Looking inside the Earth using seismic interferometry

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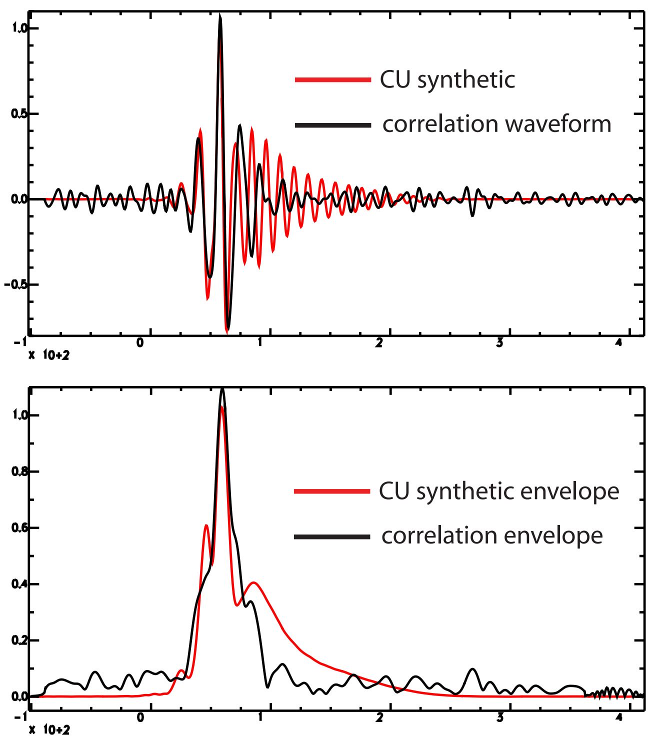

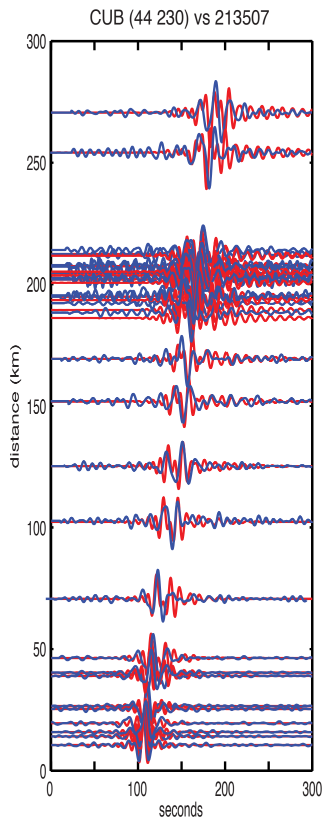

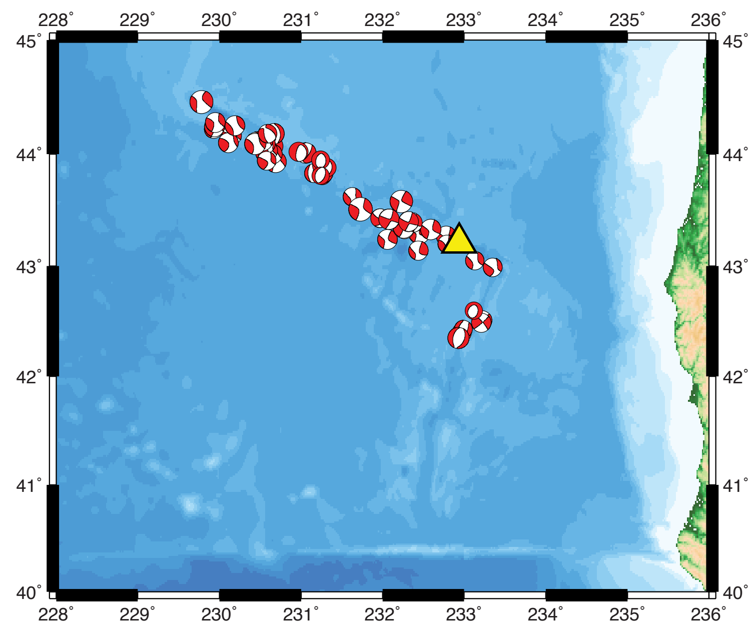

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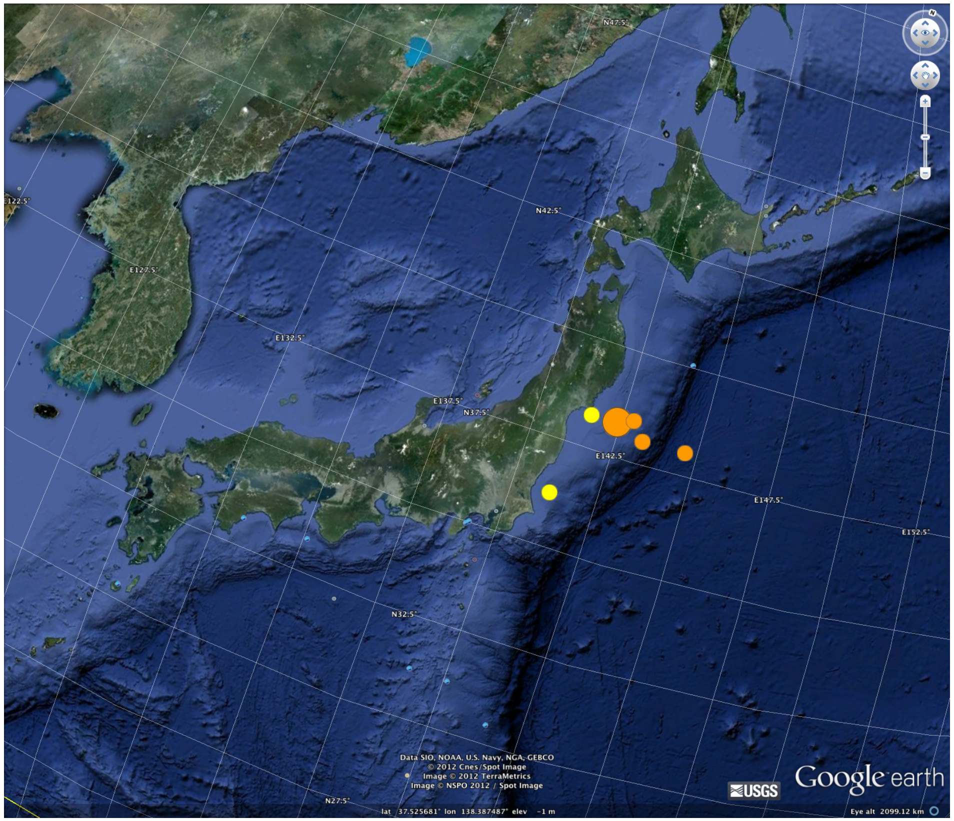
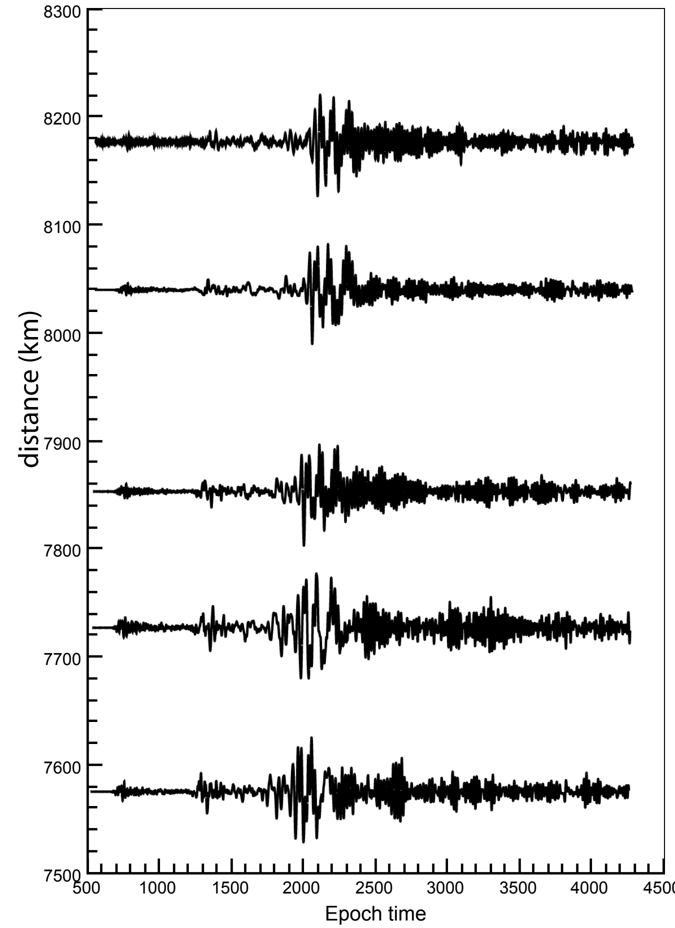
In seismology, the Green's function (GF) is defined as the response of the Earth at one point due to an impulsive source at another.

