Solar-powered seismology: studying the Earth's interior based on correlations of ambient seismic noise

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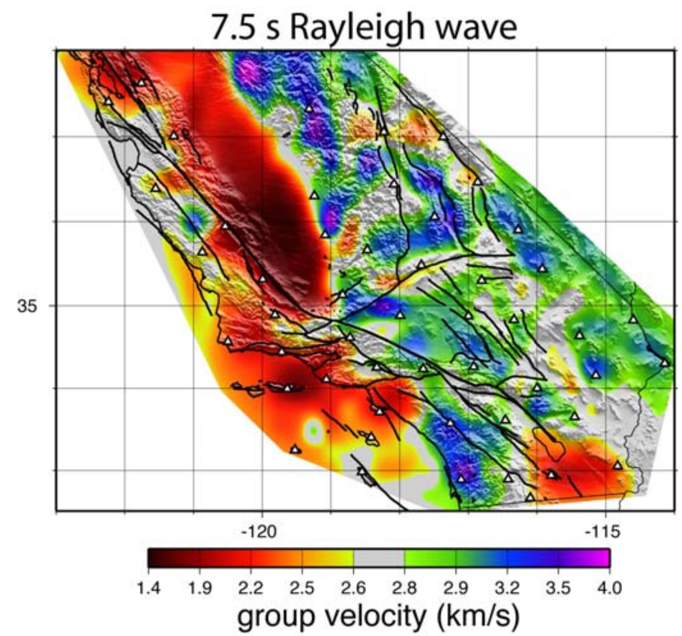
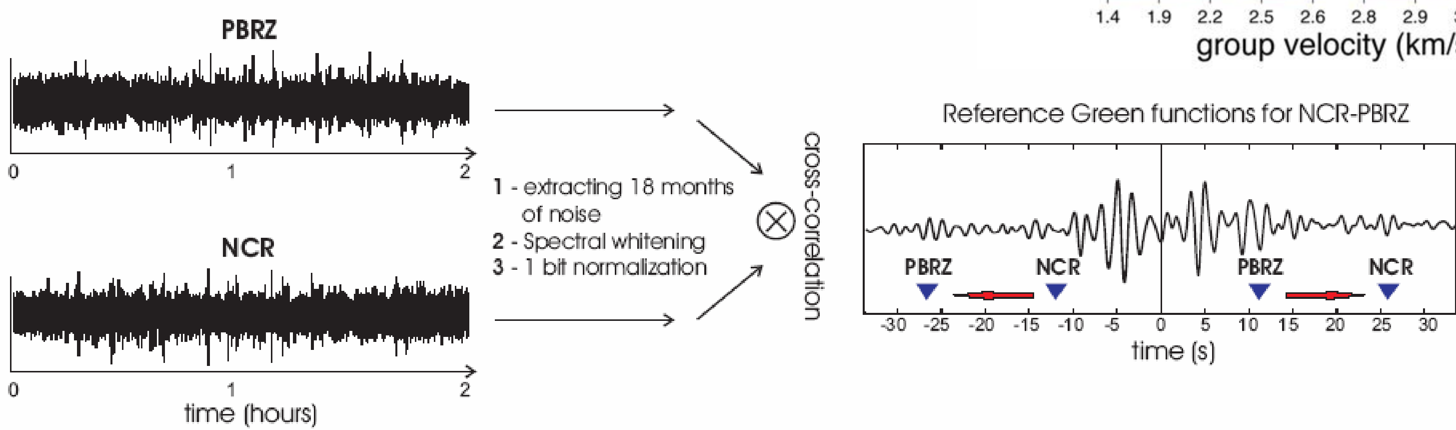


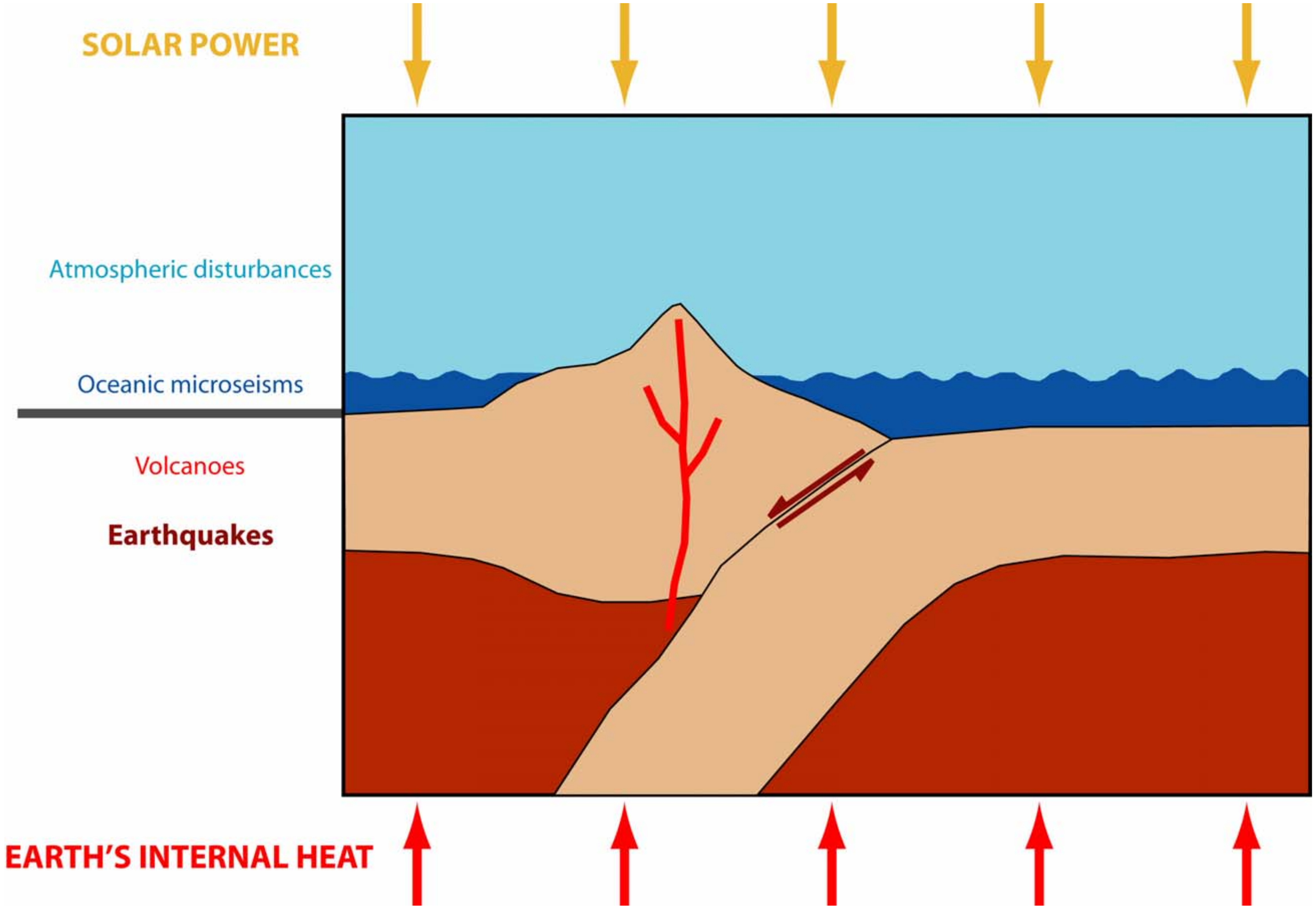


More information in publications at: http://www.ipgp.jussieu.fr/~nshapiro

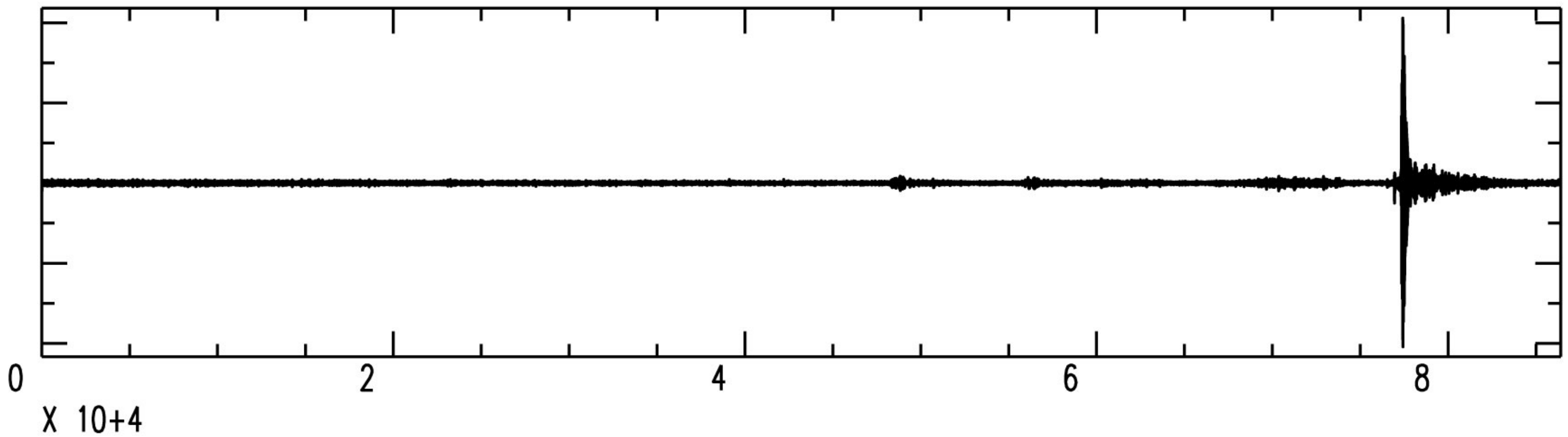
Outline

1. Extraction of surface waves from correlations of seismic noise: introduction
2. Earthquake-based surface wave tomography and its limitations
3. Extraction of surface waves from correlations of seismic noise: data processing and example
4. Surface wave tomography from the ambient seismic noise
5. Tracing the origin of the seismic noise

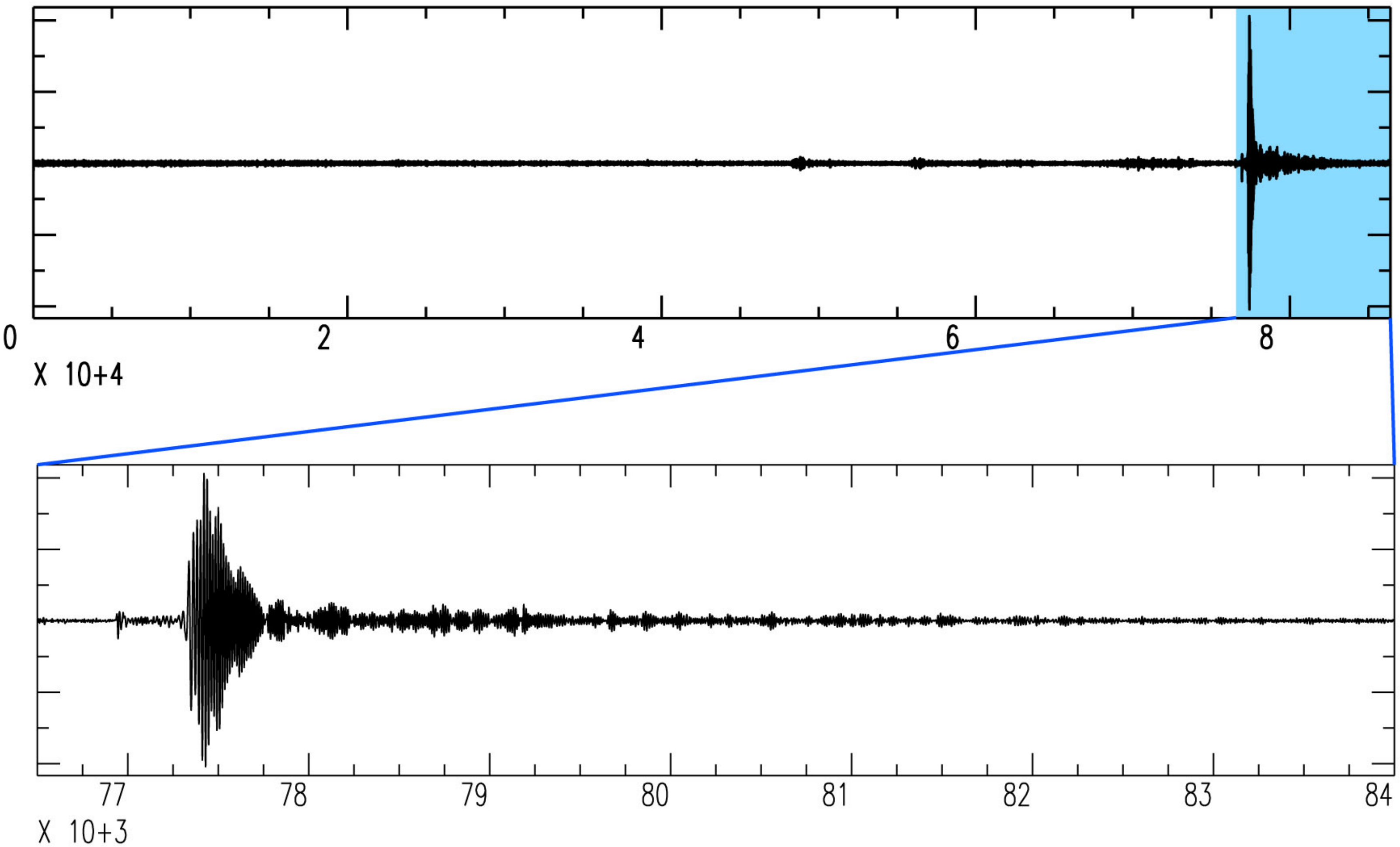
Natural sources of seismic signals

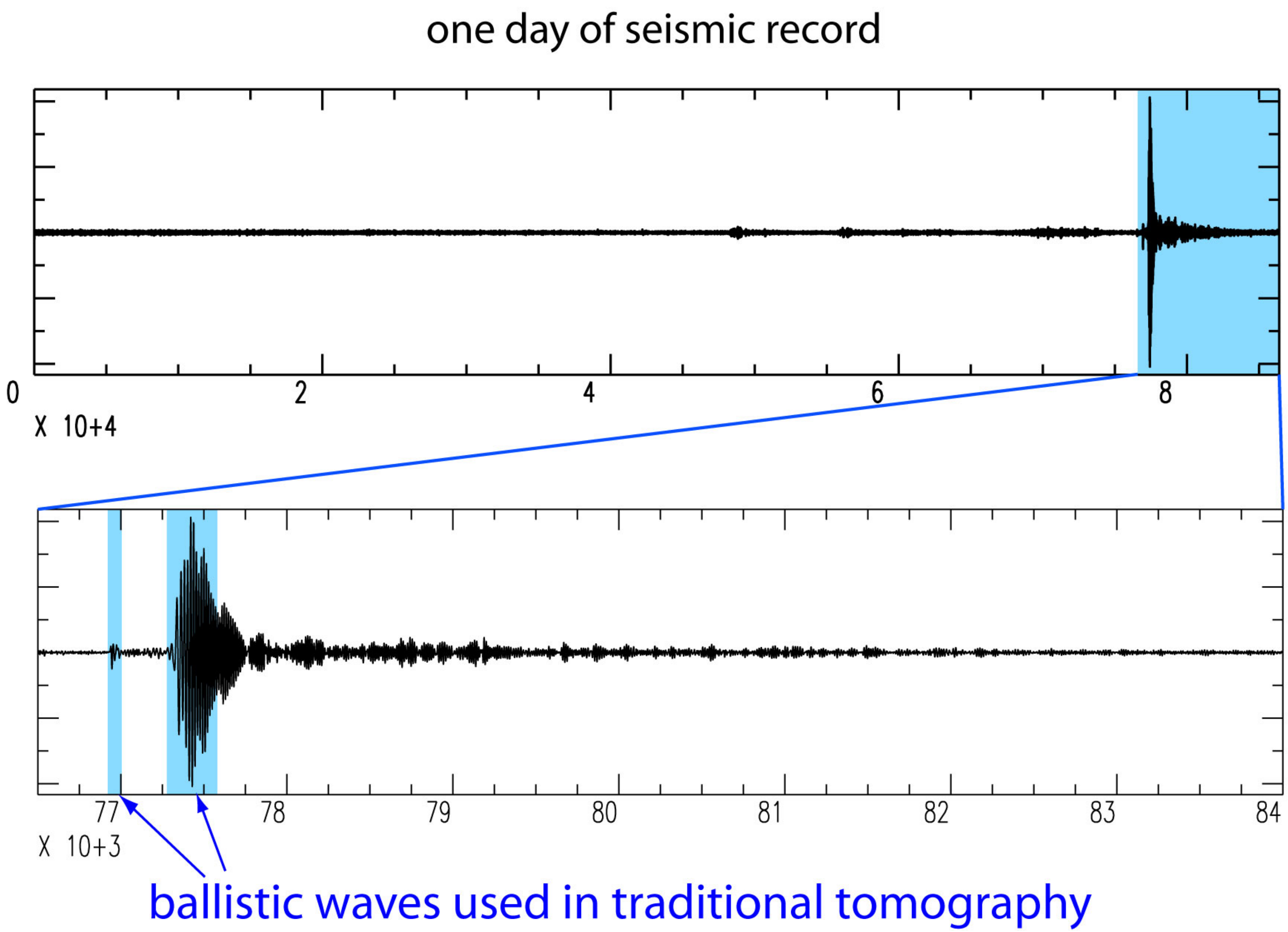


one day of seismic record

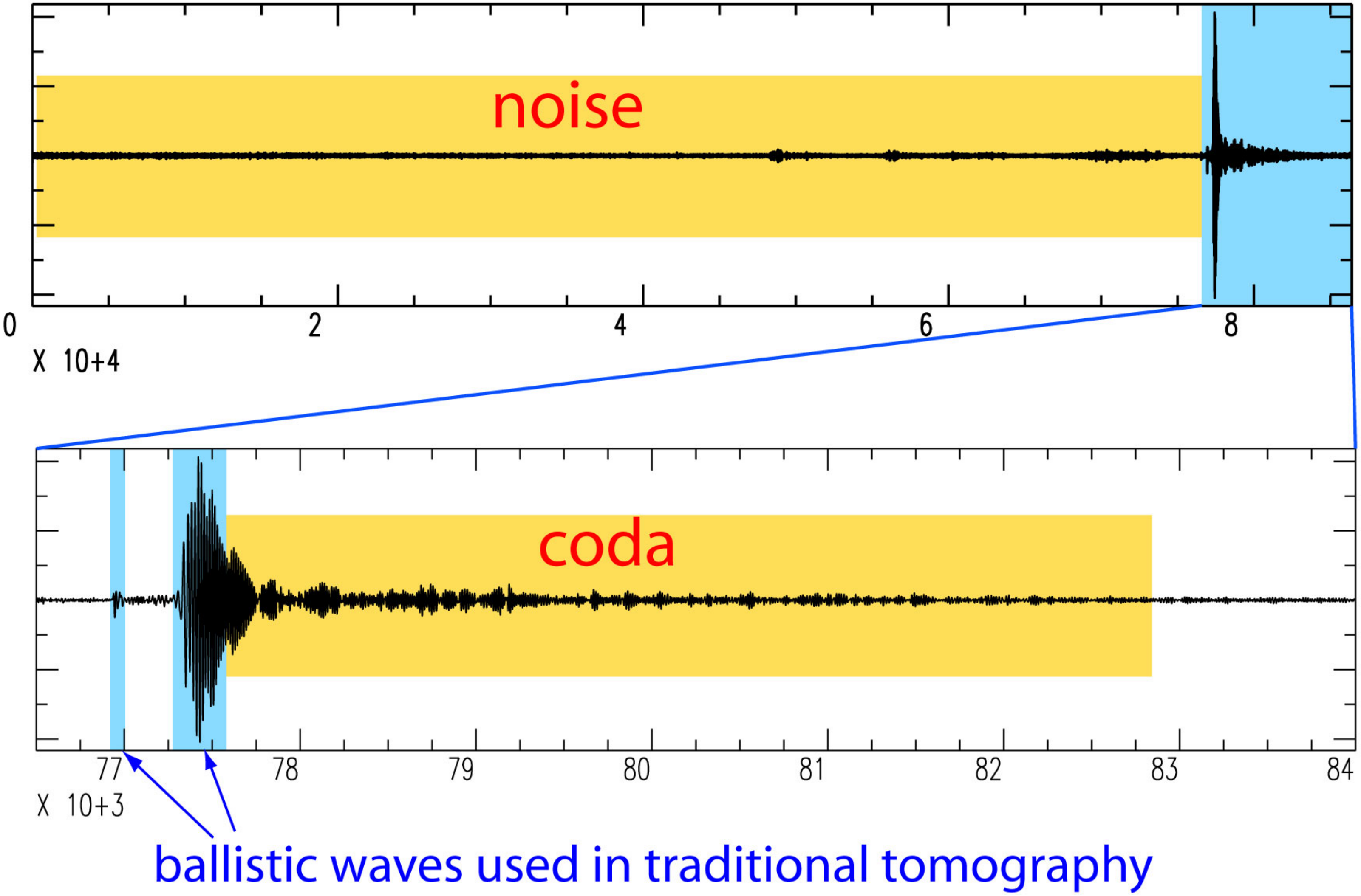


one day of seismic record




one day of seismic record
0
2
4
6
8
X 10+4
77
78
79
80
81
82
83
84
X 10+3
ballistic waves used in traditional tomography

one day of seismic record



Why using solar powered sources (***noise***)?

1. Measurements in absence of earthquakes:

   - improved resolution

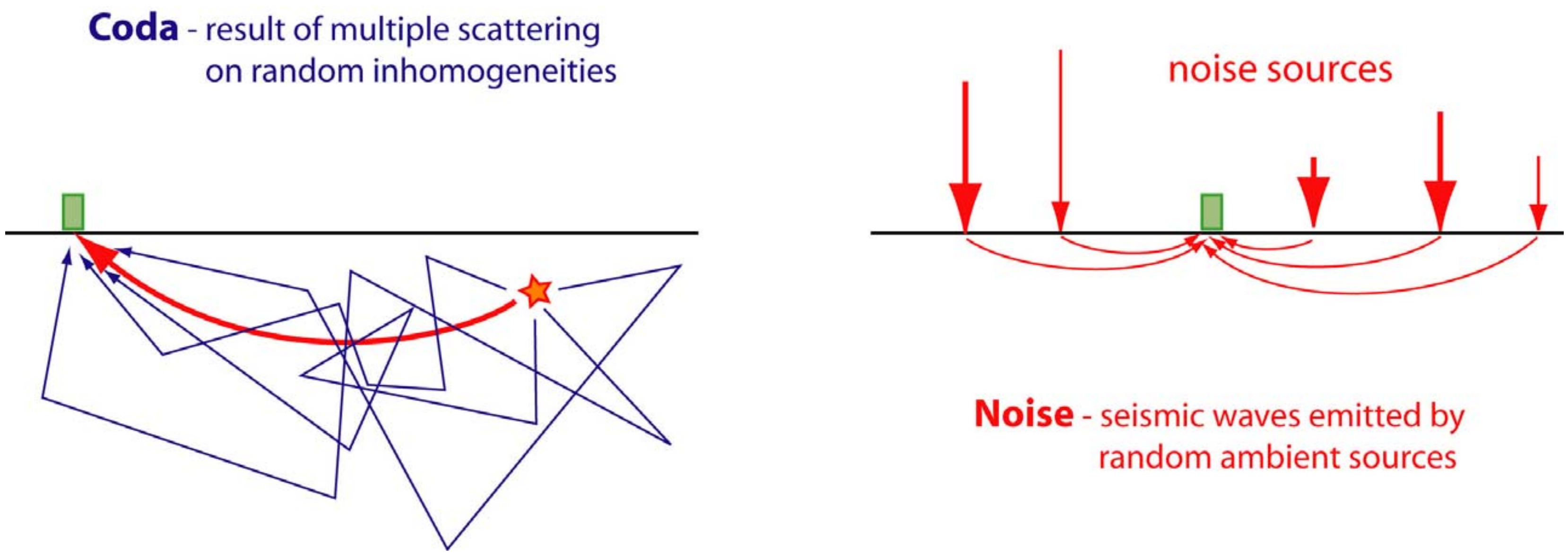
   - repetitive measurements:

     monitoring of temporal changes (volcanoes, fault zones)

2. Possibility to study the coupling between the Solid Earth, the Ocean, and the Atmosphere

from previous lecture by M. Campillo

Seismic coda and ambient seismic noise - random seismic wavefields



Extraction of Green functions from random wavefields

from previous lecture by M. Campillo

Green function A->B ~ time correlation of fields in A and B

Applications with mechanical waves (under different names) :

Helioseismology: Duvall et al. (1993)+….
Laboratory Acoustics: Weaver and Lobkis (2001)+…
Sesimic coda waves: Campillo and Paul (2003)+…
Marine acoustics: Roux et al., (2003)+…
Ambient seismic noise: Shapiro and Campillo (2004)+…

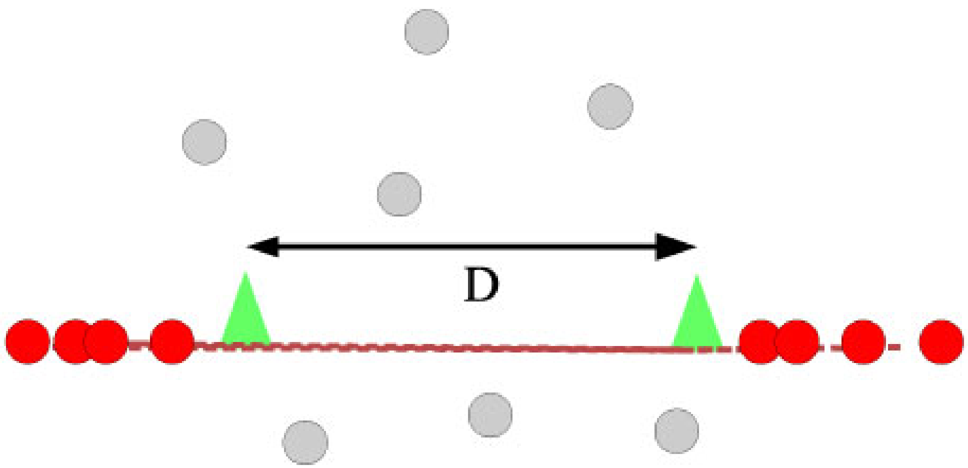
Correlations of seismic noise are dominated by
fundamental mode surface waves :

- sources acting on the Earth surface
- surface-to-surface Green function

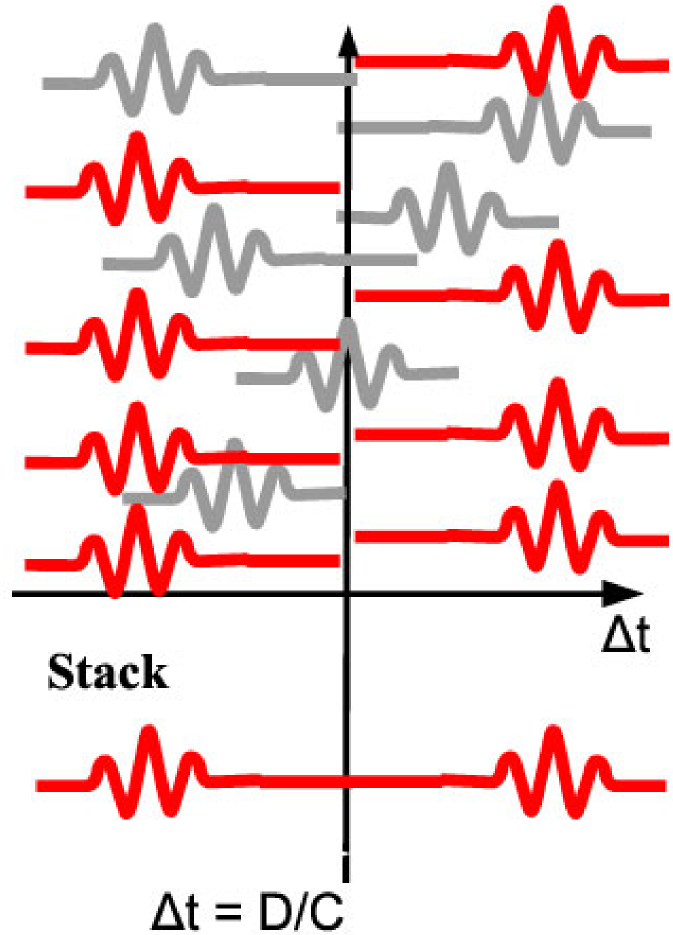
from Roux et al., Snieder, …

Correlation of waves emitted by randomly distributed sources

Results of correlations are constructive for sources aligned with stations



Stacking of different correlations results in a signal with an arrival time corresponding to the speed of waves traveling in the media



