Some aspects of seismic tomography

Peter Shearer
IGPP/SIO/U.C. San Diego

September 7, 2009

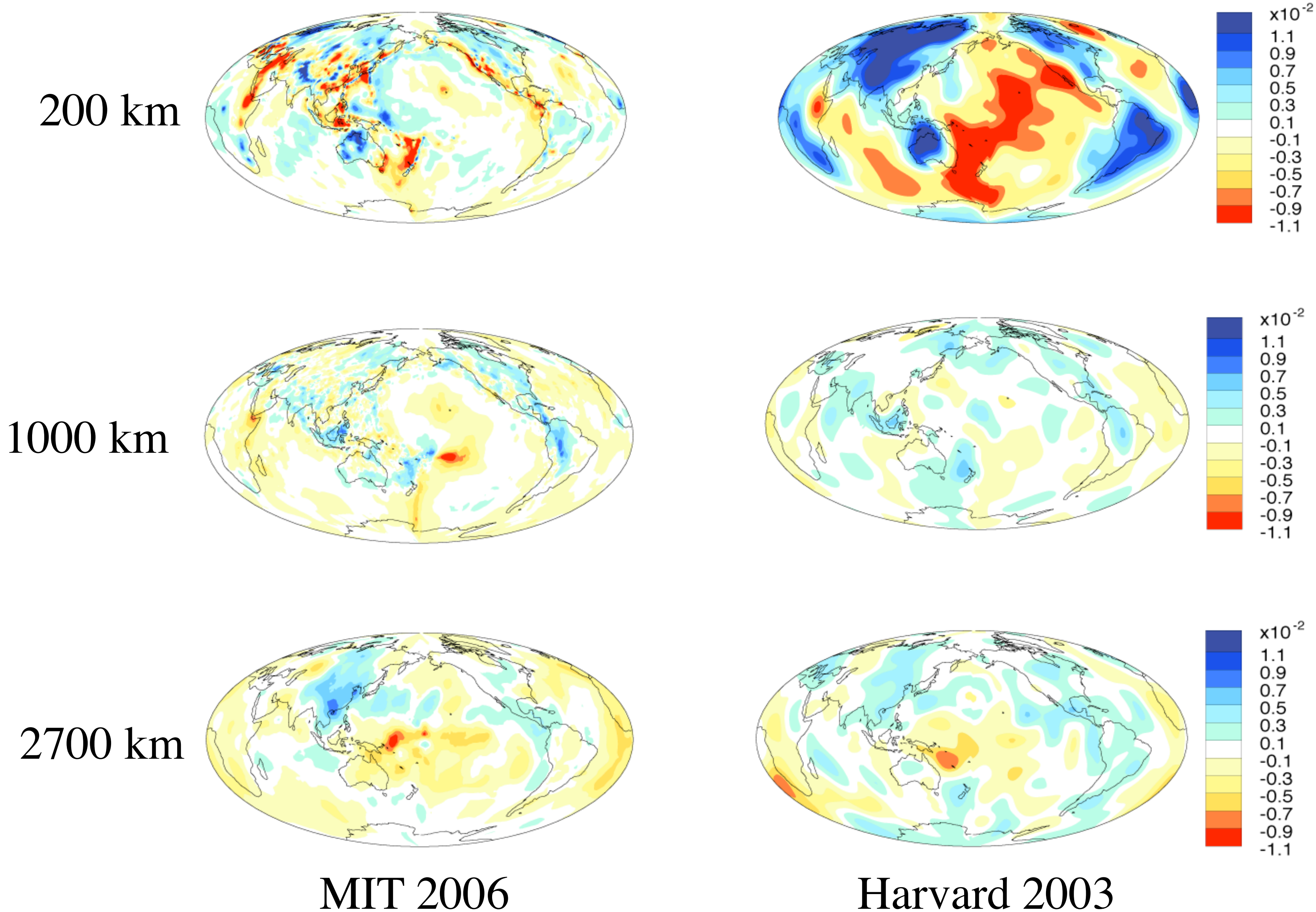
Earthquake Research Institute

UCSD

EARTHQUAKE RESEARCH INSTITUTE
VRC
Volcano Research Center
UNIVERSITY OF TOKYO

Part 1: Global Tomography

P velocity perturbations



Tomography according to Guy:

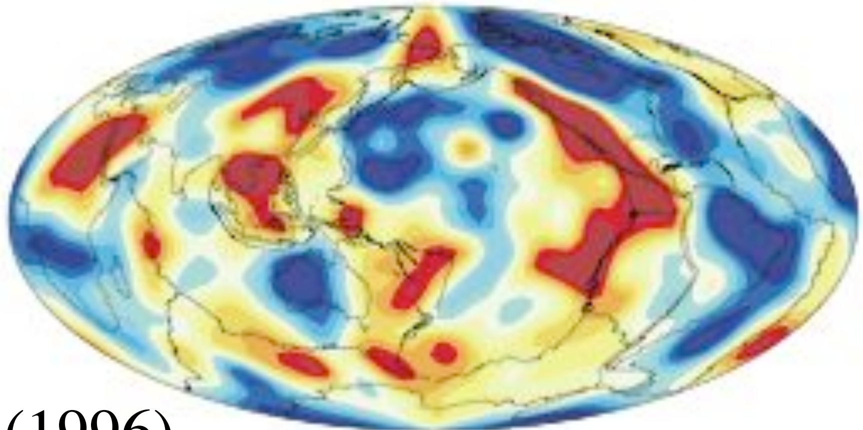
- Success depends on using all different data types: body waves, surface waves, modes.

- Data coverage is most important, theoretical and inversion considerations can play a role but are less important

- You have to do it right! Worry about source locations, crust corrections, etc.

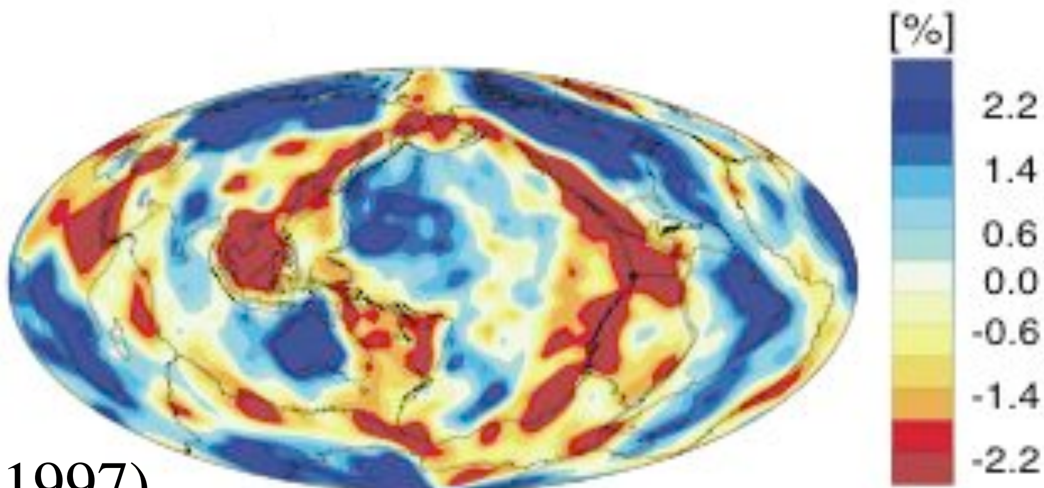
Guy Masters

Surface-wave observations are converging among different groups



Rayleigh wave phase velocity perturbations near 12 mHz (~80 s)

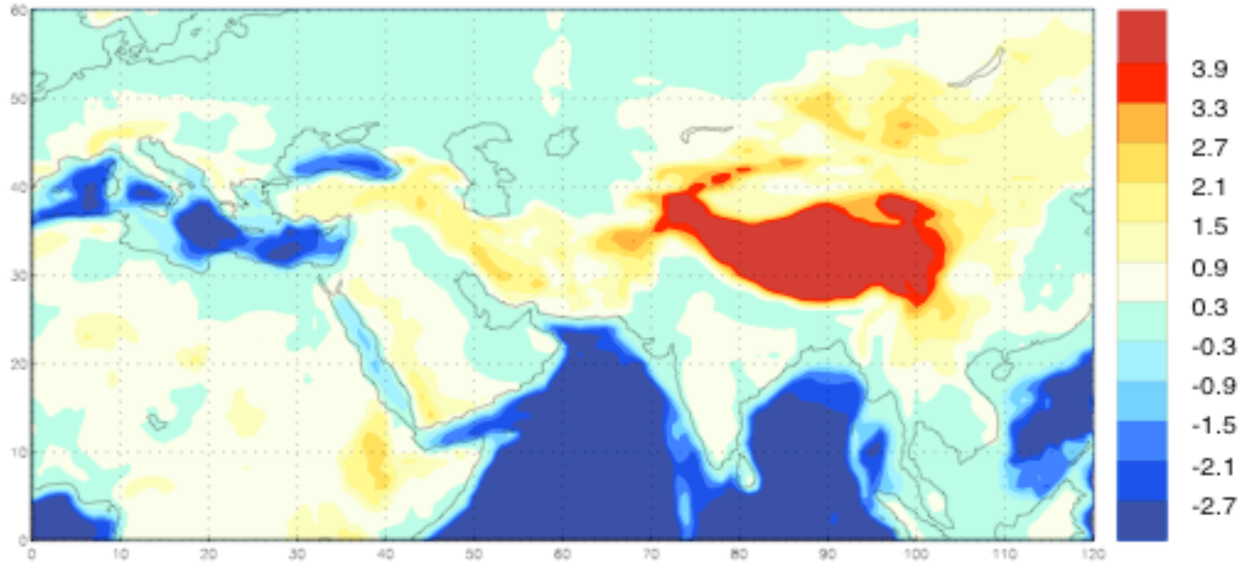
Laske & Masters (1996)



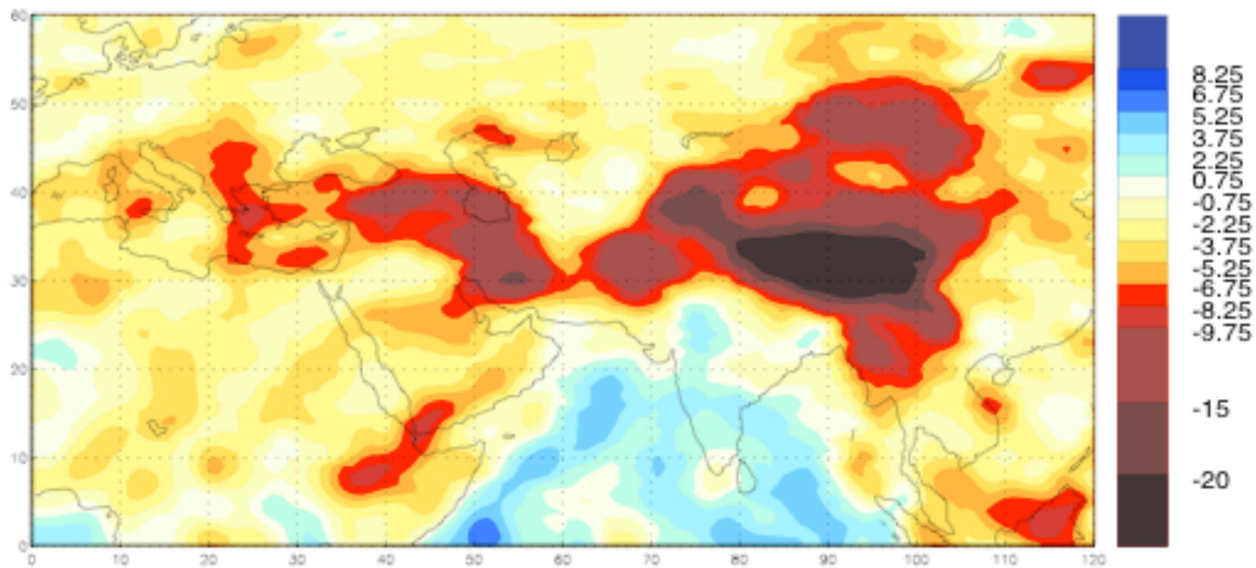
Ekström et al. (1997)

