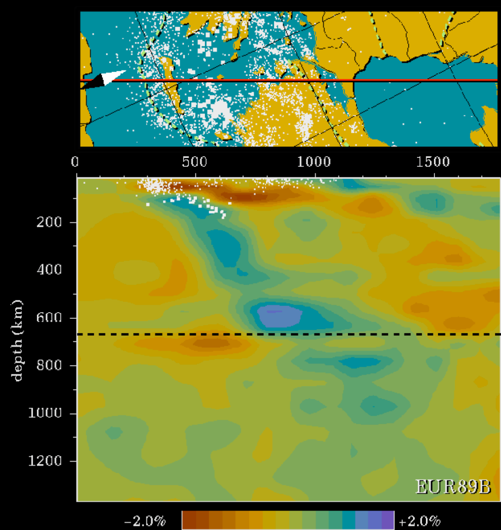
Seismic Tomography



mini course

Earthscope workshop

Monterey CA, 2007

Suzan van der Lee

Examples for

North America

Seismic Tomography

Mini-Course with contributions and inspiration from:

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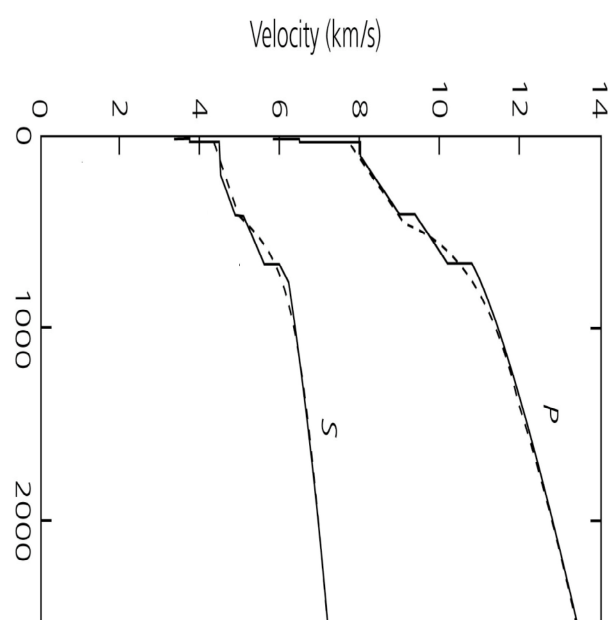
Heather Bedle,
MOMA array research team,
Berkeley Seismic Group

Seismic Tomography

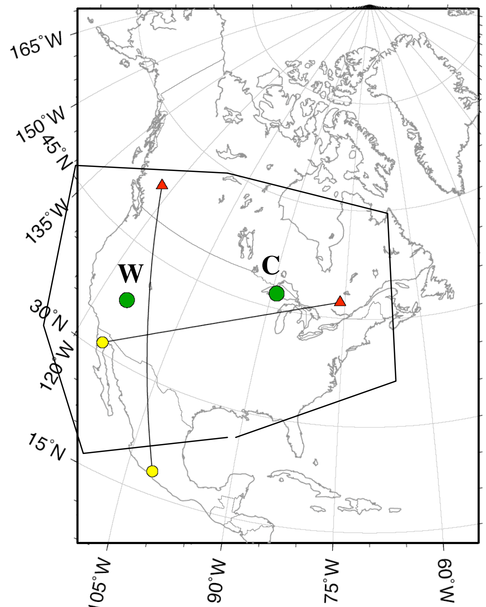
1. A Simple Exercise
2. Some Nitty Gritty
3. Resolution
4. Model Comparisons
5. Tips

Seismic Tomography: A Simple Exercise



Seismic tomography is about mapping lateral variations to these globally averaged seismic velocity profiles.

Seismic Tomography: A Simple Exercise



consider two regions:

1. **W**estern North America
2. **C**entral North America

consider two seismograms:

1. Gulf of CA to Quebec: waves on time
2. Cocos trench to BC: waves late

Seismic waves penetrate deeply in the Earth'smantle and crust. The horizontal propagation velocity of seismic waves depends on the S-wave velocity with depth, as well as on the frequency and tone of the waves. In this simplified minicourse we incorrectly assume that the horizontal propagation velocity equals the S-velocity of the uppermost mantle.

Seismic Tomography: A Simple Exercise

1. distance x = 3600 km dt = 0 s $x_W = x_C$ = 1800 km
2. distance x = 4000 km dt = 52 s $x_W = x$

Reference slowness s_0 = 0.222 s/km = 1/(4.5 km/s)

x = vt ➜ x/v = t ➜ xs = t, with s = 1/v

distance*slowness = time ➜
distance*slowness difference (ds) = time difference (dt)

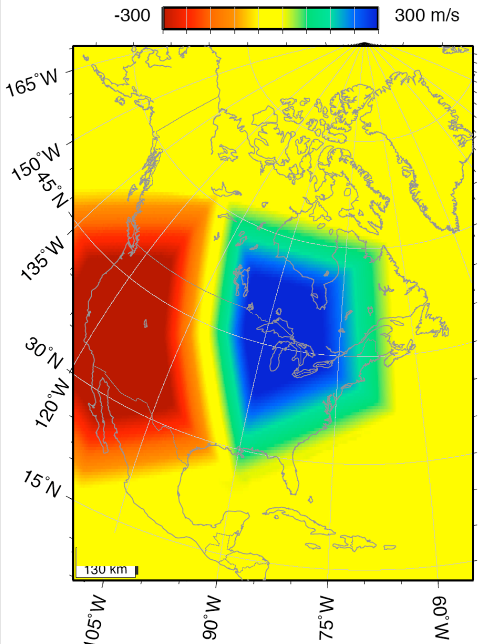
Two independent measurements (dt_1 and dt_2) yield two equations to be solved for two unknowns (ds_W and ds_C):

1. $1800ds_W + 1800ds_C = 0$
2. $4000ds_W = 52$

Solution: ds_W = s/km

ds_C = s/km

Seismic Tomography: A Simple Exercise



solve 2 equations for 2 unknowns:

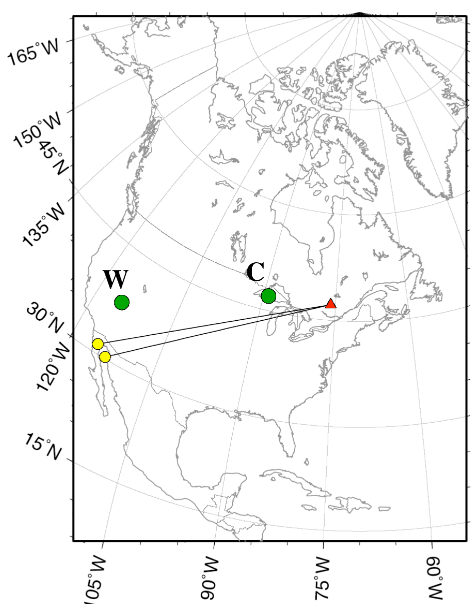
1. central North America “is” *fast*
2. western North America “is” *slow*

1. The stable Precambrian lithosphere of central North America is cool and rigid, allowing seismic waves to propagate efficiently and rapidly.

