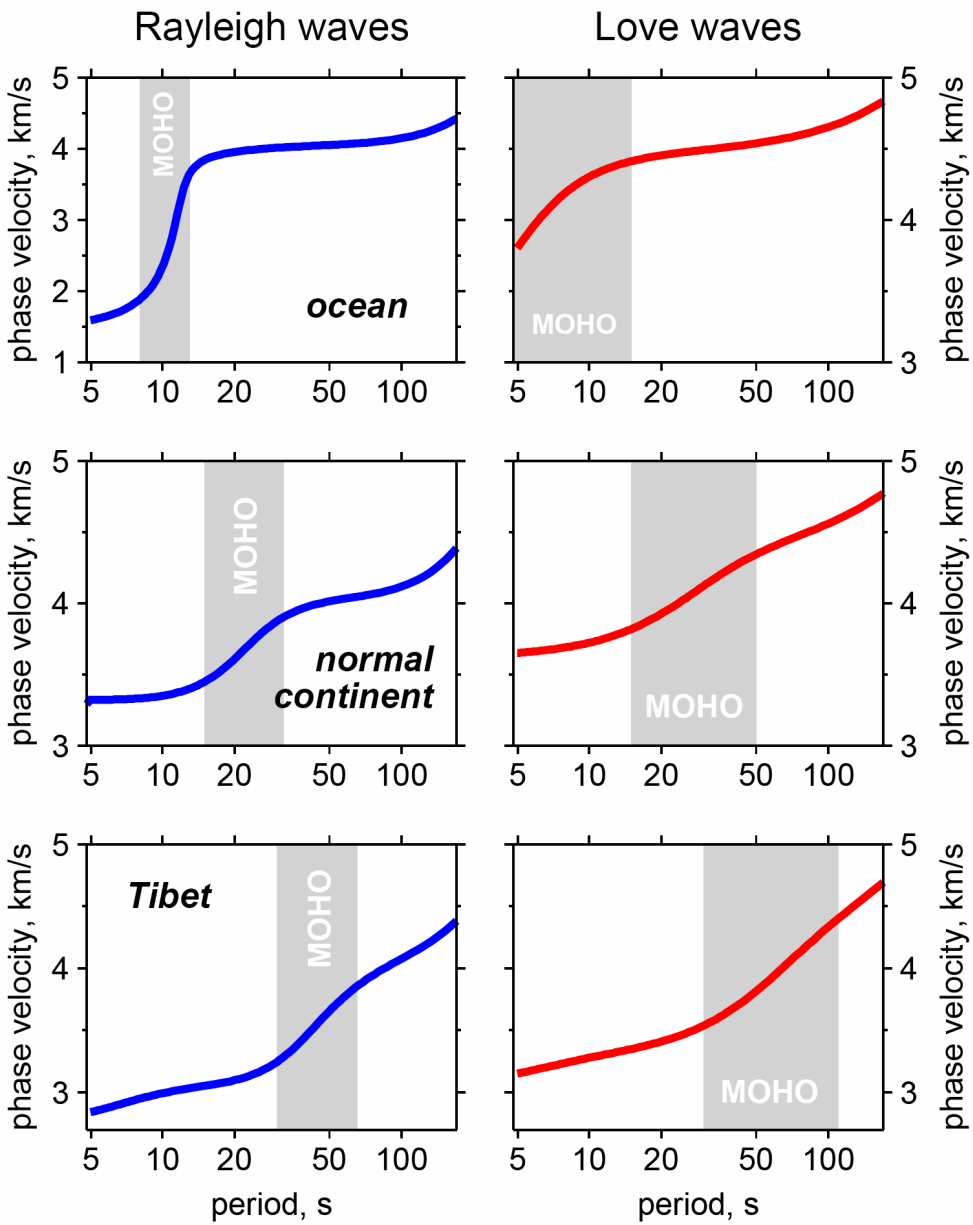
- velocities of the “main waves” could be used to study the properties of the outer shells of the Earth, by measuring phase differences between signals at nearby stations.



Surface waves

Meissner (1926):

- non-uniqueness of the inversion of surface-wave dispersion curves;
- examples of different 1-D Earth models with similar dispersion curves
- highly accurate measurements using dense networks will be required in order to determine the structure of the outer layers of the Earth

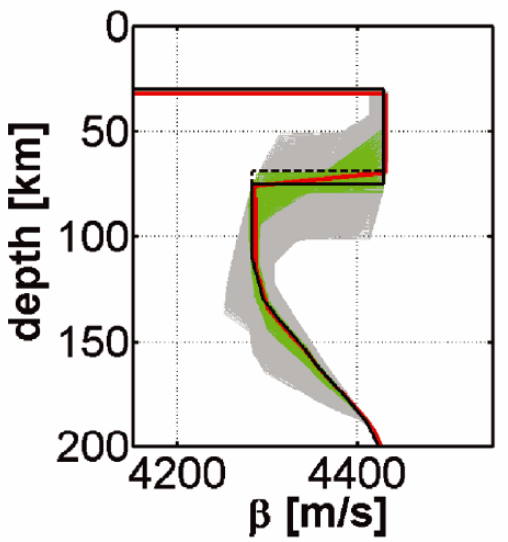


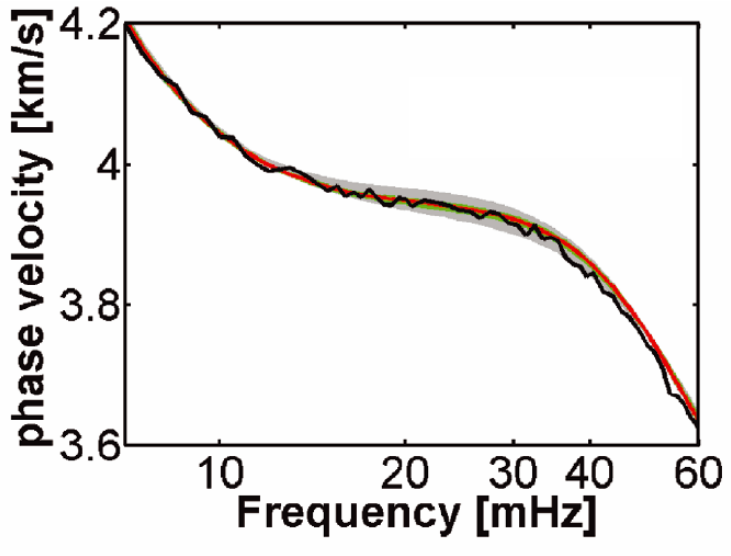
Surface waves

Meissner (1926):

- non-uniqueness of the inversion of surface-wave dispersion curves;
- examples of different 1-D Earth models with similar dispersion curves

- highly accurate measurements using dense networks will be required in order to determine the structure of the outer layers of the Earth





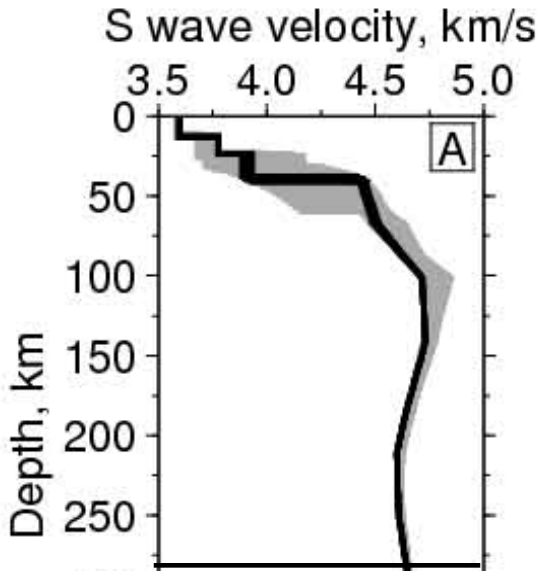
Bartzsch, Lebedev, Meier, 2011

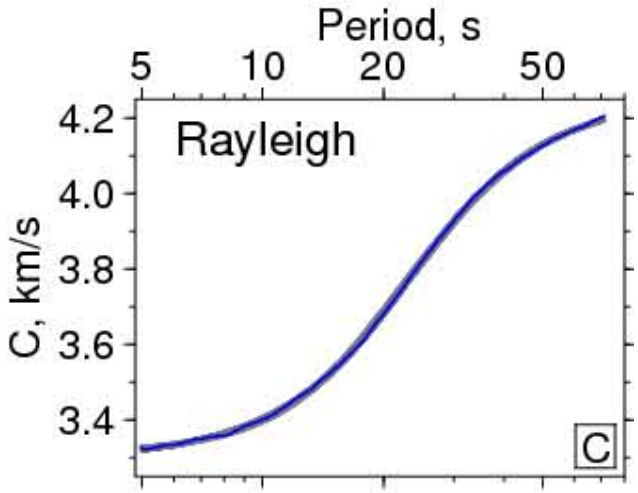
Surface waves

Meissner (1926):

- non-uniqueness of the inversion of surface-wave dispersion curves;
- examples of different 1-D Earth models with similar dispersion curves

- highly accurate measurements using dense networks will be required in order to determine the structure of the outer layers of the Earth





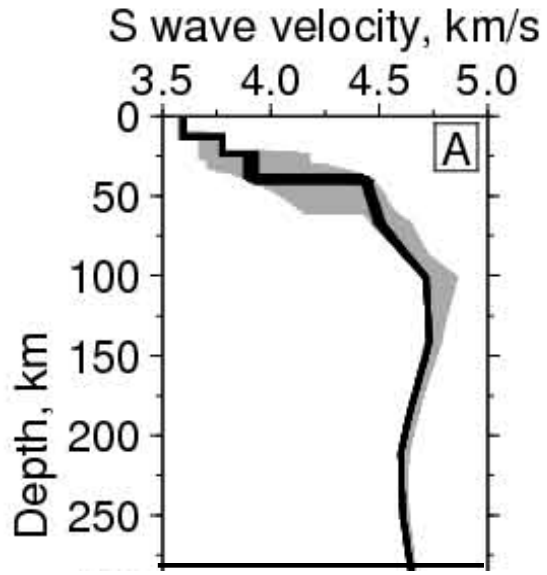
Lebedev, Adam, Meier, in prep

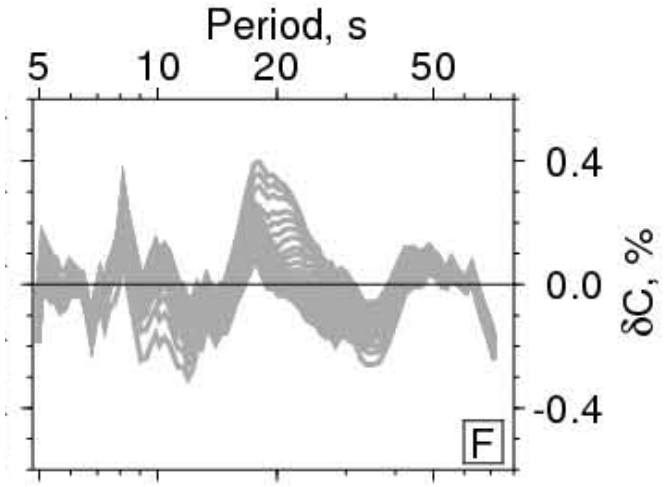
Surface waves

Meissner (1926):

- non-uniqueness of the inversion of surface-wave dispersion curves;
- examples of different 1-D Earth models with similar dispersion curves

- highly accurate measurements using dense networks will be required in order to determine the structure of the outer layers of the Earth





Lebedev, Adam, Meier, in prep

Surface-wave imaging = Quest for information

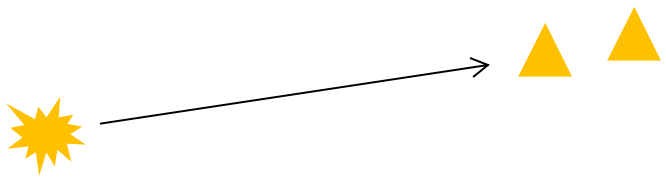
Surface-wave imaging = Quest for information

= Quest for accurate measurements in a broad period range

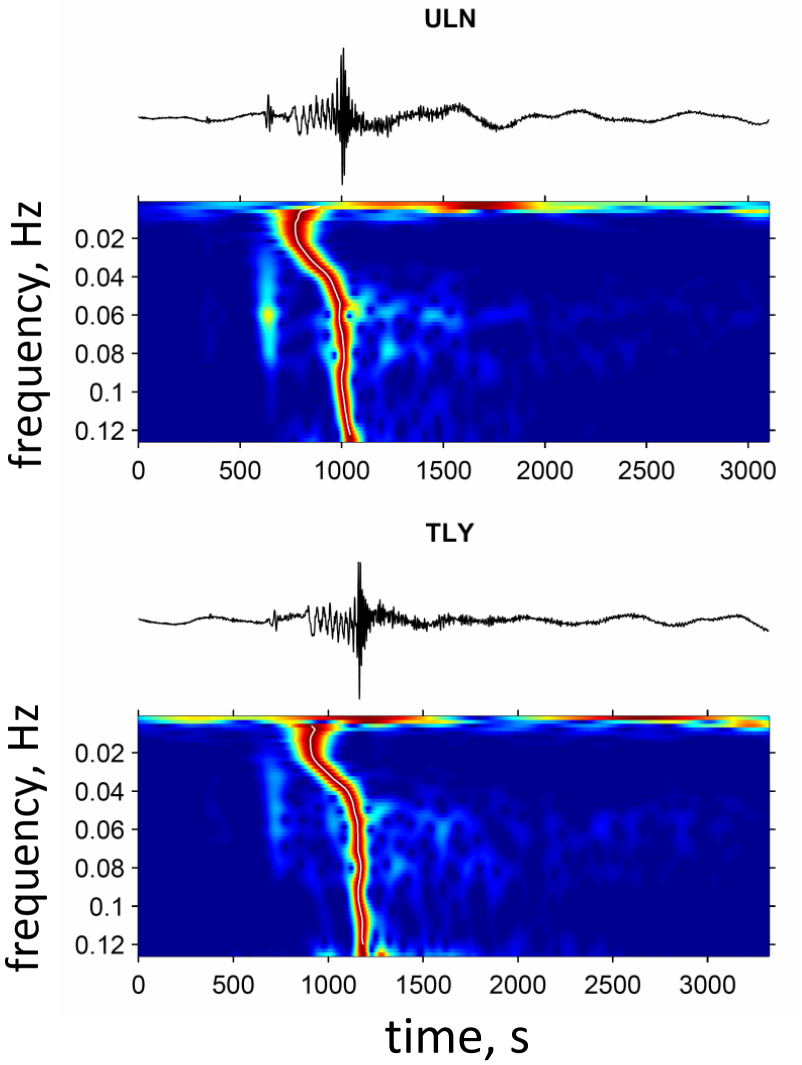
+ Quest for accurate relationships of the measurements to Earth structure

