Seismic Tomography

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Examples for North America

Seismic Tomography

Mini-Course with contributions and inspiration from:

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Seismic Tomography

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Seismic tomography is about mapping lateral variations to these globally averaged seismic velocity profiles.
Seismic Tomography: A Simple Exercise

consider two regions:
1. Western North America
2. Central 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’s mantle 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.

Reference slowness $s_0 = 0.222 \, \text{s/km} = 1/(4.5 \, \text{km/s})$

$\frac{x}{v} = t \rightarrow x = vt \rightarrow x = t s$, with $s = 1/v$

Distance*slowness = time $\rightarrow$
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: $ds_W = \frac{s}{\text{km}}$ $\quad ds_C = \frac{s}{\text{km}}$
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 unknowns:
1. \[ 1800d_{SW} + 1800d_{SC} = 0 \]
2. \[ 1900d_{SW} + 1800d_{SC} = 1.3 \]

Solution: \[ d_{SW} = \frac{s}{km} \]
\[ d_{SC} = \frac{s}{km} \]
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 unknowns:
1. $1800d_{SW} + 1800d_{SC} = 0$
2. $1900d_{SW} + 1800d_{SC} = -2$

Solution: $d_{SW} = \frac{\text{s}}{\text{km}}$
$d_{SC} = \frac{\text{s}}{\text{km}}$
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)

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

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.
Seismic Tomography: Some Nitty Gritty

A solution close to (0,0)

-300 300 m/s

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 unknowns:
1. \(3700d_{SW} + 300d_{SC} = 44\)
2. \(3700d_{SW} + 200d_{SC} = 27\)

Solution:
\[d_{SW} = \text{s/km}\]
\[d_{SC} = \text{s/km}\]
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 errors 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

*least-squares solution* = the solution that is closest to all lines

Damping will draw the solution towards the origin. Smoothing, or technically “flattening”, will draw the solution towards the yellow line.

damped/smoothed least-squares solution $\rightarrow$ the solution underestimates actual slowness values

The lines shown are from the previous examples; a set of equations with random errors.
Seismic Tomography: Some Nitty Gritty

Many more than 2 regions
Two seismograms

→ damping/smoothing
Seismic Tomography: Some Nitty Gritty

Many more than 2 seismograms

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).

Note difference in coverage between continent and ocean.
Seismic Tomography: Some Nitty Gritty

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

Seismic Tomography: Resolution

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.

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

Large structures are better resolved, but not perfectly resolved power is always better for large structures than for small structures.

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...
Seismic Tomography: Resolution

Roughness is also resolved, but not entirely.

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

Seismic Tomography: Resolution

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.

Depth resolution comes from different waves (tones) and frequencies.

Crust

Mid upper mantle

Transition zone
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.

Improved sub-lithospheric resolution by incorporating waveform data from dense seismic arrays (e.g. MOMA)
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 tomography is able to discriminate between a thick, normal and a thin, strong lithosphere
Two very recent models show similar locations, shapes and strengths of large scale structure, but small scale structure differs.
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

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