2011 Tohoku earthquake and aftershocks



Tohoku event recorded by seismic stations in California



In simple terms, GFs are the data recorded by seismometers once the peculiarities of the source and instrument are removed.

Signals previously discarded as noise; the ambient seismic wavefield and the scattered energy that makes up the seismic coda have now proven to contain significant sensitivity to Earth structure.

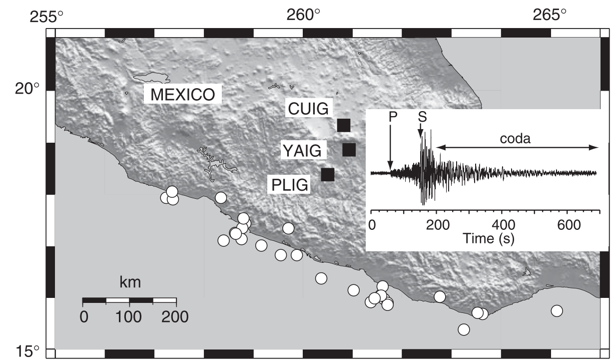


Fig. 1. Location map of the broadband stations CUIG, YAIG, and PLIG of the Mexican National Seismological Network (black squares) and epicenters of 30 earthquakes of the data set (white circles). Inset: An example of a record of one of these events at station PLIG (vertical component).

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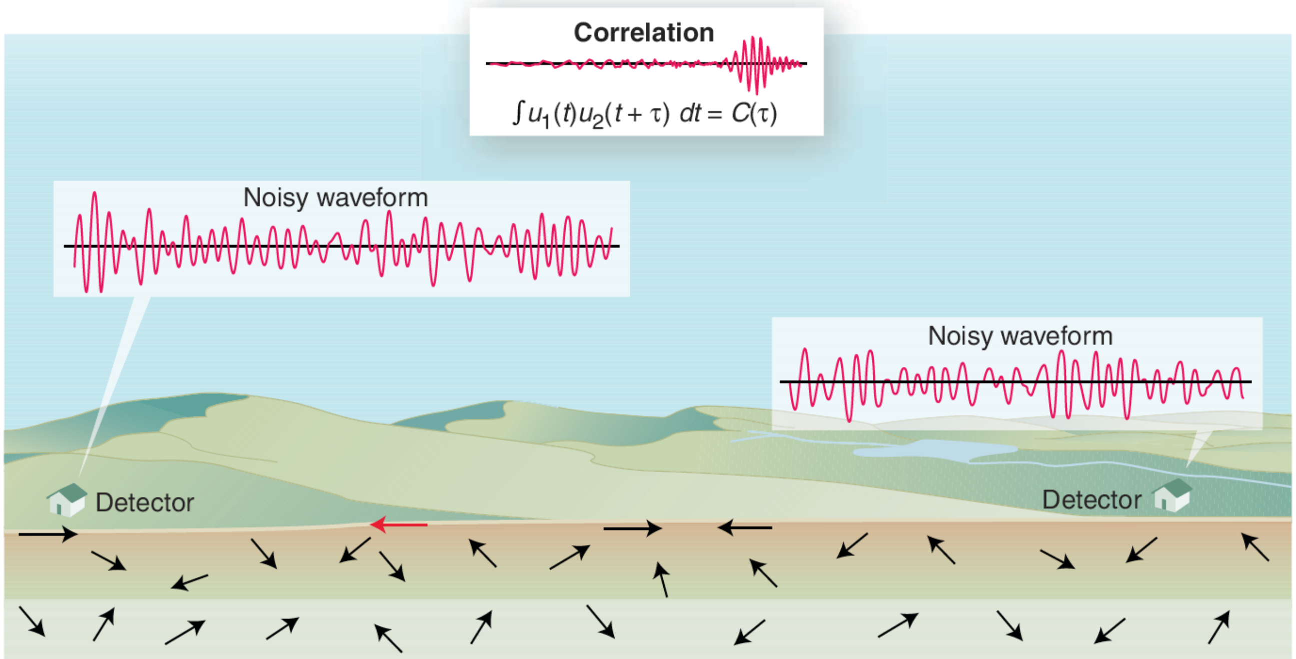
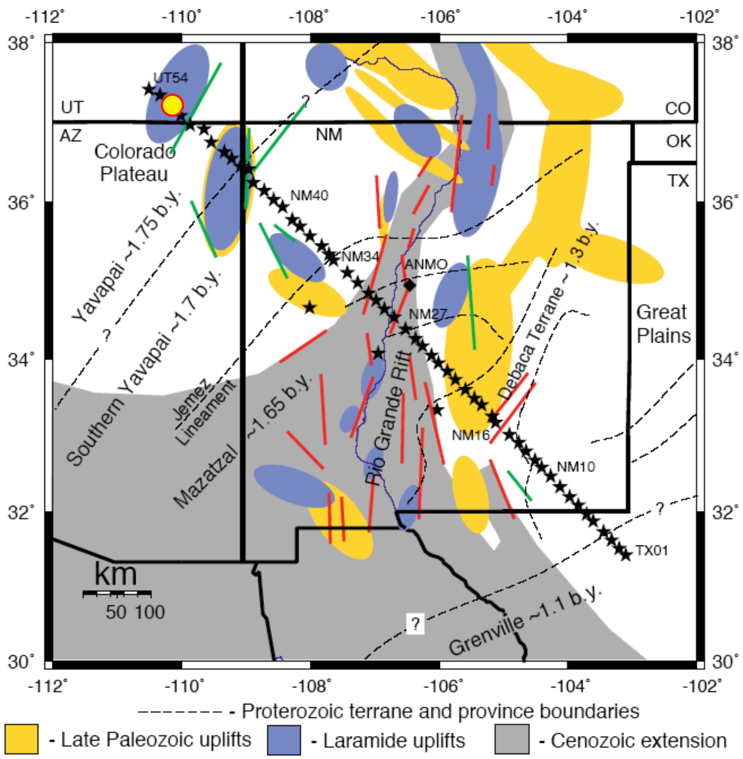


