Local earthquake traveltime tomography

Christian Haberland
GFZ Potsdam

Goals

- Getting an idea of the method
- Getting a glimpse of the theory behind
- Understand how the tomographic images are calculated
- Understand the limitations of the method
- Learning which questions to ask the tomographer
- Learning how to interpret the tomographic images

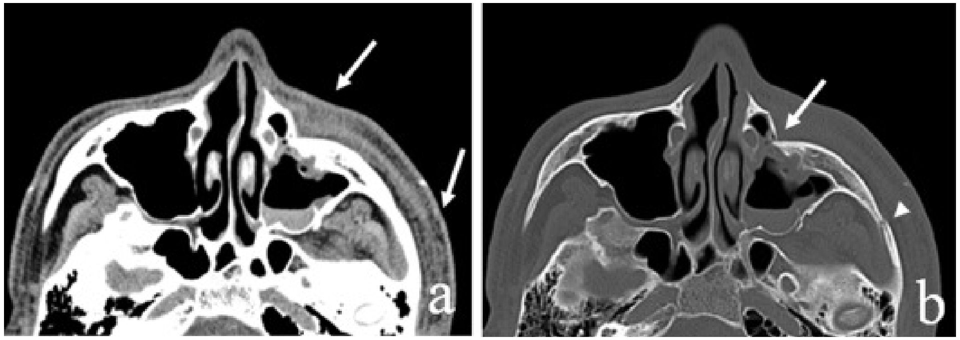
Outline LET

1) Introduction (principle, definitions, theory)
2) Characteristics of LET (parametrization, travel time calculation/raytracing, initial model, damping)
3) The input data (networks, instruments, phase picking)
4) Solution quality and resolution: Formal measures (model resolution matrix, diagonal element, spread value, covariances)
5) Solution quality and resolution: Synthetic recovery tests (checkerboard, characteristic model, realistic models)
6) Application/Interpretation

Tomography

τόμος tomos, "slice, section" + **γράφω** graphō, "to write"

CT image



Ogura et al., 2014

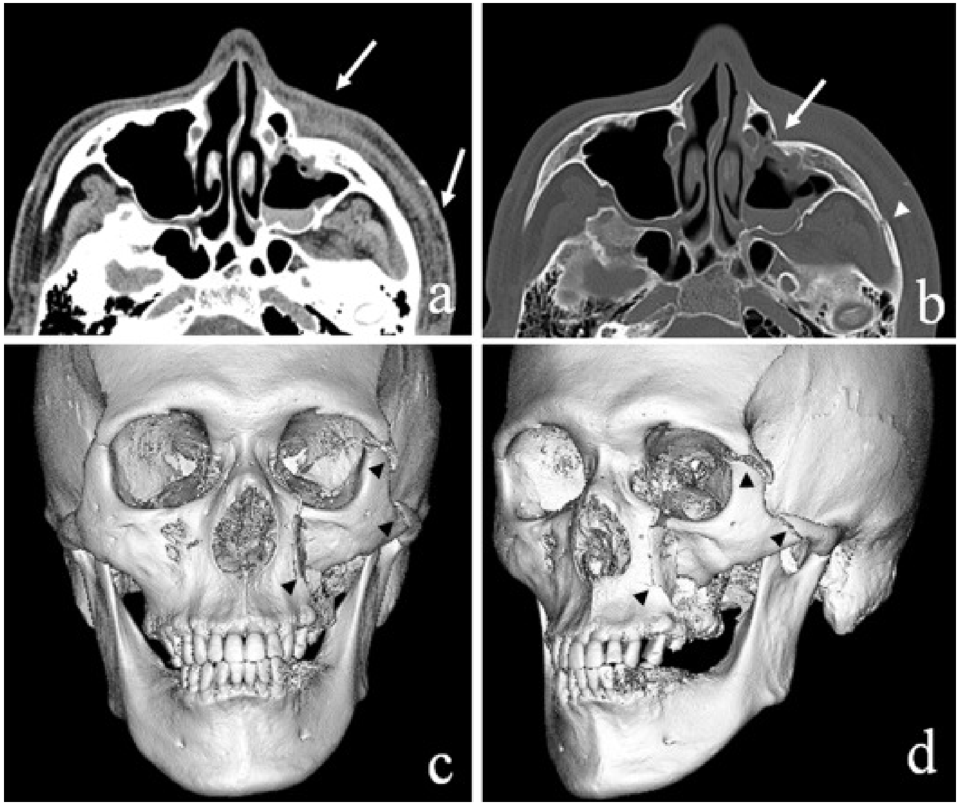
Tomography

τόμος tomos,
"slice, section"

\+

γράφω graphō,
"to write"

CT image

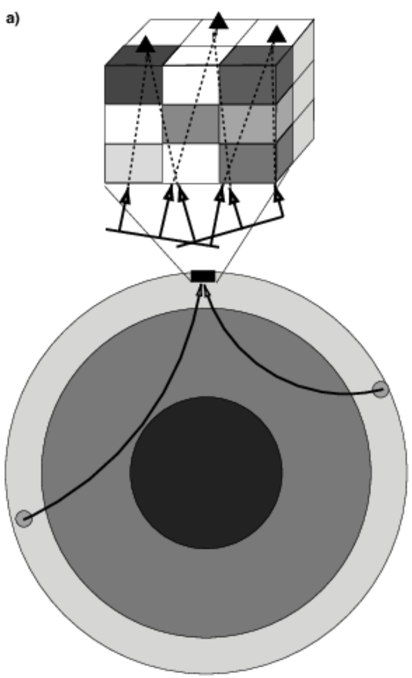


actually
3D structures...

Ogura et al., 2014

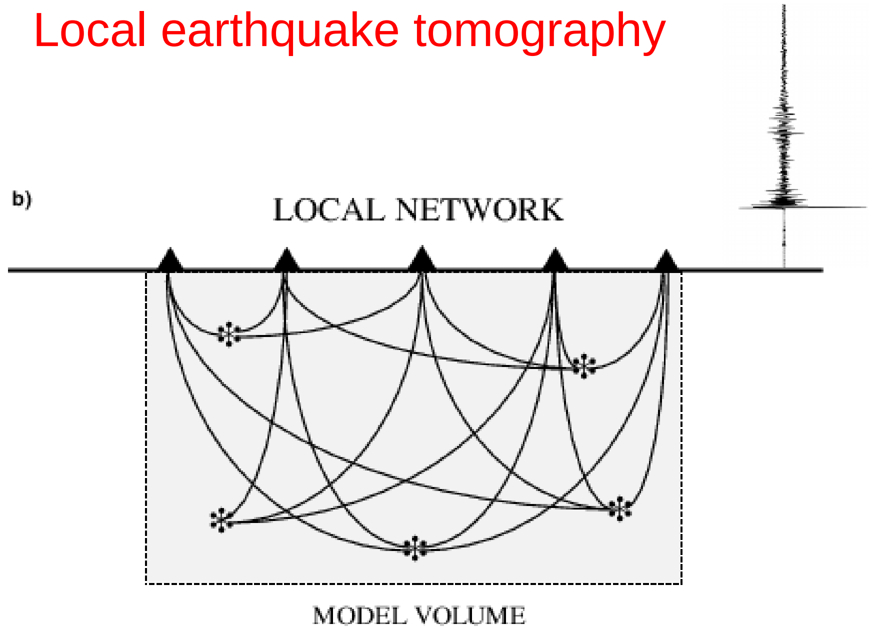
Seismic tomography

Teleseismic tomography



Distant sources,
plane wave assumption

Local earthquake tomography

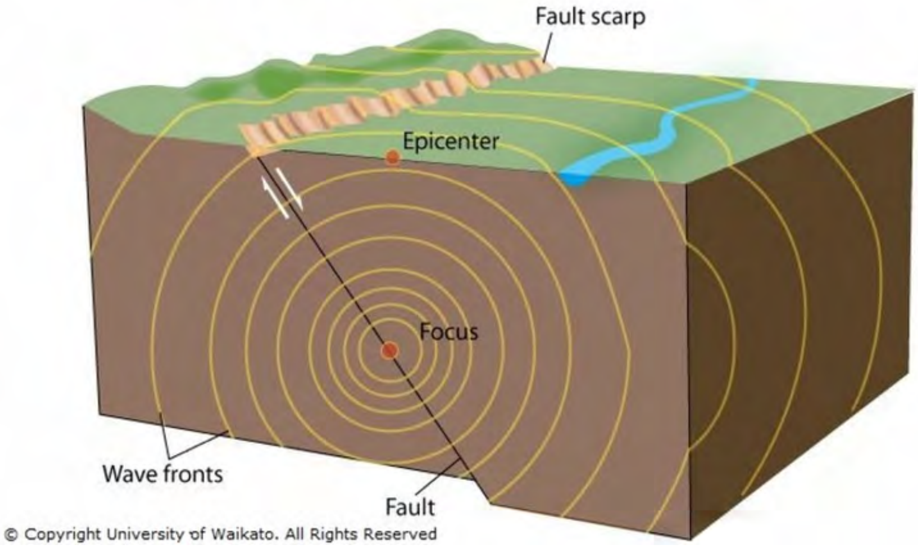


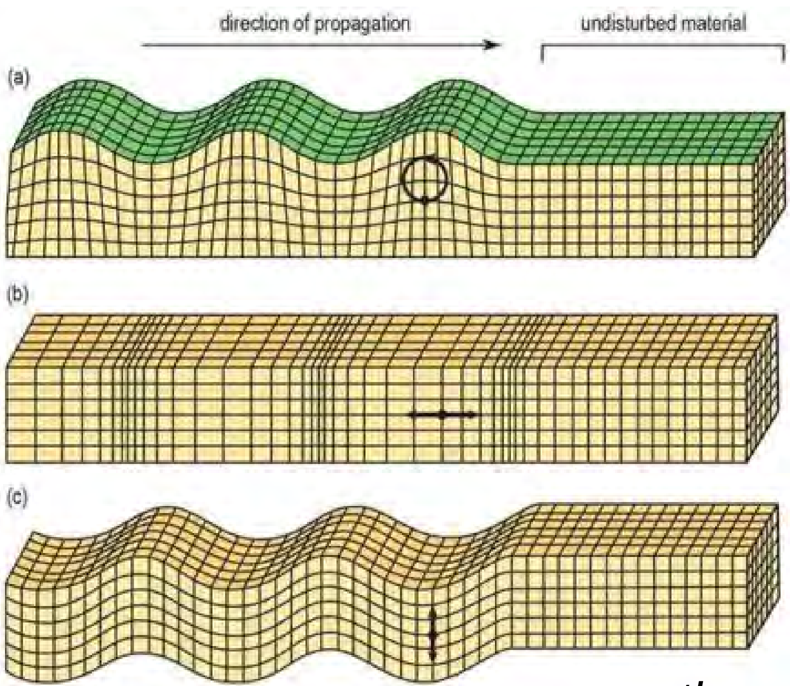
Local sources (location and origin time part of the inversion)

Calculation of subsurface models (i.e. velocity vp, vp/vs, anisotropy, attenuation Qp, Qs from seismic observations (inversion)

Thurber, 2003

Earthquakes, seismic waves, seismometer



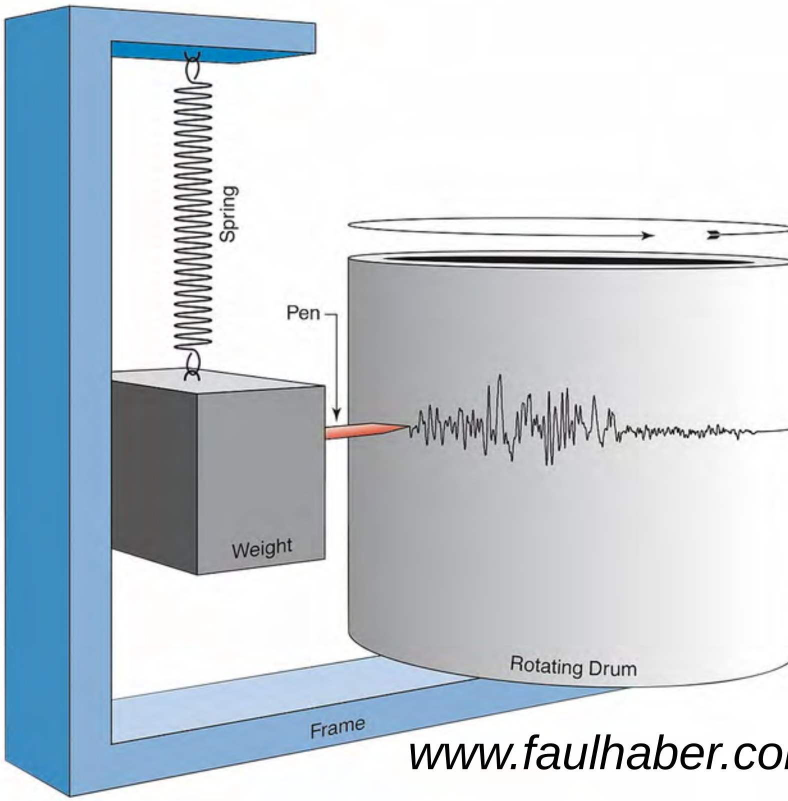


P-wave

S-wave

Surface wave

www.earthquakesreport.com



www.faulhaber.com

+ adding damping and electro-mechanical recording system...

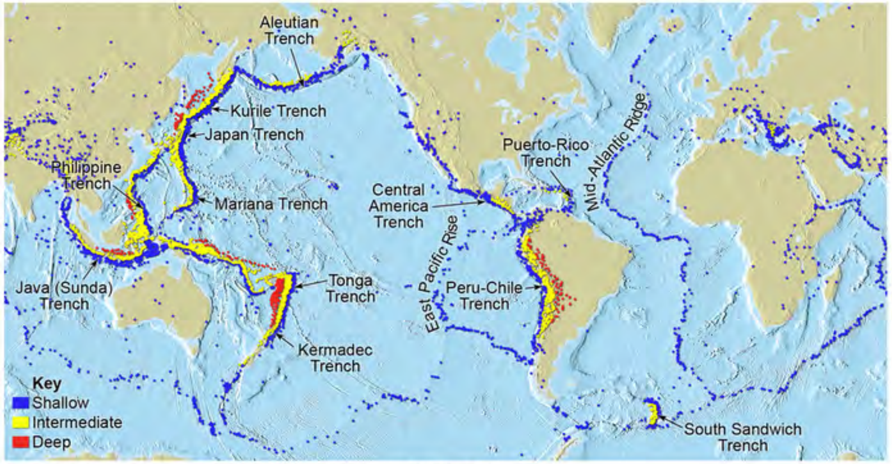
Seismic stations

- Seismic broad-band or short-period stations
- Temporary networks or permanent (regional) networks
- Digital data



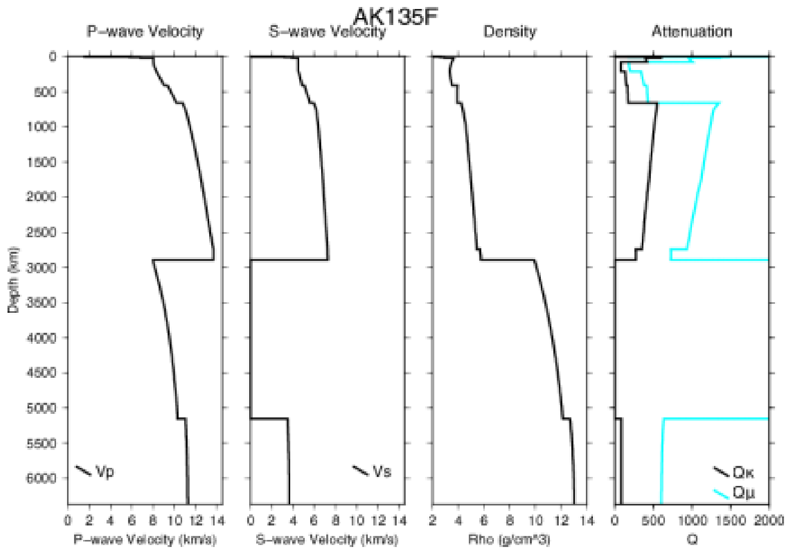


Distribution of earthquakes and first-order velocity structure of the Earth

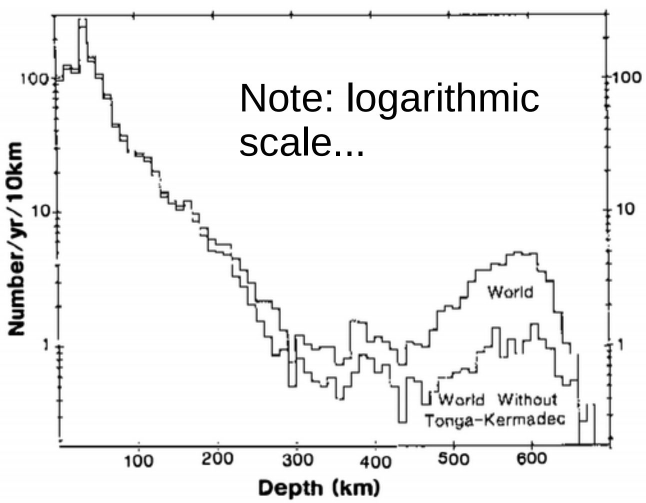


Distribution of shallow-, intermediate-, and deep-focus earthquakes. (Data from NOAA)

Global Earth models



AK135; Kennett et al., 1995



Frohlich, 1989

- Most earthquakes at plate boundaries
- Large depth range
- Global Earth models show increase of velocities with depth (in mantle)

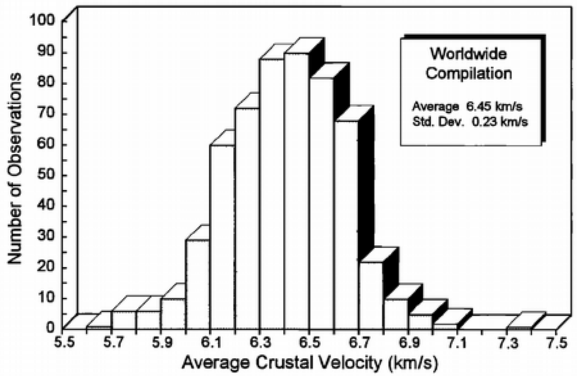
Average crustal structure

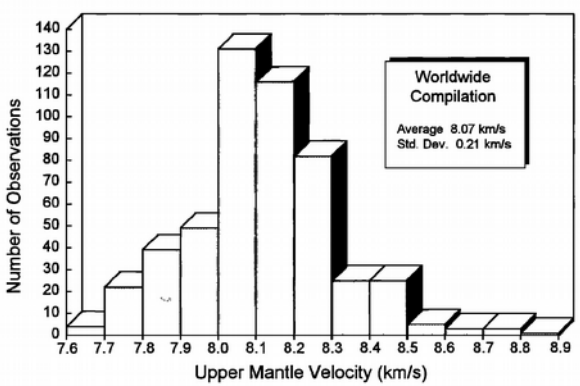
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 100, NO. B7, PAGES 9761–9788, JUNE 10, 1995

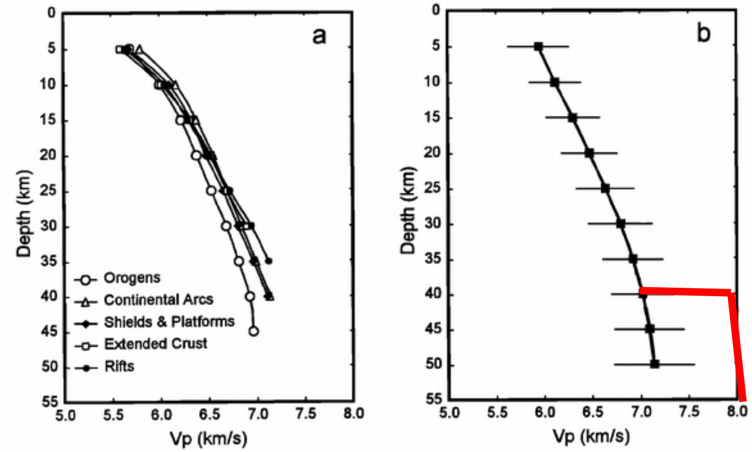
Seismic velocity structure and composition of the continental crust: A global view

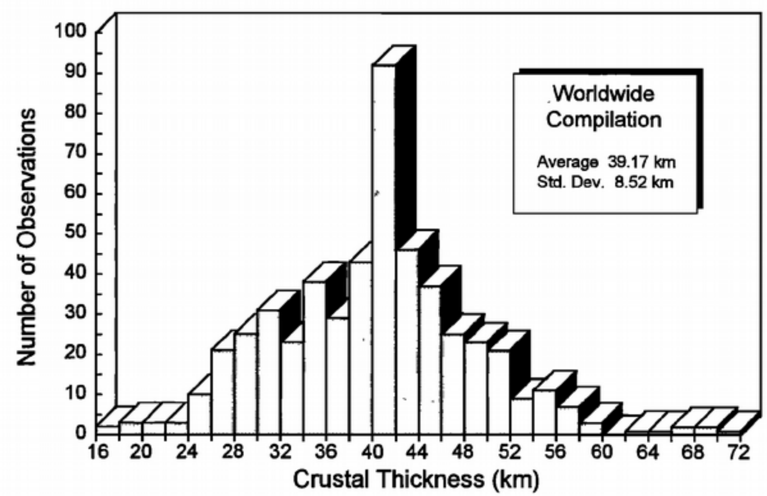
Nikolas I. Christensen
Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana

Walter D. Mooney
U.S. Geological Survey, Menlo Park, California









Rock velocities

vp

	km/sec
Unconsolidated materials	
Sand (dry)	0.2–1.0
Sand (water saturated)	1.5–2.0
Clay	1.0–2.5
Glacial till (water saturated)	1.5–2.5
Permafrost	3.5–4.0
Sedimentary rocks	
Sandstones	2.0–6.0
Tertiary sandstone	2.0–2.5
Pennant sandstone (Carboniferous)	4.0–4.5
Cambrian quartzite	5.5–6.0
Limestones	2.0–6.0
Cretaceous chalk	2.0–2.5
Jurassic oolites and bioclastic limestones	3.0–4.0
Carboniferous limestone	5.0–5.5
Dolomites	2.5–6.5
Salt	4.5–5.0
Anhydrite	4.5–6.5
Gypsum	2.0–3.5
Igneous/Metamorphic rocks	
Granite	5.5–6.0
Gabbro	6.5–7.0
Ultramafic rocks	7.5–8.5
Serpentinite	5.5–6.5
Pore fluids	
Air	0.3
Water	1.4–1.5
Ice	3.4
Petroleum	1.3–1.4
Other materials	
Steel	6.1
Iron	5.8
Aluminium	6.6
Concrete	3.6

