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

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„no seismic tomography image is fully correct“

but they are still very useful if we learn to judge and select among the 3D results

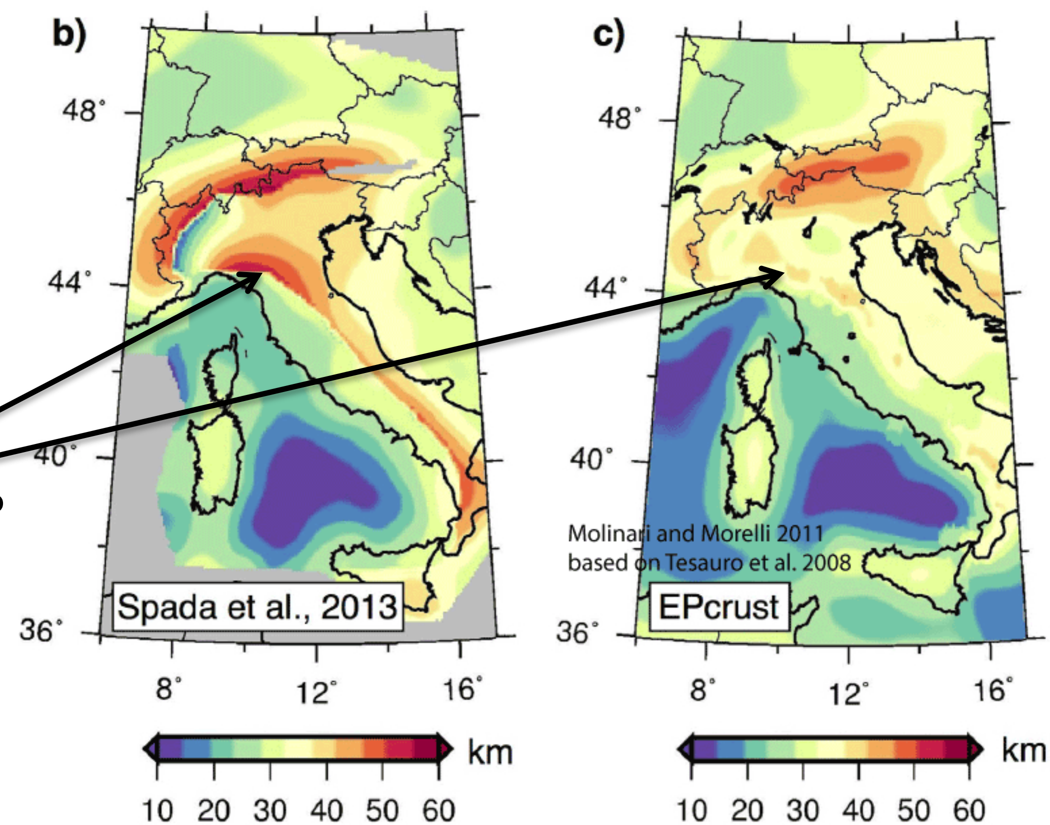
SPP short course February 1+2, 2018, Berlin, Germany

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

(comparsion by
Molinari et al. 2015)



Moho trough beneath N Apennines?

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„what one should consider when interpreting seismic tomography results“

Content:

1 a few principal characteristics of seismic tomography

1 strength and limitations of seismic methods

1 quality of data set used

2 precision, uniqueness, (intrinsic and others) assumptions of inversion procedure that combined with points 2 and 3 above lead to model (results) resolution

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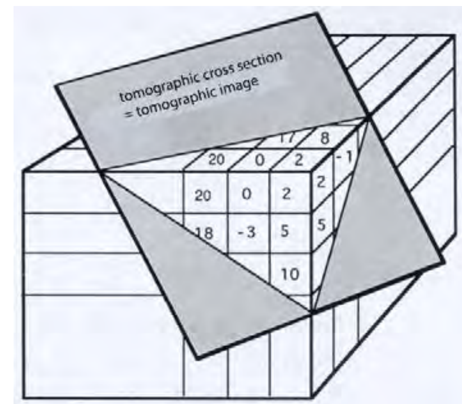
seismic tomography:

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

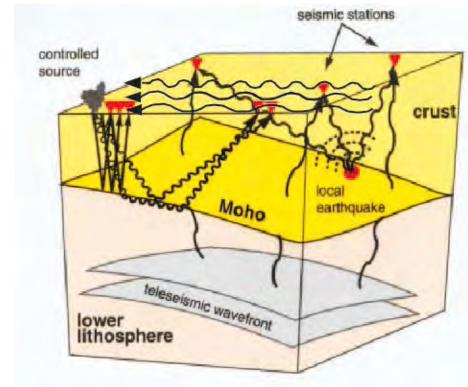
- controlled-sources seismology (refraction [1] and reflection [2] seismics)
- surface wave seismology [3]
- teleseismic tomography [4]
- local earthquake tomography [5]
- receiver functions [6]
- ambient noise tomography [7]



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:



Seismic method

(employing specific type of waves)

by experimental setup collect

data set

by inversion reconstruct

many assumptions

and approximations

wave effects approx. by rays?

3D seismic model

document results and their resolution + reliability

tomographic images

geologic interpretation

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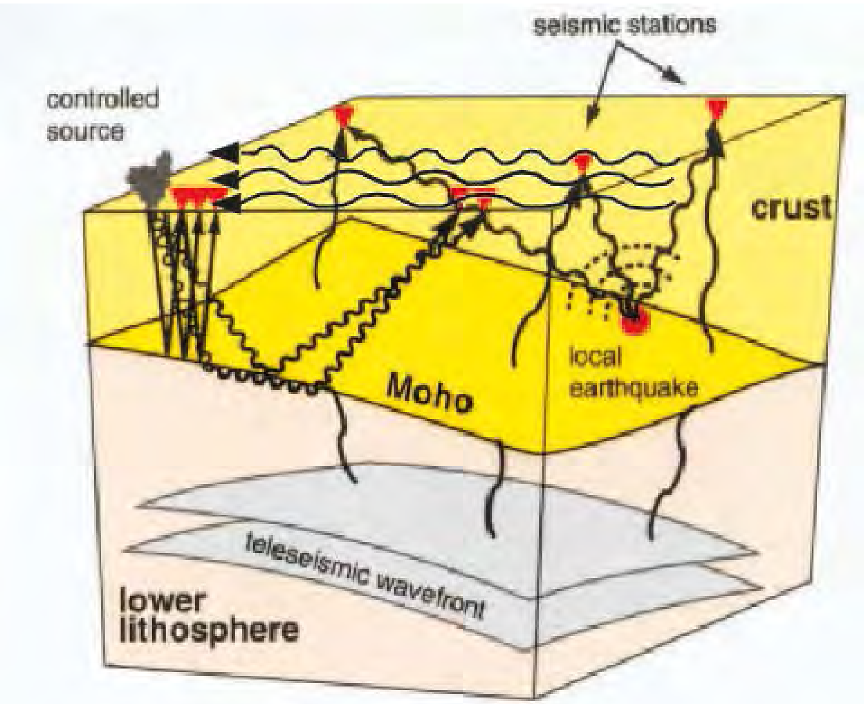
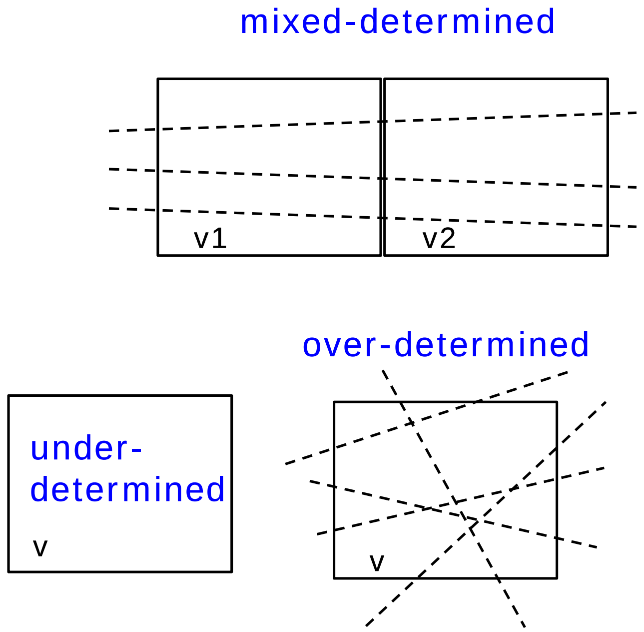
resolution and reliability

depends on seismic method and on data set

depends on assumptions made in inversion process



choices made about 3D grid, solving forward and inverse problem, damping, initital reference model, …



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

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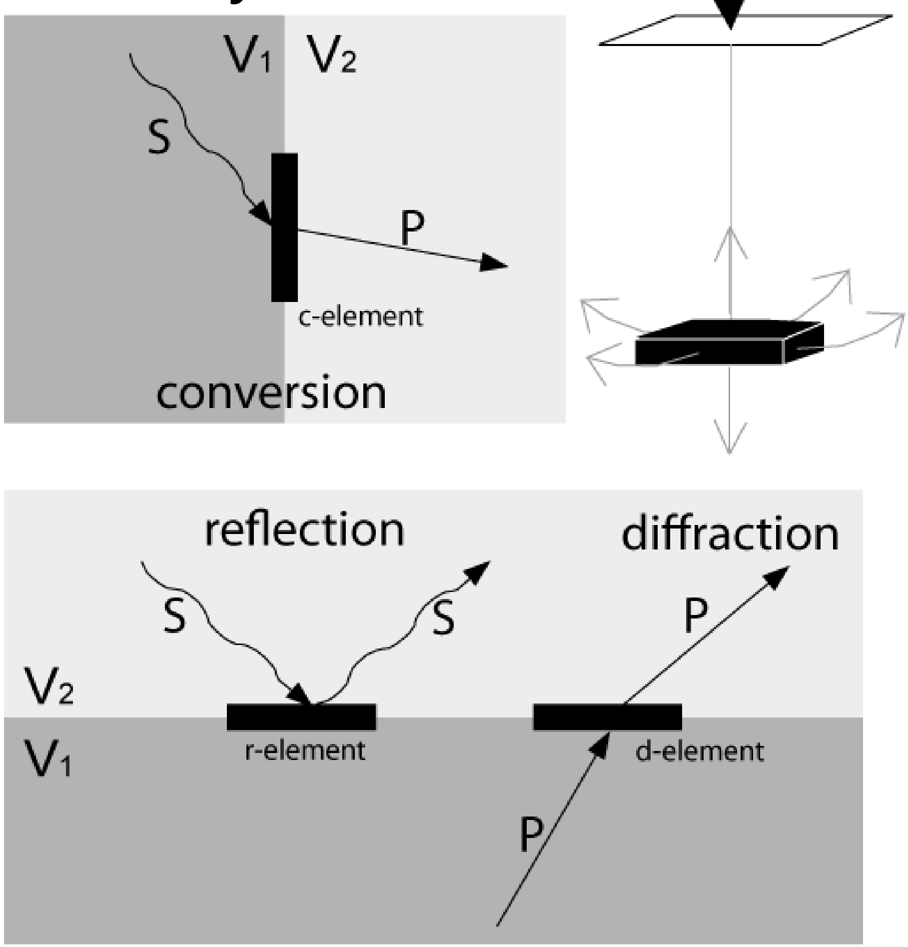
what seismic waves resolve

reflection seismics, receiver functions

surface wave, teleseismic body wave, local earthquake, ambient noise tomography, refraction seismics

Velocity interface information



mapping topography of interface
(not so much its depth)

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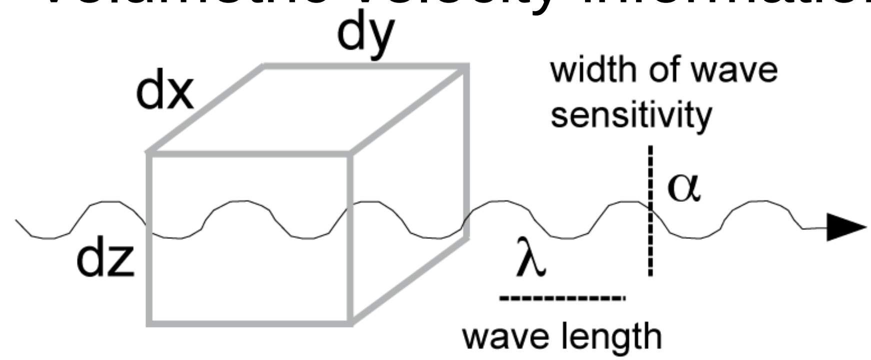
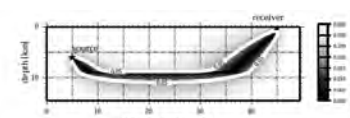
Volumetric velocity information

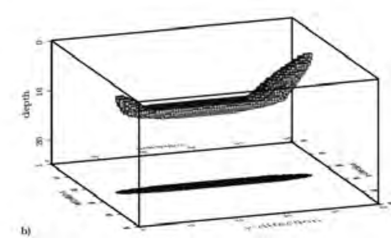


$$dx, dy, dz > \lambda, \alpha$$

cells should not be much smaller than seismic wave length



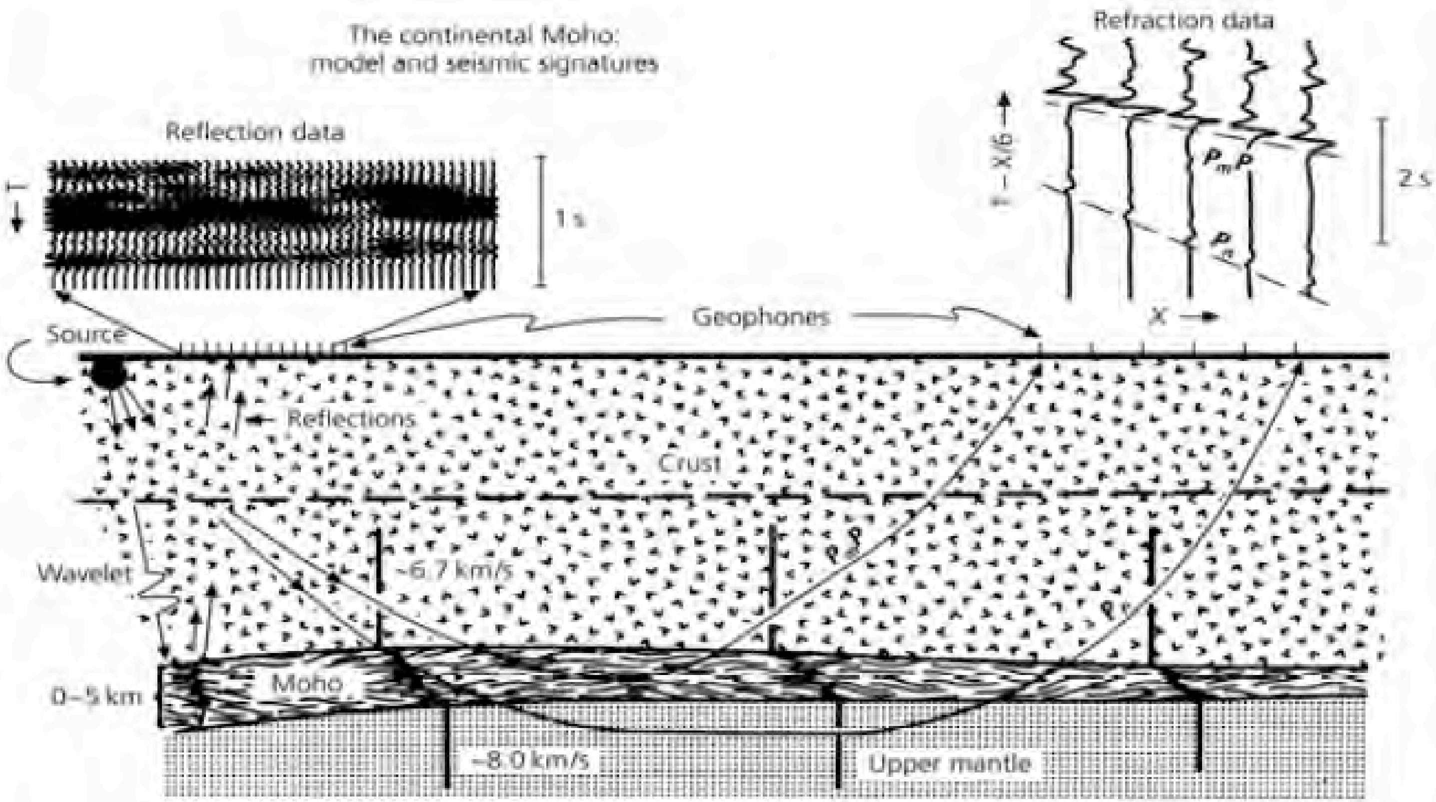
fat ray representing wave path



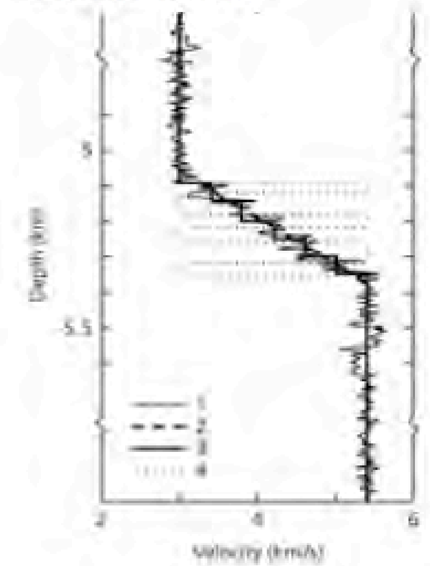
controlled source seismology

reflection seismics imaging reflectivity pattern, topography of interfaces

Frequencies: 5 Hz – 50+ Hz



The modeling of layer boundaries depends on the wavelength of the dominant wave



refraction and reflection seismics, oldest seismic imaging methods.
most reliable yet selective information about crustal structure