Using noise in seismology. When a diffuse wave field is generated by distant sources and/or by multiple scattering, detectors report random signals. Occasionally a ray (for example, the one shown in red) passes through both detectors. As a result, the signals are weakly correlated.

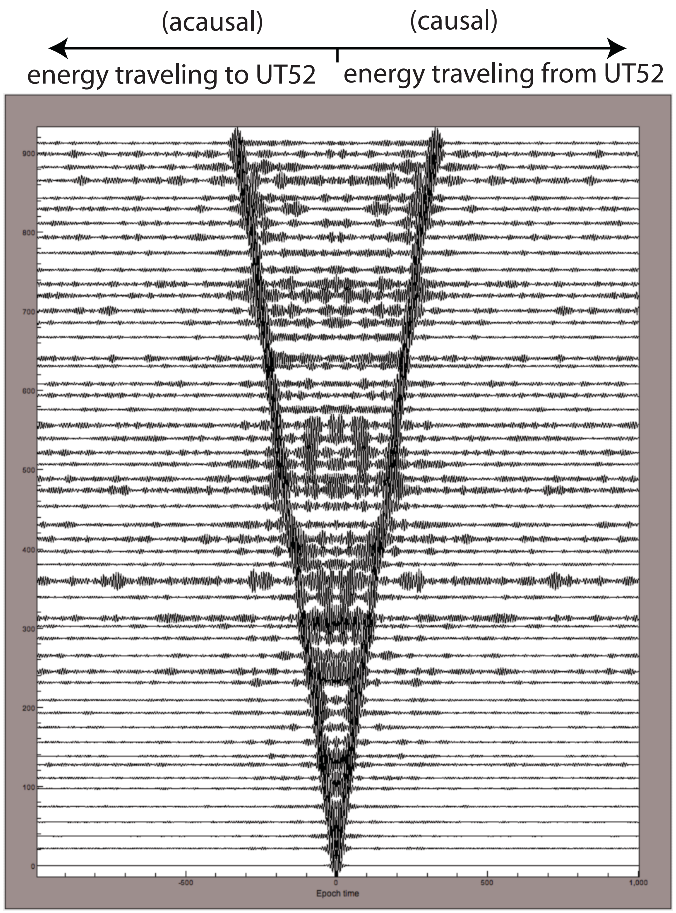
Richard L. Weaver 11 MARCH 2005 VOL 307 SCIENCE www.sciencemag.org