But crustal corrections are very important

Topography

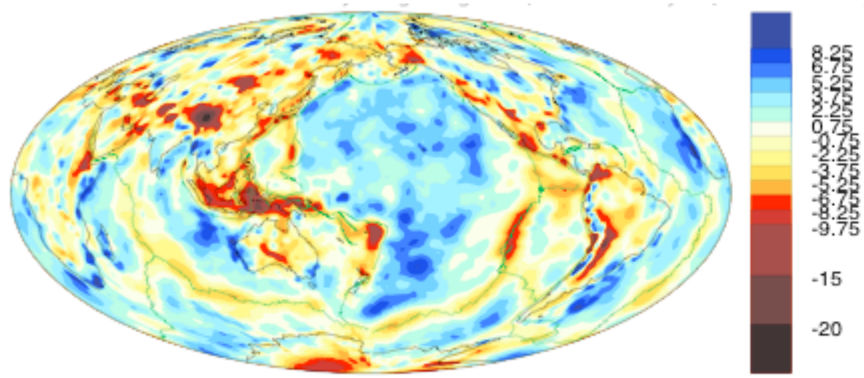


Group velocity

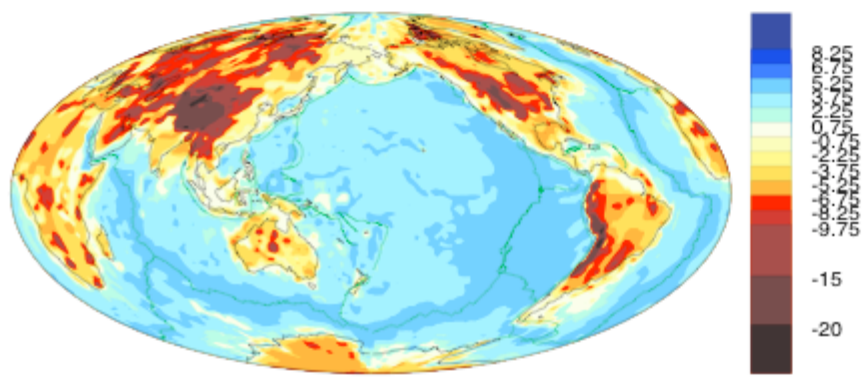


27.5 mHz group velocity

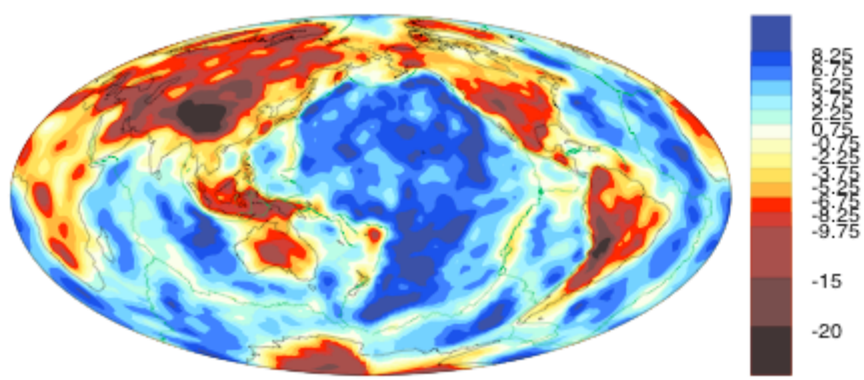
Crust-corrected



Crust2

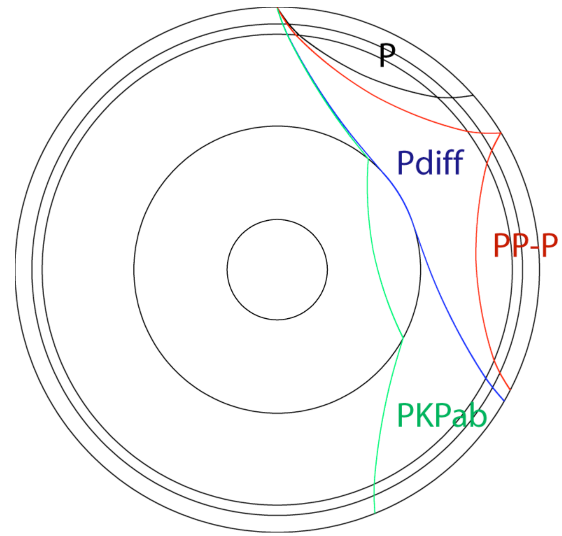


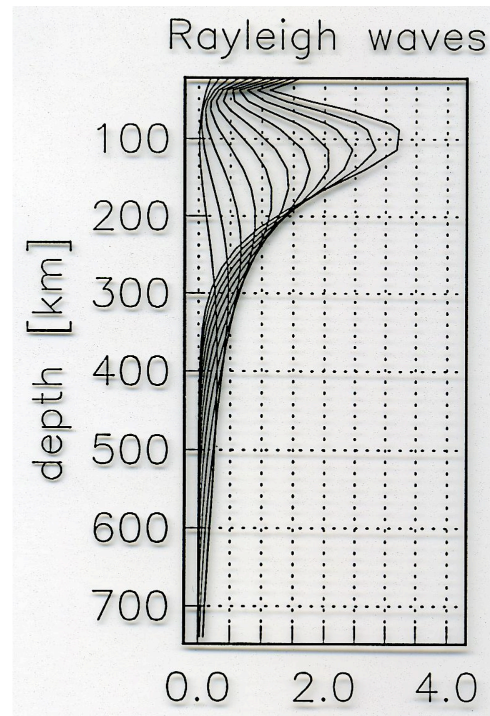
Observed



Some key facts…

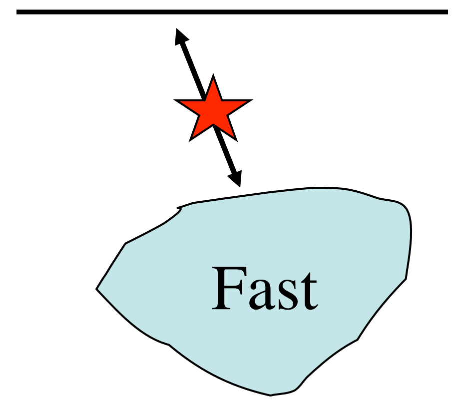
- Body waves have very limited vertical resolution in the upper mantle.
- Surface waves are needed to get upper mantle right.
- But surface waves are mainly sensitive to *S* waves.
- Thus, assumed *S*-to-*P* scaling for upper mantle is a common modeling assumption (but may not be true for real data!).
- Surface wave vertical resolution is better than teleseismic body waves but still not great.
- Crustal corrections are very important!

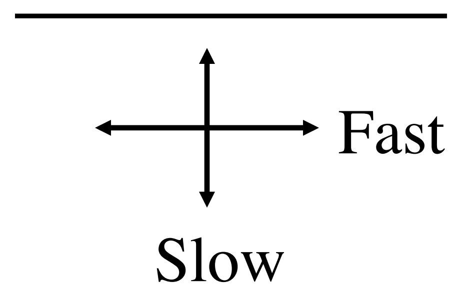




More key facts…

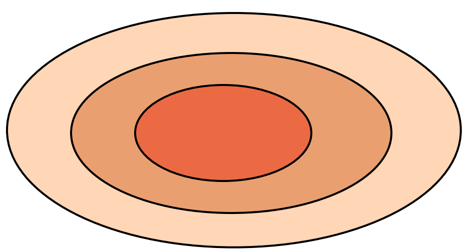
- Event relocation is important for *P* tomography.
- Simultaneous location/structure inversions are only practical for small problems.
- But iterative velocity and location methods work well and converge rapidly.
- 3-D ray tracing is not generally used in global tomography (unlike crustal tomo).
- Transverse isotropy is needed in upper mantle to fit both Love and Rayleigh waves.
- Including azimuthal anisotropy is challenging because of the number of free parameters.



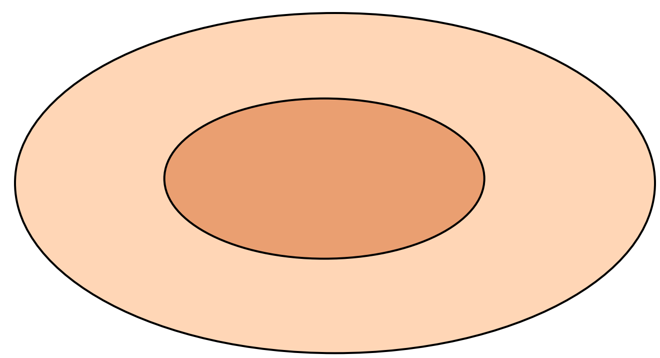


More key facts…

- Relative weighting among different data sets and inversion regularization (smoothing) have a strong effect on the final model, in particular in the amplitude of the anomalies.
- This can account for many of the differences in the appearance of the models, even those based on similar data sets.



Lightly smoothed

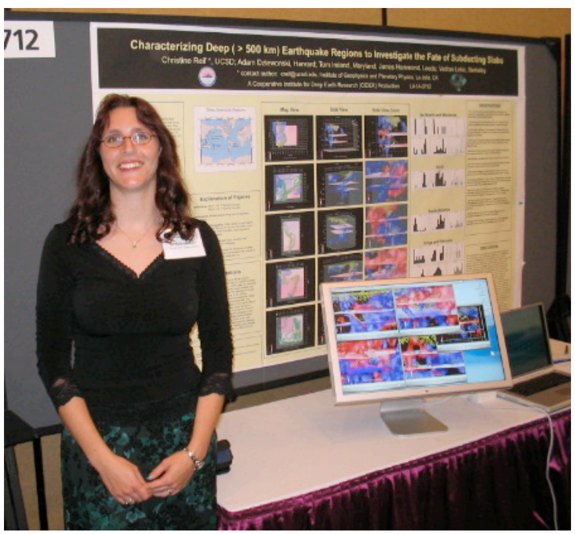


Heavily smoothed

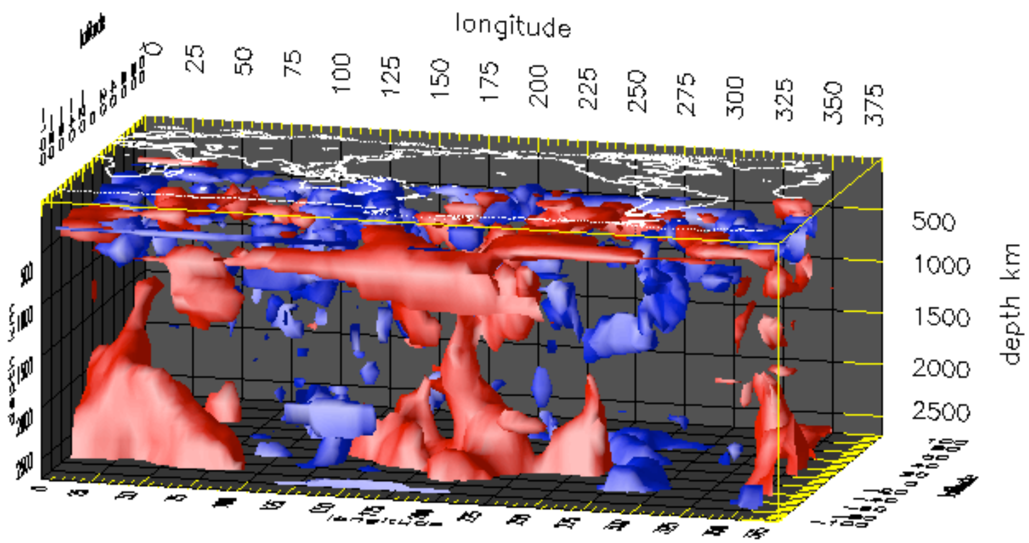
Shear and compressional velocity models of the mantle from cluster analysis of long-period waveforms

