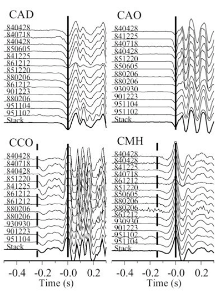
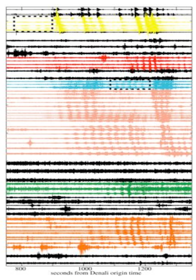
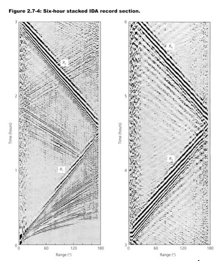
EAS 8803 - Obs. Seismology
Lec#12: Waveform Stacking

- Dr. Zhigang Peng, Spring 2013







Last Time

- Data management and basic data processing tools
- Systematic and random errors
- Waveform stacking
- Array analysis

This Time

- Data management and basic data processing tools
- Systematic and random errors
- Waveform stacking
- Array analysis

Stacking

- Random errors
- Stacking examples

Introduction to Stacking

- Seismology use seismic data to estimate quantities related to the Earth structure and seismic source.
- Ideally these estimates are both *accurate* and *precise*.
  - *Accuracy* measures the deviation of the estimate from its true value.
  - *Precision* measures the repeatability of individual estimates.

Chap. 6.5 of the Stein book

Accuracy vs. Precision

- *Accuracy* depends on systematic errors that bias groups of estimates.
- *Precision* depends on random errors that affect individual estimates.
- Estimates can be precise but inaccurate, or accurate but imprecise.
- Can you think of any example in seismology?

High accuracy, but low precision

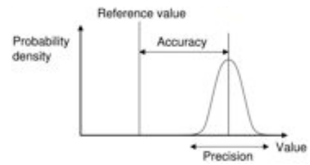
High precision, but low accuracy

Example

- An estimate of an earthquake's location depends on the quality of the travel time data and the accuracy of the velocity model.
- High-quality travel time data with an incorrect velocity model, can yield location that is precise (small uncertainty), but inaccurate in that the resulting location is not where earthquake occurred.
- Conversely, an accurate velocity model and poor travel time data give "relatively" accurate and imprecise location.

Improving accuracy and precision

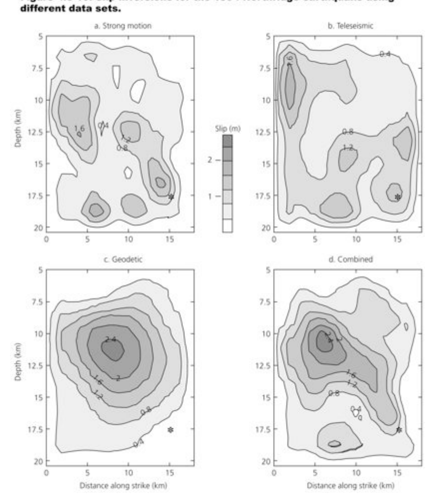
- Accuracy can be improved by using different measuring tools, ideally calibrated against each other.
- Precision can be improved by making multiple measurements, ideally by different people.



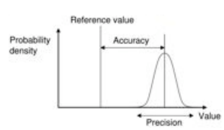
Complications

- For example, an earthquake is (in most cases) a non-repeatable experiment, so we cannot make additional measurements.
- Estimating depth from travel times and waveform modeling are only partially independent – both can be biased similarly by incorrect assumptions about near source mechanisms.
- A further complication is that different methods can measure related but not identical entities. For example, finite source modeling from near-field strong-motion recordings, teleseismic waveforms, and geodetic measurements often differ with each other.
- Can you provide other examples?

Figure 4.5-10: Slip inversions for the 1994 Northridge earthquake using different data sets.



Systematic error



- Most discussions focus on random errors because they are easy to estimate from the scatter of measurements.
- It appears that assessments of the formal or random uncertainty often significantly underestimate the systematic error, so the overall uncertainty is dominated by the unrecognized systematic error and thus larger than expected.
- Measurements of a quantity often remains stable for a while, then suddenly change by much more than the previously assumed uncertainty.
- Systematic biases are difficult to detect, but sometimes are identified from discrepancy between different approaches.