An example data profile obtained using ambient noise correlation

Wilson and Aster, 2003



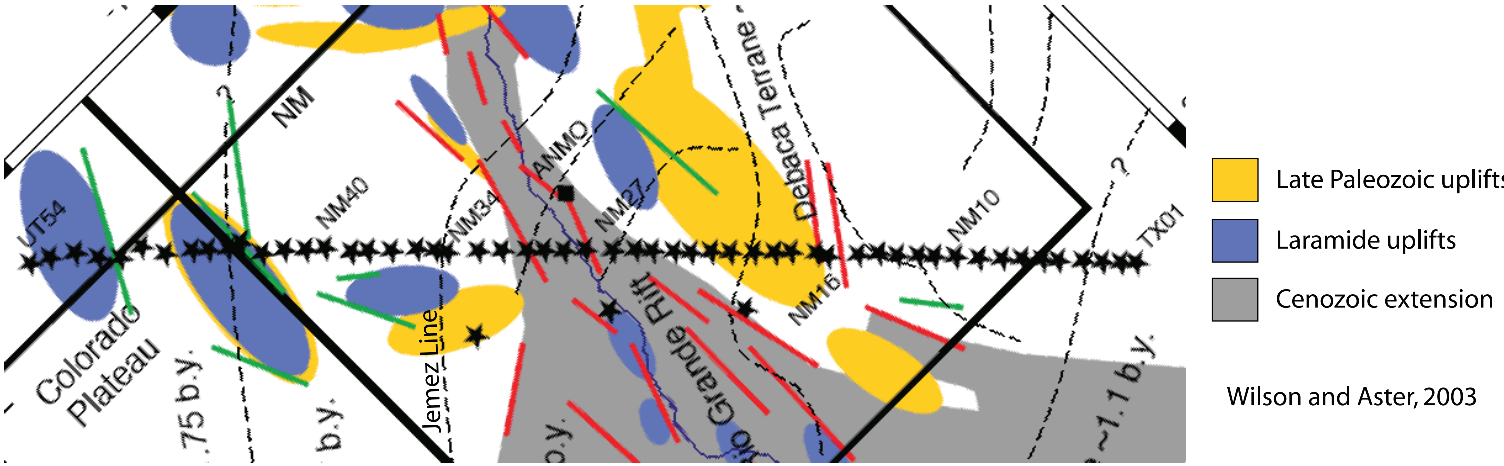
Map of the Ristra Experiment



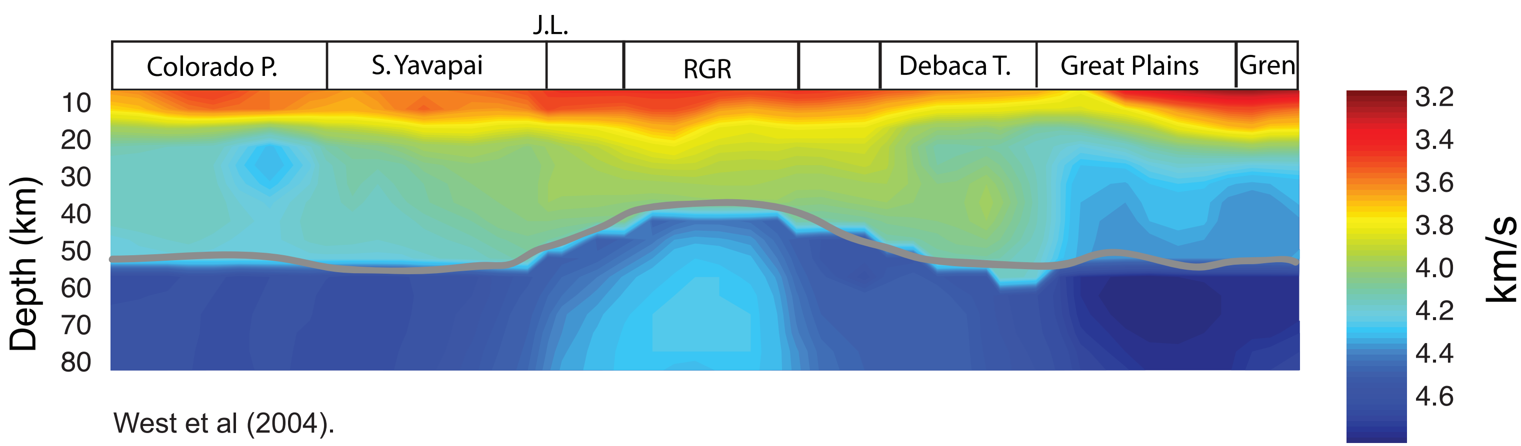
Profile of correlations between UT52 and all stations to the Southeast

Comparison: seismic velocity tomography of the Rio Grande Rift using traditional methods

(data used were distant earthquakes recorded by stations in the array)