Vs (or vp/vs or poisson ratio)

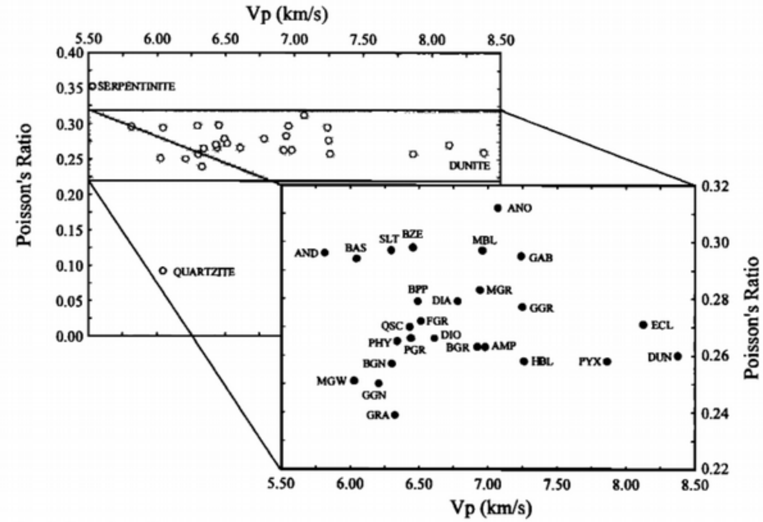


Figure 8. Poisson's ratio versus compressional wave velocity (V_p) at 600 MPa. Rock abbreviations are

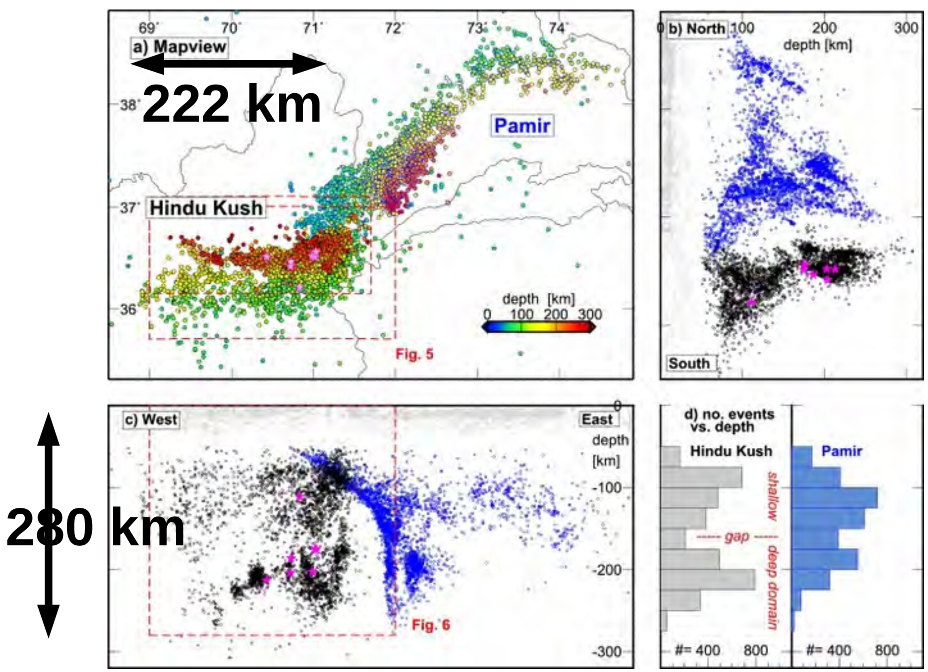
Table 6. Average Crustal Velocities (V_p, V_s), Velocity Ratios (V_p/V_s), and Poisson's Ratios (σ)

Crustal Type	V_p, km s^{-1}	V_s, km s^{-1}	V_p/V_s	σ	Reference
Oceanic crust, Samail Ophiolite, Oman	6.464	3.440	1.879	0.302	*Christensen and Smewing* [1981]
Oceanic crust, Bay of Islands Ophiolite, Newfoundland	6.608	3.494	1.891	0.306	*Christensen and Salisbury* [1982]
Arc crust, Kohistan, Pakistan	6.691	3.780	1.770	0.266	*Miller and Christensen* [1994]
Average continental crust	6.454	3.650	1.768	0.265	*Christensen and Mooney* [1995]

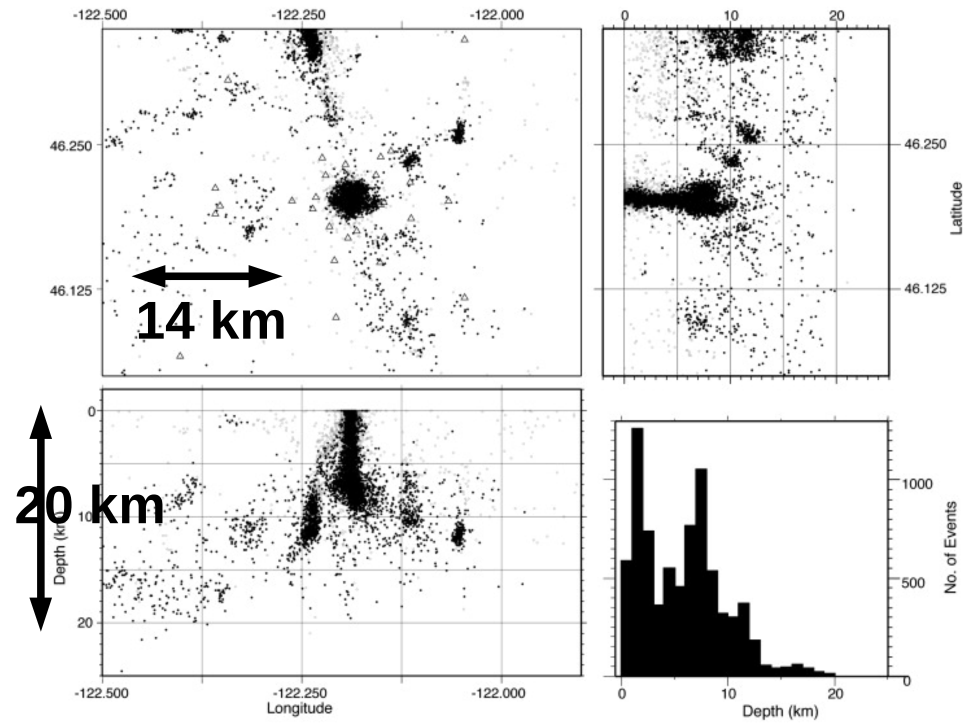
Christensen 1996

Typical depths/distances of earthquakes used

- From surface to seismogenic depths (~15km in continental crust); in subduction zones down to some 100 km
- Epicentral distances from 10 – to few 100 km



Pamir/Hindukush: Kufner et al., 2017

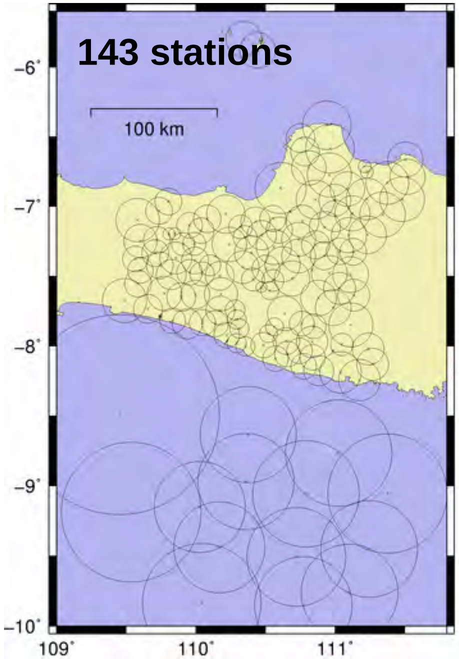


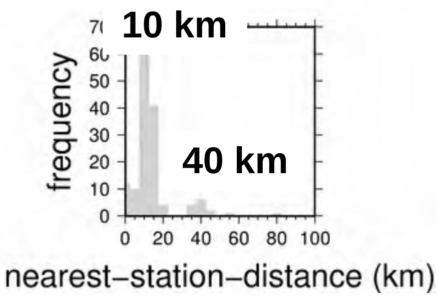
Mt. St. Helens: Waite & Moran, 2009

Network dimension/size

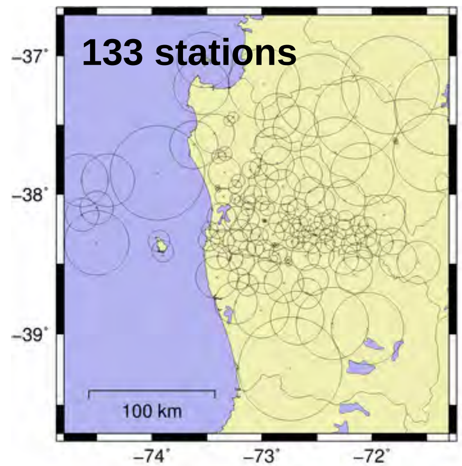
Aperture: 10 - 800 km
Inter-station dist: 1 – 50 km
stations: 10 – 500
earthquakes: 20 - 10000

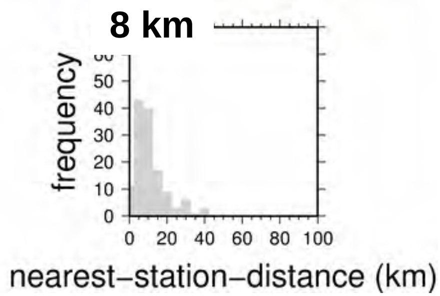
MERAMEX (Java)



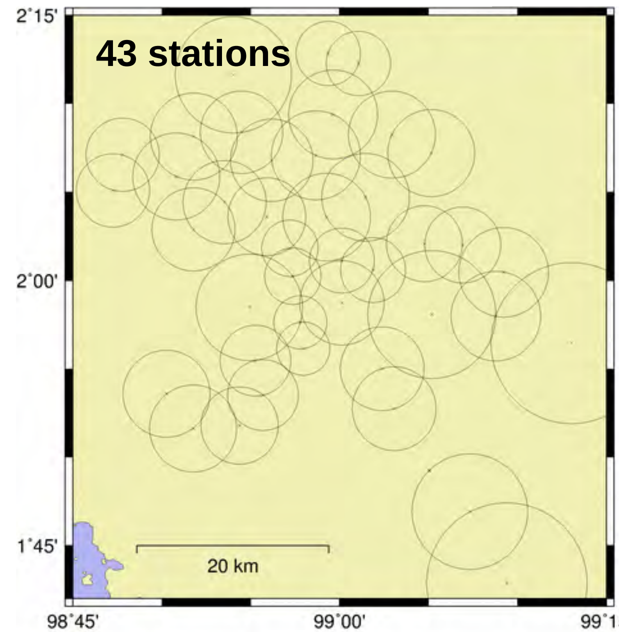


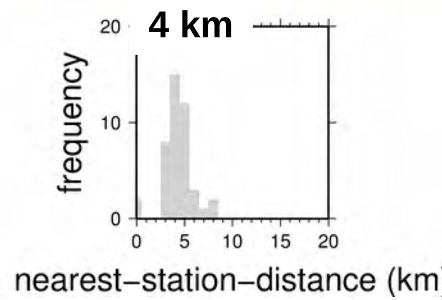
TIPTEQ (S-Chile)



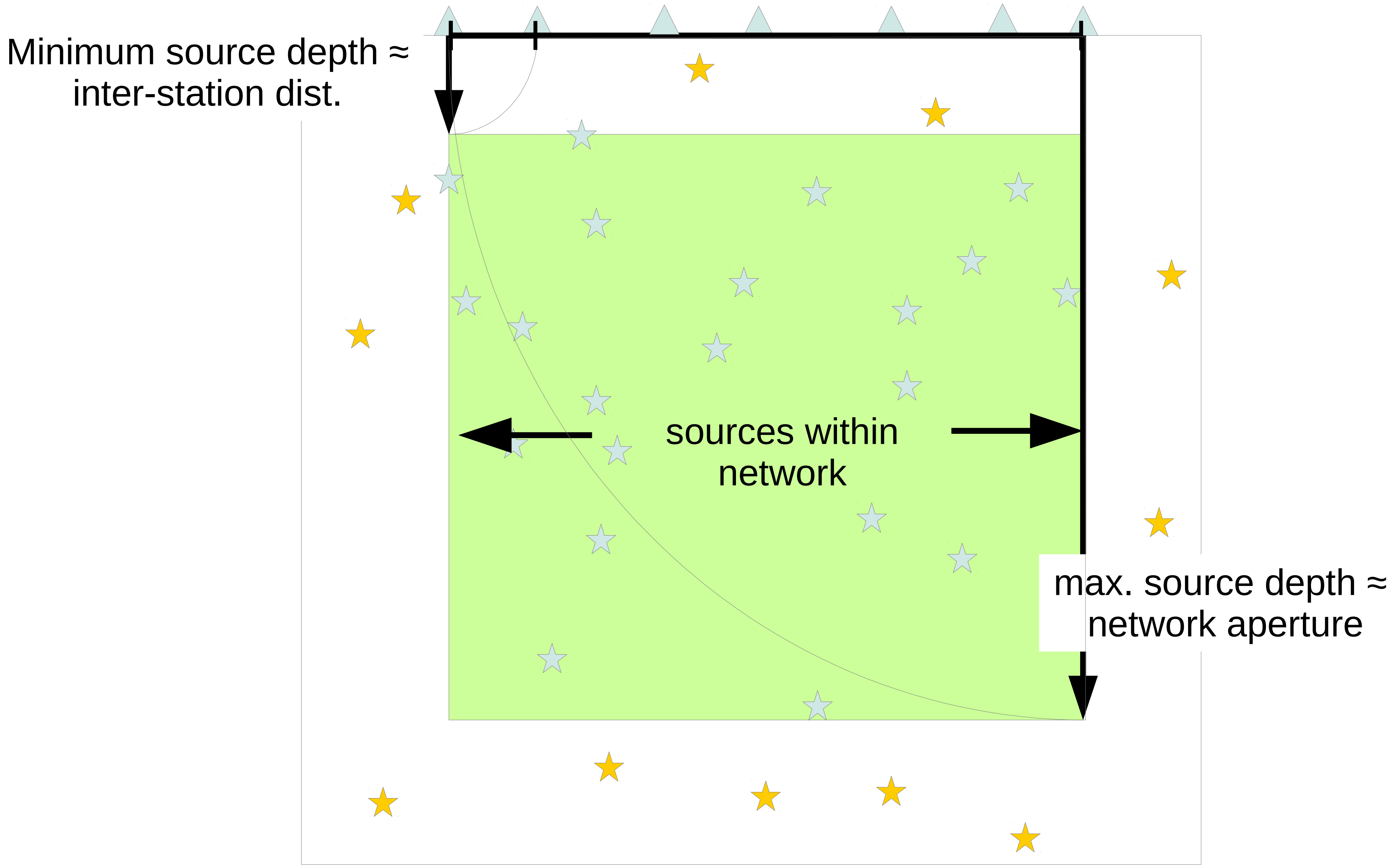


TARUTUNG (Sumatra)