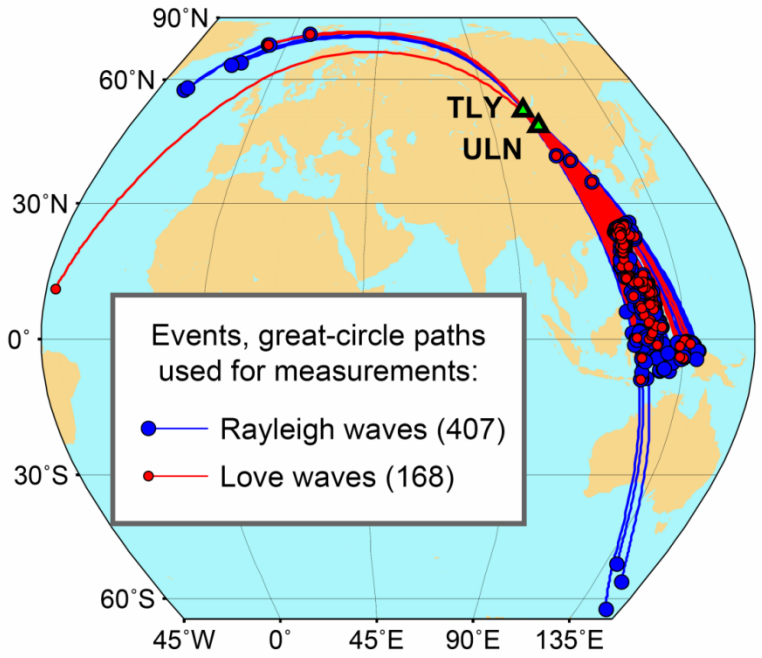
Inter-station phase-velocity measurements:
The classical two station method

- Two-station method in the frequency domain: *Sato (1955)*
- Yields an average phase-velocity curve along a path between two stations
- Needs sources on the same great circle path with the two stations
- Effects of the source mechanism and the structure away from the station pair are removed
- Surface waves should not be strongly diffracted; the method is not applicable at periods below 15-20 s

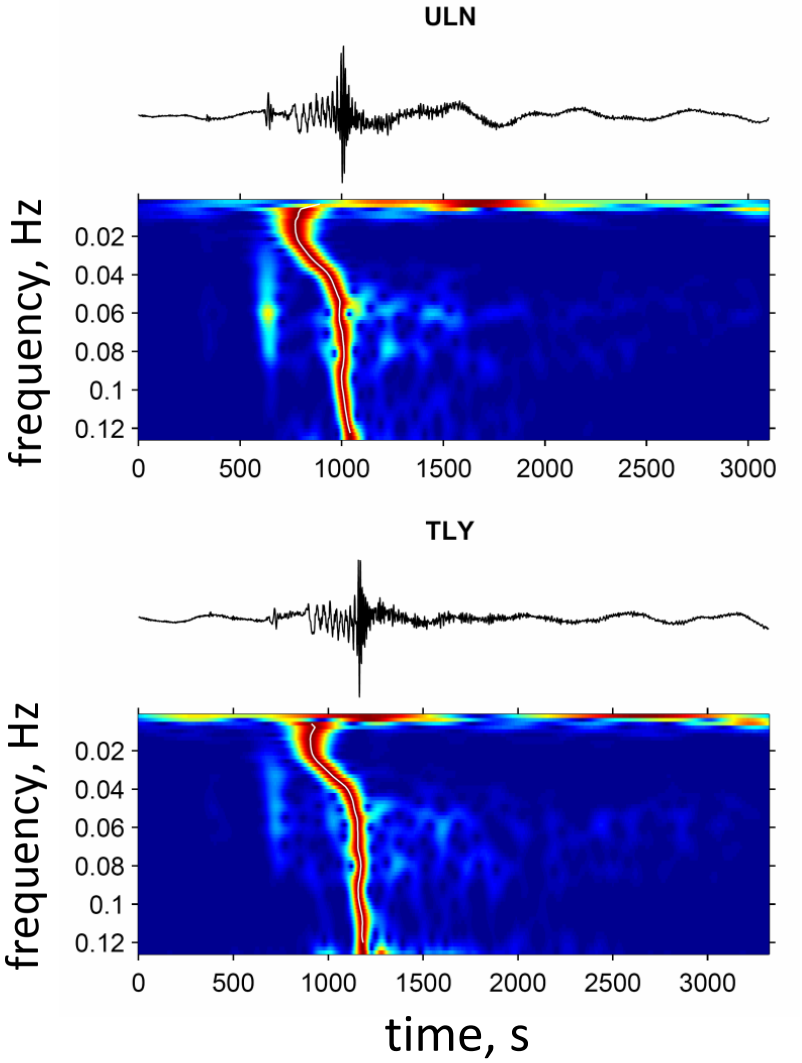


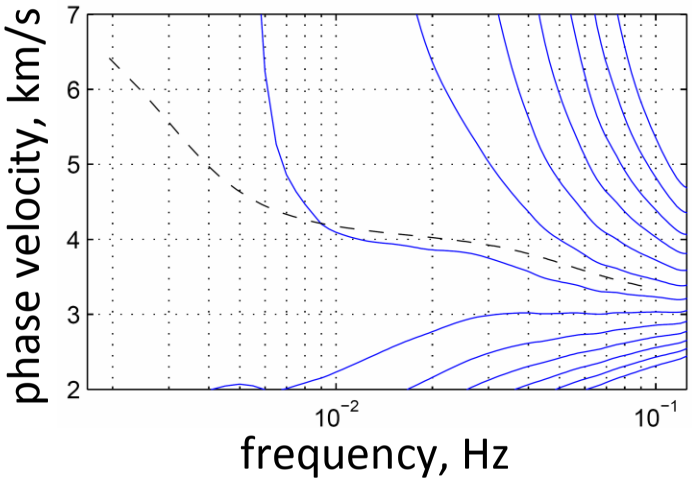
Inter-station phase-velocity measurements