Random Error

- We estimate a quantity x from multiple measurements, x_i (due to noise and limitations of the measurements).
- With enough measurements, a pattern generally emerges in which the values x_i are distributed around x.
- If we neglect system errors of measurements, we can estimate x from the measured value x_i, and associated uncertainties.

Gaussian Distribution

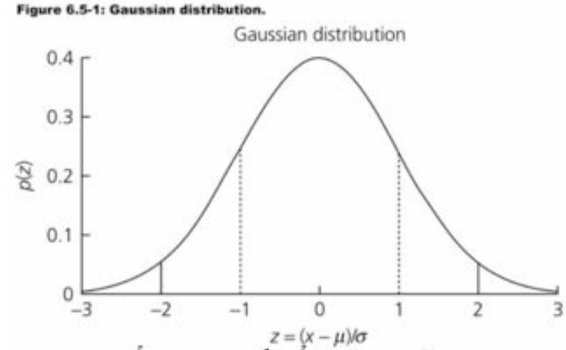
$$p(x_i) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x_i-\mu}{\sigma}\right)^2\right]$$

Two variable: the mean μ, and the standard deviation σ.

$$z = (x-\mu)/\sigma$$

$$p(z) = \frac{1}{\sqrt{2\pi}} \exp\left[-z^2/2\right]$$

Figure 6.5-1: Gaussian distribution.



$$A(z) = \int_{-z}^{z} p(y)dy = \frac{1}{\sqrt{2\pi}} \int_{-z}^{z} \exp\left[-y^2/2\right]dy$$

For $z = 1, A(z) = 0.68$; $z = 2, A(z) = 0.95$; $z = 3, A(z) = 0.997$.

Reducing errors by stacking

- One of the most useful methods for improving measurements from seismological data: stacking
- Stacking: taking multiple measurements and averaging them.
  - By averaging measurements such as travel times from different seismograms.
  - By adding many seismograms and then estimating parameters.
- Stacking will have two effects:
  - It improves precision by reducing the effects of random noise in the data.
  - If the data are averaged in special ways, the precision, and perhaps accuracy, can be improved by suppressing some features in the data while enhancing other desired features.

Stacking

$$\mu = \lim_{N\to\infty}\left[\frac{1}{N}\sum_{i=1}^{N} x_i\right]$$

$$\sigma^2 = \lim_{N\to\infty}\left[\frac{1}{N}\sum_{i=1}^{N} (x_i-\mu)^2\right]$$

$$\sigma_{\mu'}^{\ 2} = \sigma^2/N$$

•For stacking, the variance of the mean is $1/N$ times the variance of the individual measurements. Hence making N measurements reduces the standard deviation of the mean by $1/\sqrt{N}$

•This is the basic idea behind stacking, averaging multiple measurements of some quantity yields an estimate that a smaller uncertainty than the individual measurements.

Example of stacking

- Stacking in exploration geophysics
- Stacking to obtain reliable deep Earth structure
- Stacking to estimate seismic source properties

Figure 3.3-10: Cartoon geometry of a multichannel seismic reflection profile.