2. The mantle beneath Phanerozoic western North America is hot and weak, hindering the efficient propagation of seismic waves, slowing them down.

Our model has only two variables: the velocity difference for West and Central North America. Everywhere else we keep the velocity difference fixed to zero (yellow).

Seismic Tomography: Some Nitty Gritty



Same two regions (**W** and **C**)

consider 2 *different* seismograms:

1. Gulf of CA to Quebec: waves on time
2. Baja to Quebec: waves almost on time

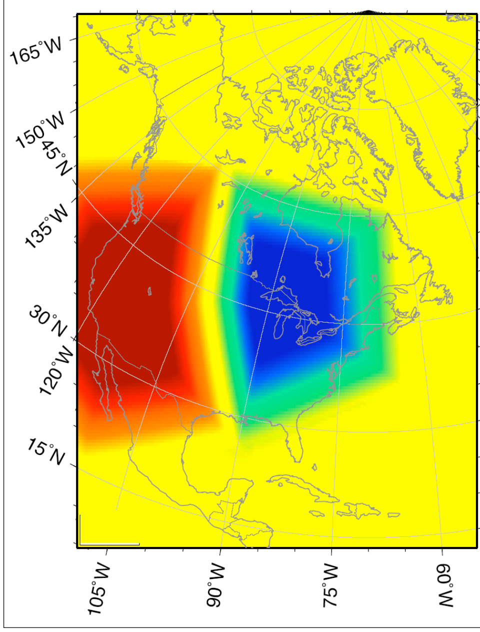
Again: two eqns & two unknwns:

1. $1800ds_W + 1800ds_C = 0$
2. $1900ds_W + 1800ds_C = 1.3$

Solution: $ds_W =$ s/km

$ds_C =$ s/km

Seismic Tomography: Some Nitty Gritty



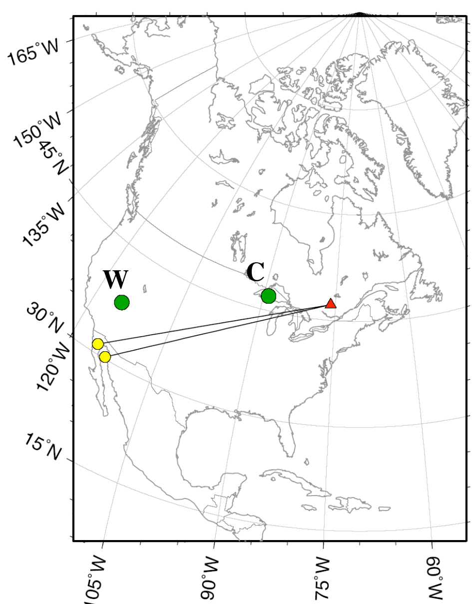
solve 2 equations for 2 unknowns:

1. central North America "is" *fast*
2. western North America "is" *slow*

But measurements have errors:

- station clock & instrument response
- measurement precision
- origin time, epicenter & depth
- precise travel path unknown

Seismic Tomography: Some Nitty Gritty



Same two regions (**W** and **C**)

Same two seismograms

Different time difference

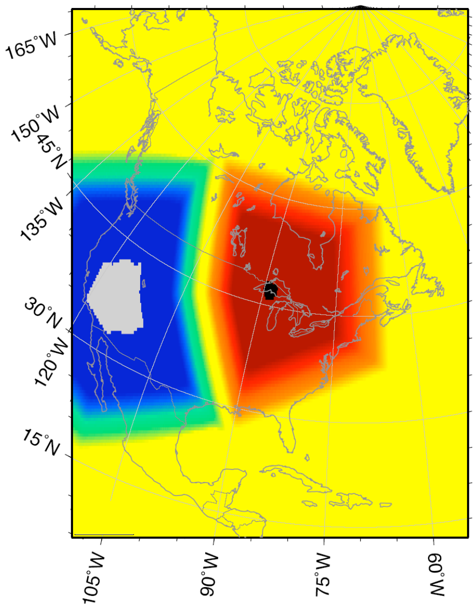
Again: two eqns & two unknwns:

1. $1800ds_W + 1800ds_C = 0$
2. $1900ds_W + 1800ds_C = -2$

Solution: $ds_W =$ s/km

$ds_C =$ s/km

Seismic Tomography: Some Nitty Gritty



solve 2 equations for 2 unknowns:

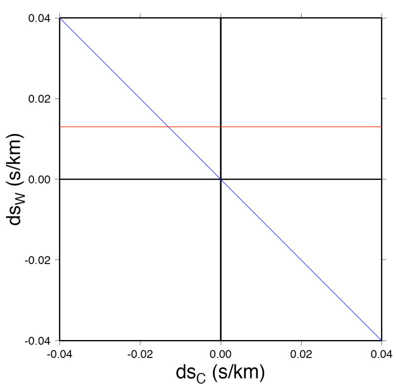
1. central North America "is" ***slow***
2. western North America "is" ***fast***

??

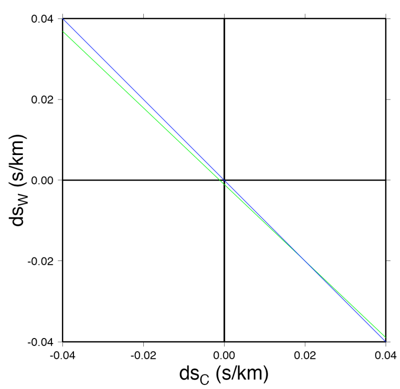
What went wrong?

The grey and black areas indicate that the velocity difference is "off the chart".

Seismic Tomography: Some Nitty Gritty



Case 1: The 2 seismograms clearly identify one crossover point in model space: (-0.013, 0.013)

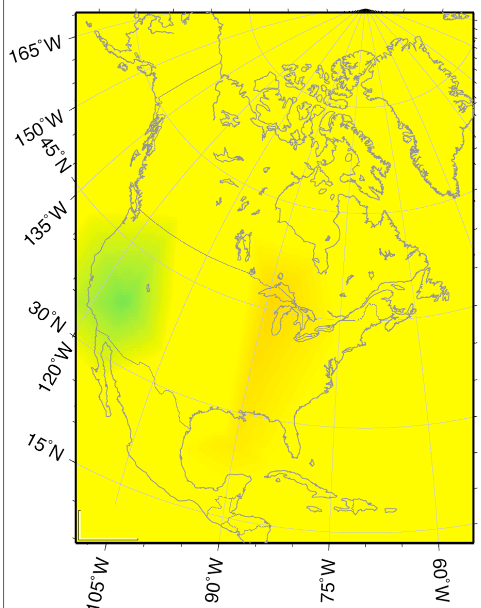


Case 2: The 2 seismograms are so close that, within error, the crossover point is no more meaningful as a solution than any other point on the 2 lines, including: (-0.013, 0.013)

Case 2 and milder variants are common in seismic tomography, at least for a subset of model variables. Case 1 is also common, but unfortunately rarely for more than a subset of model variables.