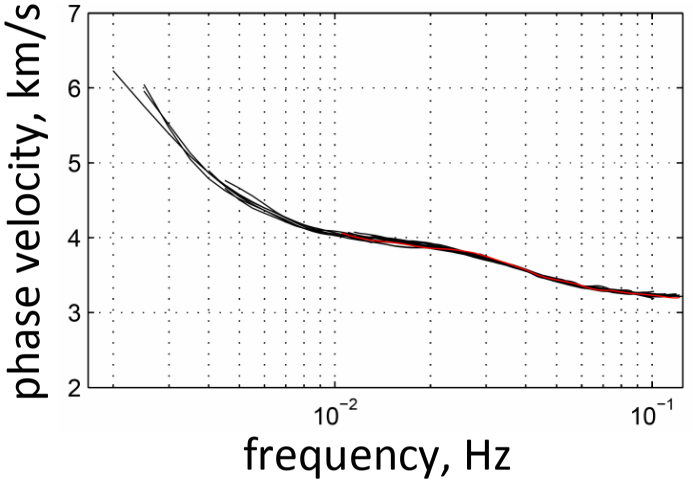




Inter-station phase-velocity measurements

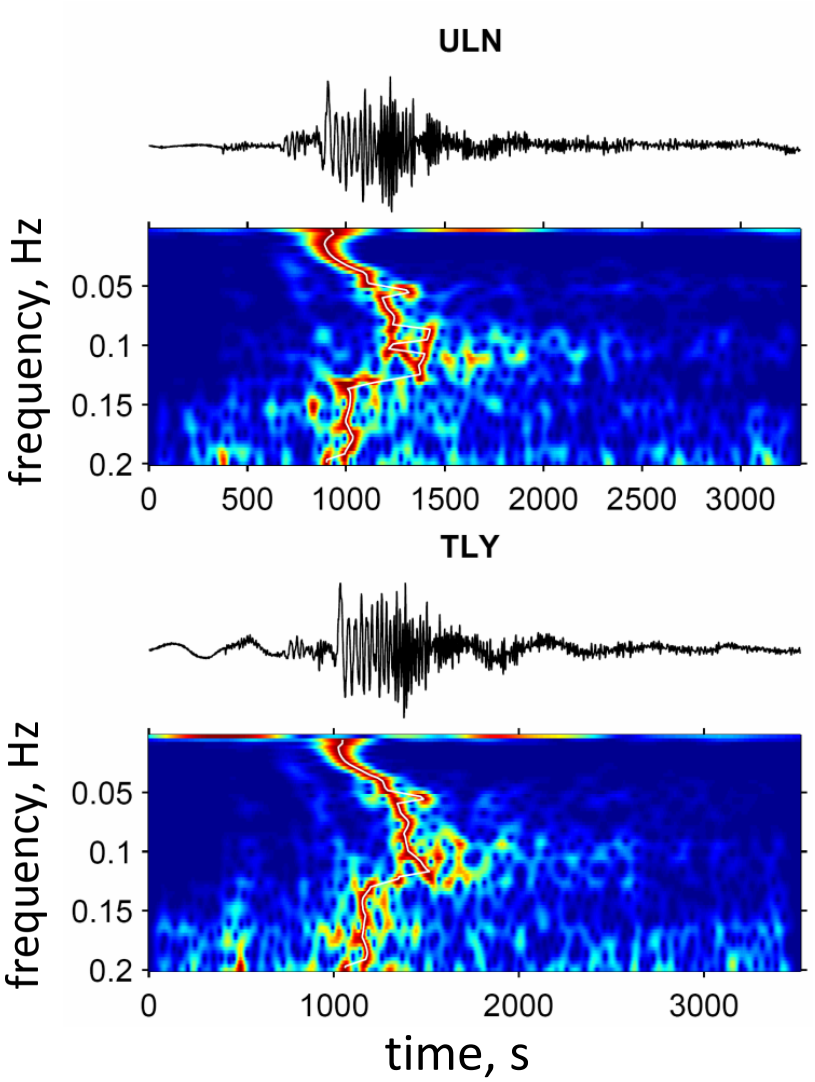


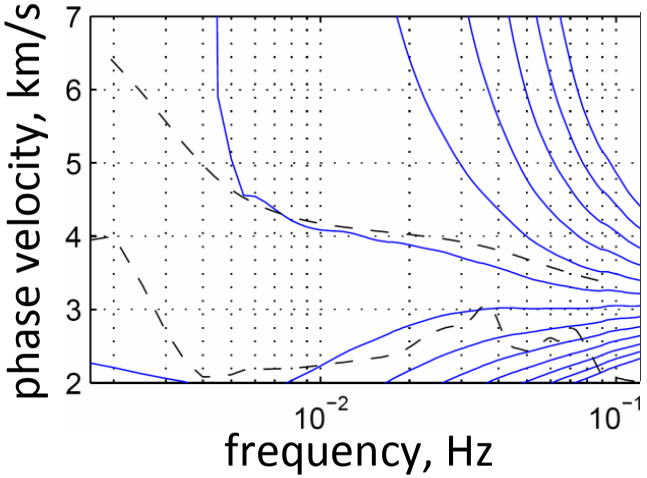


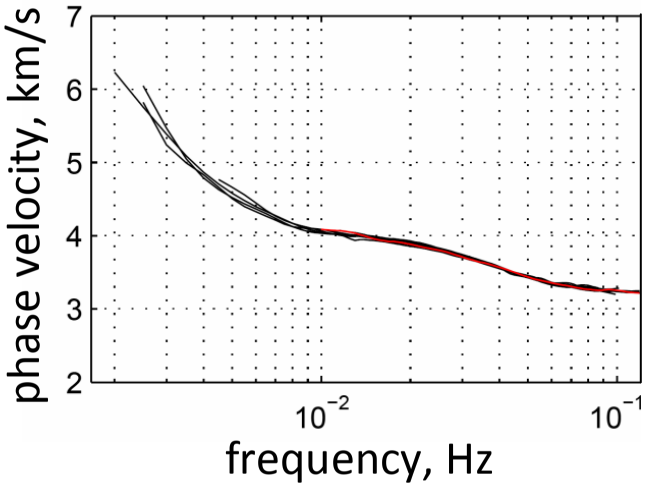


Method, implementation by *Meier et al.,* 2004

Cross-correlating diffracted waves

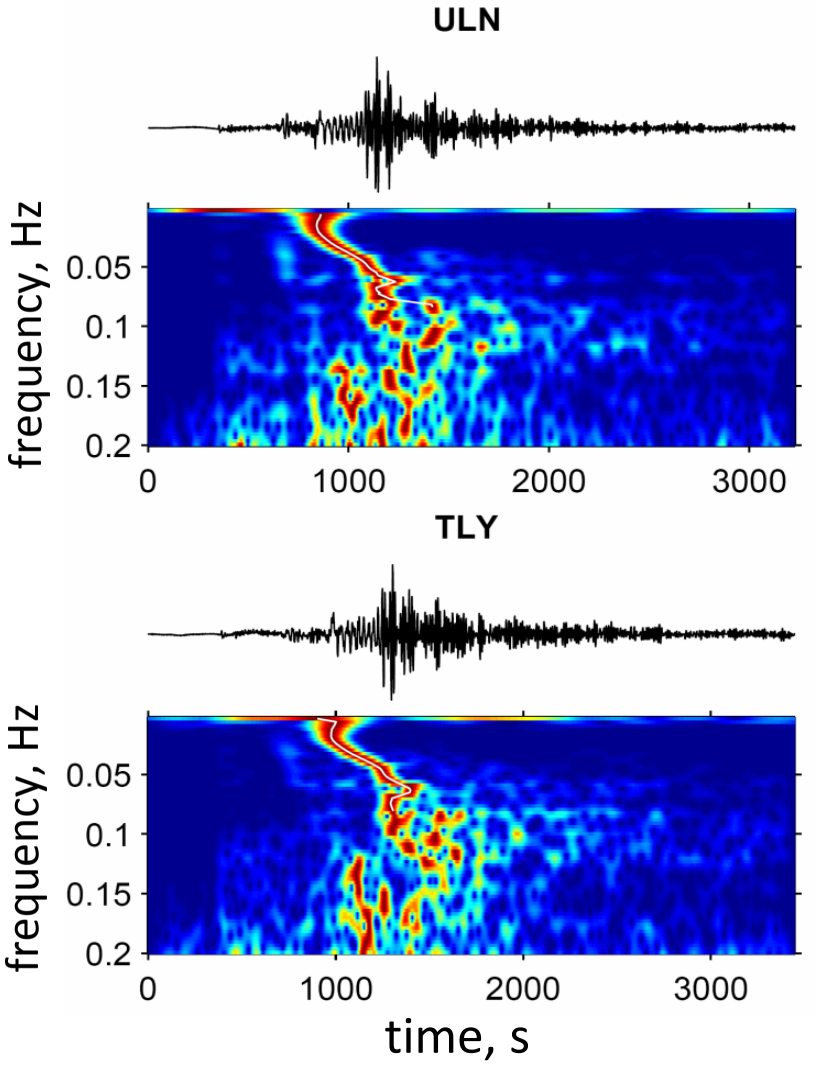


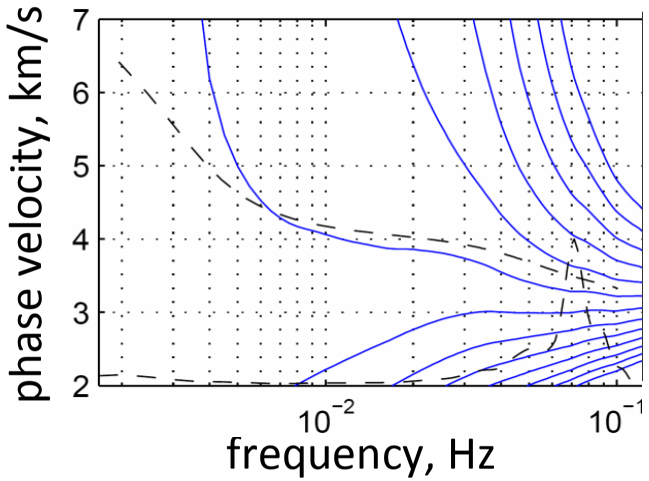


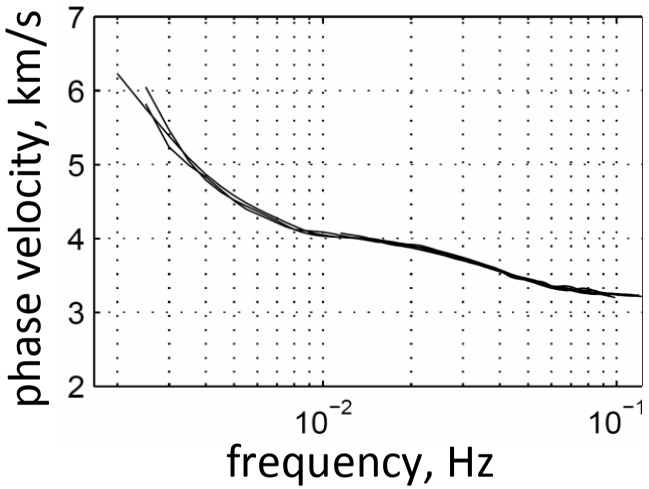


Method, implementation by *Meier et al.,* 2004

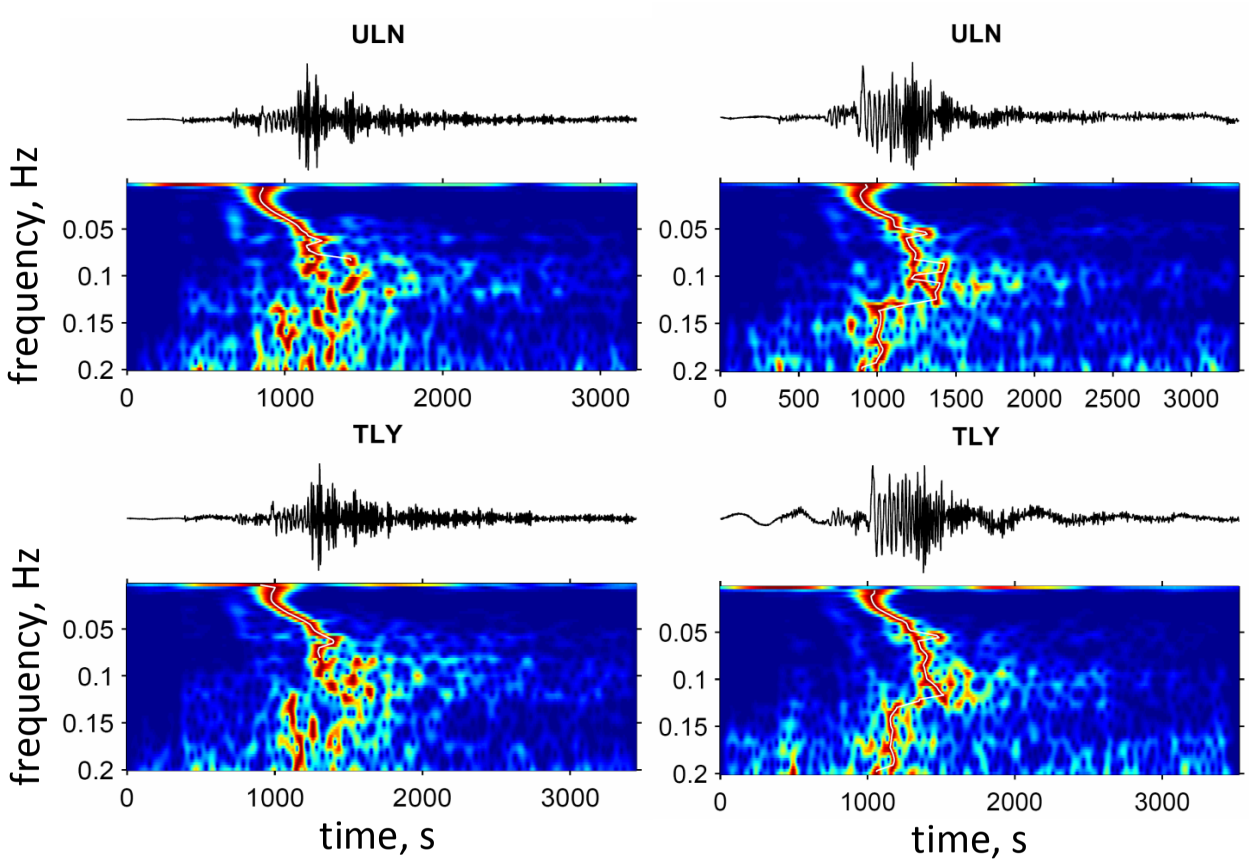
Cross-correlating diffracted waves

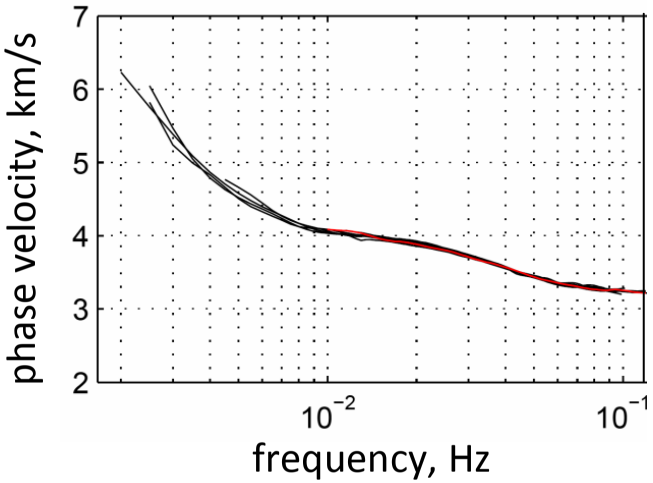


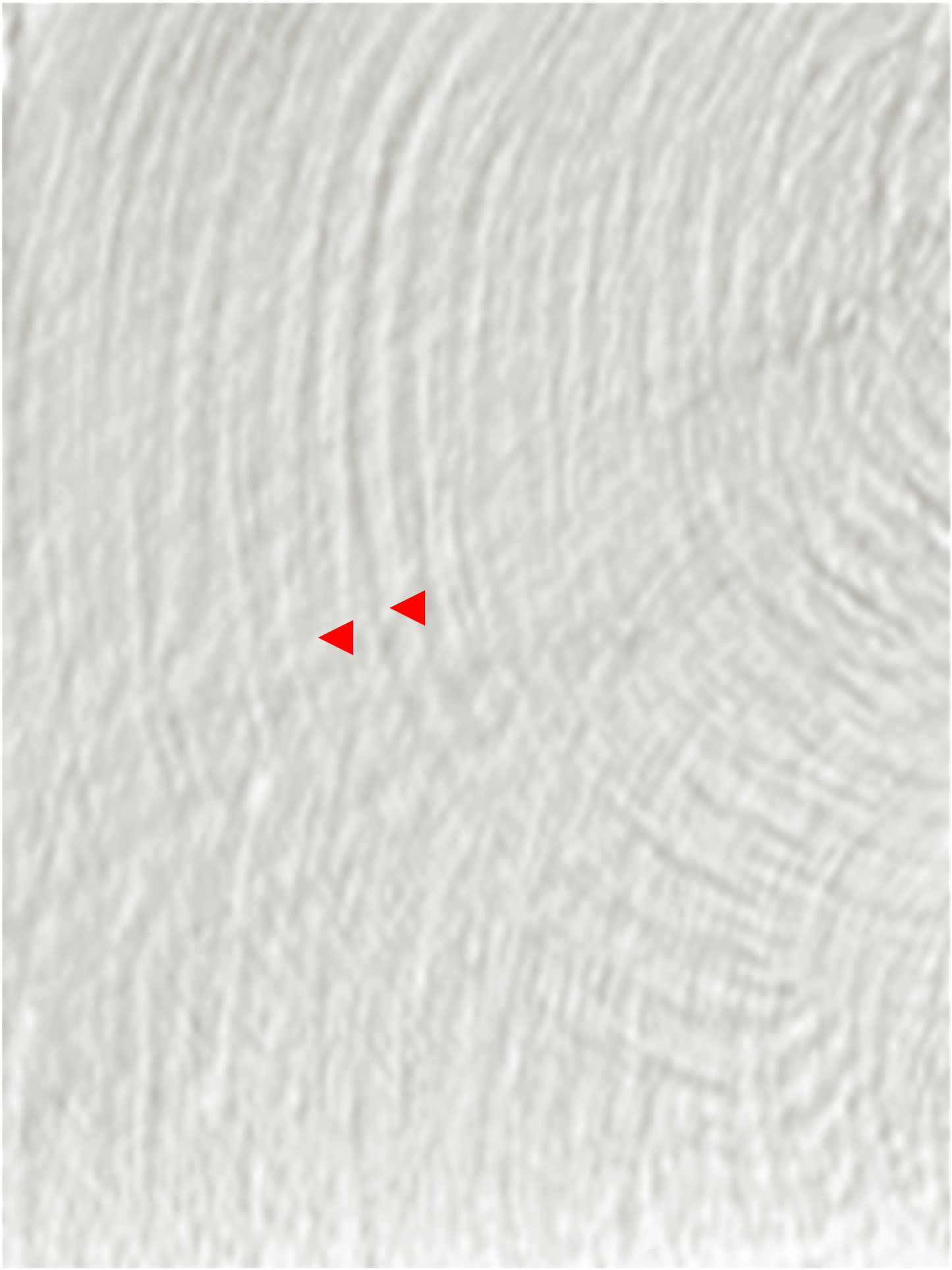




Method, implementation by *Meier et al.,* 2004

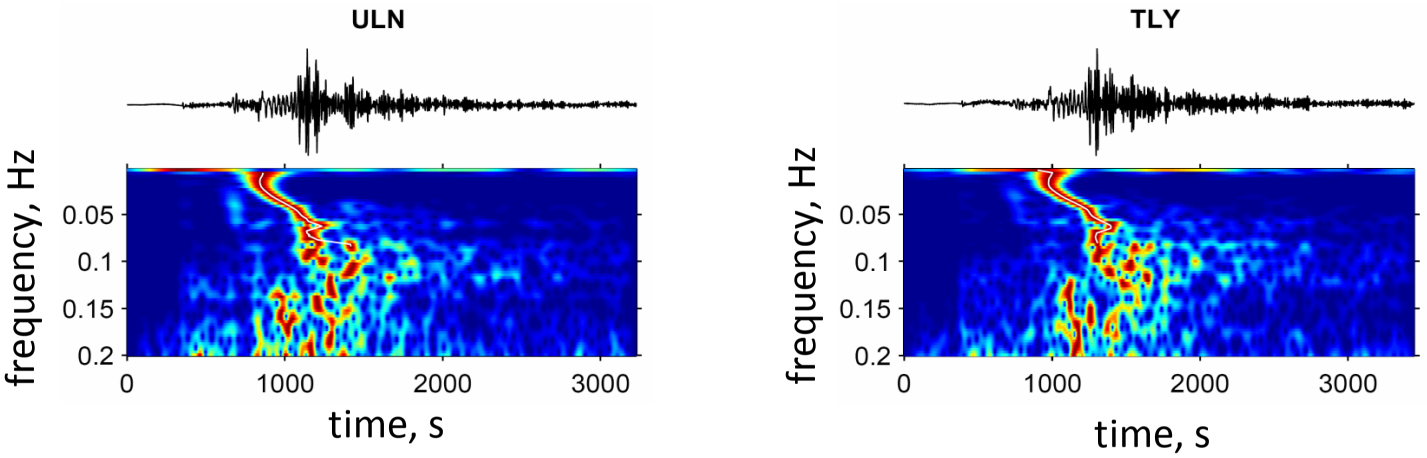

ULN
ULN
TLY
TLY
frequency, Hz
frequency, Hz
0.05
0.1
0.15
0.2
0
1000
2000
3000
500
1500
2500
time, s
time, s


phase velocity, km/s
frequency, Hz
7
6
5
4
3
2
10^{-2}
10^{-1}



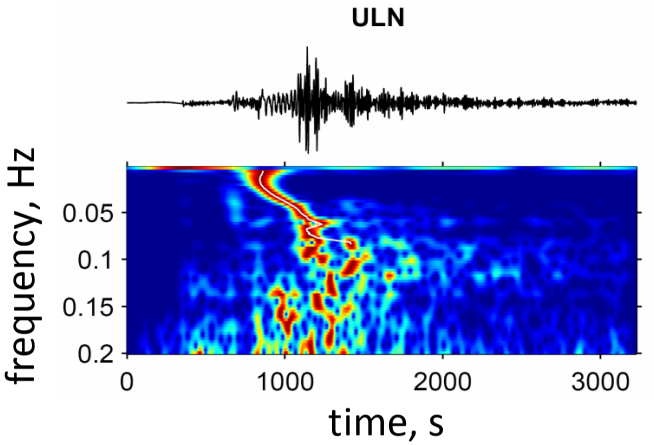
Cross-correlating teleseismic surface waves

- Works even on surface waves that are strongly diffracted
- Removal of rough (not smooth) measured curves and outliers
- Averaging over tens to hundreds to thousands of measurements
  (few measurements won't give a robust average)
- Teleseismic measurements down to periods of 5 s and below



Cross-correlating teleseismic surface waves

- Works even on surface waves that are strongly diffracted
- Removal of rough (not smooth) measured curves and outliers
- Averaging over tens to hundreds to thousands of measurements
  (few measurements won't give a robust average)
- Teleseismic measurements down to periods of 5 s and below

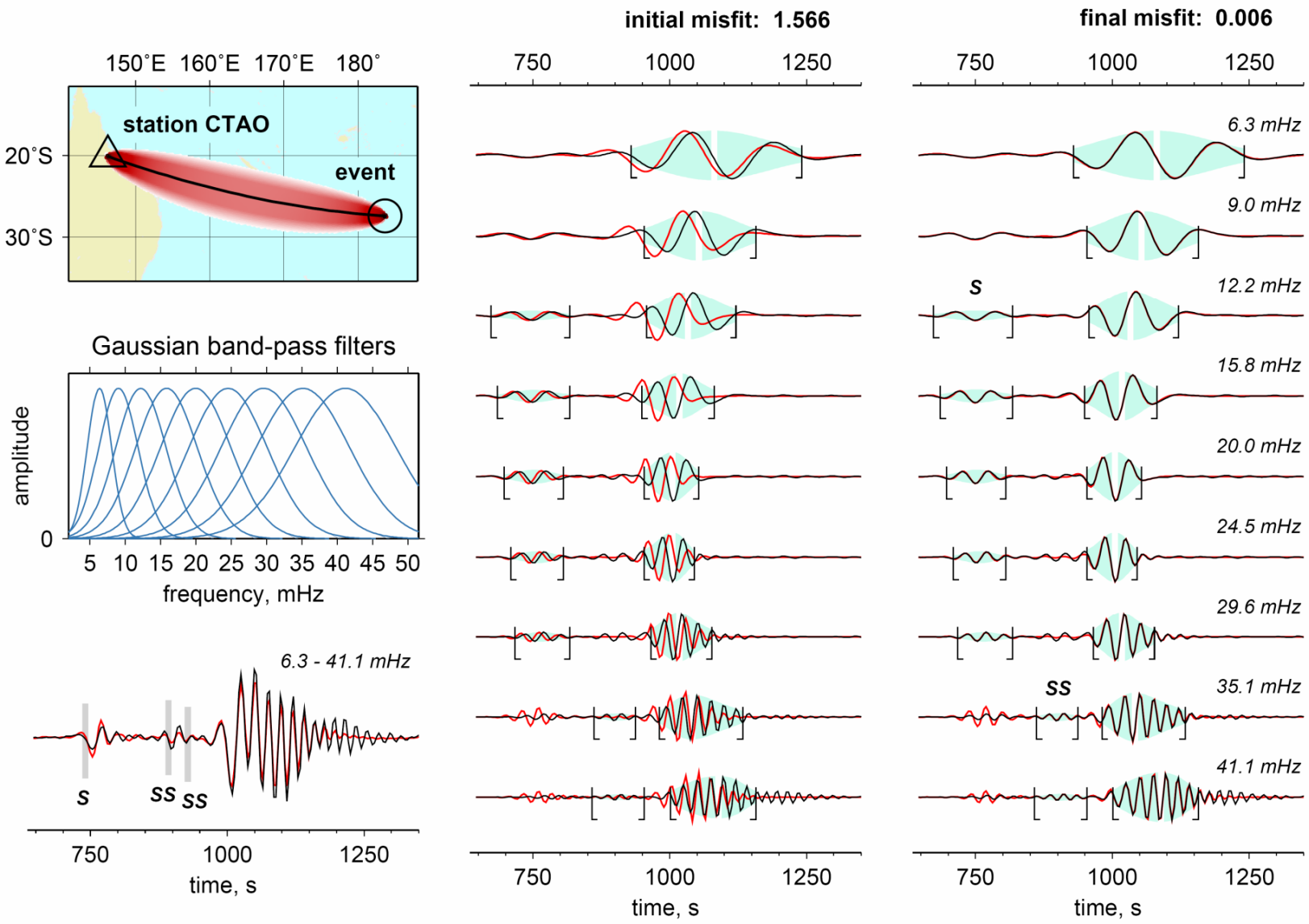


Remaining problem:

Interference of the fundamental and higher modes.