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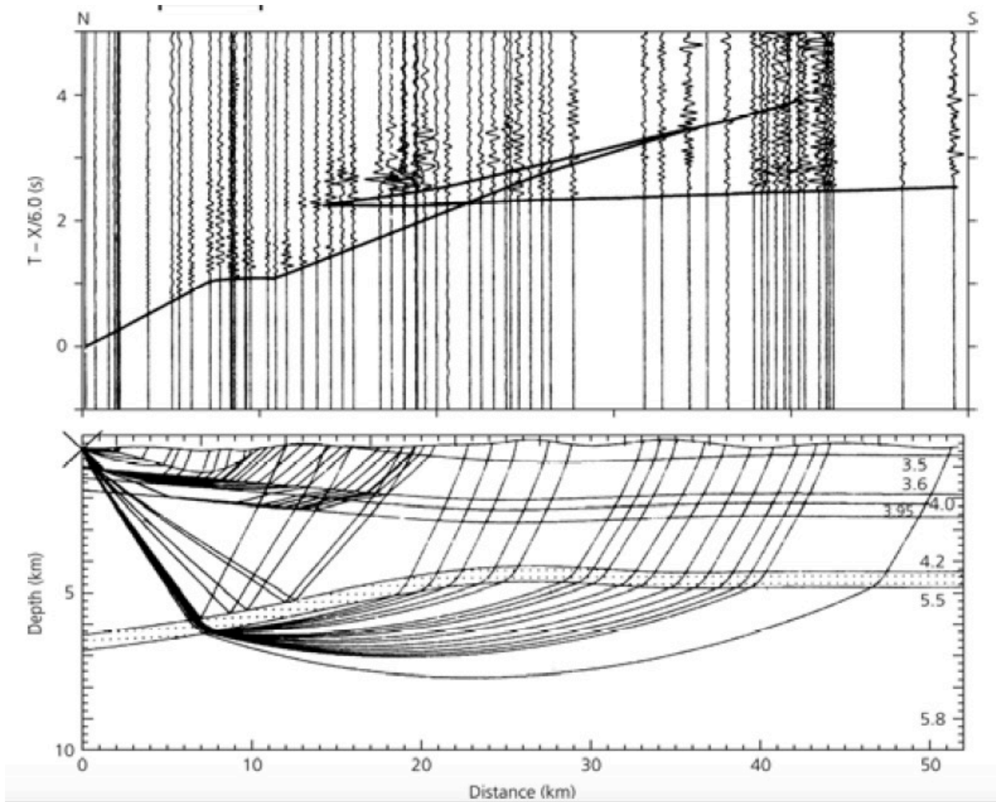
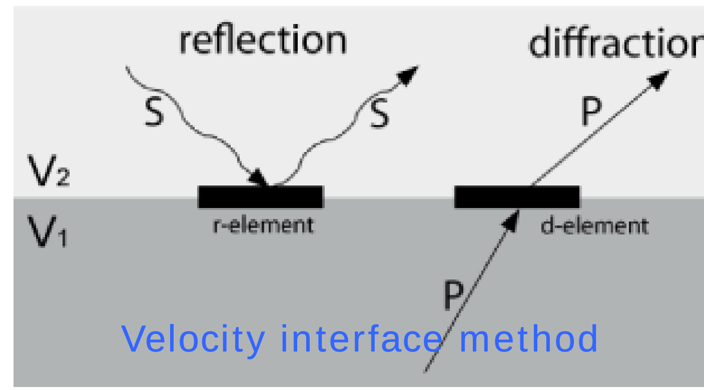
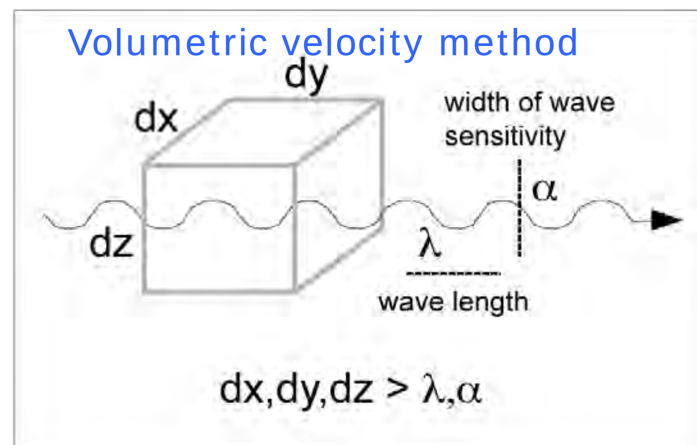
controlled source seismology

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

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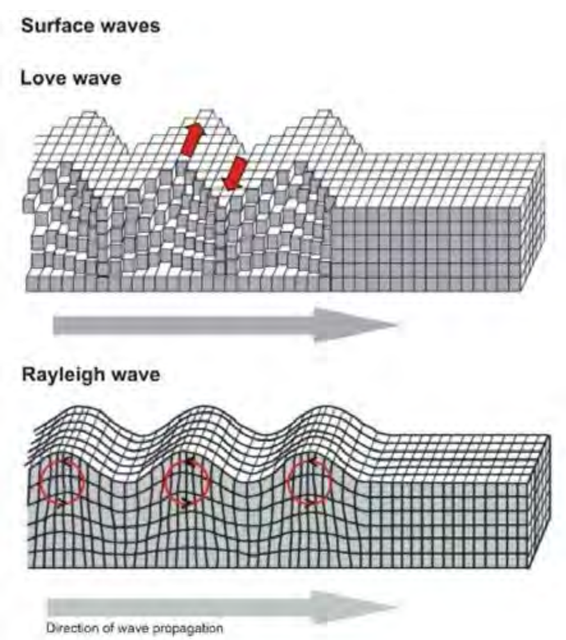
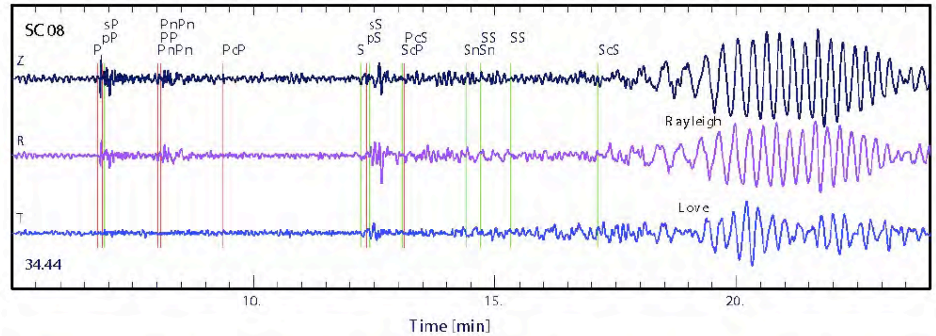
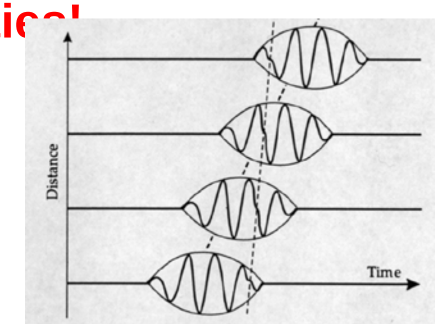
Surface wave tomography

Frequencies: 0.03 Hz – 0.004 Hz

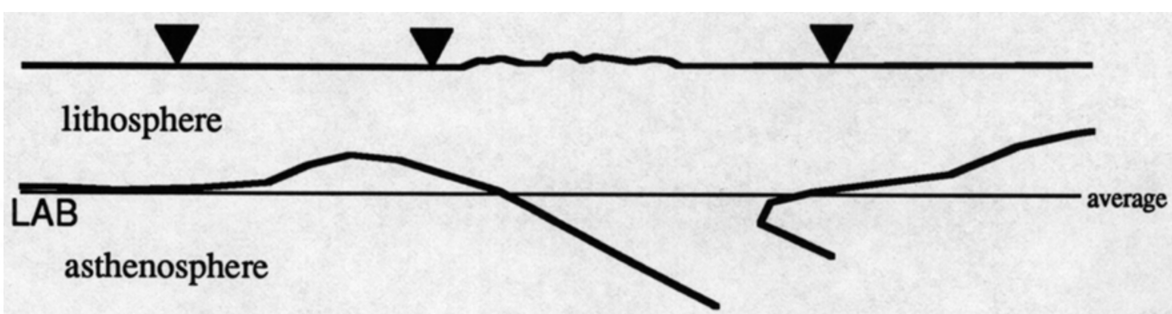


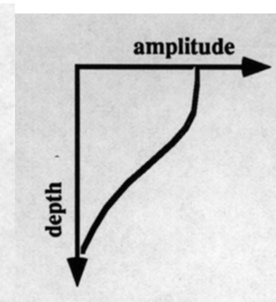


Dispersion: different frequency waves travel with different velocities, => differentiate phase and group velocities!



surface waves are excellent to illuminate the upper mantle
- asthenosphere, the MOR, cratons and large plumes





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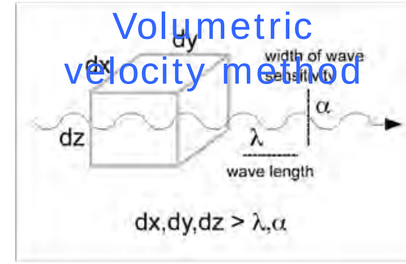
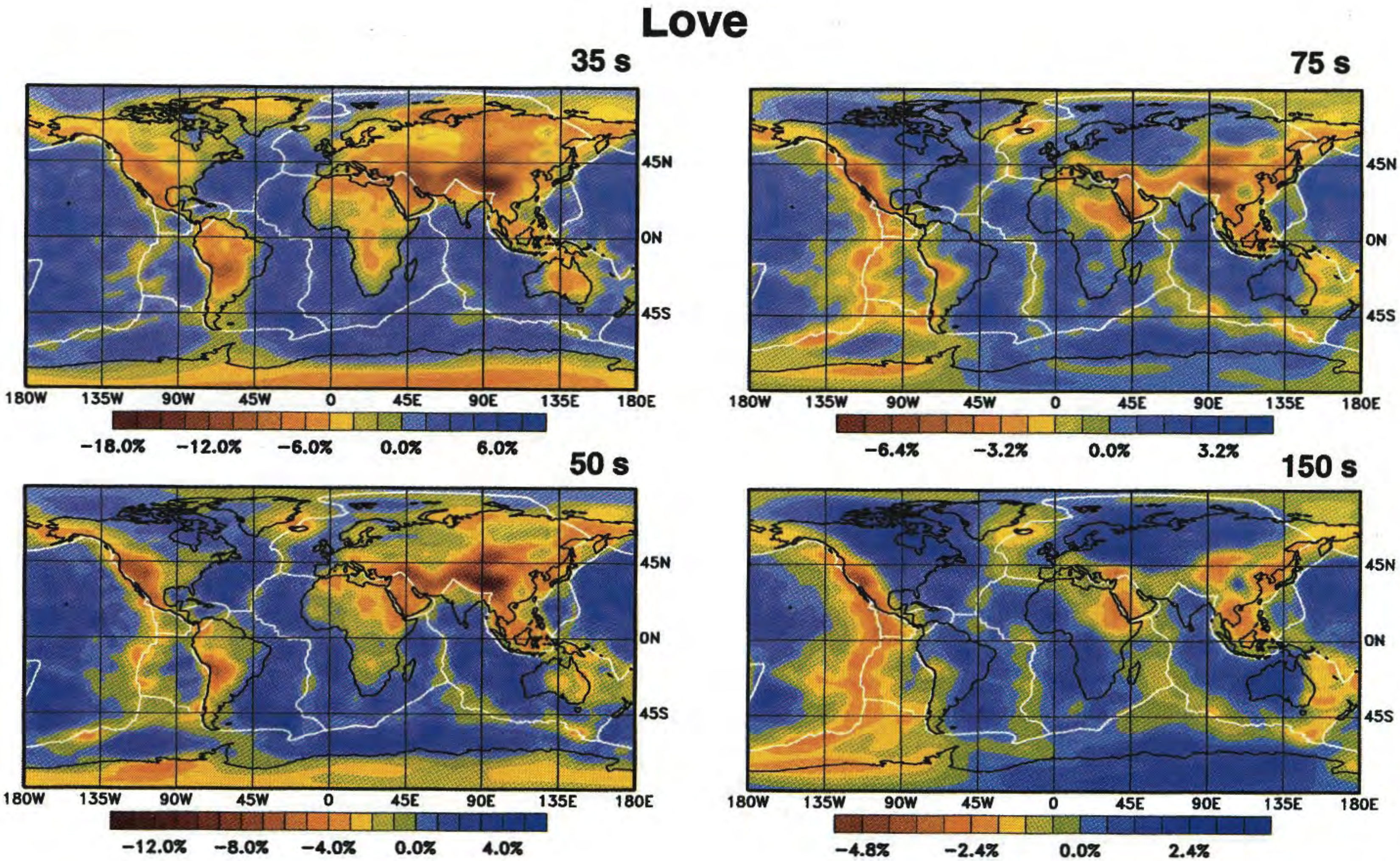
Surface wave tomography- -phase velocity maps

Increasing depth sensitivity with increasing wave length

Volumetric velocity method



cont. crust



Ekström, Tromp and Larson (1997)

MOR, large plumes, no difference oceanic + young cont. lithosphere

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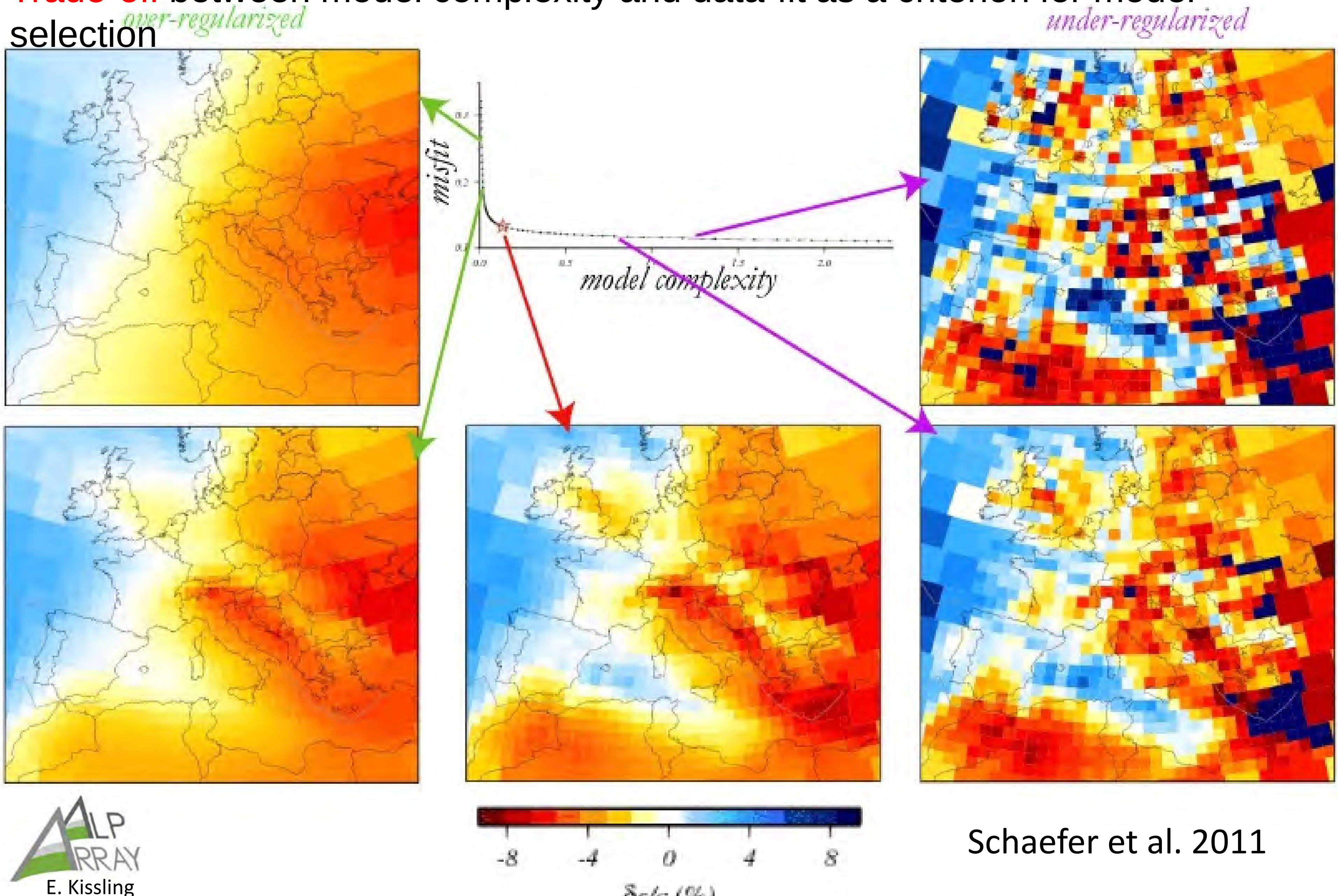
Tomography results depend on damping!