→ New strategy: Pick a solution close to (0,0)

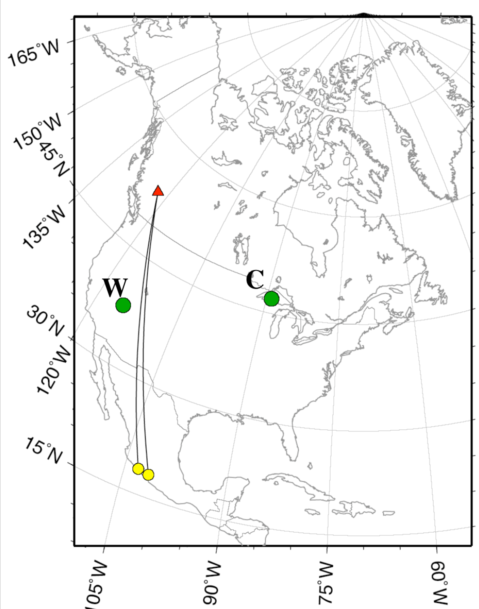
Seismic Tomography: Some Nitty Gritty



A solution close to (0,0)

Additional lesson: Tomographic models that look simple may mean that the Earth's structure is simple or that we do not have the data coverage to discern complexity.

Seismic Tomography: Some Nitty Gritty



Same two regions (**W** and **C**)

consider 2 *different* seismograms:

1. Cocos trench to BC: waves late
2. Cocos trench 2 to BC: waves late

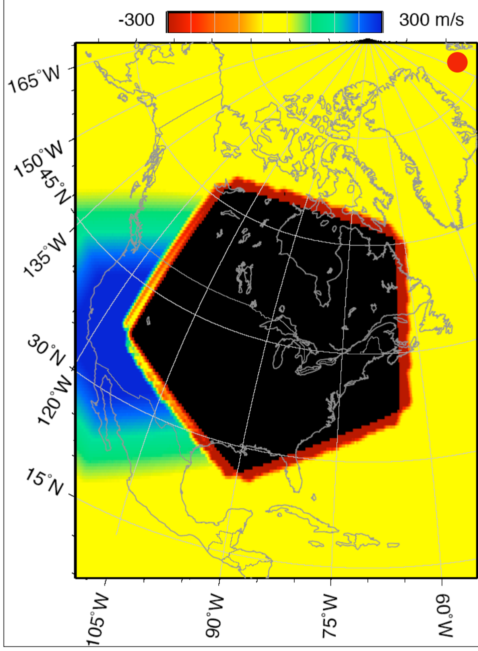
Again: two eqns & two unknwns:

1. $3700ds_W + 300ds_C = 44$
2. $3700ds_W + 200ds_C = 27$

Solution: $ds_W =$ s/km

$ds_C =$ s/km

Seismic Tomography: Some Nitty Gritty



solve 2 equations for 2 unknowns:

1. central North America "is" **slow**
2. western North America "is" **fast**

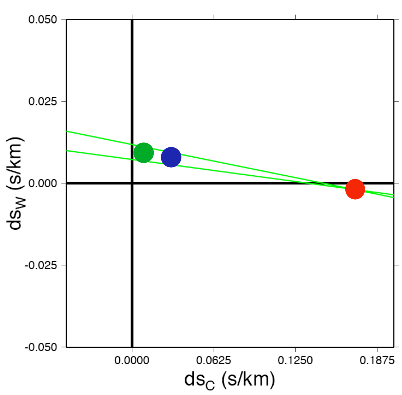
??

Apply new strategy: ➡

pick a solution close to (0, 0)

Again, small error in the data lead to large errors in the imaged velocity differences. The negative velocity difference for Central North America is, again, off the chart.

Seismic Tomography: Some Nitty Gritty

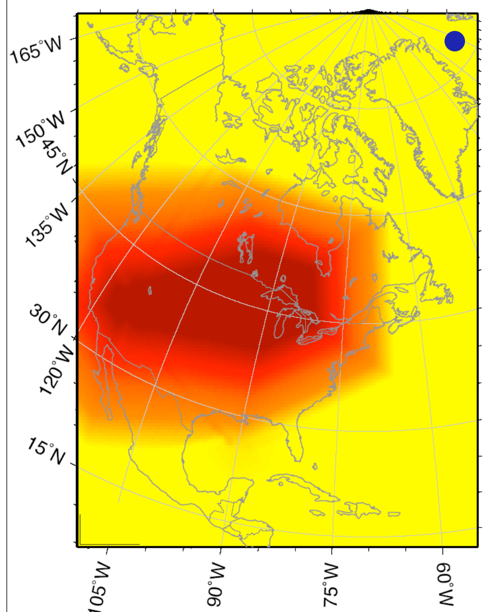


- 🔴 formal solution (previous map)
- 🟢 solution close to (0, 0)
- 🔵 smooth solution (next map)

New strategy:

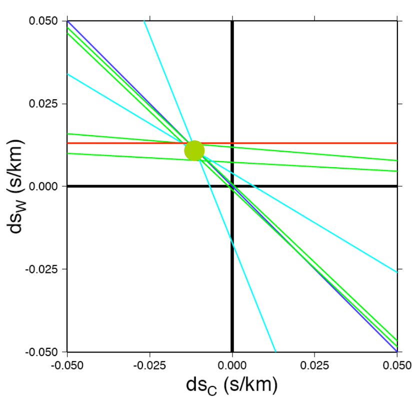
pick a smooth solution:
values are like each other

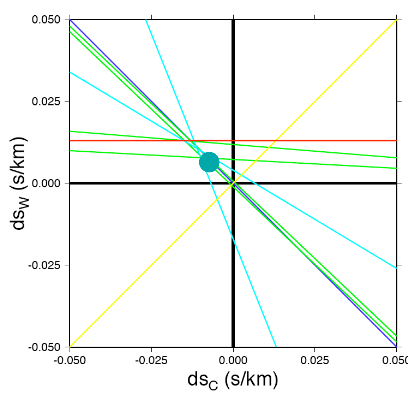
Seismic Tomography: Some Nitty Gritty



- A smooth solution

Seismic Tomography: Some Nitty Gritty

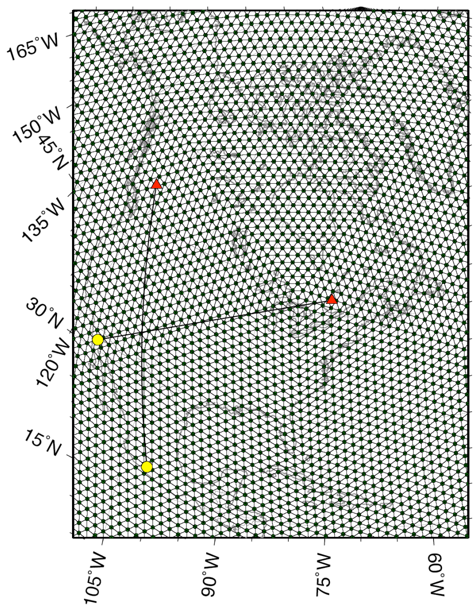




- least-squares solution =
  the solution that is closest to all lines
- damped/smoothed least-squares solution ➜
  the solution underestimates actual slowness values

The lines shown are from the previous examples; a set of equations with random errors. "Damping" will draw the solution towards the origin. "Smoothing", or technically "flattening", will draw the solution towards the yellow line.