C. Houser, G. Masters, P. Shearer and G. Laske

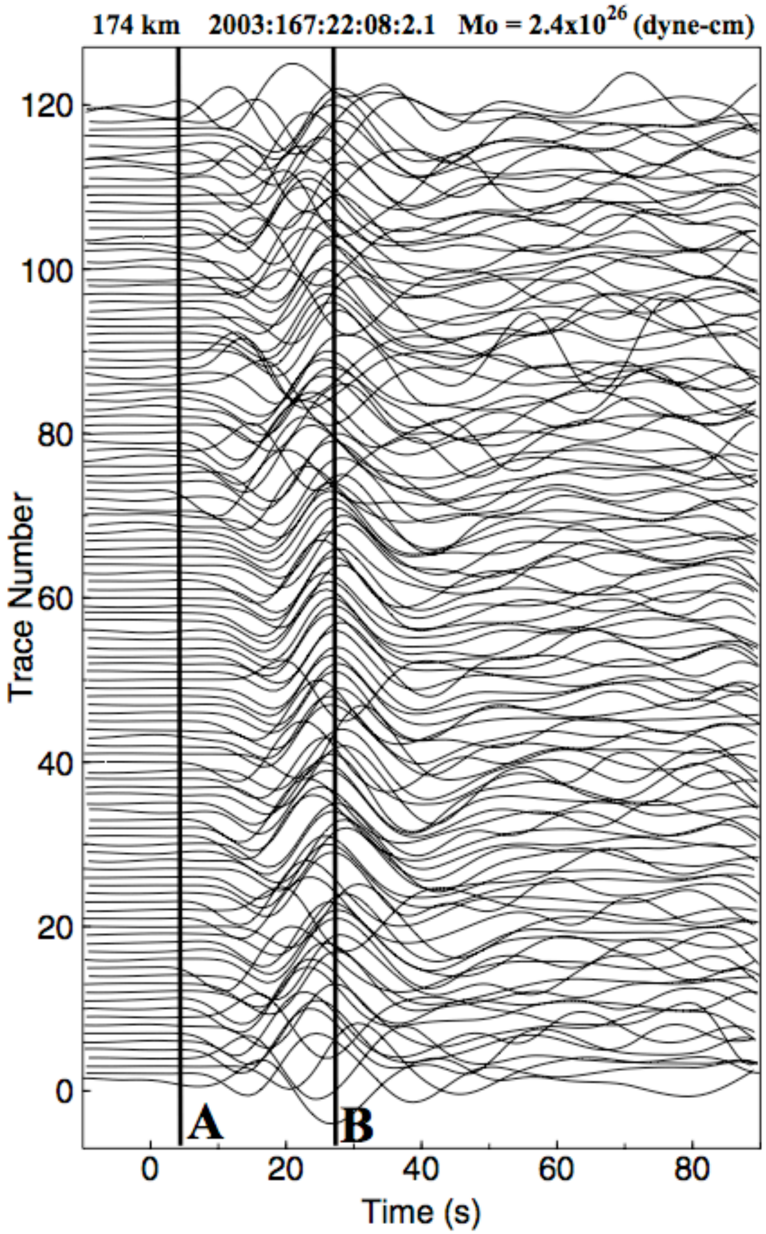
Geophys. J. Int. **174**, doi: 10.1111/j.1365-246X.2008.03763.x, 2008



Christine Houser

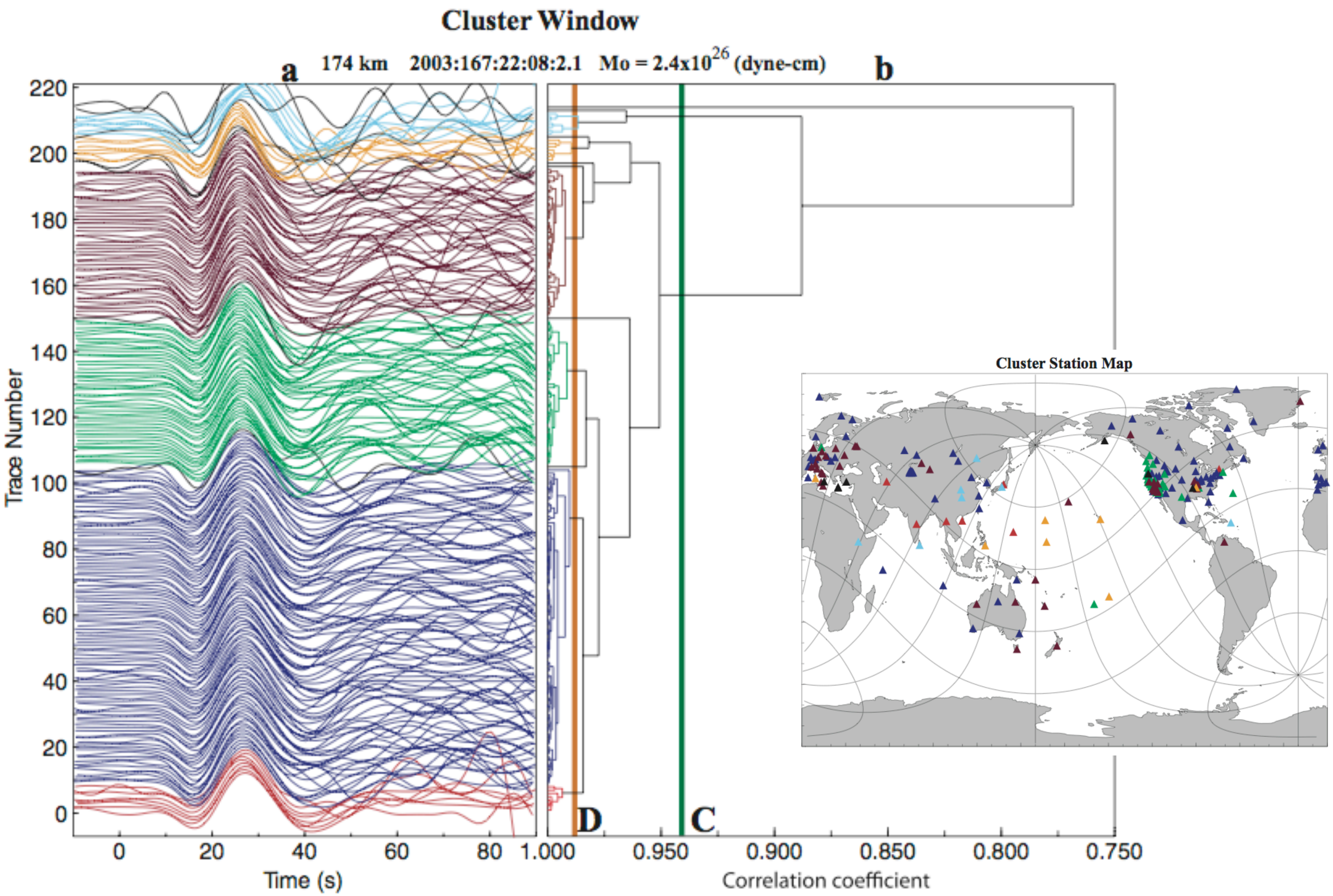


Long-period S-wave arrivals



- Aligned on predicted (1-D) travel time
- Misaligned waveforms are due to 3-D structure
- Relative arrival times can be measured using waveform cross-correlation, but precise results depend on waveform similarity