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



Schaefer et al. 2011

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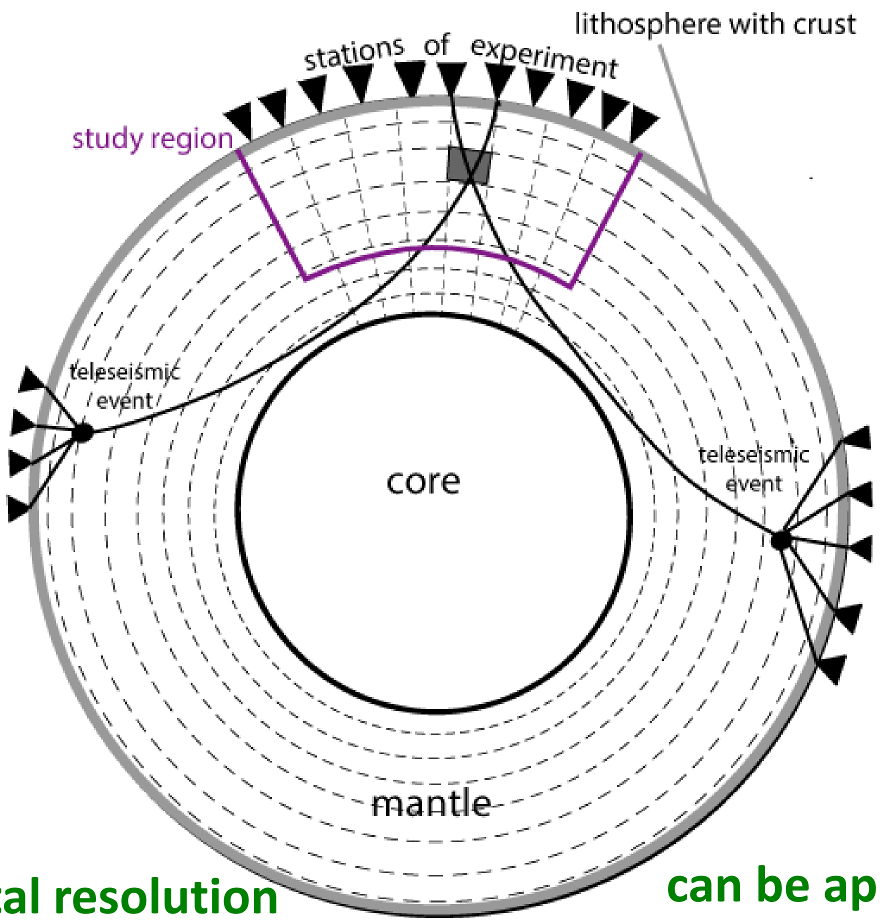
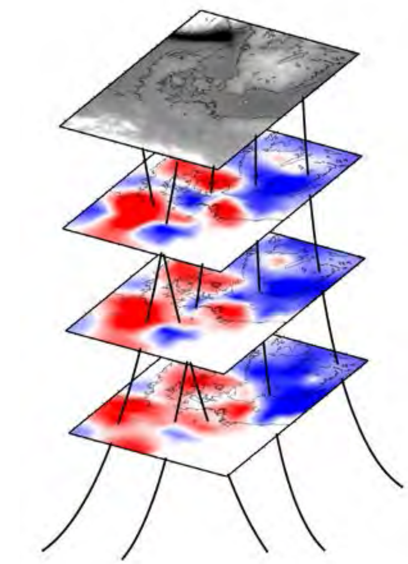
teleseismic (body wave) tomography TET

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



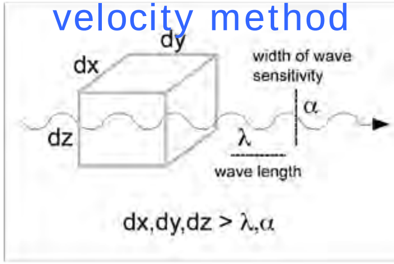
poor crustal resolution



frequencies: 0.3 Hz – 3 Hz

can be applied everywhere

Volumetric velocity method



global data set used: Int. Seism. Center ISC

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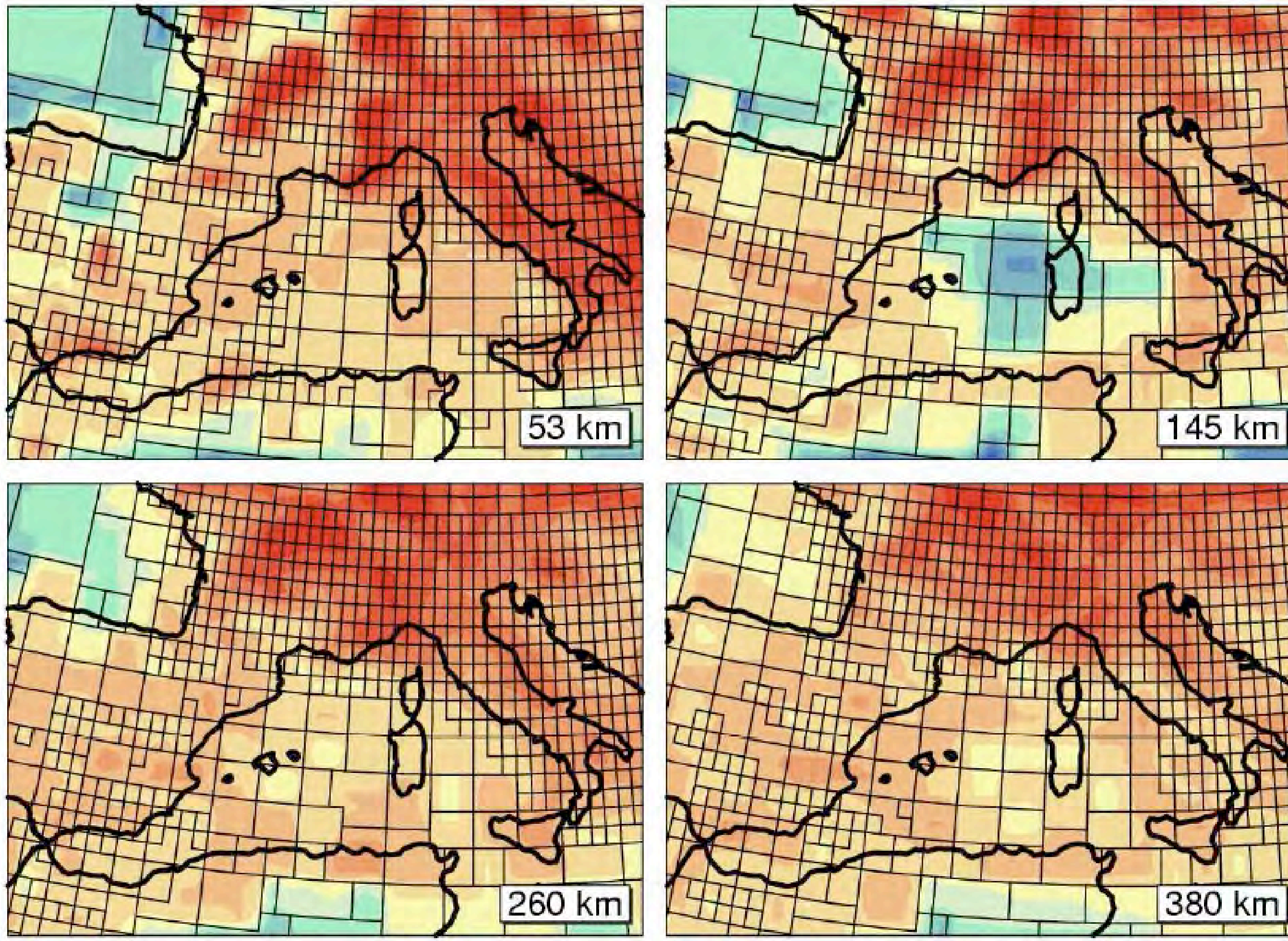
teleseismic (body wave) tomography TET

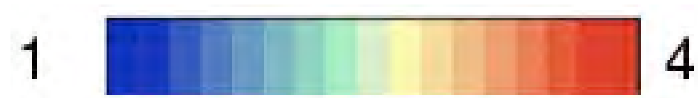
global and regional

cell size adjusted relative to hit count

(minimal cell size according to shortest wave length)



Bijwaard & Spakman 2000



10log of hit count

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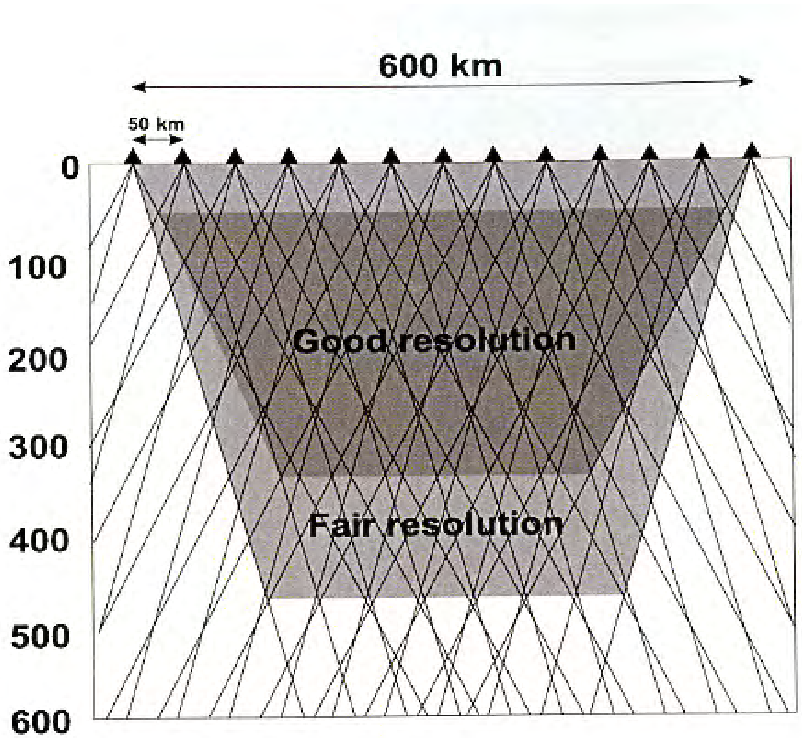
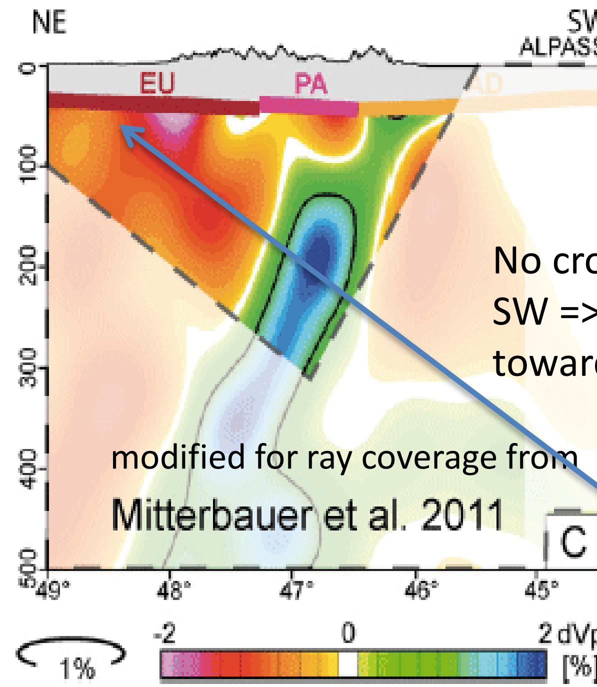
Ray geometry and resolution in teleseismic tomography

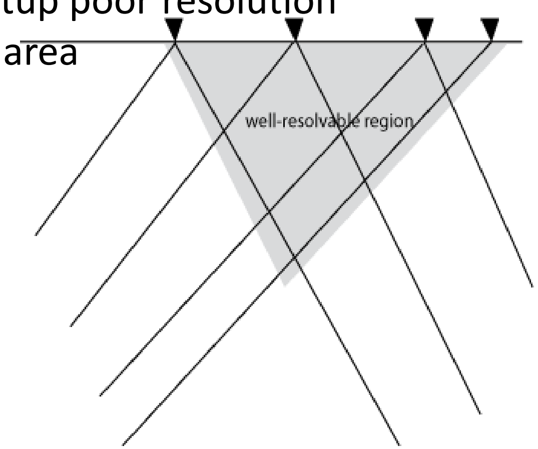


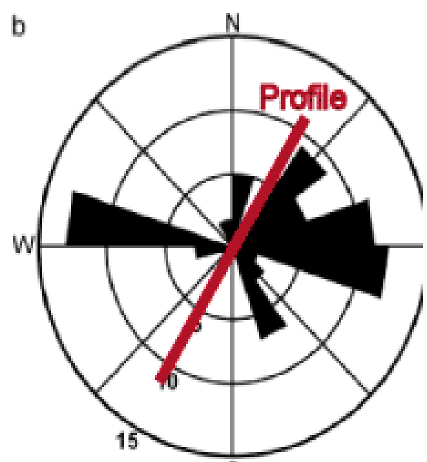


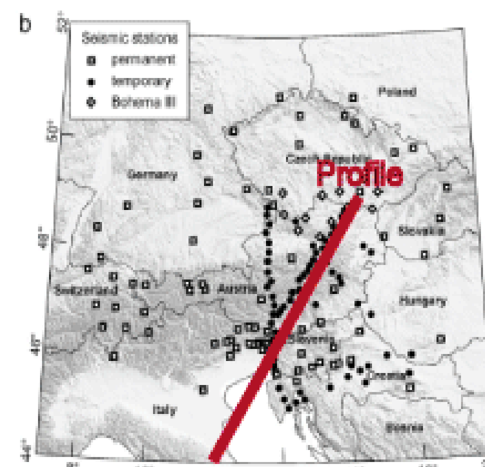
No crossing ray from SW => smearing toward NE at depth

modified for ray coverage from Mitterbauer et al. 2011

With such setup poor resolution outside grey area







Mitterbauer et al. 2011: event and station distribution

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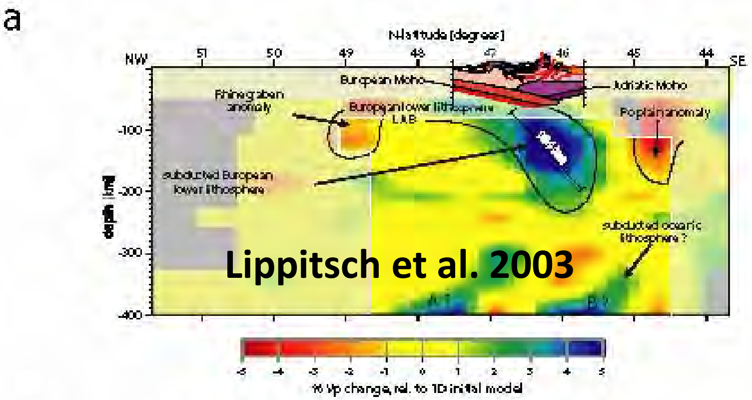
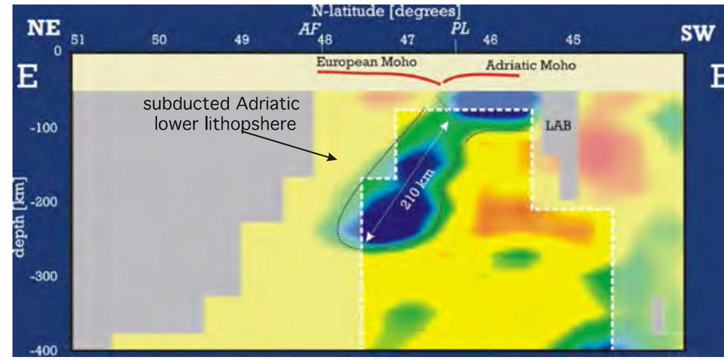
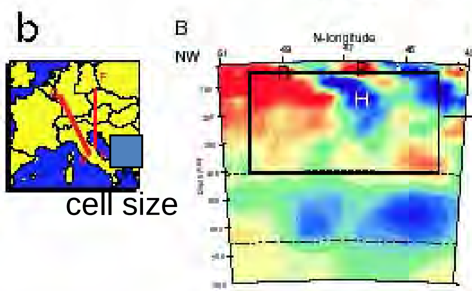
High-resolution teleseismic tomography

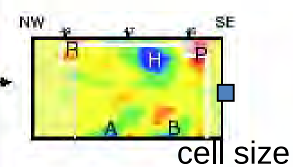
(f.e., Lippitsch et al. 2003)