Seismic Tomography: Some Nitty Gritty



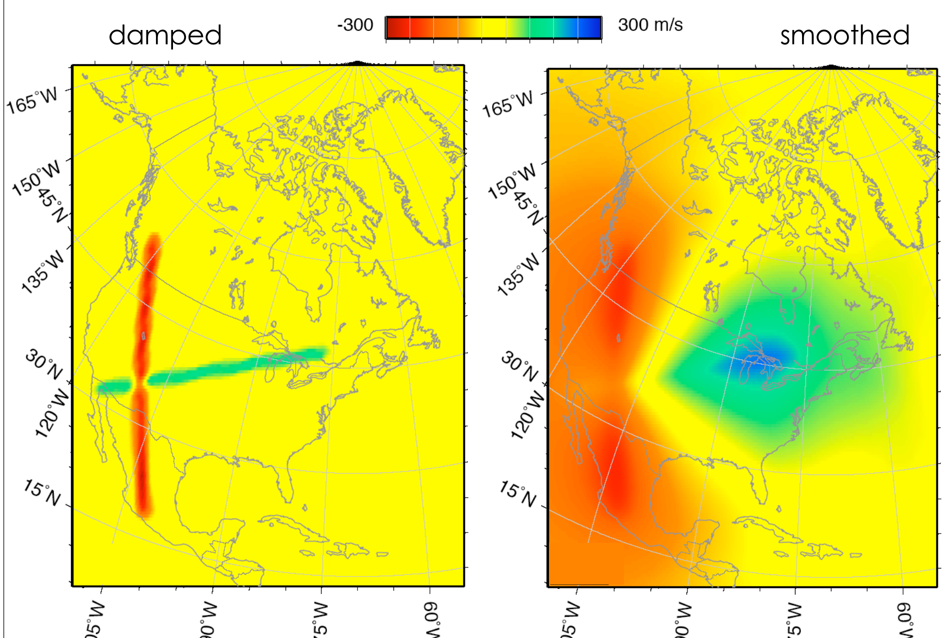
Many more than 2 regions

Two seismograms

→ damping/smoothing

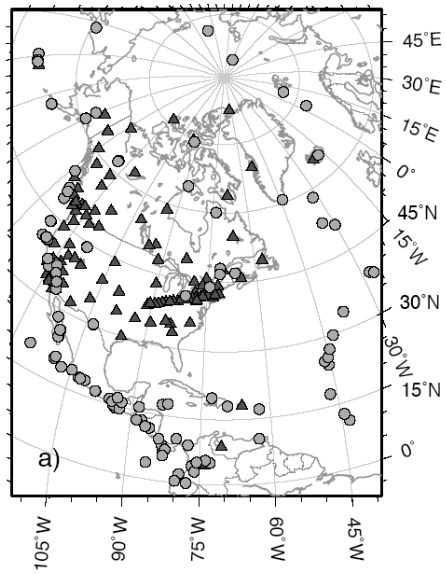
Beyond west and central North America:
Now consider many more than two model variables,
but still with only two equations that
constrain the model variables.

Seismic Tomography: Some Nitty Gritty



Seismic Tomography: Some Nitty Gritty

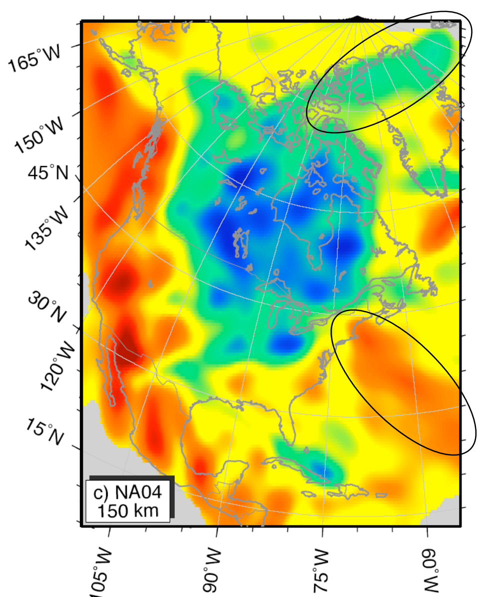
Now consider many more than two model variables * and* many more than two equations.



Many more than 2 seismograms

Note difference in coverage between continent and ocean

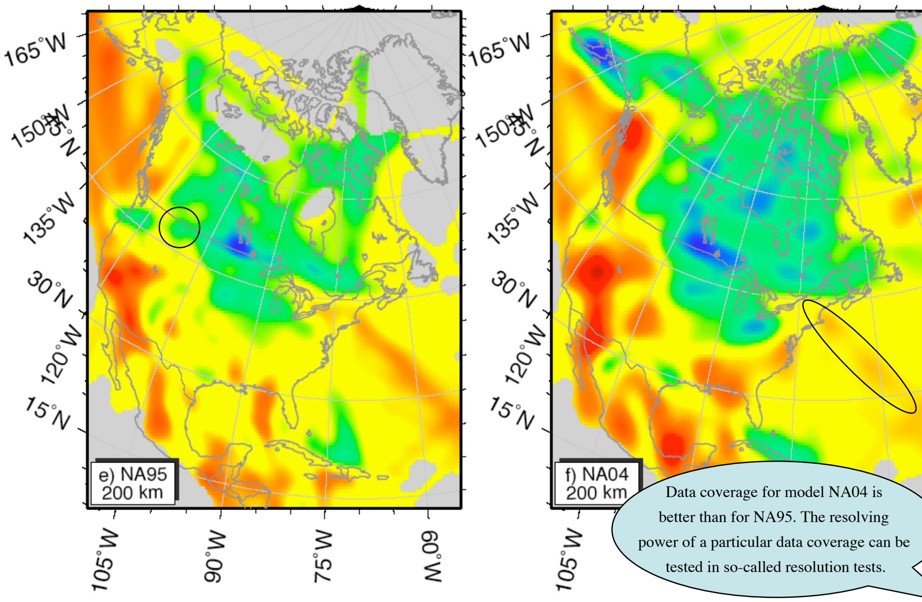
Seismic Tomography: Some Nitty Gritty



Example 1: N Greenland: structure **smoothed** along wave paths from continent into ocean (*even though true structure may have edge at margin*), but **not smoothed** much in N-S direction (***true*** *structure may not be so fast in better covered South*)

Example 2: Atlantic Ocean: structure **smoothed** along wave paths between ridge and continental margin (*even though* ***true*** *structure may change with age of ocean floor*), but **not smoothed** much parallel to the ridge/margin (*even though in that direction* ***true*** *structure may be more homogeneous*)