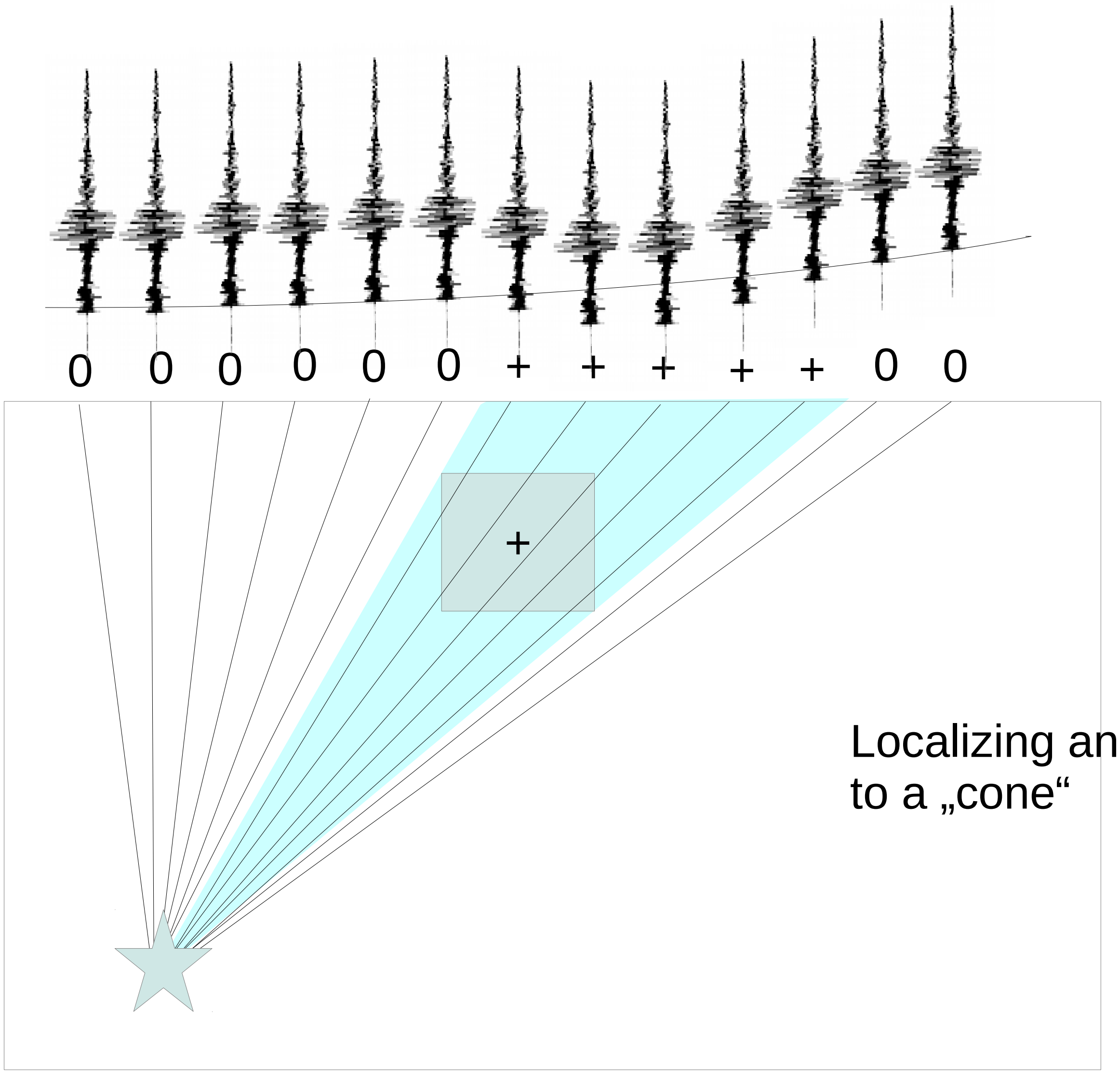




Network parameter vs. hypocenter position



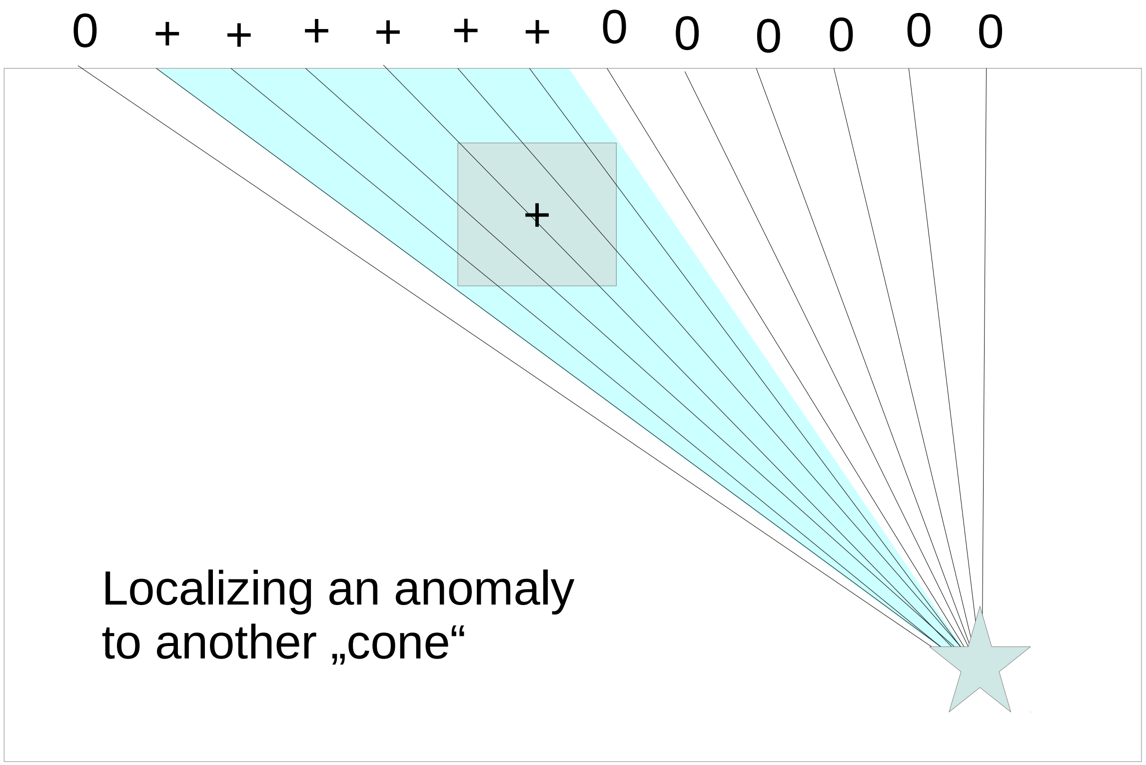
Tomography principle



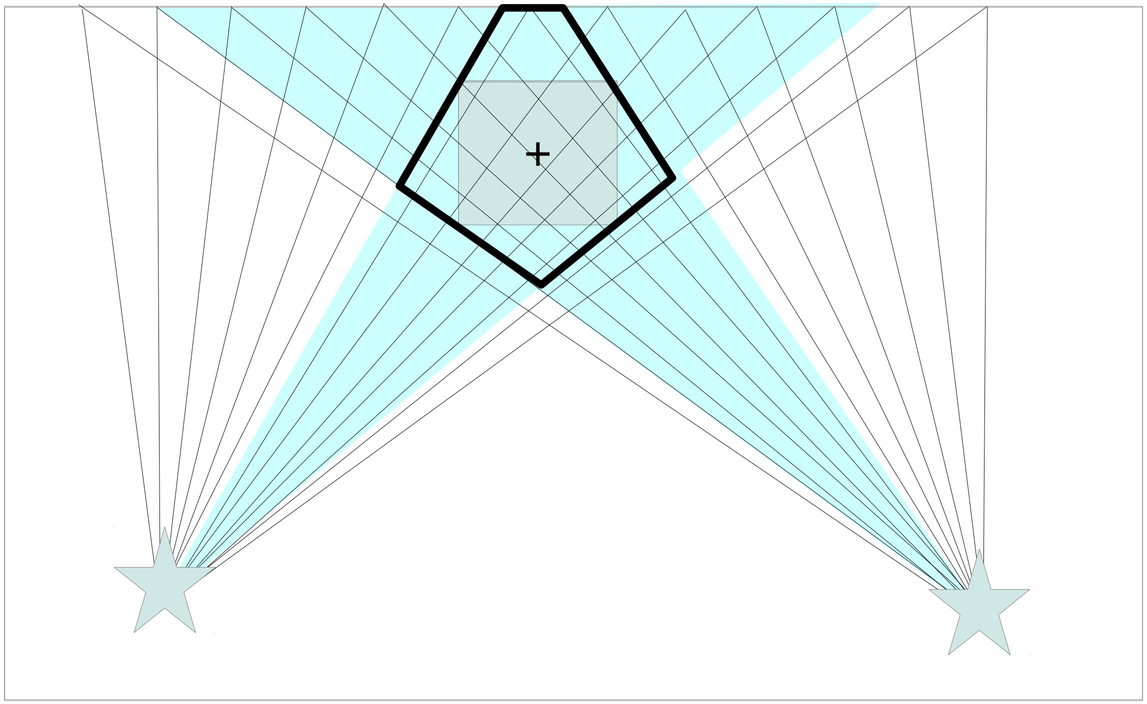
Localizing an anomaly to a „cone“

after Zhang & Thurber

Tomographic principle

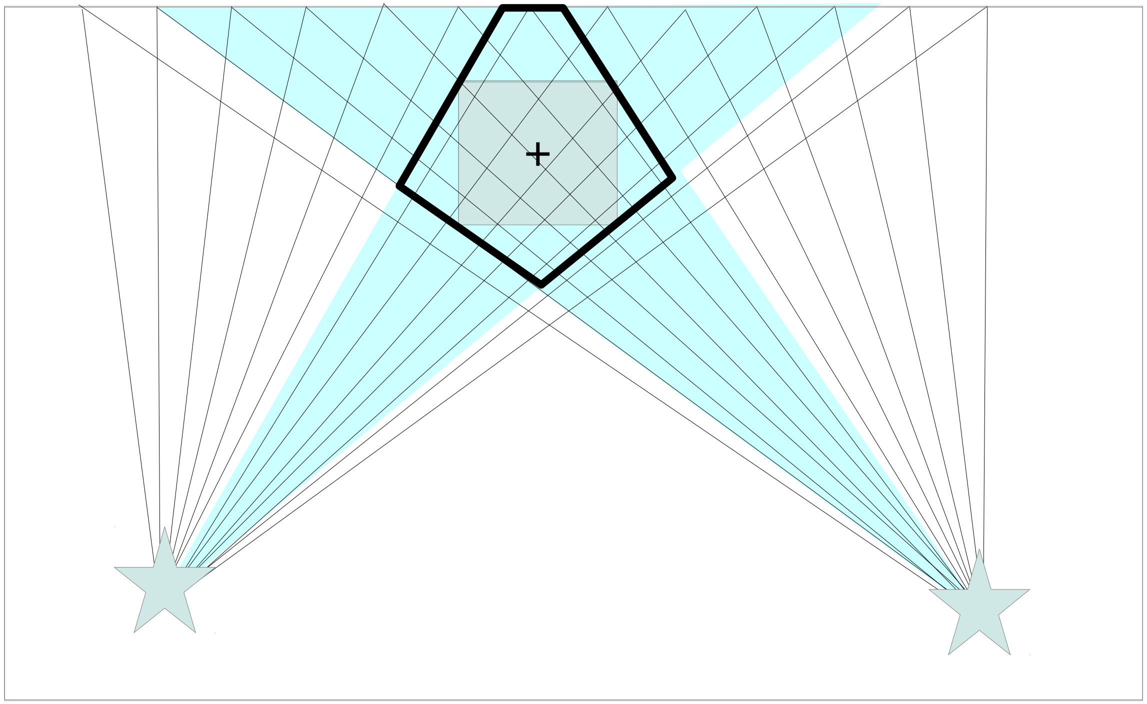


Tomographic principle



Combining observations from multiple Earthquakes to image anomaly

Tomographic principle



Combining observations from multiple
Earthquakes to image anomaly

The beginning of LET...

VOL. 81, NO. 17 JOURNAL OF GEOPHYSICAL RESEARCH JUNE 10, 1976

Crustal Structure Modeling of Earthquake Data
1. Simultaneous Least Squares Estimation
of Hypocenter and Velocity Parameters

ROBERT S. CROSSON

Geophysics Program, University of Washington, Seattle, Washington 98195

Bulletin of the Seismological Society of America. Vol. 66, No. 2, pp. 501–524. April 1976

THREE-DIMENSIONAL SEISMIC STRUCTURE OF THE LITHOSPHERE
UNDER MONTANA LASA

BY KEIITI AKI, ANDERS CHRISTOFFERSSON,* AND EYSTEIN S. HUSEBYE†

VOL. 81, NO. 23 JOURNAL OF GEOPHYSICAL RESEARCH AUGUST 10, 1976

DETERMINATION OF THREE-DIMENSIONAL VELOCITY ANOMALIES UNDER A SEISMIC
ARRAY USING FIRST P ARRIVAL TIMES FROM LOCAL EARTHQUAKES
1. A HOMOGENEOUS INITIAL MODEL

Keiiti Aki

Department of Earth and Planetary Sciences, Massachusetts Institute
of Technology, Cambridge, Massachusetts 02139

W. H. K. Lee

National Center for Earthquake Research, U. S. Geological Survey
Menlo Park, California 94025

EARTH STRUCTURE AND EARTHQUAKE LOCATIONS
IN THE COYOTE LAKE AREA, CENTRAL CALIFORNIA

by

Clifford H. Thurber

Submitted to the Department of Earth and Planetary Sciences
on May 9, 1981, in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 88, NO. B10, PAGES 8226–8236, OCTOBER 10, 1983

Earthquake Locations and Three-Dimensional Crustal Structure
in the Coyote Lake Area, Central California

CLIFFORD H. THURBER[1]

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 95, NO. B10, PAGES 15,343–15,363, SEPTEMBER 10, 1990

Three-Dimensional *P* and *S* Velocity Structure
in the Coalinga Region, California

DONNA EBERHART-PHILLIPS

U.S. Geological Survey, Menlo Park, California

A glimpse of the theory...

How can we relate arrival times (of P- and S-waves) to the subsurface (model)?

$$T_{i,j} = f(h_l, m_k)$$

Non-linear function

arrival time $T_{i,j}$ of seismic wave from source i at receiver j

h_l: hypocentral parameters (l=1...4; x,y,z,t)

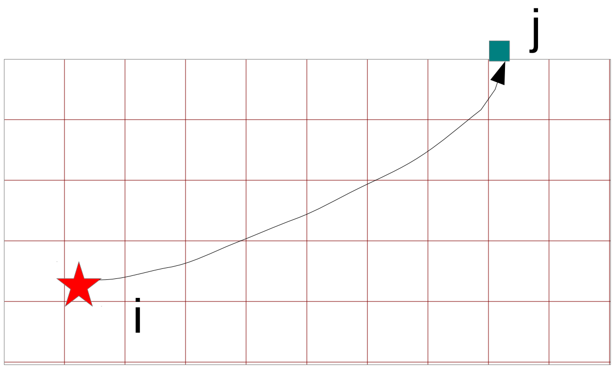
m_k: seismic velocities (k=1...k_{total})

$$T_{i,j} = t_0 + \int_{raypath} \frac{1}{v(r(s))} ds$$

Includes unknown hypocenter location

t_0: origin time

v: velocities along ray r



Travel time residual

Instead of using absolute times we use travel time residuals:

$$r_{i,j} = t_{i,j}^{obs} - t_{i,j}^{calc}$$

travel time residual

observed $f(h_l, m_k)$

calculated $f(h_l^{est}, m_k^{est})$

Goal of arrival time tomography is to minimize travel time residuals by changing the model parameters

→ **initial/starting model!**

Linearization and normal equations

Taylor series expansion and truncation after first term
→ linear relation between travel time residual and model parameters

origin time — hypocenter — vel model

$$r_{i,j} = \Delta t_e + \frac{\partial t}{\partial x_e}\Delta x_e + \frac{\partial t}{\partial y_e}\Delta y_e + \frac{\partial t}{\partial z_e}\Delta z_e + \sum_{k=1}^{k_{total}} \frac{\partial t}{\partial m_l}\Delta m_k$$

Partial derivatives
(from forward calculations)

Perturbations/model
changes (searched for)

In matrix notation (many observations):

$$\mathbf{t} = \mathbf{H}\,\mathbf{h} + \mathbf{M}\,\mathbf{m} = \mathbf{A}\,\mathbf{d}$$

vector of travel-time residuals

matrix with partial derivatives

vector of model corrections

→ hypocenter-velocity coupling!
→ simultaneous inversion

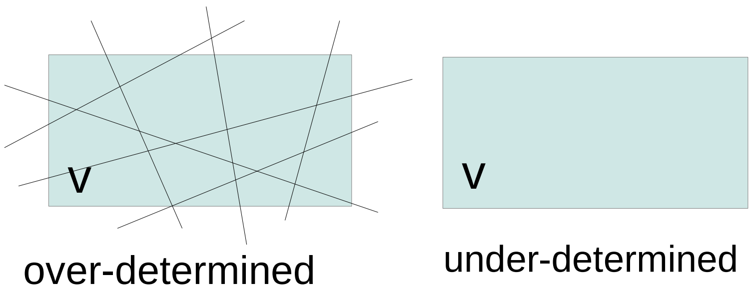
→ problems can be separated (iterative solution)

Damped least-squares solution

Solving the coupled hypocenter-velocity problem

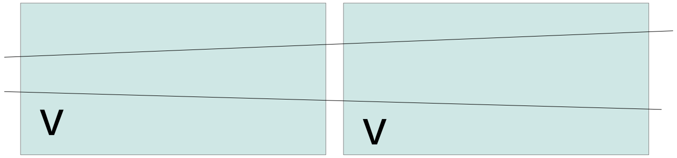
$$\mathbf{t} = \mathbf{A}\,\mathbf{d}$$

The problem is mixed determined.
The data have errors.



<u>Solution:</u>
Damped least squares inversion

Minimize $\boldsymbol{\Psi} = \mathbf{e}^T\mathbf{e} + \boldsymbol{\Theta}^2\,\mathbf{d}^T\mathbf{d}$



$$\mathbf{d} = (\mathbf{A}^T\mathbf{A} + \boldsymbol{\Theta}\,\mathbf{I})^{-1}\,\mathbf{A}^T\mathbf{t}$$

Θ: damping parameter

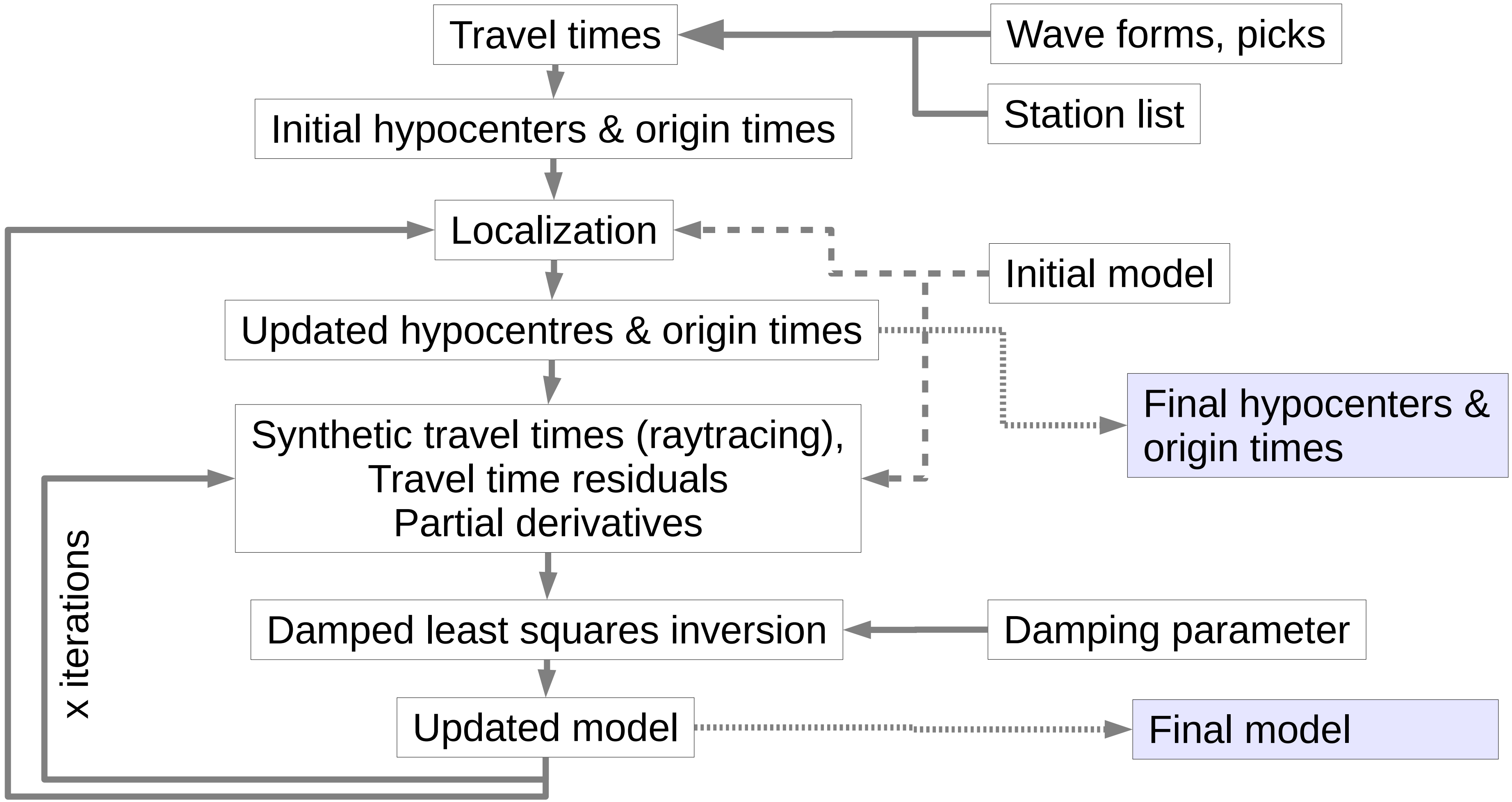
→ Inversion theory (e.g. Menke, 1989)

→ **damping parameter**

also inversion for vp/vs
shots can also be used

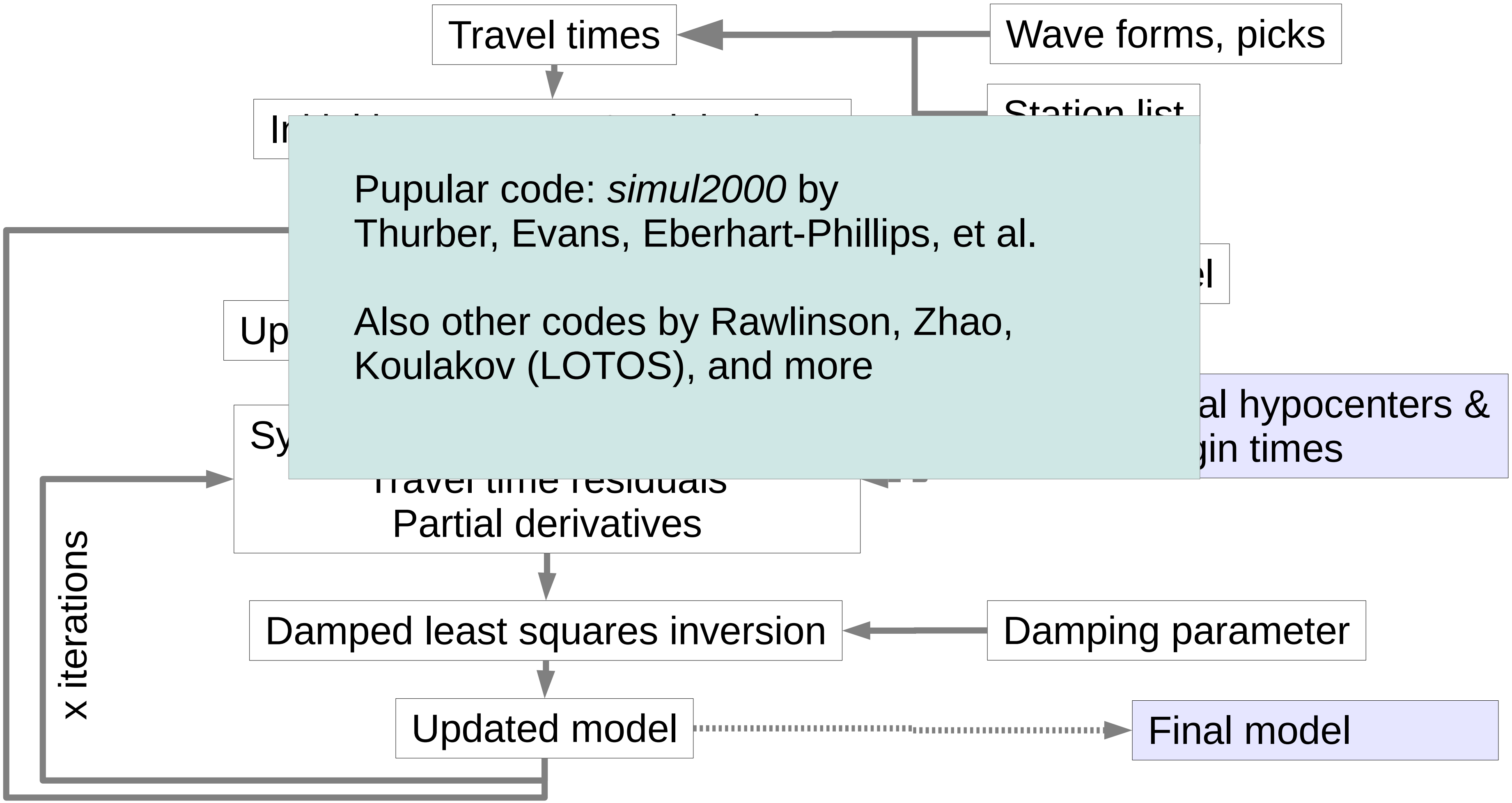
Simplified LET workflow

(Iterative) Simultaneous inversion for 3D velocity model, hypocenter parameters (and station corrections)



Simplified LET workflow

(Iterative) Simultaneous inversion for 3D velocity model, hypocenter parameters (and station corrections)

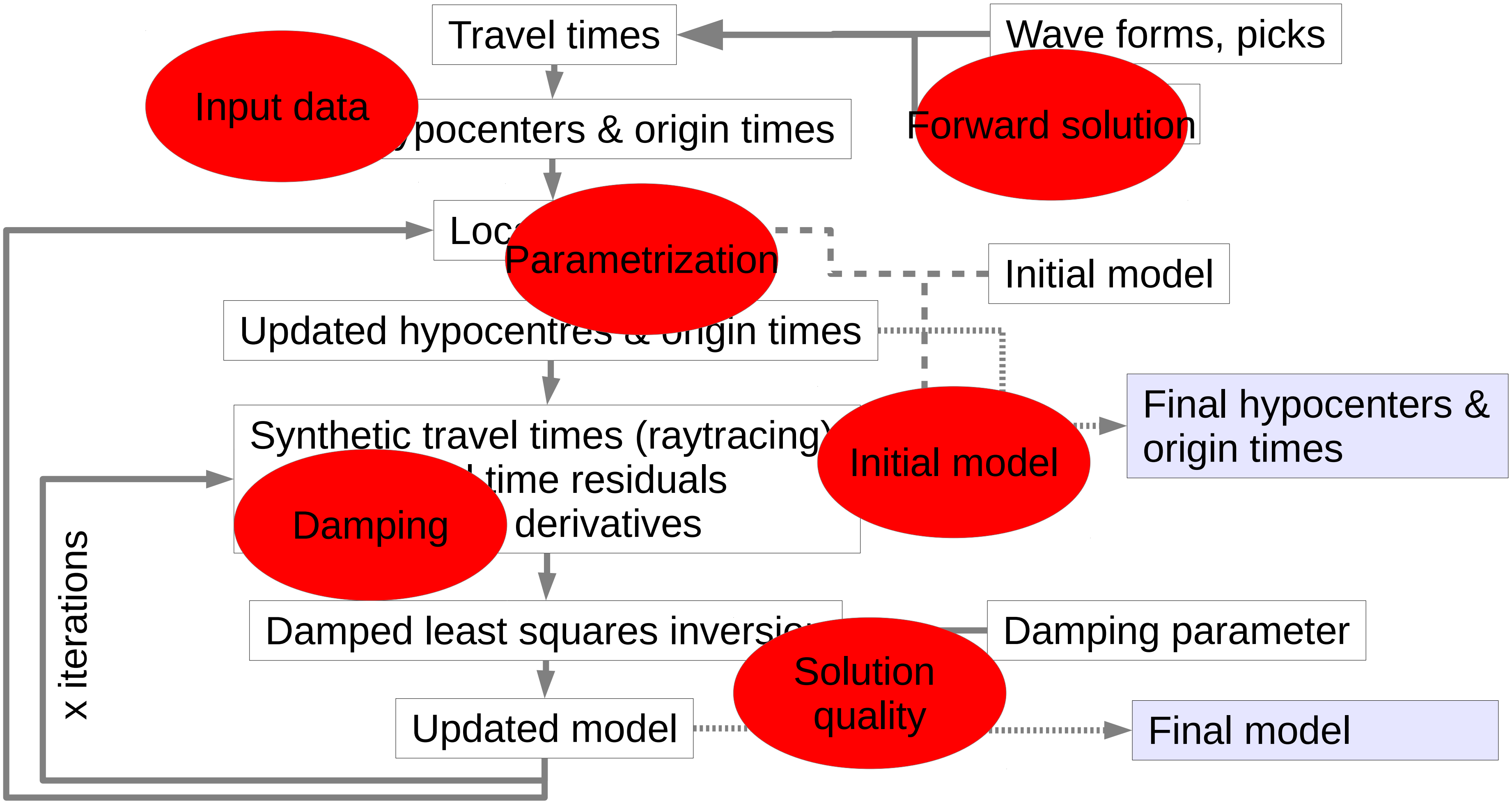


Pupular code: *simul2000* by Thurber, Evans, Eberhart-Phillips, et al.