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







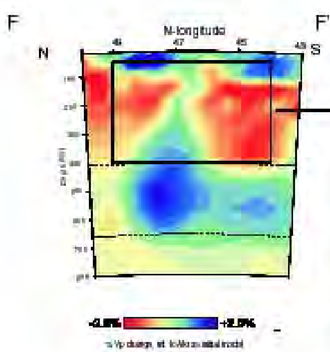


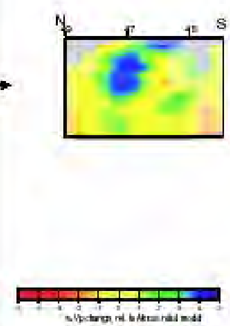
Lippitsch et al. 2003

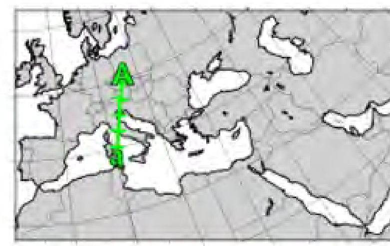
Bijwaard and Spakman 2000

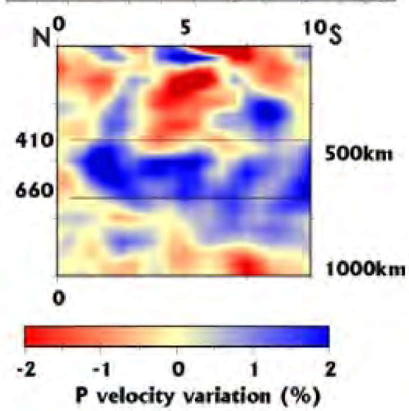
small high-quality data set

ISC data









ISC data

Piromallo and Morelli 2003

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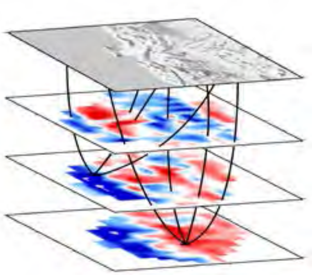
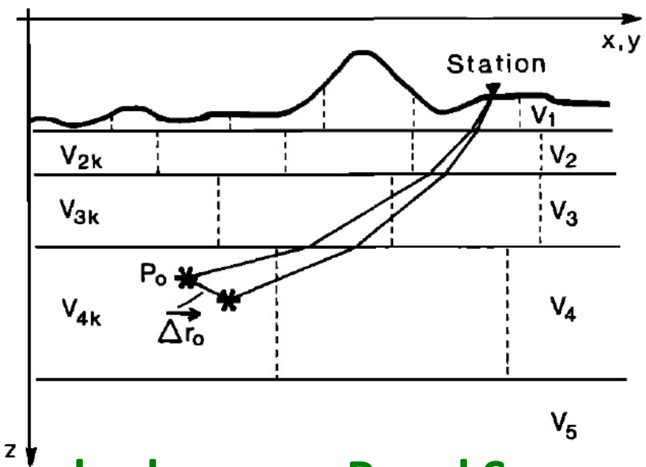
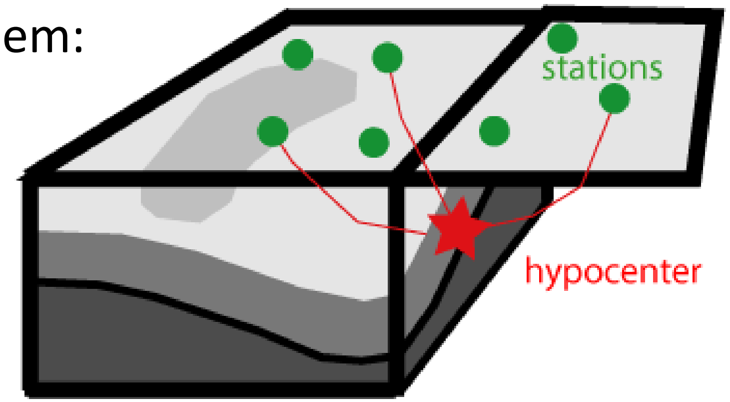


local earthquake tomography LET

The coupled hypocenter-3D velocity problem:



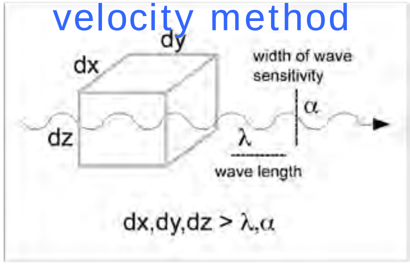


body waves P and S

true 3D method, high-resolution and potentially very reliable 3D velocity information if consistent data set is established.

Frequencies: 0.5 Hz – 20+ Hz

Volumetric velocity method



only applicable in regions with local seismicity

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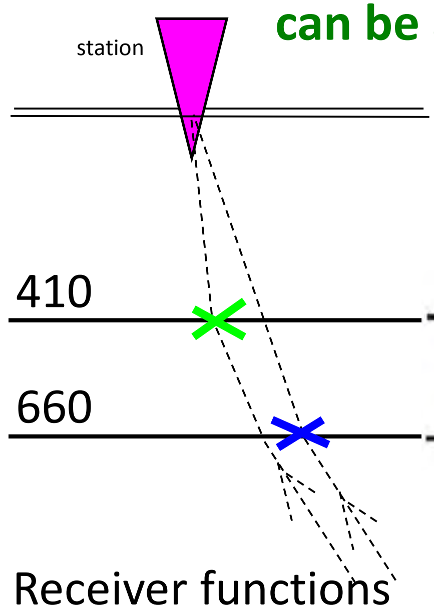
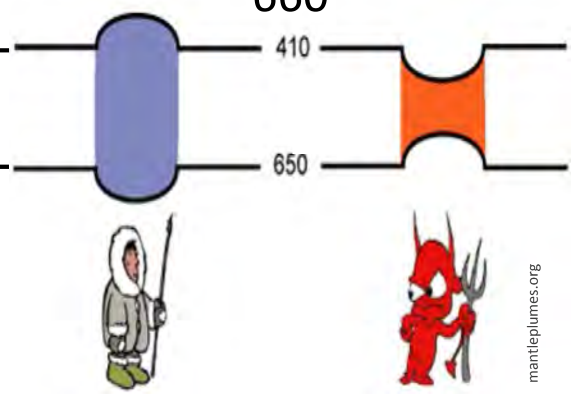
receiver functions
tomography RF

can be applied everywhere

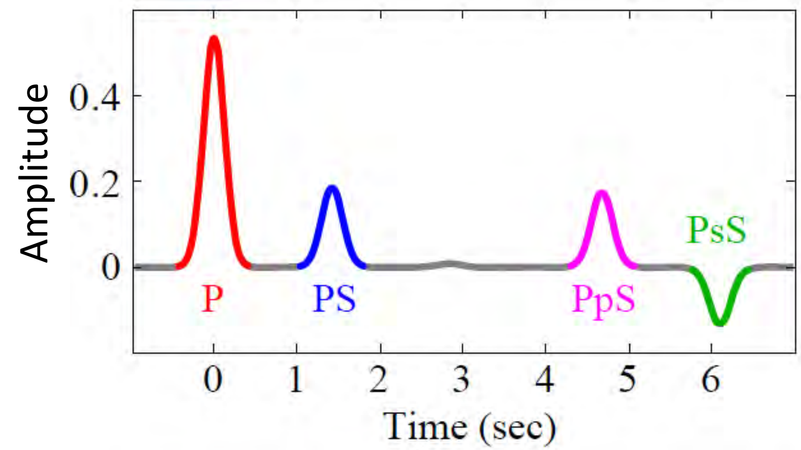


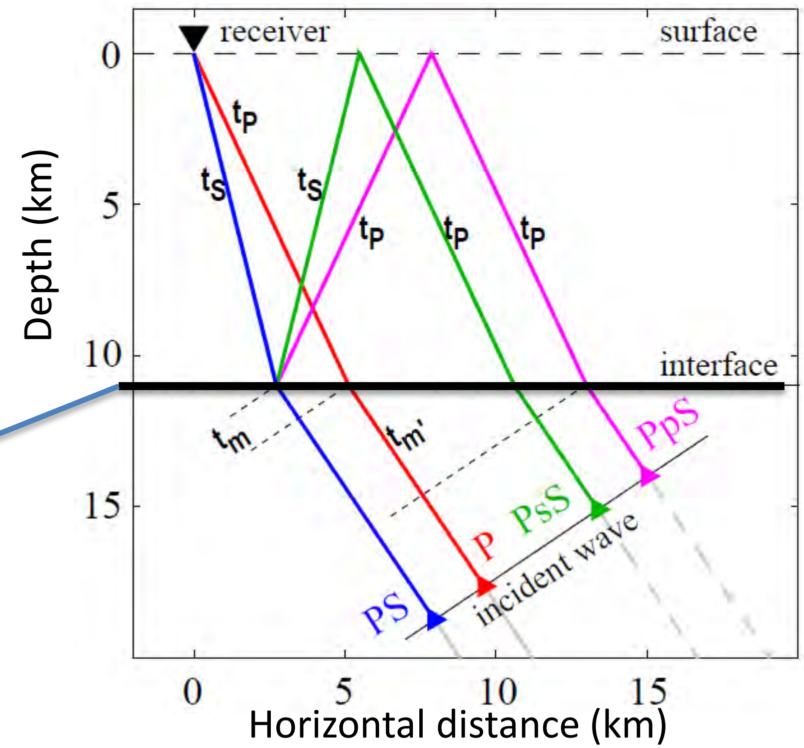
Diagnosis based on geometry of '410' and '660'



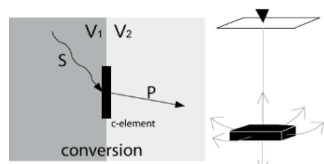
First-order velocity discontinuity between two isotropic layers

Corresponding receiver function





Velocity interface method



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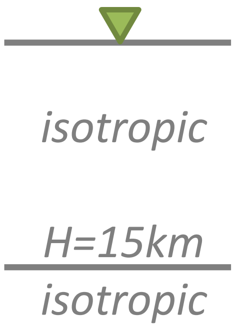
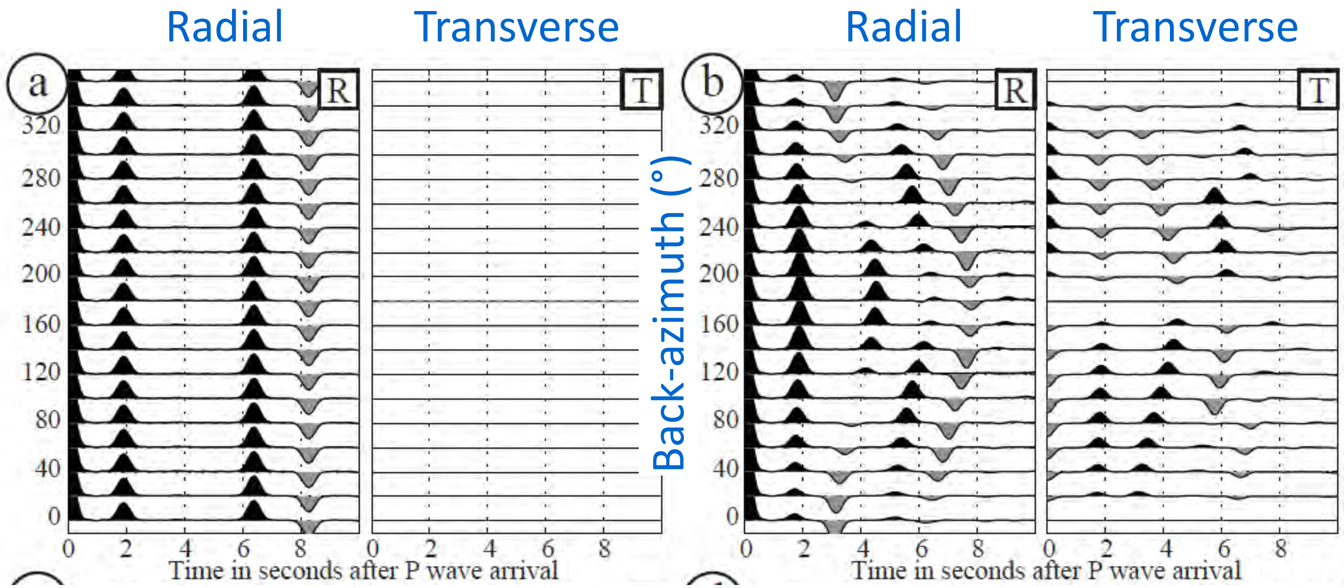
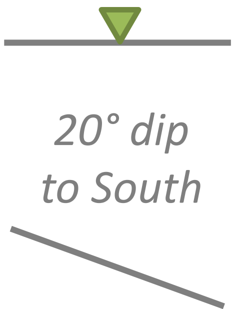
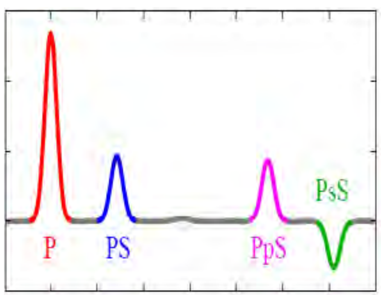
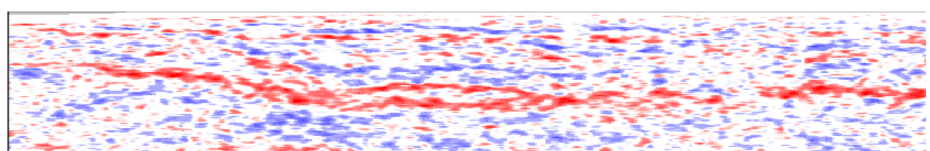
receiver functions tomography RF





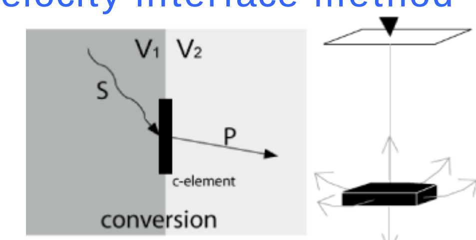






excellent to map topography of first-order interfaces

Velocity interface method



intrinsic absolute depth uncertainty

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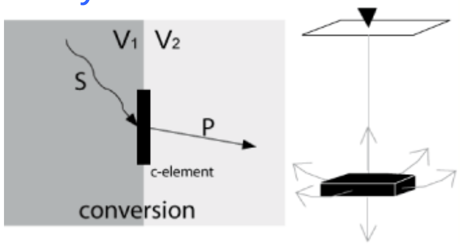
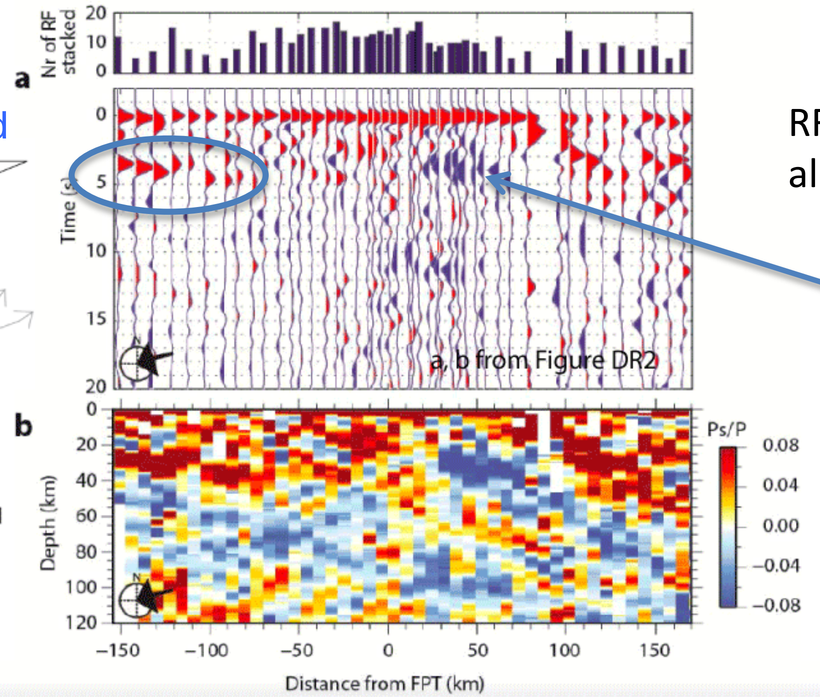
main result of RF: topography of converting interface

Velocity interface method



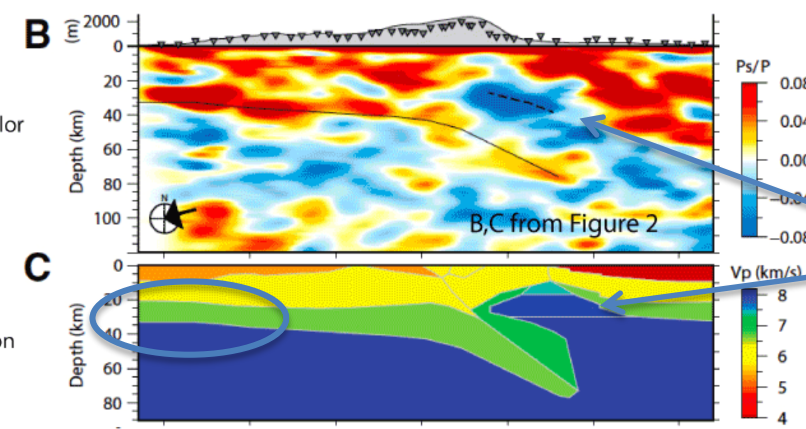


color converted

RF data quality non-uniform along profile

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

overly optimistic re-sampling and display



smoothed color converted

interpretation

overly optimistic color interpolation + smoothing

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

Zhao et al. 2015 Geology
(figure in supplement)

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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

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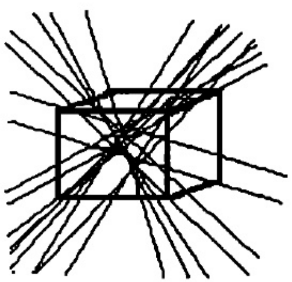
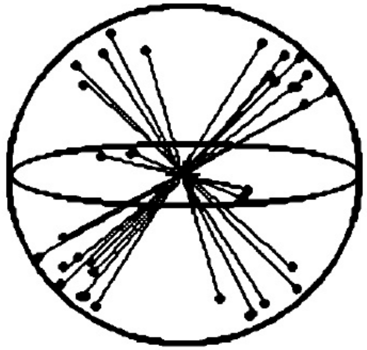
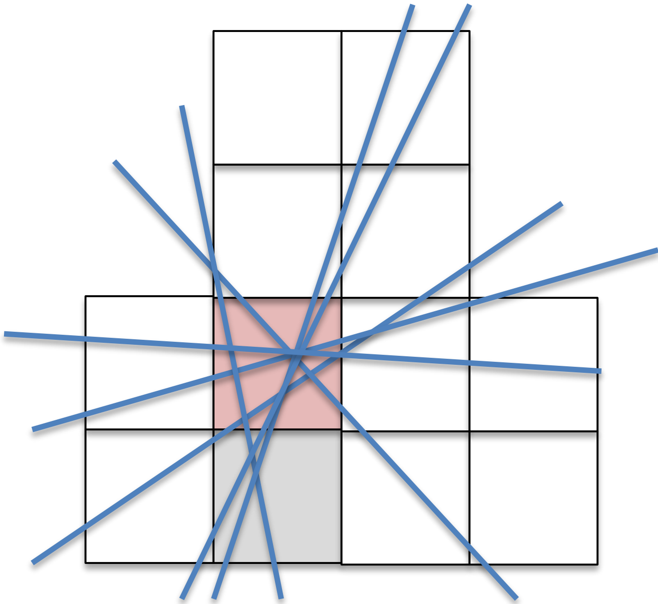
model resolution