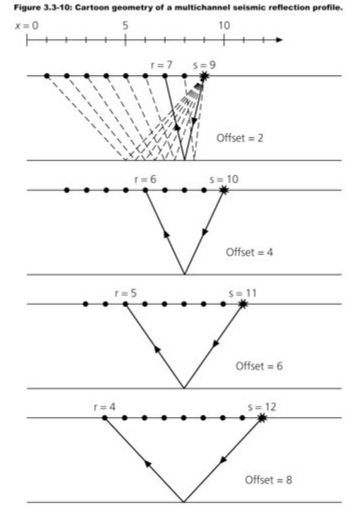
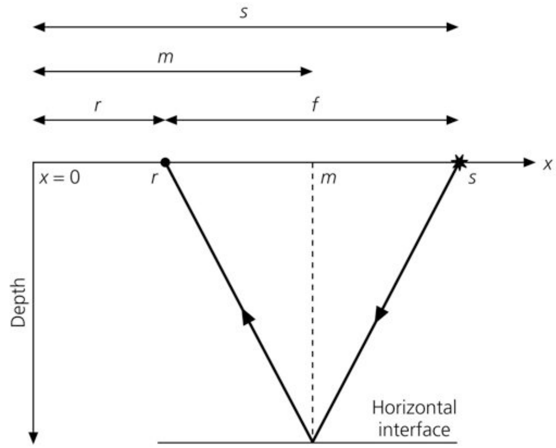
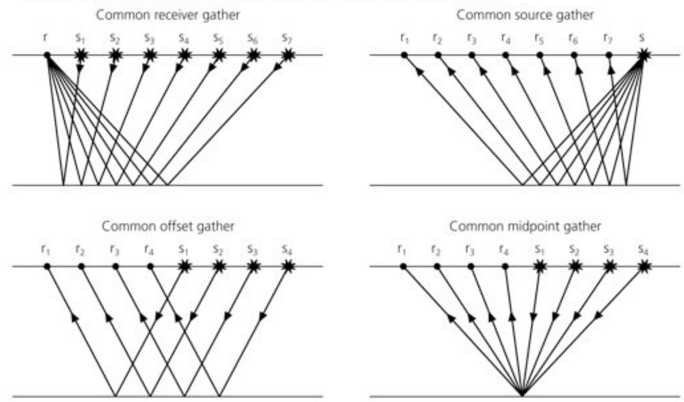


Figure 3.3-11: Relation between source, receiver, midpoint, and offset.



Stacking in exploration geophysics

Figure 3.3-13: Cartoon of the four different gather types.



NMO: a reflection whose variation in travel time with offset is the normal moveout

$$T(x) - t_0 = (x^2/\bar{V}^2 + t_0^2)^{1/2} .$$

A hyperbolic time shift lines up reflections with hyperbolic travel time curves (analogous to the reduced travel time plot).

Figure 3.3-15: Diagram of the normal moveout correction.

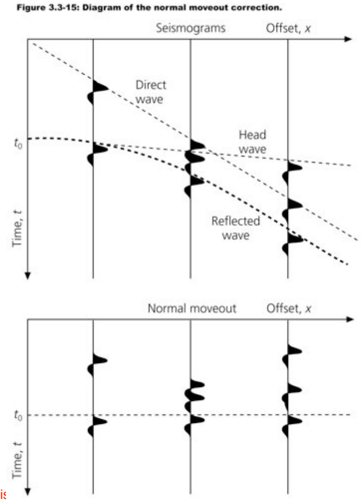


Figure 3.3-16: Cartoon of CMP stacking and velocity analysis.

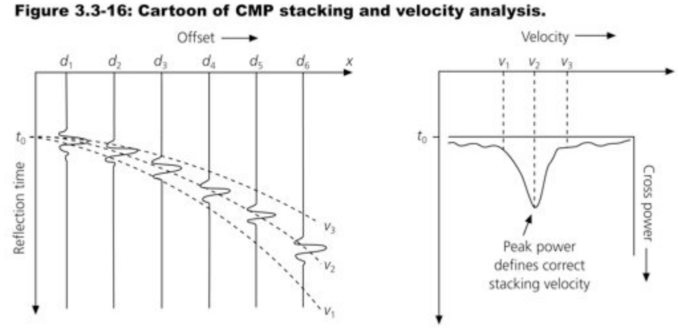


Figure 3.3-17: Example of CMP stacking and velocity analysis.

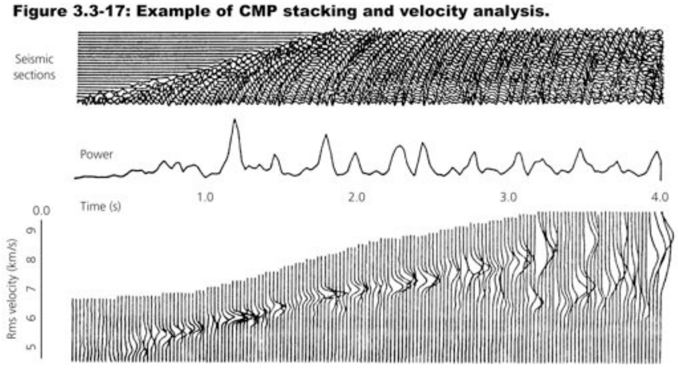


Figure 3.3-19: CMP stacking for flat and dipping layers.

