tomography for non-tomographers: assessing quality of seismic tomography results

Edi Kissling ETH Zürich

„no seismic tomography image is fully correct“
but they are still very useful if we learn to judge and select among the 3D results

SPP short course February 1+2, 2018, Berlin, Germany
resolution always varies across a tomographic image (due to inhomogeneous data and non-Gaussian error distributions)

Such resolution and reliability variation should be marked but often it is not. Then the reader must be able to judge based on such principles, as outlined in this presentation.

Example: Moho maps

( comparison by Molinari et al. 2015)

Moho trough beneath N Apennines?
Content:

1. A few principal characteristics of seismic tomography

2. Strength and limitations of seismic methods

3. Quality of data set used

4. Precision, uniqueness, (intrinsic and others) assumptions of inversion procedure that combined with points 2 and 3 above lead to model (results) resolution
seismic tomography:

Tomography means “description by cross sections”

The term seismic tomography is well applicable to any kind of seismic imaging and presently we may list (in historical order) the seismic methods:

- surface wave seismology [3]
- teleseismic tomography [4]
- local earthquake tomography [5]
- receiver functions [6]
- ambient noise tomography [7]

Note that the differences regard the type of waves and the source-receiver distributions. Principally with each seismic method one may use full wave form information or just travel times or amplitudes of specific wavelets.

(there exist special applications such as 3D seismics, S-wave splitting or cross-borehole tomography)
Seismic tomography results are the product of a specific process:

1. **Seismic method** (employing specific type of waves)
2. **by experimental setup collect** data set
3. **by inversion reconstruct** 3D seismic model
4. **document results and their resolution + reliability**
5. **tomographic images**
6. **many assumptions and approximations**

**Wave effects approx. by rays?**

**Geologic interpretation**
resolution and reliability

depends on seismic method and on data set

depends on assumptions made in inversion process

What can be resolved by seismic method and how good (quality and quantity) is the data set?

choices made about 3D grid, solving forward and inverse problem, damping, initial reference model, ...

mixed-determined

over-determined

under-determined
what seismic waves resolve

reflection seismics, receiver functions

velocity interface information

fat ray representing wave path

cells should not be much smaller than seismic wave length

dx, dy, dz > λ, α

Volumetric velocity information

width of wave sensitivity

wave length

mapping topography of interface (not so much its depth)
controlled source seismology

reflection seismics imaging reflectivity pattern, topography of interfaces
Frequencies: 5 Hz – 50+ Hz

refraction and reflection seismics, oldest seismic imaging methods. Most reliable yet selective information about crustal structure
controlled source seismology

Refraction seismics provides volumetric velocity and interface information

it is a 2D method (sources and receivers on same side of target structure) => migration necessary

frequencies: 1Hz – 20+ Hz
Surface wave tomography

Frequencies: 0.03 Hz – 0.004 Hz

Dispersion: different frequency waves travel with different velocities, => differentiate phase and group velocities!

surface waves are excellent to illuminate the upper mantle - asthenosphere, the MOR, cratons and large plumes
Surface wave tomography—phase velocity maps

Increasing depth sensitivity with increasing wave length

Ekström, Tromp and Larson (1997)

MOR, large plumes, no difference oceanic + young cont. lithosphere
Tomography results depend on damping!

Trade-off between model complexity and data-fit as a criterion for model selection

Schaefer et al. 2011
teleseismic (body wave) tomography TET

global (f.e., Bijwaard & Spakman 2000) and regional (f.e., Piromallo & Morelli 2003)

global data set used: Int. Seism. Center ISC

frequencies: 0.3 Hz – 3 Hz

poor crustal resolution can be applied everywhere
strengths and limitations of seismic methods

teleseismic (body wave) tomography TET

global and regional

Bijwaard & Spakman 2000

(cell size adjusted relative to hit count)

(minimal cell size according to shortest wave length)

Bijwaard & Spakman 2000

10log of hit count
Ray geometry and resolution in teleseismic tomography

Good resolution
Fair resolution

With such setup poor resolution outside grey area

No crossing ray from SW => smearing toward NE at depth
modified for ray coverage from

Mitterbauer et al. 2011: event and station distribution
High-resolution teleseismic tomography
(f.e., Lippitsch et al. 2003)

=> high data quality and 3D crustal corrections make all the difference!