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

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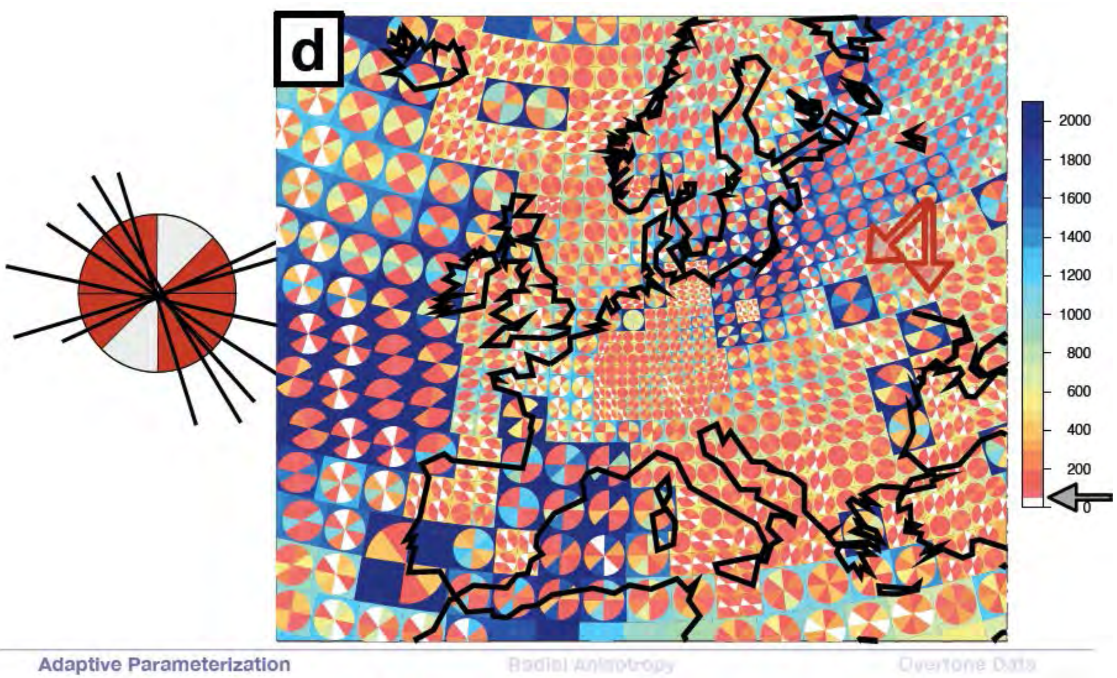
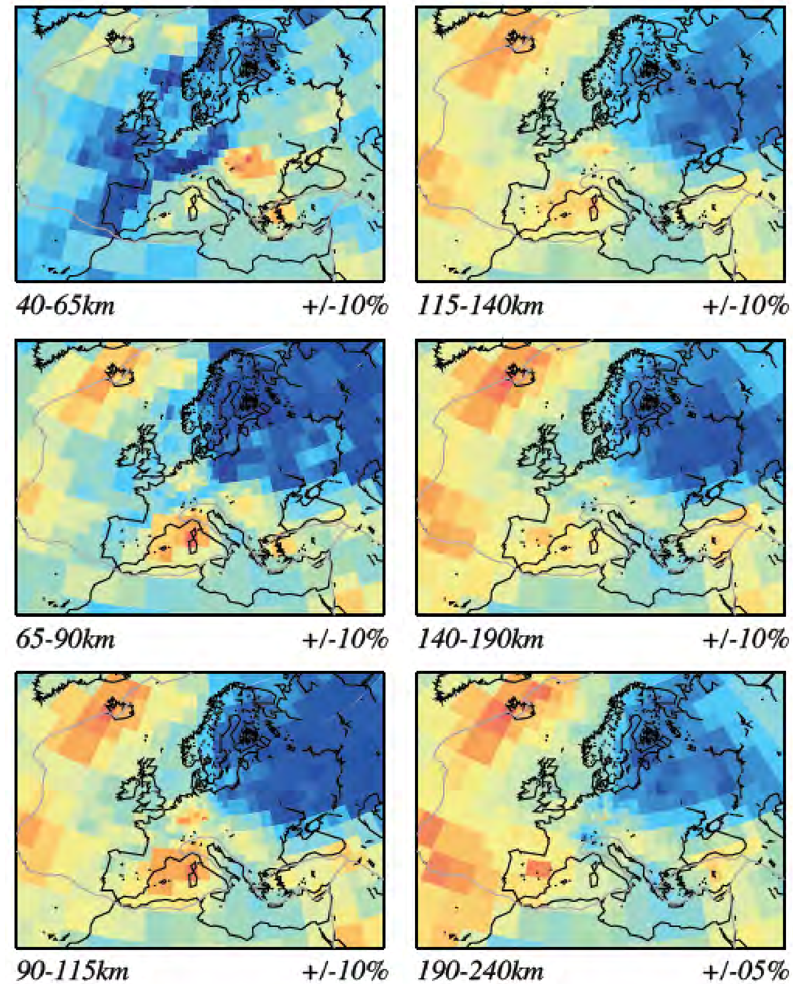
cell size adjusted due to 2D cross firing

Modern regional and global surface wave tomography

(minimal cell size according to shortest wave length)



Schaefer et al. 2011



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visualizing (model) resolution matrix

$m^{est} = \mathbf{R}\, m^{true}$

-> R is an operator that tells us how well our model reflects the true model.

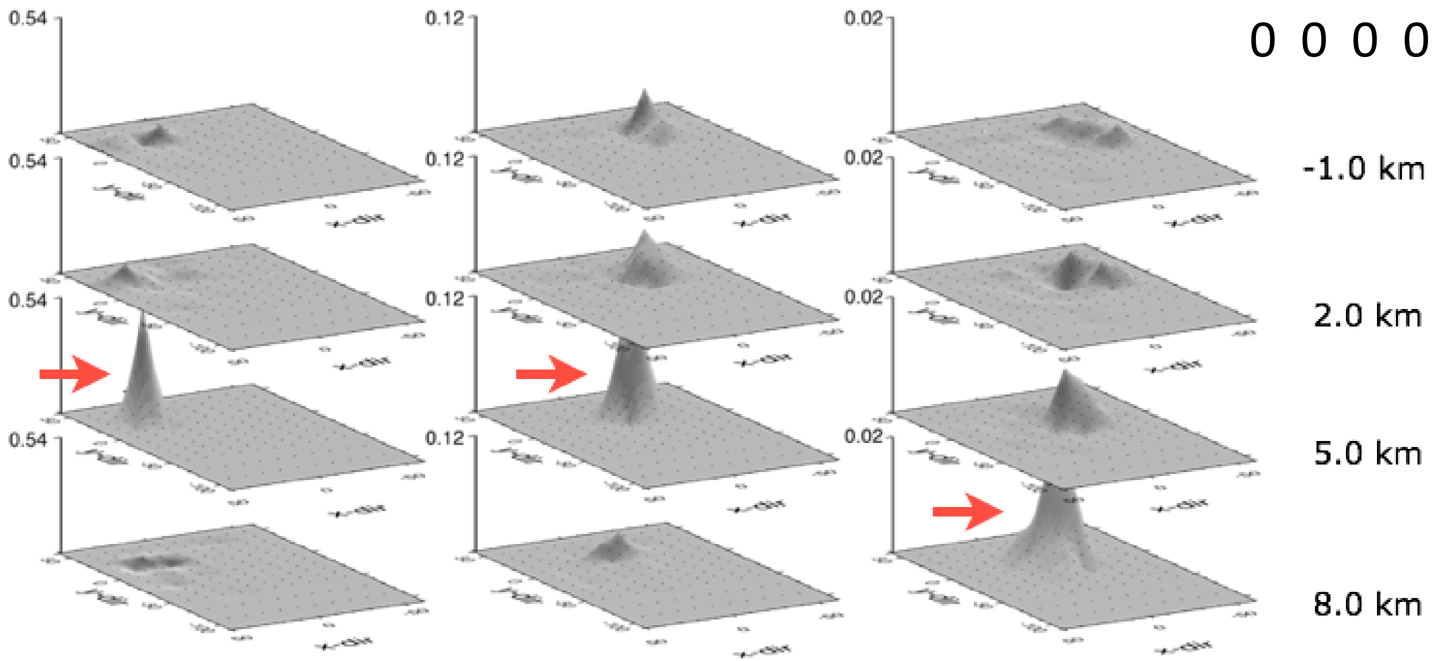
R is a m* m matrix. Each row of R describes the dependence of one model parameter on all other model parameters.

RDE= resolution diagonal element (→)

perfect resolution (for 5*5 matrix):

$$\begin{matrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{matrix}$$

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



little smearing

little vertical smearing

strong vertical and horizontal smearing

remaining question: How good is RDE=0.8 or 0.3?

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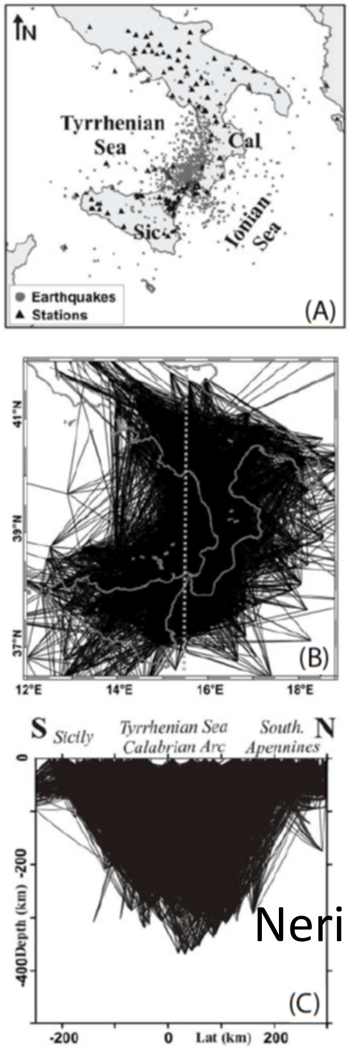
resolution spread function value



example 5*5
resolution matrix

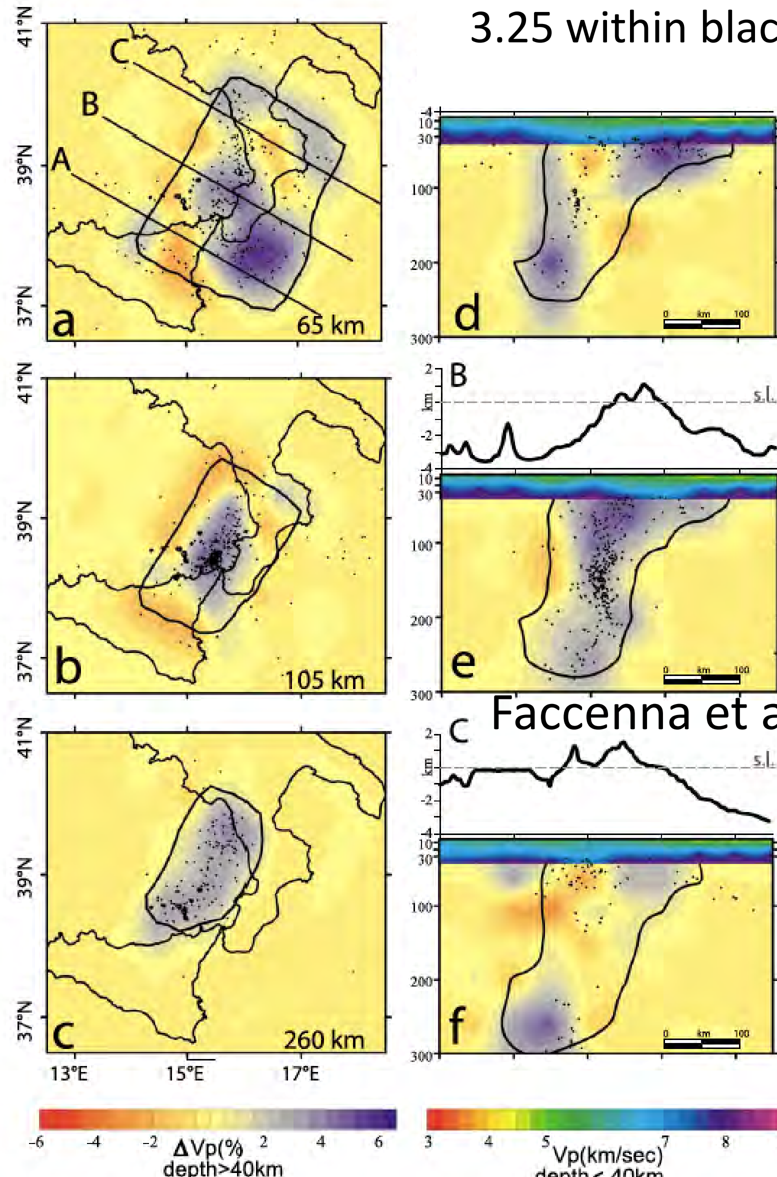
0.5	0.8	0	0.3	1.9
0.8	**0.6**	0.4	0.7	0.1
0	0.4	**0.1**	1.8	2.1
0.3	0.7	1.8	**0.3**	0.5
1.9	0.1	2.1	0.5	**0.7**

sum of non-diagonal elements = spread function

Neri et al. 2009

remaining question:
How good is resolution?

„spread function values are less than 3.25 within black line“



Faccenna et al. 2011

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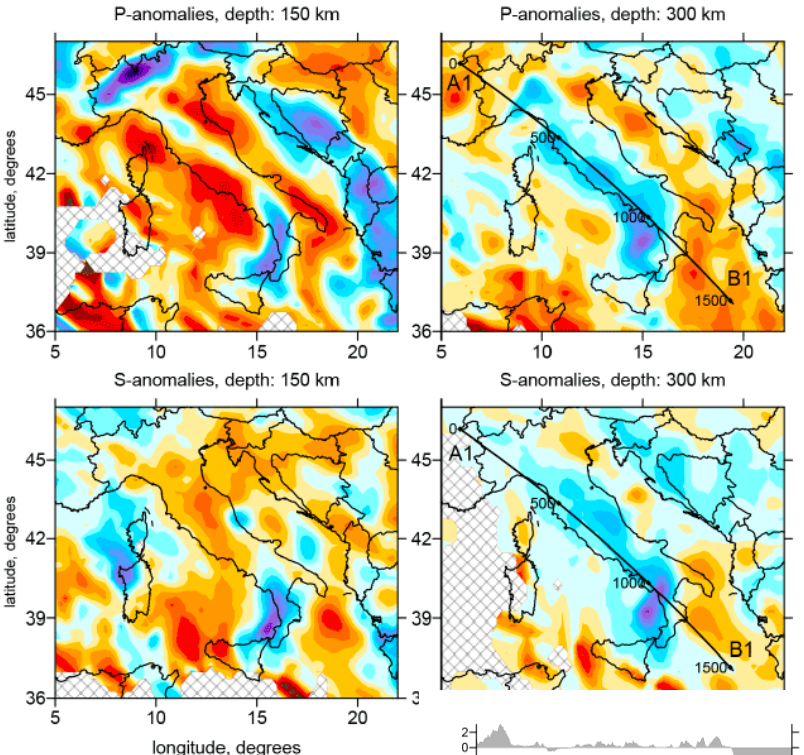
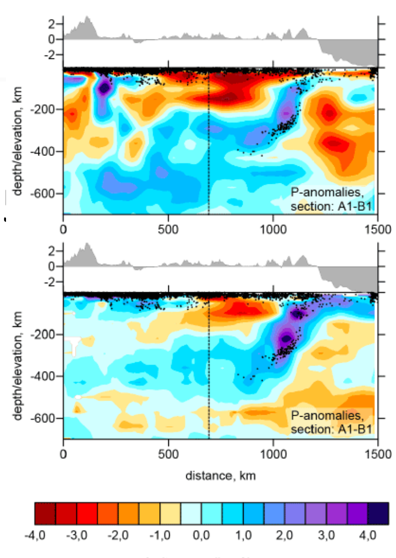
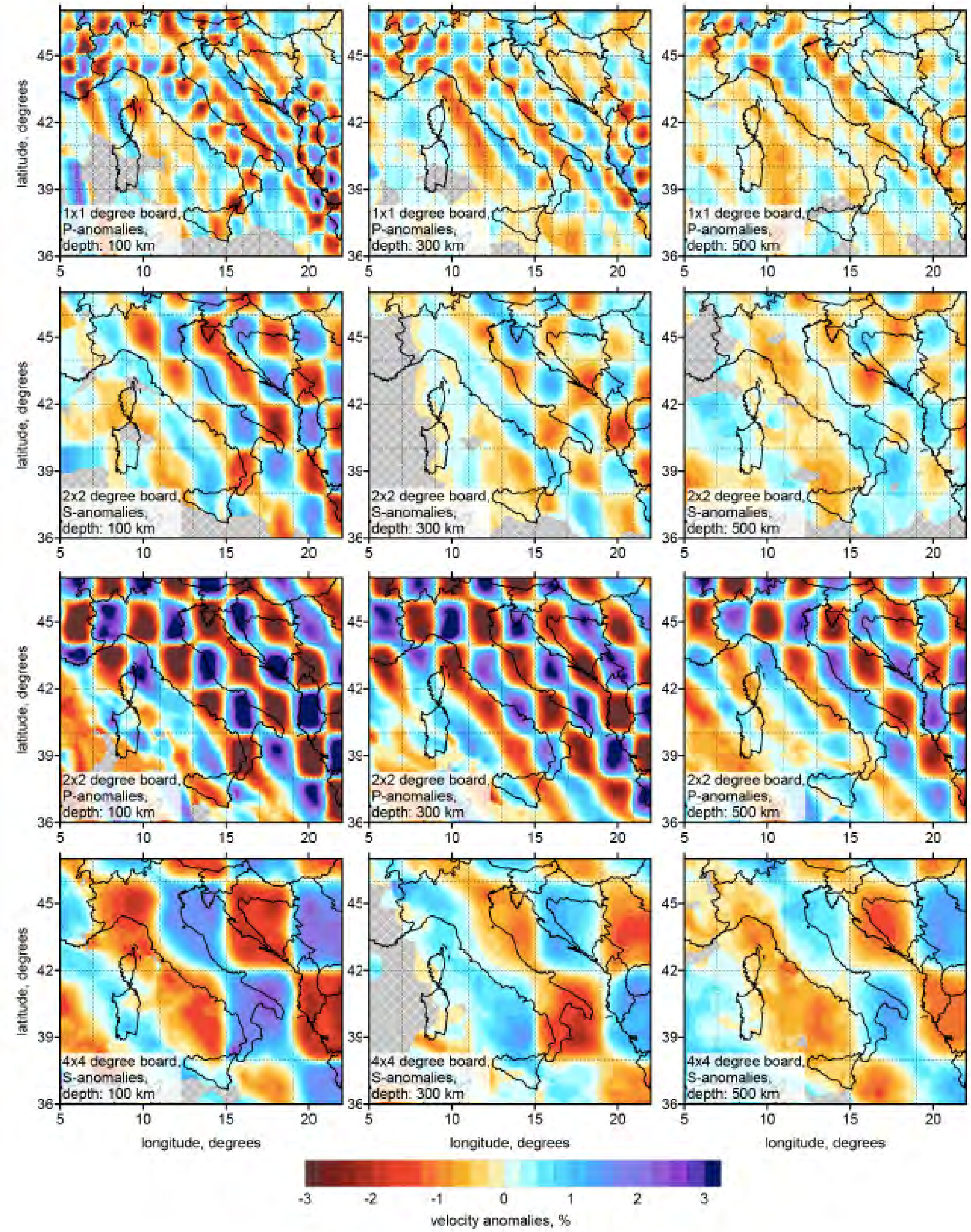
checkerboard testing reveals sensitivity