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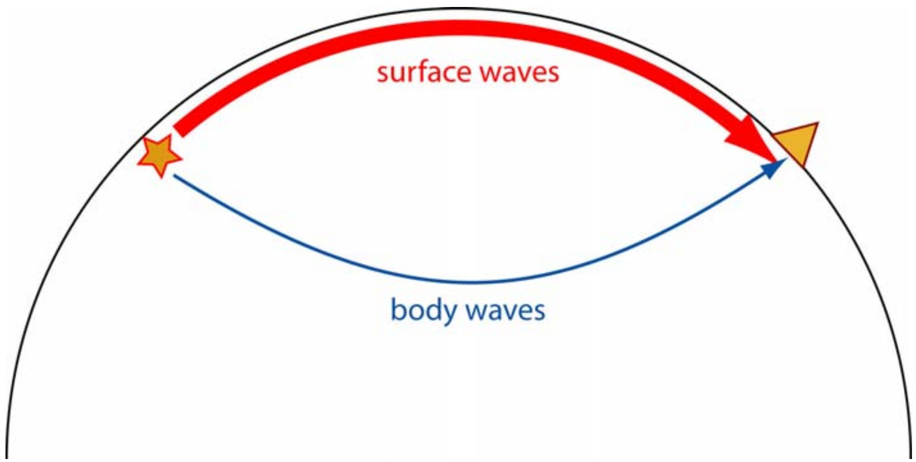
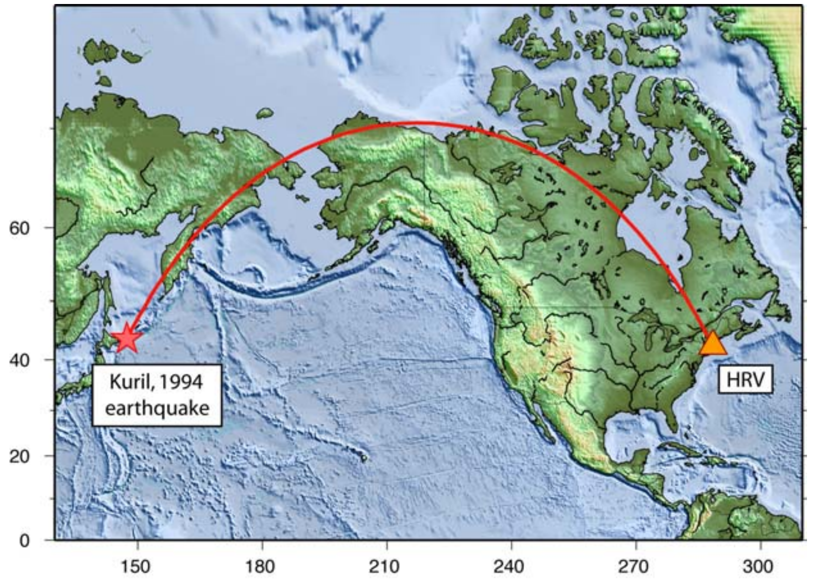
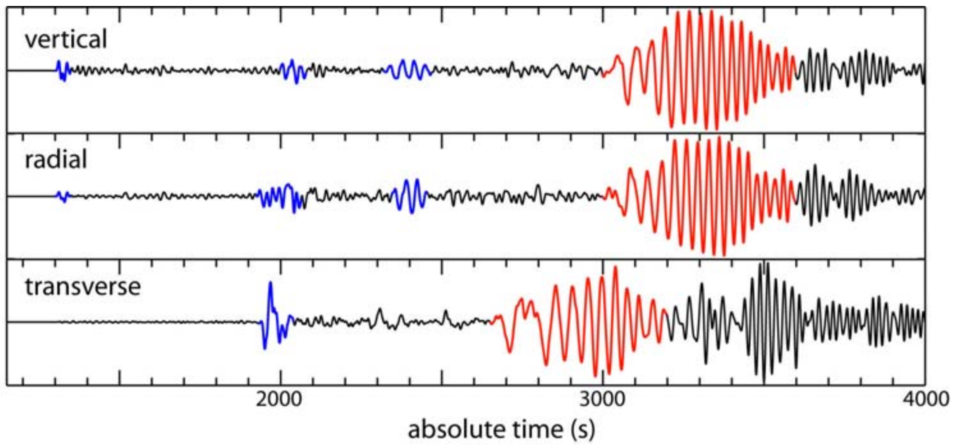
traditional surface-wave tomography

Seismic data





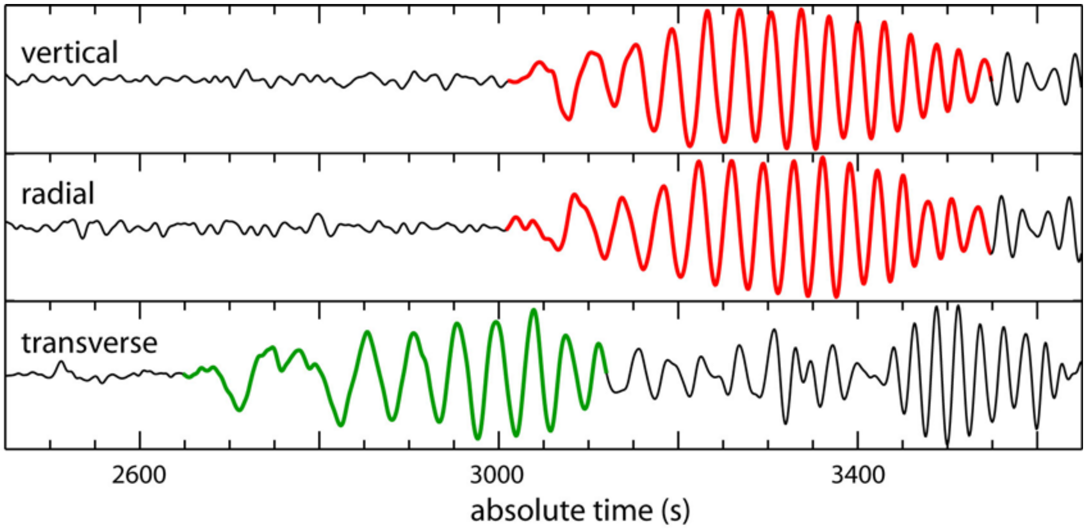


Body waves sample deep parts of the Earth

Surface waves sample the crust and upper mantle

traditional surface-wave tomography

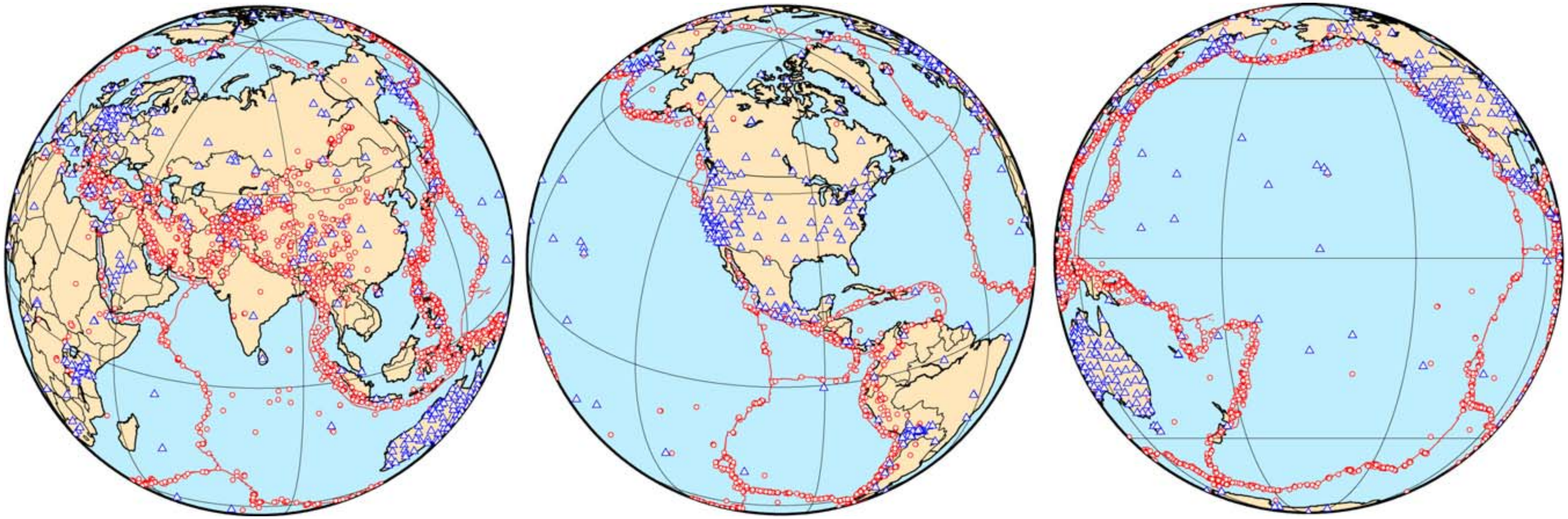
Seismic surface-waves



1. Two types: **Rayleigh** and **Love**
2. **Dispersion**: travel times depend on period of wave
3. Two types of travel time measurements: **phase** and **group**

traditional surface-wave tomography

distribution of paths for dispersion measurements



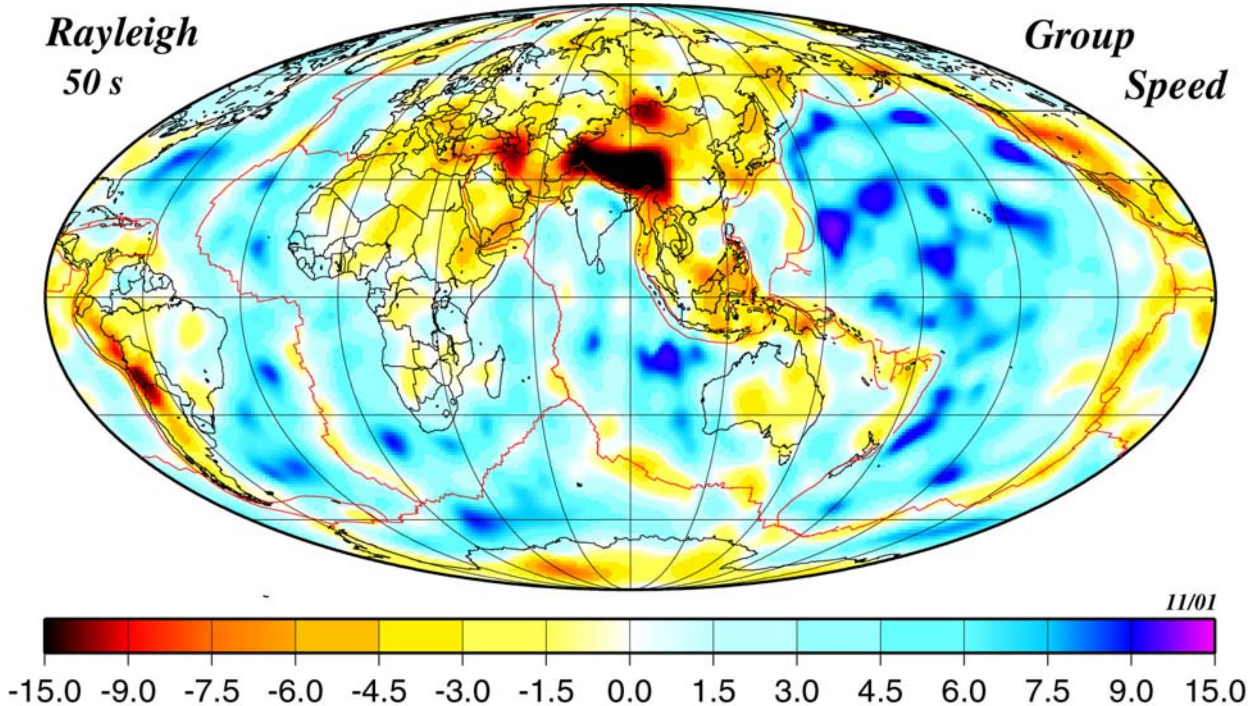
Rayleigh and Love phase and group velocity measurements for more than 200,000 paths across the Globe

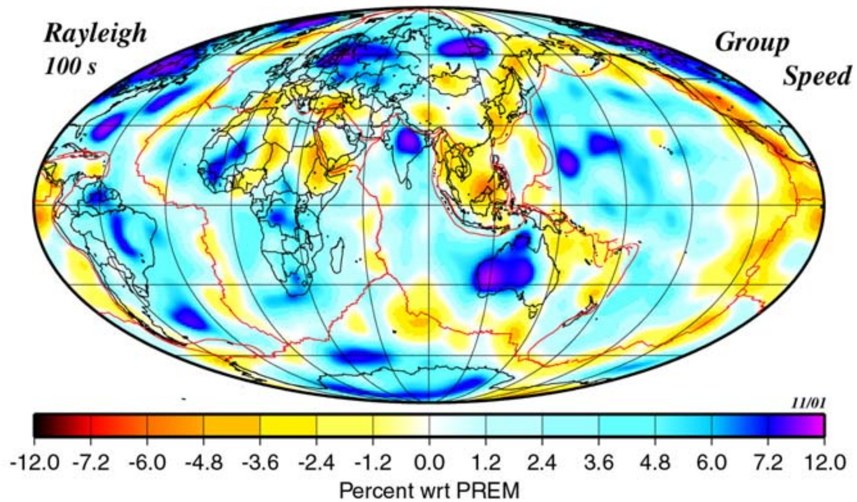
traditional surface-wave tomography

from Ritzwoller et al., 2002

Dispersion maps

2D tomography:
linear inversion of group and phase travel times on a sphere



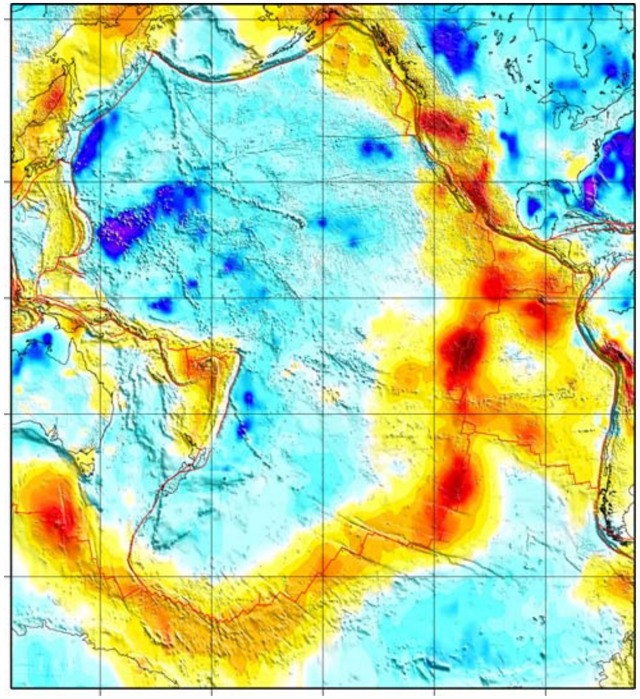


traditional surface-wave tomography

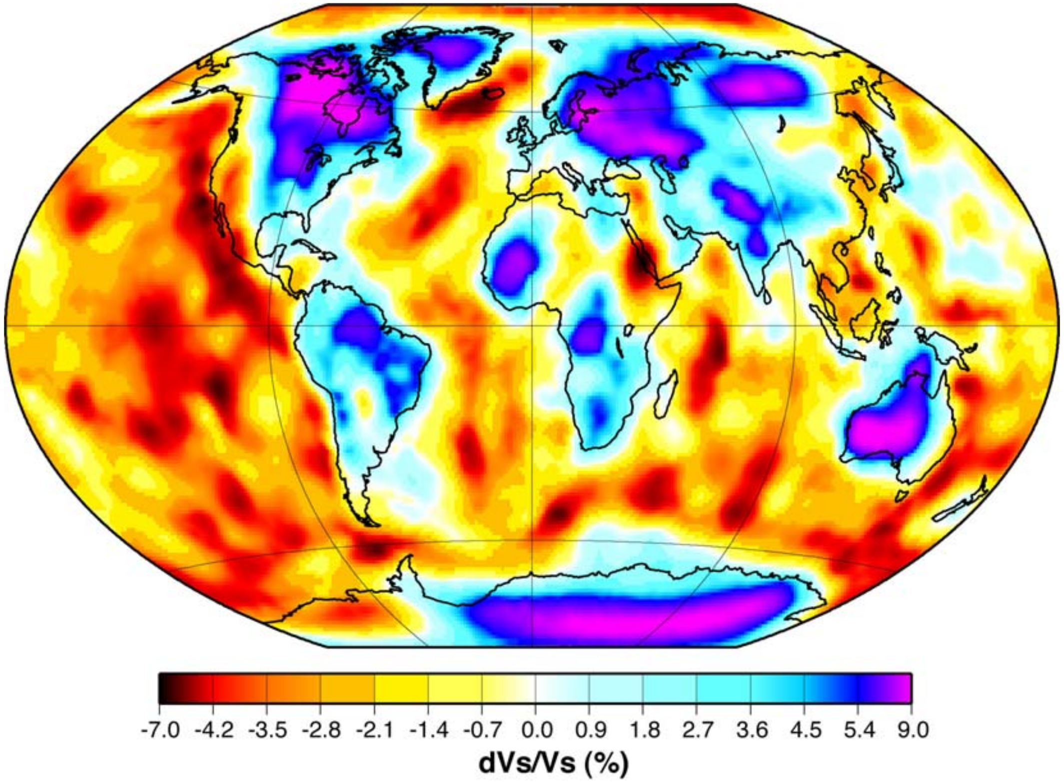
global 3D tomographic model

nonlinear inversion of local dispersion curves

50 km



150 km

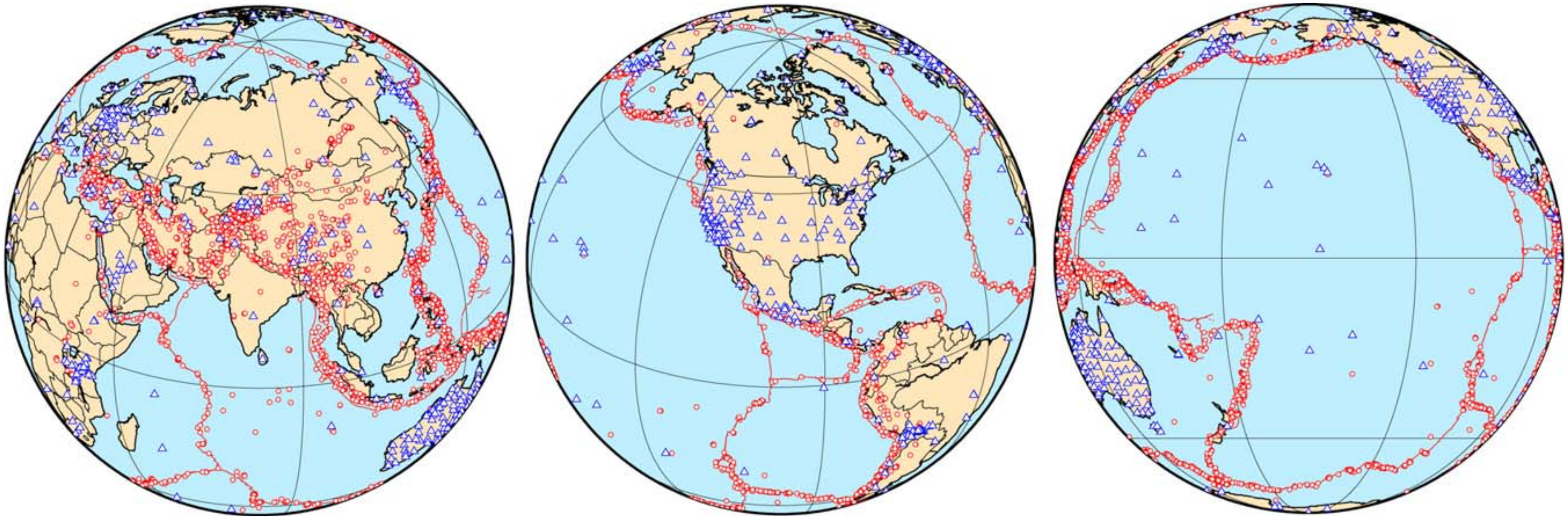


from Shapiro and Ritzwoller, 2002

Resolution of seismic models

✓Distribution of earthquakes and seismic stations is inhomogeneous

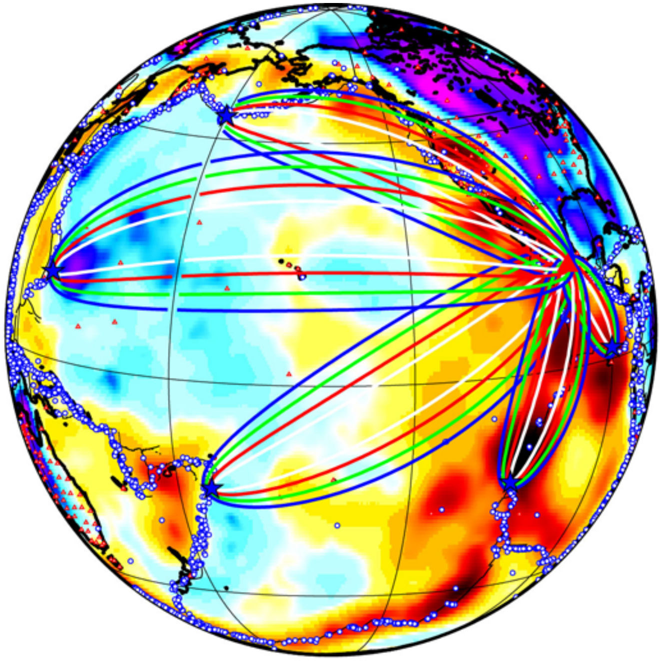
✓Resolution of seismic tomographic models is better in regions well covered by sources and receivers



Resolution of seismic models

Diffraction effects result in extended sensitivity kernels, especially for long paths

Short-period measurements are difficult to obtain for long paths



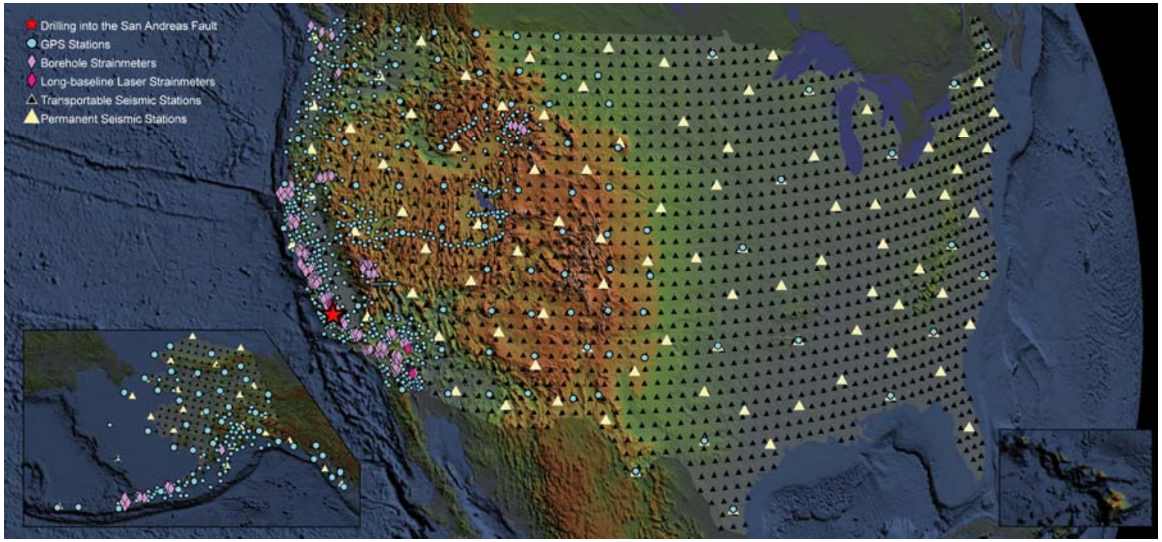
Resolution of seismic tomographic models is better in regions covered by short paths

How can we improve the resolution?

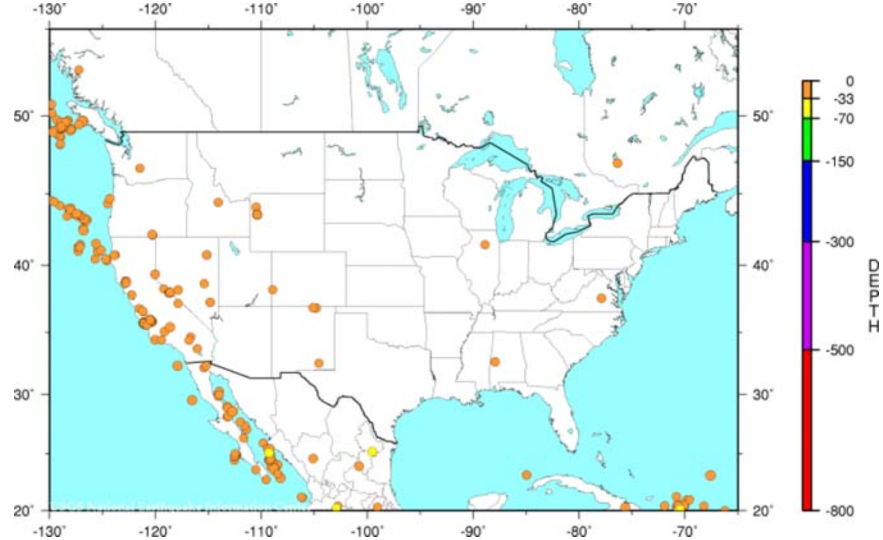
1. install more stations

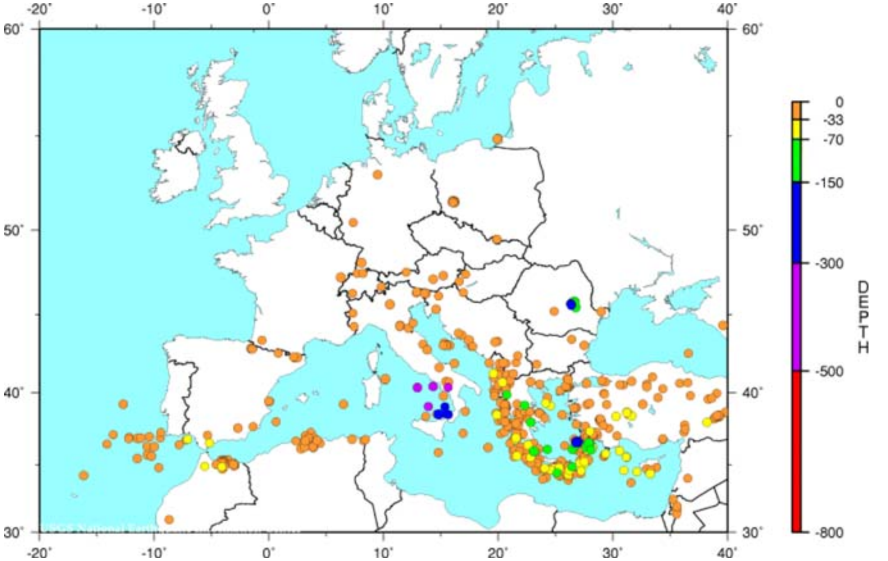
2. **new types of measurements**

Earthscope USAarray



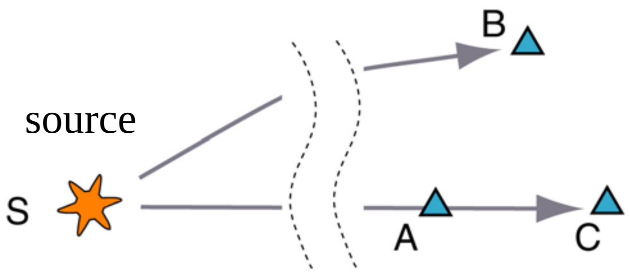
distribution of M>4 earthquakes during 1.5 years (July, 2003-December, 2004)

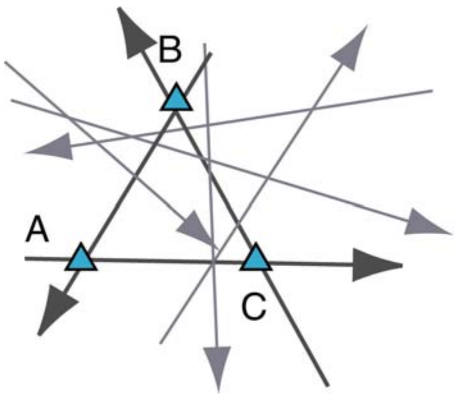




traditional approach:
using
teleseismic surface waves

Alternative solution:
making measurement from
the **ambient seismic noise**





- extended lateral sensitivity
- sample only certain directions
- difficult to make short-period measurements