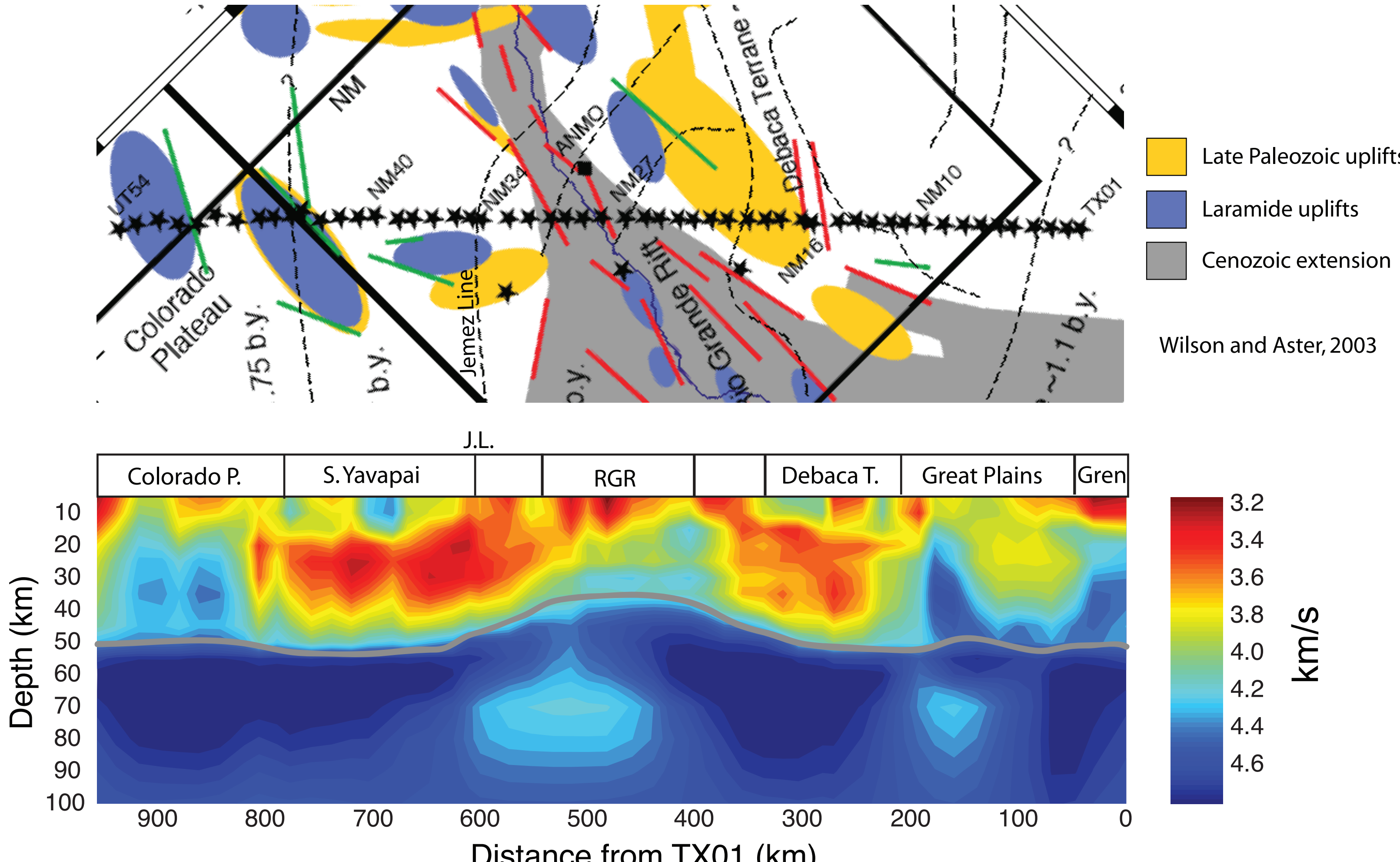
Wilson and Aster, 2003



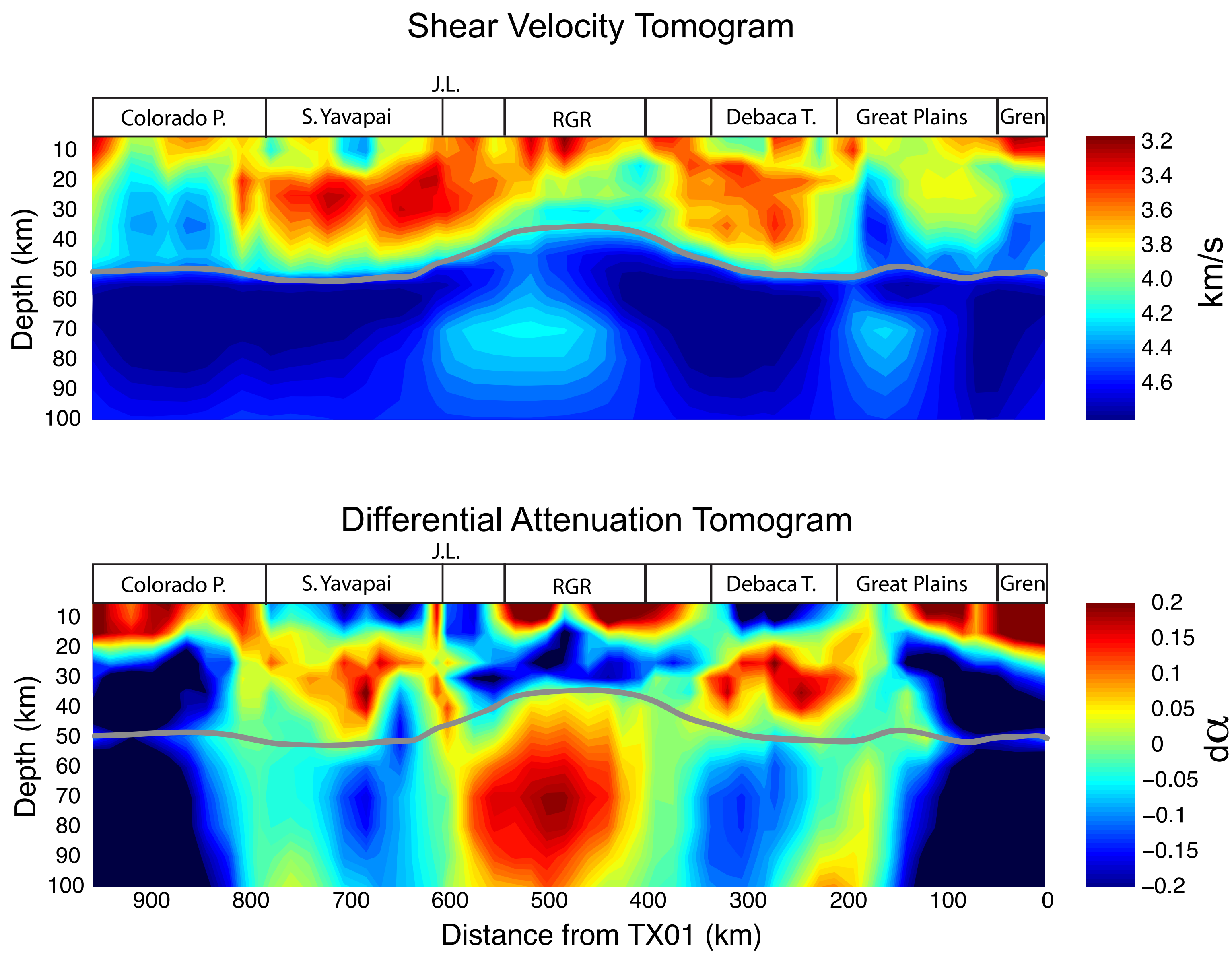
West et al (2004).

Comparison: ANC is capable of recovering much greater detail

Note seismic velocity contrasts are 2.5 x larger than West et al.



We increase resolution further by measuring seismic attenuation



Combining all our amplitude measurements, we were able to create a detailed profile of attenuation beneath the array. Over 1200 unique amplitude measurements went into the inversion (the others failed based on signal to noise criteria).

$^*d\alpha \sim (Q_o/Q_{real} - 1)$

Ambient noise correlation works very well anywhere we can easily install large numbers of seismometers.

The technique is perfectly scalable (hand sample to continental).

Experiments can be designed explicitly to scale of the problem.

But there are many areas of interest where we cannot easily install seismic instruments.

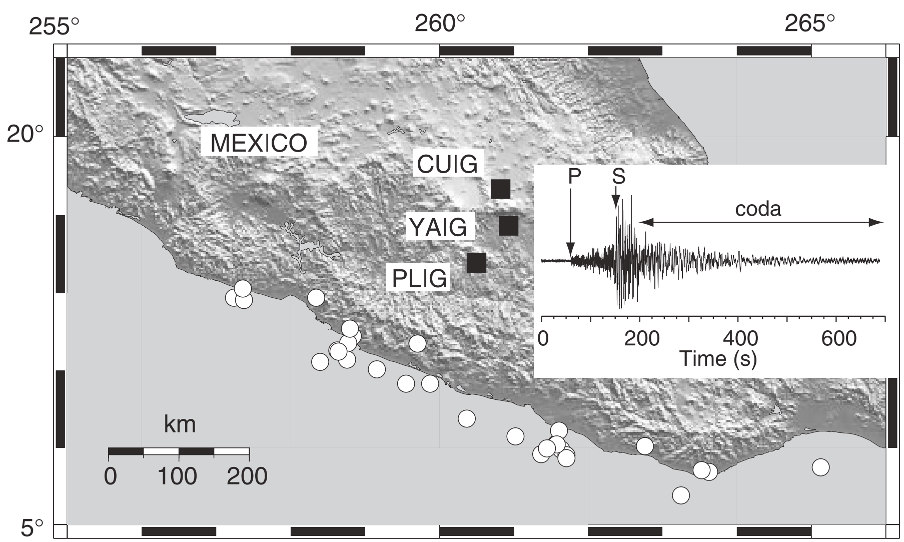
If those areas are tectonically active, we can reverse the problem and use earthquakes as “virtual seismometers”

Correlation of the seismic coda

Campillo and Paul (2003) used the cross correlation of the diffuse coda recorded at different seismic stations to obtain the Green's function of the Earth between them.

It is straightforward to flip the geometry used by Campillo and Paul and focus instead on the structure between pairs of earthquakes.

Our method, similar to that of Curtis et al. (2009), involves correlating the coda of pairs of events recorded at individual stations and then stacking the results over all stations to obtain the final waveform.