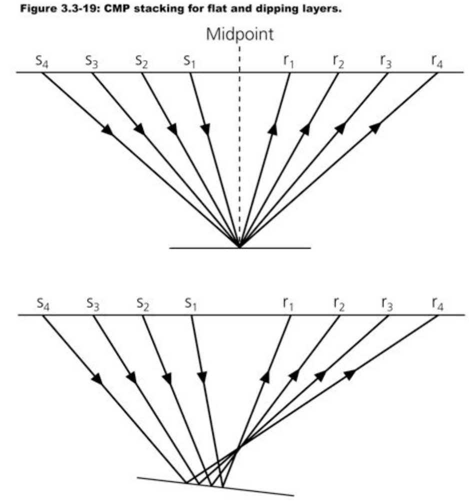


Figure 6.5-2: Results of drawing N samples from a Gaussian parent distribution.

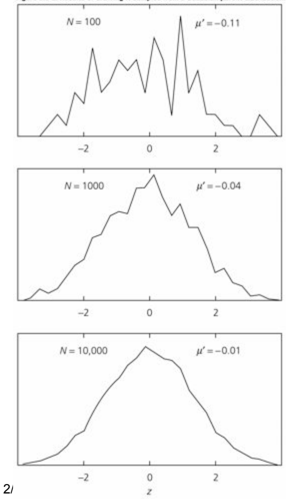


Figure 6.5-3: Example of stacking seismograms to enhance precursors to SS.

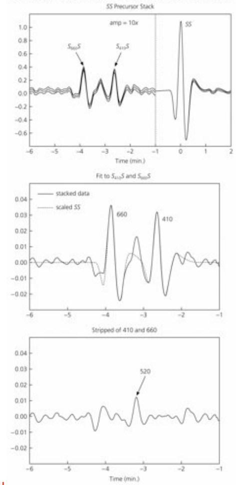


Figure 3.5-10: Ray paths for additional core phases.

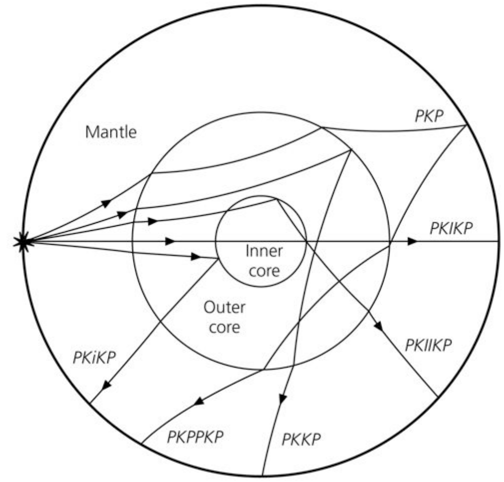
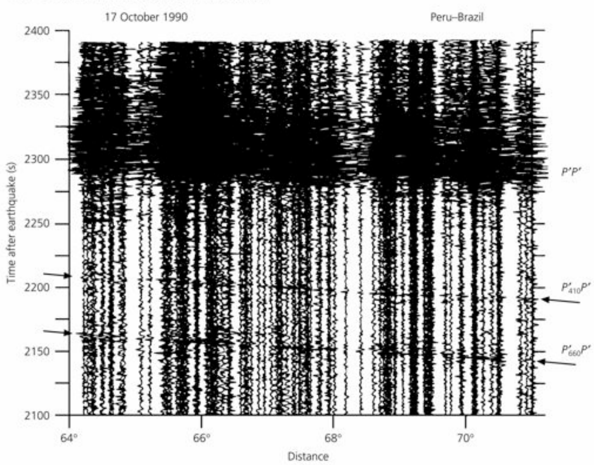
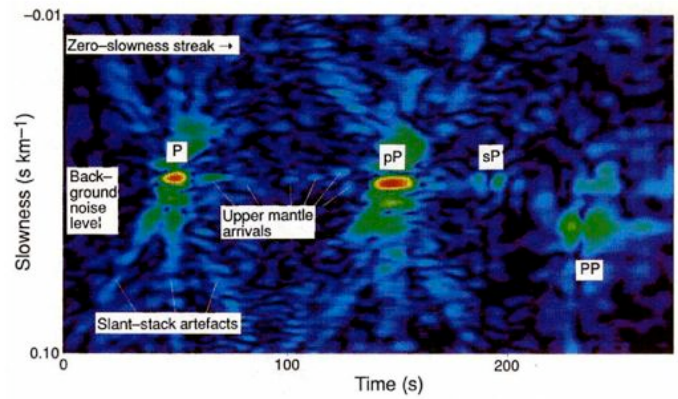


Figure 6.6-19: Example of records from the California regional networks for a South American earthquake.