Cluster analysis method



Works for Hilbert-transformed phases

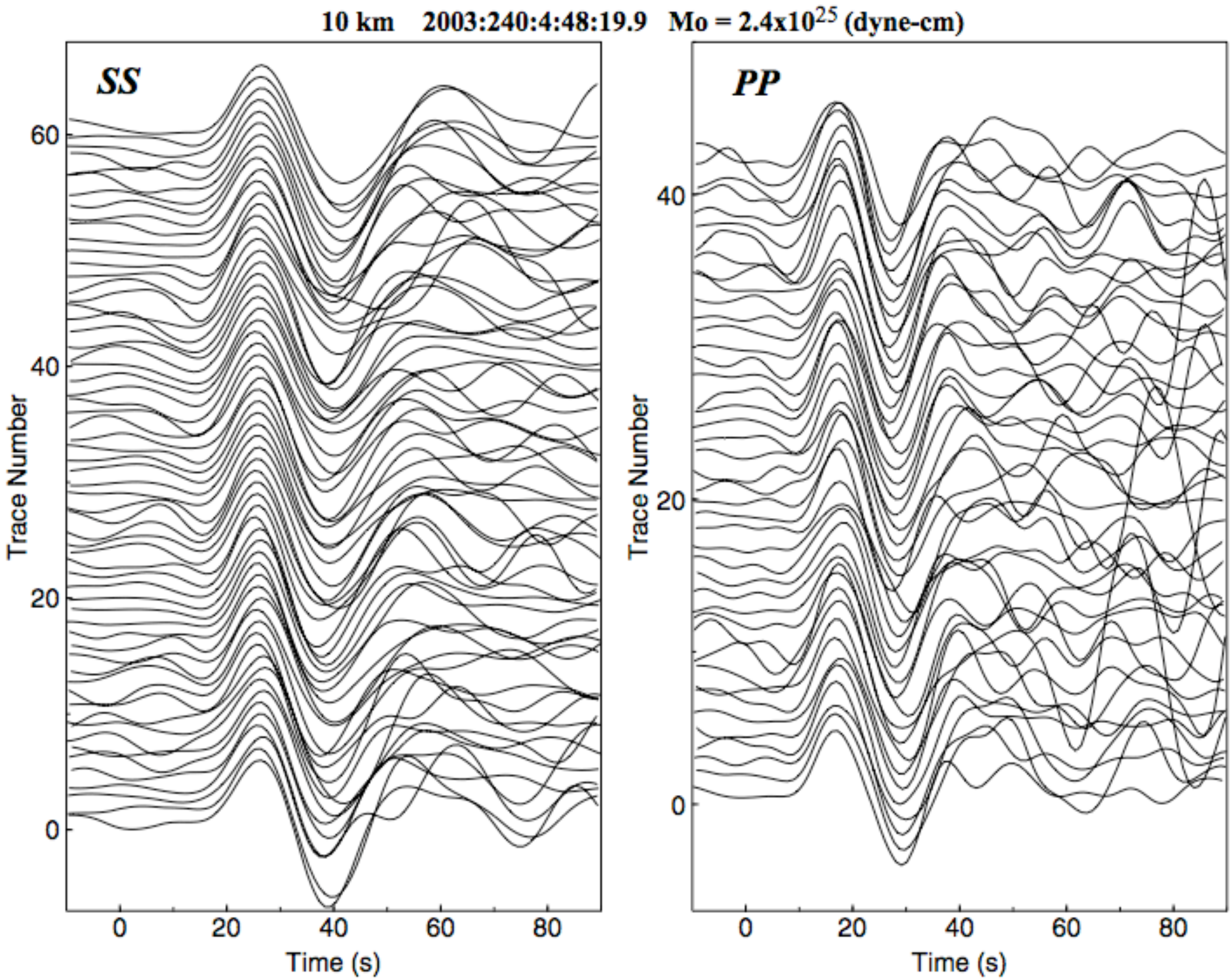
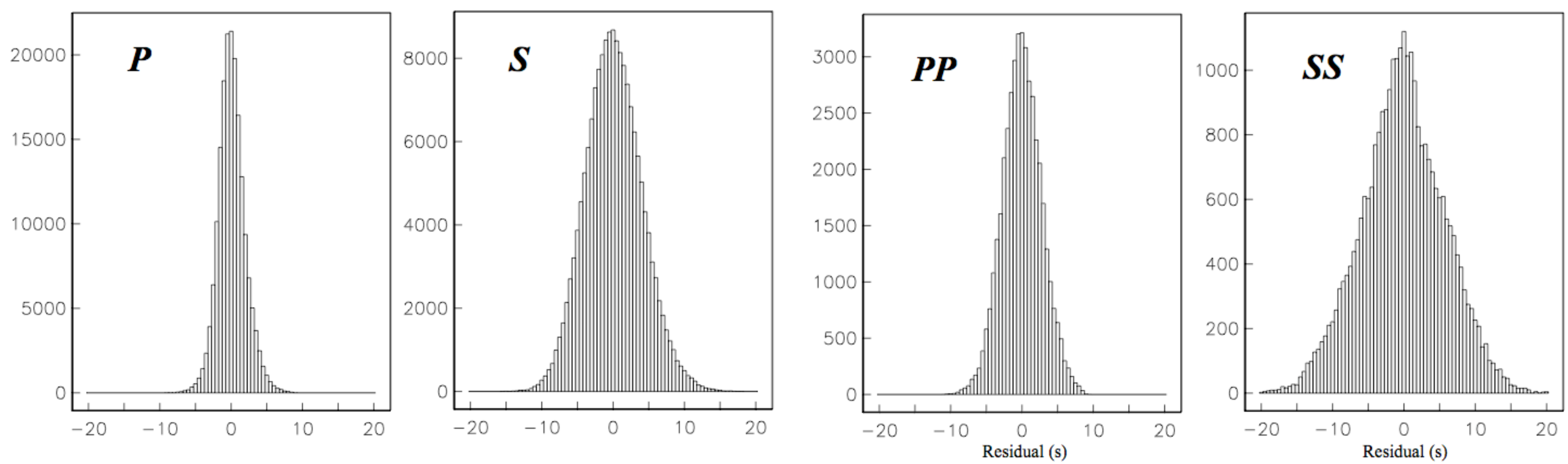
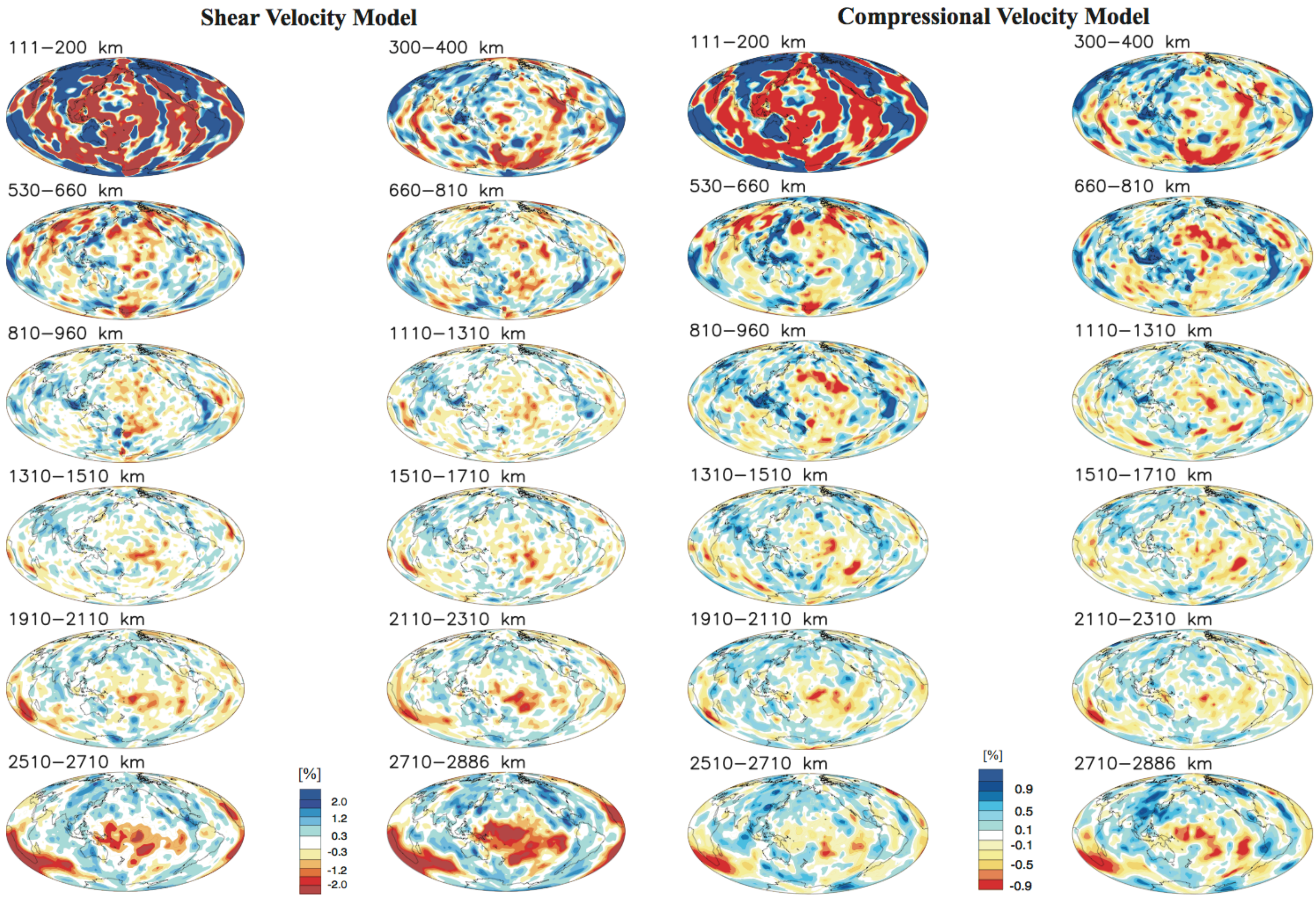


Table 1. Data sets.

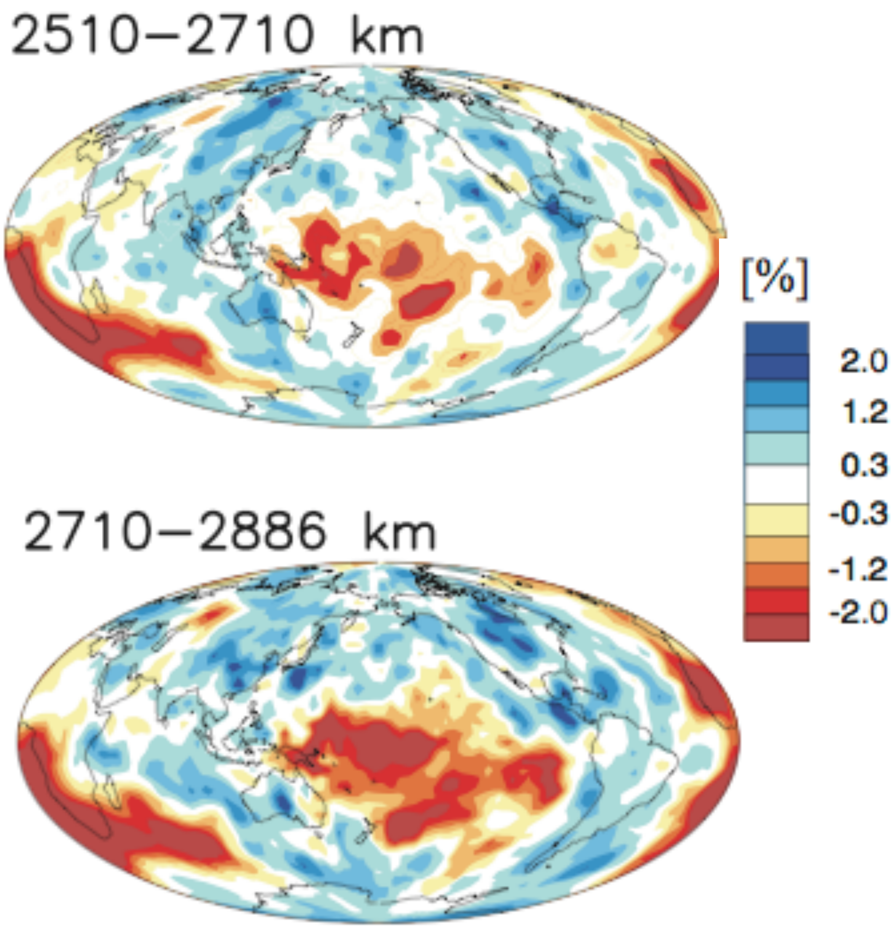
Data type	Start	End	Number of data
S	1976	2005	169 832
P	1976	2005	182 724
SS	1995	2005	28 194
PP	1995	2005	42 710
SS–S	1976	1999	27 560
PP–P	1976	1999	22 595
ScS–S	1976	2005	26 840
Love waves	1989	1999	14 000
Rayleigh waves	1989	1999	42 000



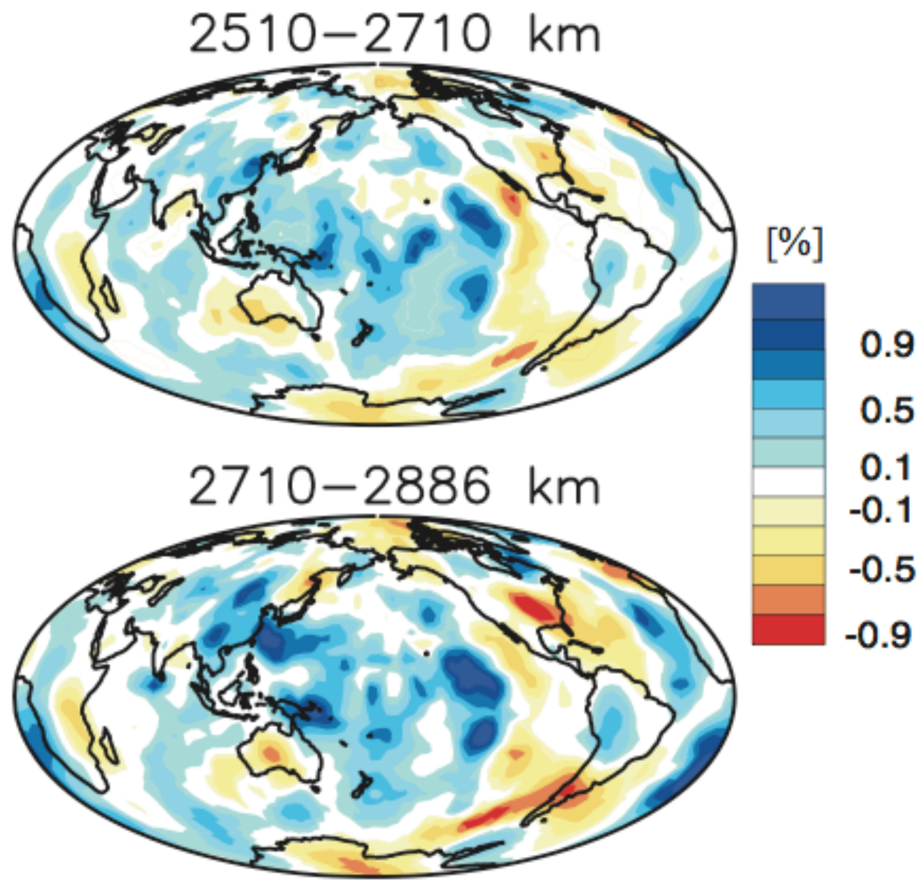

Shear Velocity Model
111–200 km
300–400 km
530–660 km
660–810 km
810–960 km
1110–1310 km
1310–1510 km
1510–1710 km
1910–2110 km
2110–2310 km
2510–2710 km
2710–2886 km
[%]
2.0
1.2
0.3
-0.3
-1.2
-2.0
Compressional Velocity Model
111–200 km
300–400 km
530–660 km
660–810 km
810–960 km
1110–1310 km
1310–1510 km
1510–1710 km
1910–2110 km
2110–2310 km
2510–2710 km
2710–2886 km
[%]
0.9
0.5
0.1
-0.1
-0.5
-0.9