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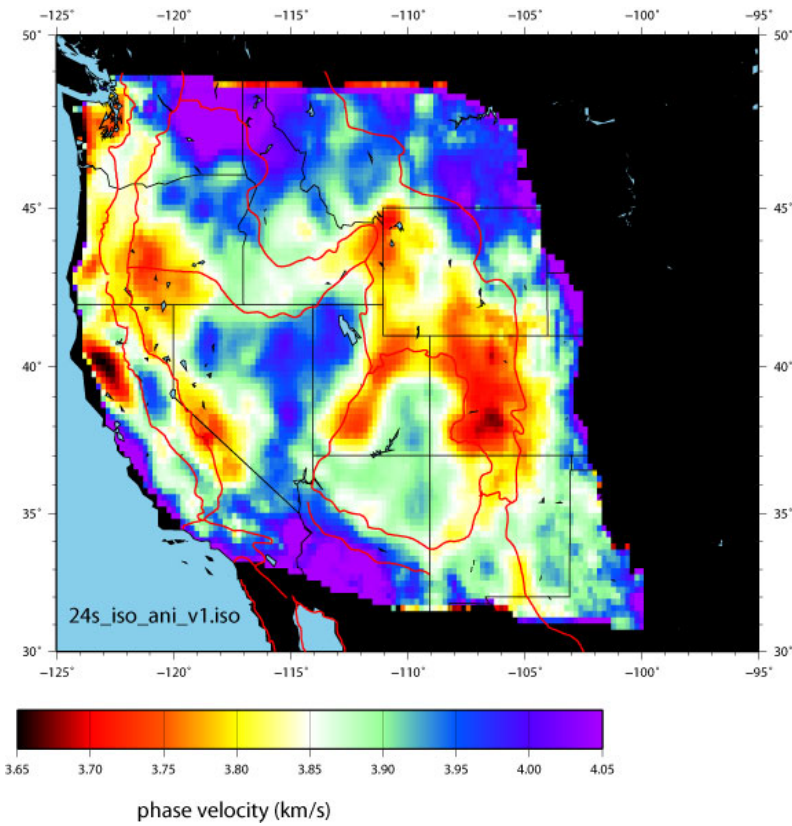
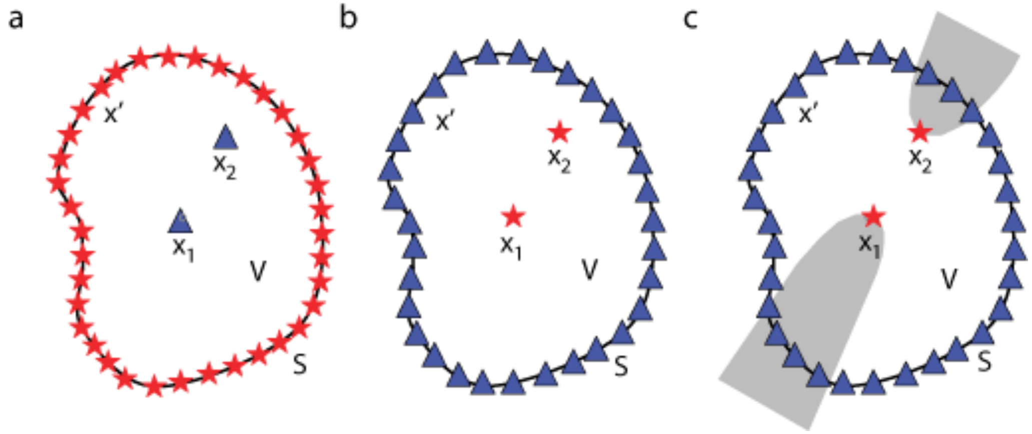
The Virtual Seismometer Method



Seismic Interferometry, Curtis (2009)



Lin et al. (2010), image of Western U.S. using ambient noise interferometry

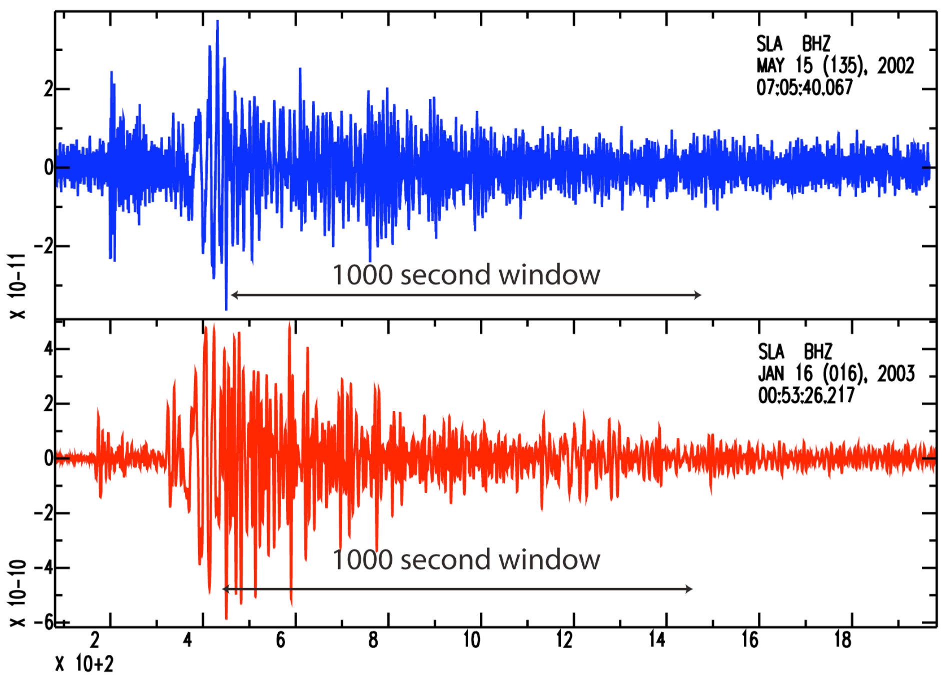
- **(VSM): correlate the coda of two earthquakes recorded at a distant seismic station**
- Coda is scattered energy that follows the main arrivals
- **Stack the results for all stations to obtain the final waveform.**
- **The result is an estimate of the seismogram expected if one quake had been a seismometer recording the other.**

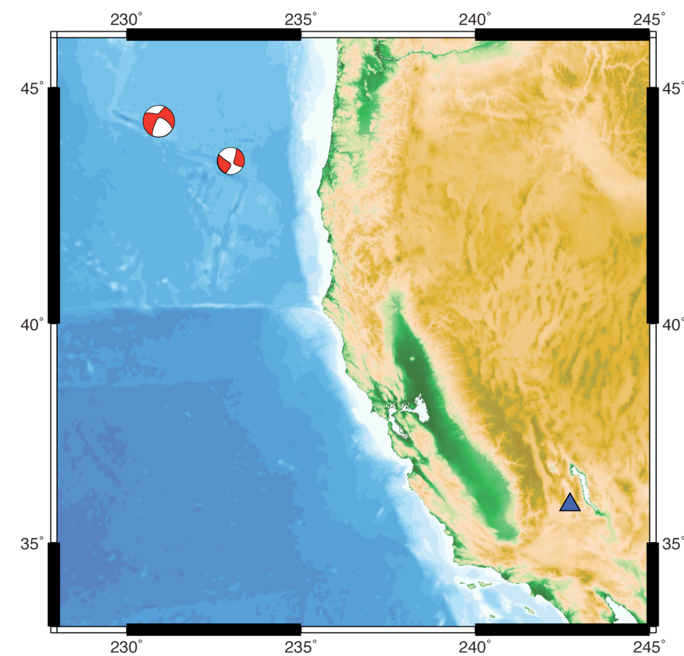
How to turn an earthquake into a virtual seismometer.