Also other codes by Rawlinson, Zhao, Koulakov (LOTOS), and more

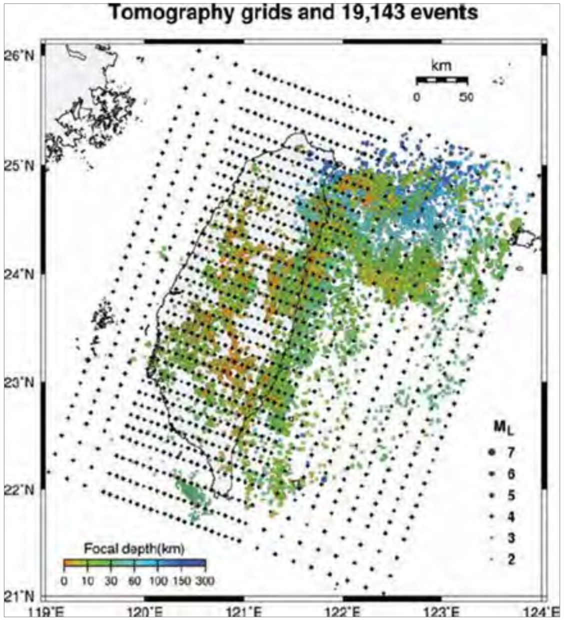
Simplified LET workflow

(Iterative) Simultaneous inversion for 3D velocity model, hypocenter parameters (and station corrections)

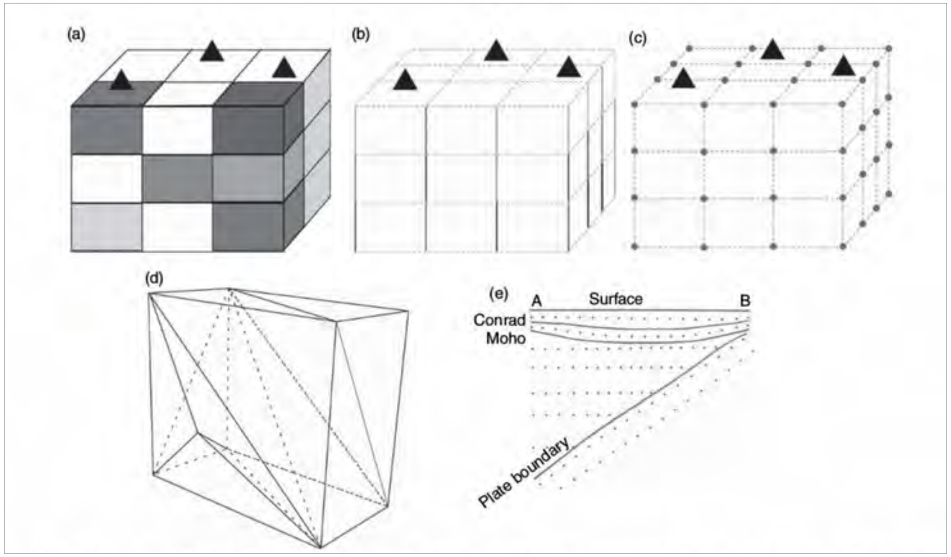


Parametrization

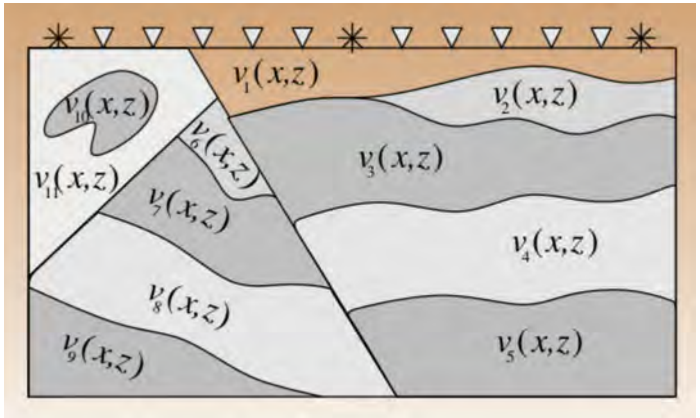
- constant parameter uniform volume blocks
- regular rectangular grid of nodes
- tetrahedral cells
- interfaces separating grids
- rectangular grid with varying distances
- constant parameters or interpolation



Wu et al., 2009



compiled by Thurber & Ritsema, 2009



Rawlinson

Linked nodes / Flexible gridding

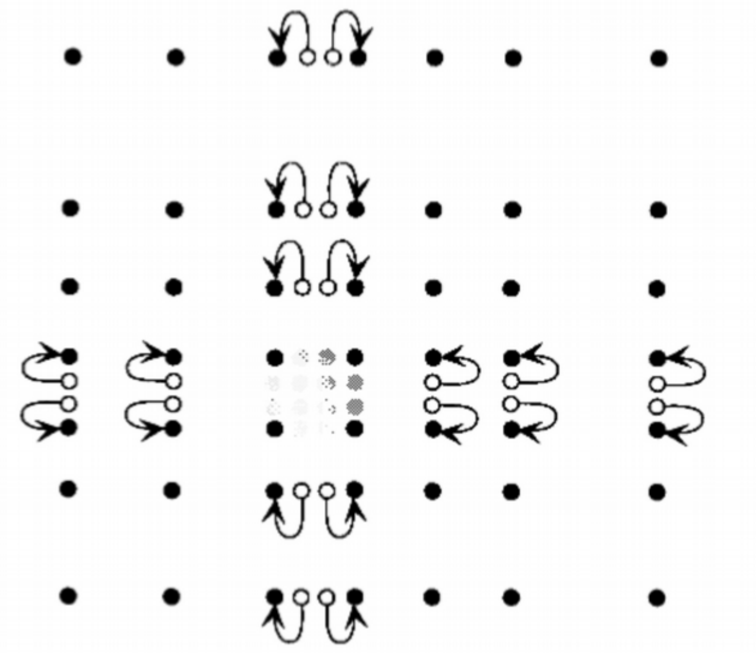
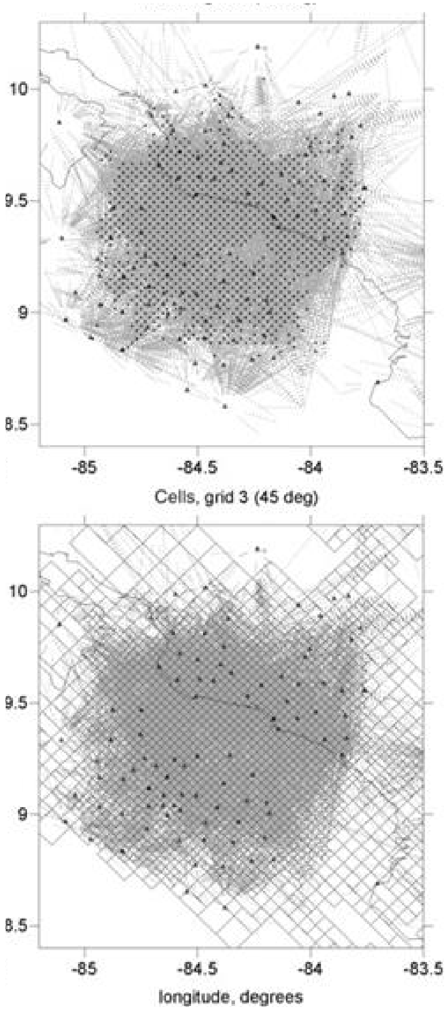


Fig. 3. With Øexible gridding, Æner-scale gridding can be introduced in localized area (gray circles) and model values of denser nodes extending away from target area (open circles) can be linked (arrows) to values at adjacent nodes of original coarser grid (black circles).

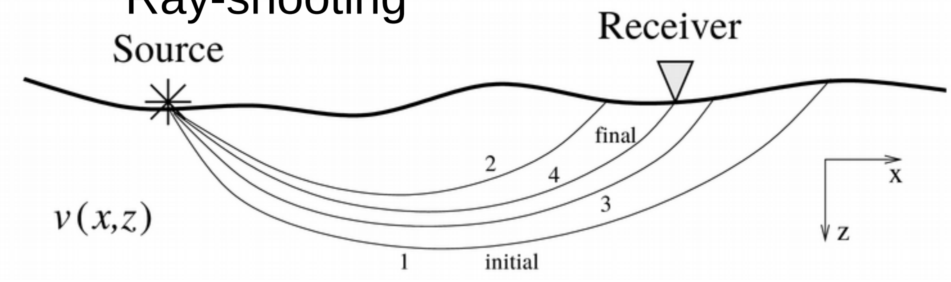
Thurber & Eberhart-Philips, 1999



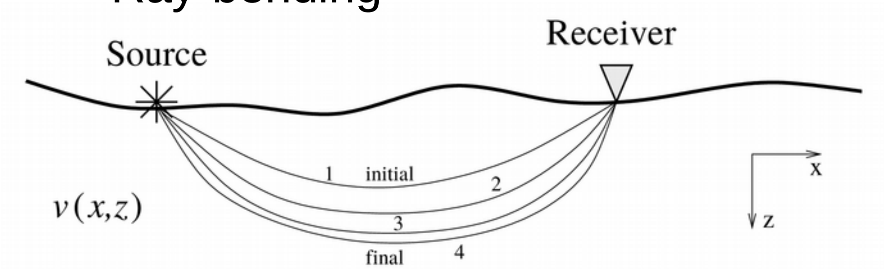
Koulakov, 2009

Travel times / raytracing / forward solution

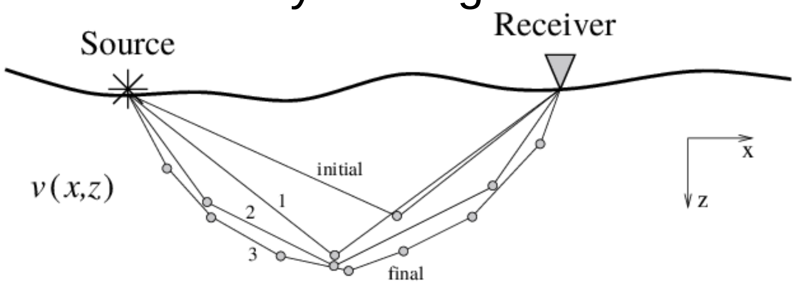
Ray-shooting



Ray-bending

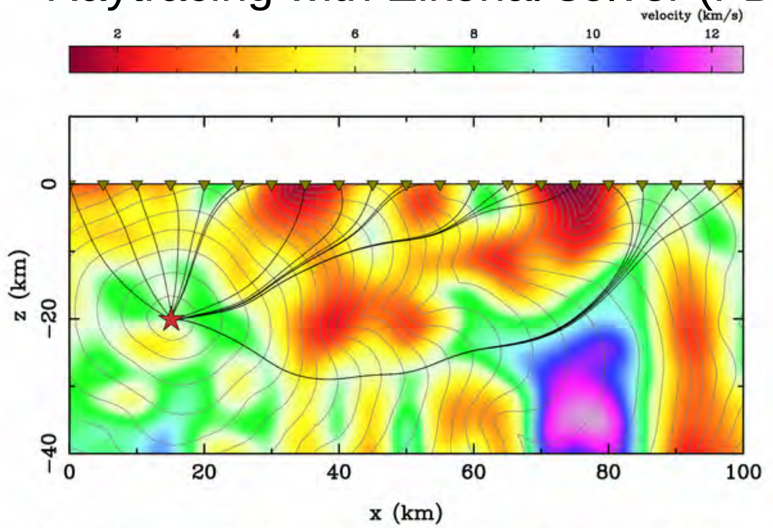


Pseudo-raybending



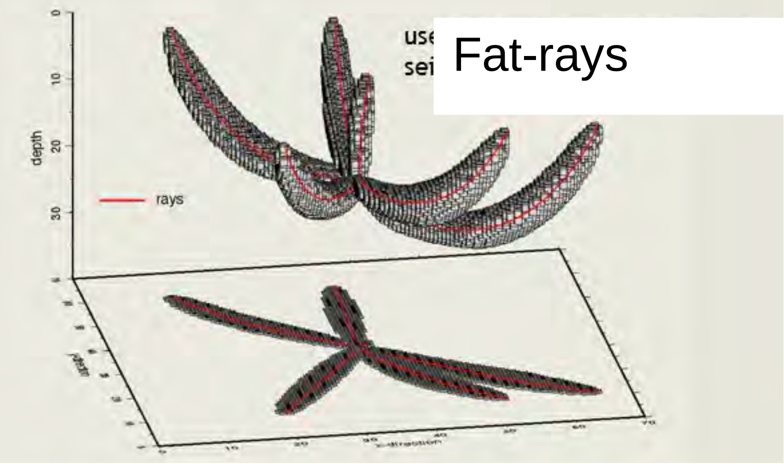
Compiled by Rawlinson & Sambridge, 2003

Raytracing with Eikonal solver (FD)



Rawlinson & Sambridge, 2003

Fat-rays



Husen & Kissling, 2001

Initial / reference model

From theory: travel time residuals $r_{i,j} = t_{i,j}^{obs} - t_{i,j}^{calc}$

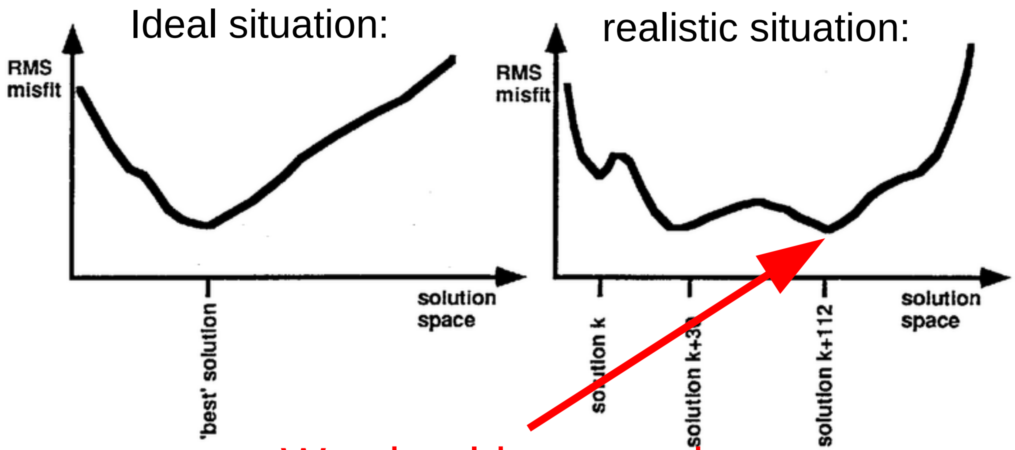
observed: $f(h_l, m_k)$

calculated: $f(h_l^{est}, m_k^{est})$

Because we solve the non-linear coupled hypocenter-velocity problem by linearization of t_i (first order Taylor series) the initial model has to be close to the true solution...

How to get h_l^{est} and m_k^{est}??

<u>Minimum 1D model</u>: the best reference model and hypocenter locations from a 1D least-square solution of the coupled velocity-hypocenter problem (Kissling et al., 1994)



We should start at the global minimum

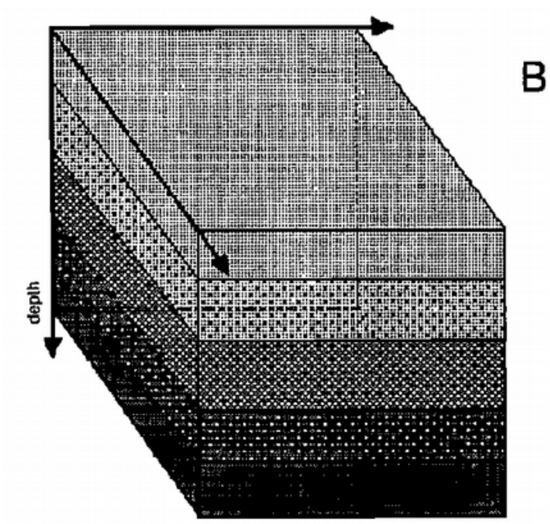
1-D initial model – *velest* code

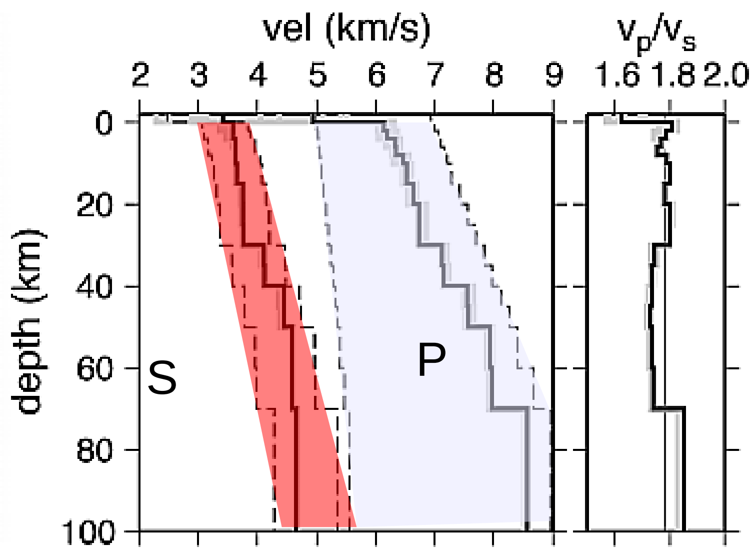
JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 99, NO. B10, PAGES 19,635–19,646, OCTOBER 10, 1994

Initial reference models in local earthquake tomography

E. Kissling,[1] W.L. Ellsworth,[2] D. Eberhart-Phillips,[3] and U. Kradolfer[1]

Minimum 1D model: „a well-suited 1-D velocity model for earthquake location and for 3-D seismic tomography"





Haberland et al., 2006

- Simultaneous inversion for <u>1D velocity model</u> (horizontally layered), <u>hypocentral parameters</u> (coordinates, origin time) and <u>station corrections</u>
- Using highest-quality (sub-)dataset
- Start with many starting velocity models (to avoid getting trapped in a local minimum)
- From coarse to fine
- Test systematic perturbations of input parameters (e.g., hypocentral locations)
- Suitable model for EQ locations
- Difficult to interpret geologically