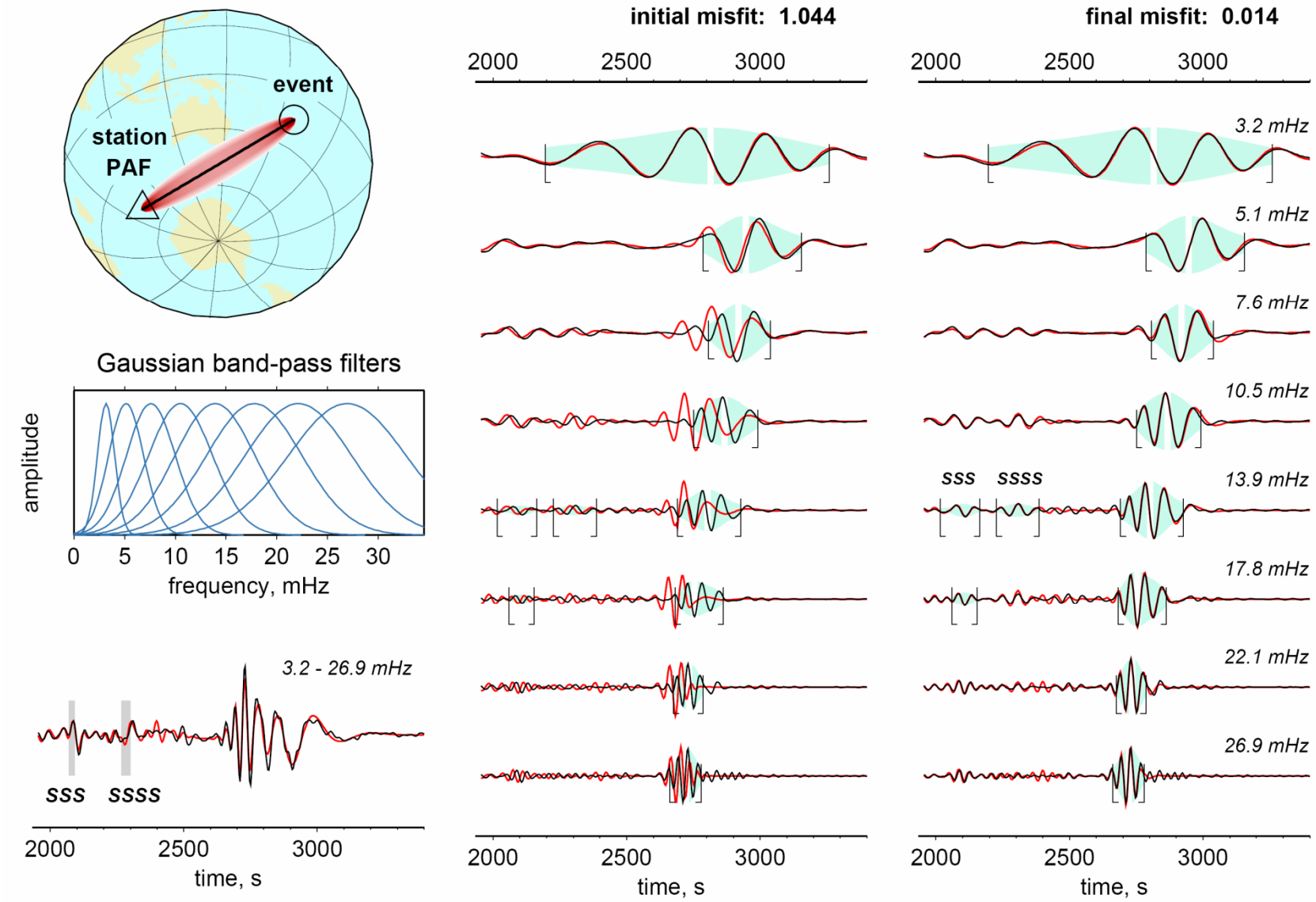
Reduces the number of long-period measurements, especially for Love-waves

Automated Multimode Inversion



Lebedev , Nolet, Meier, van der Hilst, 2005

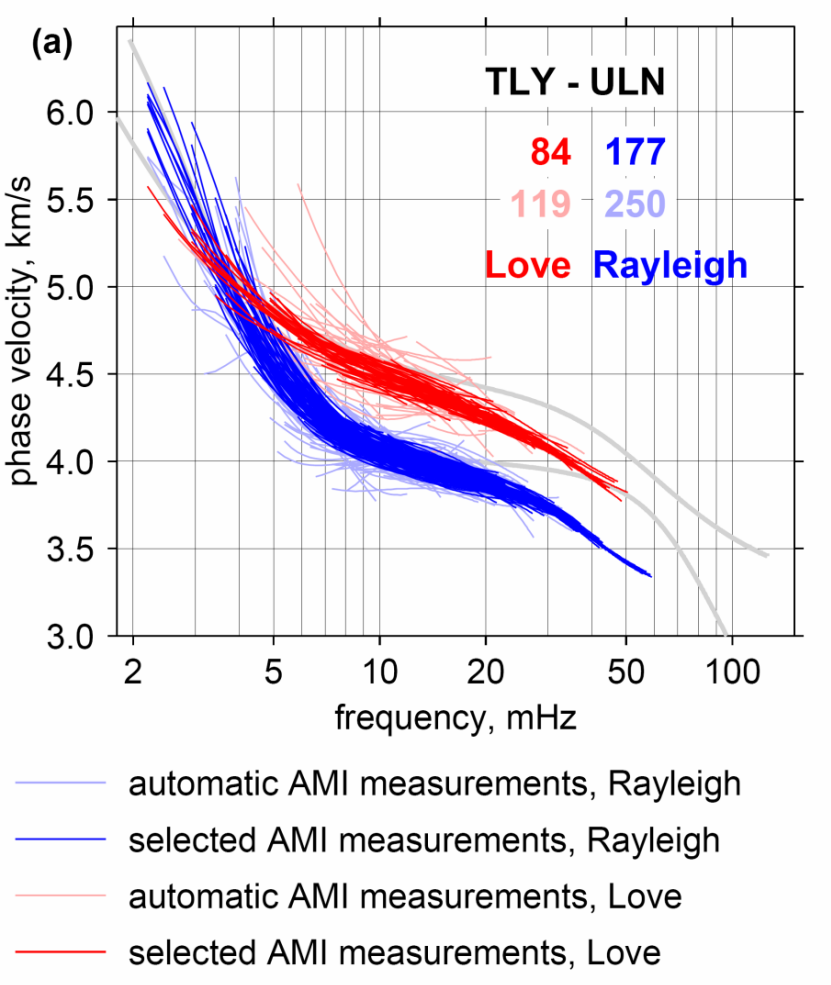
Automated Multimode Inversion

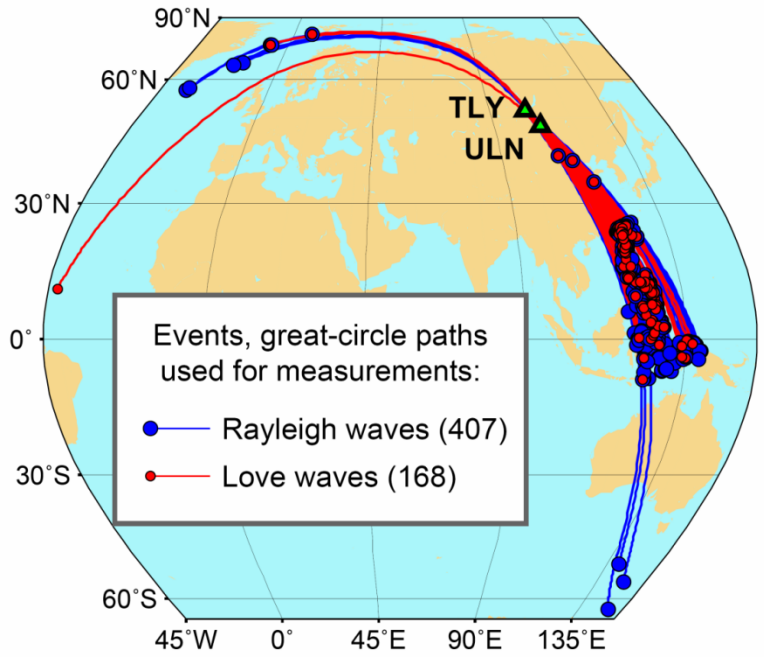


Lebedev , Nolet, Meier, van der Hilst, 2005

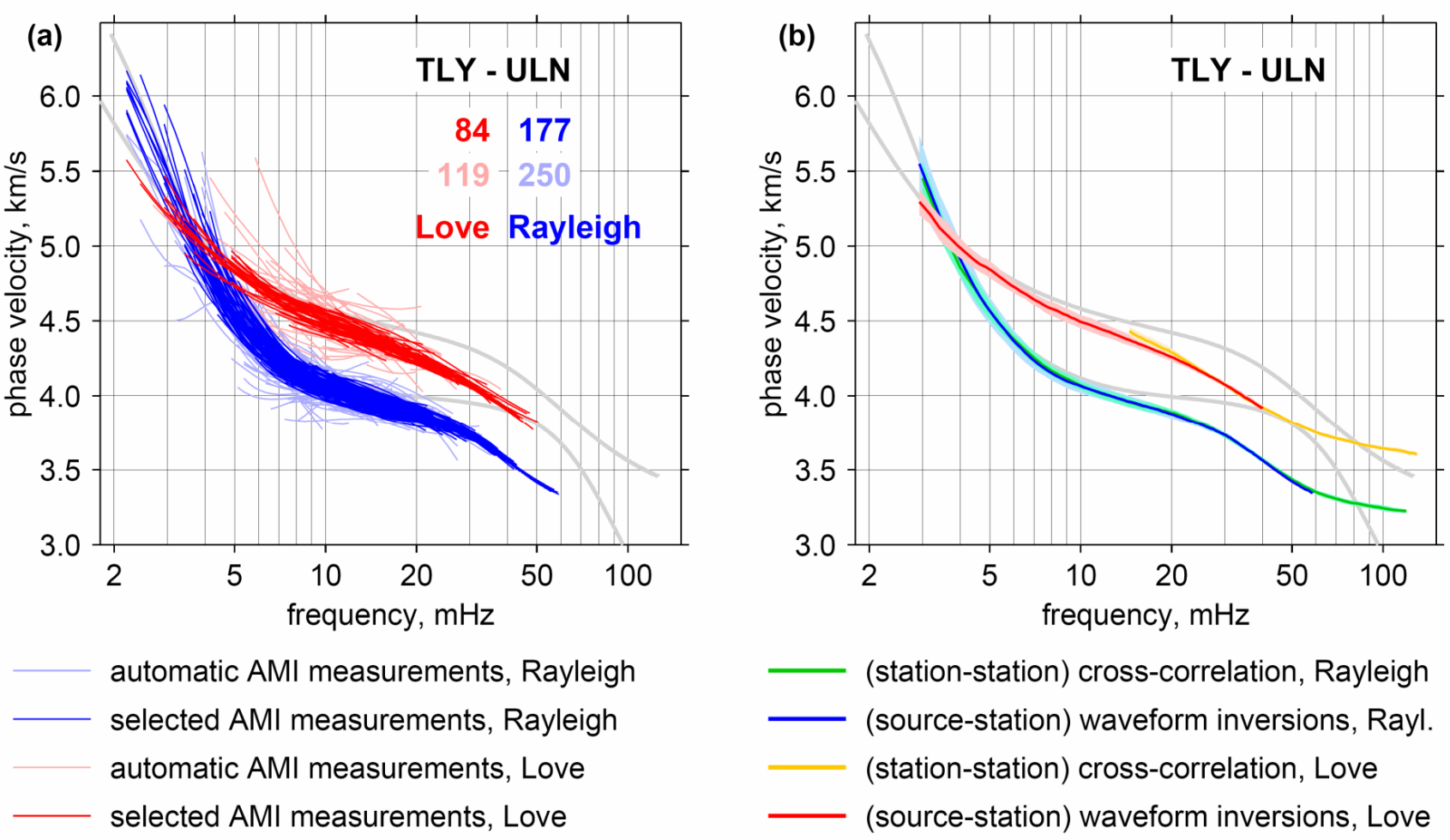
Cross-correlation + waveform inversion:

Teleseismic Interferometry





Cross-correlation + waveform inversion:
Teleseismic Interferometry

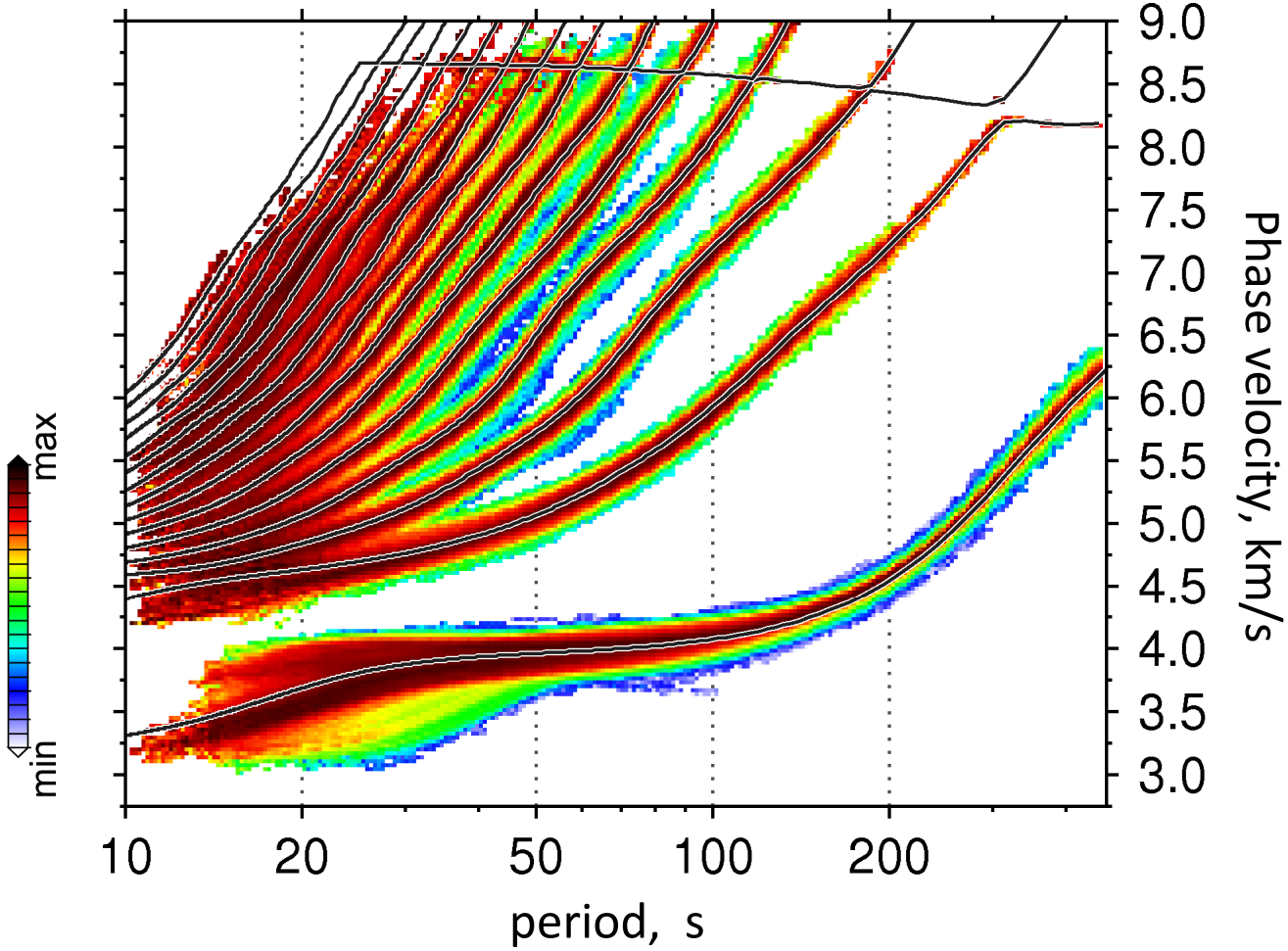


Lebedev, Meier, van der Hilst, 2006

Cross-correlation + waveform inversion:
Teleseismic Interferometry

- *Cross-correlation:* applicable even to strongly diffracted surface waves, at periods down to 5 s and below
- *Waveform inversion:* The fundamental - higher mode interference taken into account, measurements up to 300-400 s periods
- Accurate measurements in very broad frequency bands