Lippitsch et al. 2003

Bijwaard and Spakman 2000

ISC data

small high-quality data set

Piromallo and Morelli 2003
The coupled hypocenter-3D velocity problem:

- Body waves P and S
- Frequencies: 0.5 Hz – 20+ Hz

Local earthquake tomography (LET) is a true 3D method, high-resolution and potentially very reliable 3D velocity information if a consistent data set is established.

Only applicable in regions with local seismicity.
receiver functions
tomography RF

Diagnosis based on geometry of ‘410’ and ‘660’

First-order velocity discontinuity between two isotropic layers

Station

410

660

Receiver functions

Can be applied everywhere

Corresponding receiver function

Horizontal distance (km)

Depth (km)

Amplitude

Corresponding receiver function

P

PS

PpS

PsS

Time (sec)

0

1

2

3

4

5

6

Velocity interface method

E. Kissling

strengths and limitations of seismic methods
strengths and limitations of seismic methods

receiver functions tomography RF

isotropic

$H=15\text{km}$

isotropic

excellent to map topography of first-order interfaces

intrinsic absolute depth uncertainty

$20^\circ$ dip to South

Velocity interface method

$V_1$, $V_2$, $P$, $S$, $PS$, $PpS$
main result of RF: topography of converting interface

velocity interface method

RF data quality non-uniform along profile

overly optimistic re-sampling and display

overly optimistic color interpolation + smoothing

scattered image of interface from low (below) to high (above) velocity

scattered image of interface interpreted as high-velocity volume (Ivrea)? RF may not resolve such body!

Zhao et al. 2015 Geology (figure in supplement)
different types of resolution

4. image resolution: cell size and smoothing used for display of results

1. physical resolution: rock physical parameter resolved by method, for volumetric velocity information depends on wave length

2. data resolution: quality, quantity and study volume/area coverage of data set used for inversion

3. model resolution: final resolution of 3D tomographic model results (model resolution combines effects of 1 & 2 & inversion process)

image resolution should reflect model resolution
model resolution

Resolution of 3D velocity structure by body waves is based on cross firing/crossing wave paths.

Visualize ray density tensor:

Surface wave tomography: 2D cross firing/crossing wave paths along earth surface, 3D resolution by combining phase velocity information from many different periods.
cell size adjusted due to 2D cross firing

Modern regional and global surface wave tomography

(minimal cell size according to shortest wave length)

Schaefer et al. 2011
visualizing (model) resolution matrix

\[ m_{\text{est}} = R m_{\text{true}} \]

\[ \rightarrow \text{R is an operator that tells us how well our model reflects the true model.} \]

R is a \( m \times m \) matrix. Each row of R describes the dependence of one model parameter on all other model parameters.

RDE = resolution diagonal element (→)

3-D visualization of one row of the resolution matrix.

remaining question: How good is RDE=0.8 or 0.3?
resolution spread function value

example 5*5 resolution matrix

\[
\begin{bmatrix}
0.5 & 0.8 & 0 & 0.3 & 1.9 \\
0.8 & 0.6 & 0.4 & 0.7 & 0.1 \\
0 & 0.4 & 0.1 & 1.8 & 2.1 \\
0.3 & 0.7 & 1.8 & 0.3 & 0.5 \\
1.9 & 0.1 & 2.1 & 0.5 & 0.7
\end{bmatrix}
\]

sum of non-diagonal elements = spread function

remaining question: How good is resolution?
checkerboard testing reveals sensitivity

Koulakev et al. 2015


Leveque et al. 1993 “.. in contradiction to a generally accepted idea, small-size structures like the checkerboard test can be well retrieved while larger structures are poorly retrieved.”