Slant stack of 3 April 1985 Bonin earthquake (Vidale and Benz, Nature, 1992)

Figure 6.5-6: Stacking global seismograms to produce record sections.

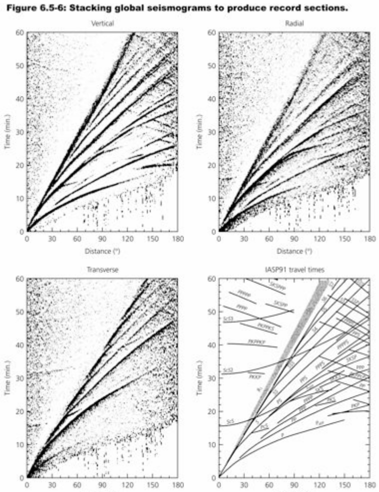


Figure 2.7-4: Six-hour stacked IDA record section.

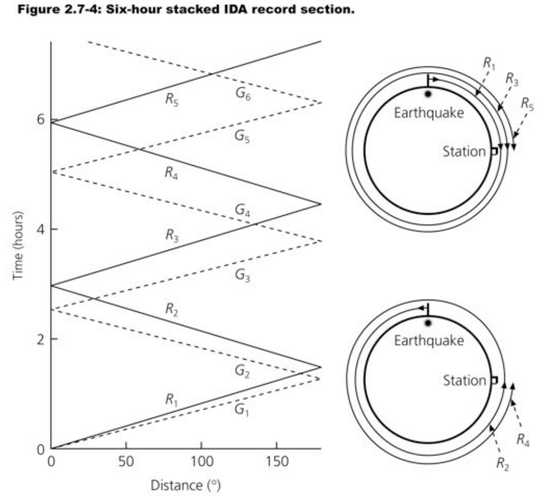
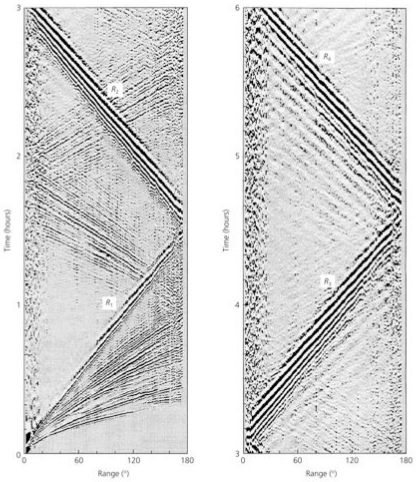
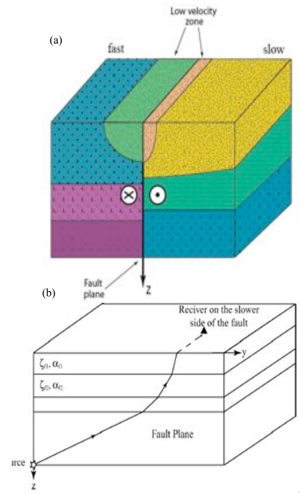
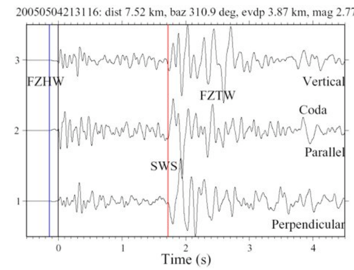


Figure 2.7-4: Six-hour stacked IDA record section.