Lowermost mantle anomalies

Shear velocity perturbations



Bulk sound speed perturbations



Anti-correlation indicates compositional variations

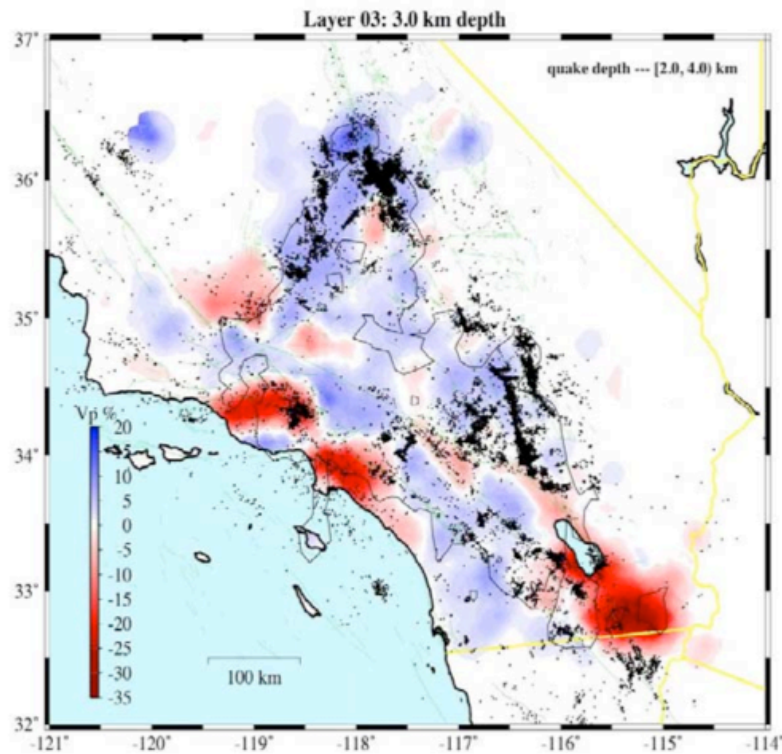
Part 2: Southern California results

A three-dimensional crustal seismic velocity model for southern California from a composite event method

Guoqing Lin, Peter M. Shearer, Egill Hauksson, and Clifford H. Thurber

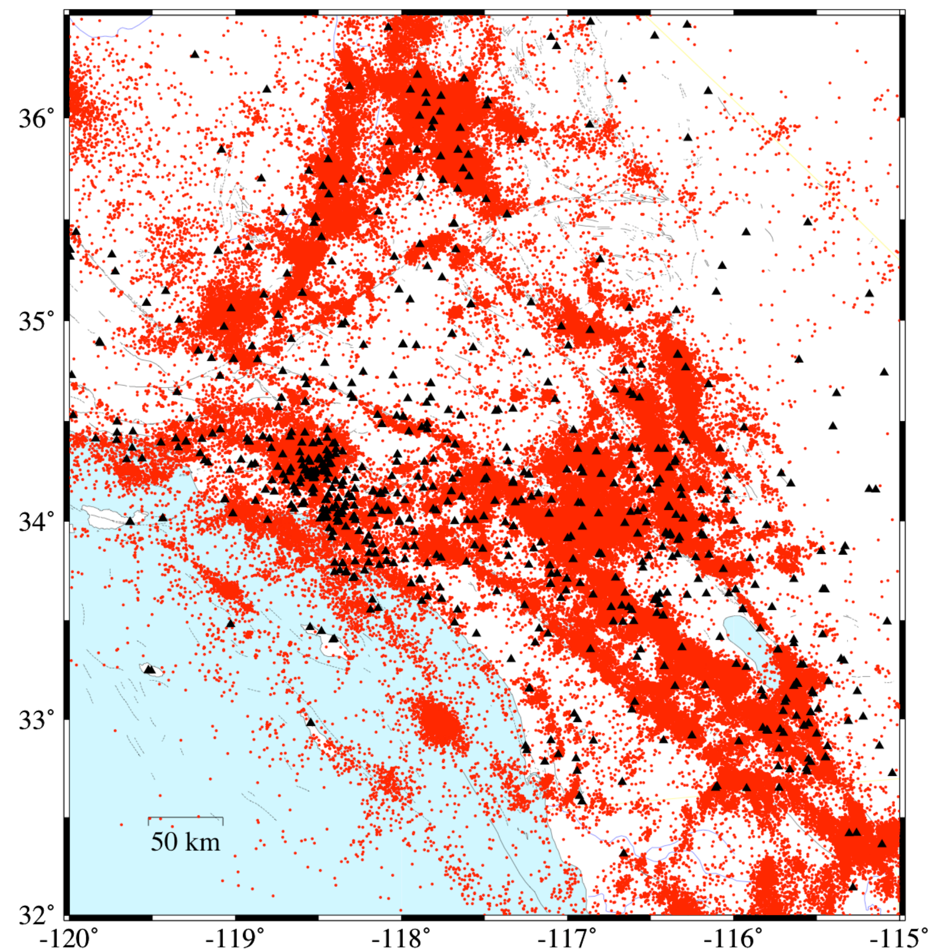
J. Geophys. Res. **112**, doi: 10.1029/2007JB004977, 2007

Guoqing Lin

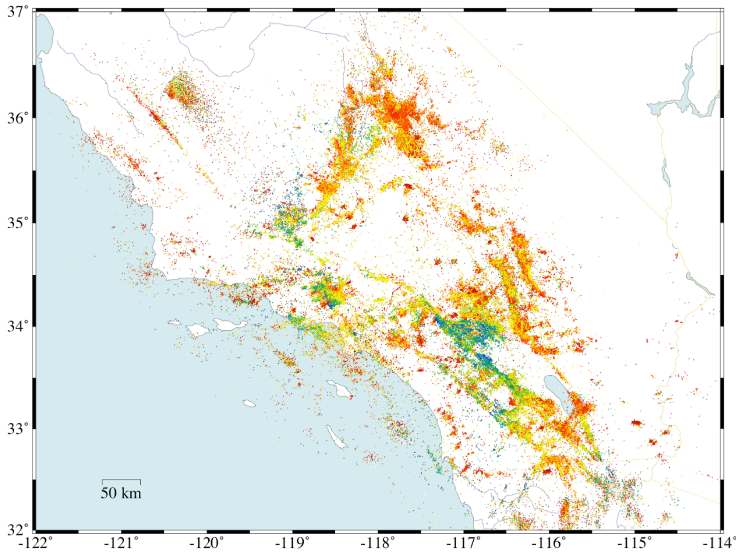


Data Sets

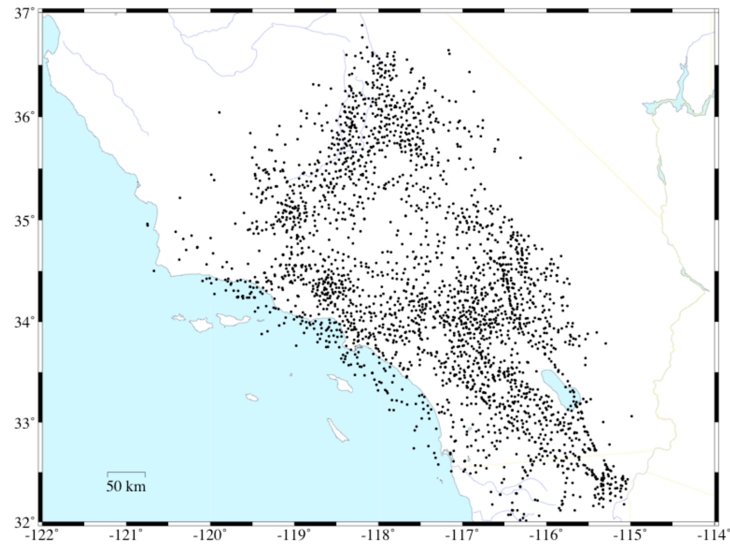
- Study Period: from 1981 to 2005
- 452,943 events
- *P*- and *S*- phase arrival times
- Waveform data
- 783 SCSN stations



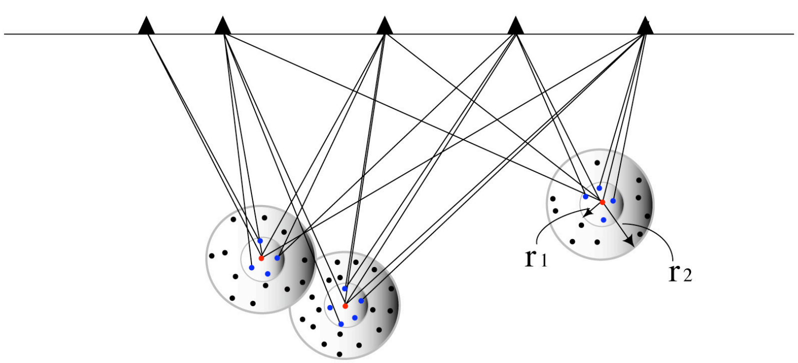
Composite Event Method



437,000 events
7.75 m picks
~20 picks/event



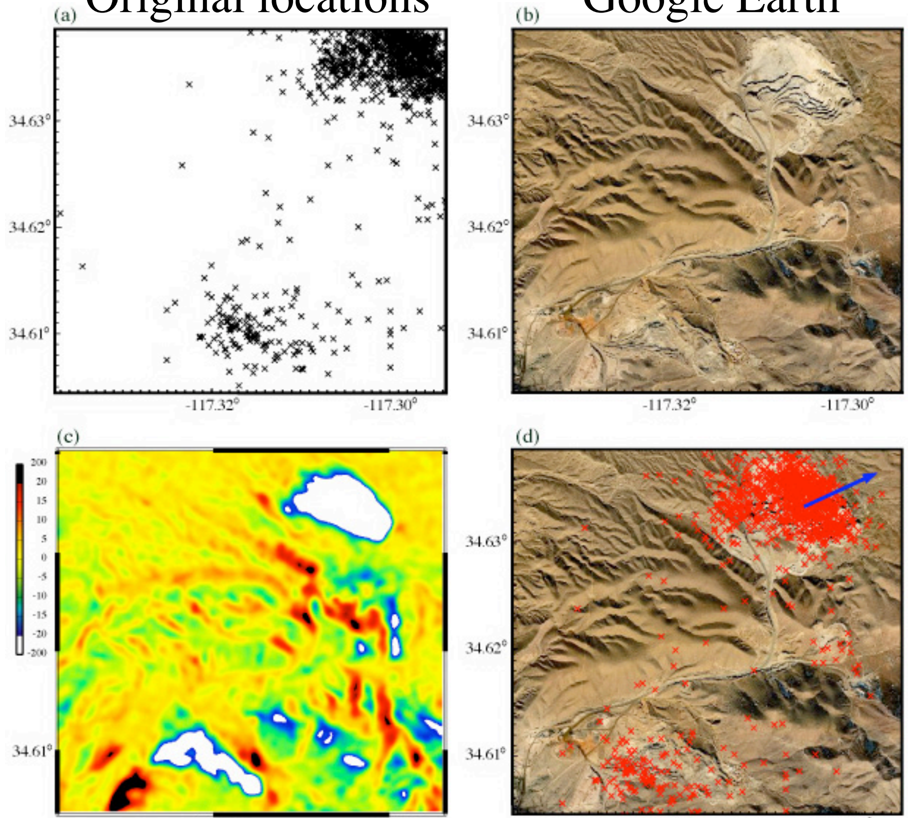
2,597 composite events (0.6%)
from 2.9 m original picks (38%)
~63 composite picks/event