- localized lateral sensitivity
- samples all directions
- may allow many short-period measurements

Consequence: **limited resolution**

Improves resolution in the crust

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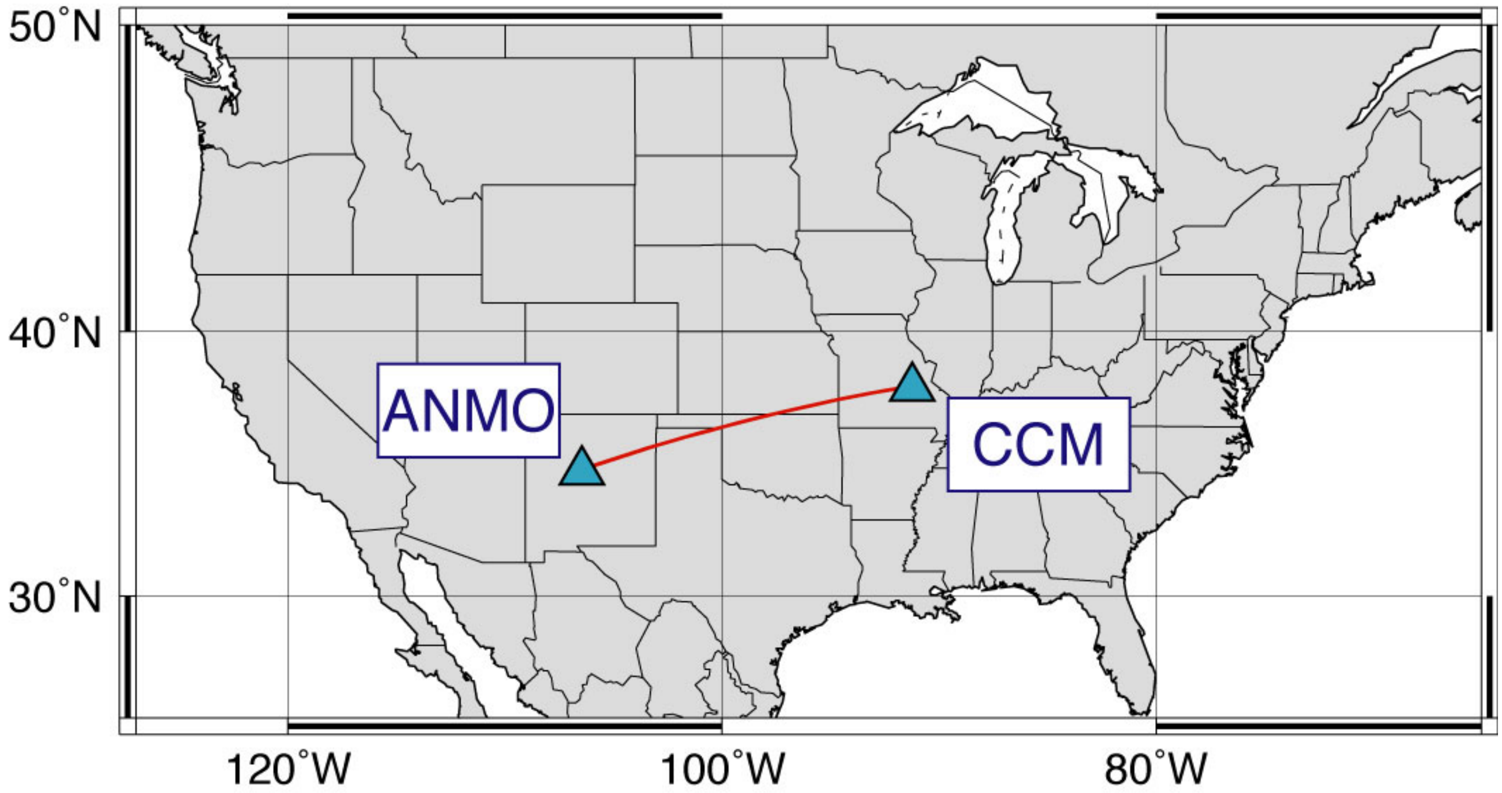
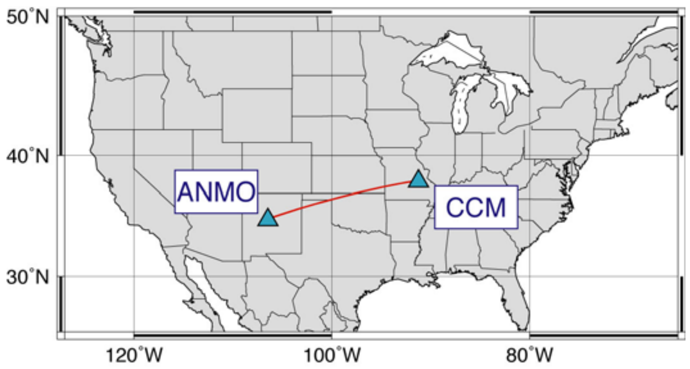
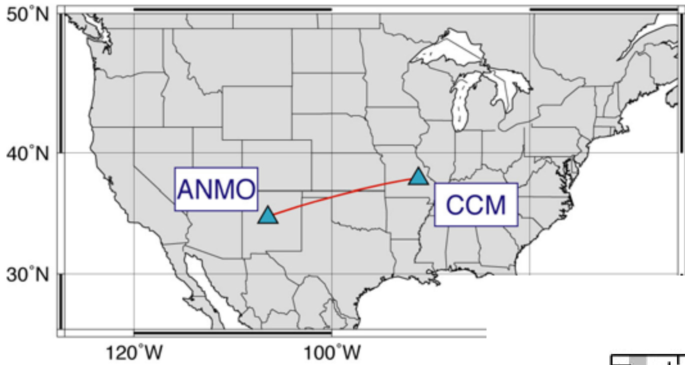
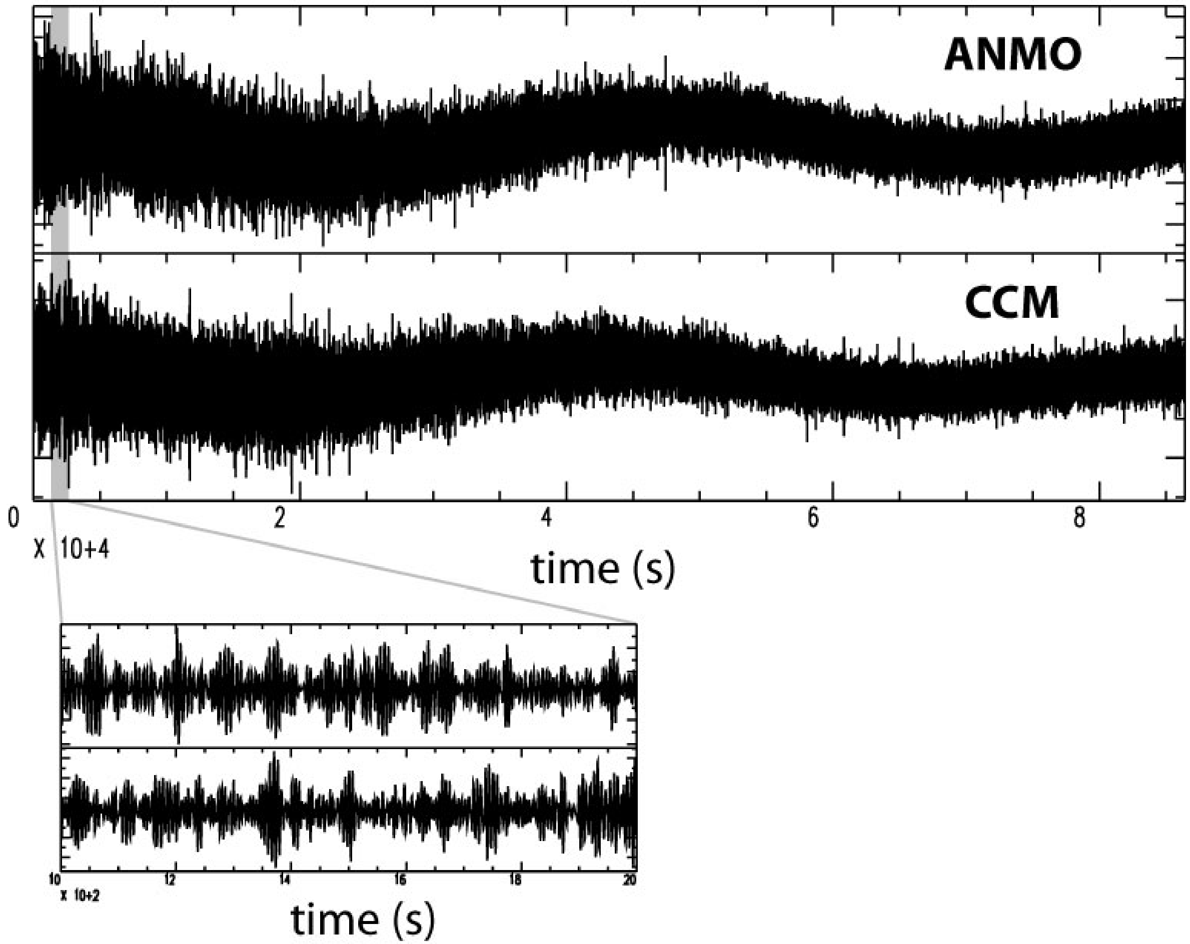
Correlation of seismic noise: data processing

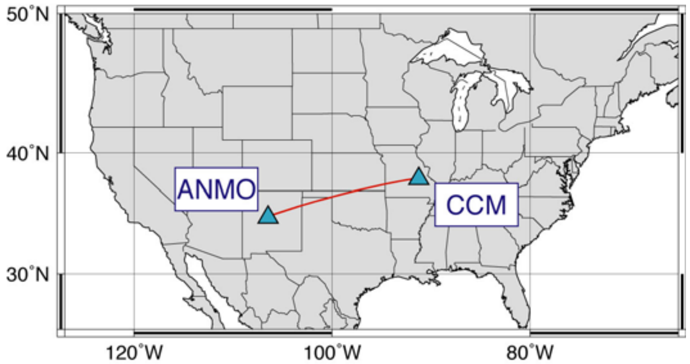



50˚N
40˚N
30˚N
120˚W
100˚W
80˚W
ANMO
CCM



1. Raw data (January 18, 2002)





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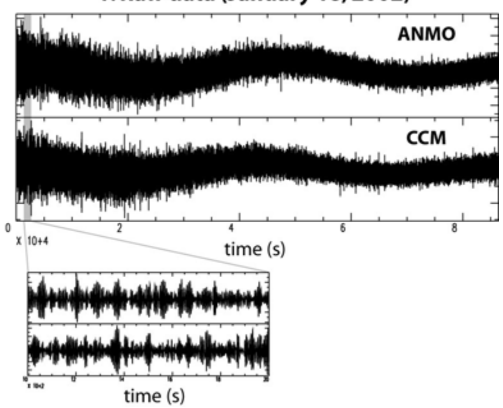
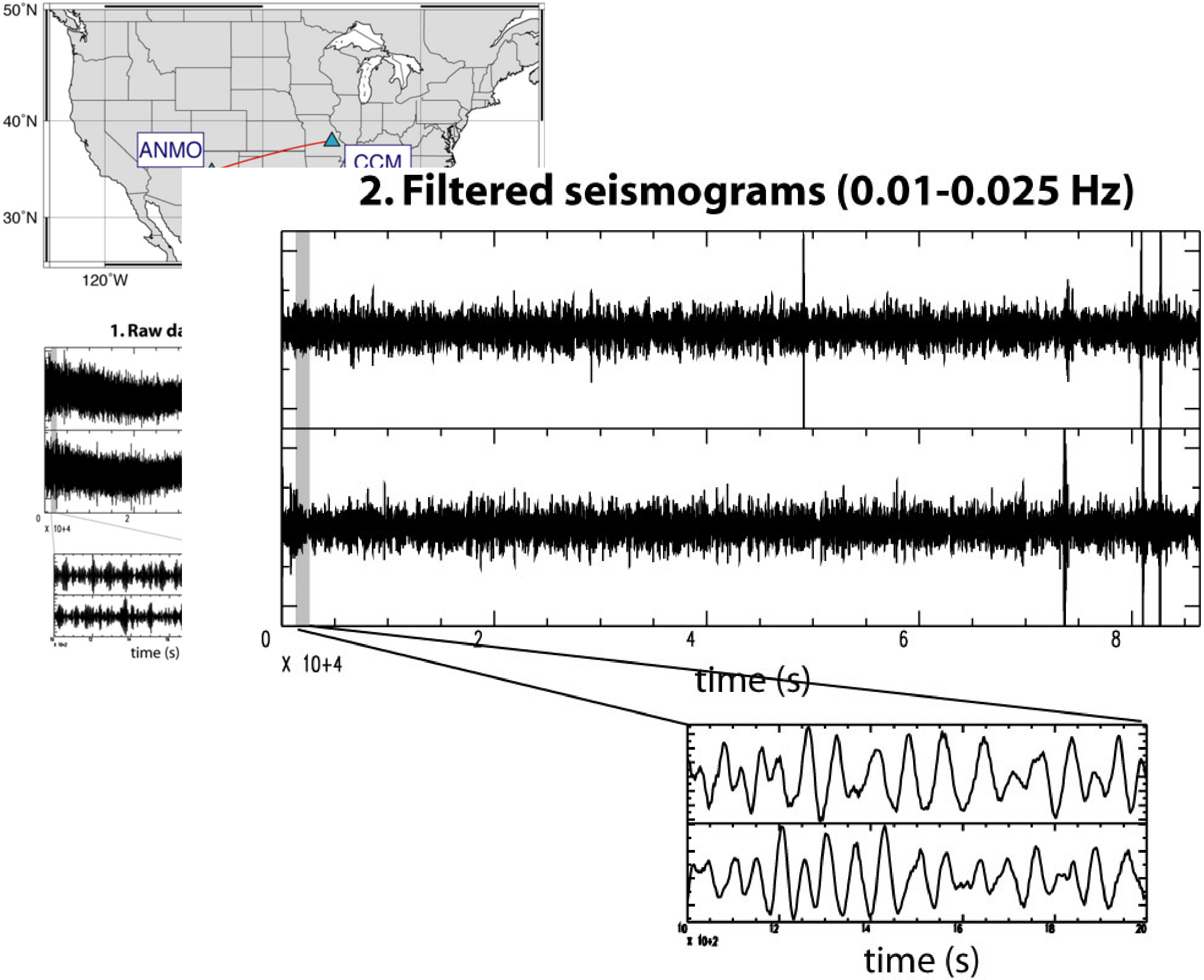
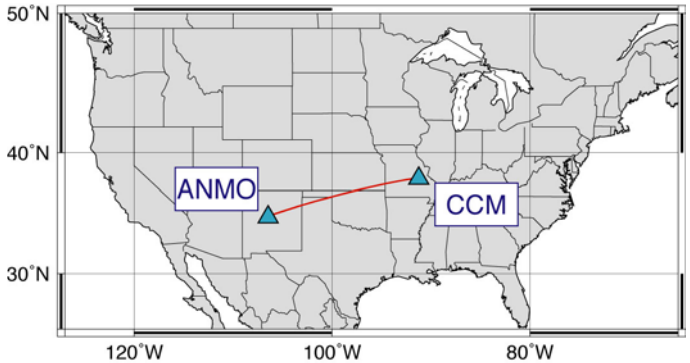



50°N
40°N
30°N
120°W
ANMO
CCM
1. Raw da
time (s)
2. Filtered seismograms (0.01-0.025 Hz)
0
2
4
6
8
X 10+4
time (s)
time (s)



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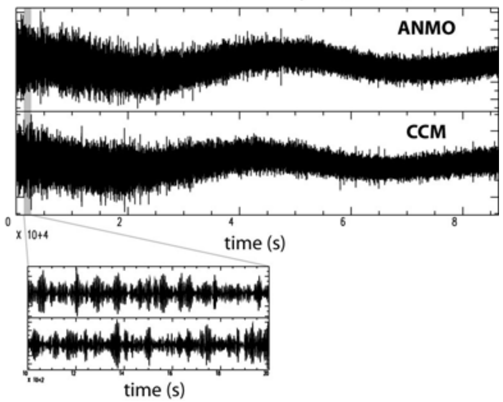
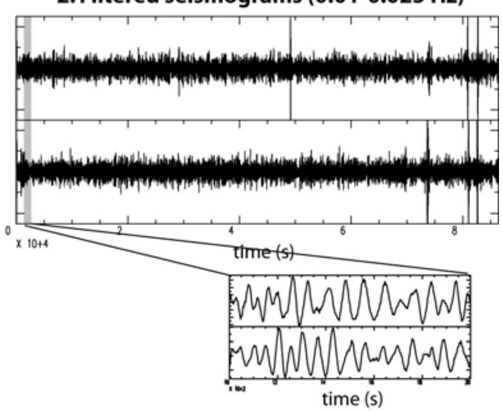
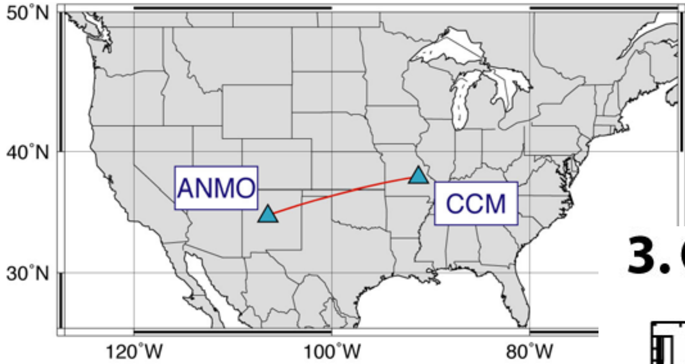


2. Filtered seismograms (0.01-0.025 Hz)





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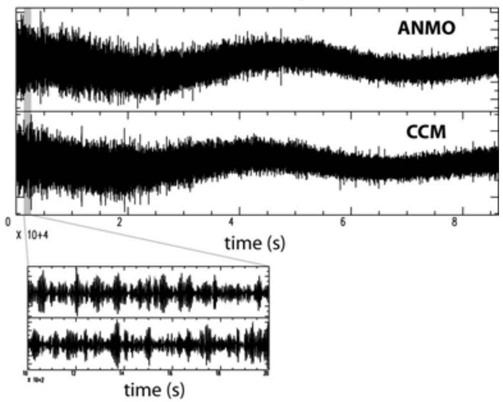

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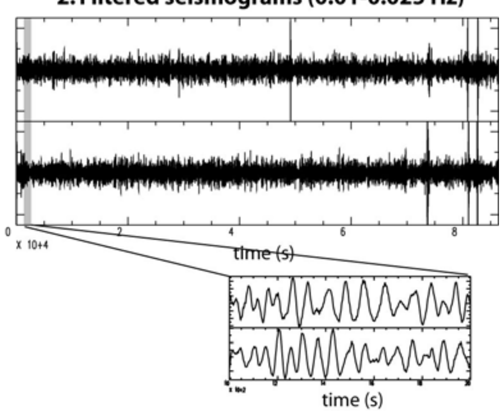
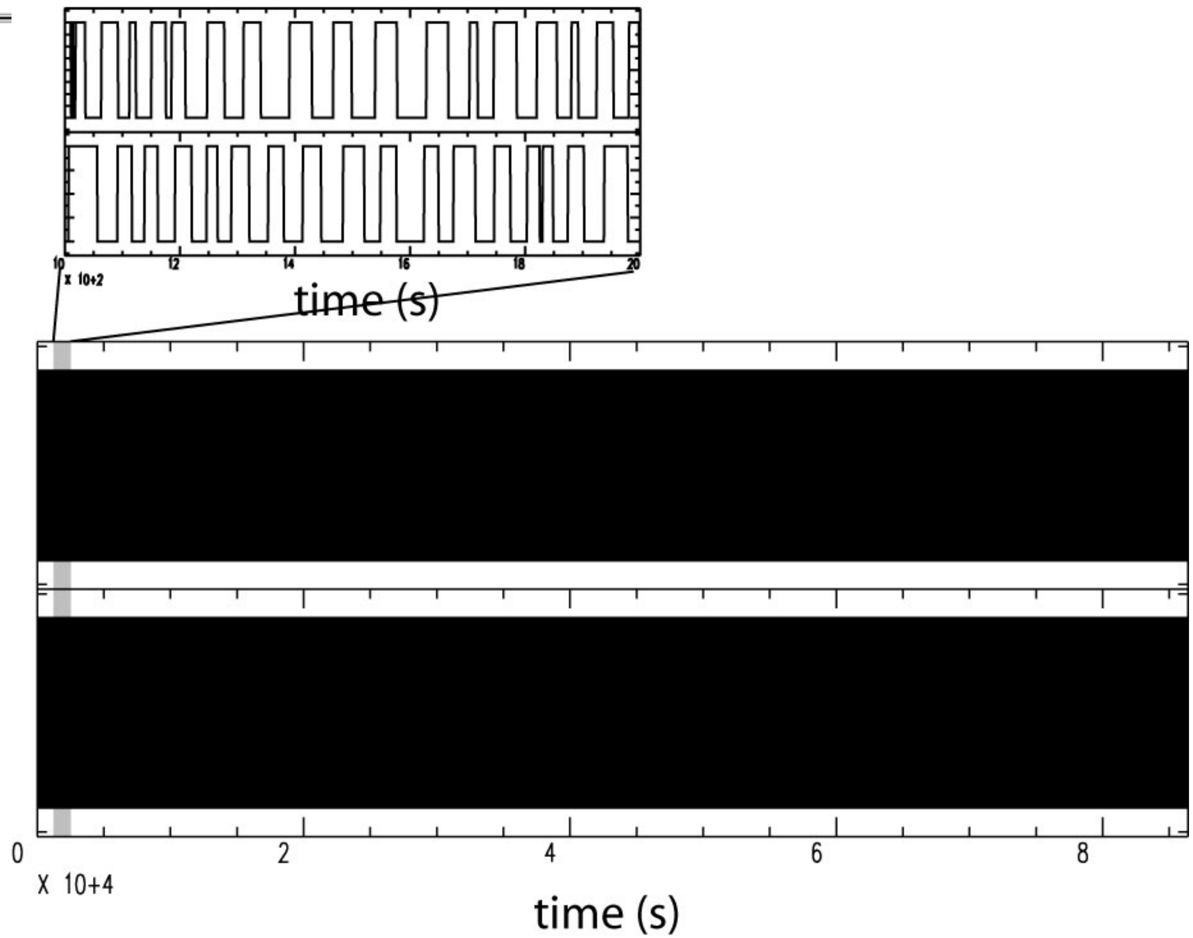
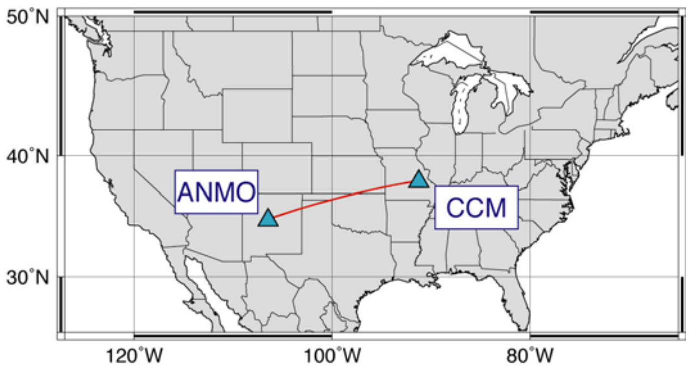


3. One-bit normalization





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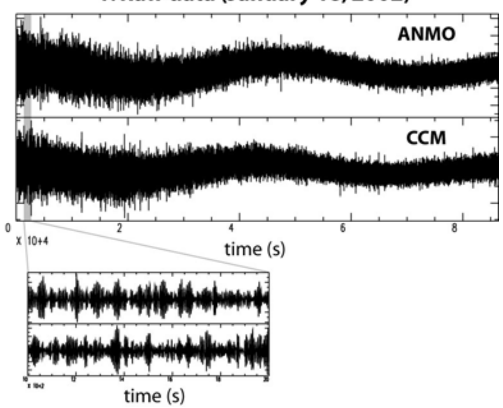
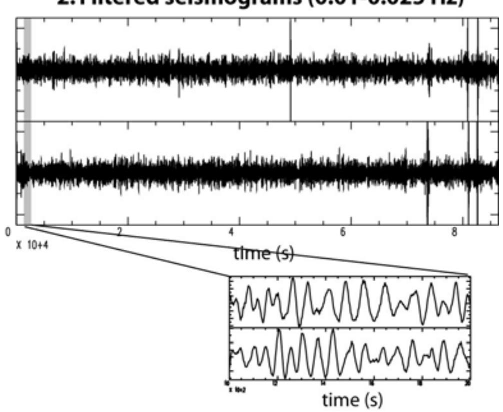


2. Filtered seismograms (0.01-0.025 Hz)



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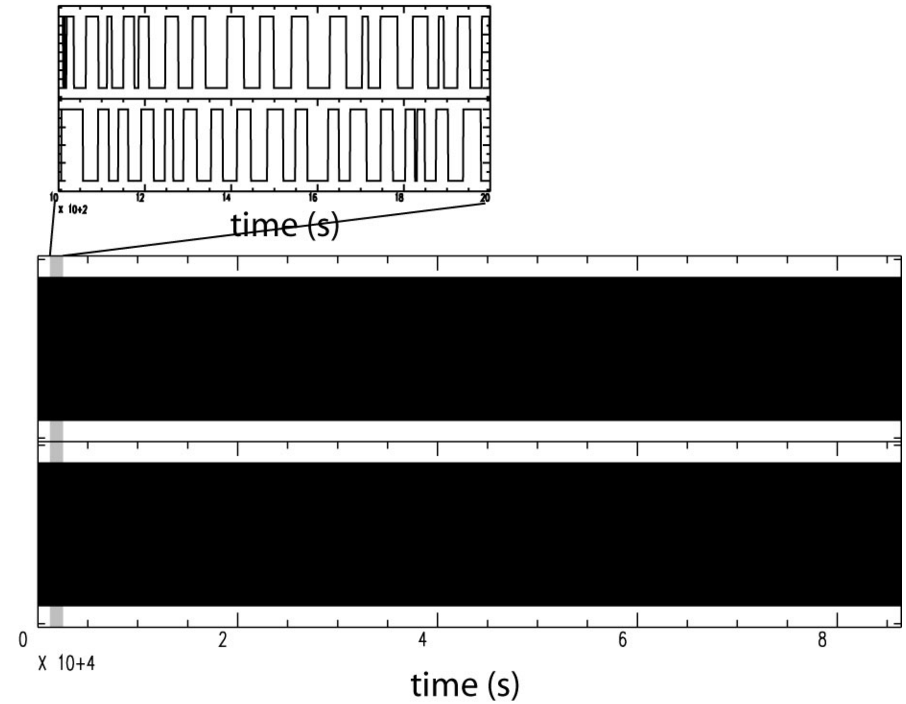
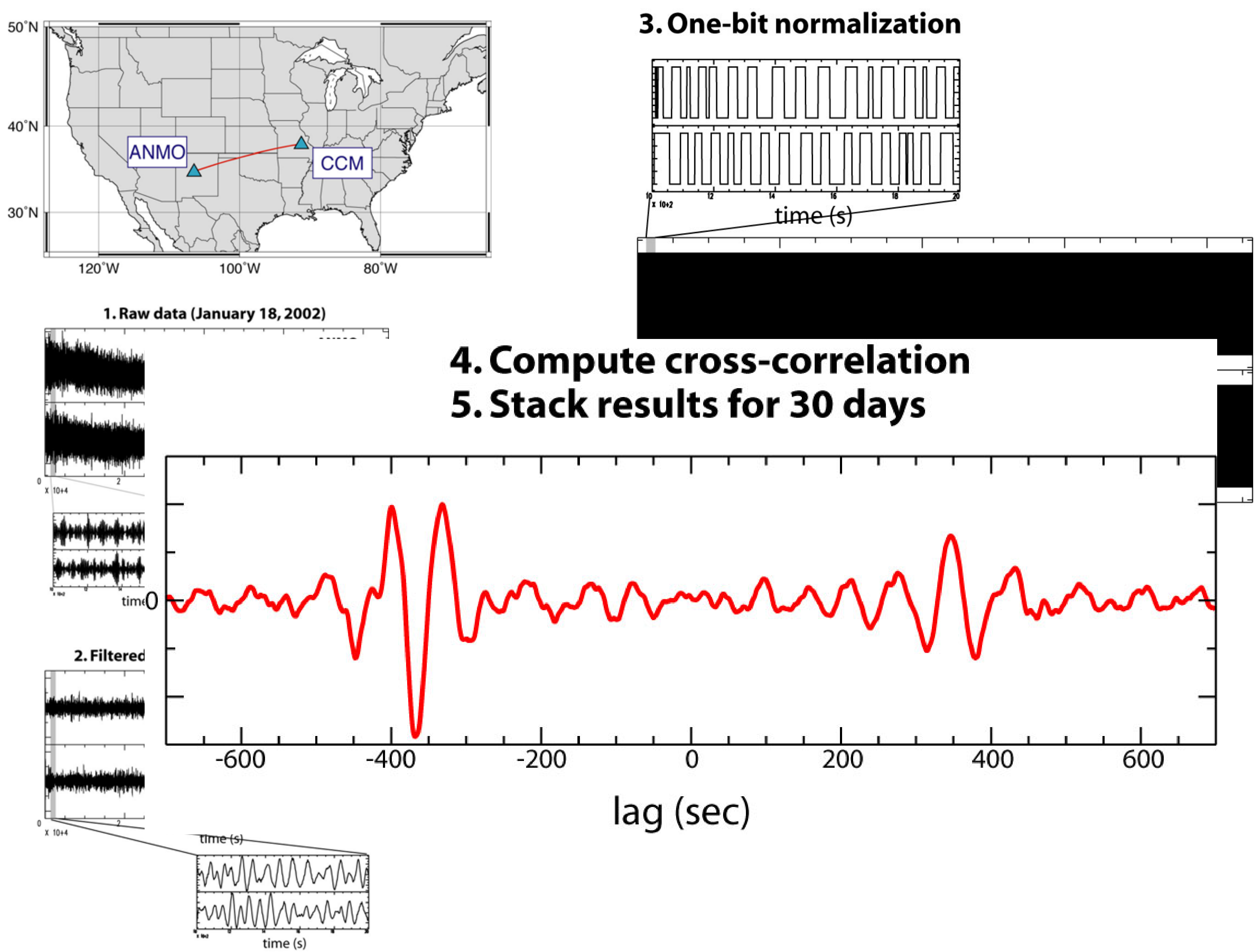
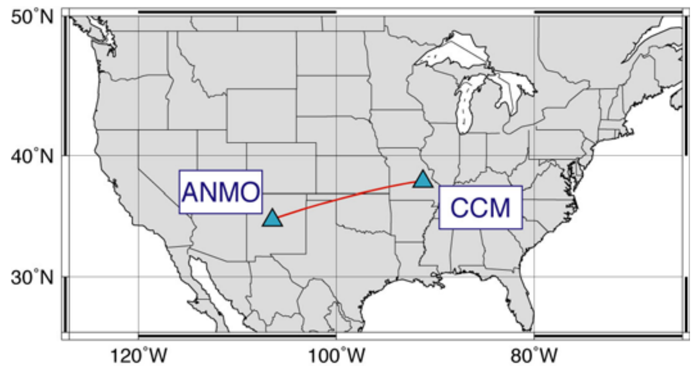