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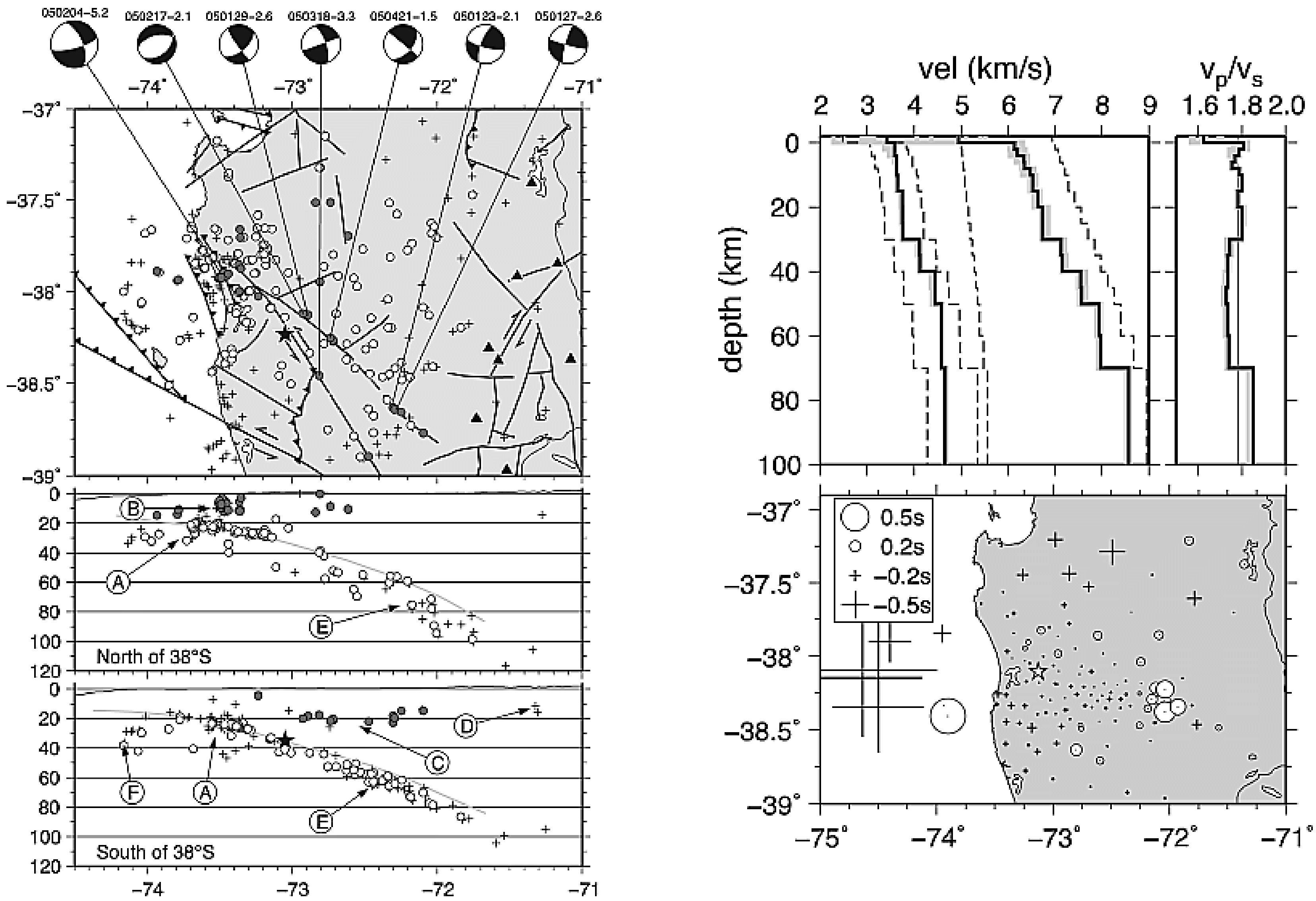
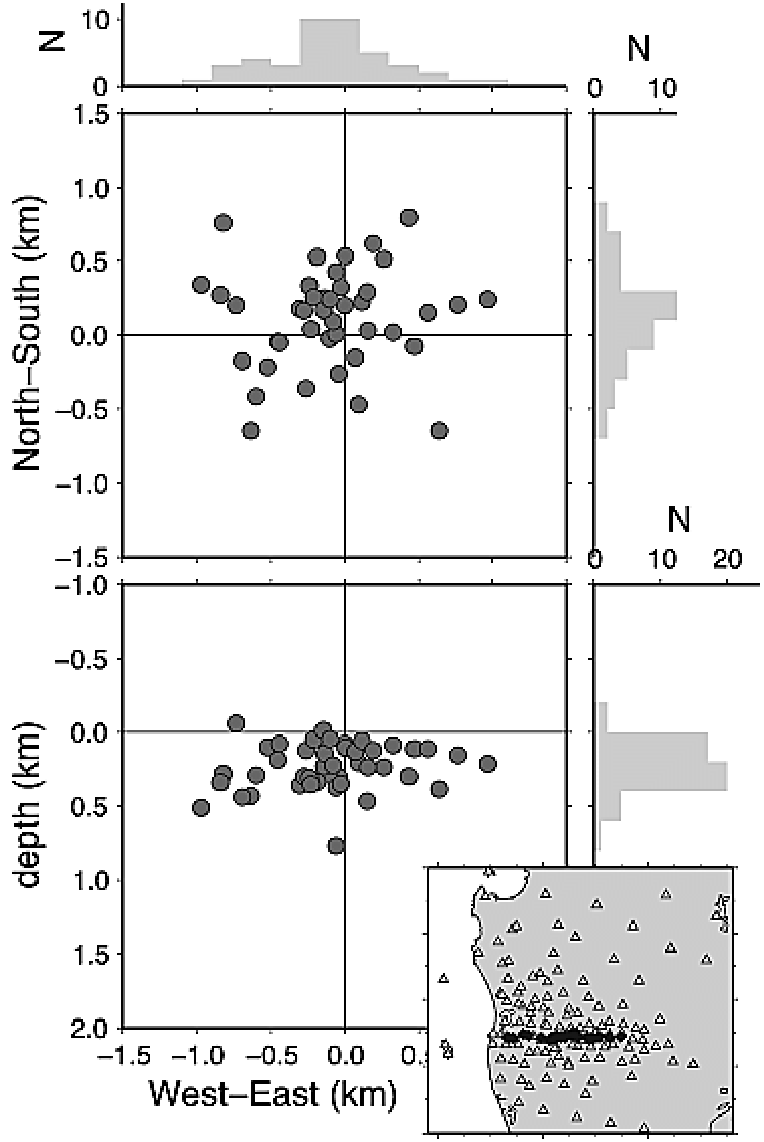
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Example velest inversion



Haberland et al., 2006

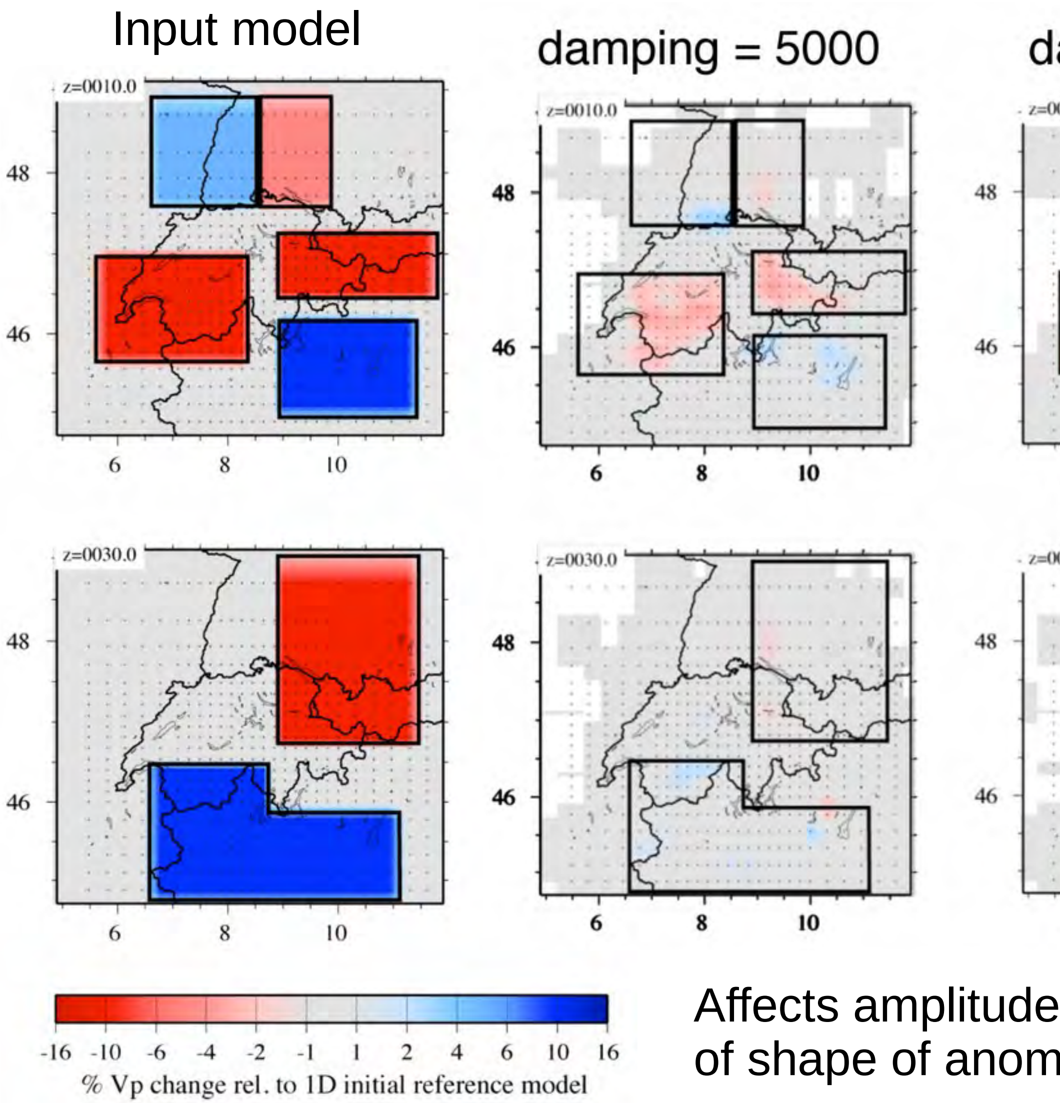
Test: relocation of known sources



- Localization of shots (with known origin time and coordinates)
- These were not used for the calculation of the min-1D model
- Mislocations provide estimates of uncertainties of hypocenters

Haberland et al., 2006

Damping parameter

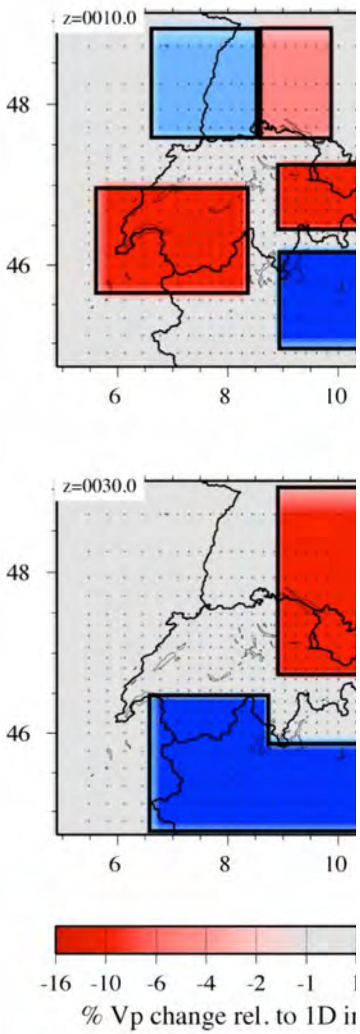


Affects amplitudes & recovery of shape of anomalies

Husen, 2011

Damping parameter

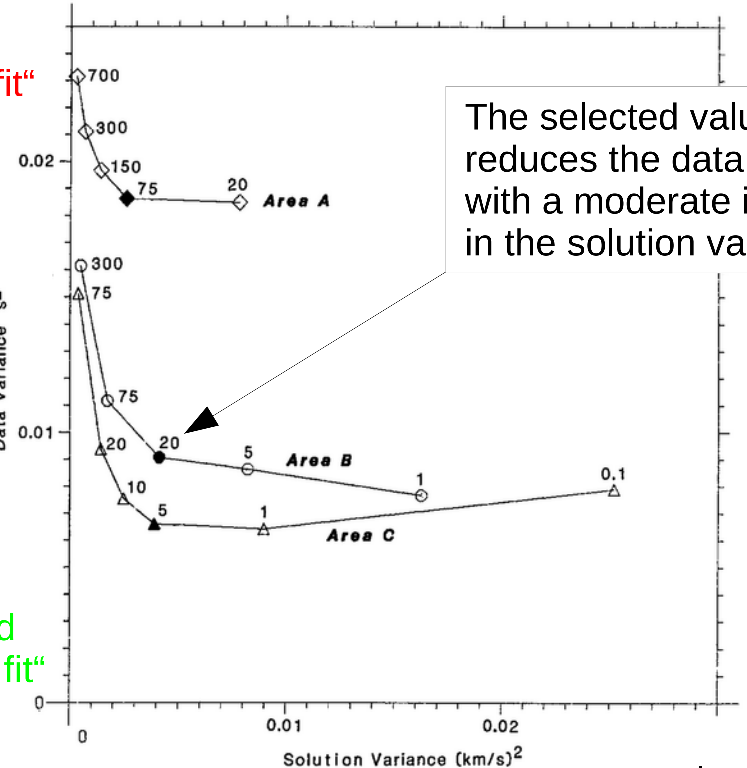
Input model



Trade-off curve:
One-step inversions with different damping

„poor data fit“

misfit



The selected value greatly reduces the data variance with a moderate increase in the solution variance

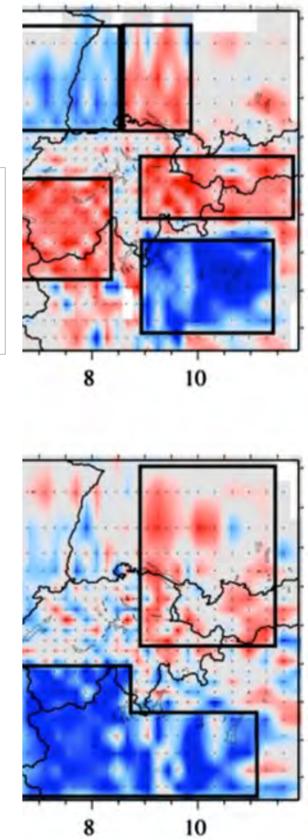
„good data fit“

„simple“ model

Model complexity

„complex“ model

ping = 10



Eberhart-Phillips, 1986

The input data

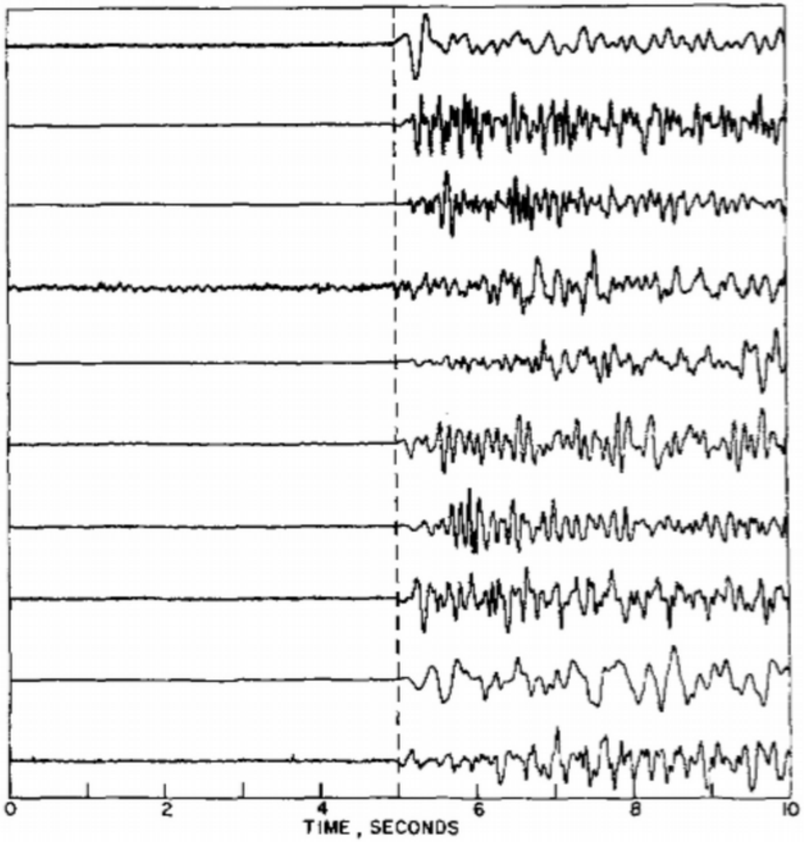
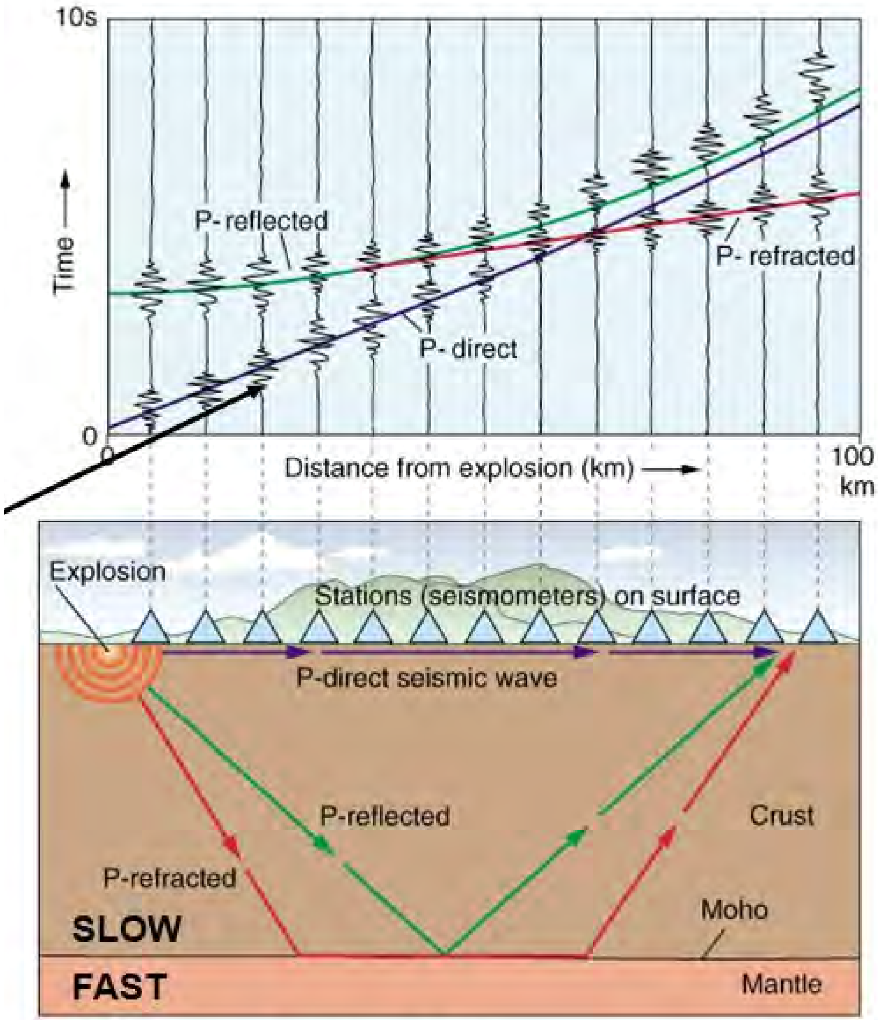


FIG. 1. Program *P*-arrival picks for magnitude 2.8 earthquake. Dotted vertical line at center of trace is pick point for each trace. Epicentral distances range from 50 to 90 km.

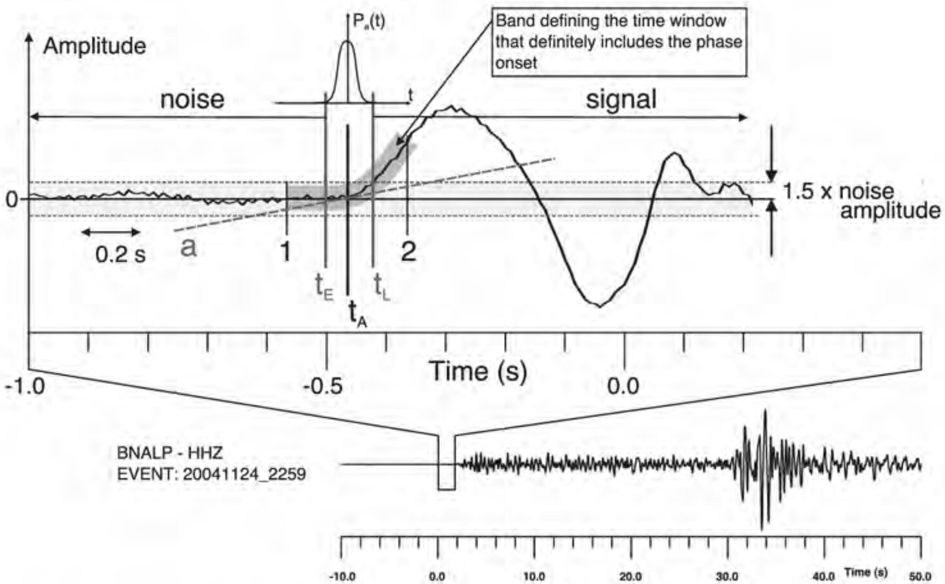
Allen, 1978

The input data - phase arrival times

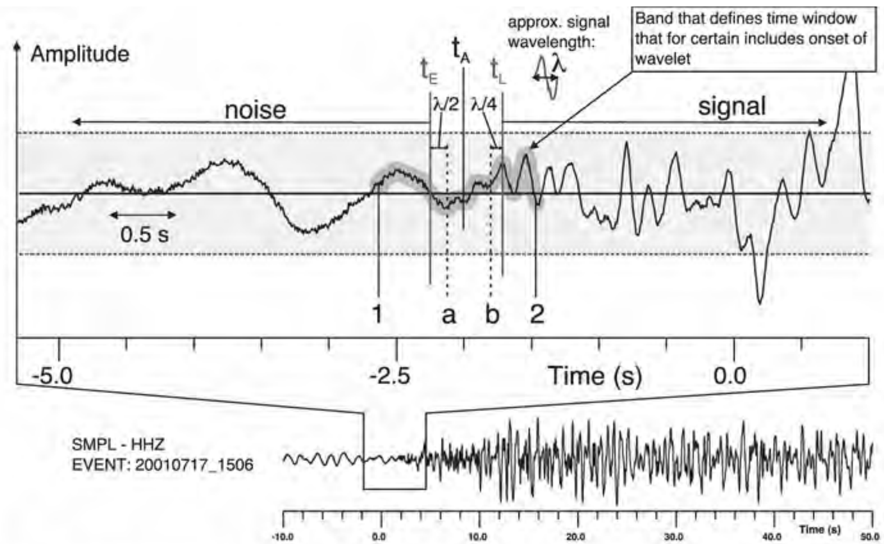


Travel-time curve for crustal phases
Here: only P-phases shown, source at surface
Direct P-phase: Pg
Refracted (mantle) phase: Pn
Reflected (Moho) phase: PmP

Consistent Picking



- Hand picking or automatic
- Consistent processing (e.g., filtering)
- Consistent picking
- Amplitude-based signal to noise ratio (ASNR)
- Frequency-based signal to noise ratio (FSNR)



- Defining S/N threshold
- Defining earliest & latest possible pick (or most-likely pick + uncertainty)
- Consistently assigned weights/quality

Class	weight	uncertainty (s)
0	1.0 $(1/2^0)$	+- 0.05
1	0.5 $(1/2^1)$	+- 0.10
2	0.25 $(1/2^2)$	+- 0.20
3	0.125 $(1/2^3)$	+- 0.40