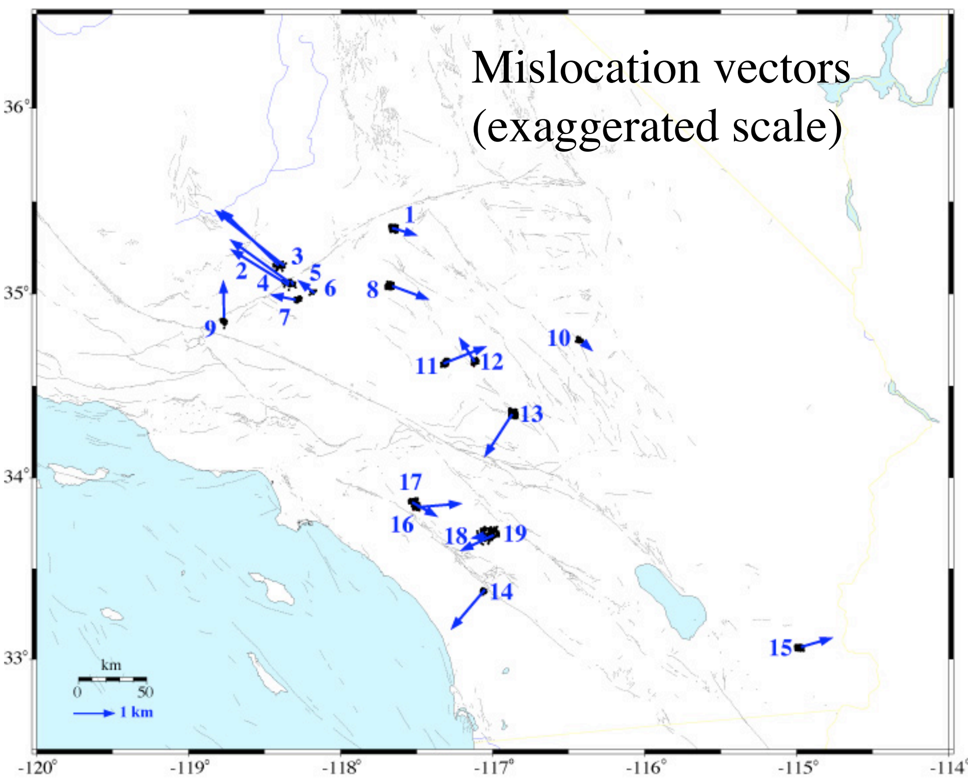
Method works by combining picks from events within r_1 = 2 km of target events, which are separated by at least r_2 = 6 km.

Use satellite data to fix quarry explosion locations

Original locations   Google Earth

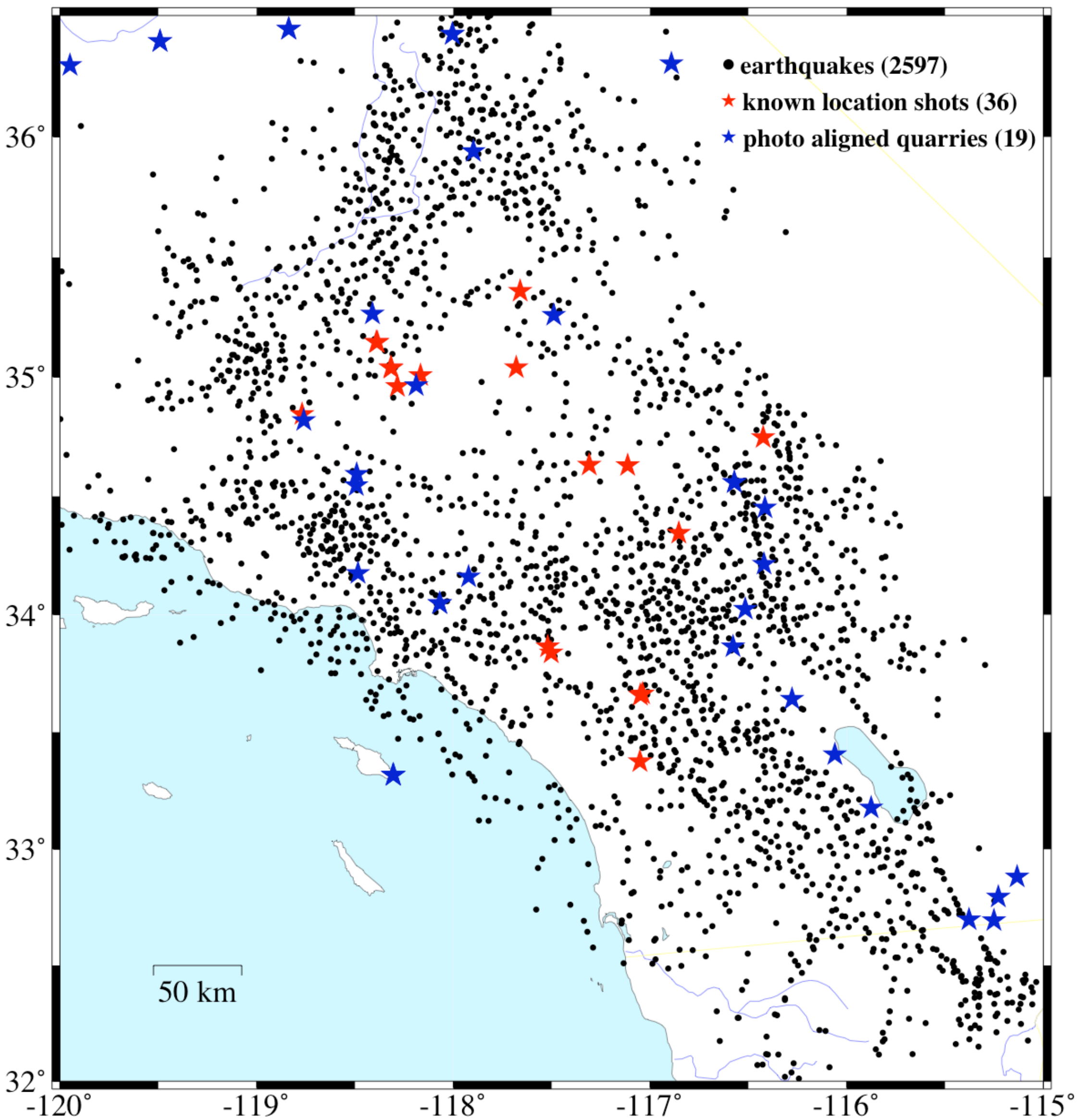


InSAR difference   Revised locations



(Lin *et al.*, 2006)

Data Sets



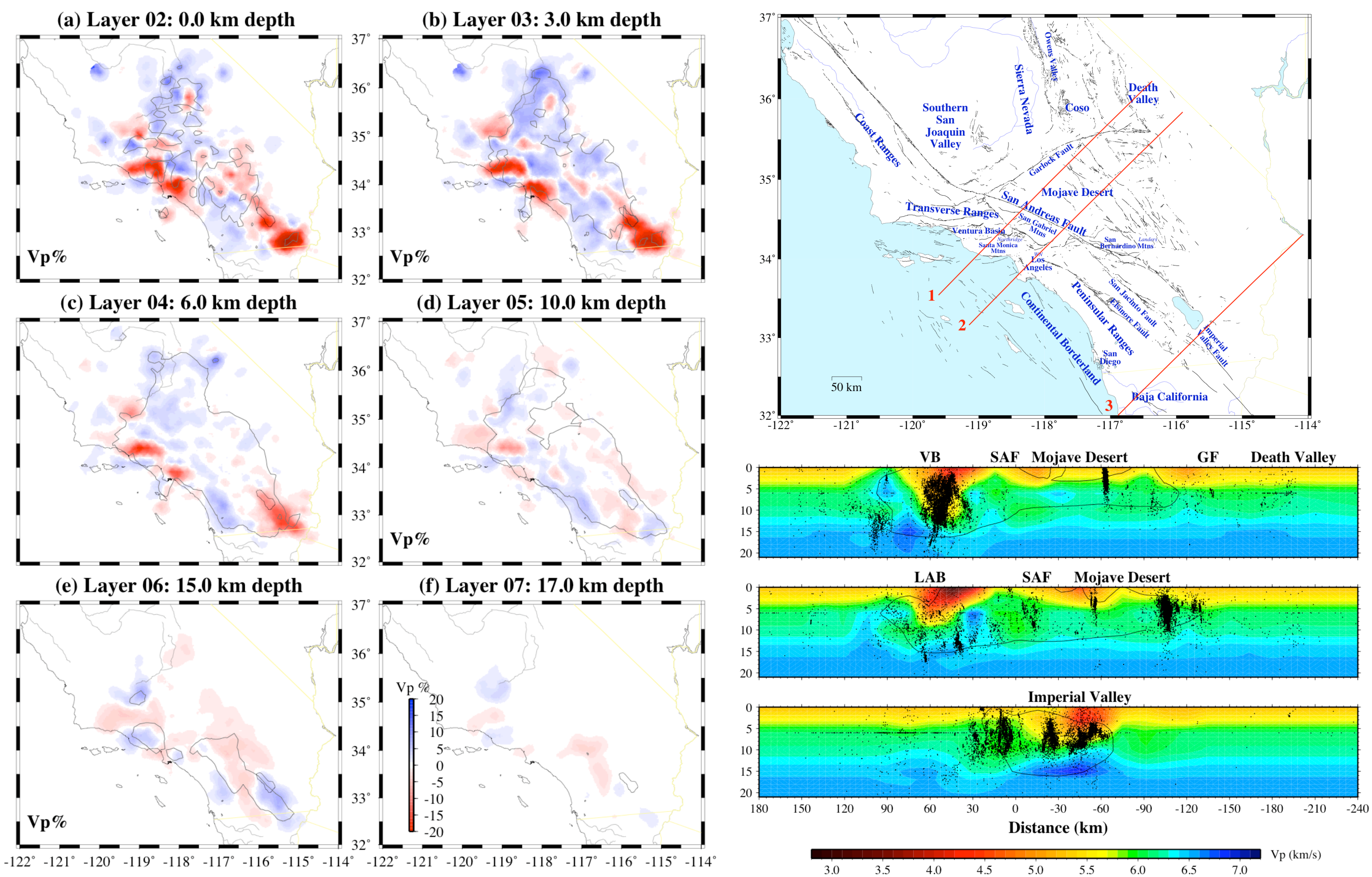
3D velocity inversion:

SIMULPS algorithm

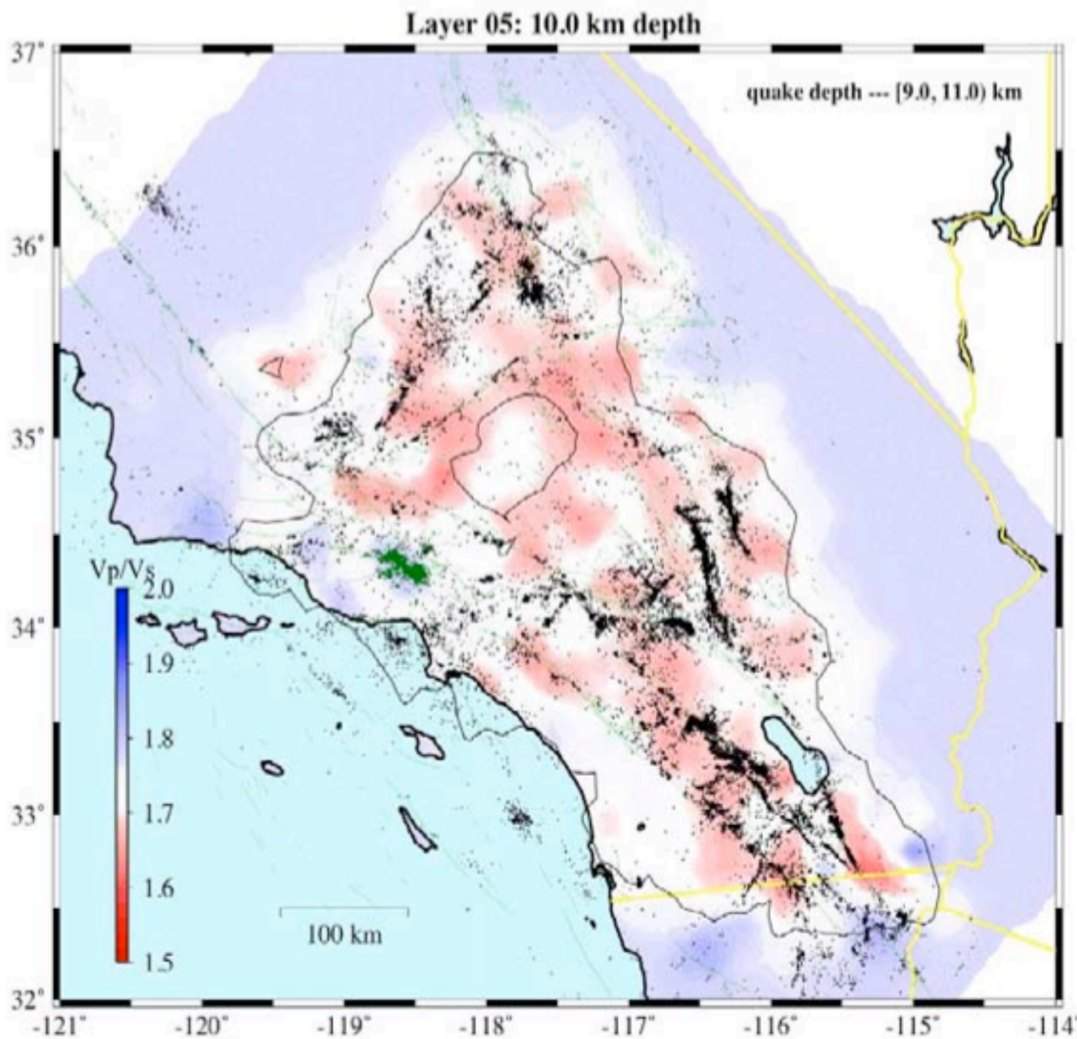
by *Thurber* [1983, 1993] and
Eberhart-Phillips [1990]
(documentation provided by *Evans et al*., 1994)

- full matrix inversion method
- parameter separation
- damped-least-squares
- uses quakes + controlled sources
- outputs quake locations + Vp + Vp/Vs
  (+ station corrections)
- resolution matrix

The Final Vp Model

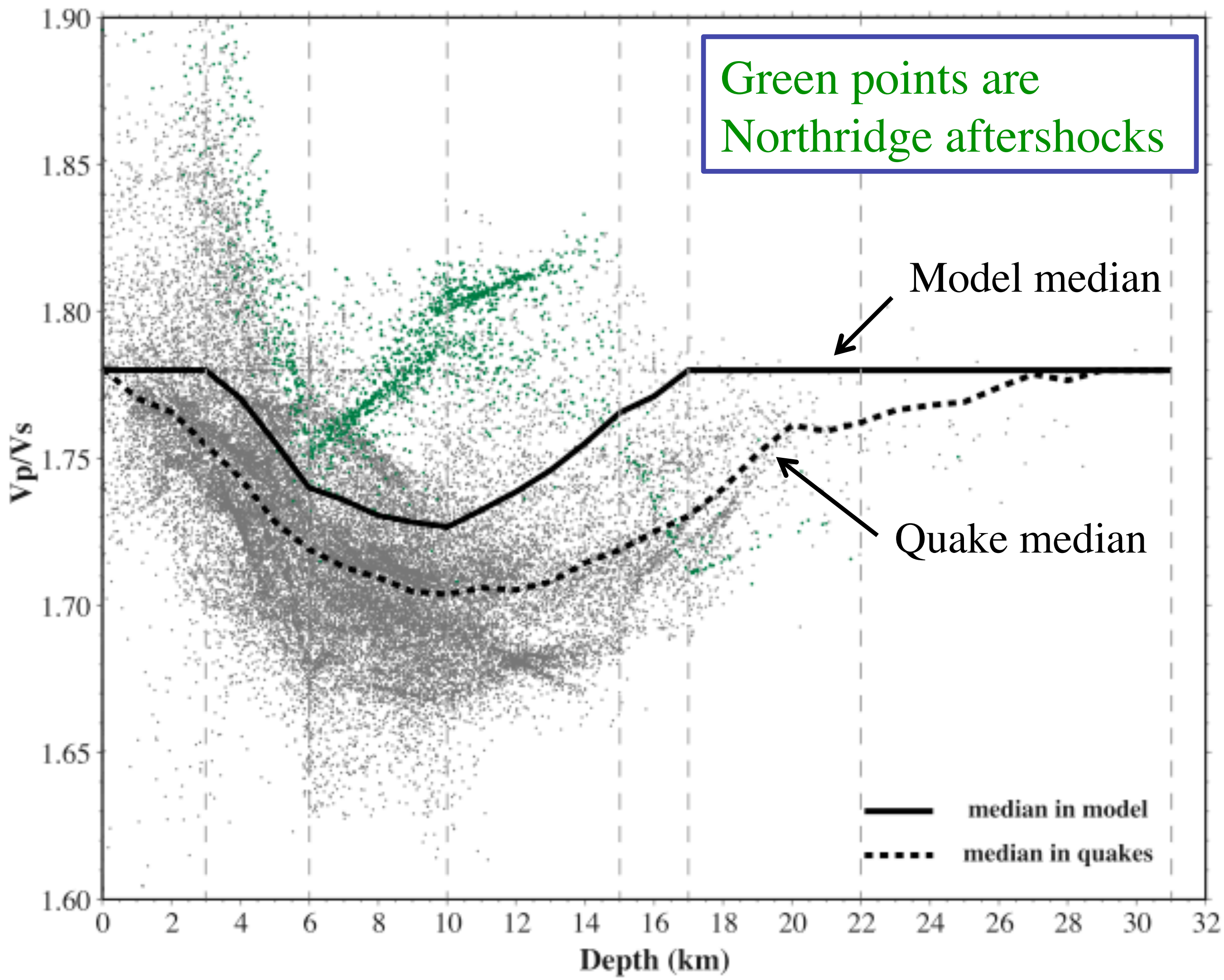


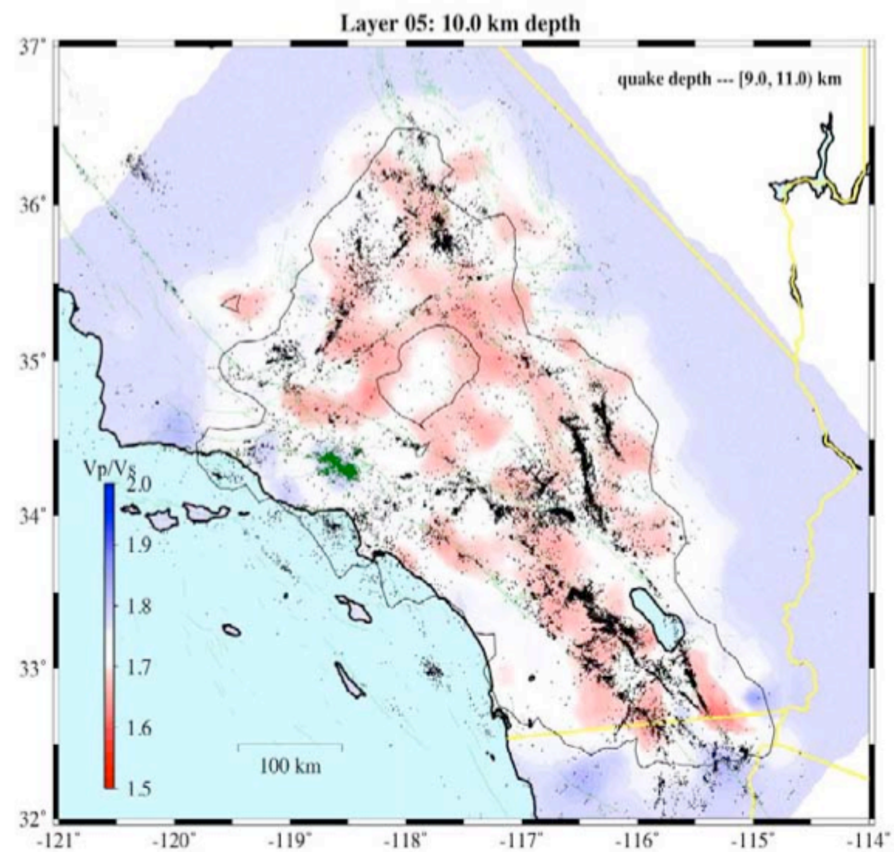
Earthquakes tend to occur in regions of low Vp/Vs ratio

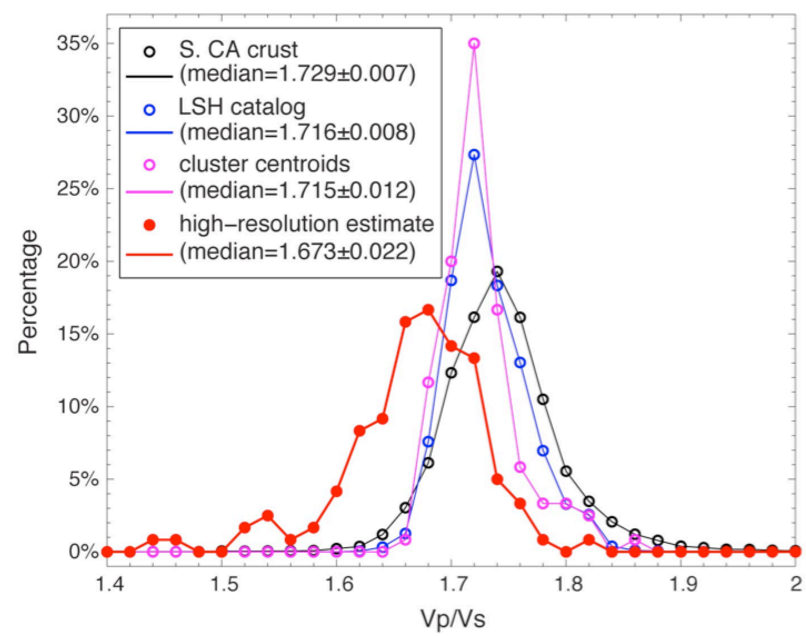


Green points are Northridge aftershocks

Earthquakes tend to occur in regions of low Vp/Vs ratio




Layer 05: 10.0 km depth
quake depth --- [9.0, 11.0) km
Vp/Vs
2.0
1.9
1.8
1.7
1.6
1.5
100 km
37°
36°
35°
34°
33°
32°
-121°
-120°
-119°
-118°
-117°
-116°
-115°
-114°