3. One-bit normalization
time (s)
50°N
40°N
30°N
ANMO
CCM
120°W
100°W
80°W
1. Raw data (January 18, 2002)
2. Filtered
4. Compute cross-correlation
5. Stack results for 30 days
0
-600
-400
-200
0
200
400
600
lag (sec)
time (s)
time (s)



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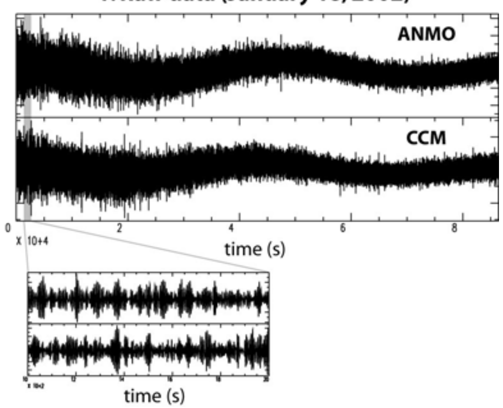
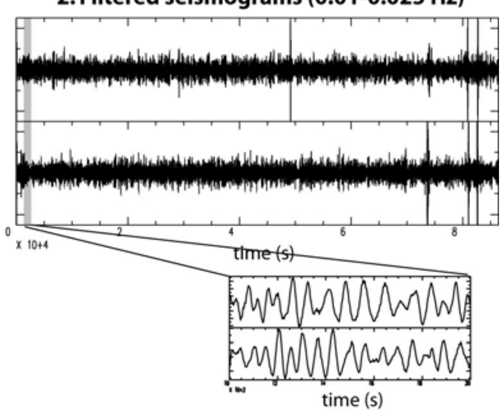


2. Filtered seismograms (0.01-0.025 Hz)



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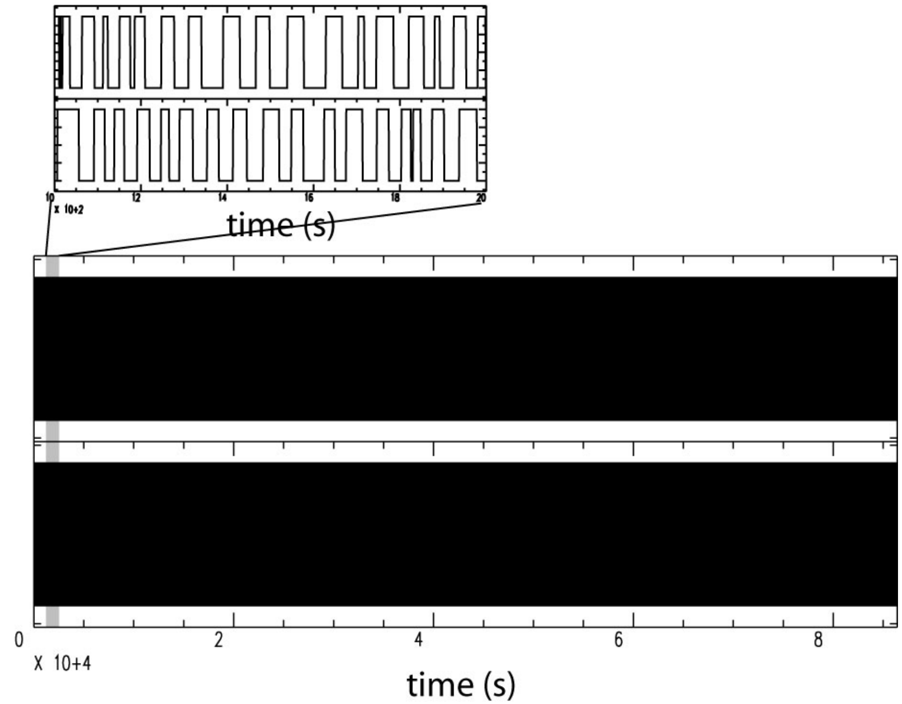

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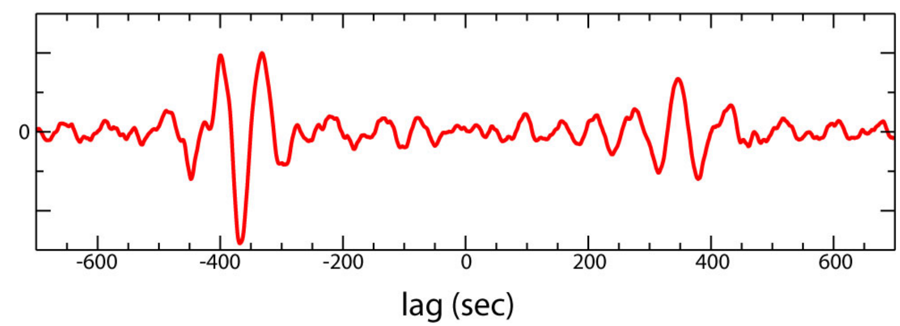
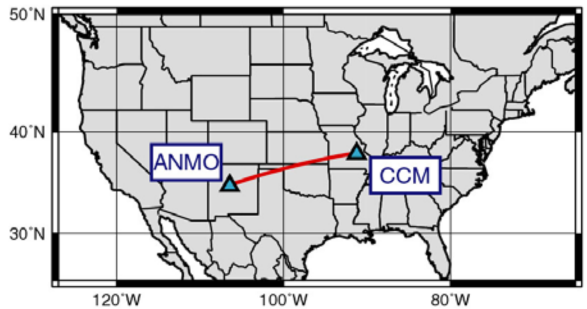
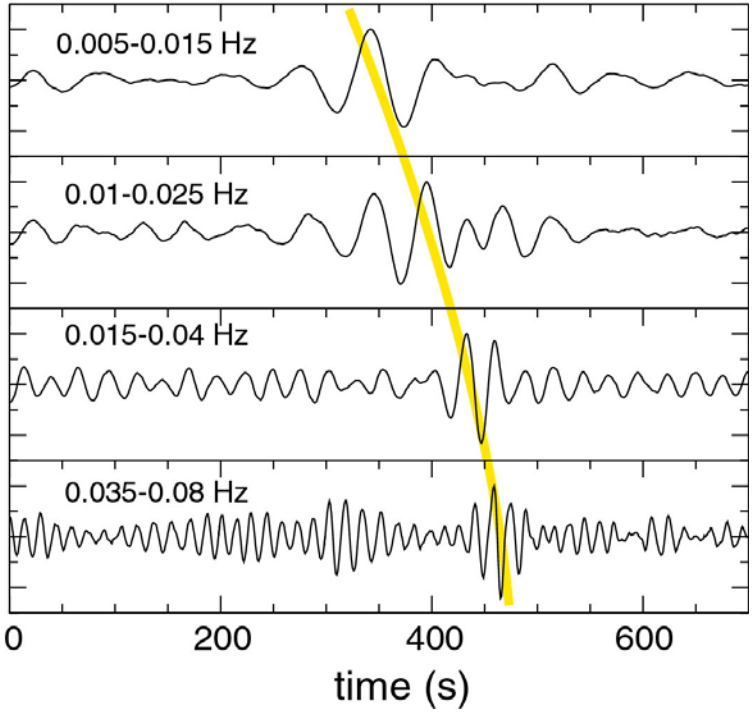


Cross-correlations from ambient seismic noise: ANMO - CCM

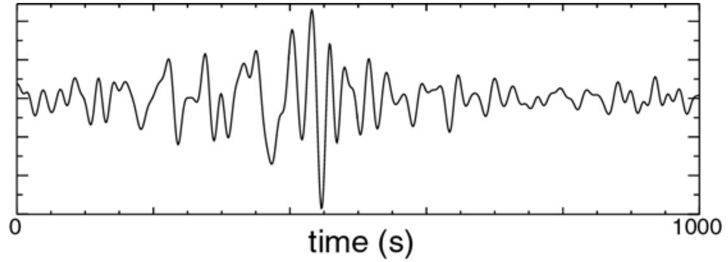
cross-correlations from 30 days of continuous vertical component records (2002/01/10-2002/02/08)

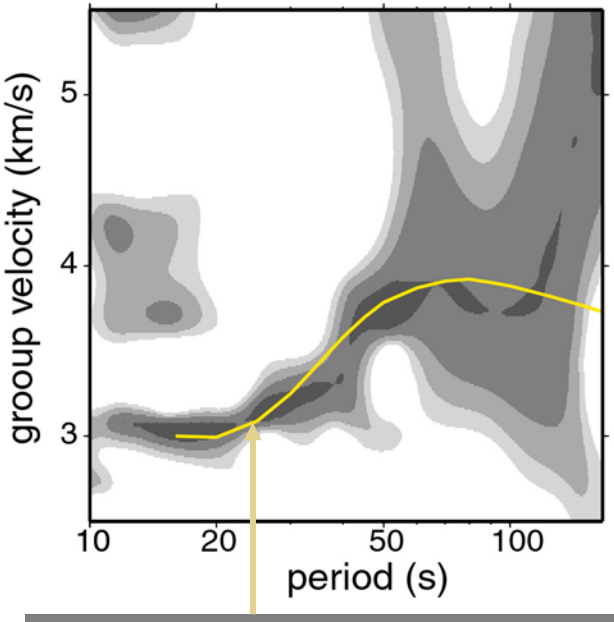




from Shapiro and Campillo, 2004

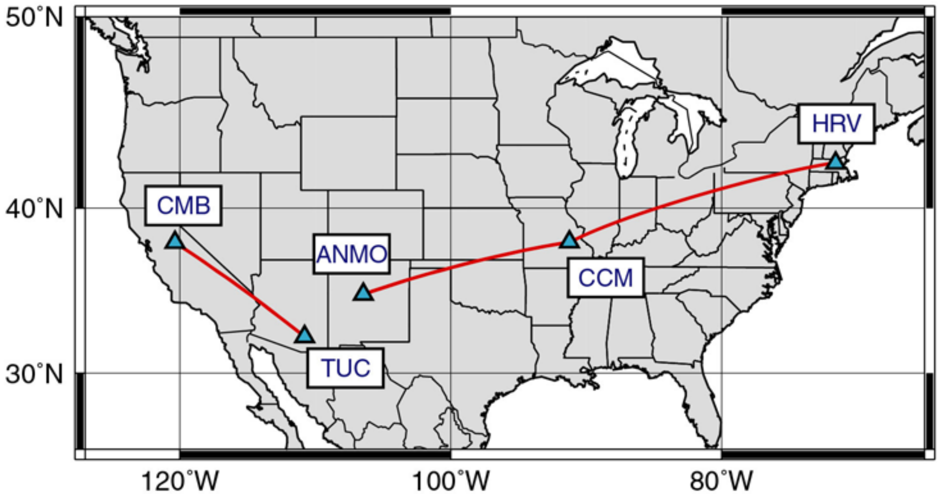
frequency-time analysis of the broadband cross-correlation



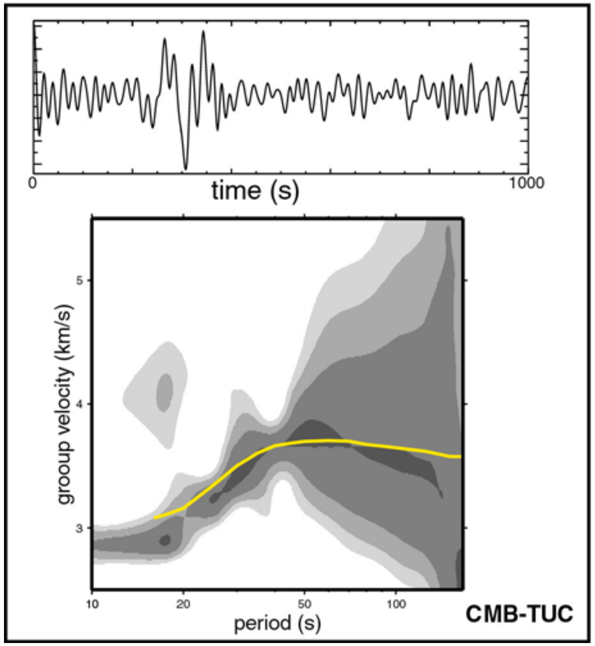


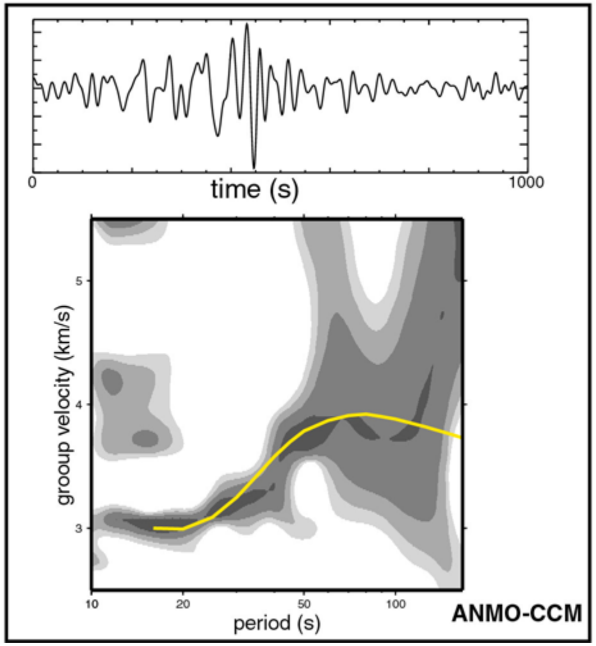
prediction from global group velocity maps of Ritzwoller et al. (2002)

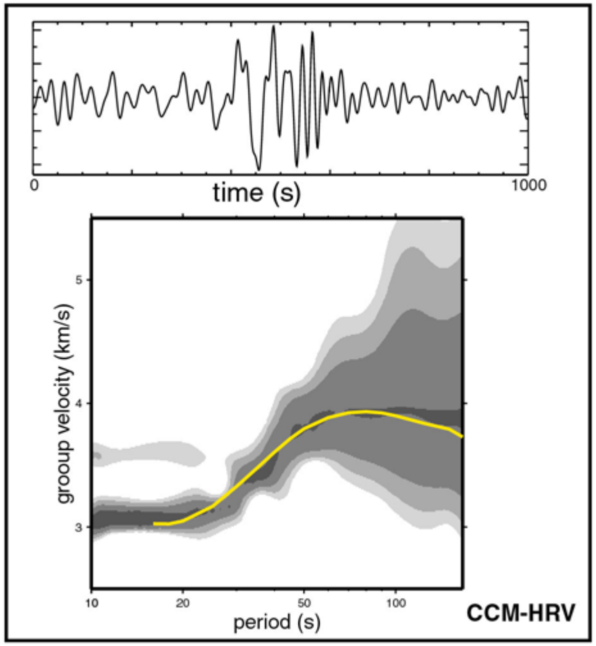
Cross-correlations from ambient seismic noise at US stations



frequency-time analysis of broadband cross-correlations computed from 30 days of continuous vertical component records



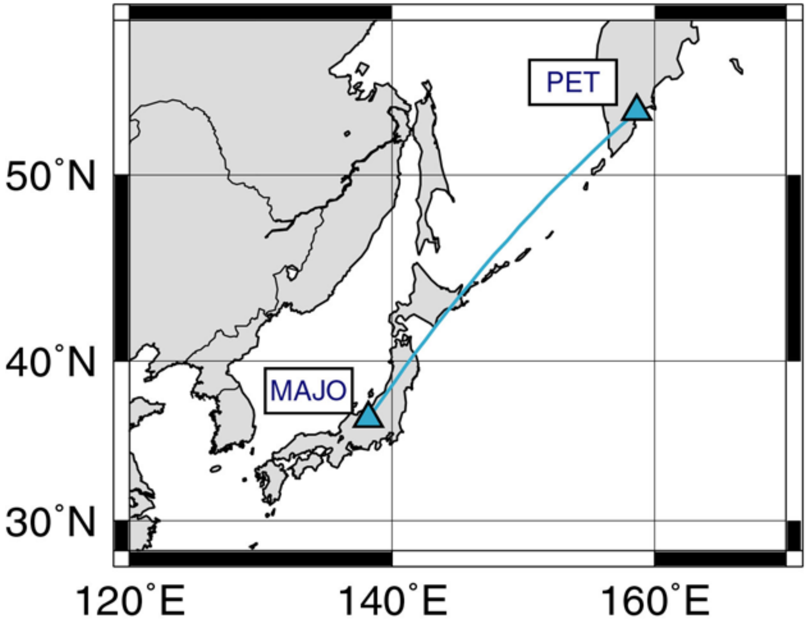


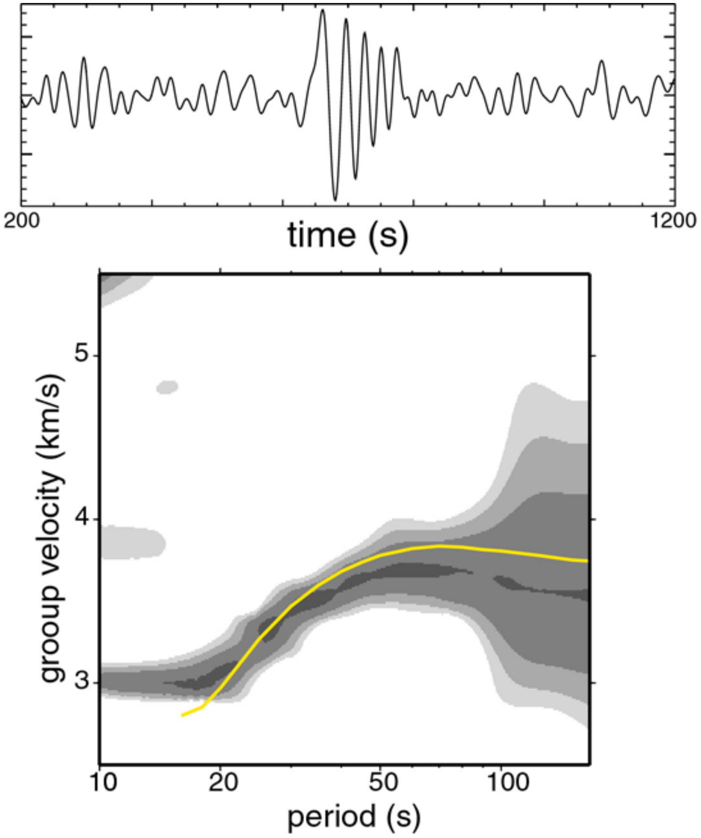


from Shapiro and Campillo, 2004

Cross-correlation from ambient seismic noise in North-Western Pacific

broadband cross-correlation computed from 30 days of continuous vertical component records





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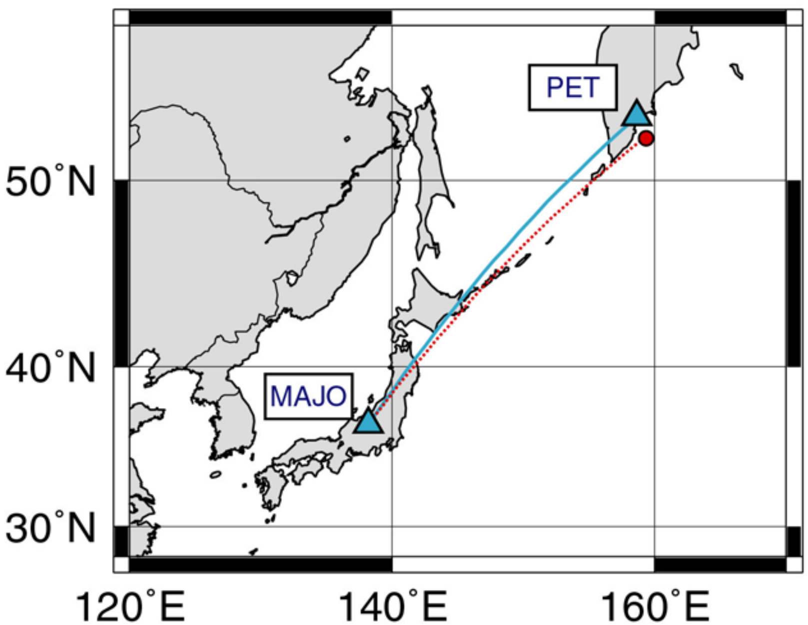
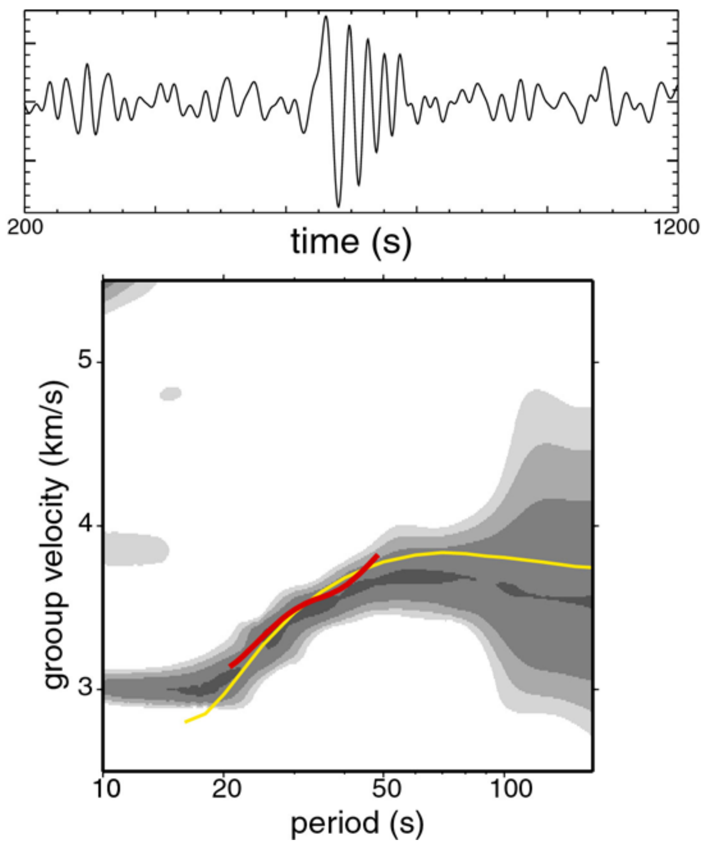
Cross-correlation from ambient seismic noise in North-Western Pacific

broadband cross-correlation computed from 30 days of continuous vertical component records

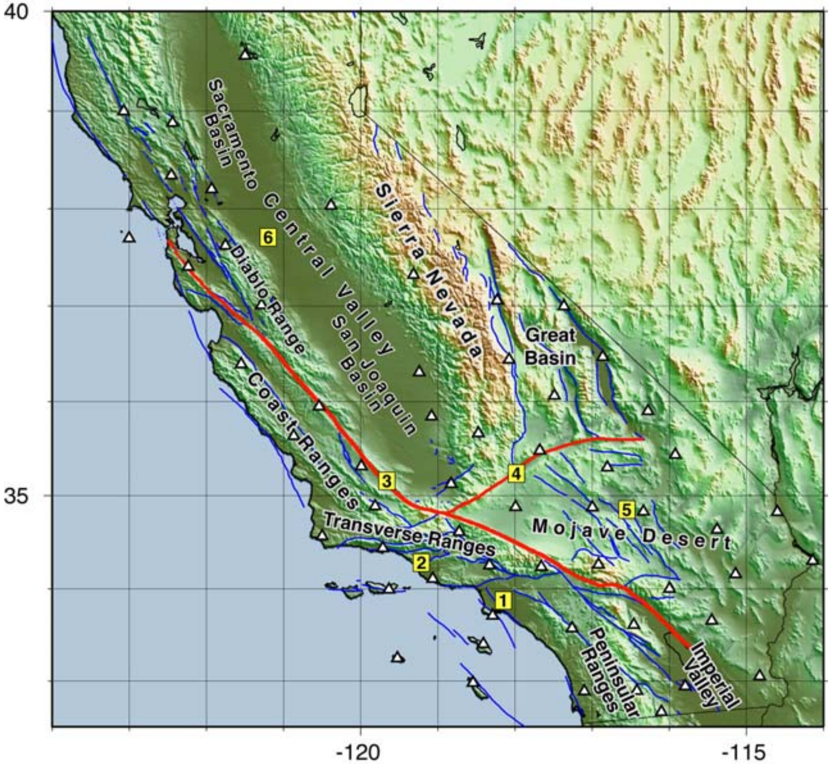




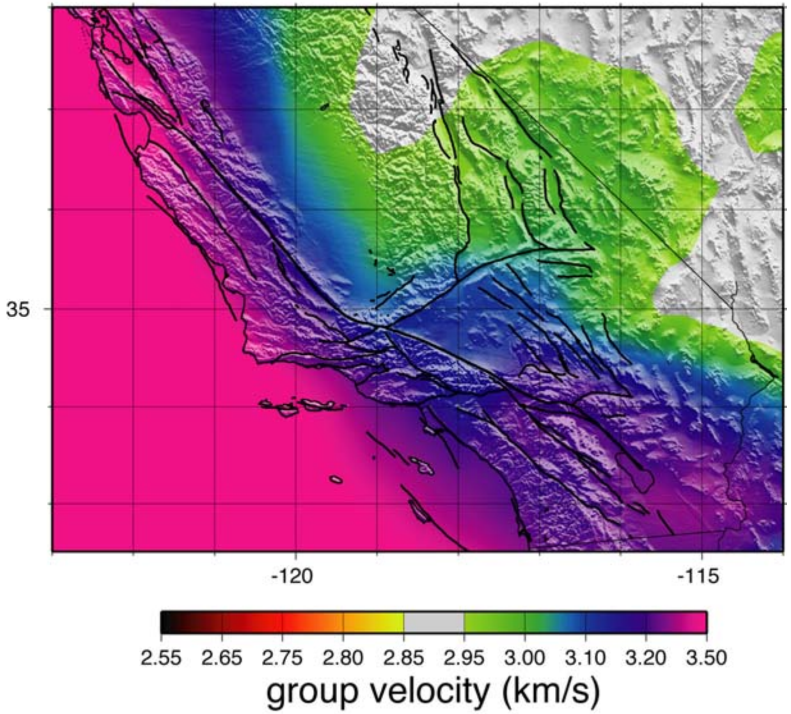
Outline

1. Extraction of surface waves from correlations of seismic noise: introduction
2. Earthquake-based surface wave tomography and its limitations
3. Extraction of surface waves from correlations of seismic noise: data processing and example
4. Surface wave tomography from the ambient seismic noise
5. Tracing the origin of the seismic noise