GFZ Helmholtz-Zentrum Potsdam

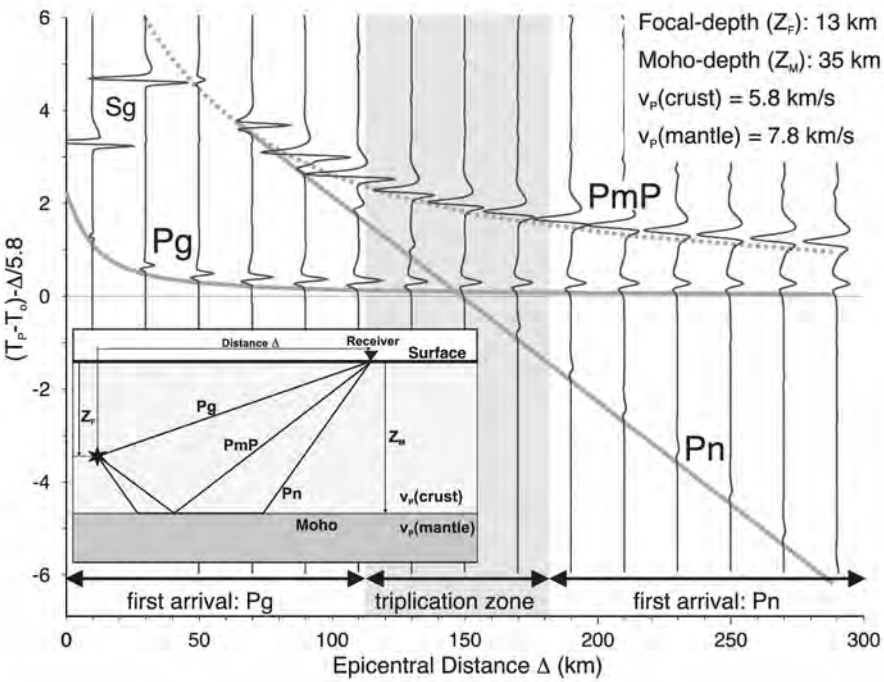
Husen, 2011

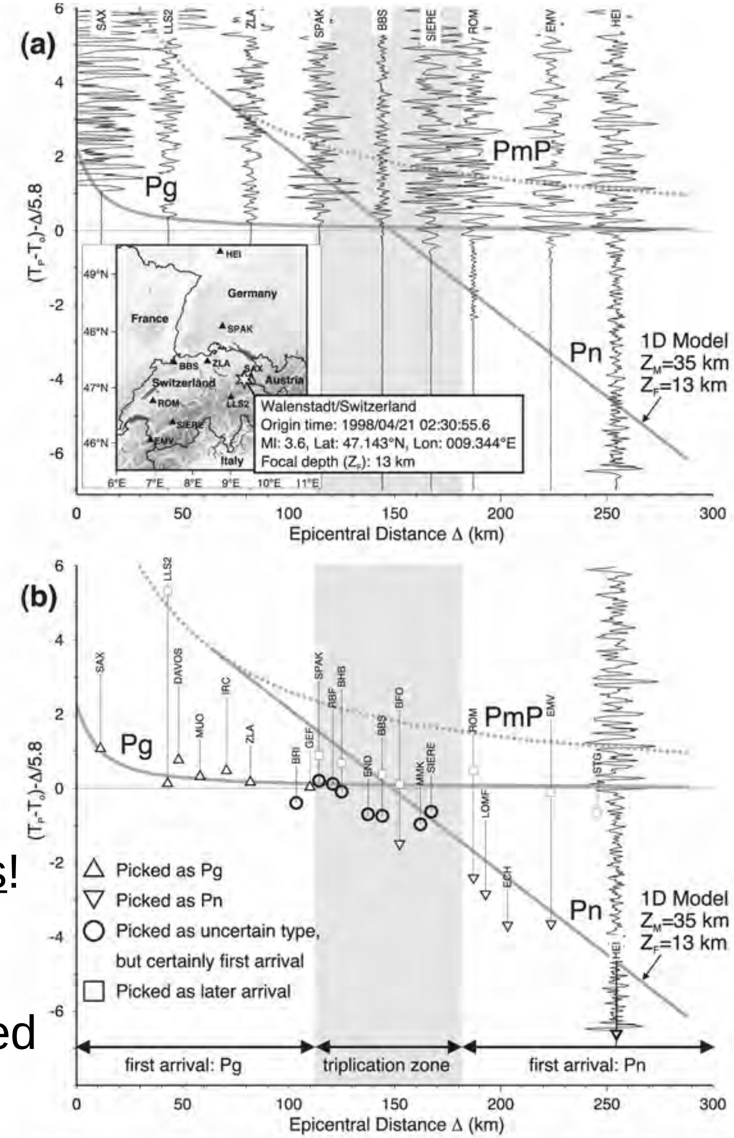
Diehl & Kissling, 2009

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Phase identification

Synthetic data (typical crustal model)





- Major phases Pg, Pn and PmP
- Conventional analysis routines <u>use first-arrivals</u>!
- Note small amplitudes of Pn
- Decreasing amplitude with increasing distance → increasing S/N → first arrival might be missed
- S-phases similar, rotation into T/R system, polarization analysis

Diehl & Kissling, 2009

Real data (Switzerland)

Seismic attenuation

Energy losses due to anelastic processes

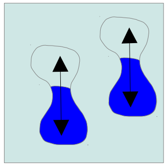
Simlar to x-ray absorption...

Deutsches Röntgenmuseum

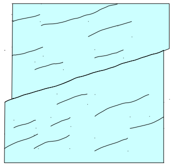
First X-ray image
(Anna-Bertha Röntgen‘s hand)

Some processes in rocks:

Porous media with fluid saturation - macroscopic flow

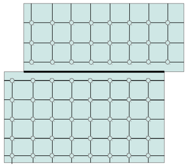


Frictional sliding across cracks



Fluid saturation

Viscous relaxation;
grain boundary relaxation;
grain boundary sliding



Thermally activated processes

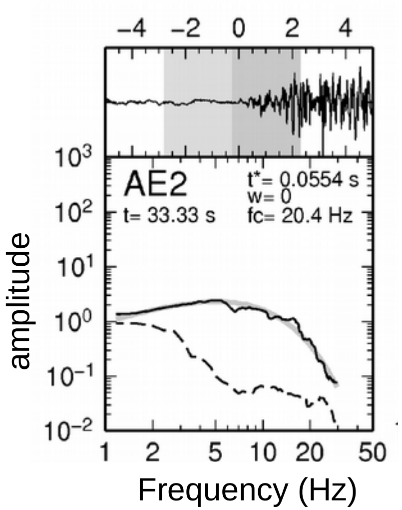
Permanent deformation; dissipation (conversion into heat)

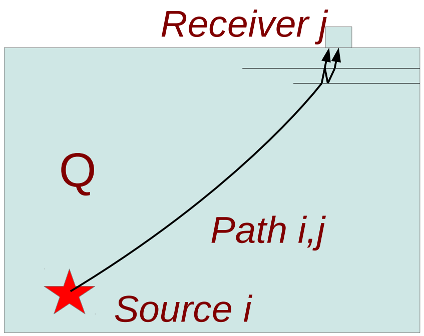
Energy loss $-\Delta E$ after one cycle of cycled stress (e.g. seismic wave):

$$\frac{1}{Q(f)} = \frac{-\Delta E}{2\pi E}$$

Q Quality factor
E peak strain energy in volume

Seismic attenuation





Seismic spectrum:

$$A_{i,j}(f)=O_i(f)\,S_j(f)\,G_{i,j}(f)\,B_{i,j}(f)$$

f: frequency
S: Site effect
G: geom. spread,

Attenuation term:

$$B(t,f)=\exp\left(-\pi f\, t\, Q^{-1}\right)$$

t: (travel-) time

Source term:

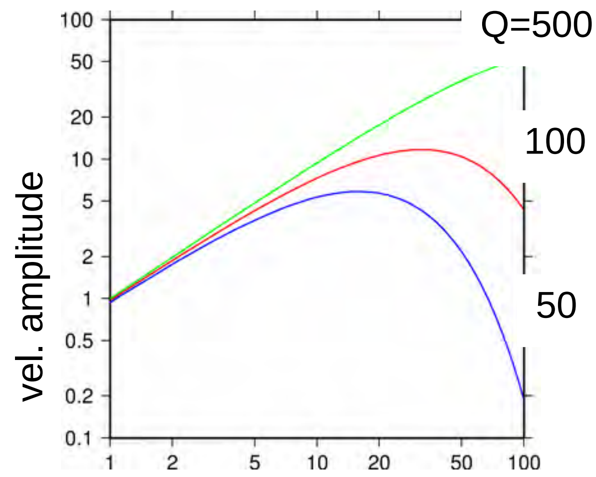
$$O_j(f)=\frac{\Omega_0}{1+\frac{f^2}{f_c^2}}$$

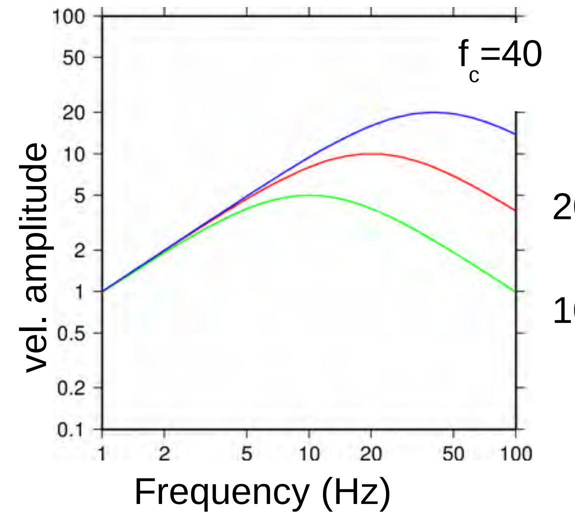
Ω_0: spectral moment
f_c: corner frequency

$$A_{i,j(f)}=\frac{\Omega'_{i,j}\exp\left(-\pi t^*_{i,j}\right)}{1+\frac{f^2}{f_{ci}^2}}$$

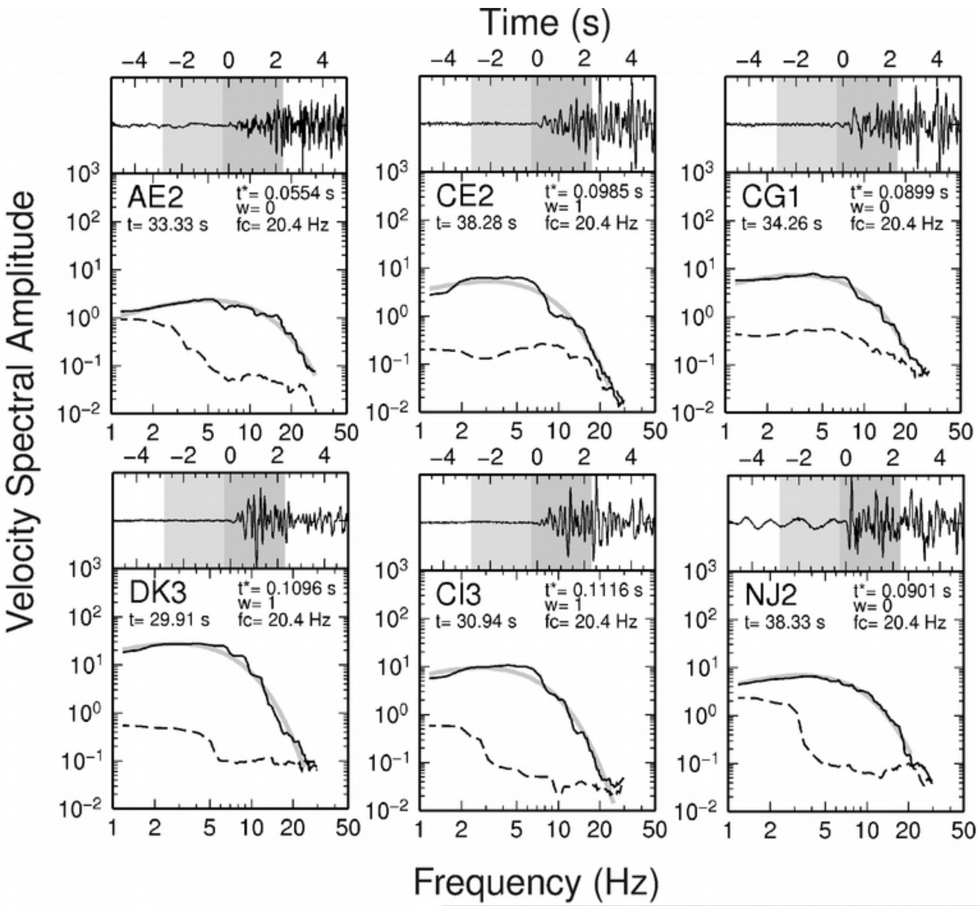
with

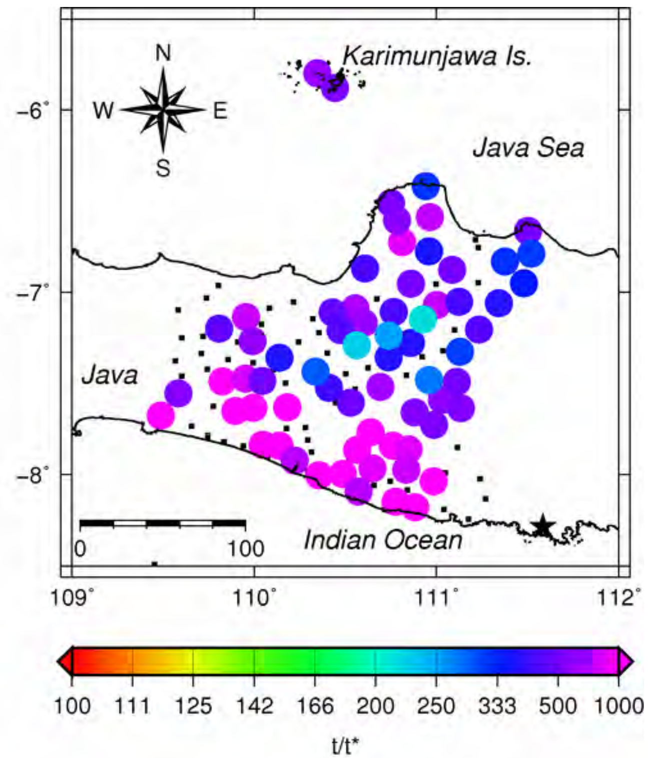
$$t^*_{i,j}=\frac{T}{\bar{Q}}$$





Seismic attenuation





Tomography:

Derive path-average attenuation by spectral inversion:

$$A_i, j(f) = \frac{\Omega'_{i,j} \exp(-\pi t^*_{i,j})}{1+\frac{f^2}{f_{ci}^2}}$$

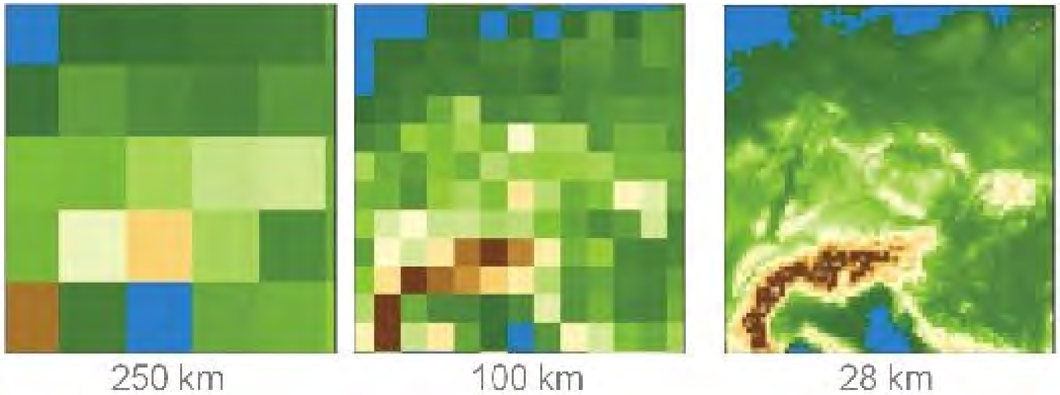
$$t_{i,j} = \int_{ray\, i,j} \frac{dr}{v(x,y,z)} + t_{station\, j}$$ travel-time

$$t^*_{i,j} = \int_{ray\, i,j} \frac{dr}{Q(x,y,z)\, v(x,y,z)} + t^*_{station\, j}$$ attenuation

Bohm et al., 2009

Solution quality / Resolution

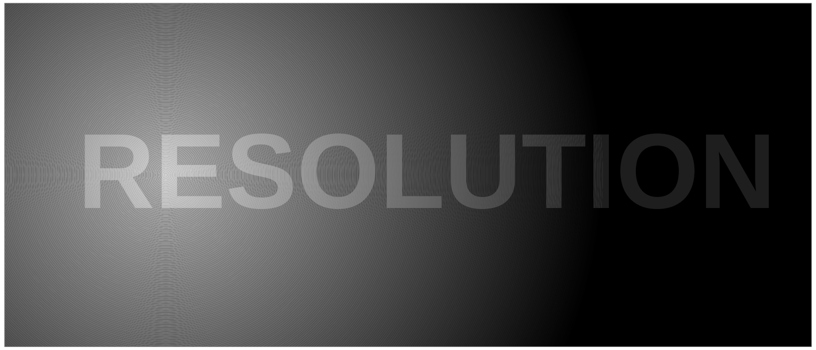
- Physical resolution (What is the smallest structure we can resolve?)
  image sharpness → depends mainly on frequency (and sample rate etc.)



http://www.optowiki.info

depends mainly on frequency (sample rate etc.)

- Mathematical resolution (Which model parameters are resolved? How well?)
  → Solution quality



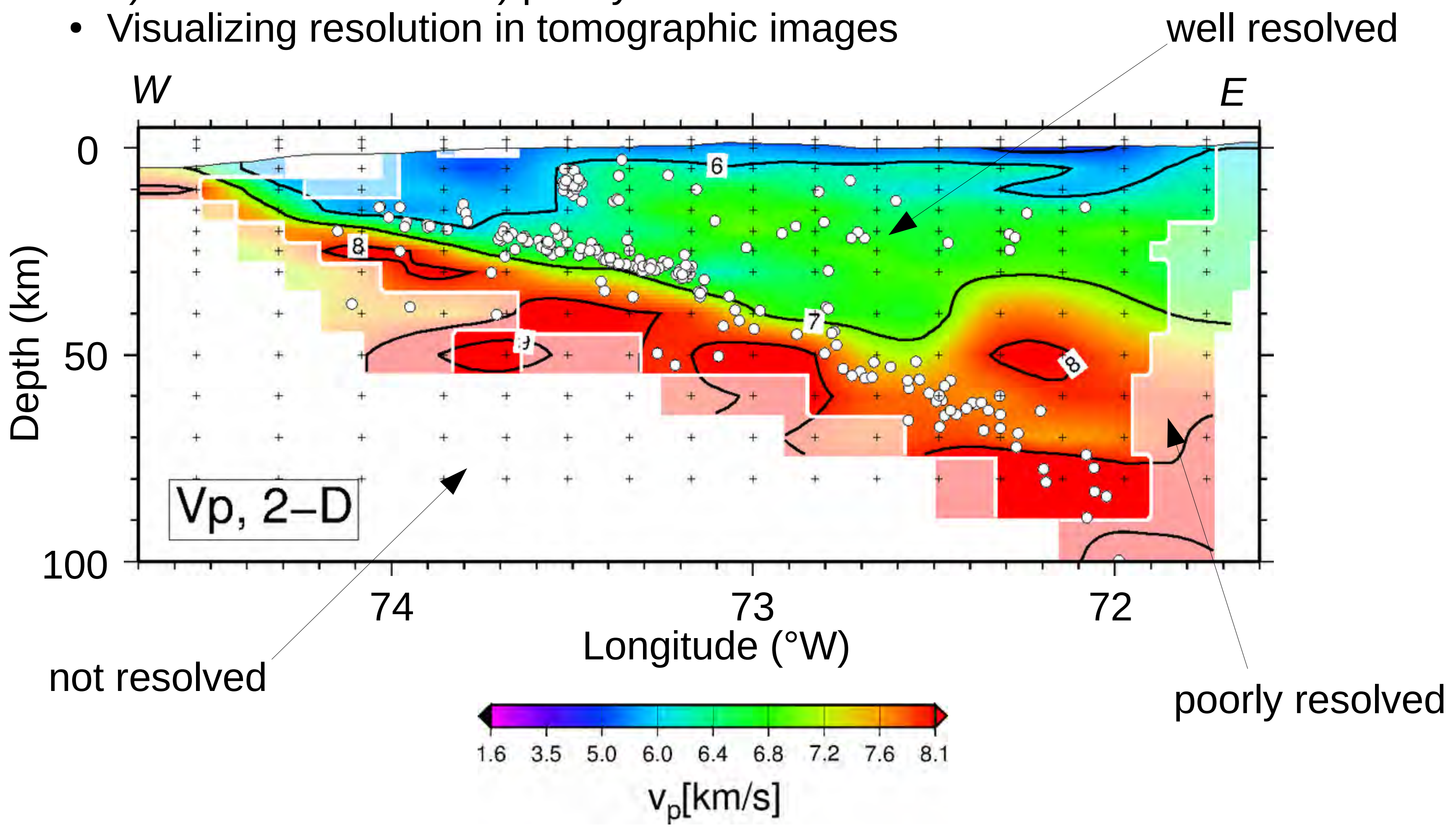
depends mainly on ray distribution (source/ receiver geometry)

- Model resolution combination

Solution quality / Resolution

Solution quality

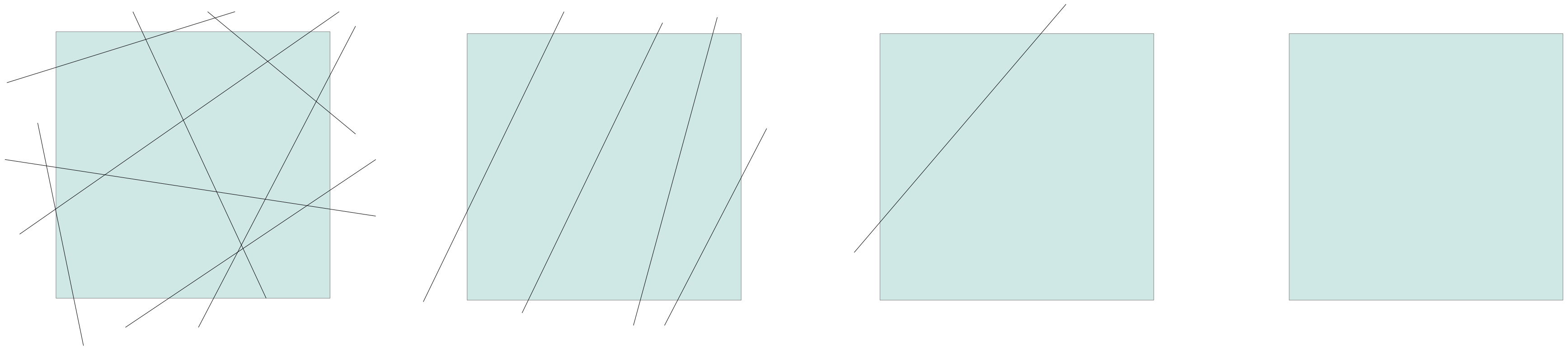
- Aim is to identify regions which are 1) unresolved,
- 2) well resolved and 3) poorly resolved
- Visualizing resolution in tomographic images