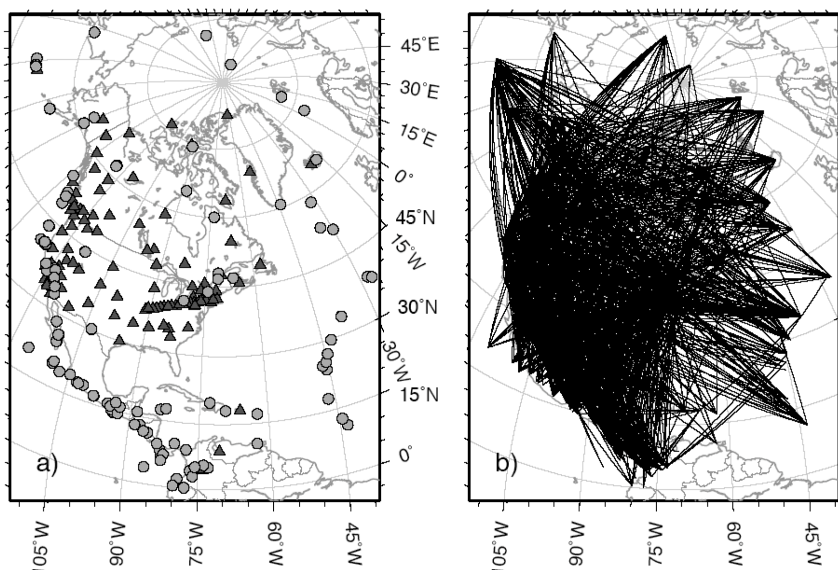
Seismic Tomography: Some Nitty Gritty



Data coverage for model NA04 is better than for NA95. The resolving power of a particular data coverage can be tested in so-called resolution tests.

Juan de fuca Plate; Craton Lithosphere; New England Seamount Chain?

Seismic Tomography: Resolution

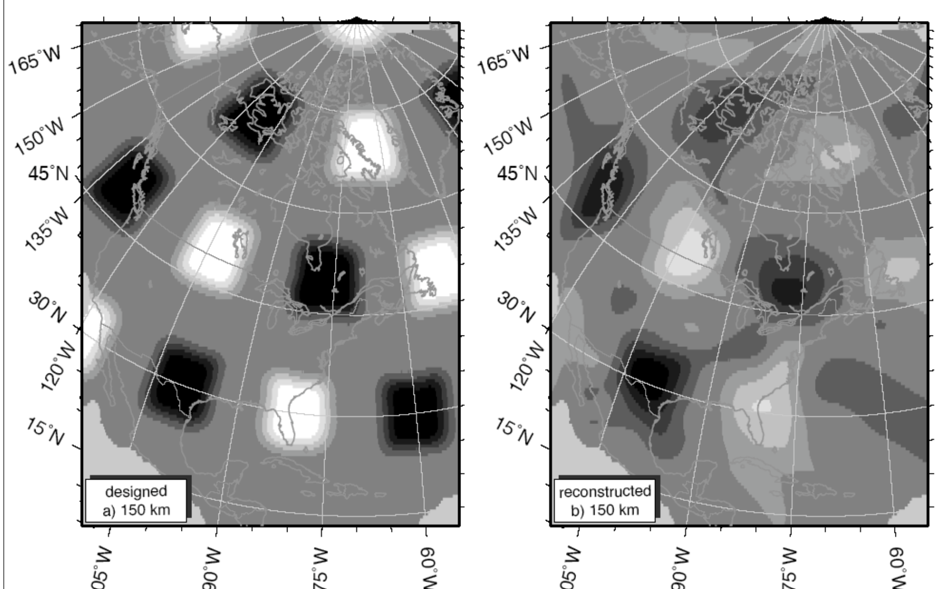


Consider a given data coverage …

…then consider a hypothetical design of
velocity differences, compute data for these differences,
add random noise to these “data”, and use the “data” to reconstruct the model (next slide).

Model-specific lessons (next slide): In the Atlantic Ocean our data cannot resolve the difference
between a single checker or a chain of anomalous velocity. Better data coverage
does a better job at defining the edge of the North American Craton,
particularly in the presence of nearby similarly rigid
structures with a different tectonic origin (such as
subducted lithosphere or old
oceanic lithosphere).

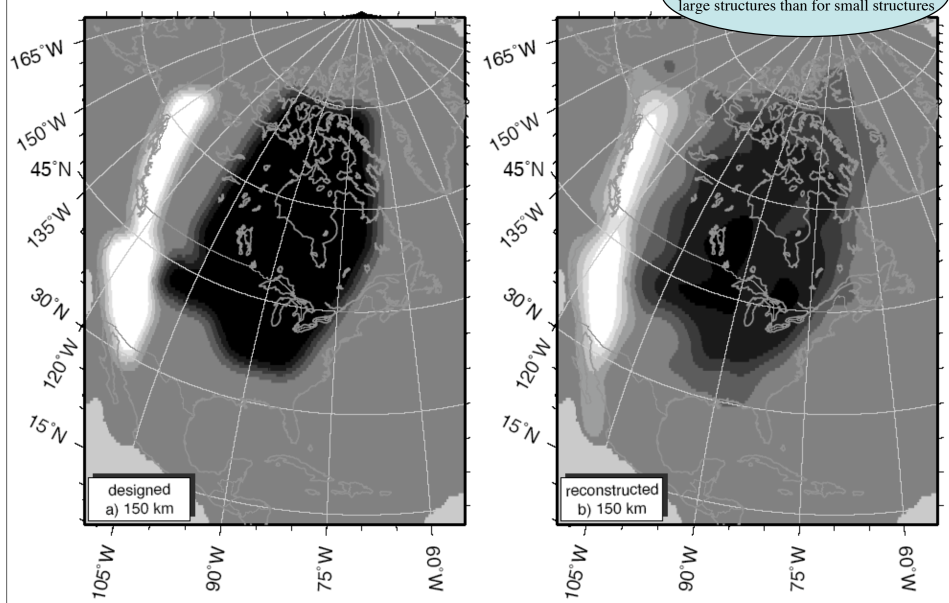
Seismic Tomography: Resolution



Velocities are underestimated, and heterogeneously resolved

Seismic Tomography: Resolution

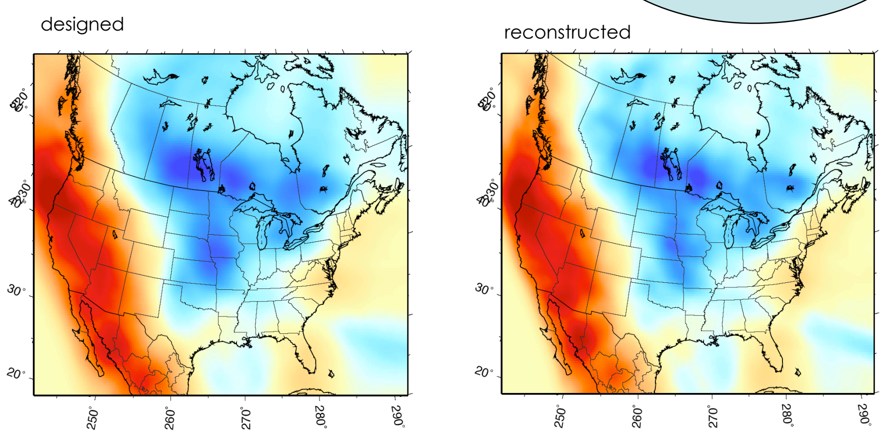
Resolving power is always better for large structures than for small structures