Koulakev et al. 201



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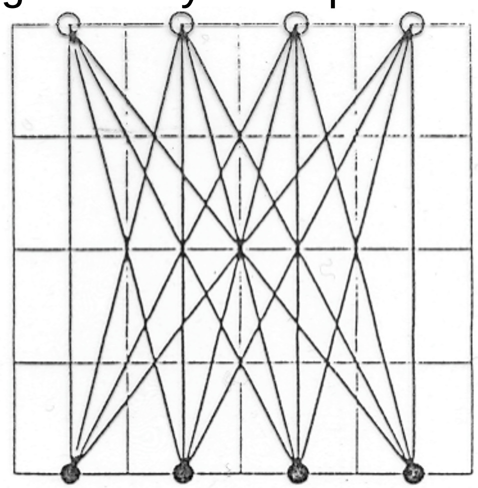
model resolution of tomography

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.”

geometry of experiment

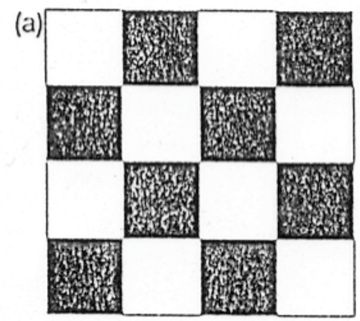


high attenuation

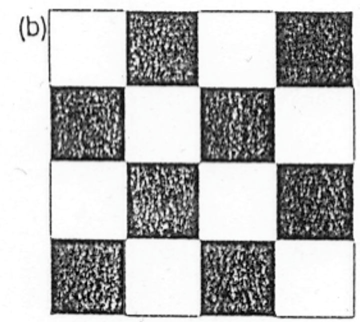
low attenuation

test 1

synthetic model

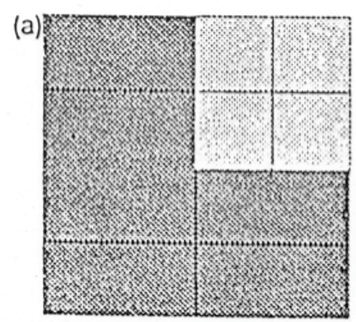


recovered structure

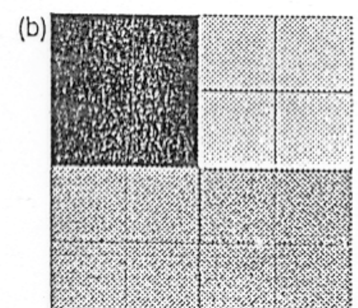


test 2

synthetic model

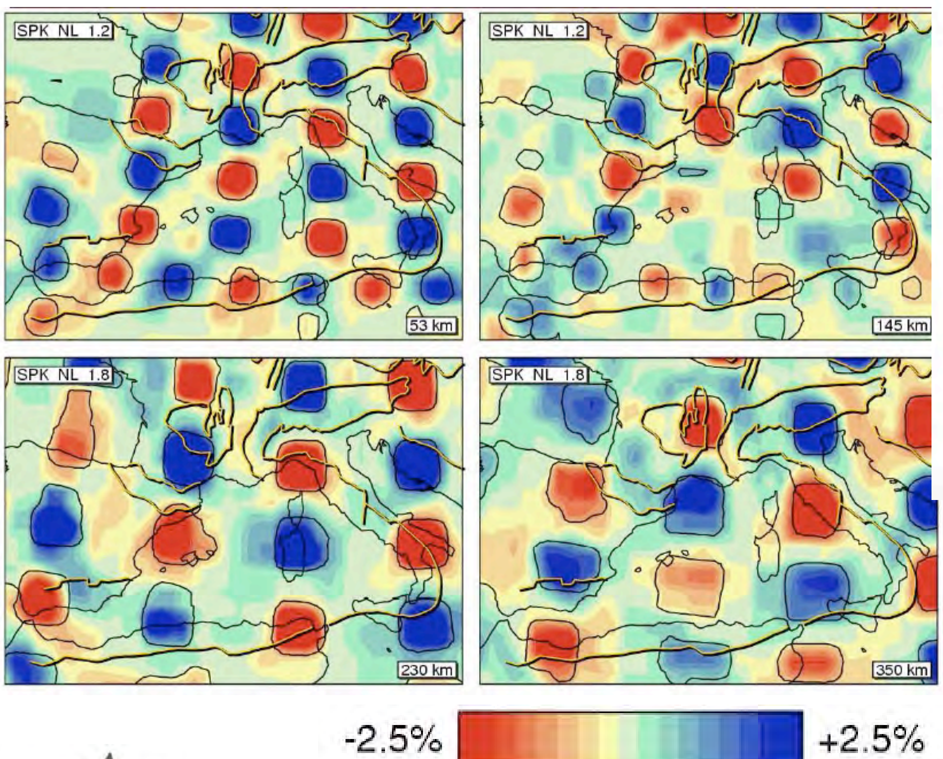


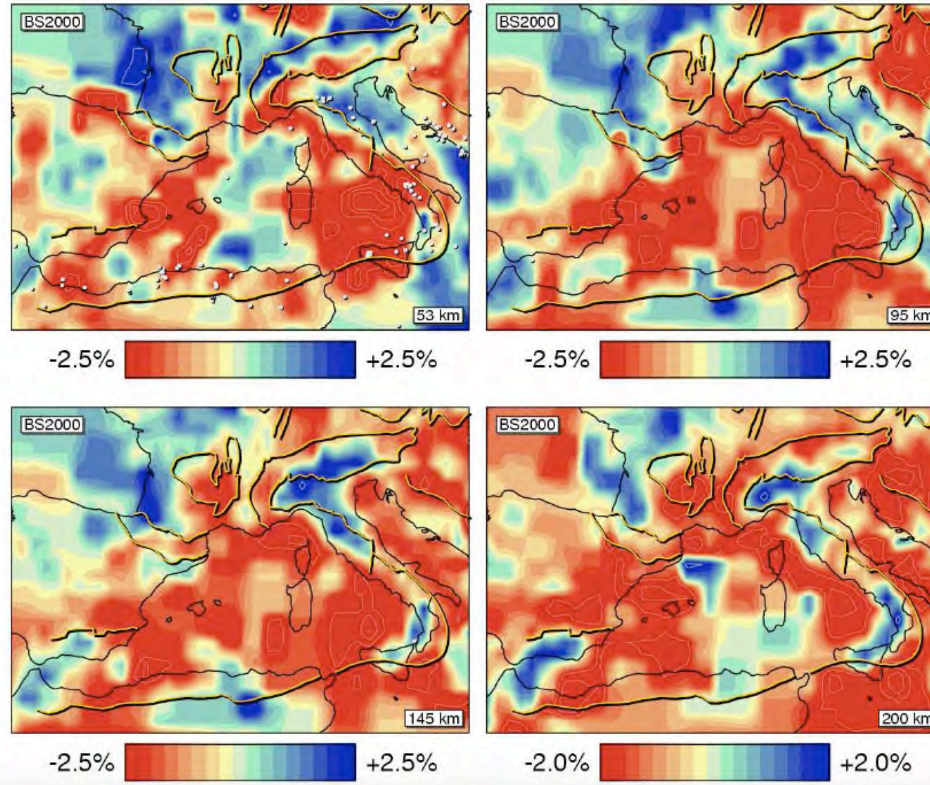
recovered structure



teleseismic (body wave) tomography TET

spike-anomalies sensitivity test





Bijwaard & Spakman 2000

realistic sensitivity testing when avoiding checkboard anomalies

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resolution varies across a tomographic image

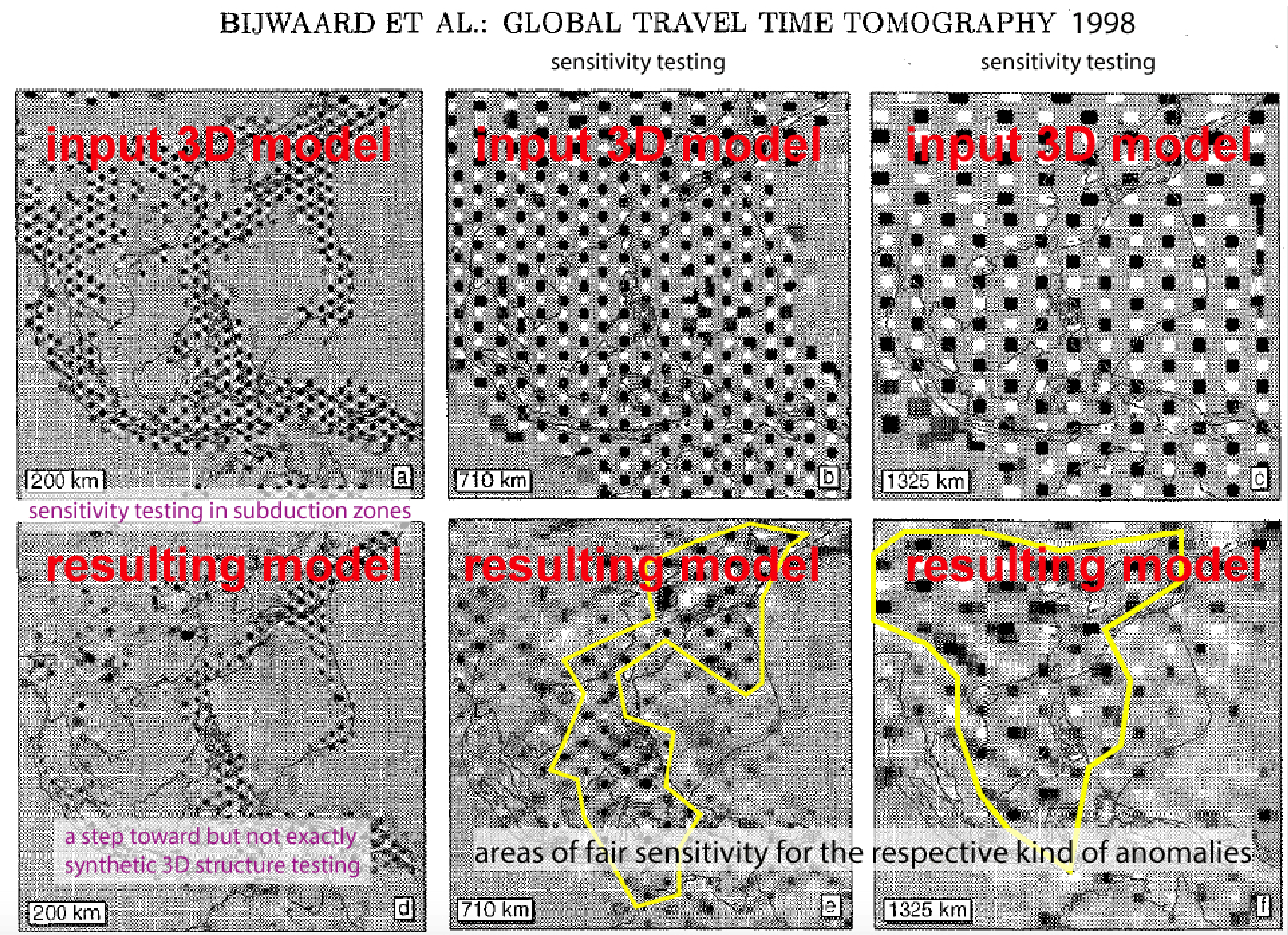
(due to inhomogeneous data and non-Gaussian error distributions)

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



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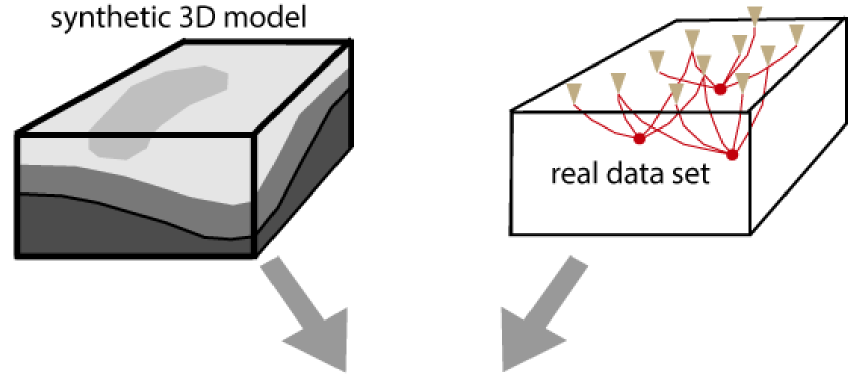
synthetic data testing (artificial model)

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 asses quality of inversion process results

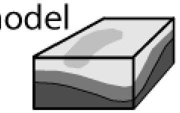


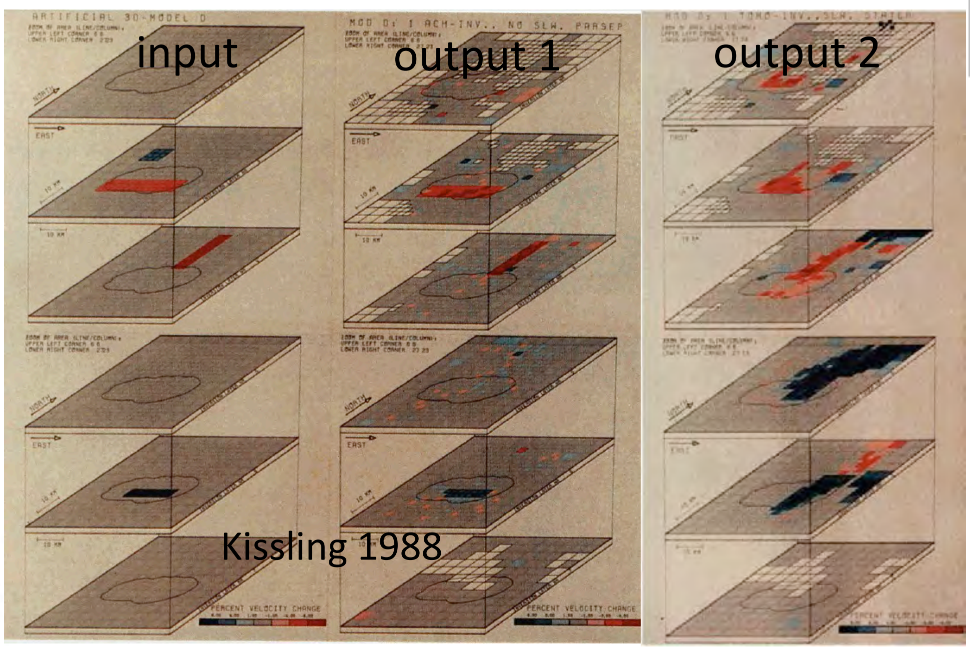
for each source-receiver pair (observation) calculate ray path and travel time for synthetic 3D velocity model