(Can be done for higher modes too)



Schaeffer & Lebedev, this meeting

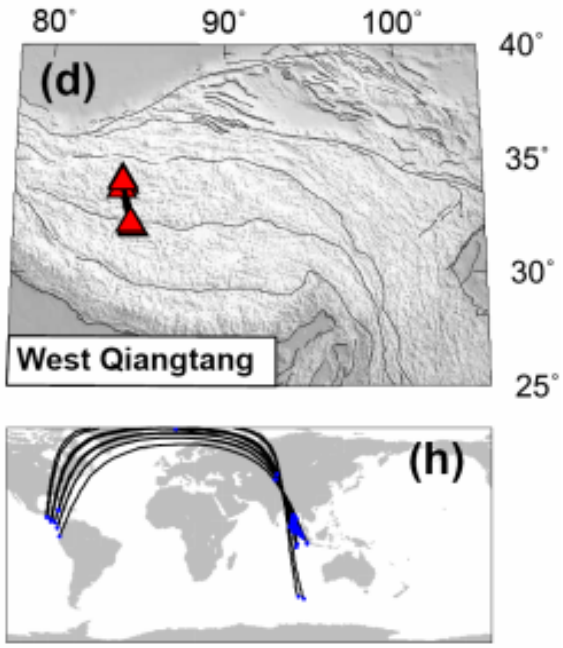
Teleseismic Interferometry applications

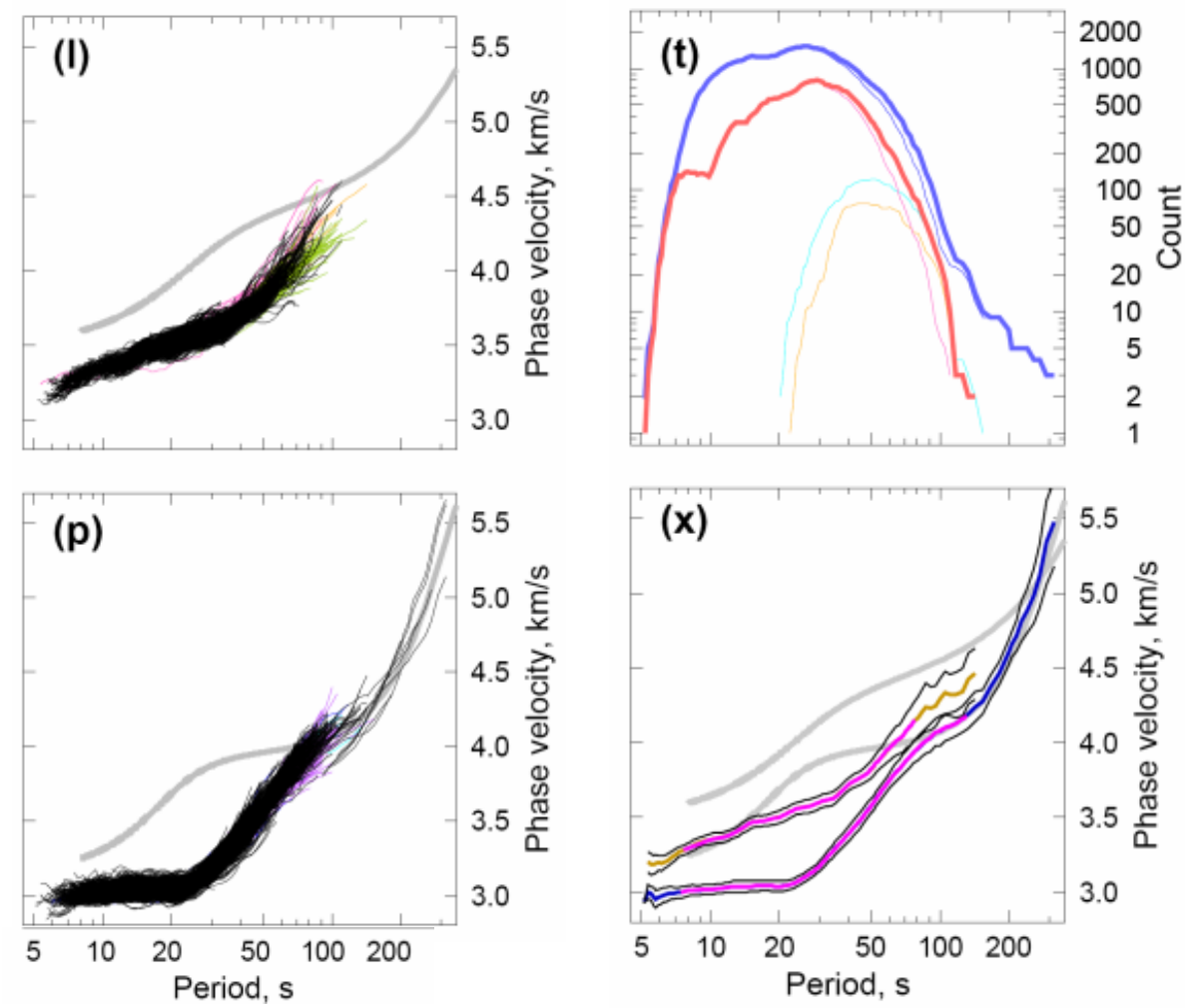
- Dispersion measurements in very broad frequency bands

Teleseismic Interferometry applications

- Dispersion measurements in very broad frequency bands

Tibet



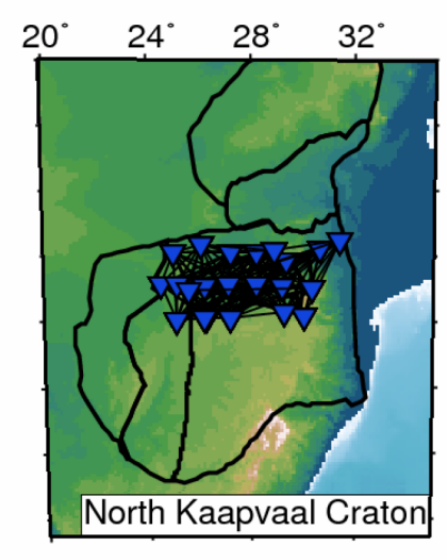


Agius & Lebedev, in prep.

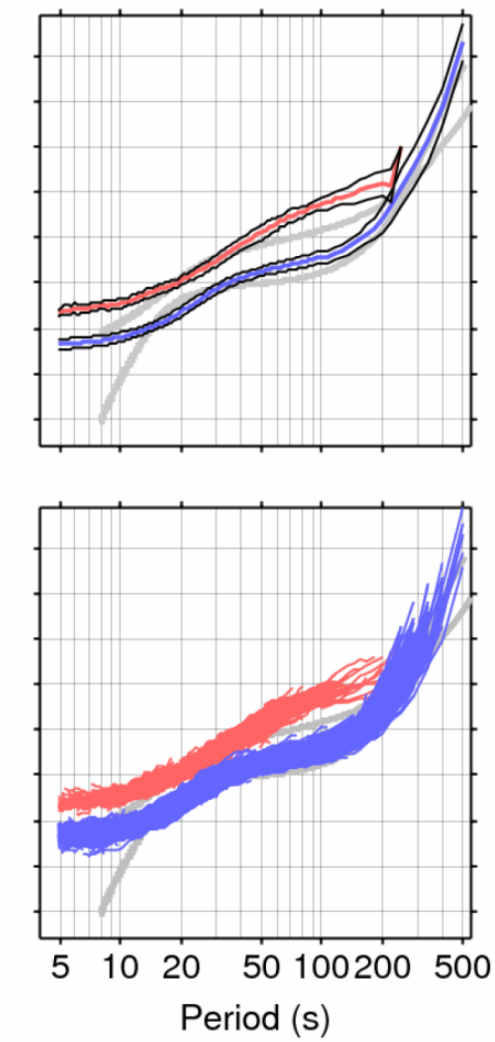
Teleseismic Interferometry applications

- Dispersion measurements in very broad frequency bands

Southern Africa



Adam & Lebedev, in revision



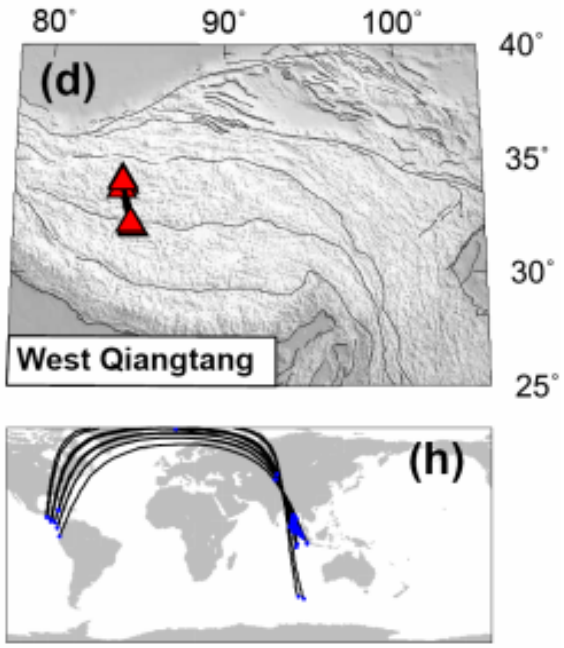
Teleseismic Interferometry applications

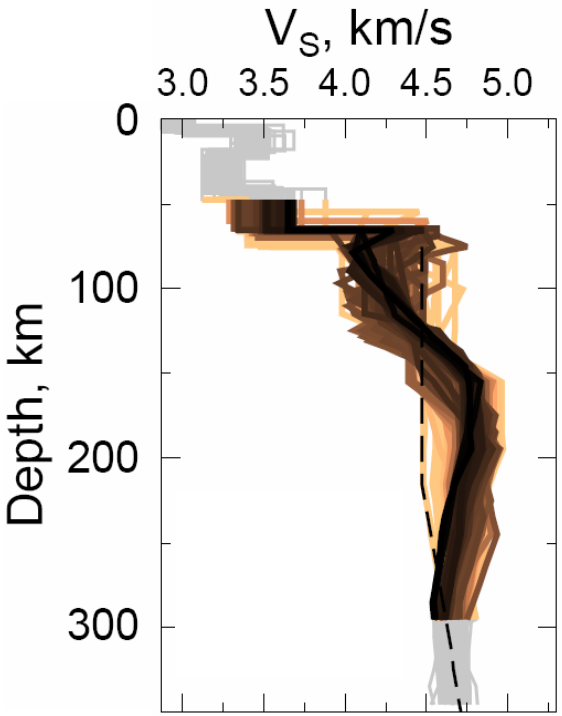
- Dispersion measurements in very broad frequency bands
- Inversions for accurate 1D profiles of *V*s and anisotropy

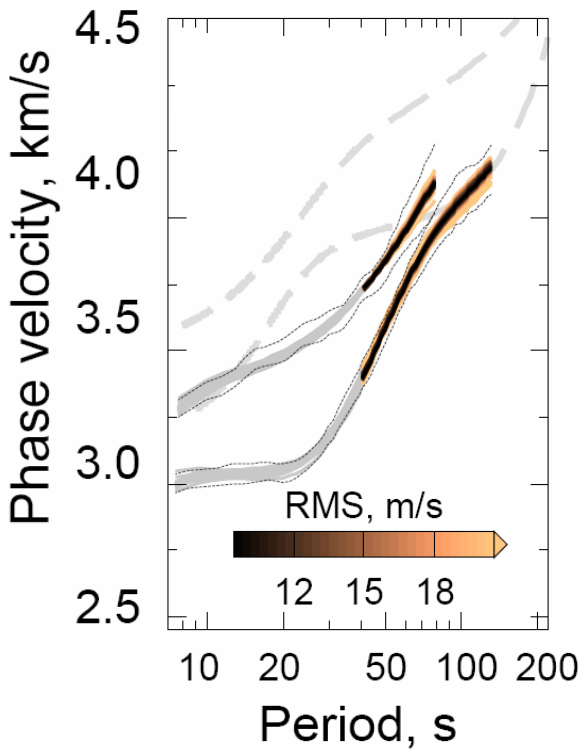
Teleseismic Interferometry applications

- Dispersion measurements in very broad frequency bands
- Inversions for accurate 1D profiles of *Vs* and anisotropy

Tibet







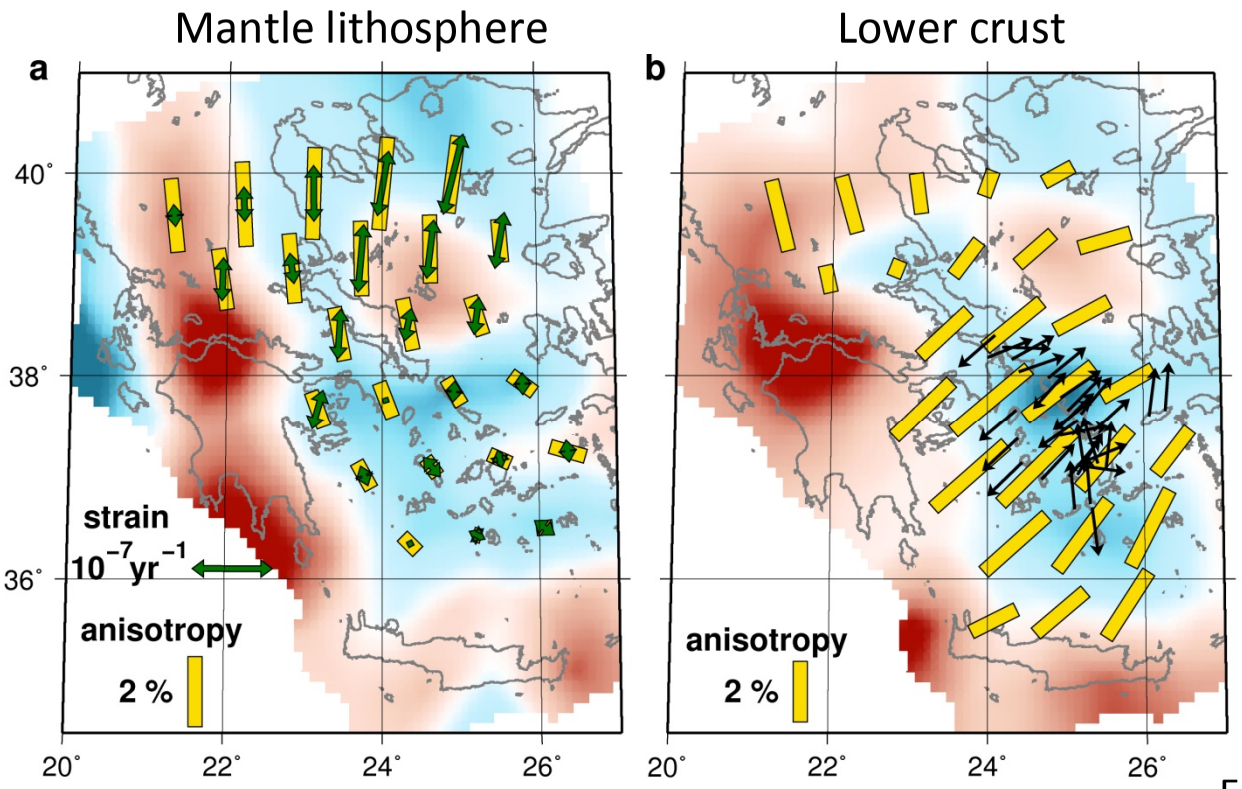
Agius & Lebedev, in prep.