Step 1: Obtain the data for 2 earthquakes recorded by a single station.

Step 2: Process the data by instrument correcting, removing the mean, and filtering within a band of interest.

Step 3: We isolate a 1000 second window with a start time defined by a group velocity of 3 km/s. *





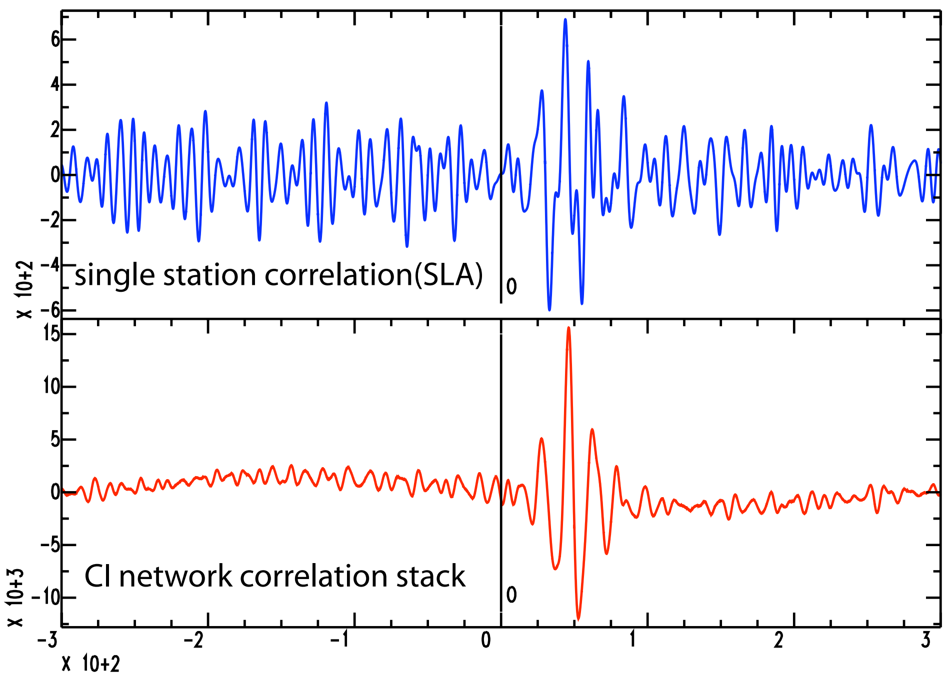
In blue, is the 5.3 Mw, 2002/5/15 earthquake at (43.27, -127.22) . In red is the 6.2 Mw 2003/01/16 earthquake at (44.07 -129.36). 189 km distance between earthquakes.

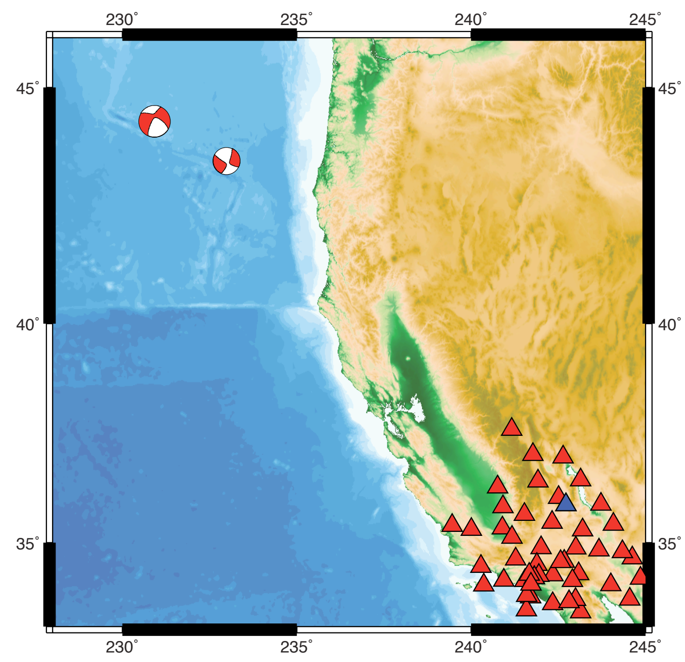
How to turn an earthquake into a virtual seismometer.

Step 4: Correlate the instrument corrected traces.

Step 5: Repeat for all stations in the network and stack the results

Correlation of the earthquake at (43.27, -127.22) and the earthquake at (44.07 -129.36).