=> synthetic data set

do tomographic inversion

compare
3D tomographic results
with synthetic 3D model





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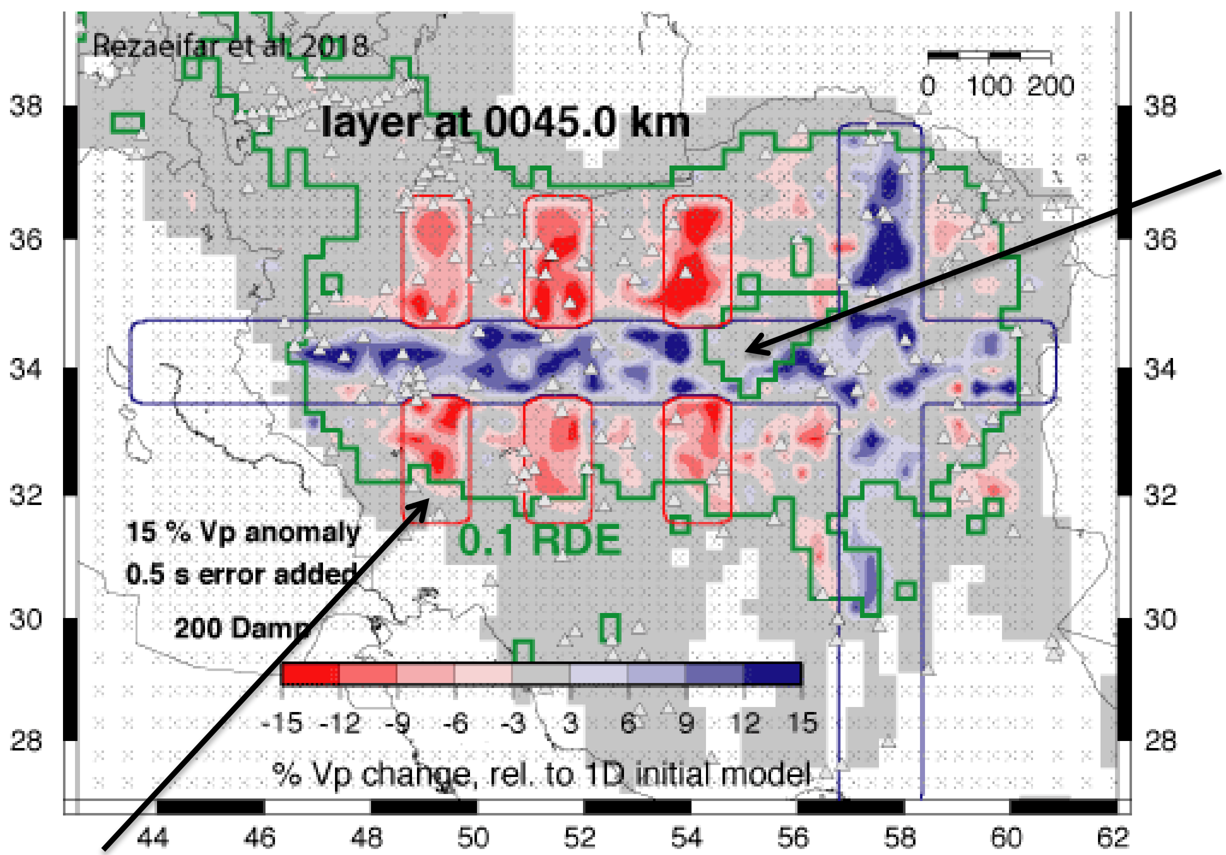
model resolution parameters provide relative information

(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**



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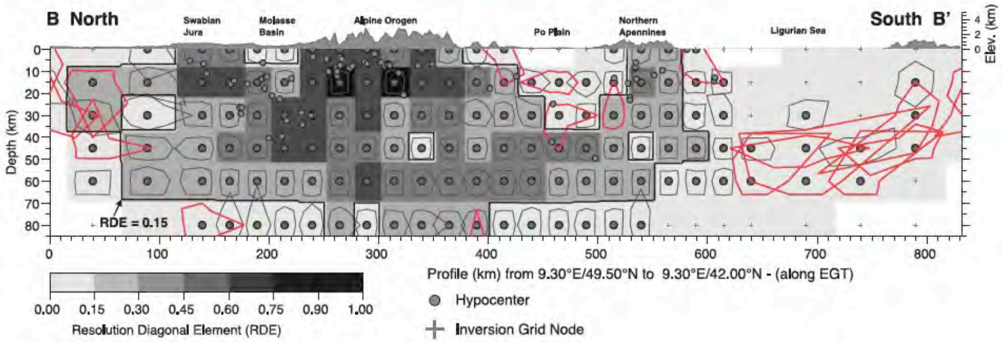
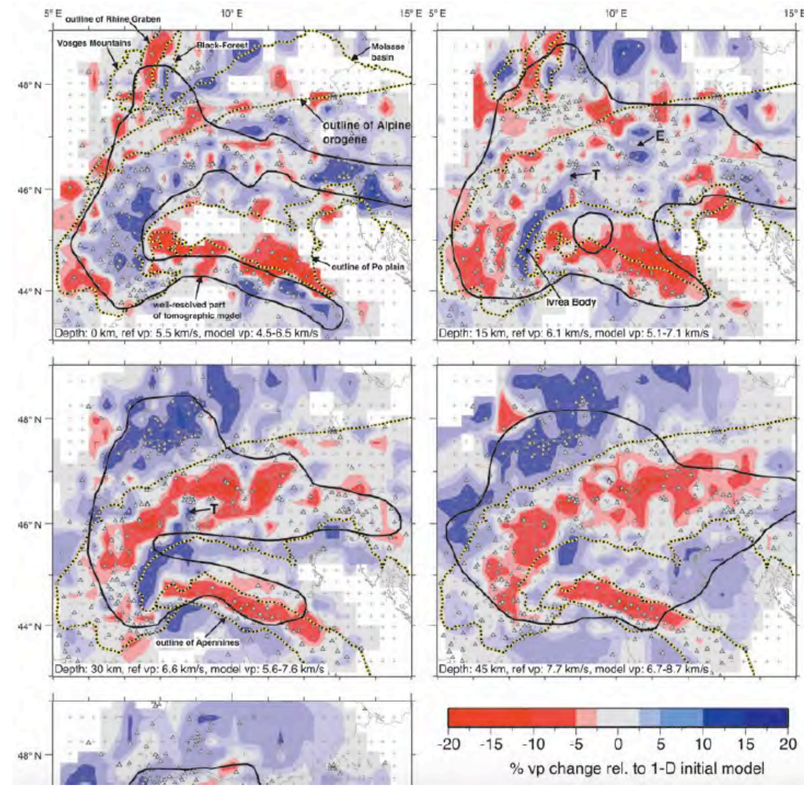
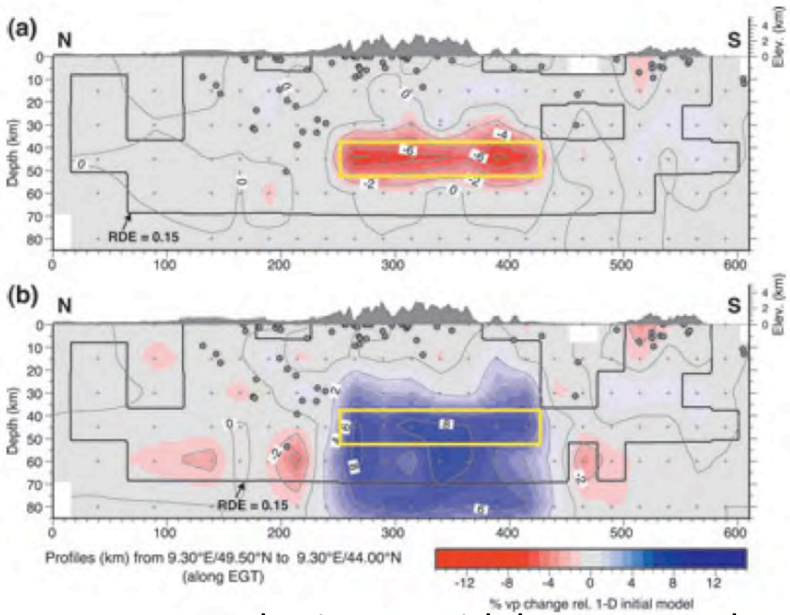
example assessing resolution in LET



RDE and resolution contours (off-diagonal elements)

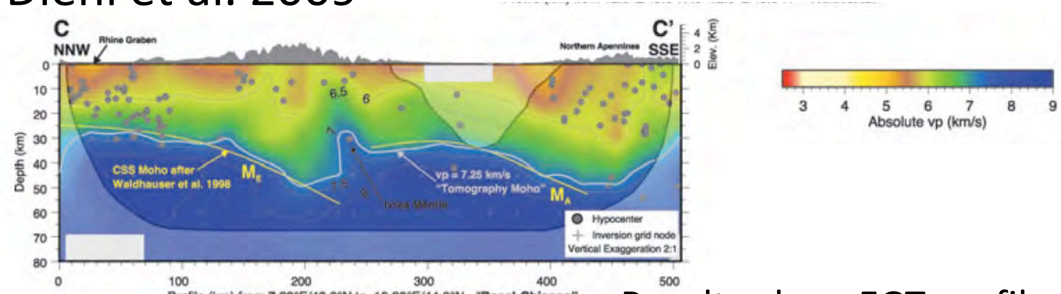


outlining well-resolved region in each layer



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

Diehl et al. 2009



Results along EGT profile

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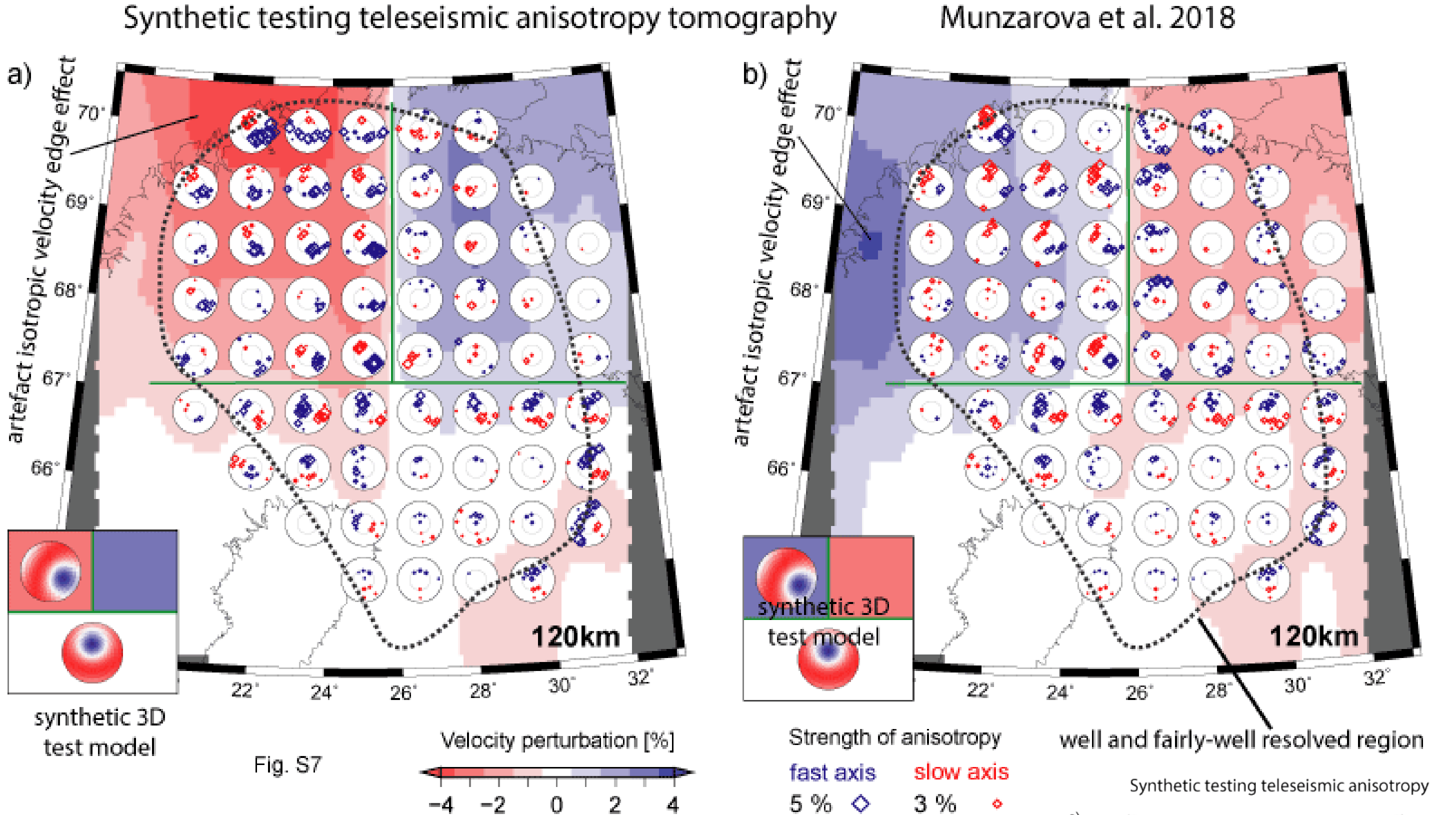
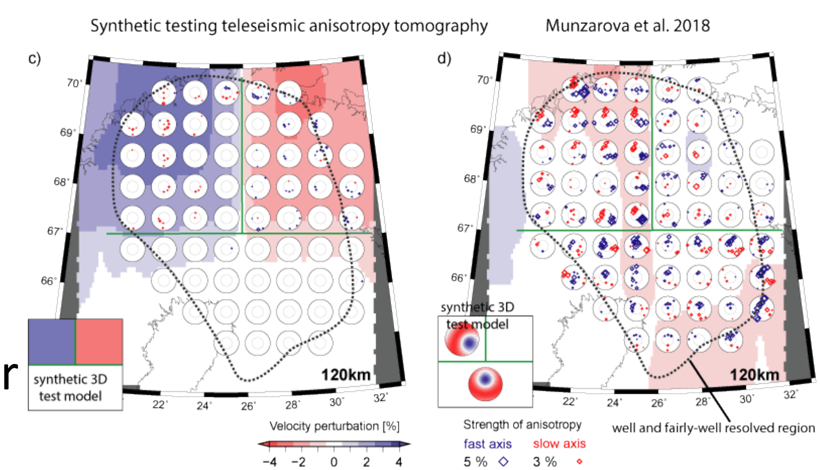
resolution assessment teleseismic anisotropy tomography



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

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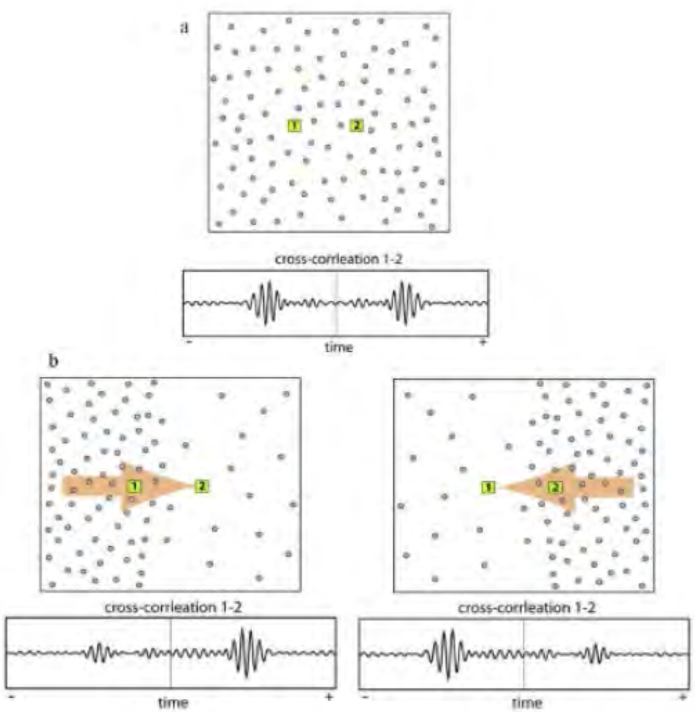
Ambient Noise Tomography (short period surface wave tomography)