Cross-correlation of seismic noise in California

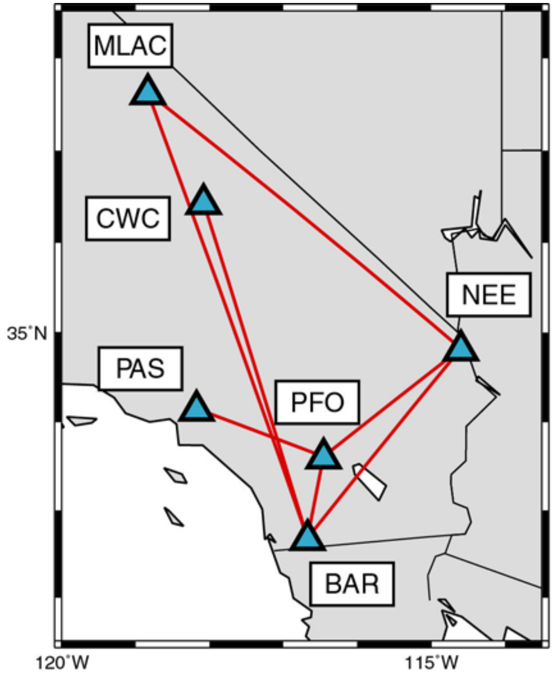


18 s global surface-wave measurements

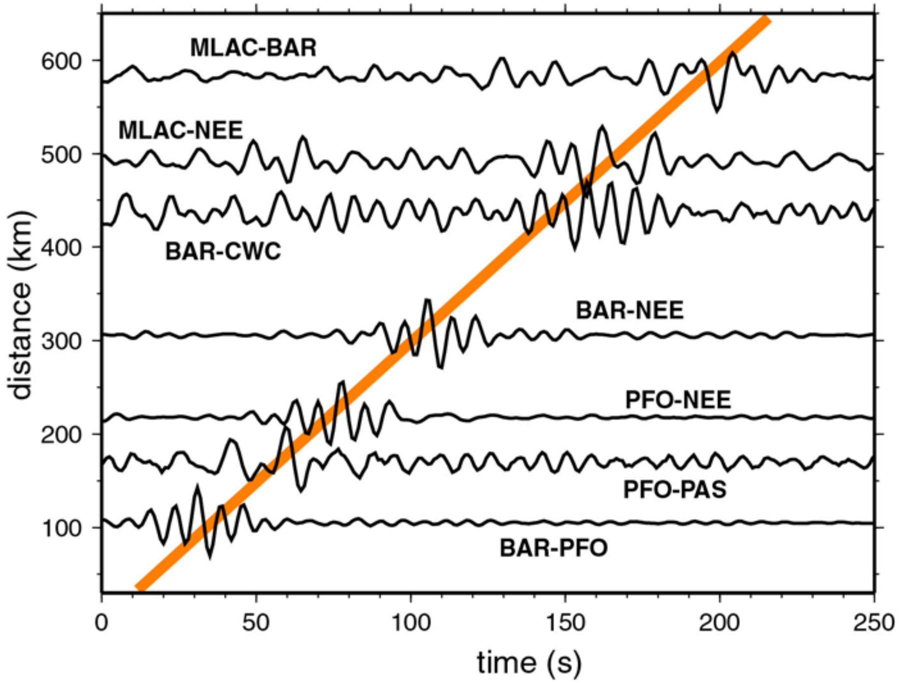


Cross-correlation of seismic noise in California

cross-correlations of vertical component continuous records (1996/02/11-1996/03/10)
0.03-0.2 Hz