Teleseismic Interferometry applications

- Dispersion measurements in very broad frequency bands
- Inversions for accurate 1D profiles of *V*s and anisotropy
- Array tomography
- Azimuthal anisotropy and its distribution with depth

Teleseismic Interferometry applications

- Dispersion measurements in very broad frequency bands
- Inversions for accurate 1D profiles of *Vs* and anisotropy
- Array tomography
- Azimuthal anisotropy and its distribution with depth

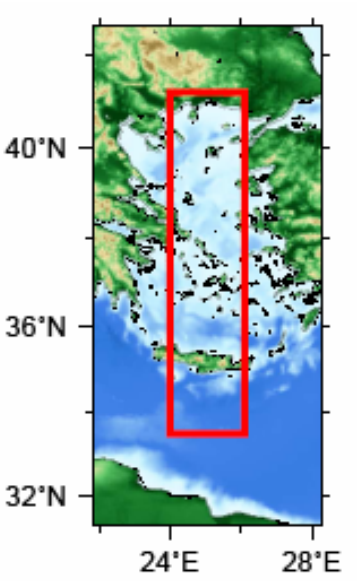


Endrun et al. 2011

Teleseismic Interferometry applications

- Dispersion measurements in very broad frequency bands
- Inversions for accurate 1D profiles of *Vs* and anisotropy
- Array tomography
- Azimuthal anisotropy and its distribution with depth
- Continental deformation, lithospheric dynamics

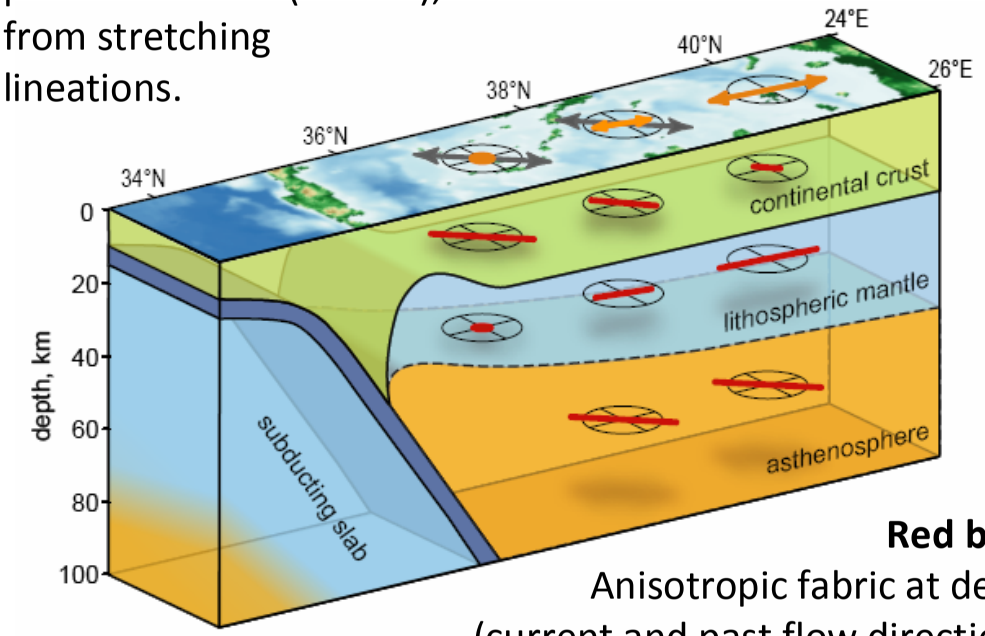
The Aegean



Endrun et al. 2011

Grey arrows:
paleo extension (> 5 Ma), from stretching lineations.

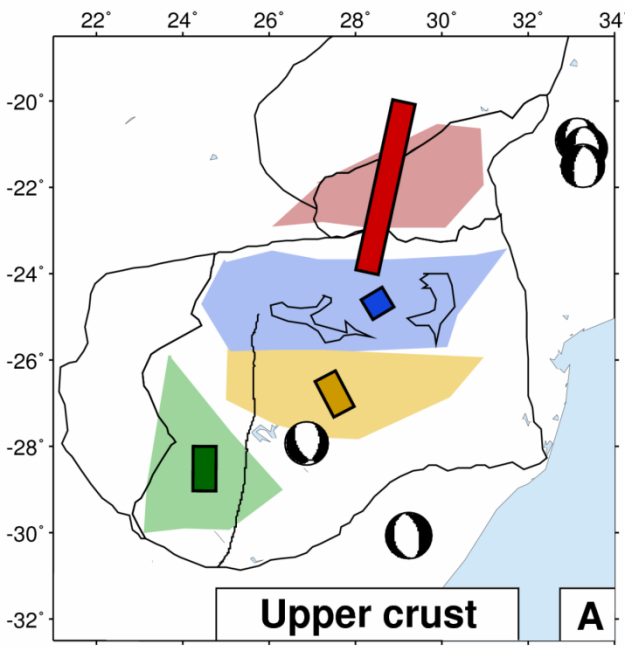
Orange arrows:
current extension (from GPS).



Red bars:
Anisotropic fabric at depth
(current and past flow directions)

Teleseismic Interferometry applications

- Dispersion measurements in very broad frequency bands
- Inversions for accurate 1D profiles of *Vs* and anisotropy
- Array tomography
- Azimuthal anisotropy and its distribution with depth
- Continental deformation, lithospheric dynamics
- Estimation of tectonic stress from anisotropy of short-period surface waves



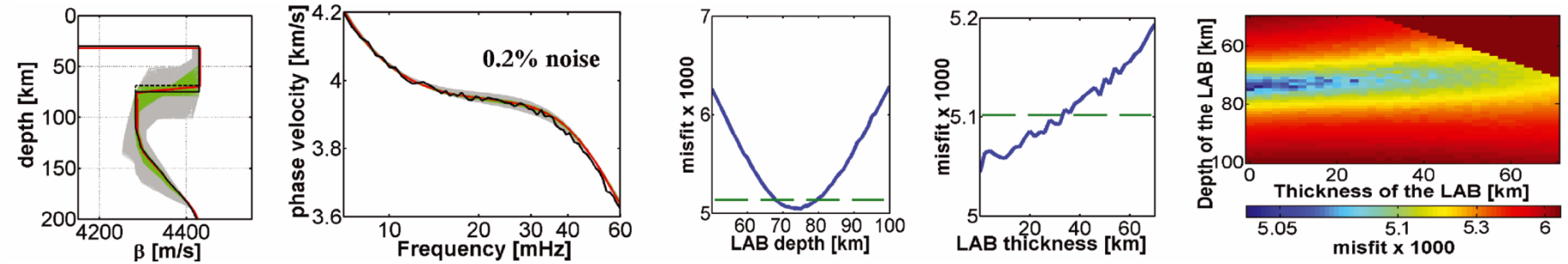
Southern Africa

Phase-velocity anisotropy,
5-7 s Rayleigh waves

: Amplitude of anisotropy, 1%

Adam & Lebedev, in revision

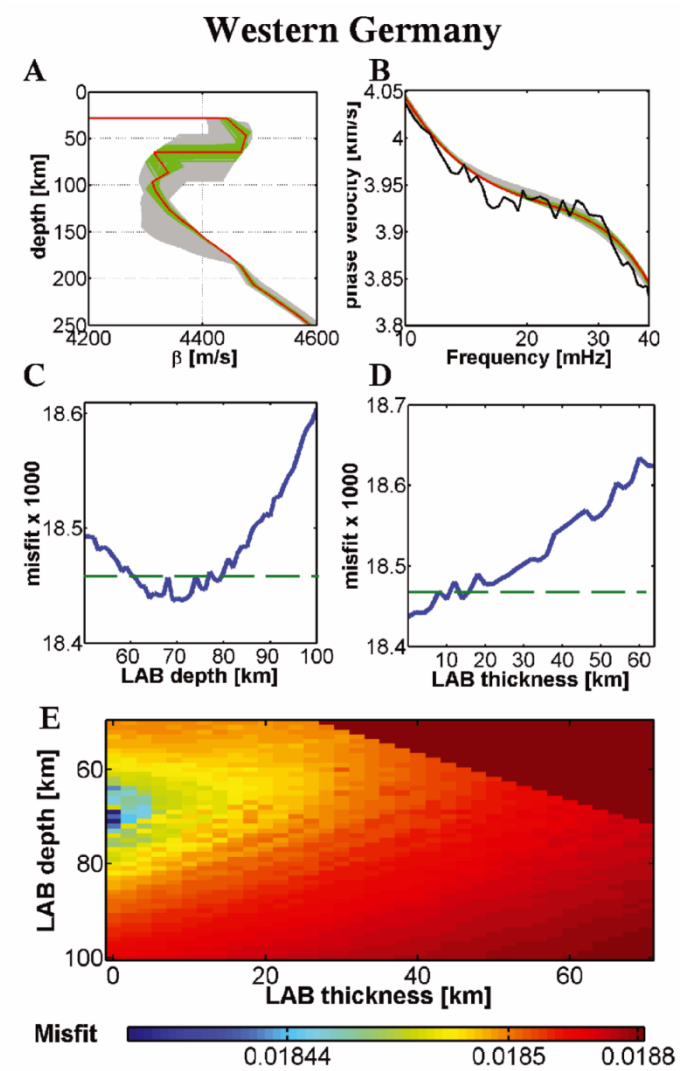
Model-space-map inversion for *Vs* structure: The lithosphere-asthenosphere boundary

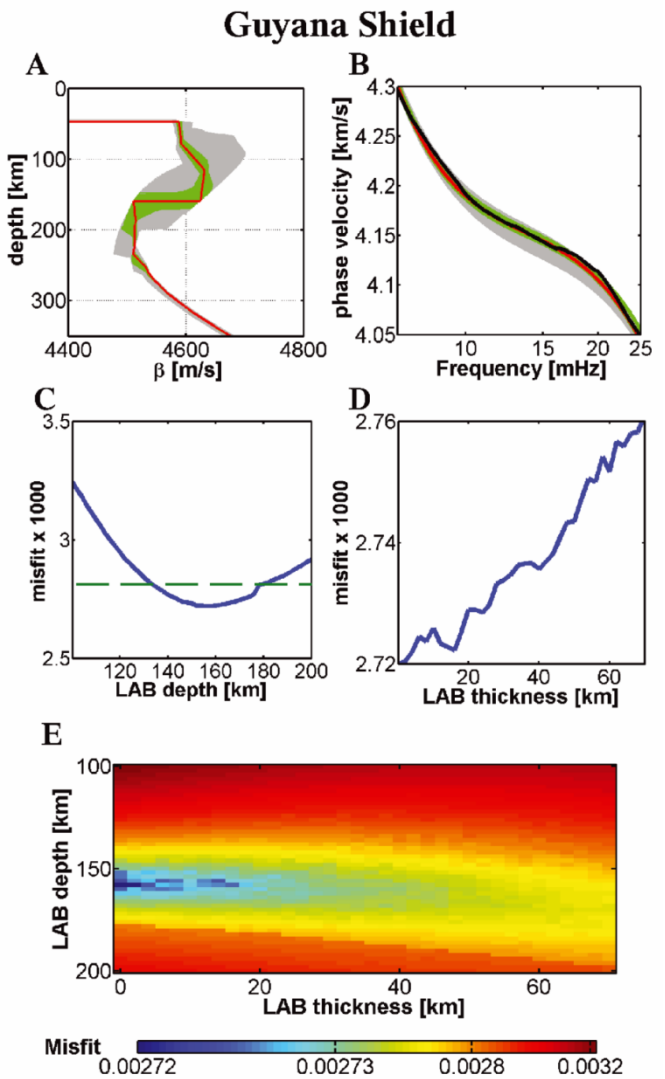


- Grid search within a model sub-space (e.g., a 2-parameter plane)
- At every point within the plane: fix the value of the two parameters; find the best-fitting model by means of a non-linear gradient search, varying all the other parameters.