Large structures are better resolved, but not perfectly

Seismic Tomography: Resolution

This test and the next were performed using our new data coverage, including some USArray data and similar damping/smoothness choices as for NA04. These choices and this data coverage can resolve smooth structures…

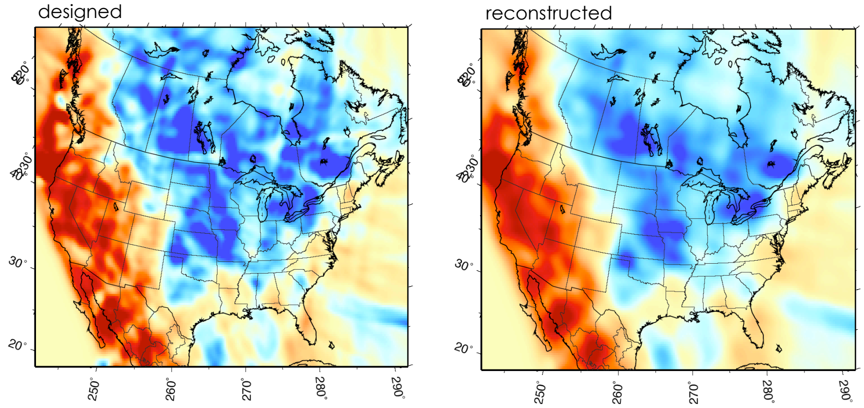


Smoothness is mostly resolved

Seismic Tomography: Resolution

…as well as rough structures. Our damping/smoothing choices filter out some small-scale structures while having the power to resolve smooth structures.

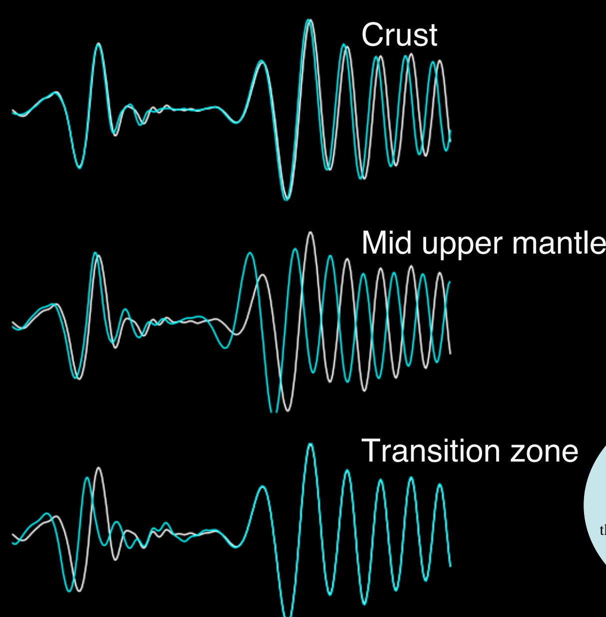
designed reconstructed



Roughness is also resolved, but not entirely

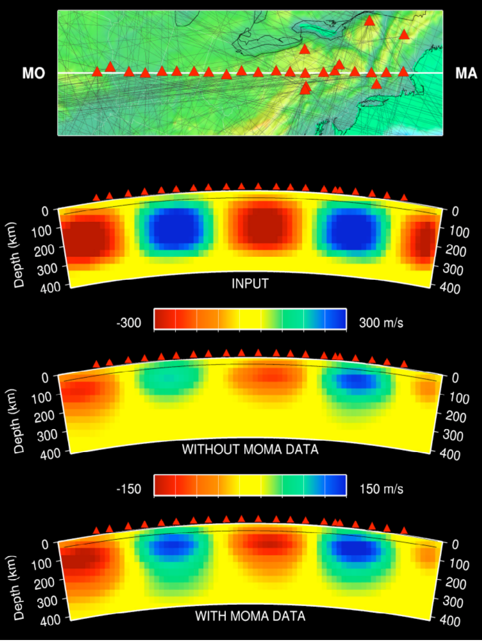
Seismic Tomography: Resolution

Depth resolution comes from different waves (tones) and frequencies



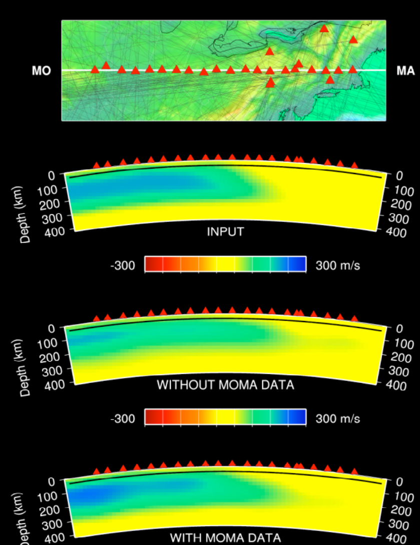
The three turquoise synthetic seismograms are for three different models with a velocity anomaly in one of each of three depth regions. They are compared with the same white reference synthetic seismogram.

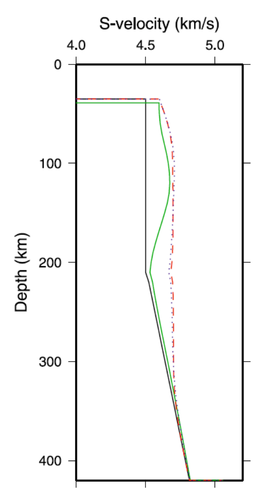
Seismic Tomography: Resolution



Like **USArray**'s Transportable Array, the dense MOMA station line improves resolving power of the data set, both in depth and for absolute values of velocity heterogeneity.

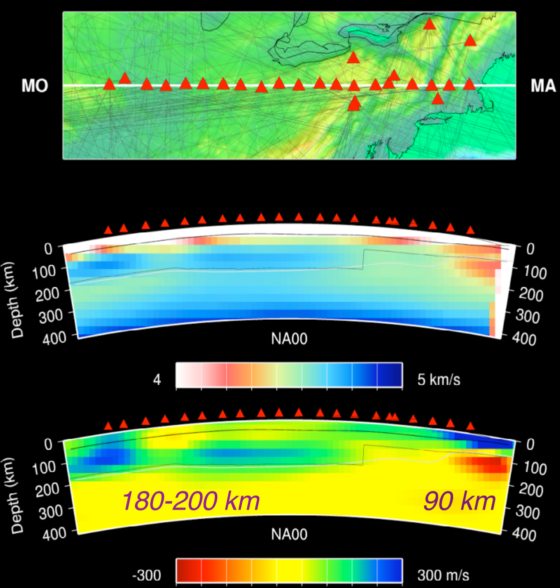
Seismic Tomography: Resolution





Improved sub-lithospheric resolution by incorporating waveform data from dense seismic arrays (e.g. MOMA)