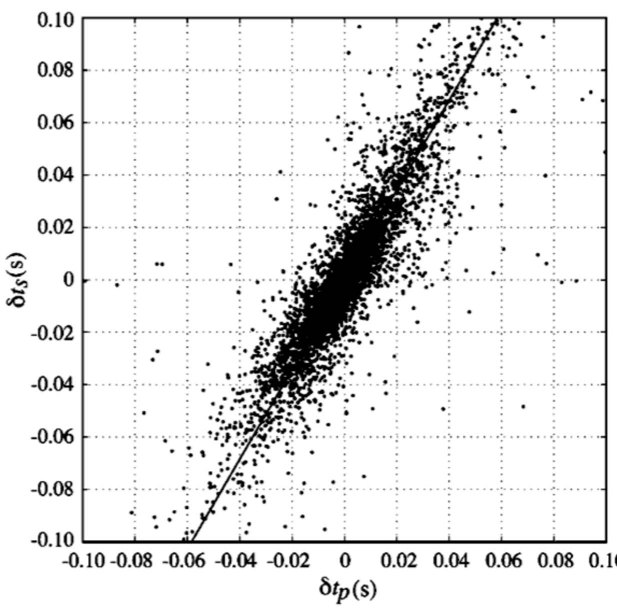

S. CA crust
(median=1.729±0.007)
LSH catalog
(median=1.716±0.008)
cluster centroids
(median=1.715±0.012)
high−resolution estimate
(median=1.673±0.022)
Percentage
35%
30%
25%
20%
15%
10%
5%
0%
1.4
1.5
1.6
1.7
1.8
1.9
2
Vp/Vs

Estimating Local Vp /Vs Ratios within Similar Earthquake Clusters

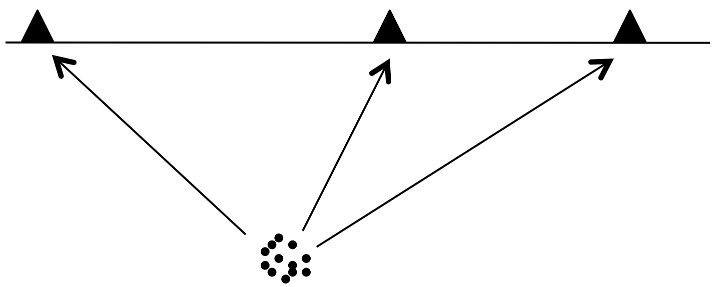
Guoqing Lin and Peter Shearer

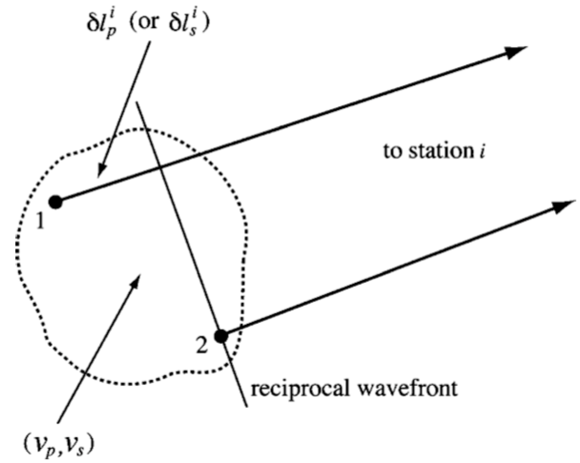
Bull. Seismol. Soc. Am. **97**, doi: 10.1785/0120060115, 2007

Guoqing Lin

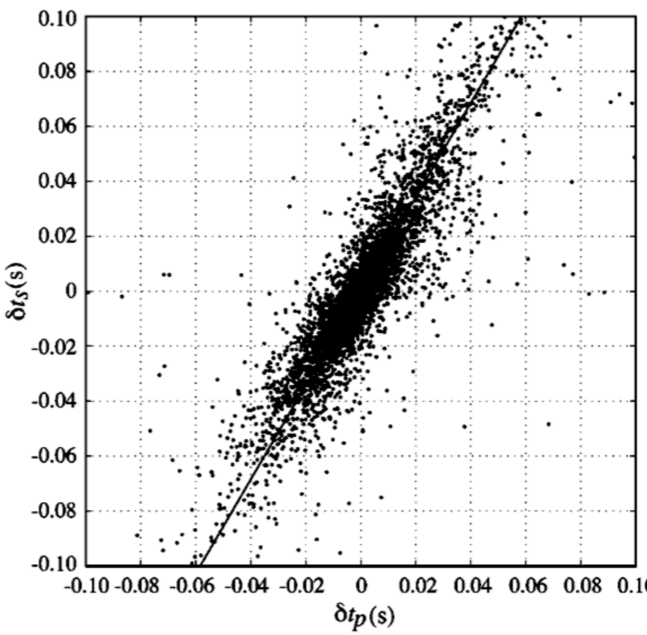


Obtaining in situ *Vp*/*Vs* estimates



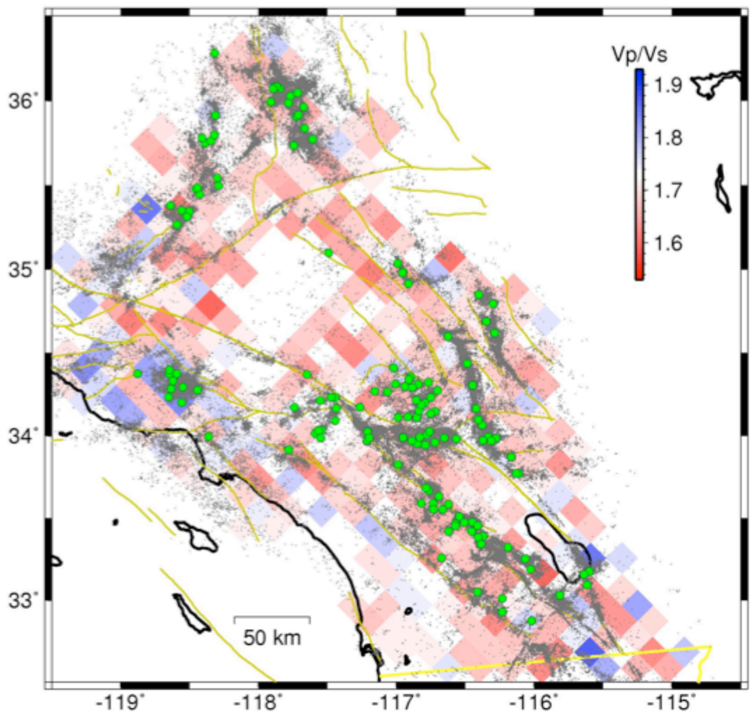


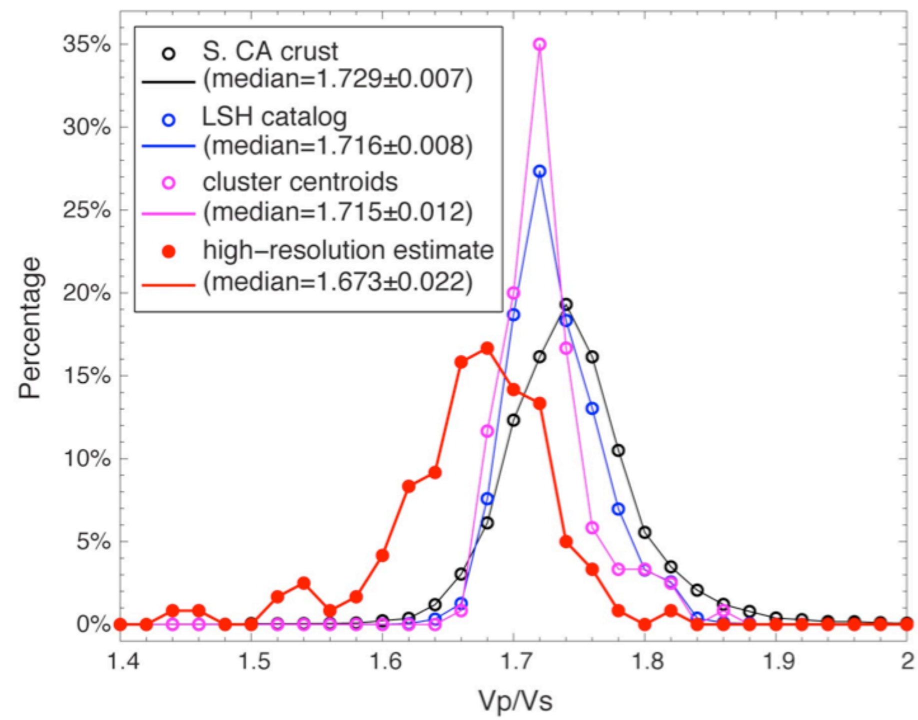
- Obtain precise differential times using waveform cross-correlation for pairs of events within similar event clusters



- Plot of δt_s vs. δt_p will have slope that gives local *Vp*/*Vs* ratio within cluster

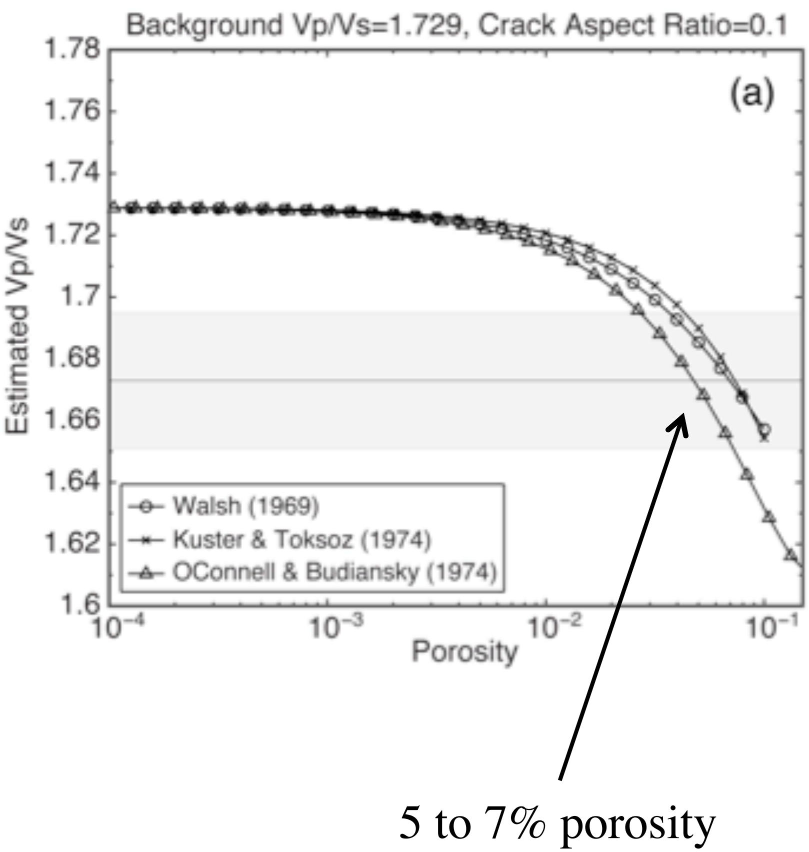
High-resolution *Vp/Vs* estimates in event clusters





Median Vp/Vs of clusters is 1.67 compared to 1.73 for background

Implies fluids in earthquake source regions



- No likely rock type in southern California crust has such low *Vp*/*Vs*
- Observations require fluid filled cracks of thick aspect ratio (e.g., 0.1)
- Roughly consistent with analysis of Nakajima et al. (2001), who used water-filled cracks to model a ~2% drop in *Vp*/*Vs* beneath volcanoes in northeast Japan
- Low *Vp*/*Vs* ratios have been widely observed in volcanic and geothermal areas—our results suggest they may also be characteristic of active areas of microseismicity, at least in southern California