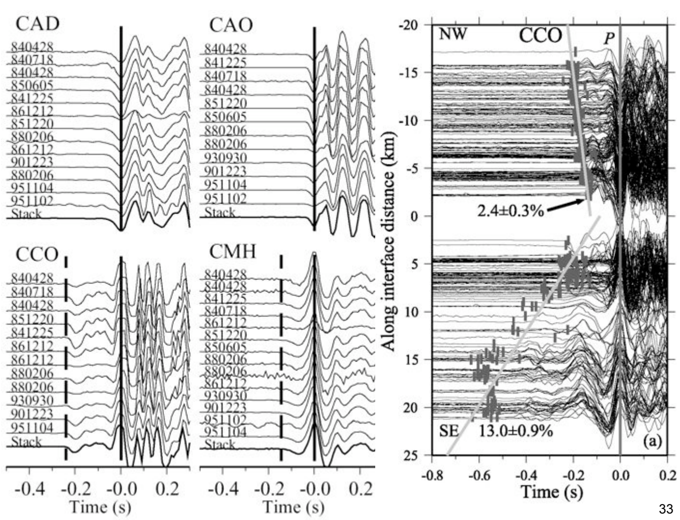




Fault zone head waves refract along bi-material interface and are recorded by stations on the slow side of the faults.



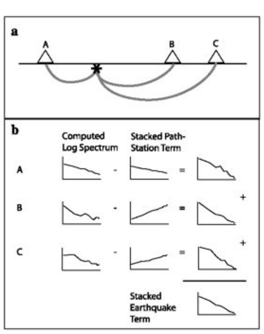
Zhao and Peng (GRL, 2008)



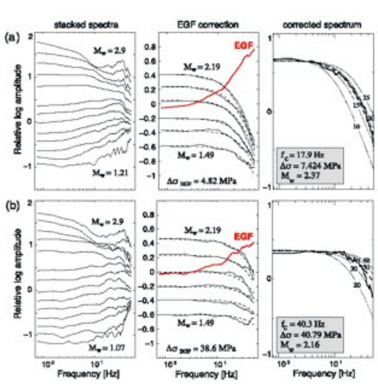
Stacking to obtain source properties

- Stacking is used to obtain reliable source properties (e.g., source time functions, source spectra, etc) under the following assumption:
  - Earthquake source is a common term for seismograms recorded at by multiple stations.
  - Hence stacking will help to enhance the source terms while suppressing other near-station effects.

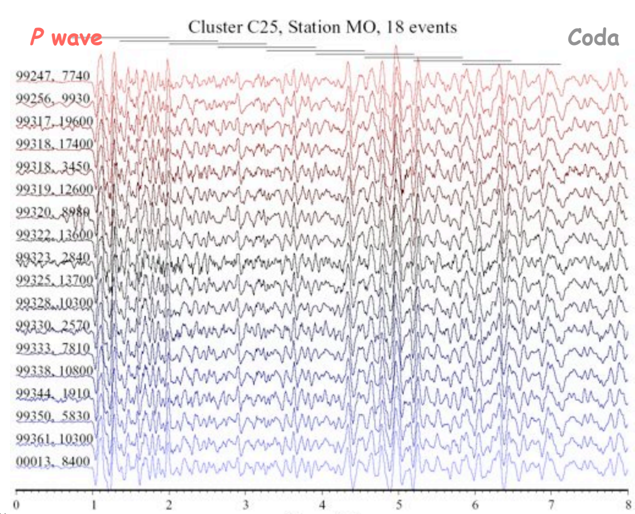
Stacking for reliable earthquake spectra



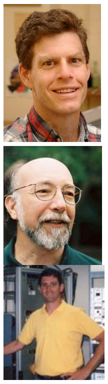
Prieto et al. (JGR, 2004)

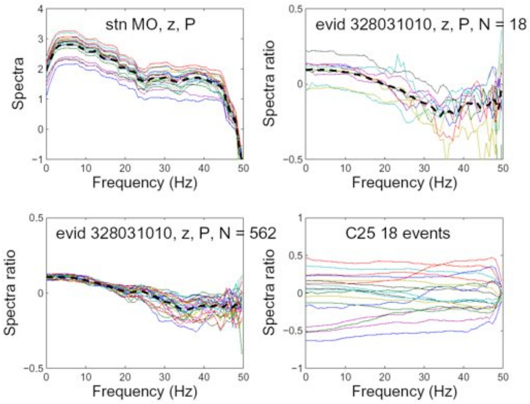


Allmann and Shearer (JGR, 2007)