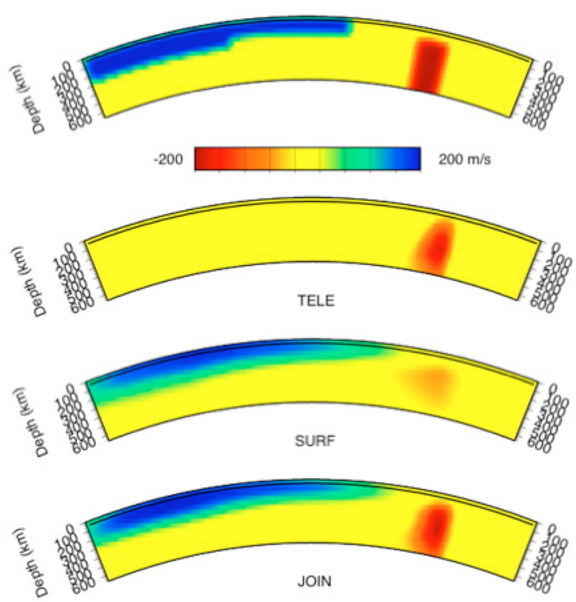
Seismic Tomography: Resolution



Well-resolved seismic thickness estimate agrees with

- *petrologic thickness from xenoliths*
- *thermal thickness from mineral physics and tomography*
- *thermal thickness from heat flow*
- *twice the elastic thickness from topography and gravity*

Seismic Tomography: Resolution



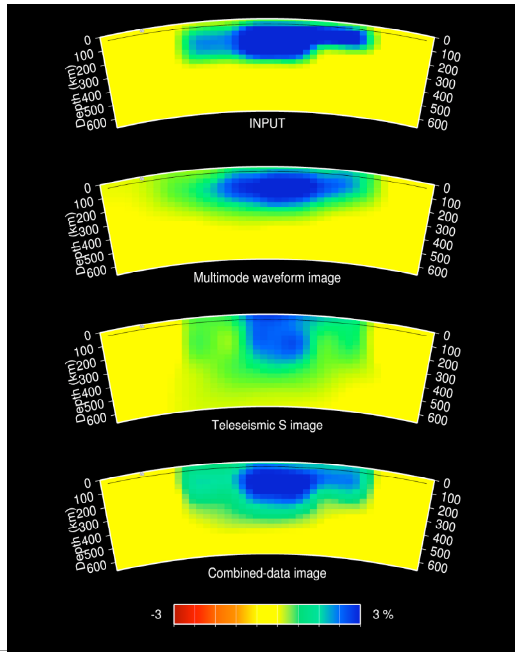
A. Teleseismic arrivals sense structures directly beneath stations

B. Regional waveforms sense structures between stations

A. Teleseismic arrivals sense structures relative to unknown average

B. Regional waveforms sense absolute structures

Seismic Tomography: Resolution

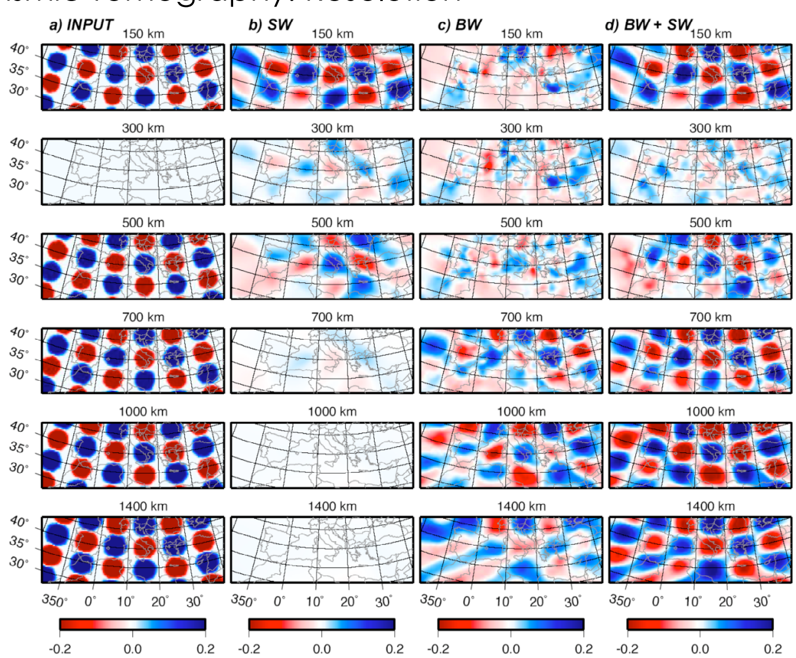


A. Teleseismic arrivals sense structures with greater lateral resolution

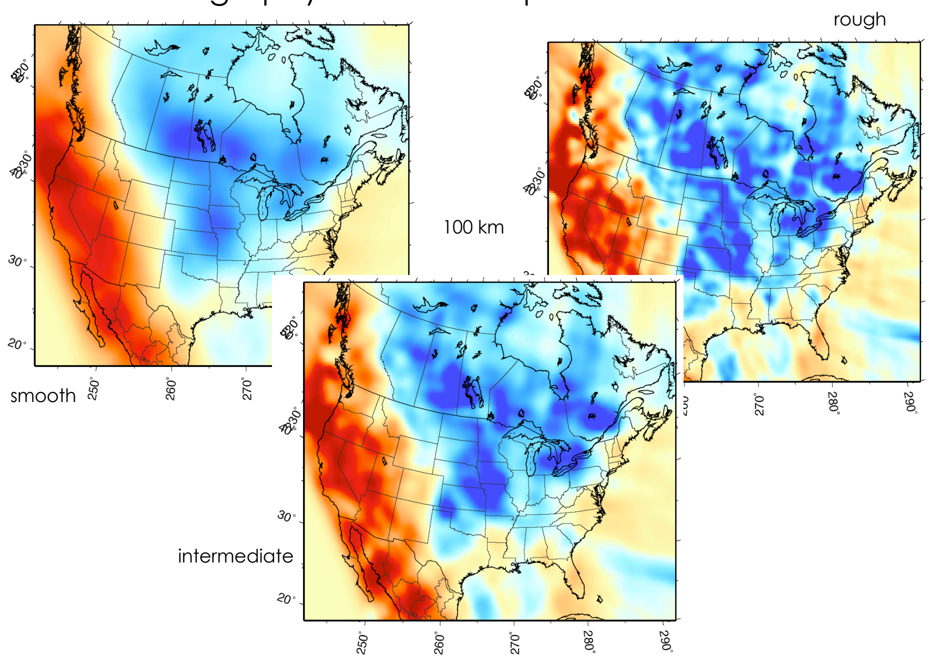
B. Regional waveforms sense structures with greater depth resolution

Combined tomographyis able to discriminate between a a thick, normal and a thin, strong lithosphere