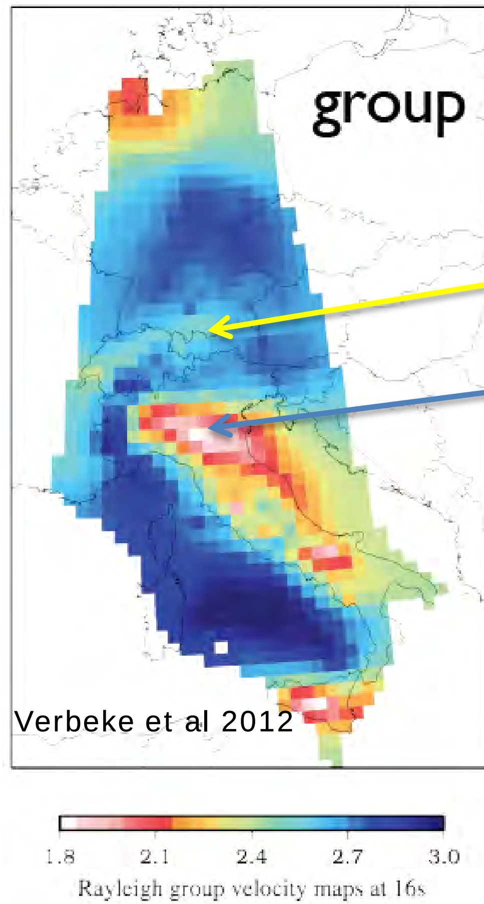
Frequencies: 0.025 Hz – 0.3 Hz

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

requires good distribution of scatterers and noise sources



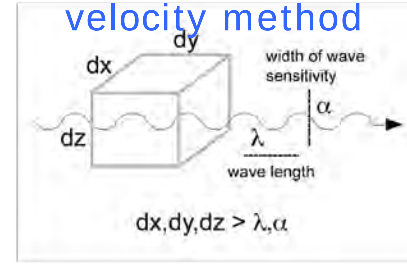
3D by use of many frequencies combined



Molasse basin

Po basin

Volumetric velocity method



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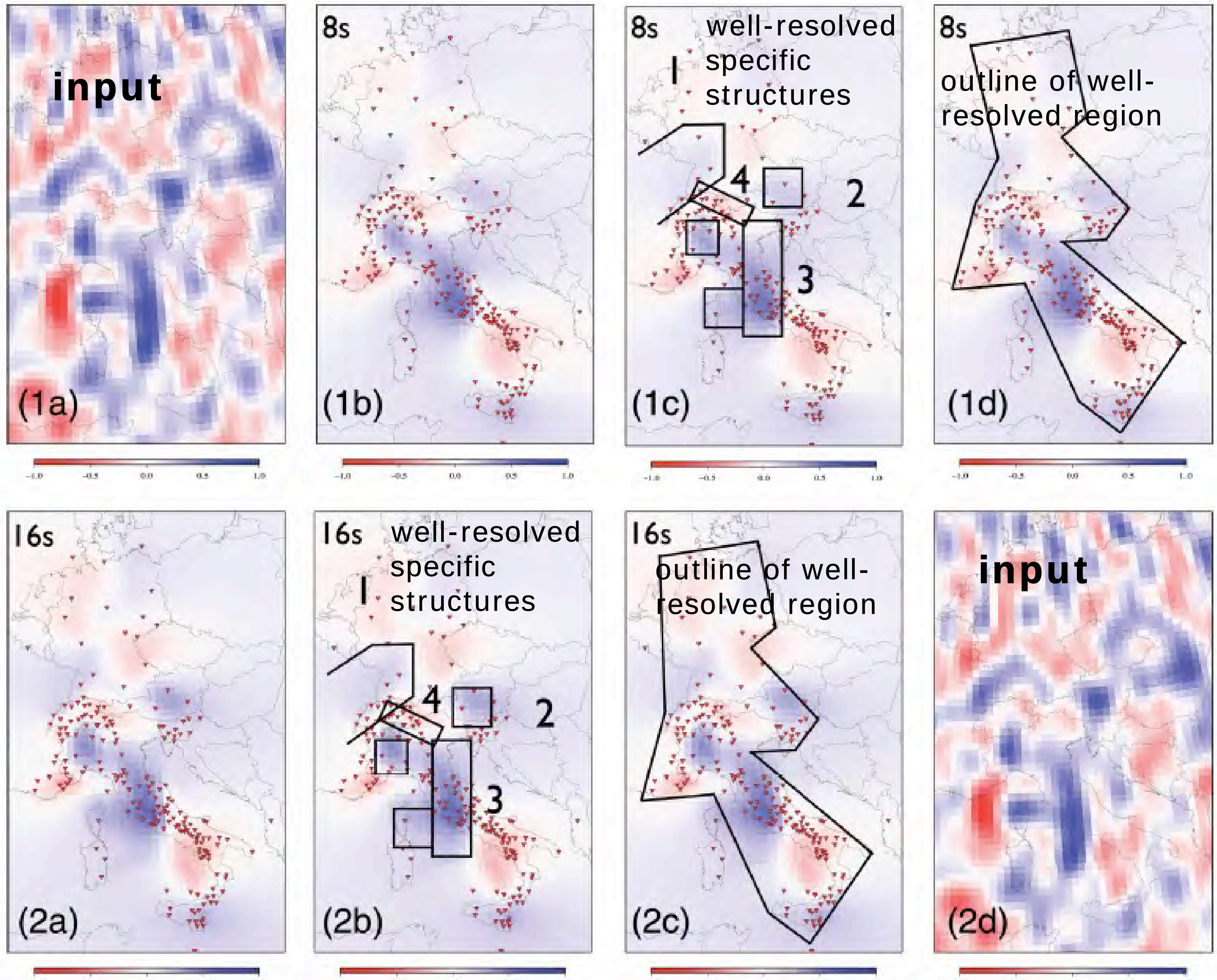
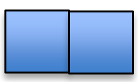
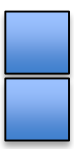
ambient noise tomography synthetic test

figures b,c,d = same recovered image

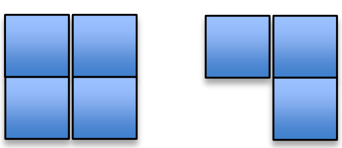


We would like to know the length of the shortest structure (of what velocity variation) that can be resolved well.





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



Verbeke et al 2012

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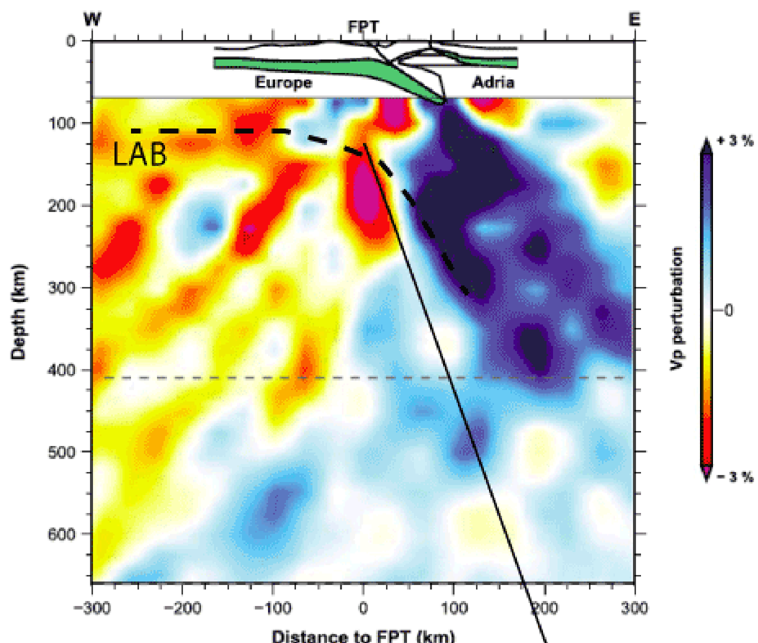
teleseismic (body wave) tomography TET

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

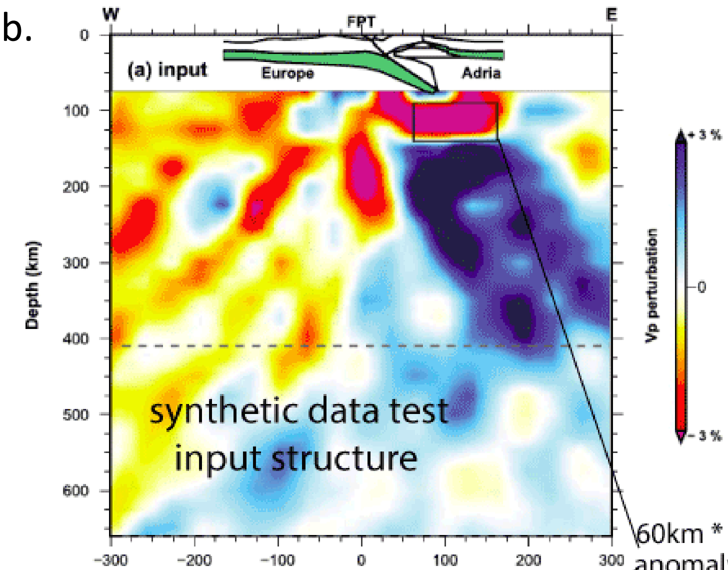
Zhao et al. 2016 JGR

interpreted resulting image:
"lithosphere slab continuous"

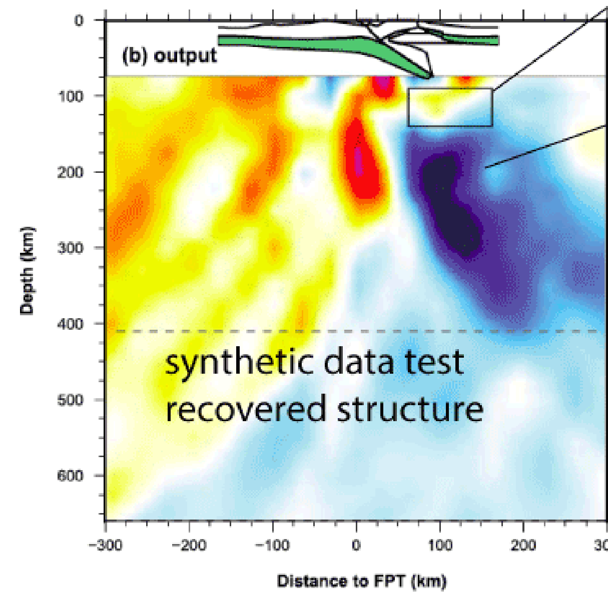


if 100km thick W-Alpine lithosphere is continuous, what does this (well-resolved) low-velocity anomaly mean

(comments in black by E. Kissling 2018)



60km * 100km (4%) anomaly is invisible



but high-velocity anomaly is significantly reduced in size

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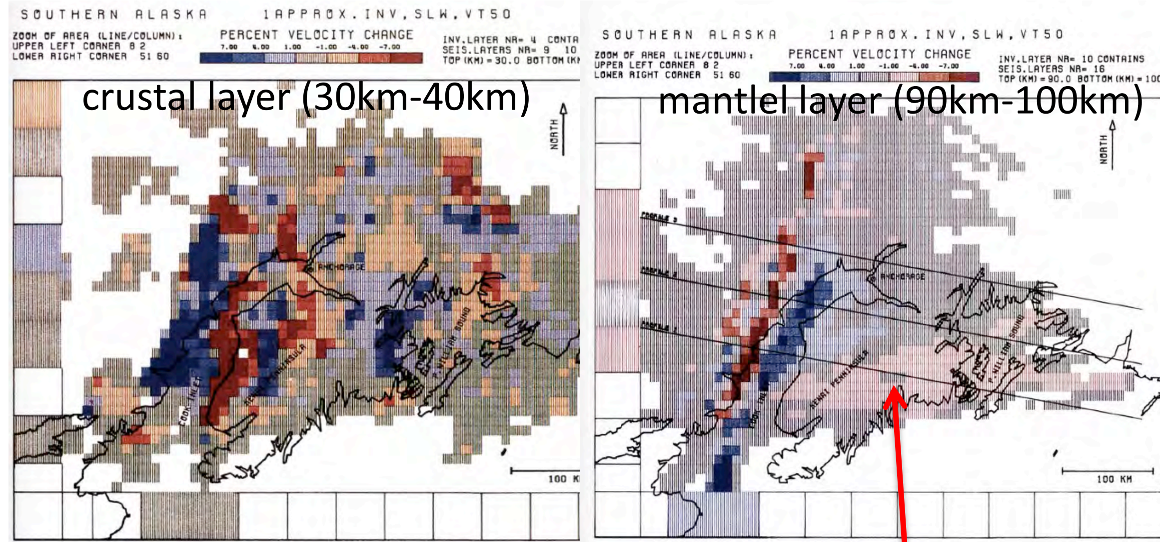
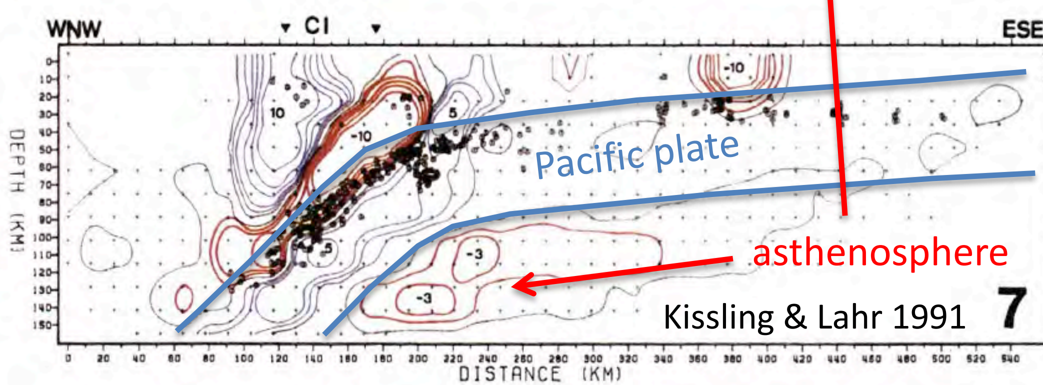
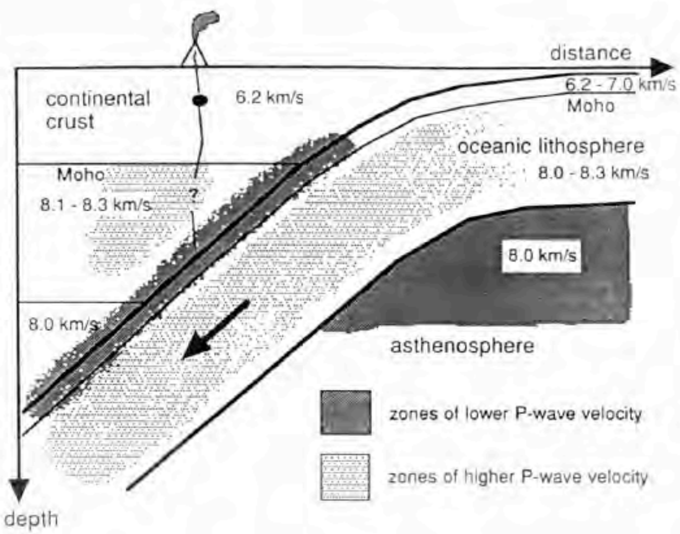
display of tomography results



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

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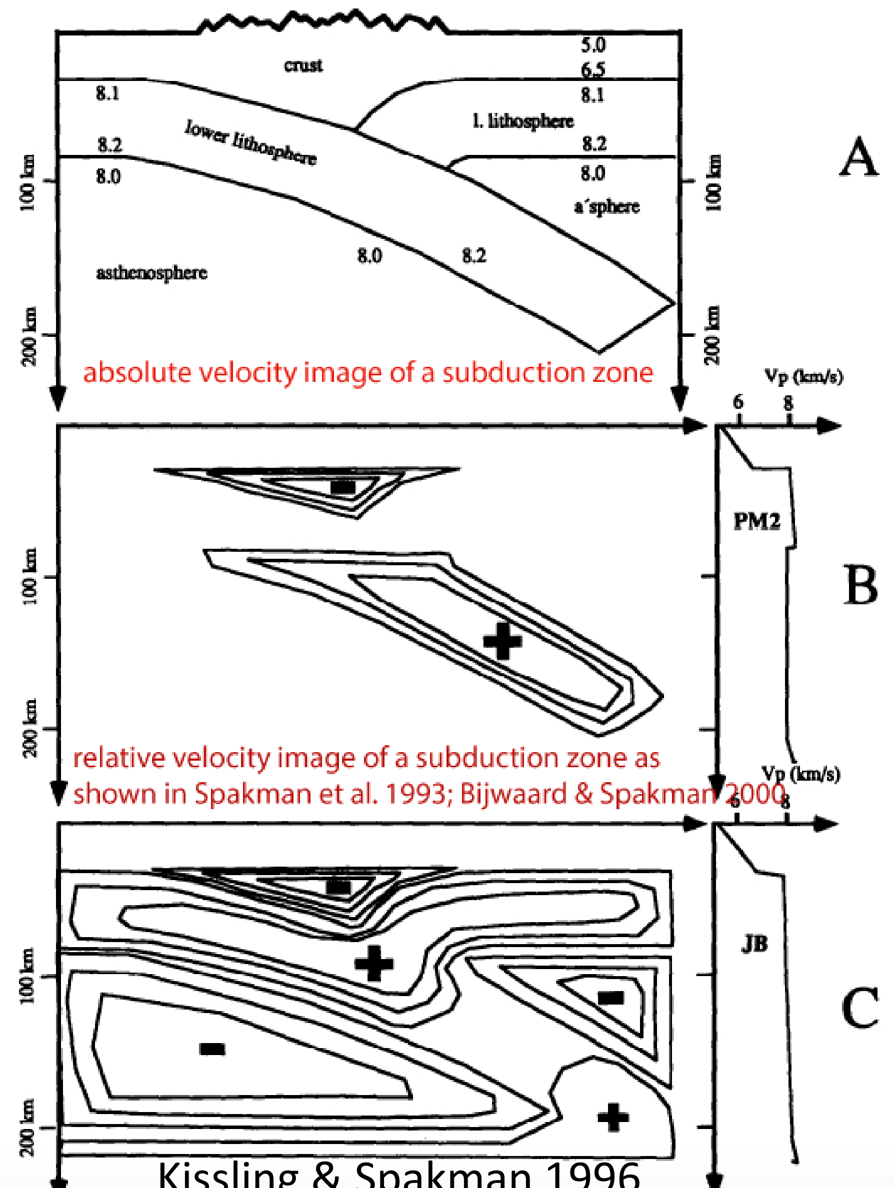
relative and absolute velocity variations

Relative velocity variations of 10% do not have 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



Kissling & Spakman 1996

quality estimate of seismic tomography results require authors to

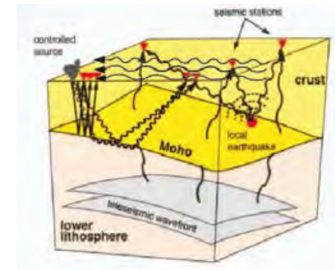
- define what parts of image/3Dmodel are well-resolved (and what parts should be ignored if they are not already hidden)
- in well-resolved regions define what kind of information about 3D structure and what type of structure are reliably resolved by specific application
- present results of synthetic model tests (to back up their resolution claims and to help readers to judge on their own)

conclusions

all users of tomography results please

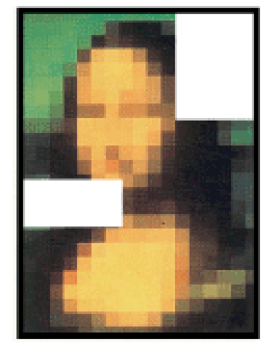
- check seismic method

  What physical parameter and what structural information may be derived? strengths and limitations?



- check the data

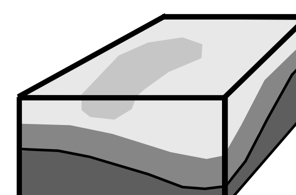
  What region is sampled by data set? How variable is data quality? What can be resolved by best data?



- 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



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