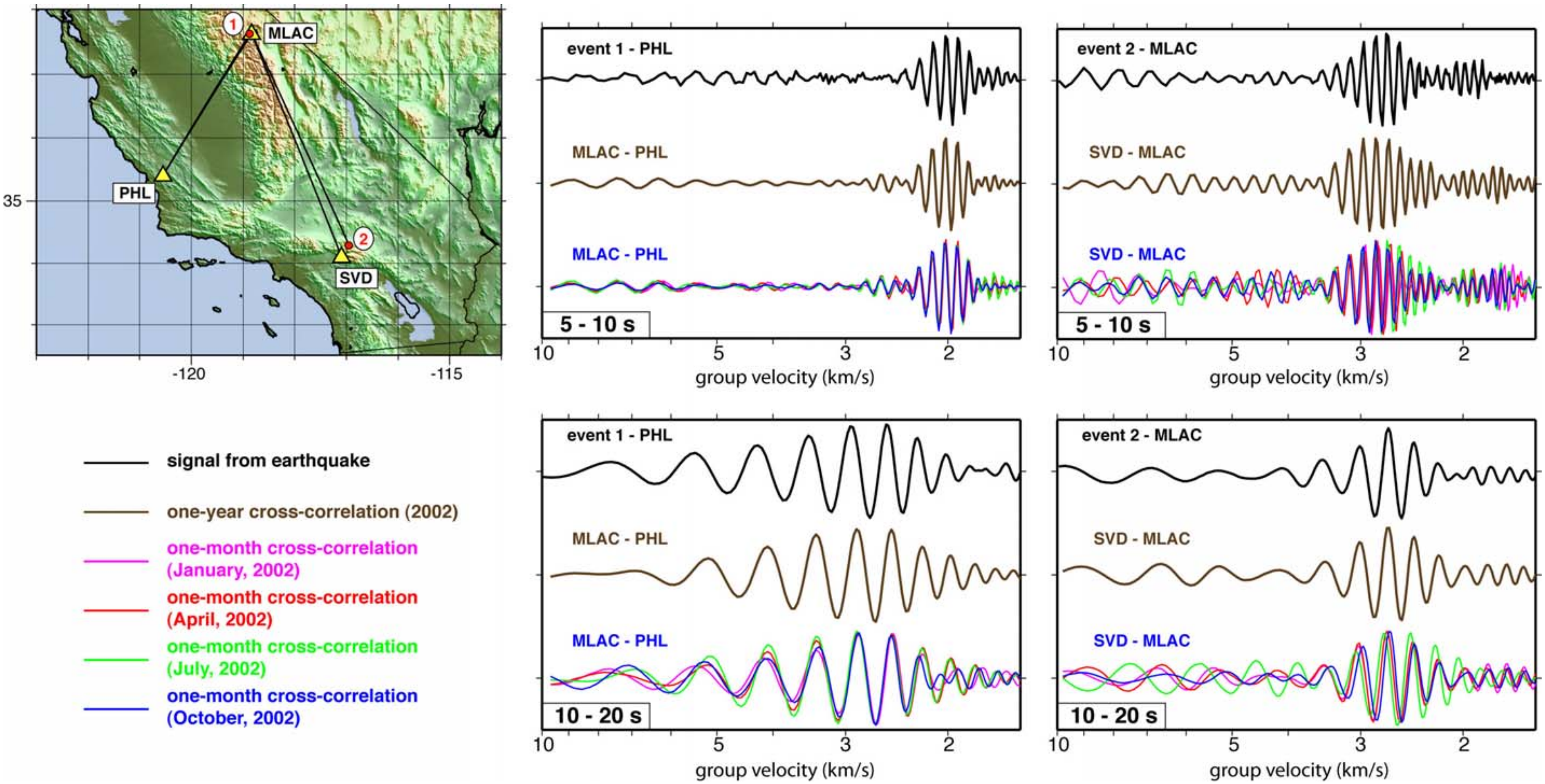


3 km/s - Rayleigh wave



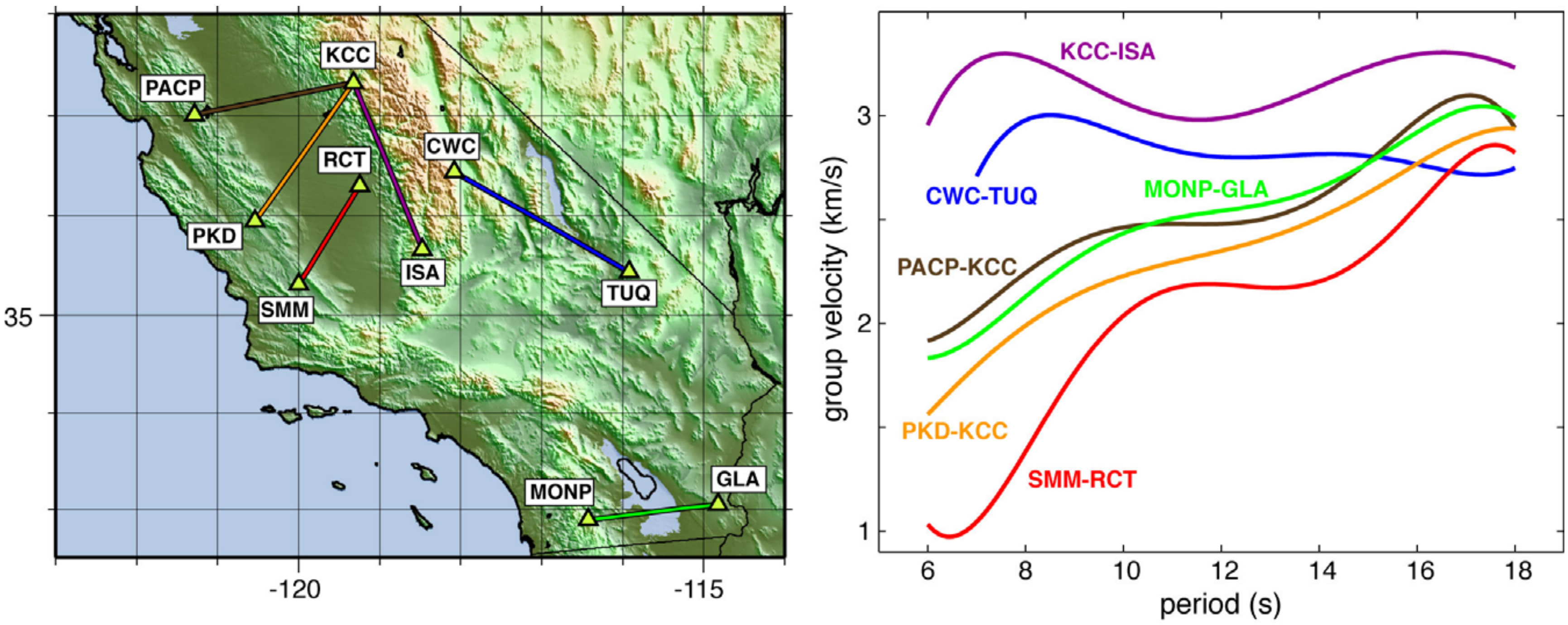
from Shapiro and Campillo, 2004

Comparison with signals from earthquakes



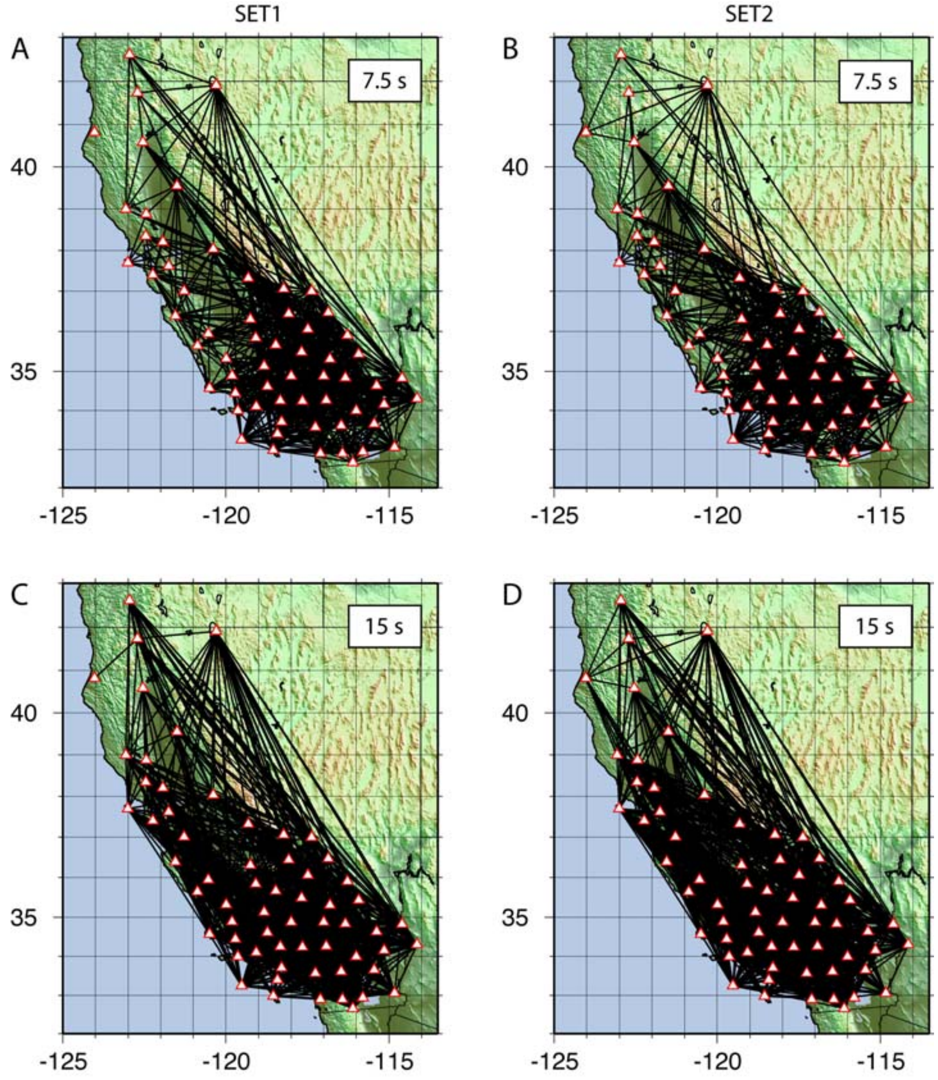
from Shapiro et al., 2005

Examples of Rayleigh-wave dispersion curves



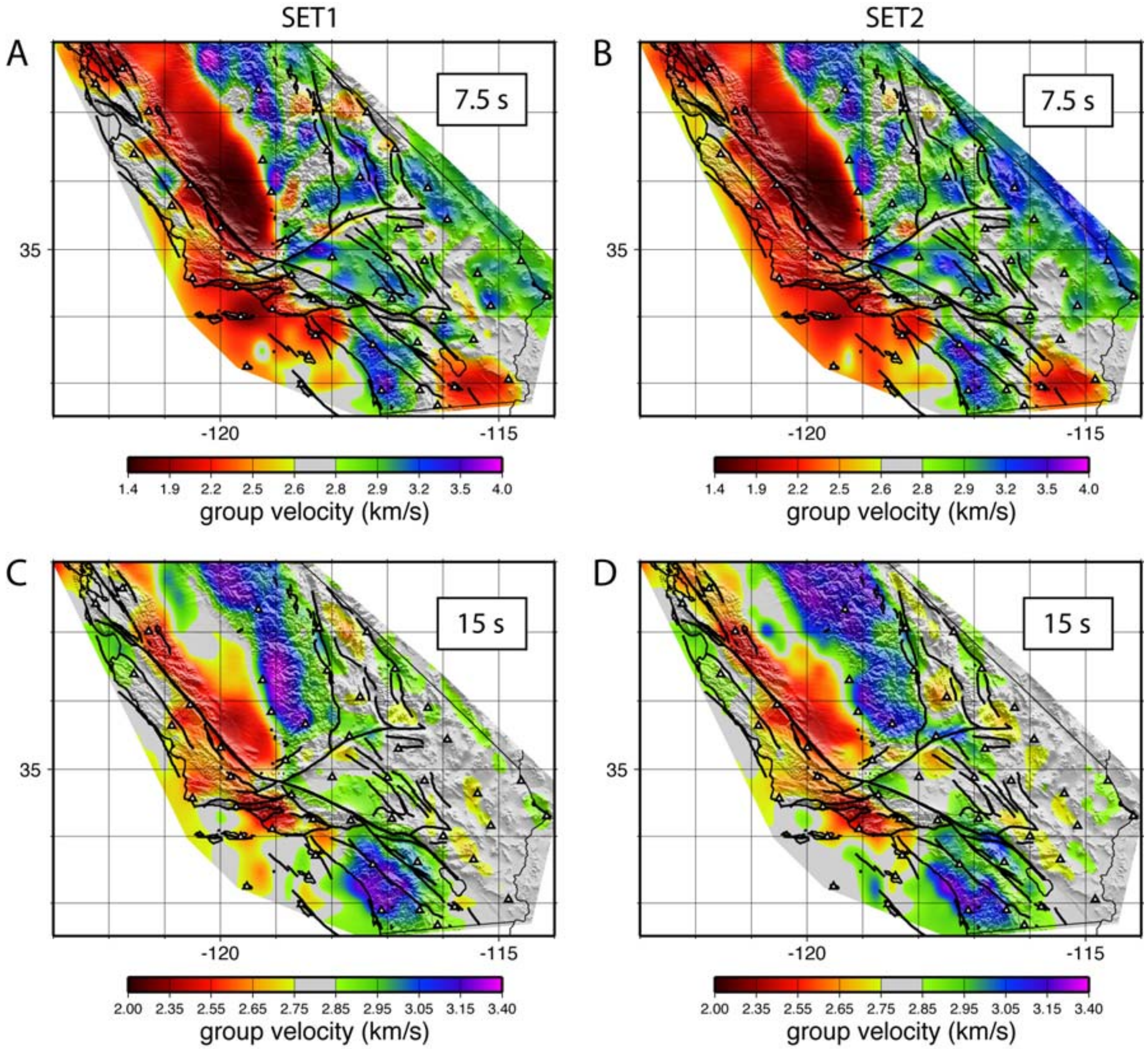
from Shapiro et al., 2005

Measurements from two different months



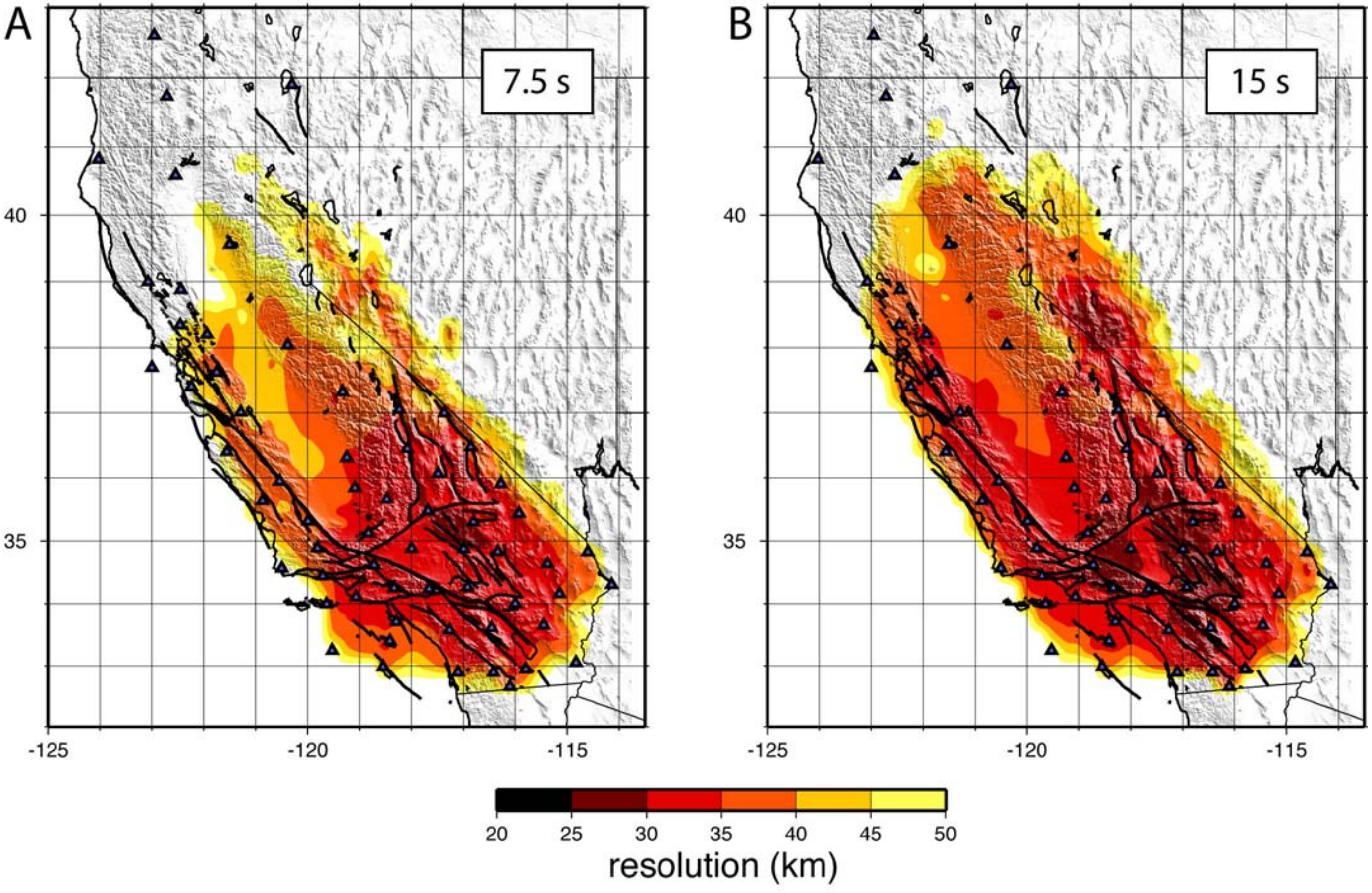
from Shapiro et al., 2005

Repetitive tomography



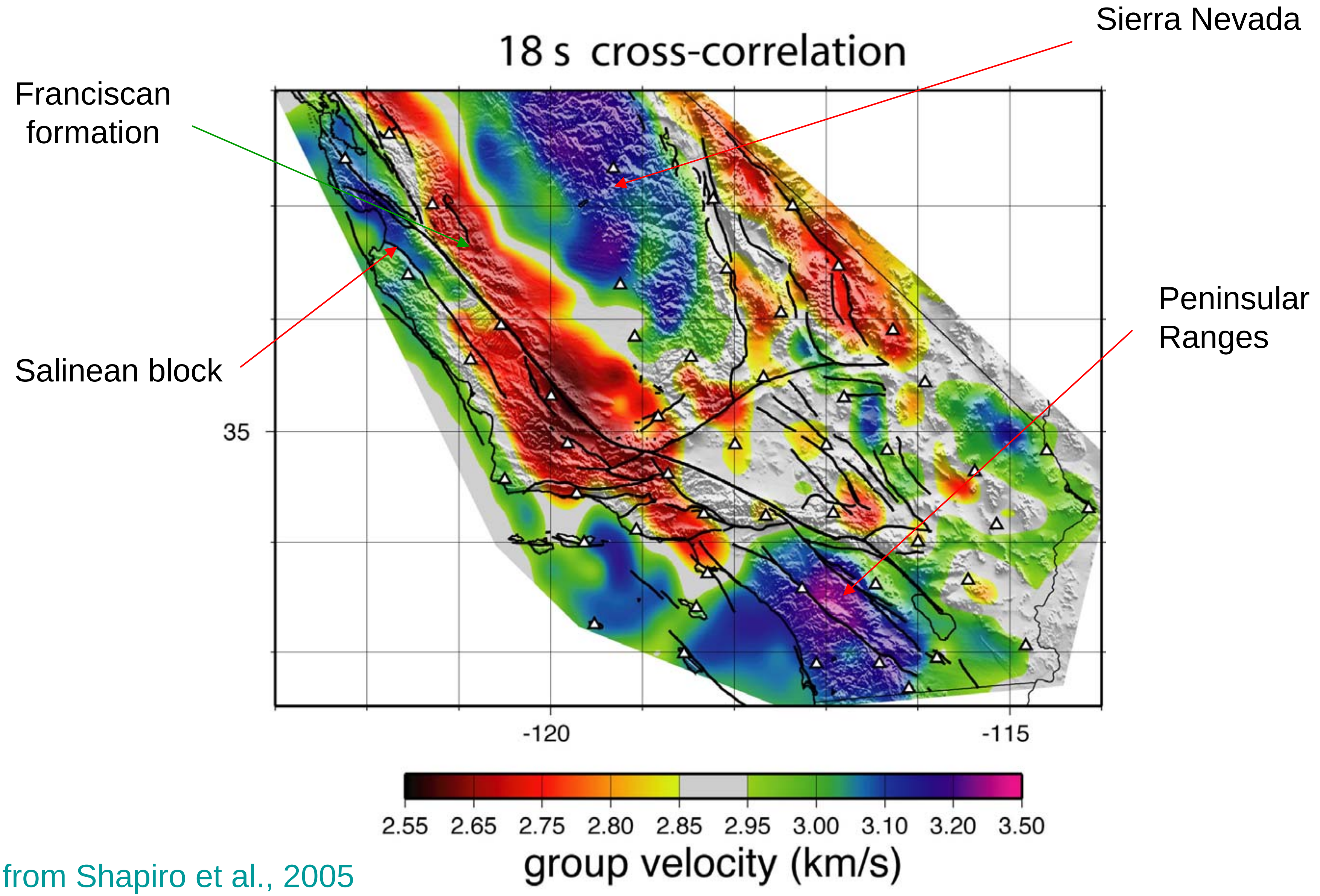
from Shapiro et al., 2005

Resolution



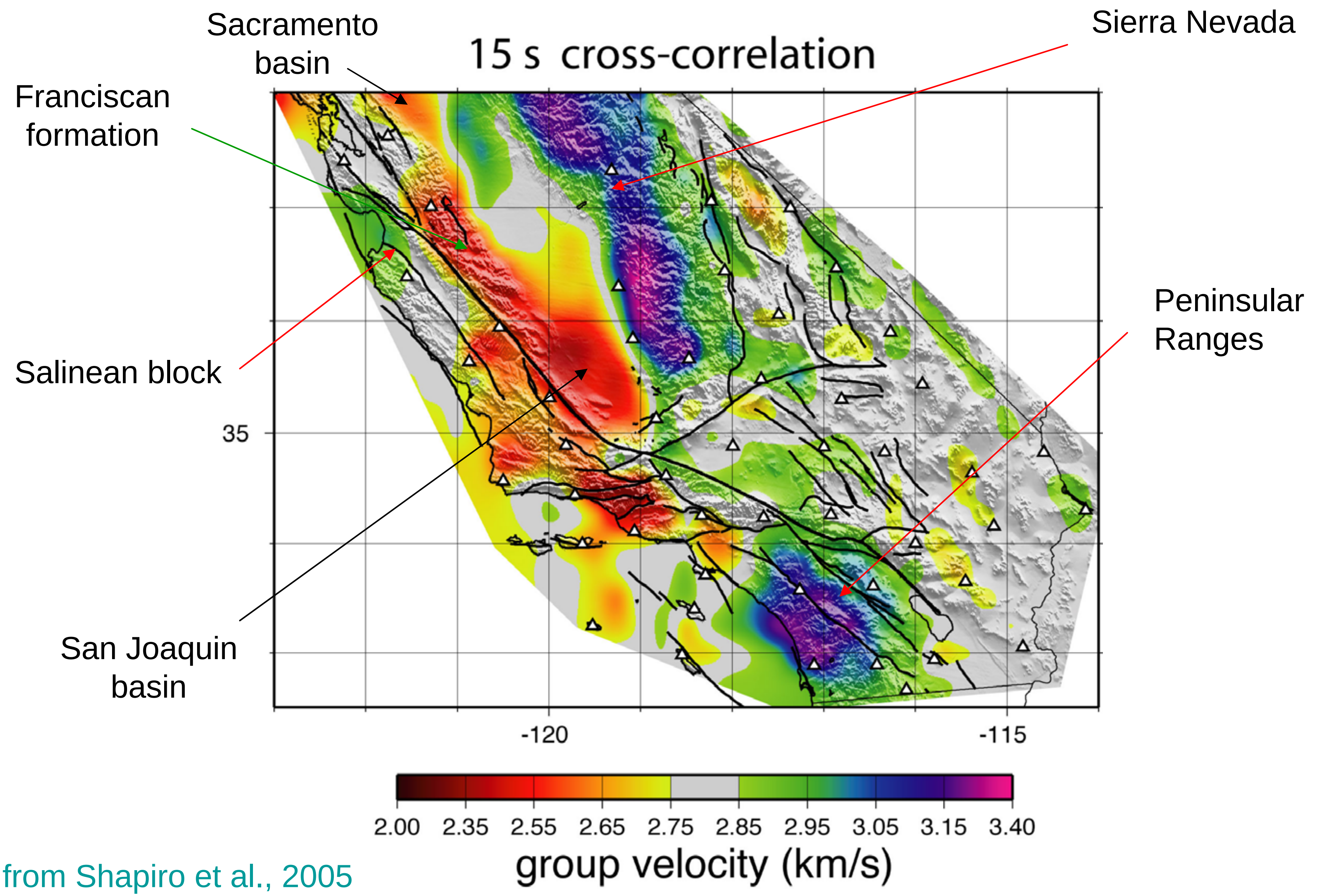
from Shapiro et al., 2005

dispersion maps



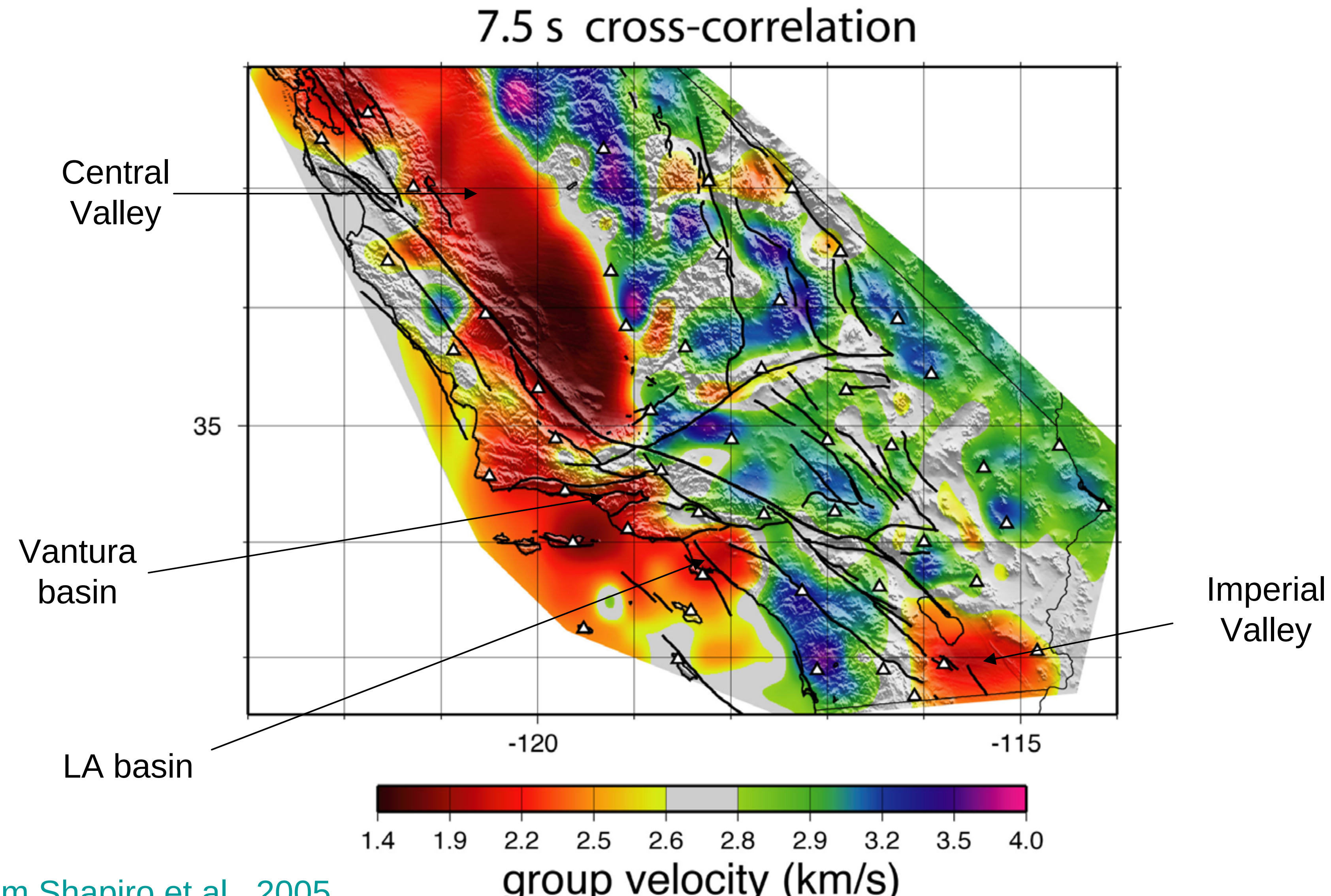
from Shapiro et al., 2005

dispersion maps



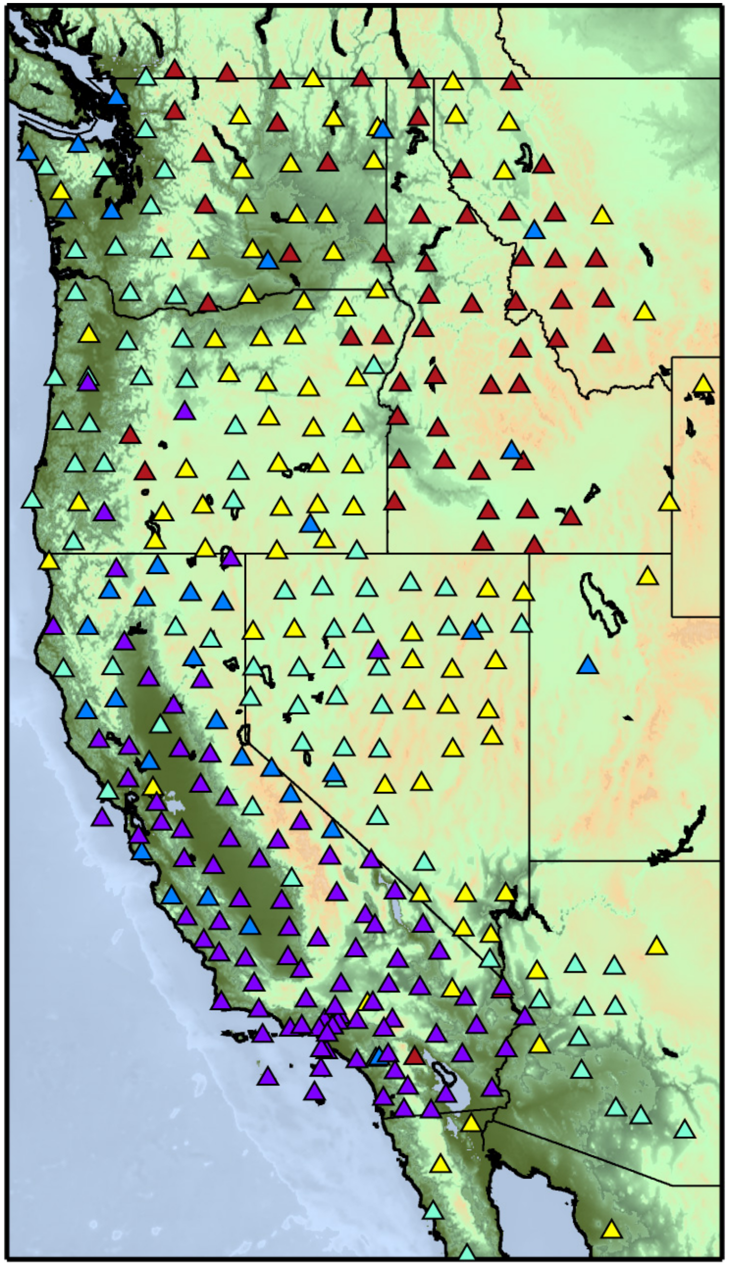
from Shapiro et al., 2005

dispersion maps



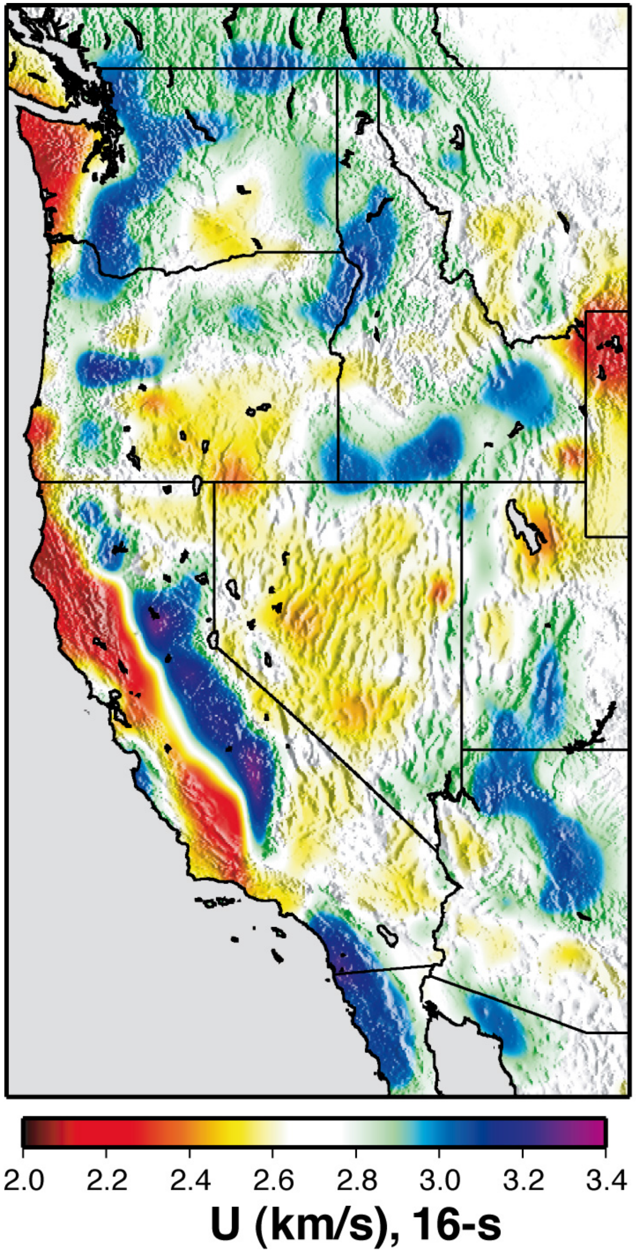
from Shapiro et al., 2005

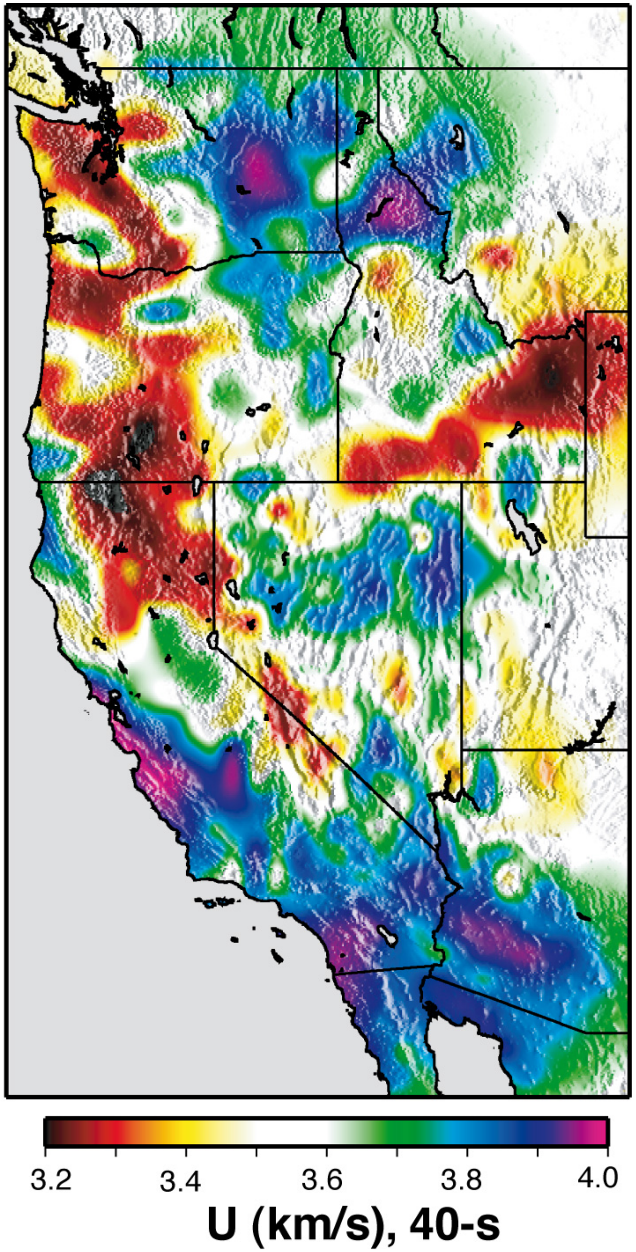
Exploring the USArray data



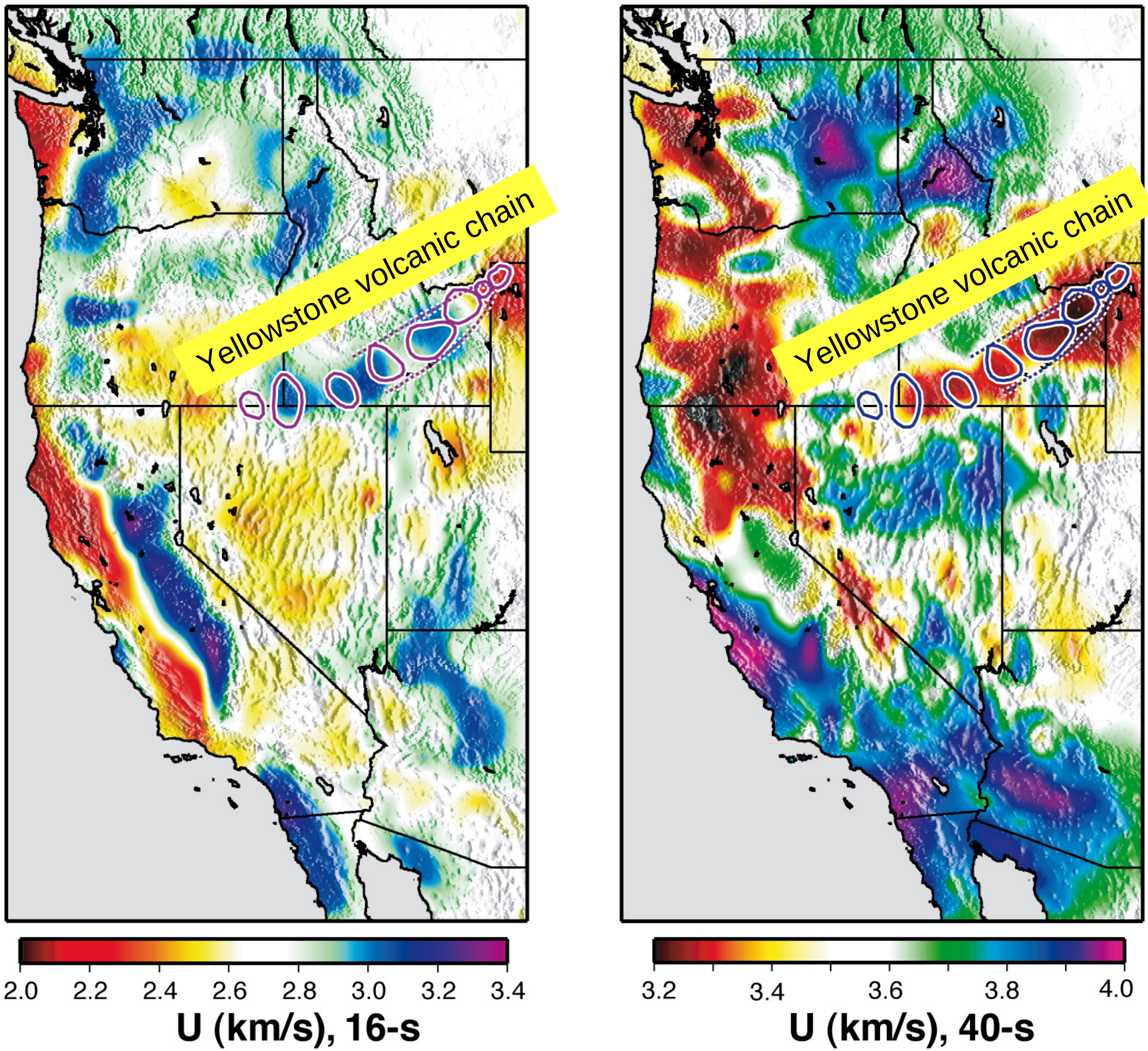
Moschetti et al., work in progress

USArray: noise-based Rayleigh-wave group velocity maps

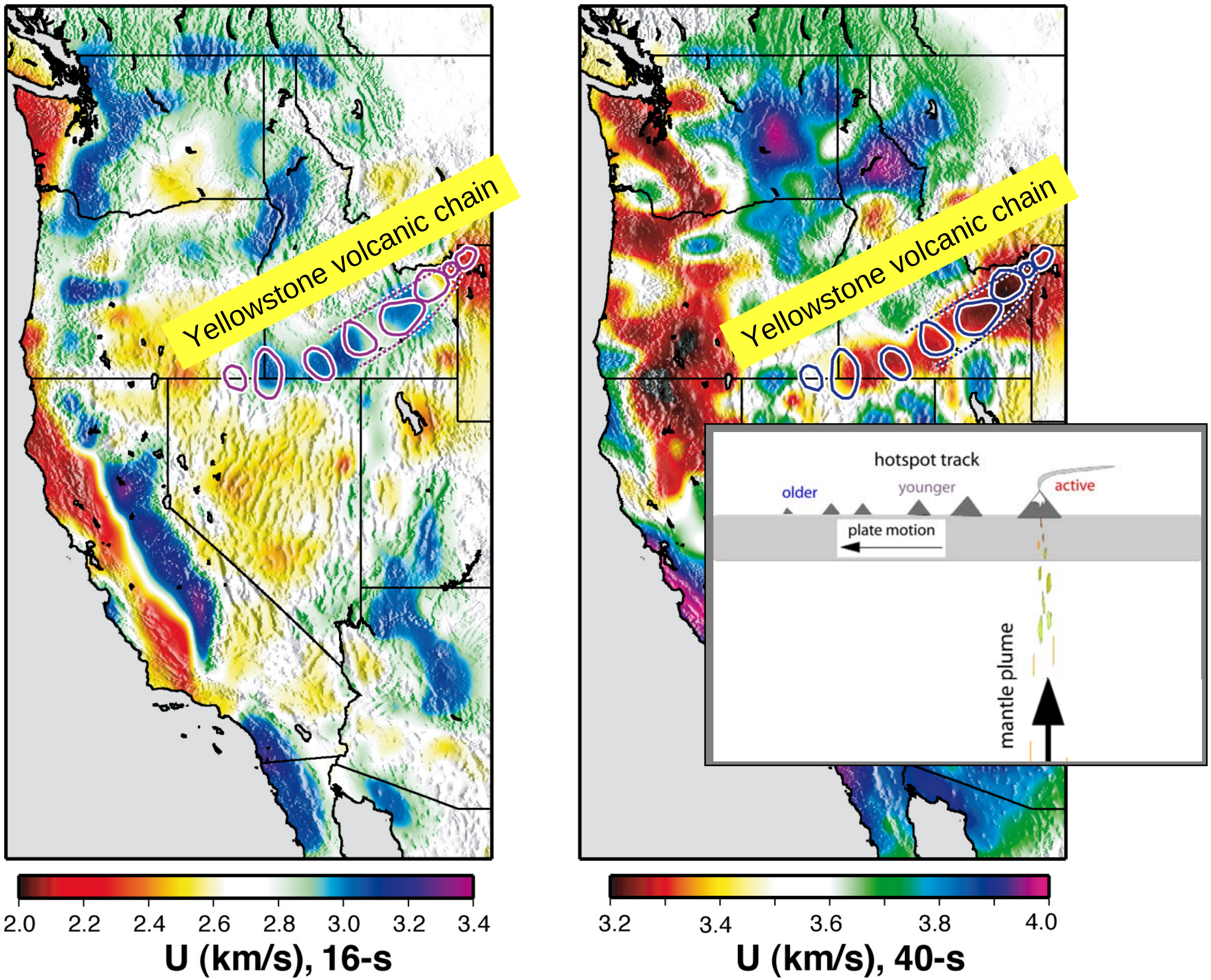


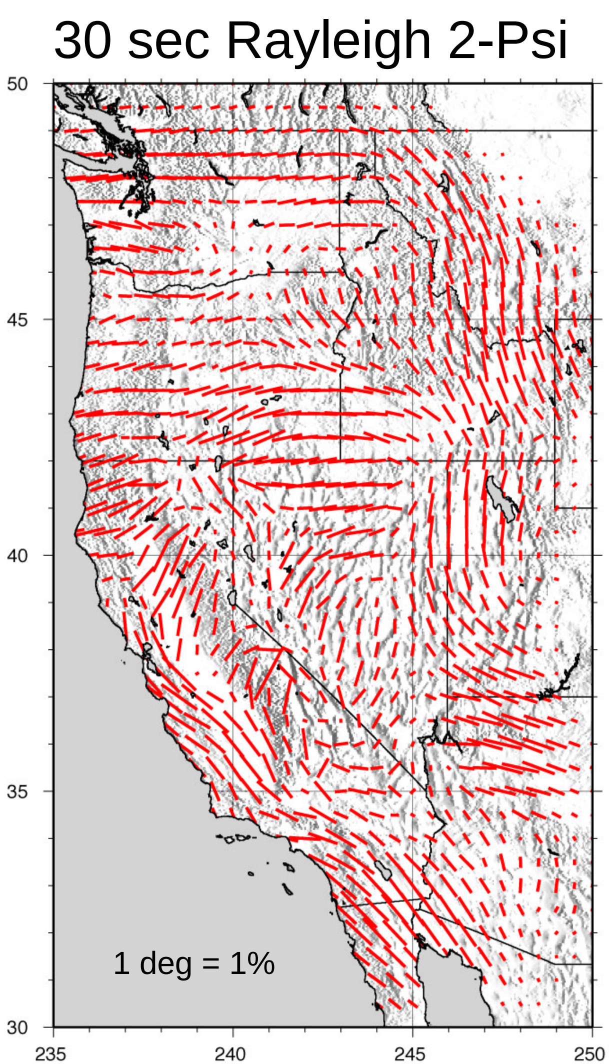


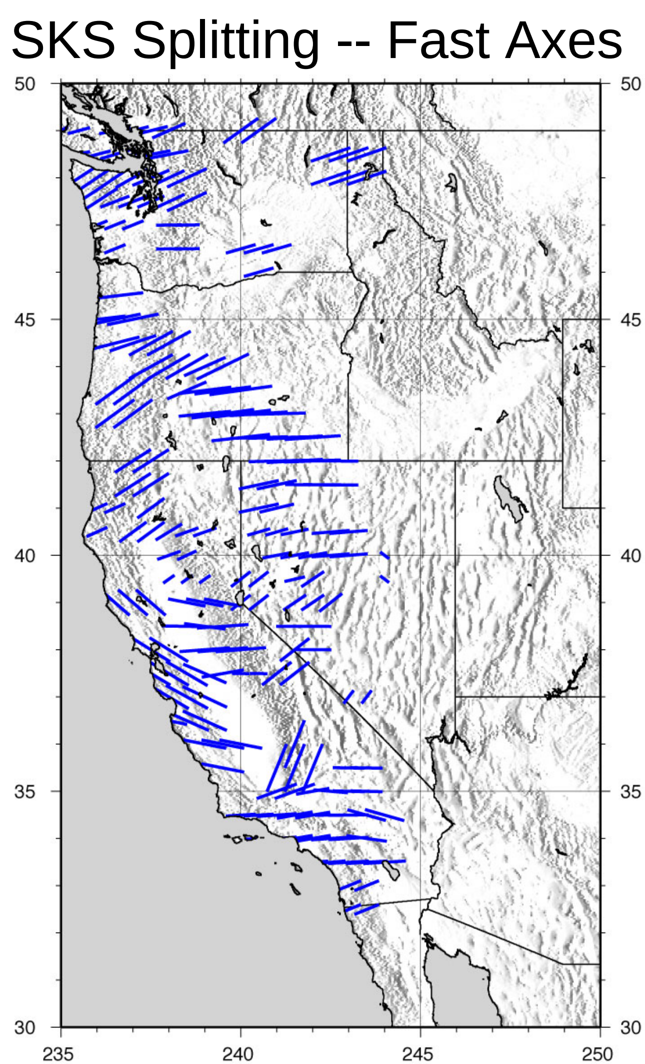
USArray: noise-based Rayleigh-wave group velocity maps