**model resolution of tomography**

---

**test 1**

- **synthetic model**
  - (a)
  - (b)

- **recovered structure**
  - (a)
  - (b)

**test 2**

- **synthetic model**
  - (a)
  - (b)

- **recovered structure**
  - (a)
  - (b)

---

**resolution**

---

geometry of experiment

---

<table>
<thead>
<tr>
<th></th>
<th>high attenuation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low attenuation</td>
<td></td>
</tr>
</tbody>
</table>

---

E. Kissling
strengths and limitations of seismic methods

teleseismic (body wave) tomography TET

spike-anomalies sensitivity test

Bijwaard & Spakman 2000

realistic sensitivity testing when avoiding checkboard anomalies
Resolution varies across a tomographic image (due to inhomogeneous data and non-Gaussian error distributions).

But this variation may not be documented by Hit-Matrix! (because resolution depends on cross firing and while single ray is not enough, how many are?)

Sensitivity of data set is documented by checkerboard tests.
synthetic data testing (artificial model)

Concept:

(1) establish realistic data set for known 3D structure
(2) use this data set as input to inversion process
(3) compare tomographic results with original structure to assess quality of inversion process results

for each source-receiver pair (observation)
calculate ray path and travel time for synthetic 3D velocity model

=> synthetic data set

input
output 1
output 2

Kissling 1988
model resolution parameters provide relative information

(because they depend on choices made regarding 3D grid and control parameters for inversion)

Example: see model recovery in synthetic data test within region of RDE = 0.1
example assessing resolution in LET

RDE and resolution contours (off-diagonal elements)

Diehl et al. 2009

synthetic test with lower crustal model structure. Note different results for high- and low velocity anomalies.

Results along EGT profile
Synthetic testing teleseismic anisotropy tomography

Fig. S7

Strength of anisotropy
fast axis 5 %
slow axis 3 %

well and fairly-well resolved region

Synthetic testing teleseismic anisotropy tomography
Munzarova et al. 2018

E. Kissling

resolution assessment teleseismic anisotropy tomography

synthetic tests document good resolution in outlined region to separate anisotropy and isotropic velocity variations in cratonic mantle lithosphere of Baltica

they also show typical isotropic border artefacts outside well-resolved region
Ambient Noise Tomography (short period surface wave tomography)

Frequencies: 0.025 Hz – 0.3 Hz

excellent method for mapping shallow S-wave crustal structure (2D phase velocity maps)

requires good distribution of scatterers and noise sources

3D by use of many frequencies combined

Molasse basin

Po basin

Rayleigh group velocity maps at 16s

Volumetric velocity method
ambient noise tomography synthetic test

We would like to know the length of the shortest structure (of what velocity variation) that can be resolved well.

Distinguish these geometries of small scale structure (no single cell anomaly!)

Verbeke et al 2012
teleseismic (body wave) tomography TET

In my view, the results of this synthetic test clearly show poor vertical resolution, significant high-velocity smearing effect and a detached mantle slab.

Zhao et al. 2016 JGR
interpreted resulting image: “lithosphere slab continuous”

if 100km thick W-Alpine lithosphere is continuous, what does this (well-resolved) low-velocity anomaly mean

(comments in black by E. Kissling 2018)
display of tomography results

the challenge to display lateral velocity variations of a few percent when vertically the velocity increases by 100%

the challenge is to display results attractively and easy to read (smoothed, interpolated, color scale) and precisely tuned to their model resolution
Relative velocity variations of 10% do not have the same meaning near surface and at lower crustal levels!

In mantle small lateral velocity variations are indicative but how small is still reliably imaged?

In crust show absolute velocities in cross sections
In mantle show relative velocity variations also in cross sections

Horizontal cross sections usually best with relative velocity variations
quality estimate of seismic tomography results require authors to

• define what parts of image/3D model are well-resolved (and what parts should be ignored if they are not already hidden)

• in well-resolved regions define what kind of information about 3D structure and what type of structure are reliably resolved by specific application

• present results of synthetic model tests (to back up their resolution claims and to help readers to judge on their own)
conclusions

all users of tomography results please

• check seismic method
  What physical parameter and what structural information may be derived? strengths and limitations?

• check the data
  What region is sampled by data set? How variable is data quality? What can be resolved by best data?

• check the model resolution
  What kind of structure (geometry, amplitude) can be reliably resolved at best?

• and/or make use of synthetic data tests and use your own good judgement