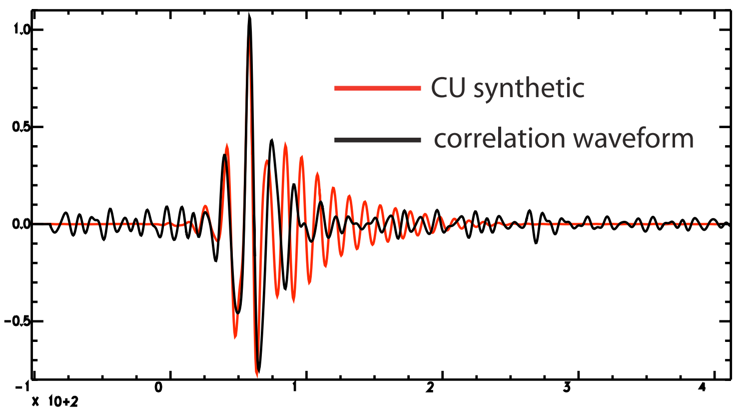


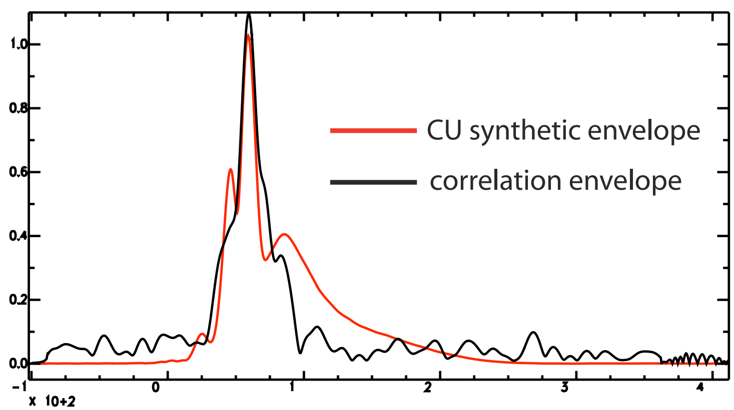


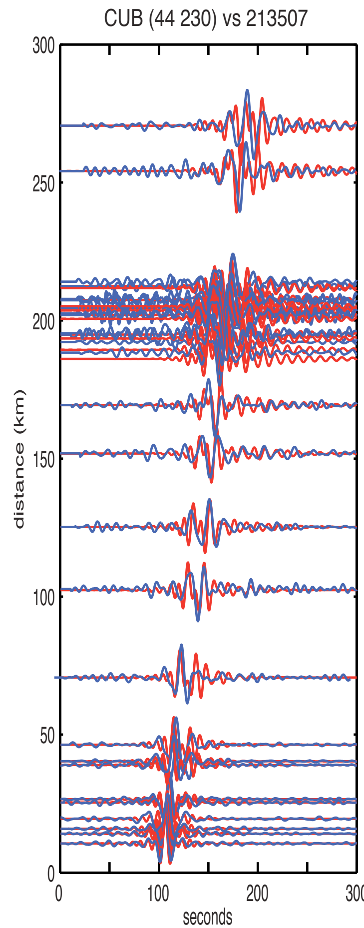
189 km distance between earthquakes.

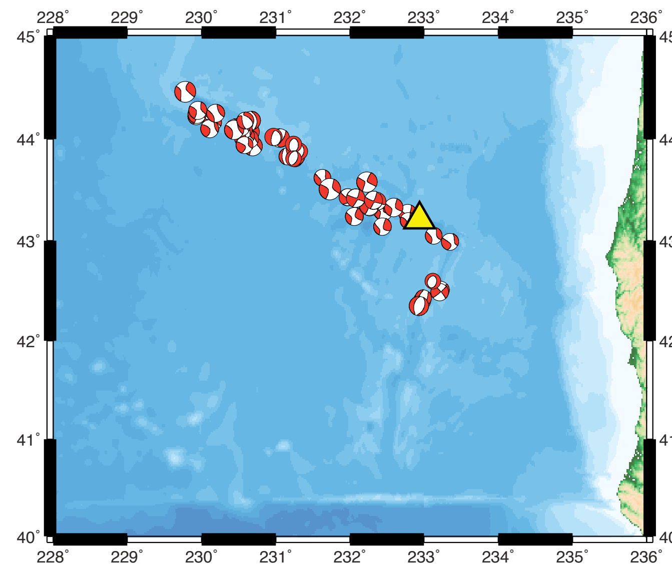
How to turn an earthquake into a virtual seismometer.

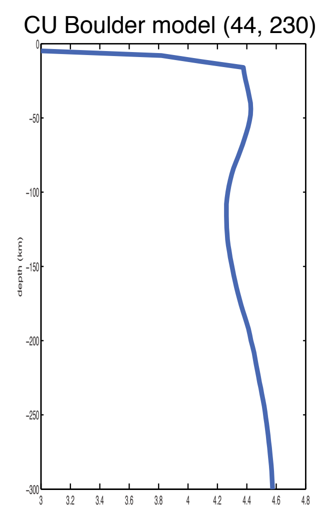
The resulting waveforms closely match those predicted by large-scale global models.











CU model reference: Ritzwoller, et al., Global surface wave diffraction tomography, J. Geophys. Res., 107(B12), 2335, 2002.

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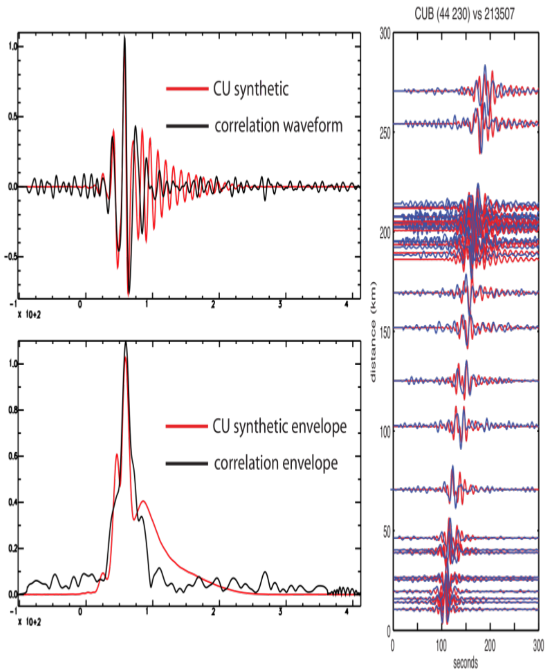
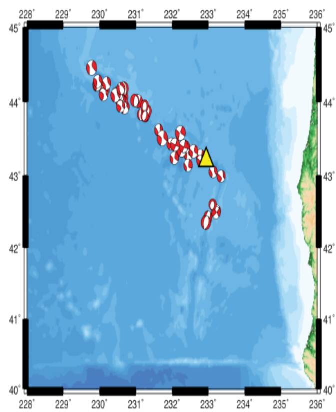
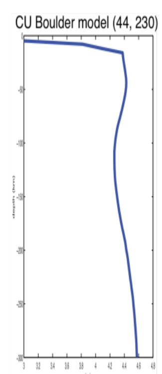
How to turn an earthquake into a virtual seismometer.

The resulting waveforms closely match those predicted by large-scale global models.







Matzel (2010)

CU model reference: Ritzwoller, et al., Global surface wave diffraction tomography, J. Geophys. Res., 107(B12), 2335, 2002.

- Number of GF = $(N^2 / 2)$
- 100 quakes → 5,000 v. seismograms
- 1000 quakes → 500,000 v. seis.

- (VSM) effectively replaces each earthquake with a "virtual seismometer" recording all the others.
- Isolates the energy that is sensitive to path between the quakes
- Dramatically increases our ability to see into tectonically active features where seismic stations either can't or haven't been located
- A key advantage is that the virtual seismograms come directly from the correlation.
- We can measure the ground motion between two points even if we do not know the Earth model.
- This saves us from having to make expensive finite difference calculations to study energy as it travels along the fault.

Conclusions:

Seismic interferometry is transforming our ability to image the Earth's interior.

Ambient Noise Correlation (the "virtual earthquake" method) provides high resolution on scales ranging from hand samples (mm) to continents (1000s of km).

> It can be employed anywhere seismometers can be installed in large numbers.
>
> Since it completely strips away the need for earthquake or artificial sources, experiments can be designed explicitly to the problem at hand.

By contrast, the VSM works by effectively replacing each earthquake with a "virtual seismometer" recording all the others.

> This isolates the portion of the data that is sensitive to the source region and dramatically increases our ability to see into tectonically active features where seismometers either can't or haven't been located, such as fault zones, mid-ocean ridges, convergent margins and the interiors of subducting slabs.