USArray: noise-based Rayleigh-wave group velocity maps



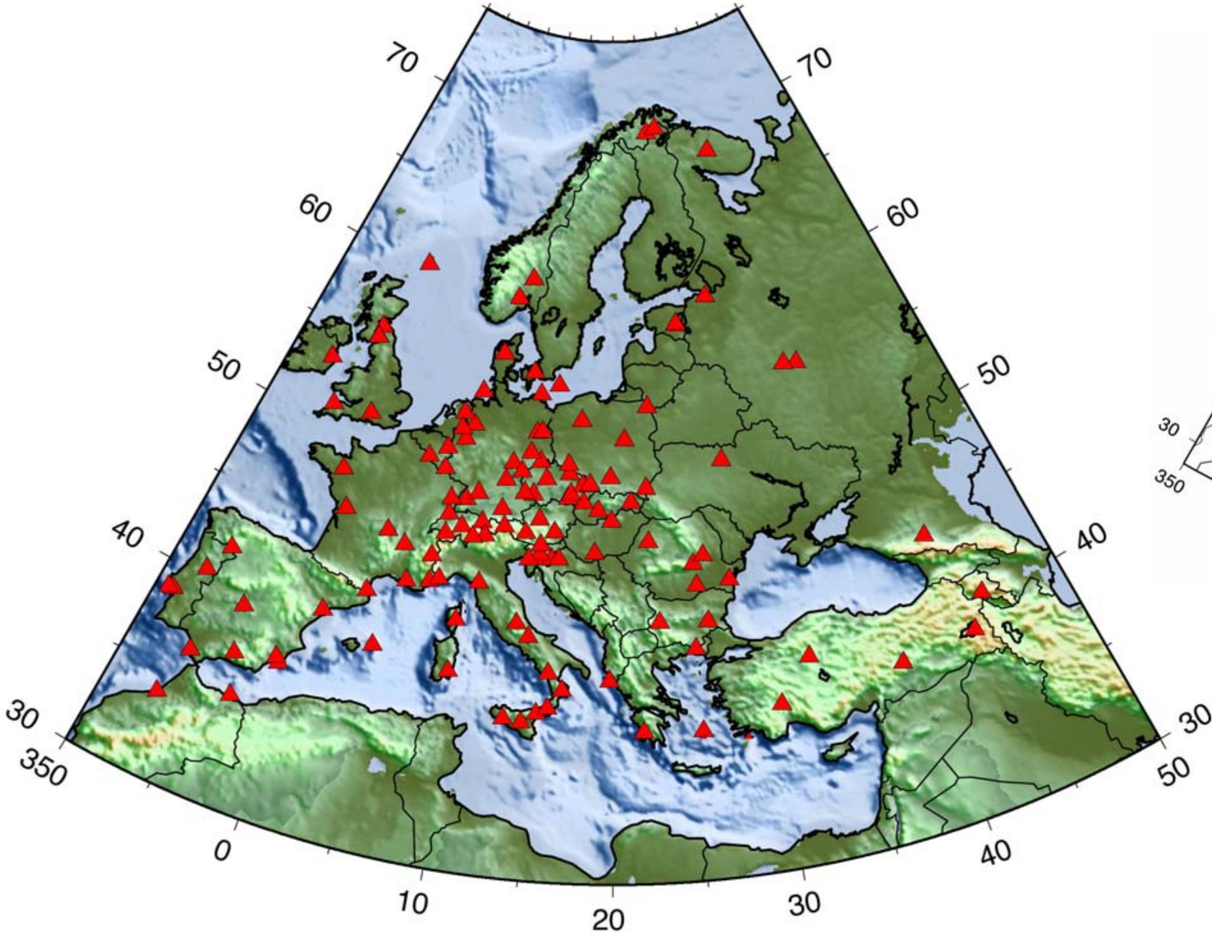


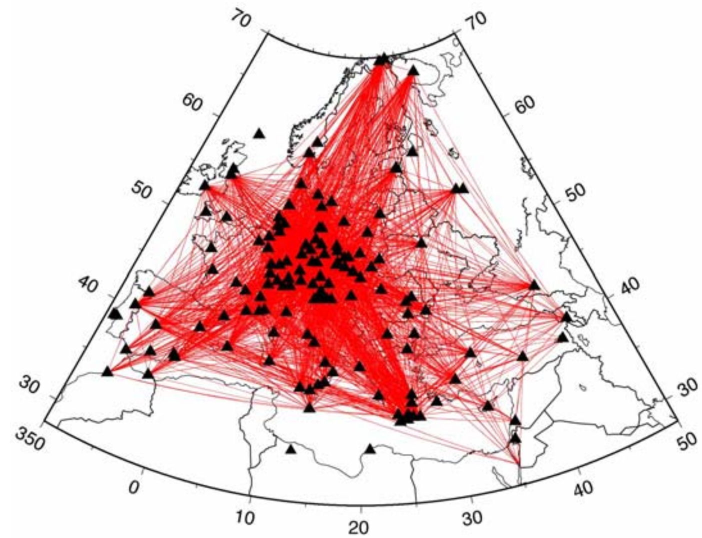


Data Courtesy of Thorsten Becker

Noise-based surface-wave tomography in Europe

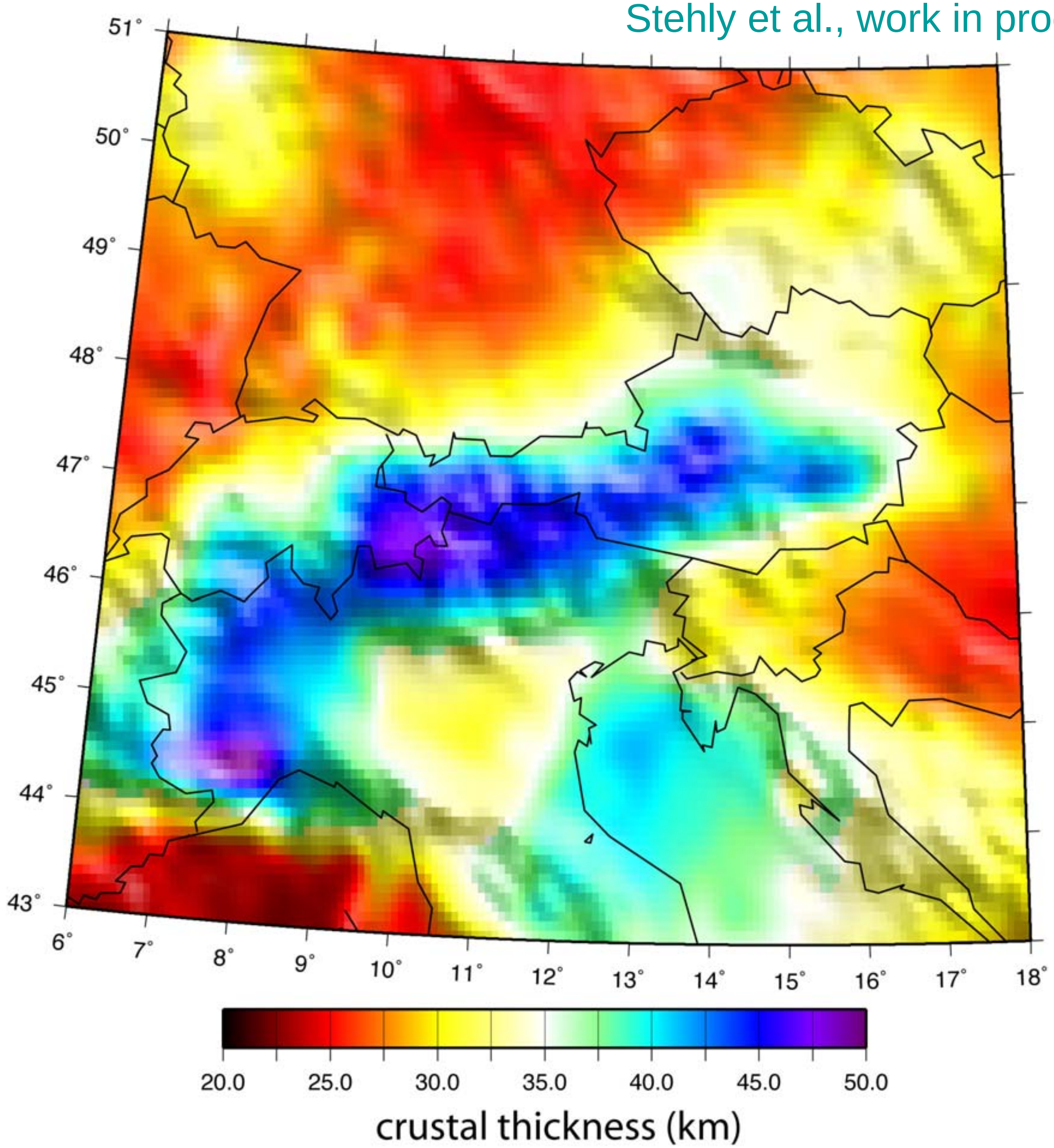
Stehly et al., work in progress





Noise-based surface-wave tomography in Europe

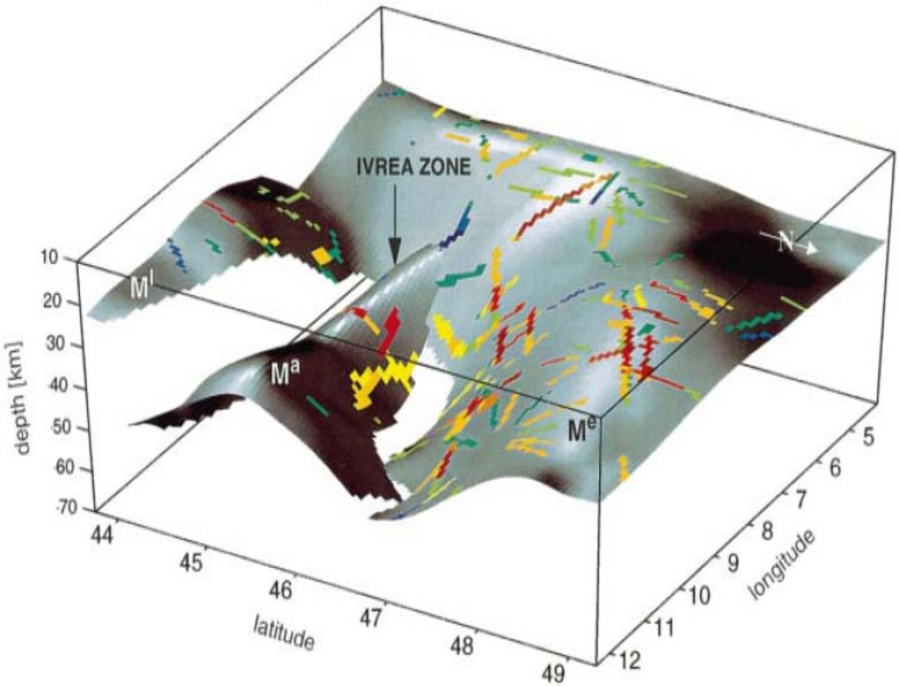
Stehly et al., work in progress



Crustal thickness beneath the European Alps

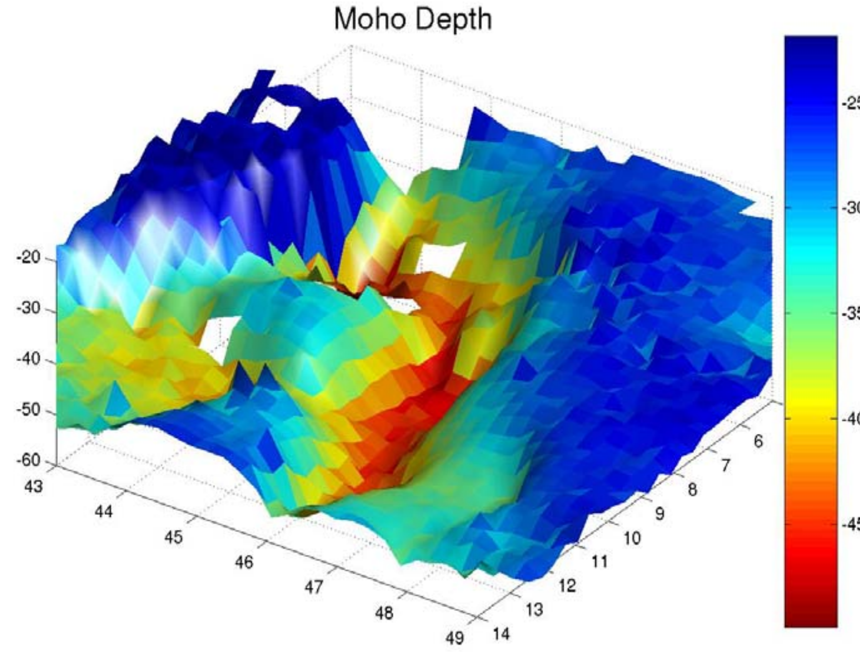
estimations from seismic reflection/refraction data

Waldhauser et al., 1998



noise-based estimations

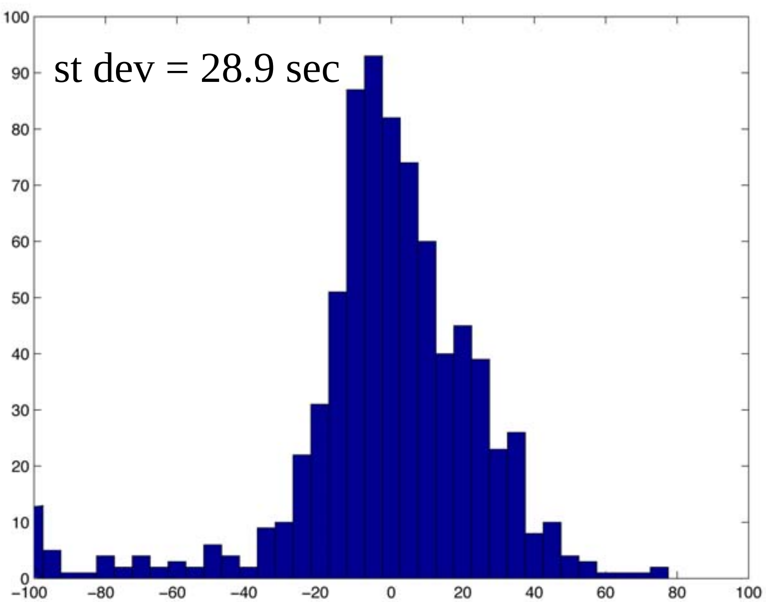
Stehly et al. (work in progress)



Coherence Among Measurements -- 12 sec period?

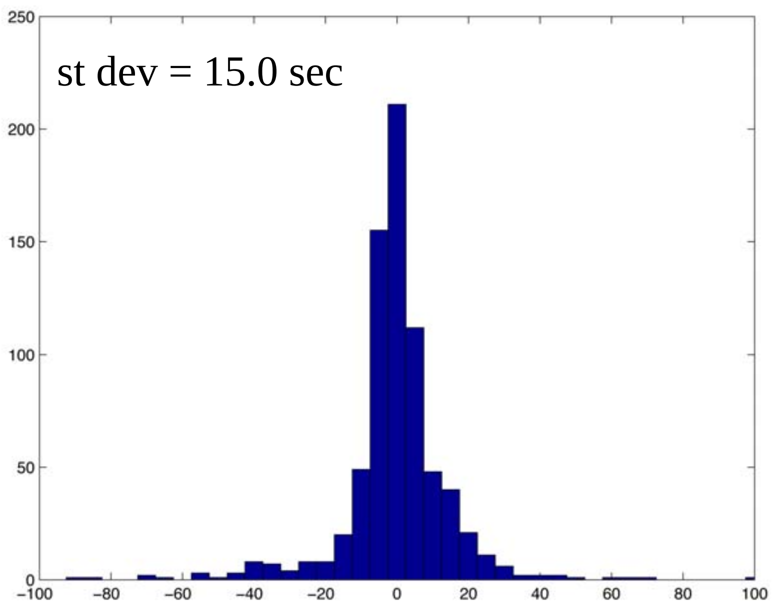
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography



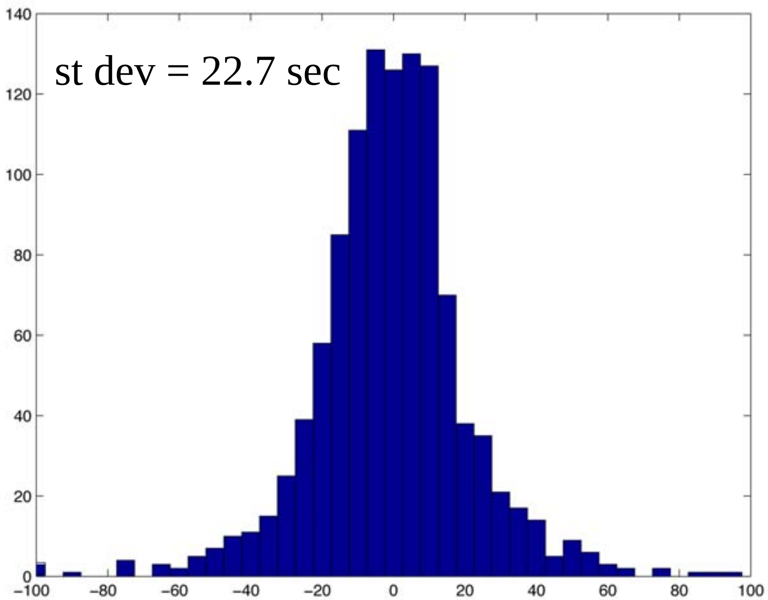
misfit (sec)

from Yang et al., 2006

Coherence Among Measurements -- 16 sec period?

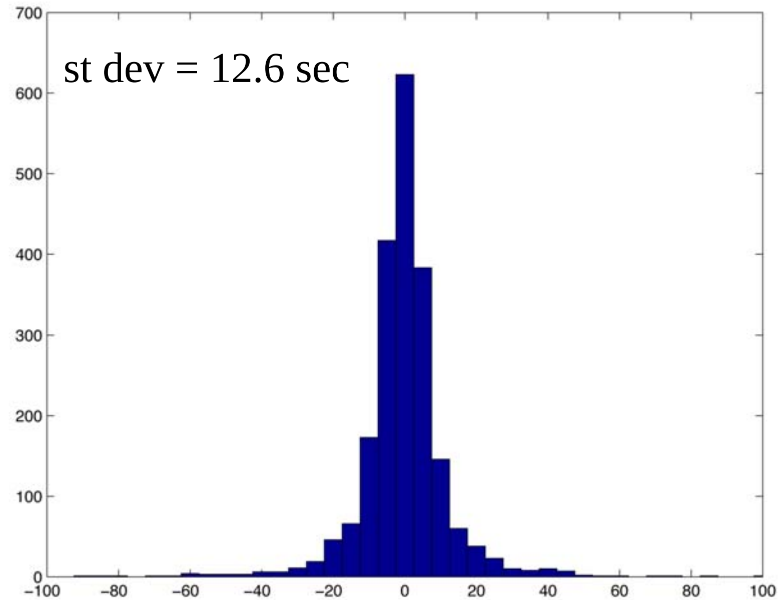
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography



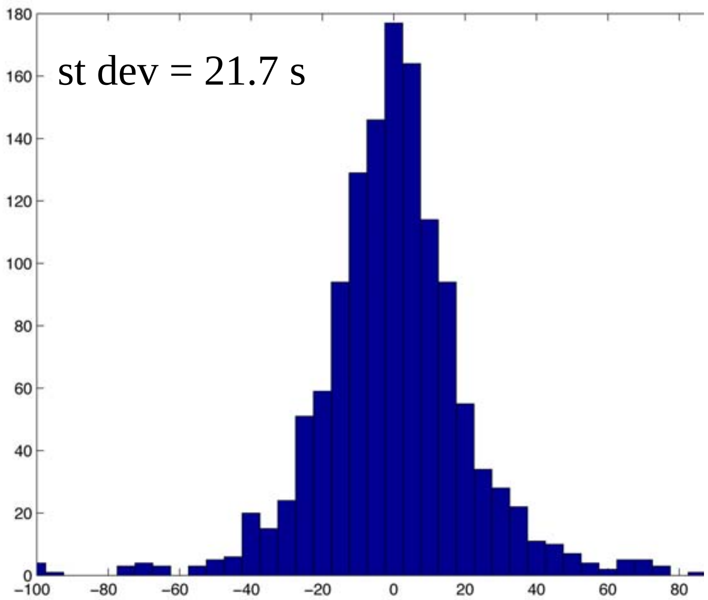
misfit (sec)

from Yang et al., 2006

Coherence Among Measurements -- 20 sec period?

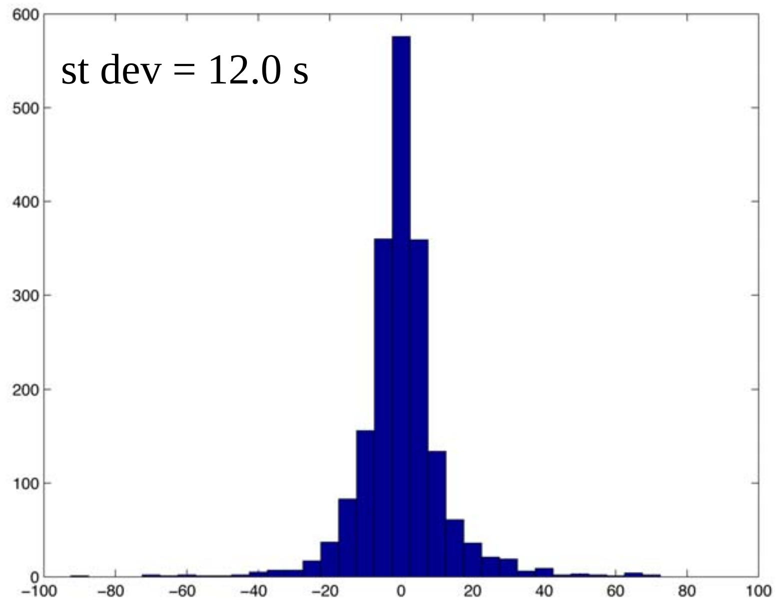
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography



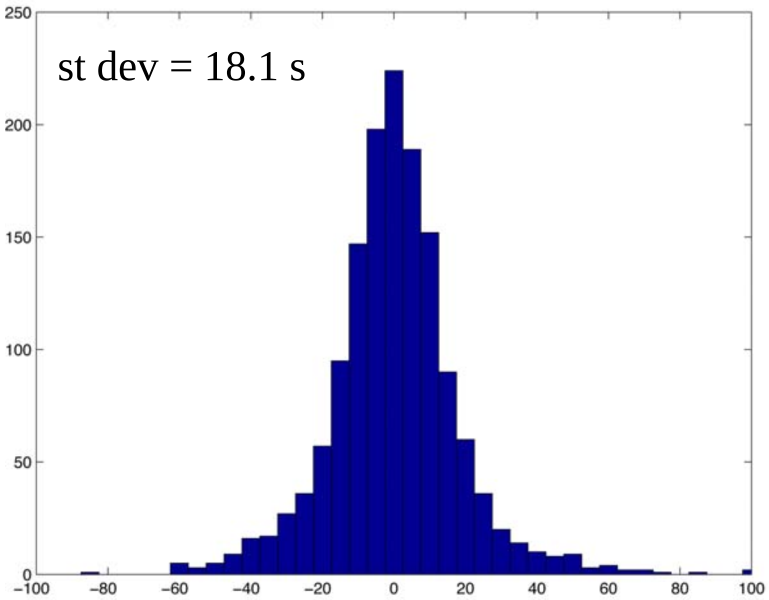
misfit (sec)

from Yang et al., 2006

Coherence Among Measurements -- 30 sec period?

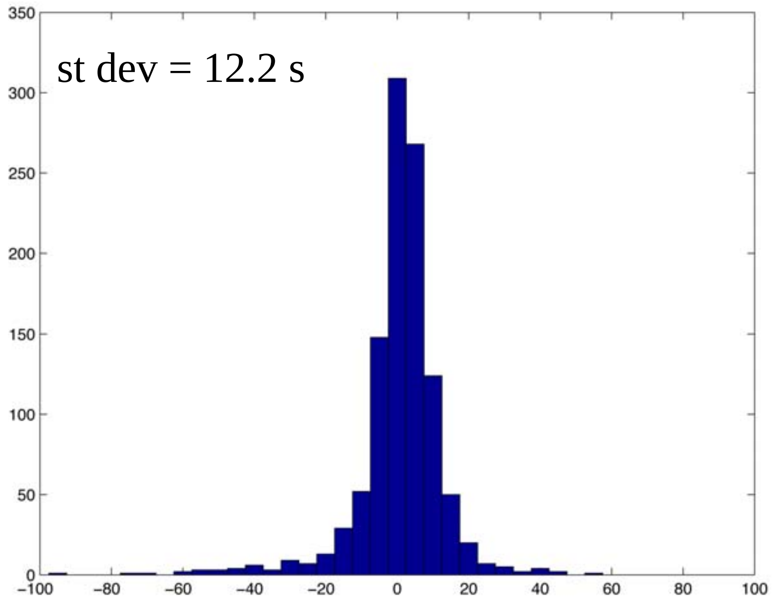
As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



misfit (sec)

Misfit to Ambient Noise Measurements
From Ambient Noise Tomography



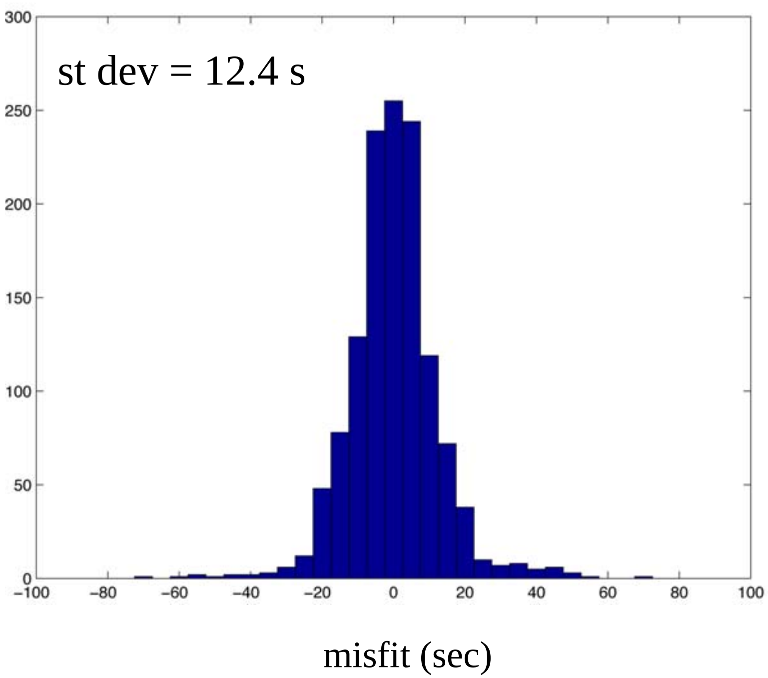
misfit (sec)

from Yang et al., 2006

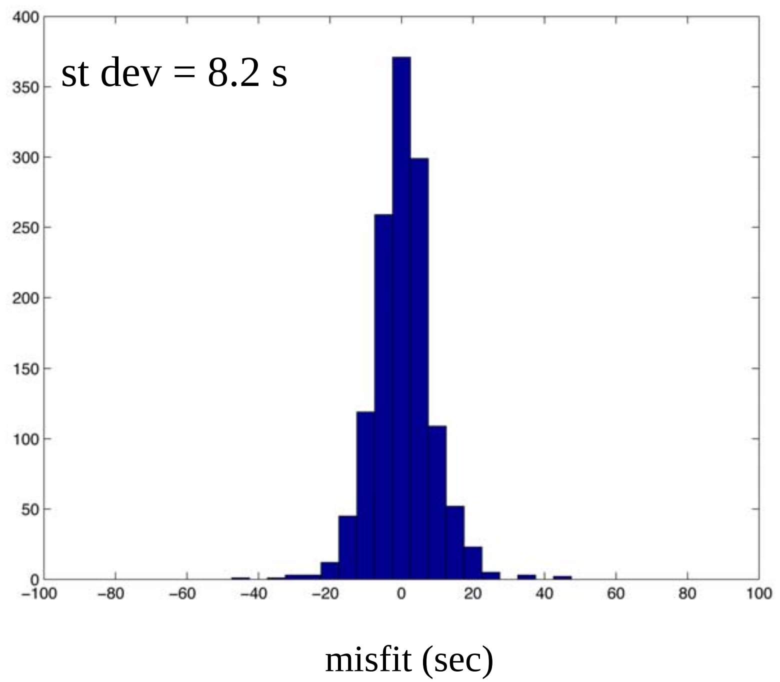
Coherence Among Measurements -- 40 sec period?

As measured by the ability to fit data sets when doing tomography…..

Misfit to Earthquake Measurements
From Earthquake Tomography



Misfit to Ambient Noise Measurements
From Ambient Noise Tomography



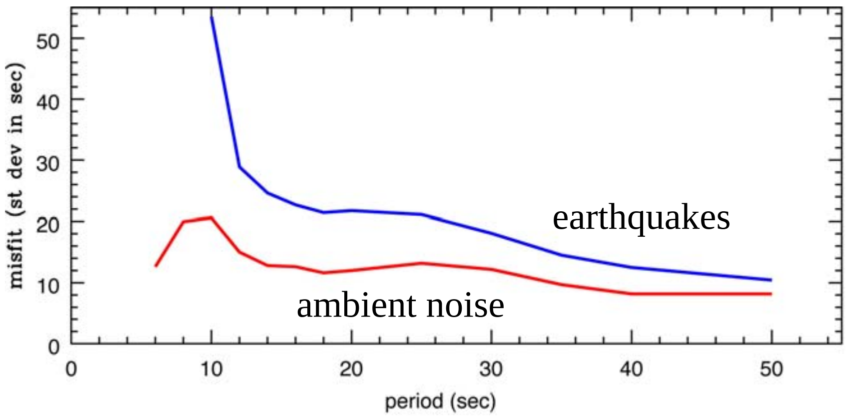
from Yang et al., 2006

Coherence Among Measurements -- Summary

As measured by the ability to fit data sets when doing tomography…..

Dispersion measurements from ambient noise are more internally consistent than measurements following earthquakes:

+ earthquake measurements are difficult to obtain below ~ 20 sec,
+ source processes, mislocation, etc. are eliminated.