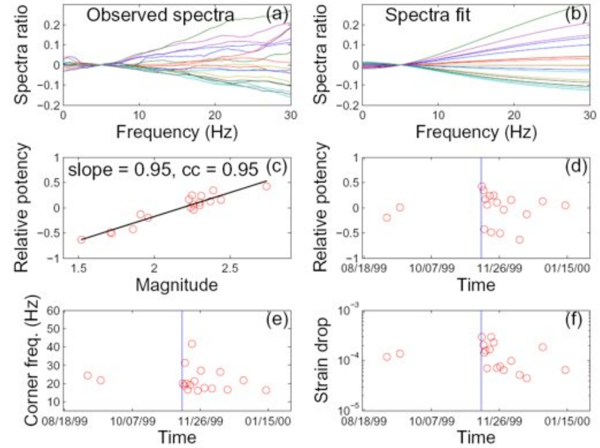


Two-step stacking procedure [Vidale et al., 1994] to isolate source and site spectra

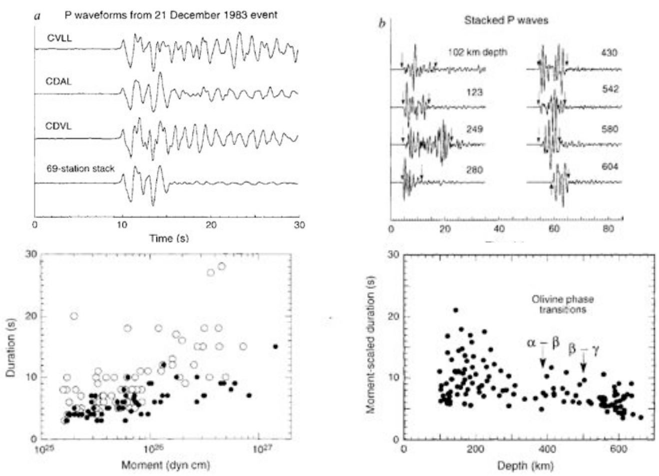




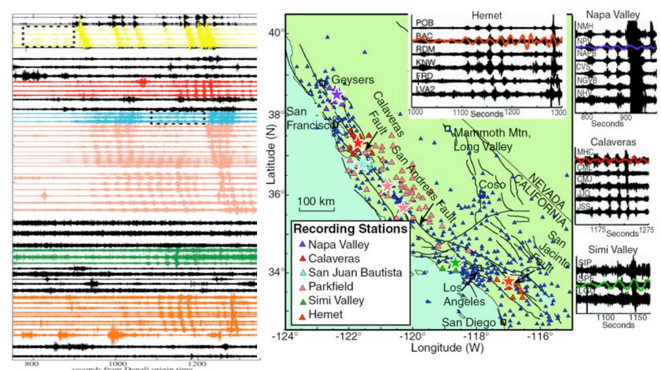
Assuming an average strain drop of 10^-4



Stacking for source time function (Vidale and Houston, Nature, 1993)



Triggered tremors at California



Gomberg et al. (Science, 2008)

Example of stacking using SAC

- The easiest way is to use the command “addf” in SAC:
  - SAC> r wf1.sac
  - SAC> addf wf2.sac
  - SAC> …
  - SAC> div 10
  - SAC> w stack.sac
  - # Note: the data has to be the same length
- Another way is to use my own command: sacStack

sacStack

- usage: sacStack [-E(t(0-9,-5(b),-3(o),-2(a))|vel)] [-N] [-Q] [-Rt1/t2] [-Sbaz/p] -Ooutput_file (sac_traces in the argument list or from the stdin)
  - -E: align with a time mark or with an apparent velocity (b)
  - -N: normalize (off)
  - -Q: square traces before stacking (off)
  - -R: time window t1 and t2
  - -S: set baz and user0 (p) in head
- Example:
  - sacStack –Et-3 –R0/20 –Ostack.sac wf*.sac

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- Data management and basic data processing tools
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Next Time

- Data management and basic data processing tools
- Systematic and random errors
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- Array analysis