Bartzsch, Lebedev, Meier, 2011

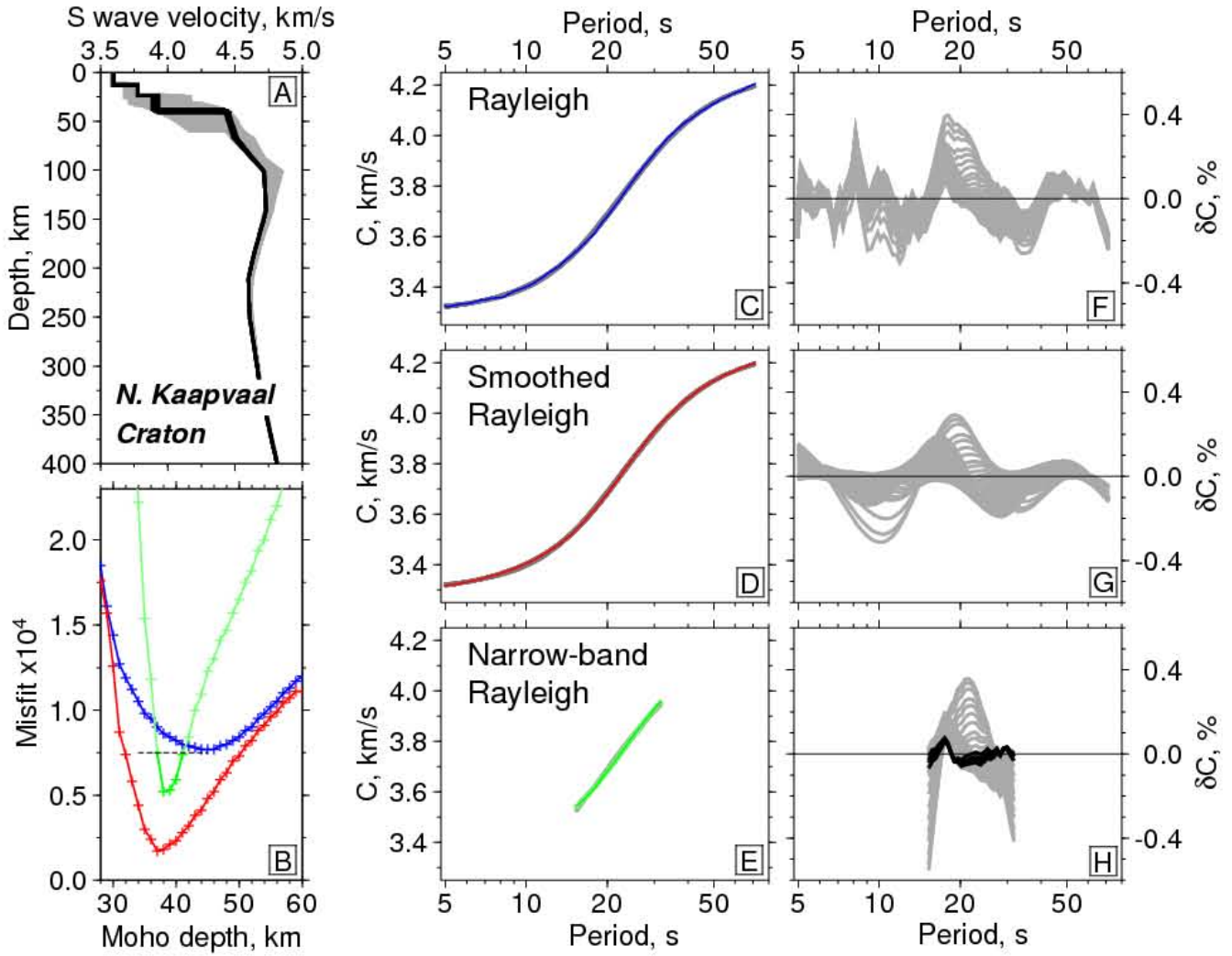
Model-space-map inversion for *Vs* structure: The lithosphere-asthenosphere boundary





Bartzsch, Lebedev, Meier, 2011

Model-space-map inversion for *Vs* structure: The Moho depth



Lebedev, Adam, Meier, in prep

Teleseismic vs Ambient-Noise Interferometry

Similarity:

- simple measurements from complex wavefields
- averaging is essential (over many events or over a period of time)

Period ranges of the measurements:

- teleseismic earthquake sources: ~5 s to 300-400 s
- ambient noise sources: Hz to 30-40 s

Signal availability:

- greater for ambient noise, up to 30-40 s

Conclusion:

- the two types of signal are complementary, both should be utilised

Teleseismic Interferometry

PERSPECTIVES

- interstation measurements for Rayleigh and Love higher modes
- automation, application to massive global datasets
- imaging of deformation and flow in the lithosphere and asthenosphere; lithospheric dynamics; combination with geodetic and geological data, and with petro-physical and geodynamic modelling
- routine estimation of tectonic stress from anisotropy of short-period surface waves

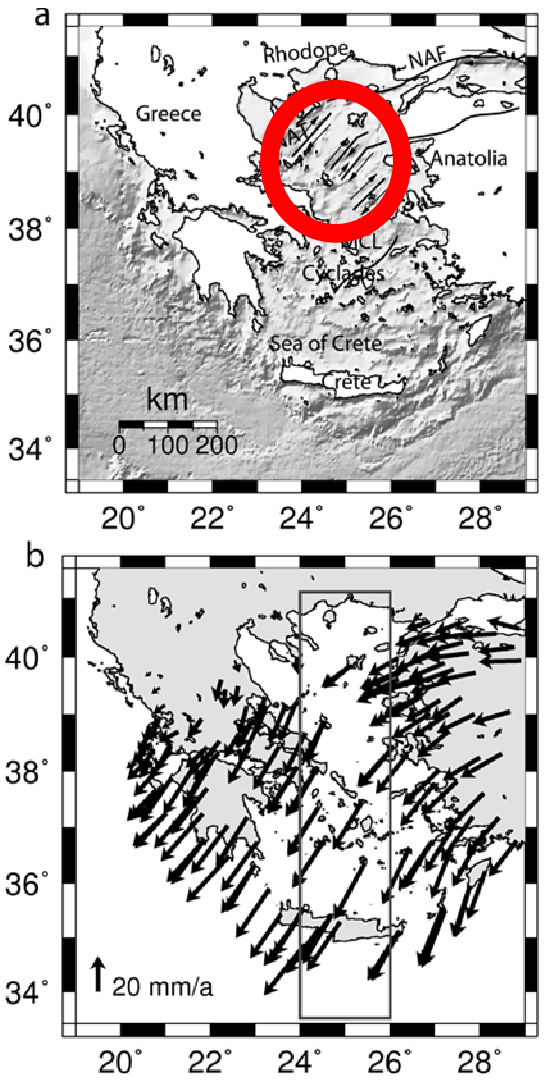
Teleseismic Interferometry

PERSPECTIVES II

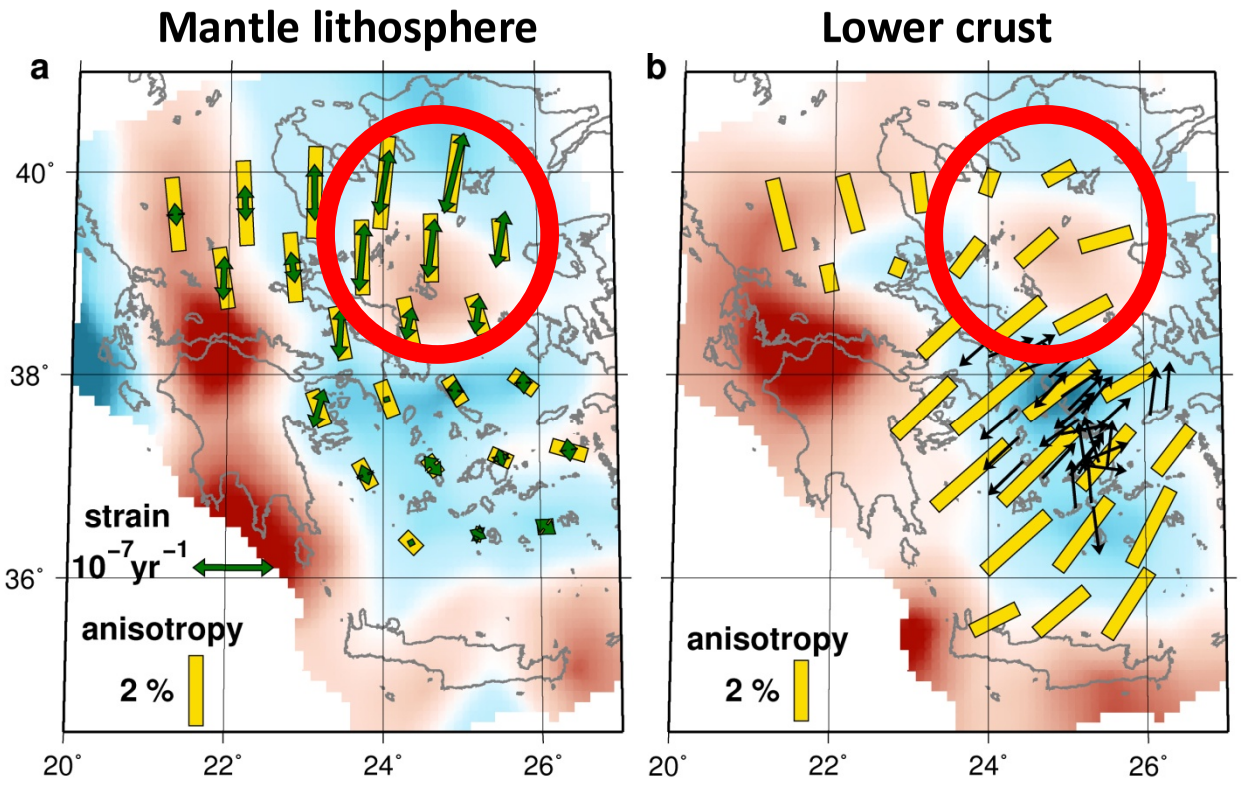
- understanding the interstation measurements:
  - modelling of the wave propagation
  - modelling of the measurement sensitivity
    (*de Vos, Paulssen, Fichtner, this meeting*)
- wavefield tomography

Appendices

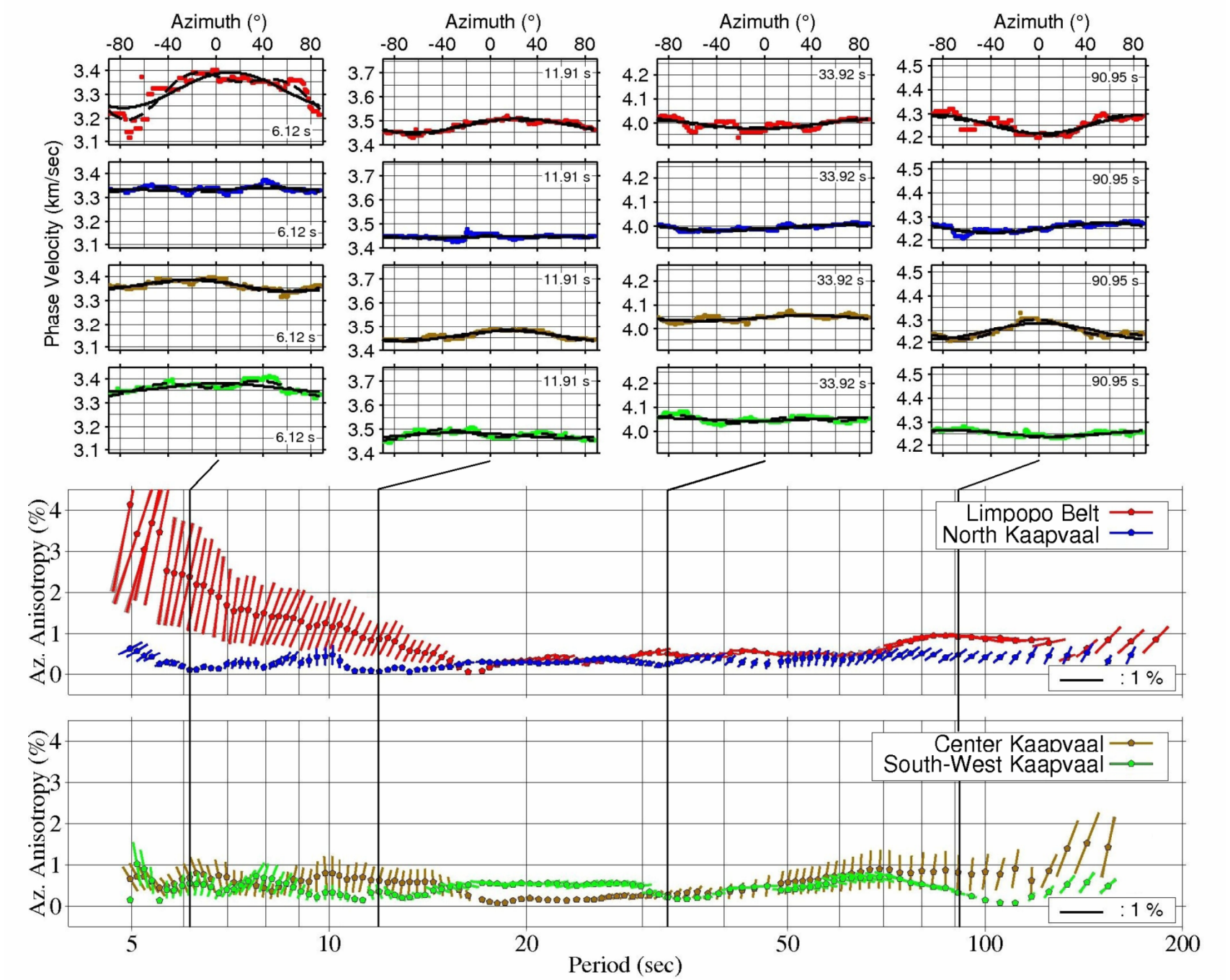
Extension mechanism in the northern Aegean Sea