Above ~30 sec, earthquake measurements are about as reliable as ambient noise measurements and the data sets can be combined without degrading the ambient noise measurements.

from Yang et al., 2006

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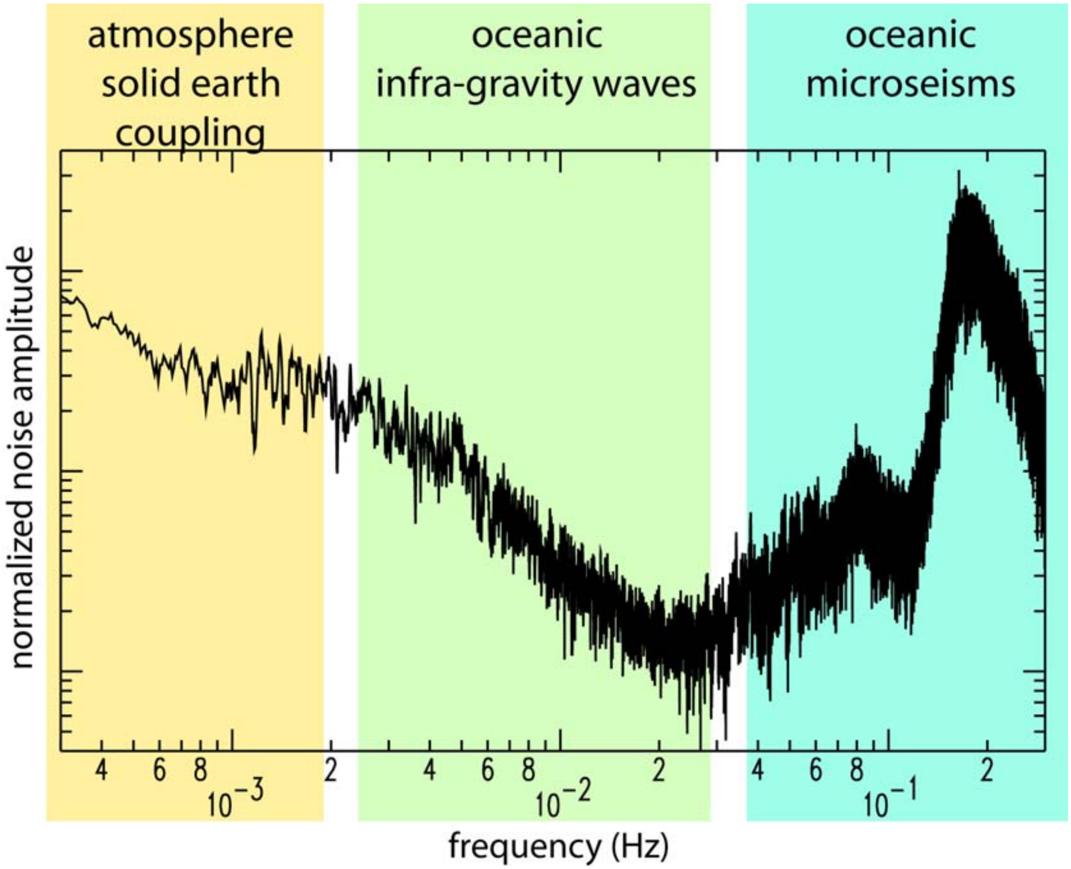
Understanding the origin of the seismic noise

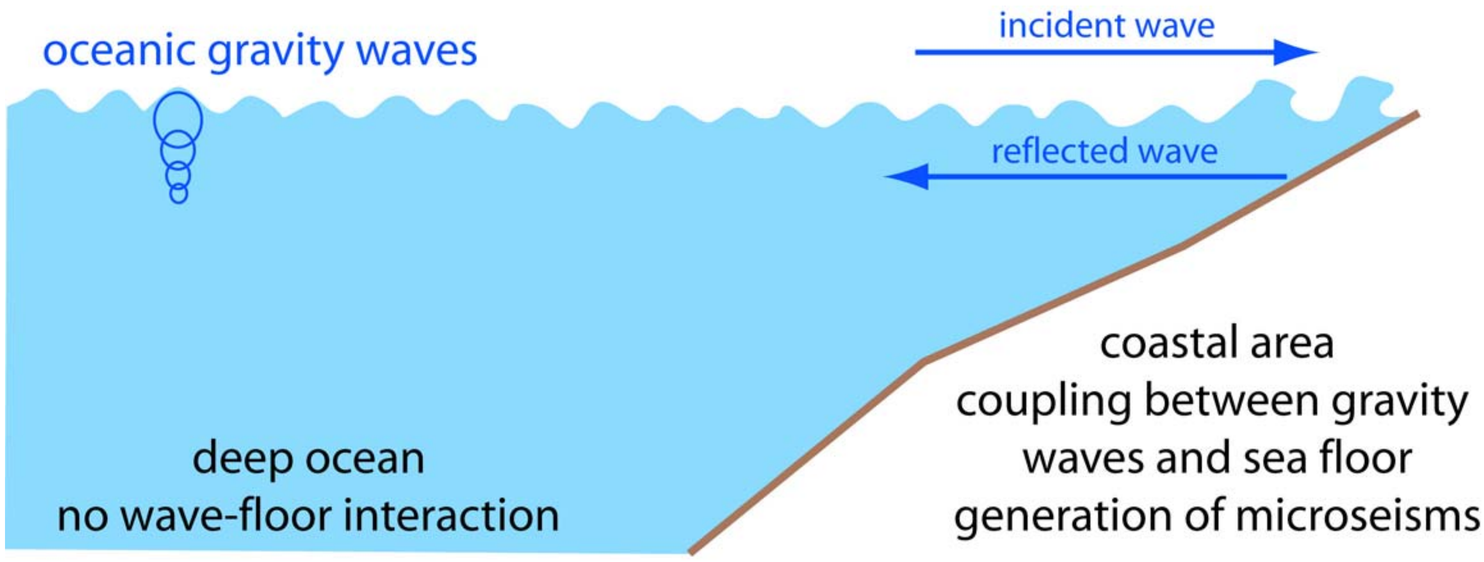
Motivations:

- Optimizing nose-based imaging
- Obtaining information about process in the ocean and the atmosphere

Fourier spectrum from one day of seismic noise (August 21, 2003; station OBN)



Origin of oceanic microseisms: traditional explanation



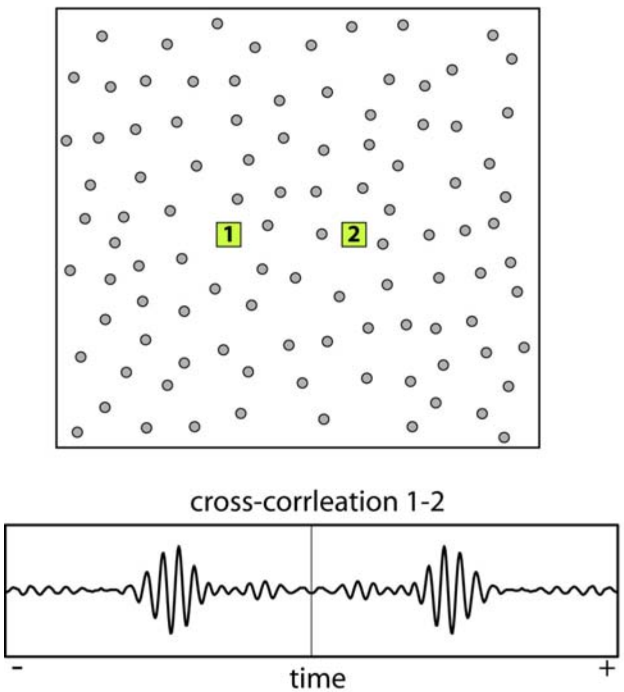
primary microseism is excited at frequencies corresponding to the spectrum of incoming oceanic gravity waves (periods of **10-20 s**)

secondary microseism is exited at doubled frequencies due to the nonlinear interaction between incident and reflected waves (periods of **5-10 s**)

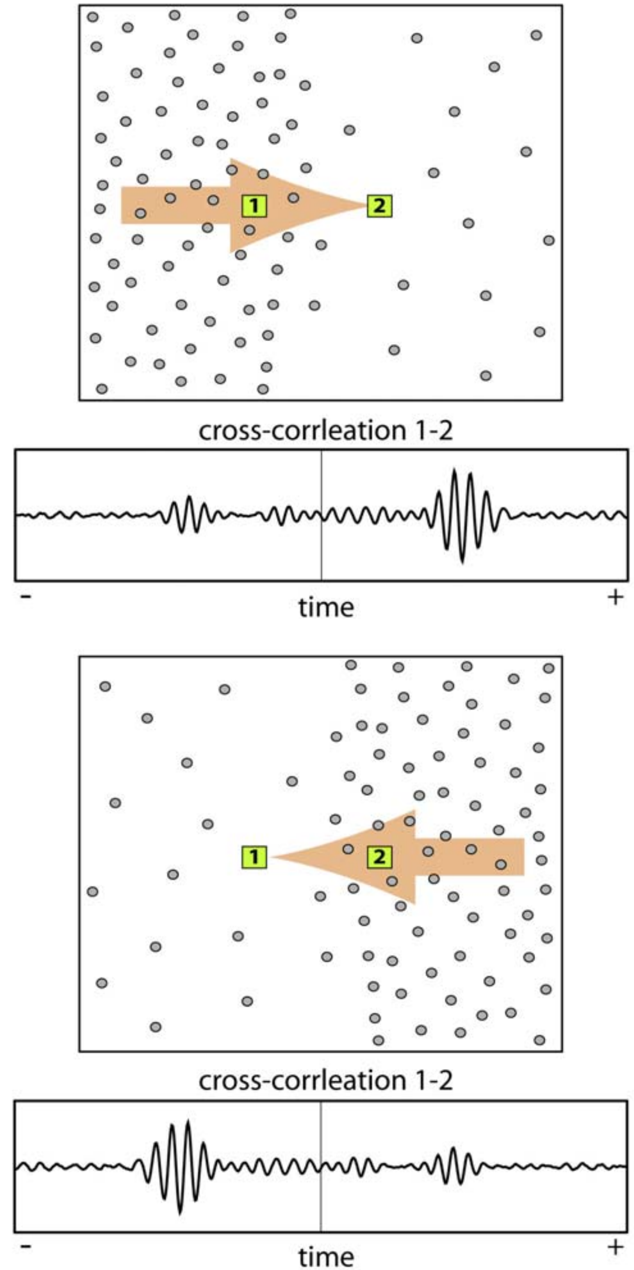
both microseims originate in coastal areas

Tracing the origin of the seismic noise

Isotropic distribution of sources: symmetric cross-correlation

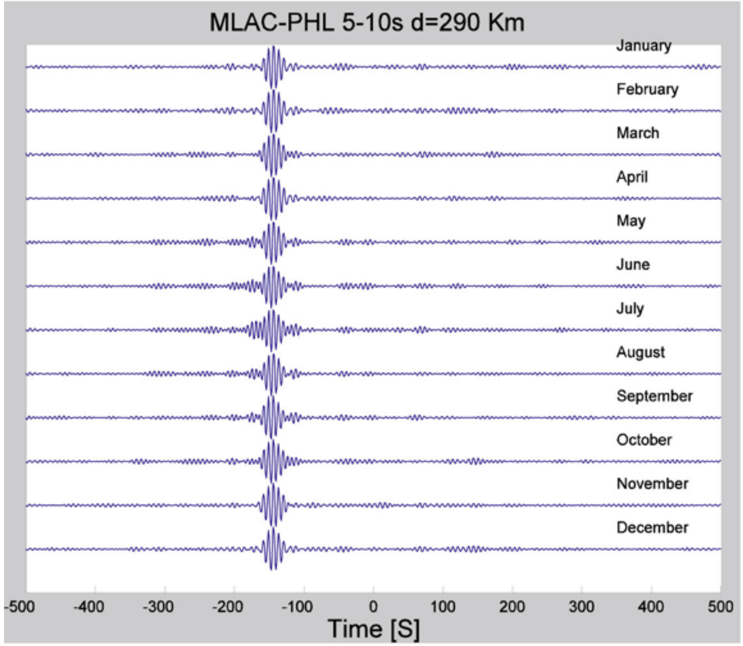


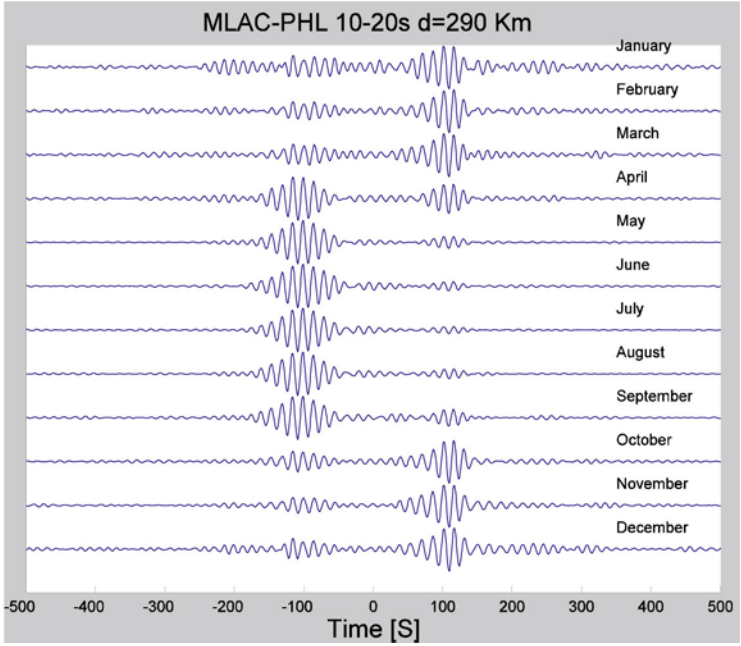
Anisotropic distribution of sources: asymmetric cross-correlation



from Stehly et al., 2006

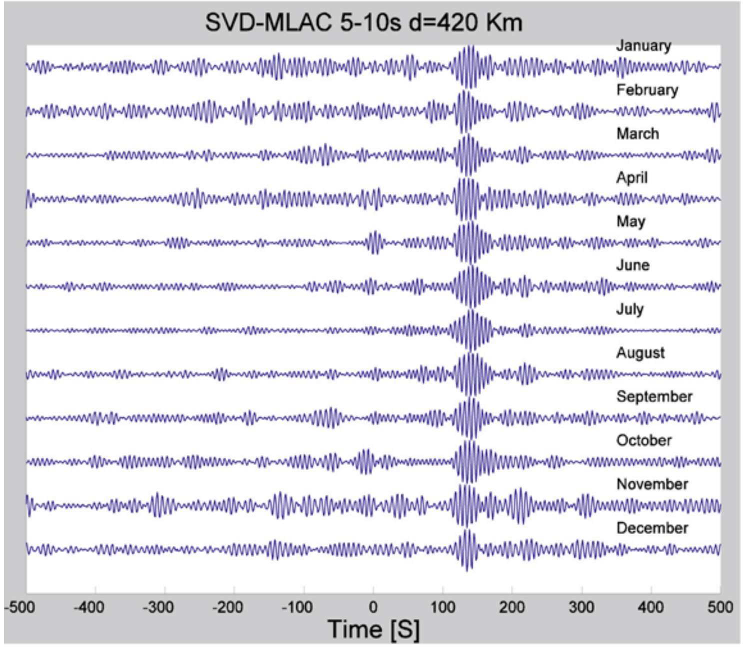
Tracing the origin of the seismic noise

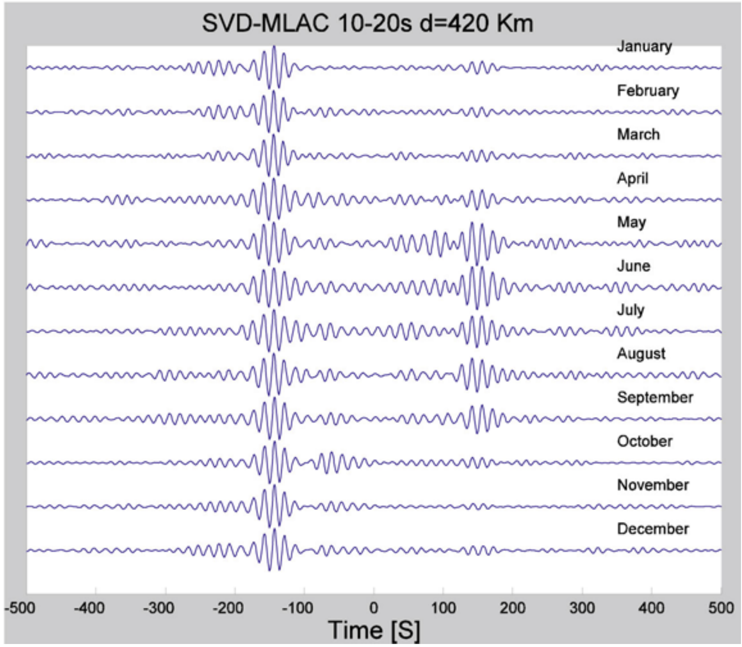




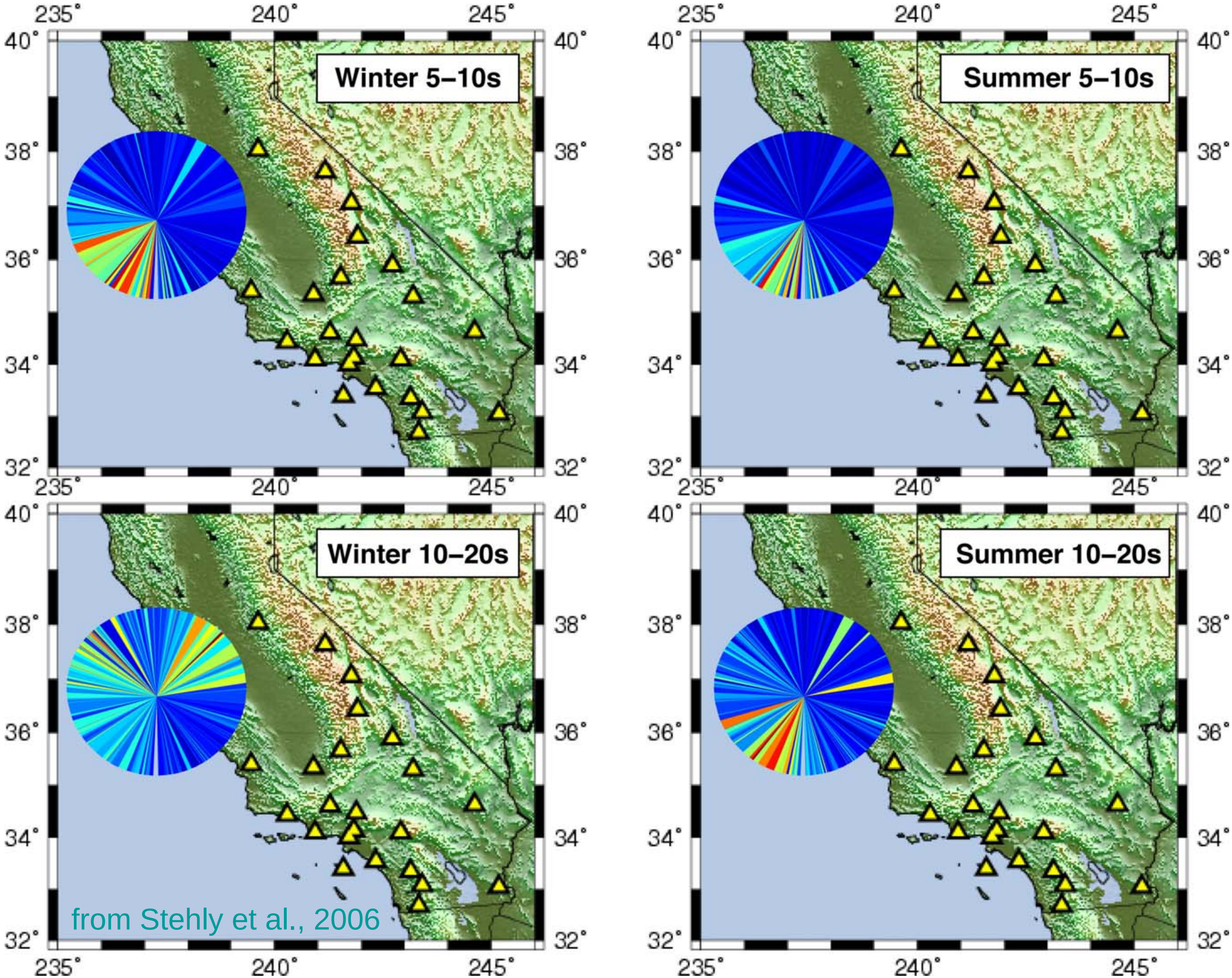
from Stehly et al., 2006

Tracing the origin of the seismic noise



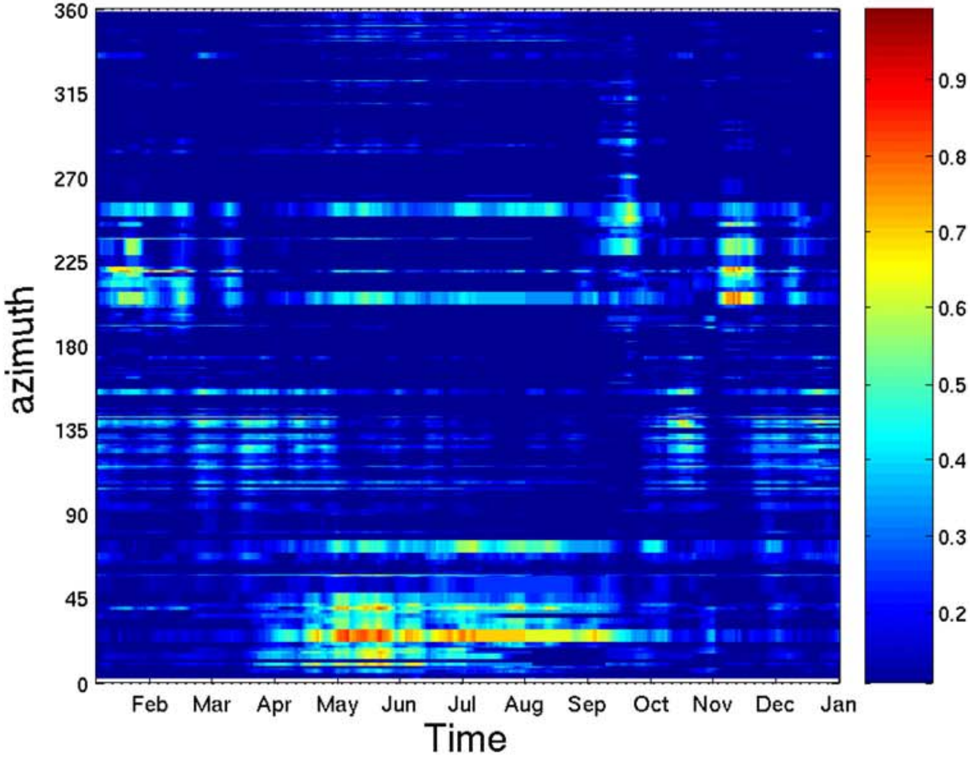


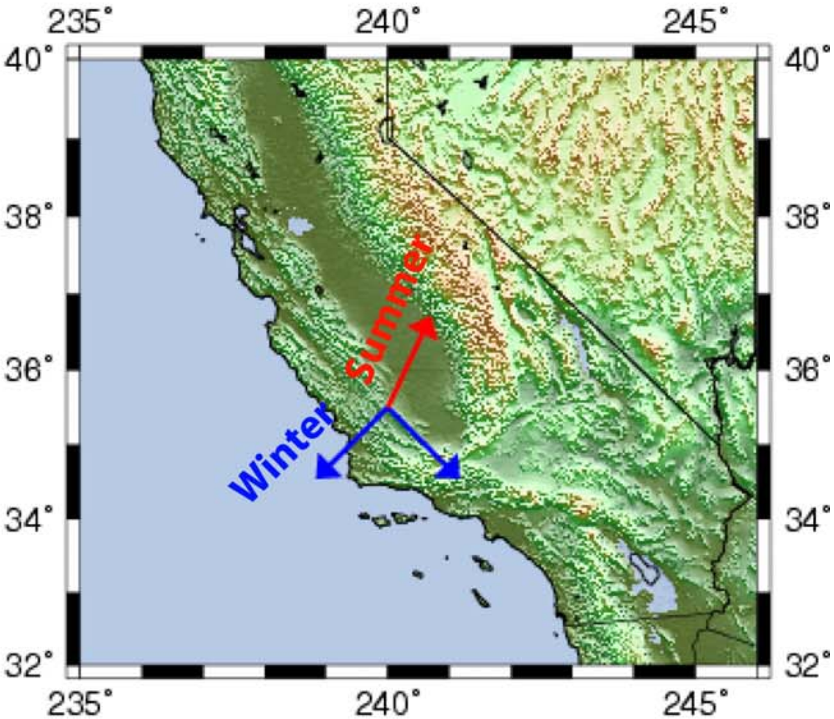
from Stehly et al., 2006


Winter 5–10s
Summer 5–10s
Winter 10–20s
Summer 10–20s
235°
240°
245°
40°
38°
36°
34°
32°
from Stehly et al., 2006

Tracing the origin of the seismic noise

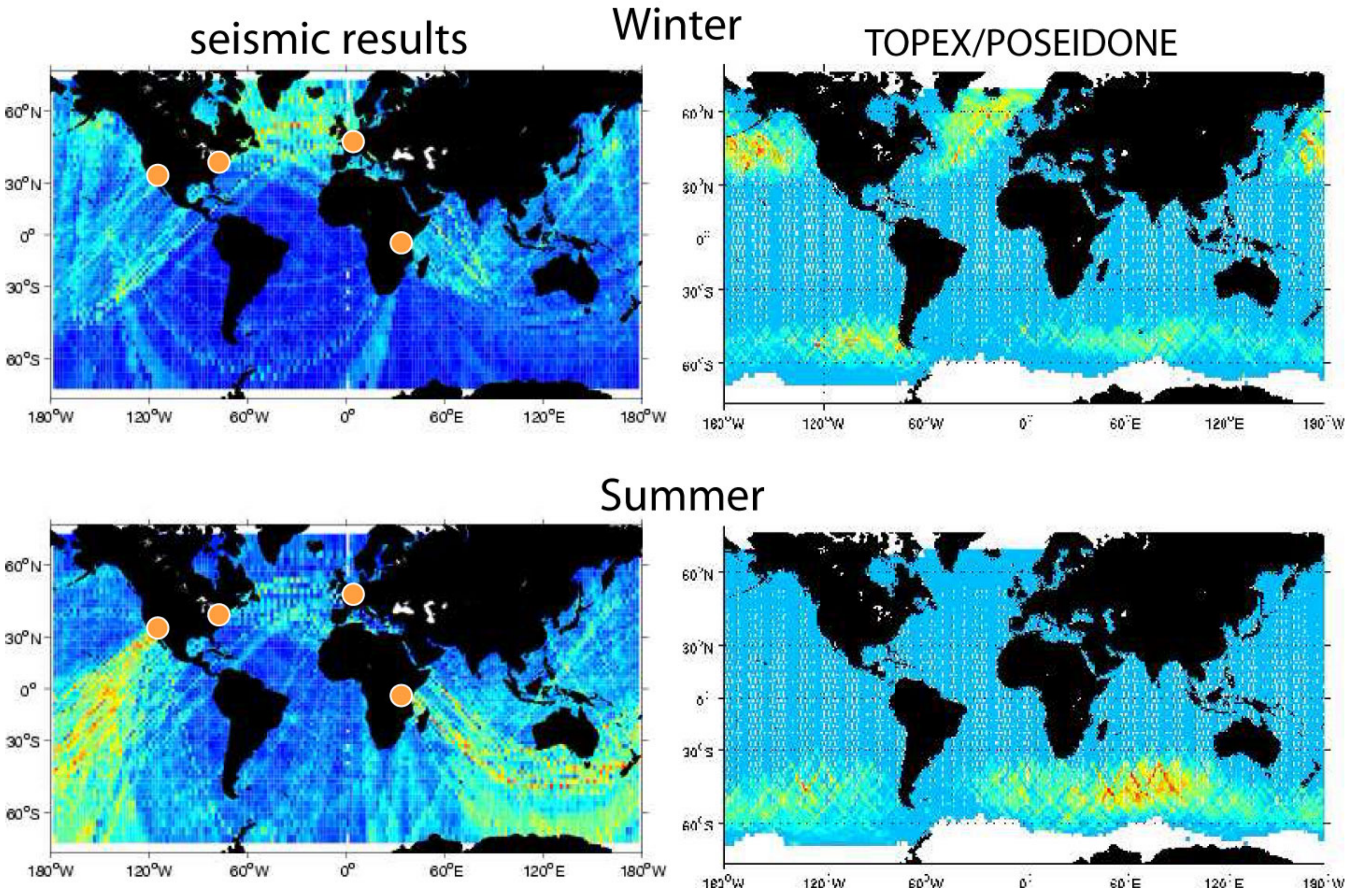
10 - 20 s





from Stehly et al., 2006

Seismic noise sources (10-20 s)



from Stehly et al., 2006

Origin of oceanic microseisms: new results

- primary and secondary microseisms do not originate from the same areas
- primary microseism seems to partially originate in the deep oceans
- primary microseism is clearly related to the meteorological conditions in the ocean:

  possibility to study climate-related phenomena from seismic data

- prominence of the primary microseism is strongly seasonal

  the seasonality must be accounted for during travel time measurements for the tomography; better to use long time series (> 1 year)

- noise sources are not distributed homogeneously on the Earth’s surface

  source heterogeneity must be accounted for more accurate inversion of the waveforms emerging form noise cross-corelations

Conclusions

Seismic surface waves can be easily extracted from correlations of ambient seismic noise

- measurements without earthquakes
- improved resolution of seismic images of shallow parts of the Earth
- monitoring of seismic velocity variations within the media with an accuracy better than 0.1%

Possible applications:

- imaging of the crust and the uppermost mantle
- structure of sedimentary basins for seismic hazard
- seismic calibration for nuclear monitoring
- passive monitoring of temporal changes (volcanoes, fault zones, oil reservoirs, nuclear waste deposits …)

Remaining problems:

- extraction of body waves from noise cross-correlations?
- optimizing the data processing
- going beyond the ray-theory-based inversion methods
- understanding the source of background seismic noise