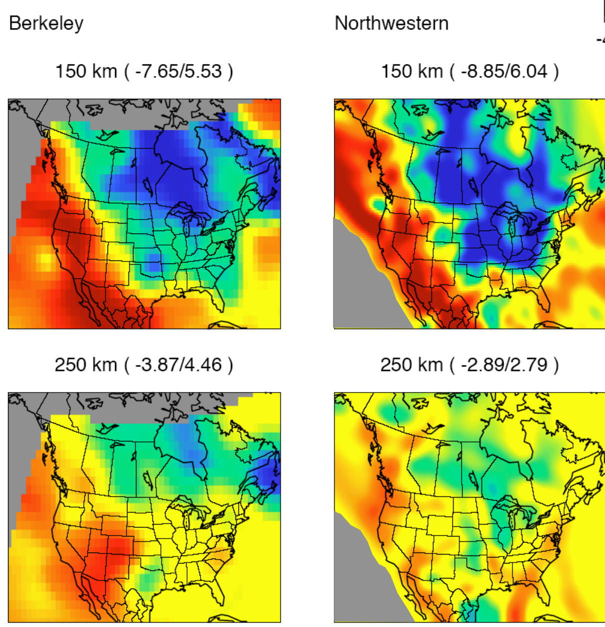
Seismic Tomography: Resolution

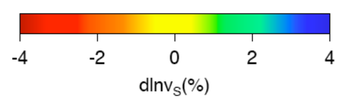


Seismic Tomography: Model Comparisons



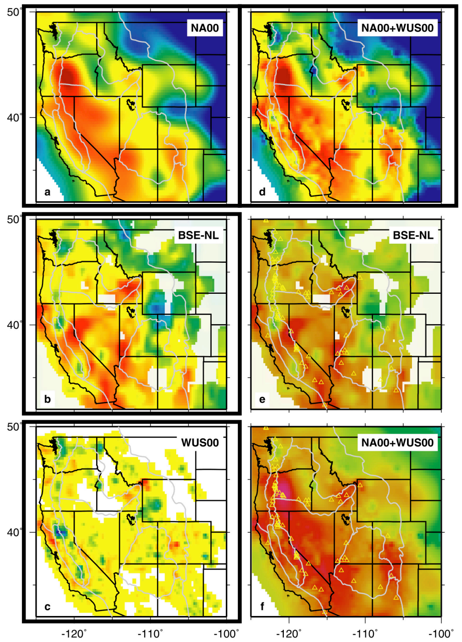
Seismic Tomography: Model Comparisons





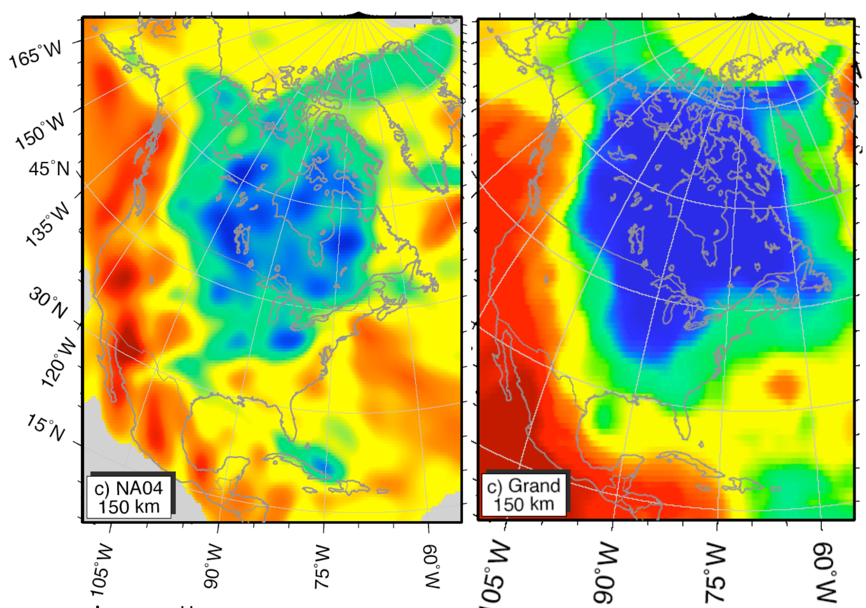
Two very recent models show similar locations, shapes and strengths of large scale structure, but small scale structure differs

Seismic Tomography: Model Comparisons



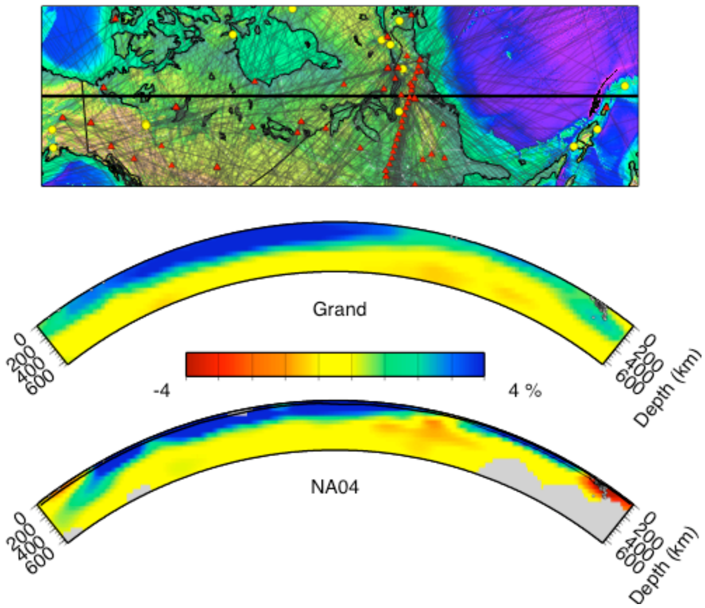
Two older models (one very smooth, one very rough) show practically nothing in common, but when combined are similar to third, intermediate-scale model

Seismic Tomography: Model Comparisons

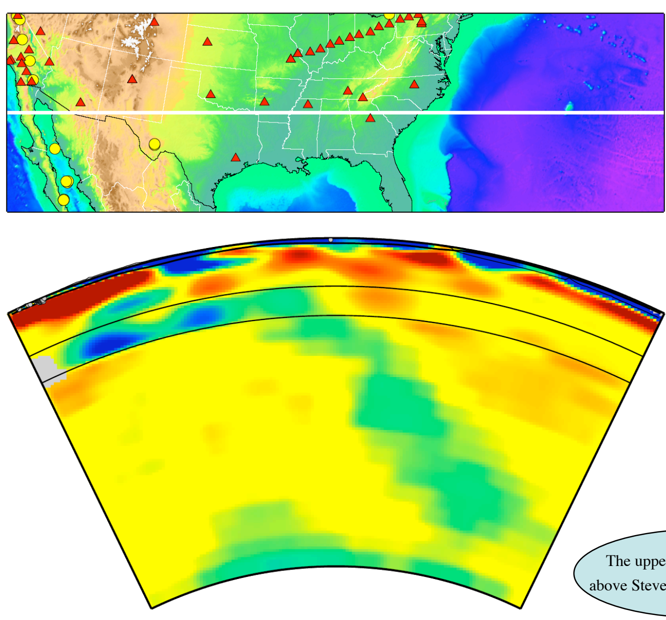


emerging pattern: …

Seismic Tomography: Model Comparisons



Seismic Tomography: Model Comparisons



The upper mantle from NA04 above Steve Grand's lower mantle.

Seismic Tomography: Tips

When seriously interested in a tomographic model:

1. **Read** the associated peer-reviewed publication
2. Examine the accompanying **resolution test** results
3. **Compare** the model with other models for the region
4. **Discuss** the model and its details with your seismology colleagues and or its authors

The End