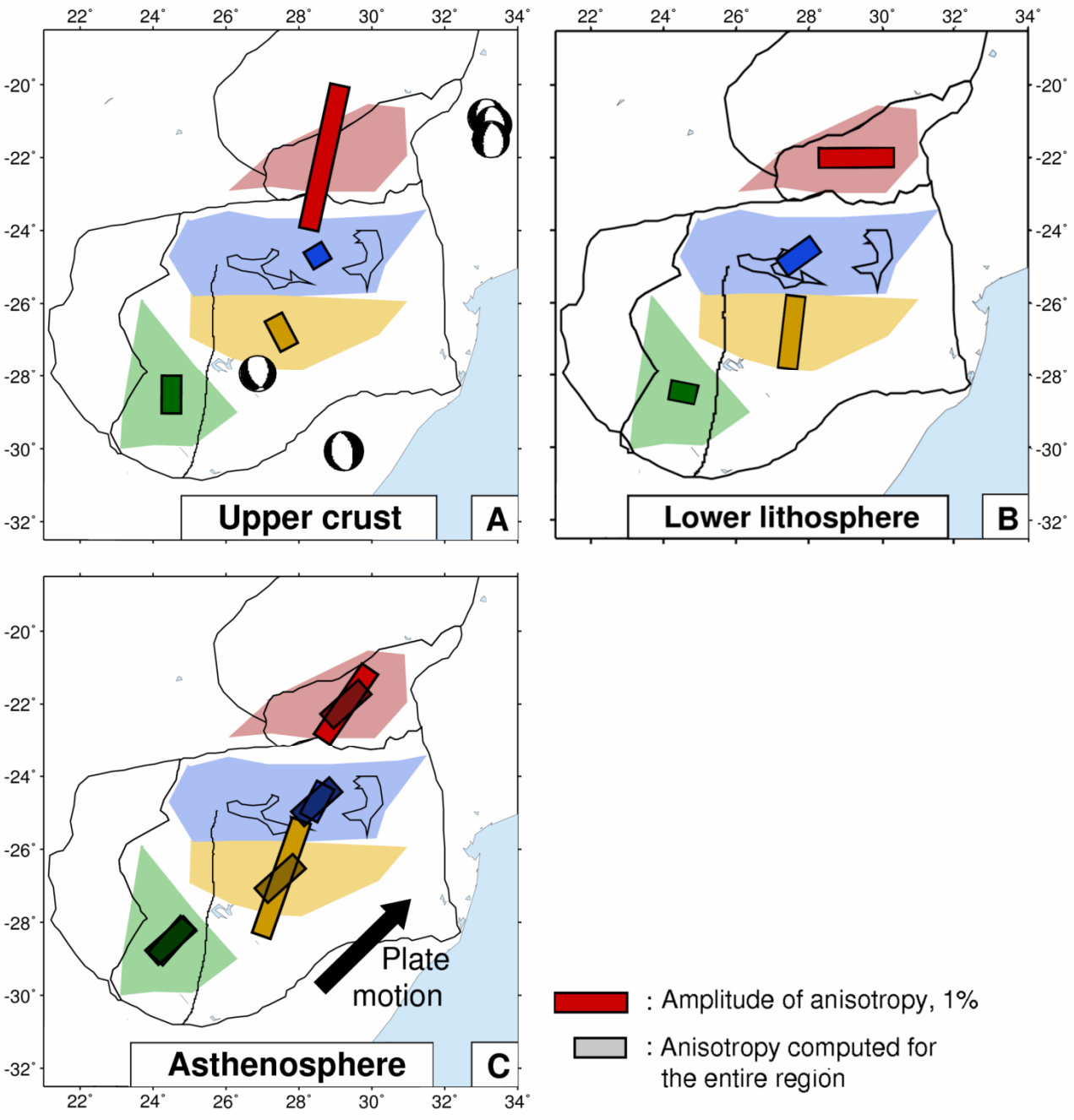


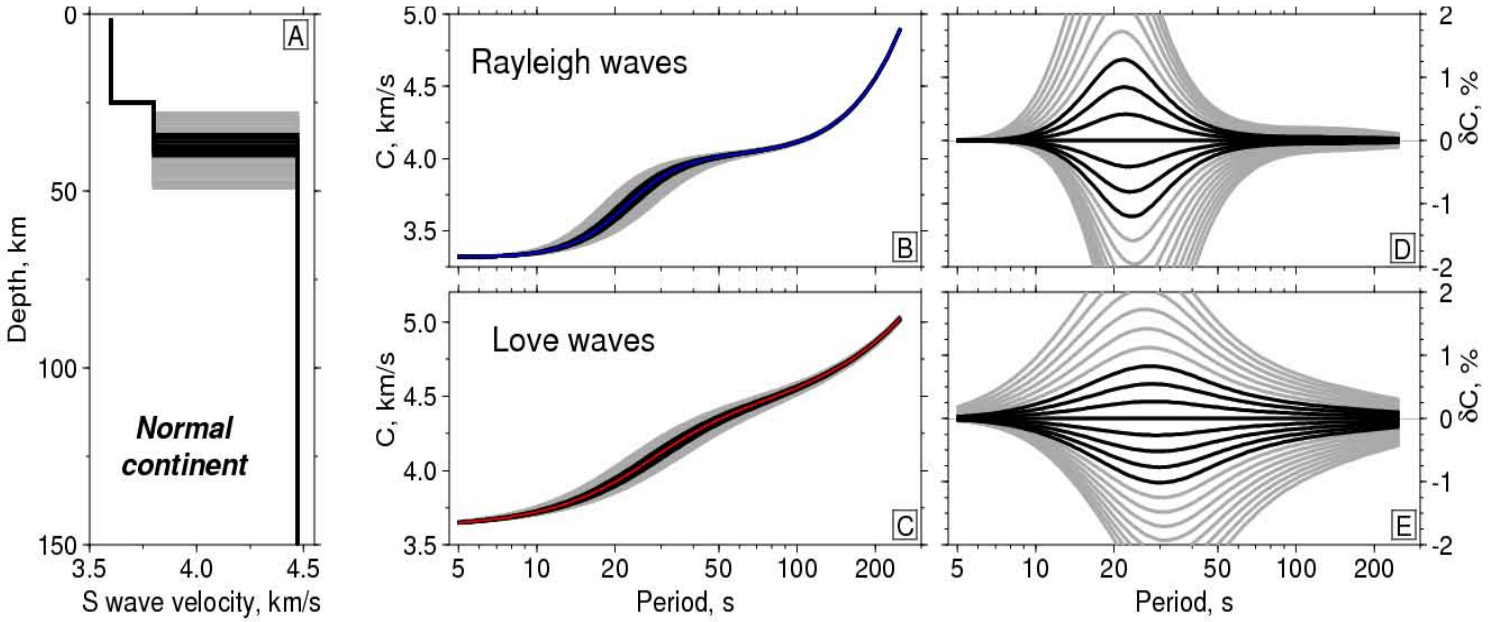
- **Upper crust:** strike-slip faulting, counter-clockwise rotation, stretching
- **Mantle lithosphere:** viscous flow North-South, parallel to the extensional component of the strain rate field
- **Lower crust:** transitional layer, with viscous flow parallel to the strike-slip faults



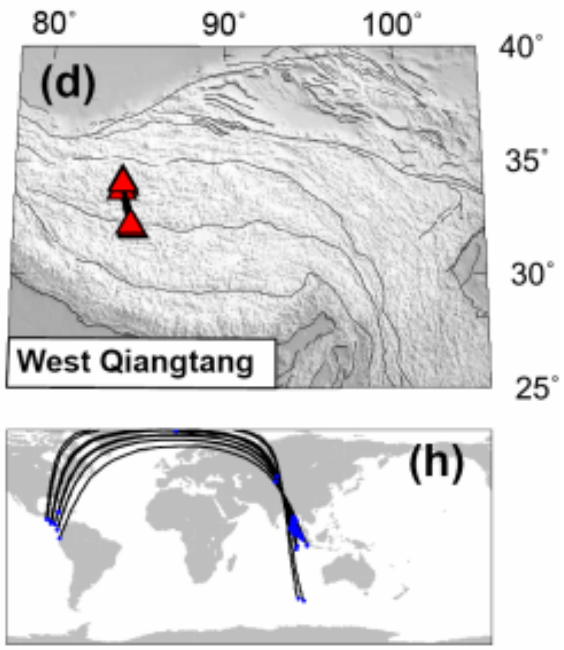
Endrun *et al.*, Nature Geo 2011

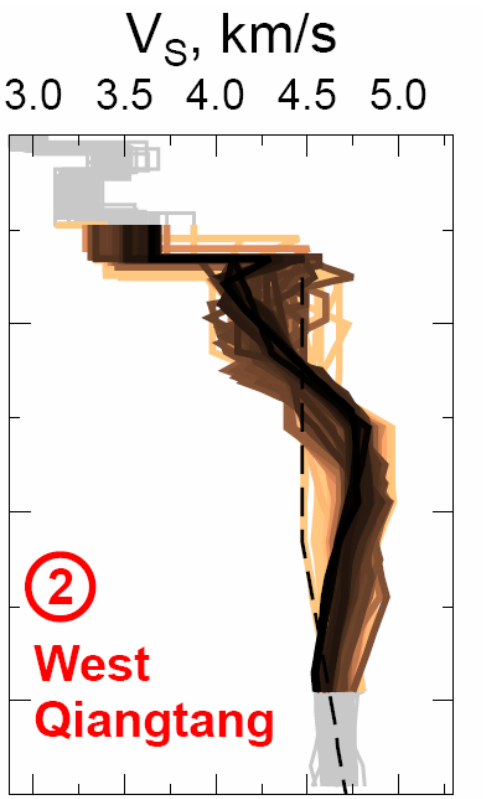

Azimuth (°)
-80 -40 0 40 80
Phase Velocity (km/sec)
6.12 s
11.91 s
33.92 s
90.95 s
Az. Anisotropy (%)
Limpopo Belt
North Kaapvaal
Center Kaapvaal
South-West Kaapvaal
: 1 %
Period (sec)
5 10 20 50 100 200

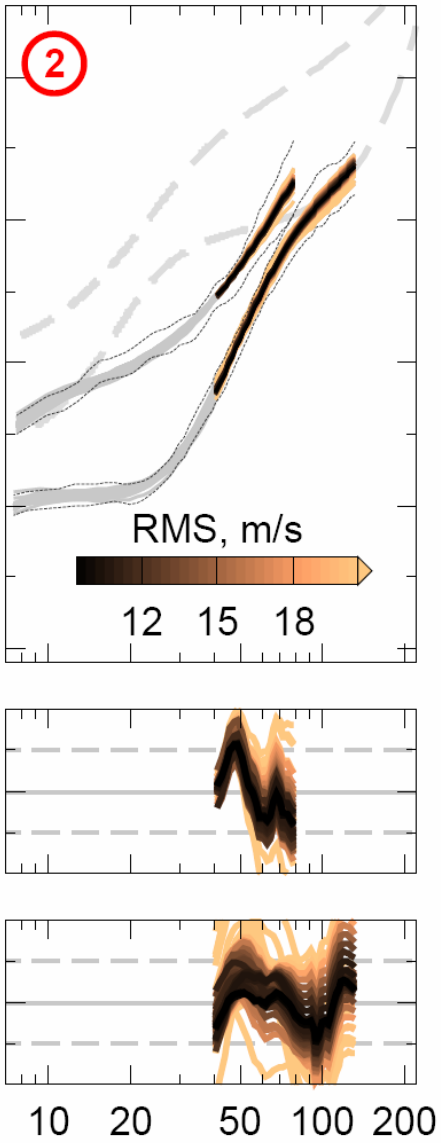

22˚
24˚
26˚
28˚
30˚
32˚
34˚
-20˚
-22˚
-24˚
-26˚
-28˚
-30˚
-32˚
Upper crust
A
Lower lithosphere
B
Asthenosphere
C
Plate
motion
: Amplitude of anisotropy, 1%
: Anisotropy computed for
the entire region


A
Depth, km
0
50
100
150
3.5
4.0
4.5
S wave velocity, km/s
Normal
continent
Rayleigh waves
Love waves
B
C
D
E
C, km/s
5.0
4.5
4.0
3.5
5
10
20
50
100
200
Period, s
δC, %
2
1
0
-1
-2

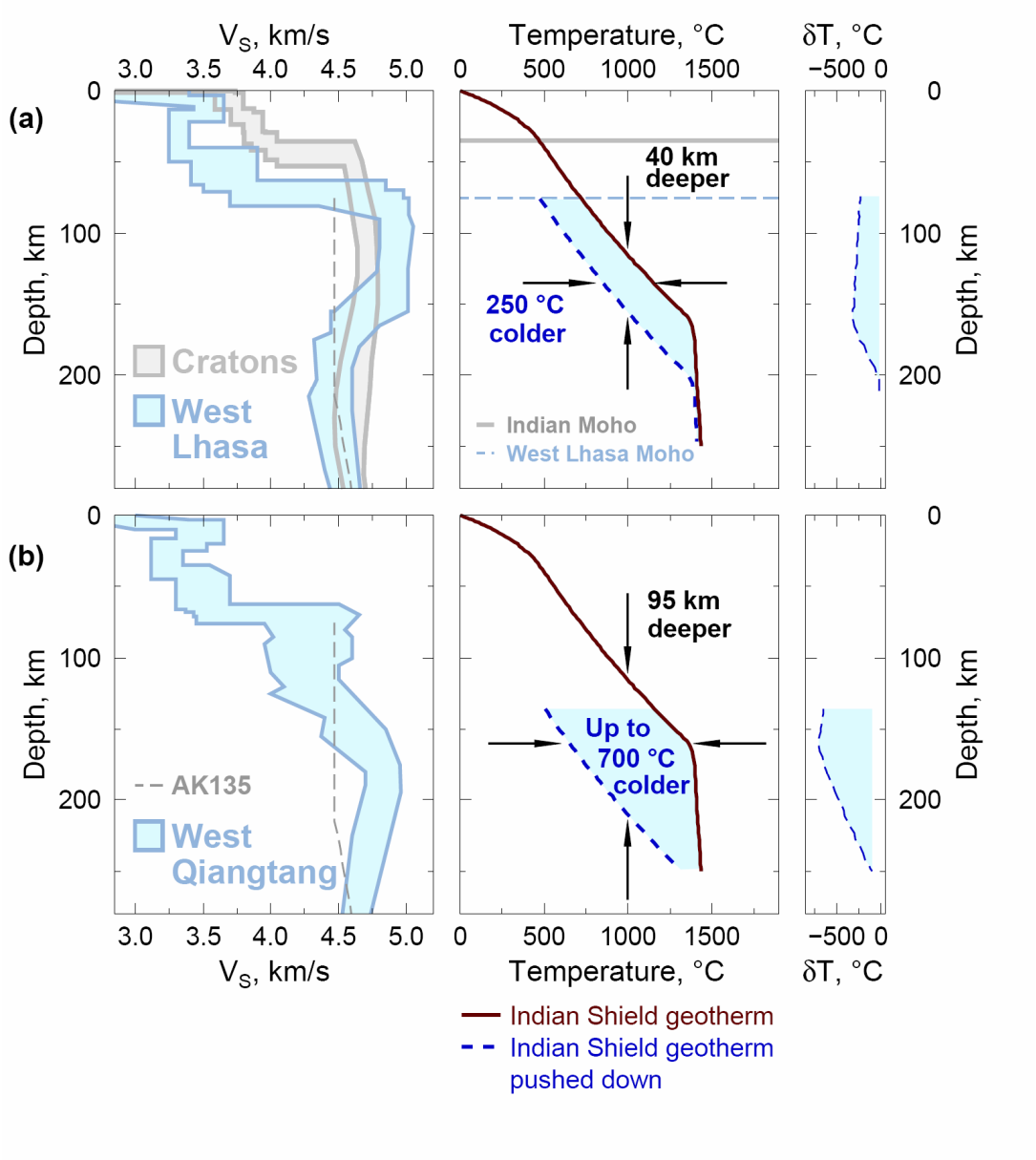
Tibet



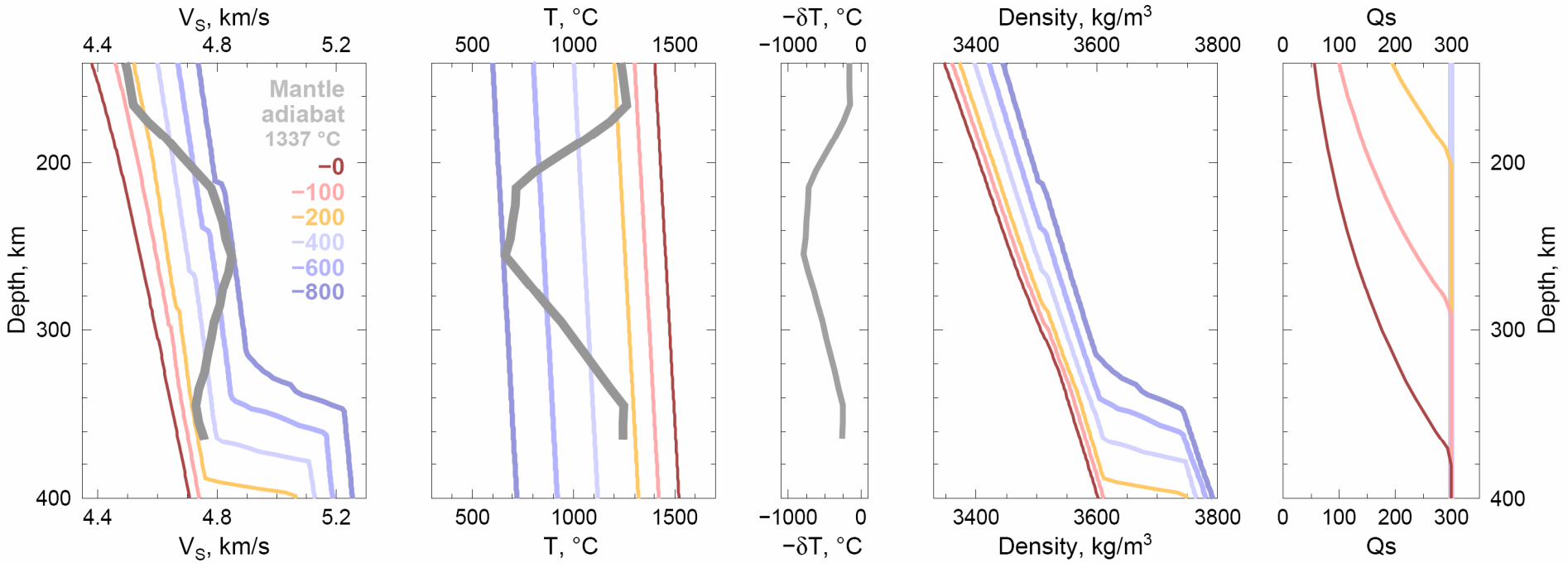




Agius & Lebedev, in prep.



Agius & Lebedev, in prep.



Agius & Lebedev, in prep.


WAVE
FIELD
ACTIONS