Haberland et al., 2009

Solution quality / Resolution

Ray distribution per inversion cell



Well resolved	Moderately resolved	Poorly resolved	unresolved
Many rays Good crossing	many rays no crossing	few rays no crossing	no rays no crossing

Ray number and distribution has an effect on the solution quality of the corresponding model parameter

Different ways to assess solution quality:

- formal estimates (e.g. hit count,DWS, resolution matrix, covariance matrix)
- Synthetic recovery tests

Resolution Matrix

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

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

$\mathbf{R} = \mathbf{G}^{-g}\, \mathbf{G}$

with $\mathbf{G}^{-g} = (\mathbf{G}^T\mathbf{G} + \Theta\, \mathbf{I})^{-1}\, \mathbf{G}^T$ ← damped least squares inversion

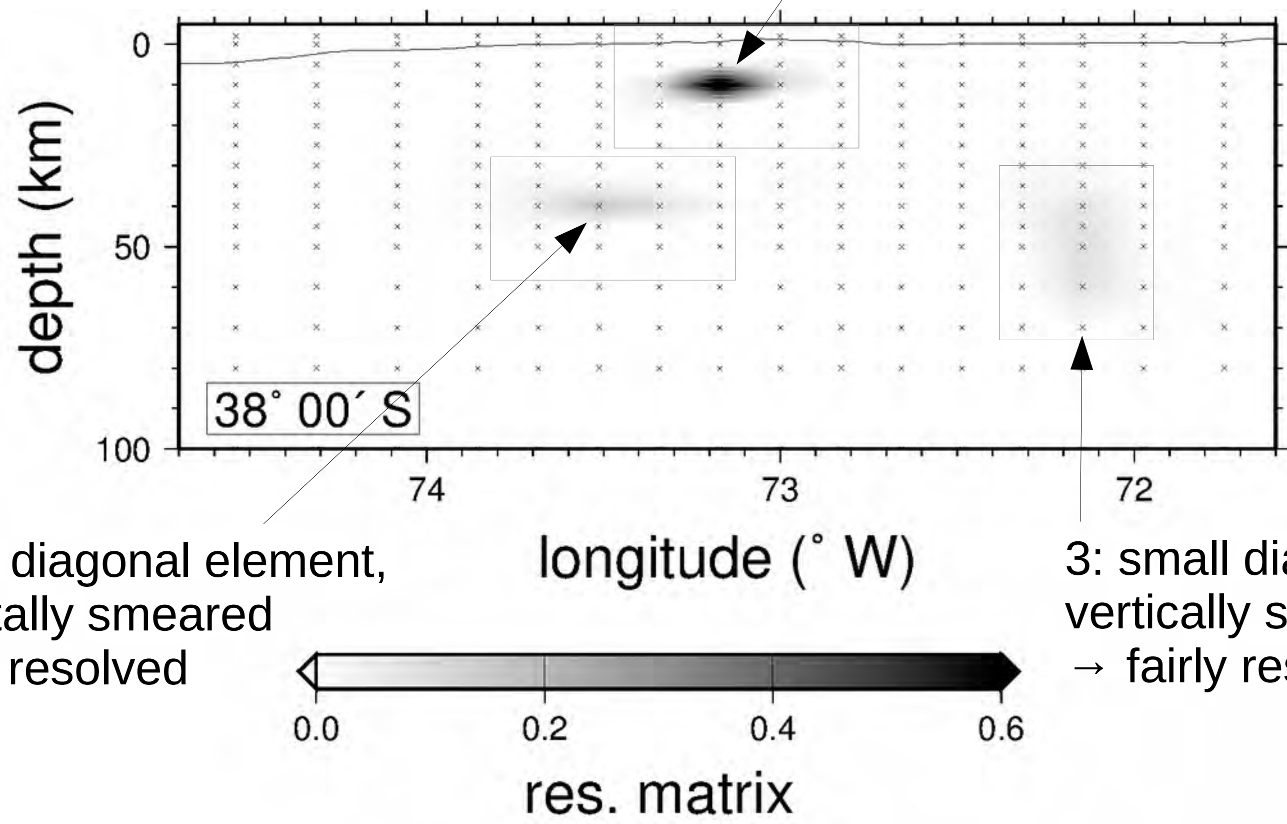
Properties of R:
- R is n x n matrix (n: number of model parameters)
- each row of R describes the dependence of one model parameter on all other model parameters
- diagonal element of R between 0 and 1
  1: perfect resolution (little dependence); 0: no resolution
- amplitude of diagonal element depends on damping!

Large matrix, not so easy to vizualize...
- showing only diagonal element
- showing only example nodes
- calculated spread (+ contours of R)

Resolution matrix

For three exemplary nodes all elements of the particular row are displayed

1: large diagonal element, peaked → well resolved



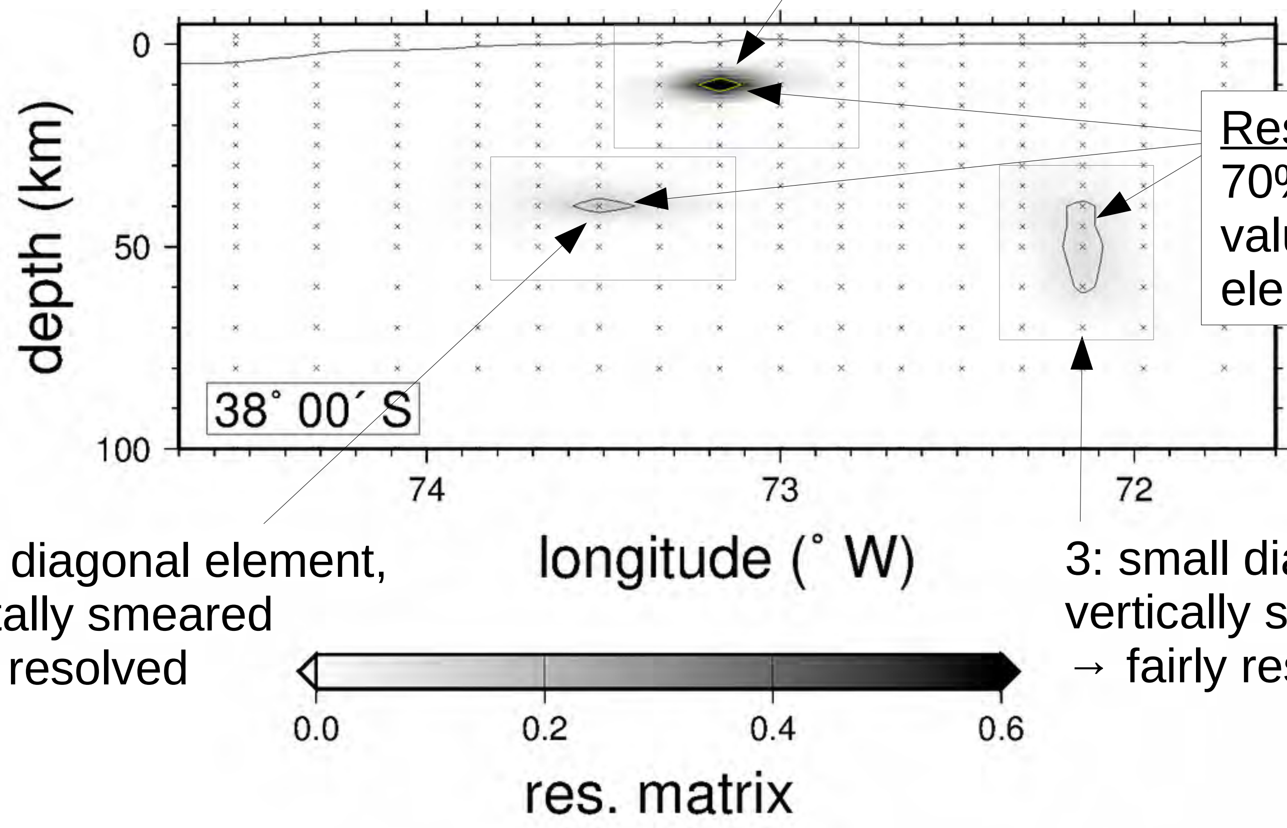
2: small diagonal element, horizontally smeared → fairly resolved

3: small diagonal element, vertically smeared → fairly resolved

Resolution matrix

For three exemplary nodes all elements of the particular row are displayed

1: Large diagonal element, peaked → well resolved

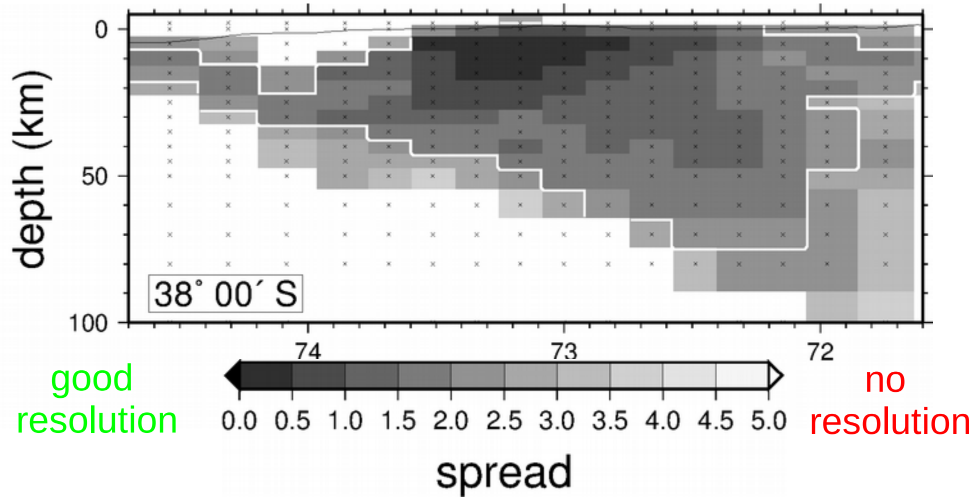


Resolution contours
70% contour of the value of the diagonal element

2: small diagonal element, horizontally smeared
→ fairly resolved

3: small diagonal element, vertically smeared
→ fairly resolved

Spread value



Spread function of a particular model parameter j:

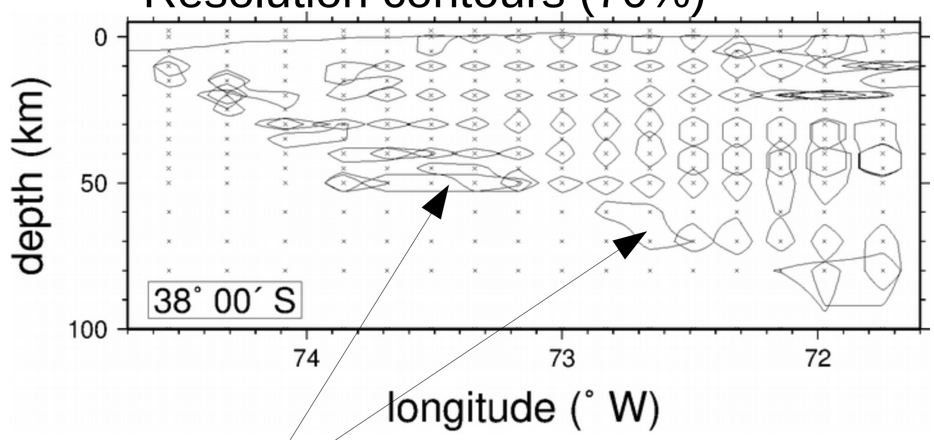
$$Spread_j = \log\left[|R_j|^{-1}\sum_{k=1}^{m}\frac{R_{kj}}{R_j}D_{jk}\right]$$

R_j: diagonal element (j'th row)

R_{kj}: other elements of j'th row

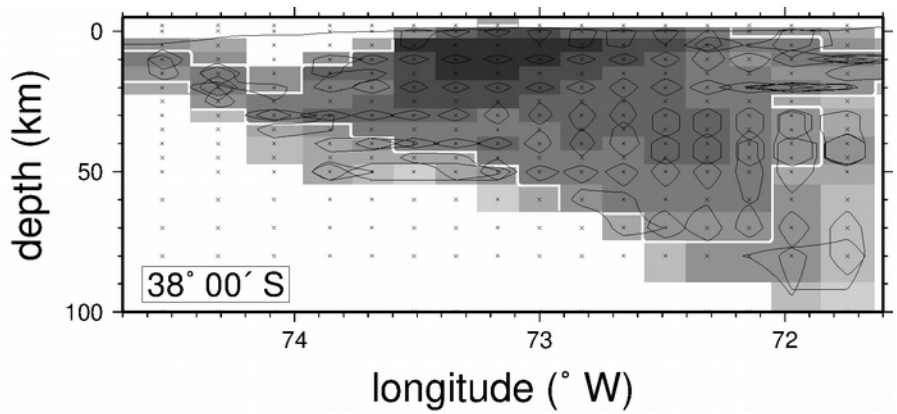
D_{kj}: spatial distance between parameter j and k

Resolution contours (70%)



Strong (sub-)horizontal smearing

Superposition

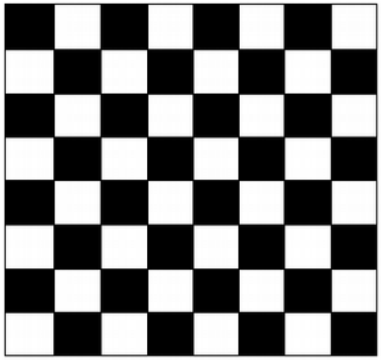


Haberland et al., 2009

Synthetic recovery tests

General approach:

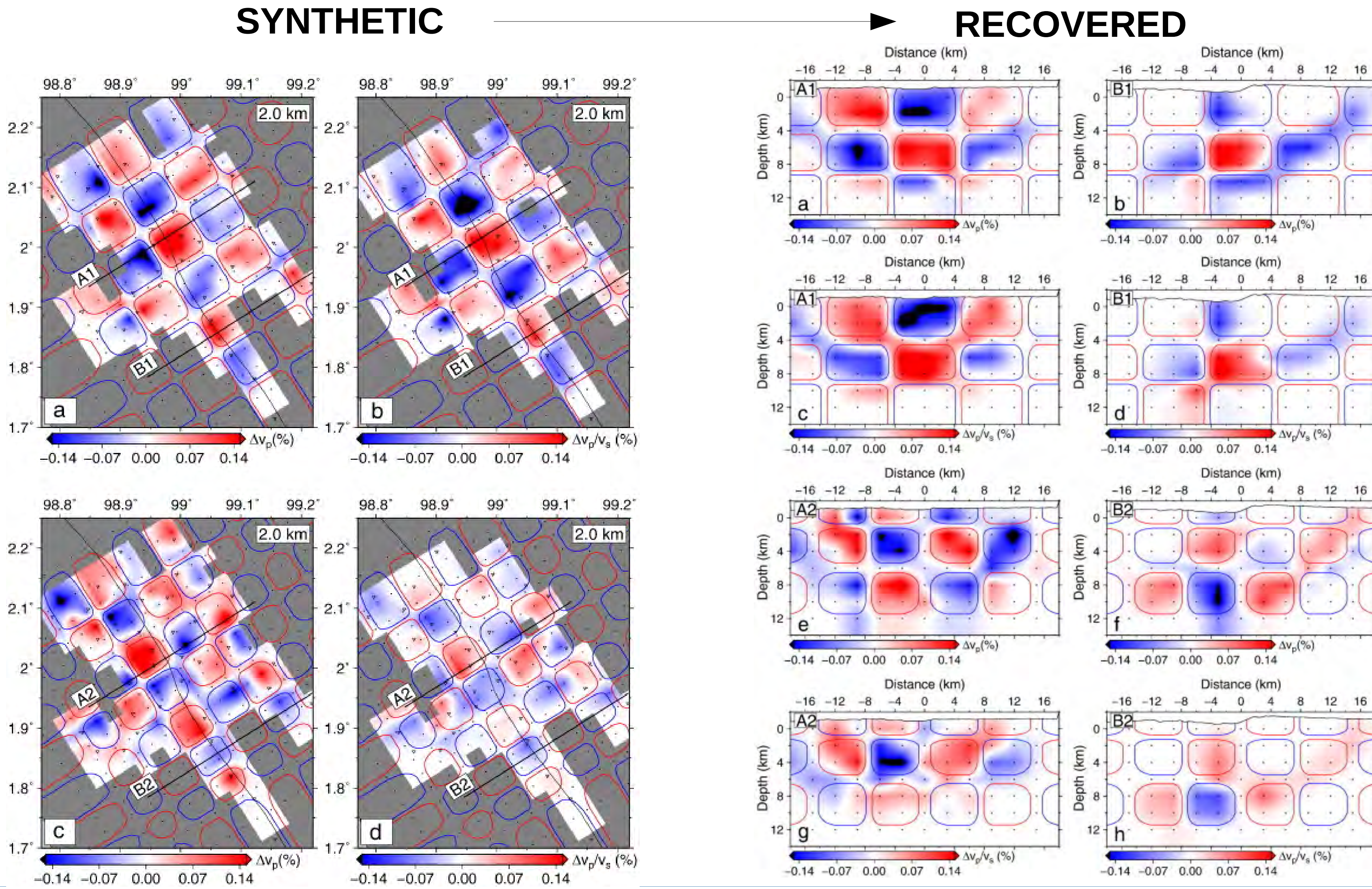
- Set up synthetic model
- Usually background model similar to „real" model/initial model (to assure similar general raypaths/ray distribution) + perturbations (e.g. in %)
- Compute travel times for same source-receiver geometry as in real data
- Add random (e.g. Gaussian) noise to synthetic traveltimes
- Invert synthetic travel time dataset in the same way as the real data
- Compare input and output model (assess smearing, resolved region, amplitude of anomalies, dimension of resolved features)
- Sensitivity tests



Popular model /-classes:

- Checkerboard tests
- Characteristic model test
- Realistic models

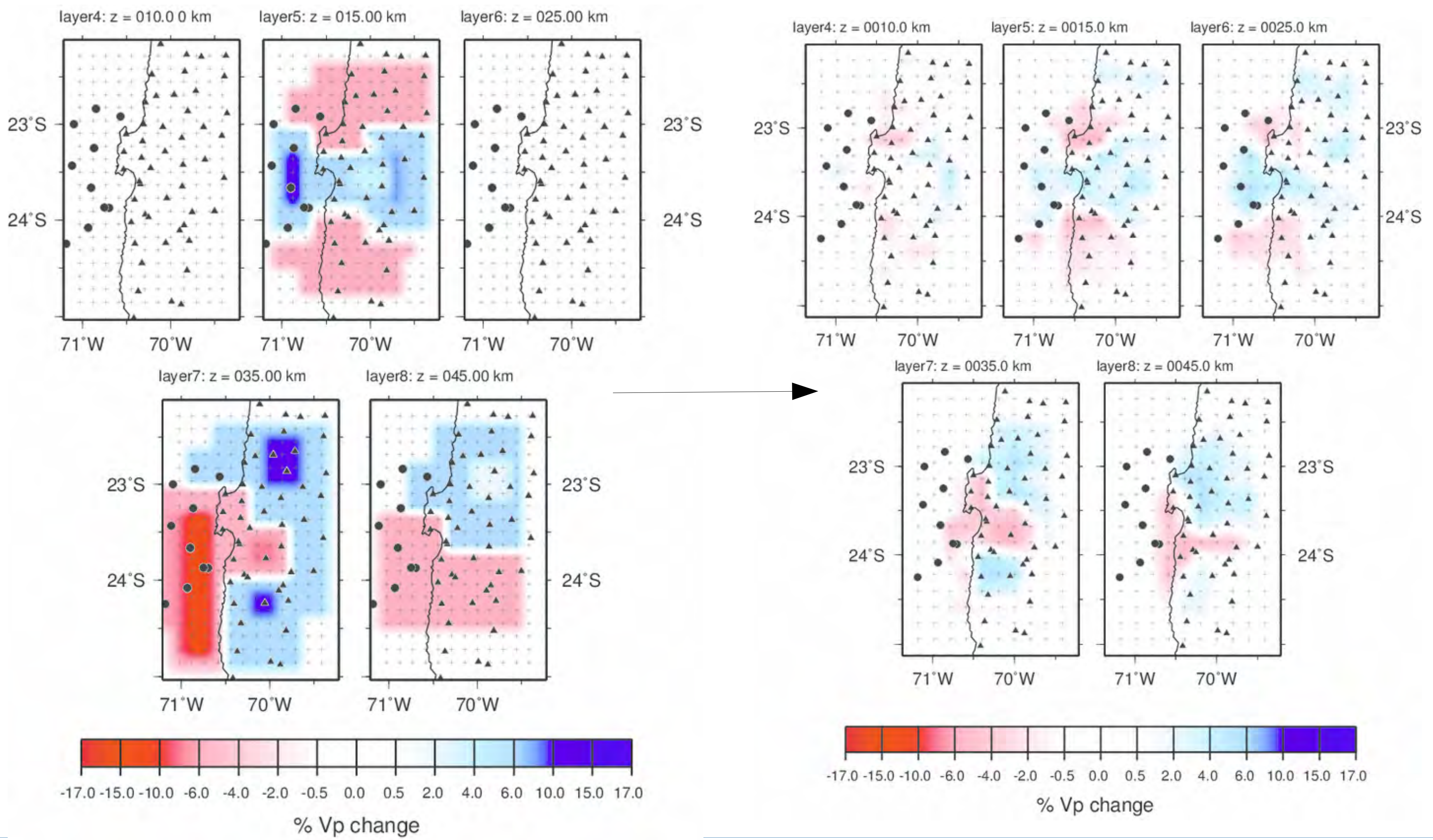
Checkerboard recovery tests



Muksin et al., 2013

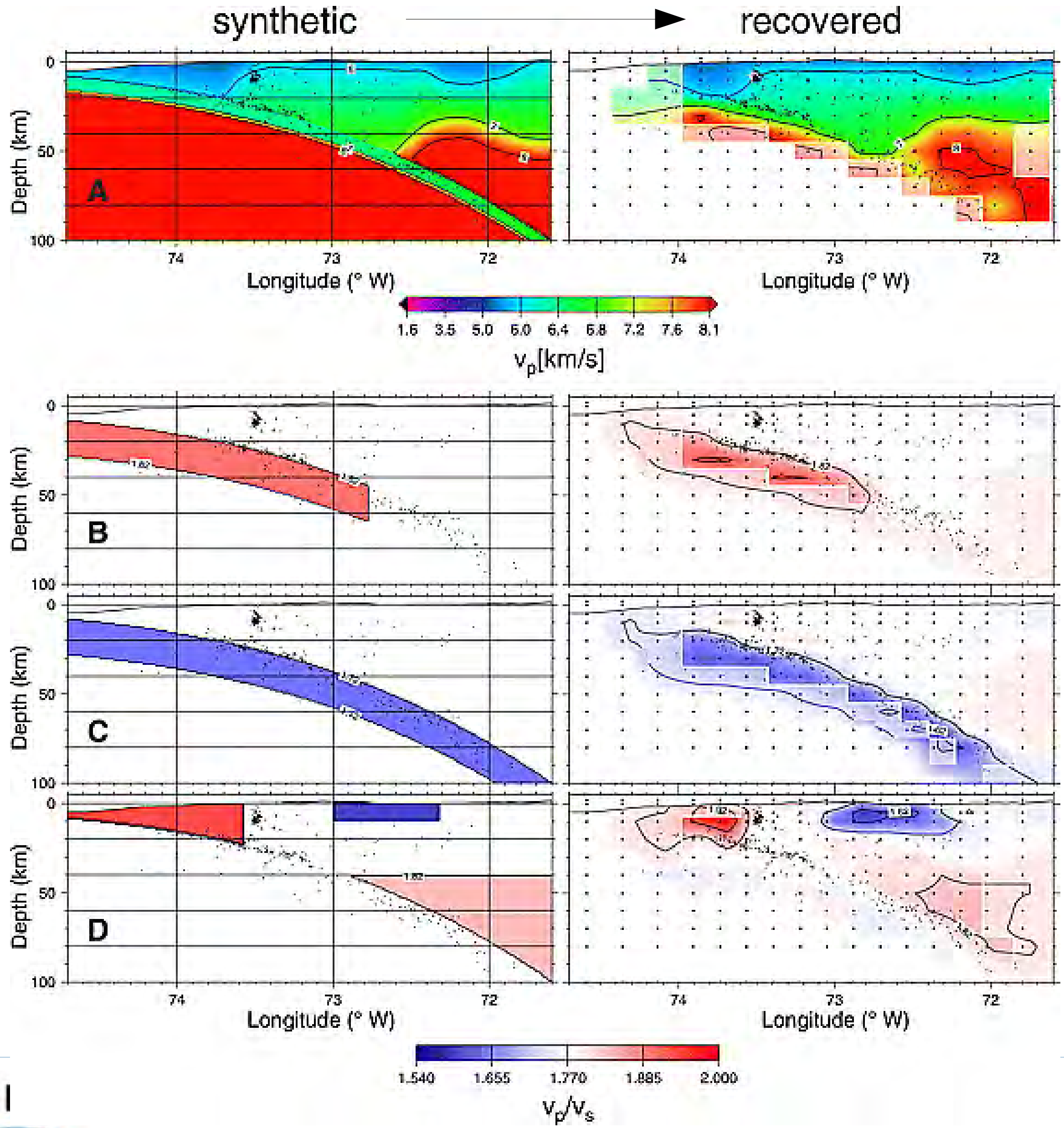
Characteristic models

SYNTHETIC → **RECOVERED**



Husen et al., 2000

„Realistic" synthetic models - I



- Synthetic travel-times calculated with FD/Eikonal solver (different to raytracer in inversion)
- Checking resolution of specific features (depth extent of anomaly related with subducting plate, sign of amplitude, inclined oceanic Moho, etc.)

Haberland et al., 2009

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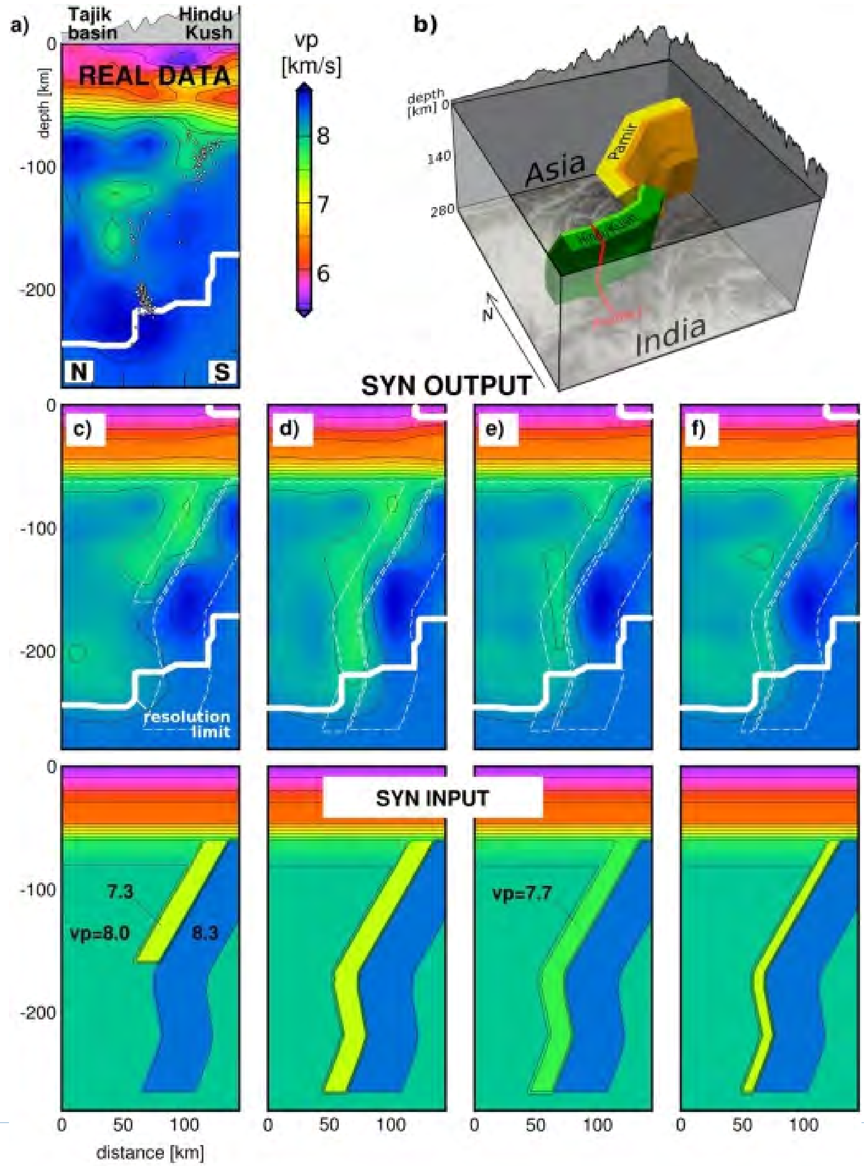
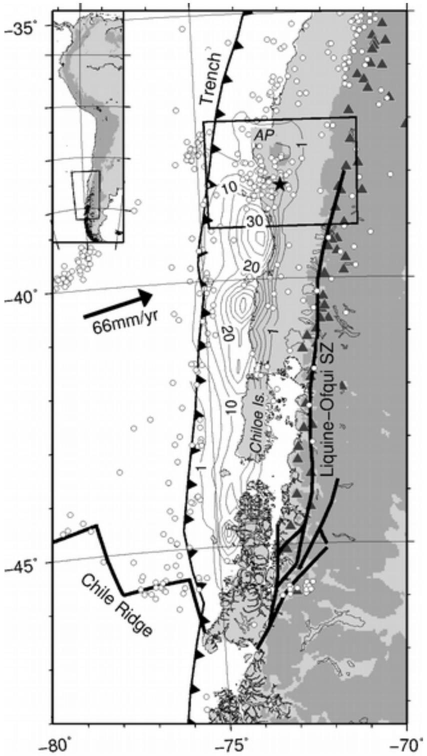
„Realistic“ synthetic models - II



- Complicated 3D-slab structure in the Pamir/ Hindukush region
- Test of resolvebility of slab properties, shape and thicknesses
- Use of Eikonal (FD) solver
- Part of model set-up using vtk/paraview routines

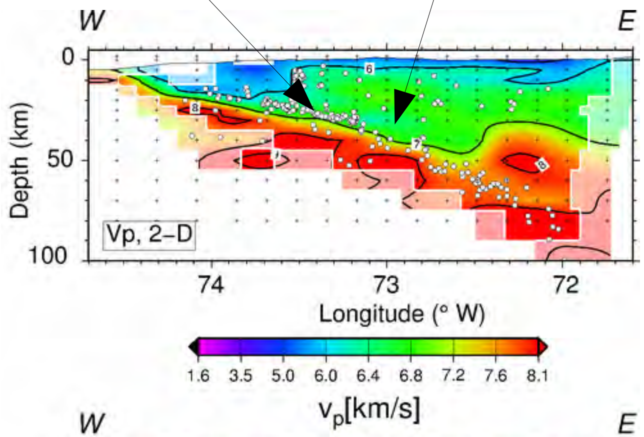
Kufner et al., 2017

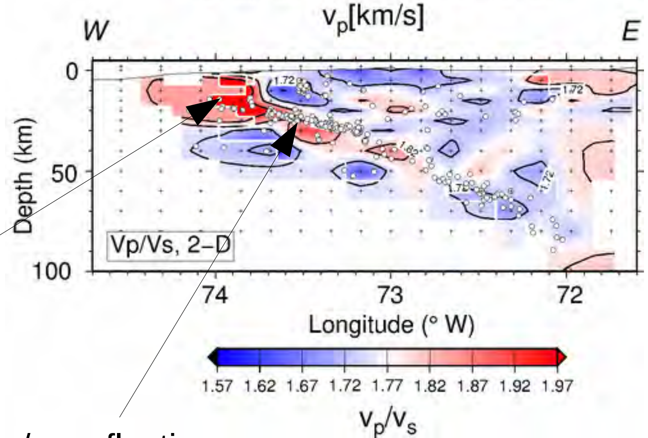
Applications/Interpretation



Crustal/mantle structure

megathrust



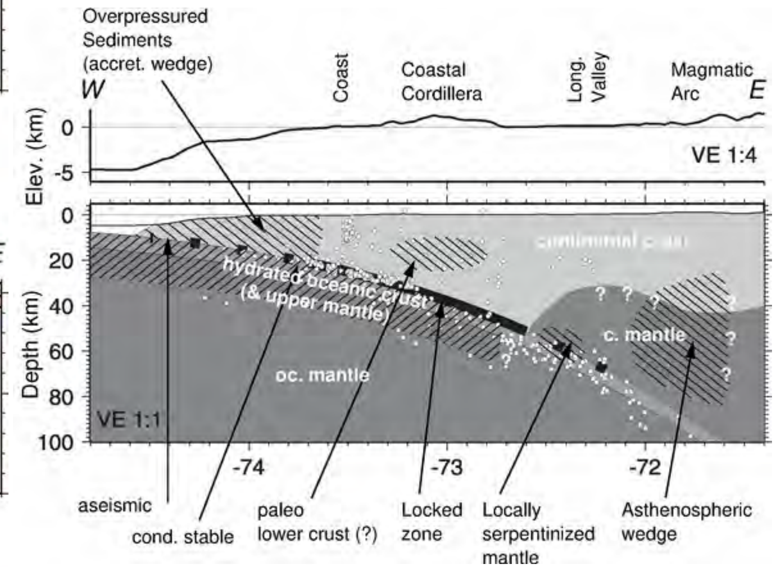


High vp/vs in marine forearc indicating fluid processes

High vp/vs reflecting hydrated slab

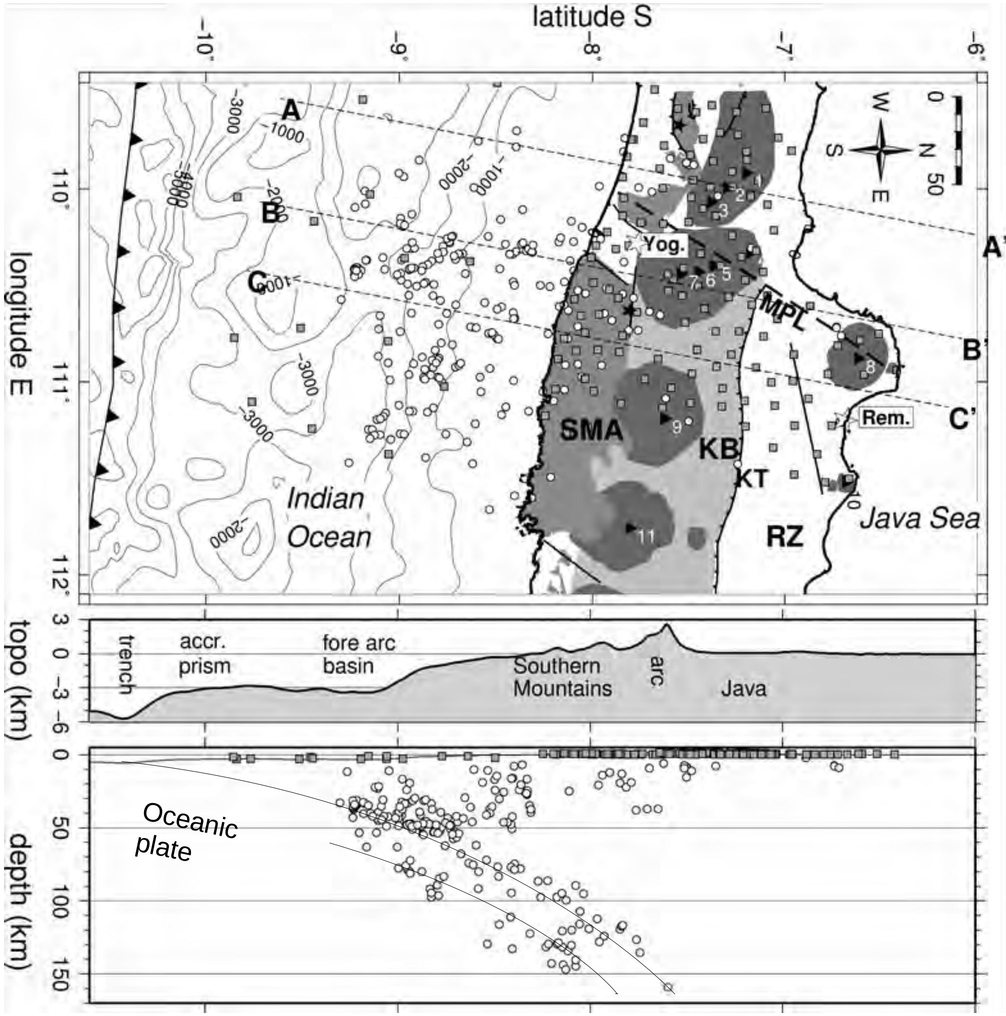
Imaging of the 3D structure of subduction zones

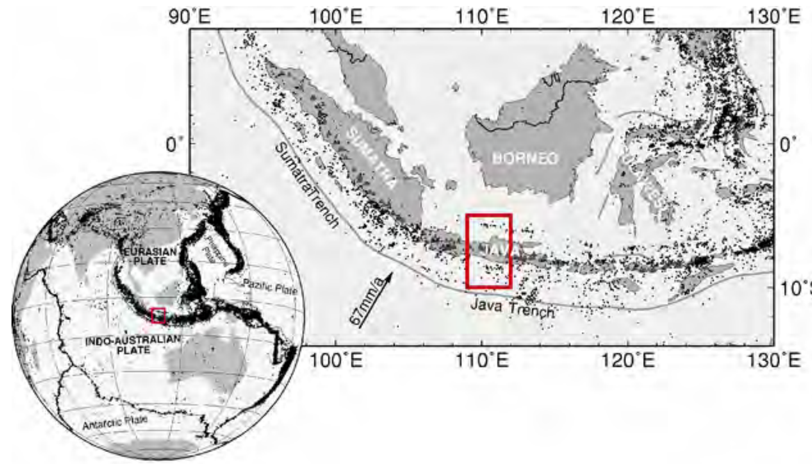
Example: S-Central Chile (nucleation area of the 1960 Mw 9.5 EQ)



Haberland et al., 2009

Applications / Interpretation

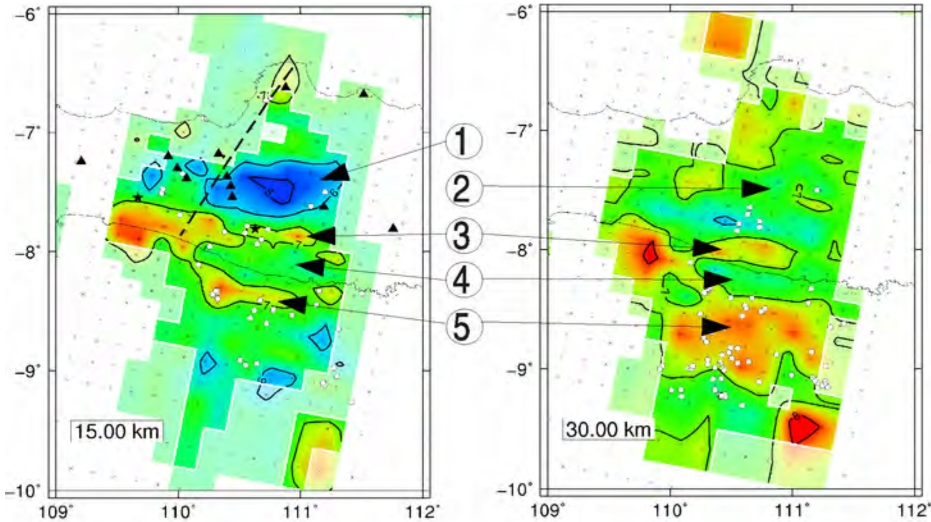


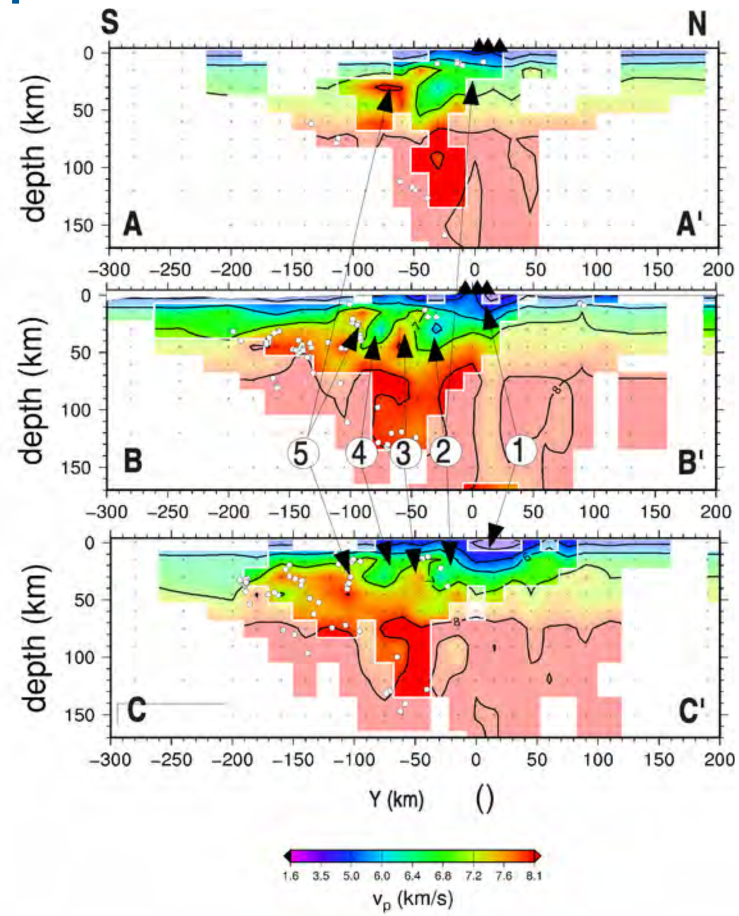


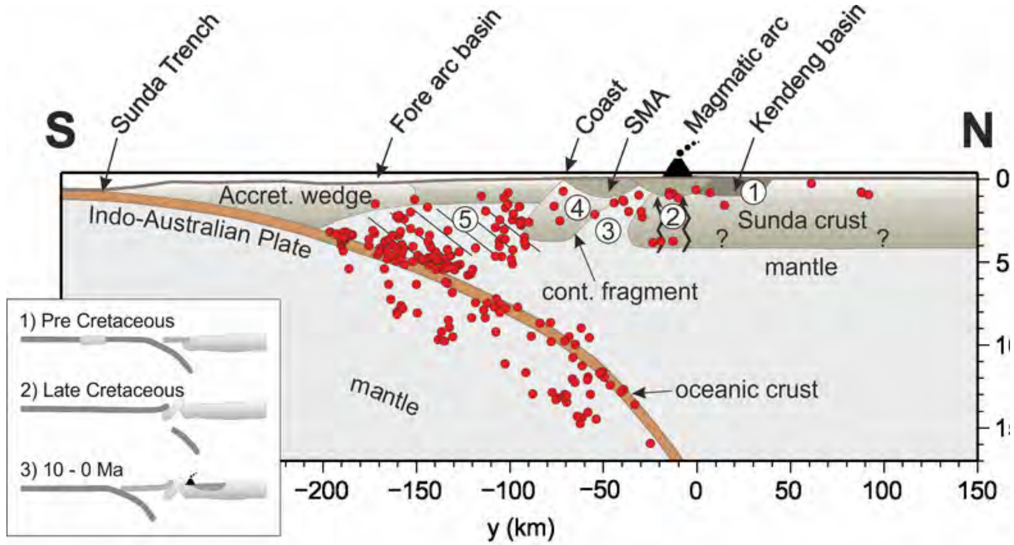
- Ocean-continent subduction
- Subducting plate indicated by local seismicity; double seismic zone
- slab traced into lower mantle
- SE Asia region is composite of terranes accreted Paleozoic/Cenzoic
- Paleogene @ Neogene accretionary prism
- Marine forearc basin (4km thick sediments)
- SMA: Southern mountain arc (Middle Eocene – middle Miocene)
- KB: Kendeng basin (<10km thick sediments)
- Modern volcanic arc with prominent volcanoes (e.g., Merapi)

Haberland et al., 2009

Applications / Interpretation



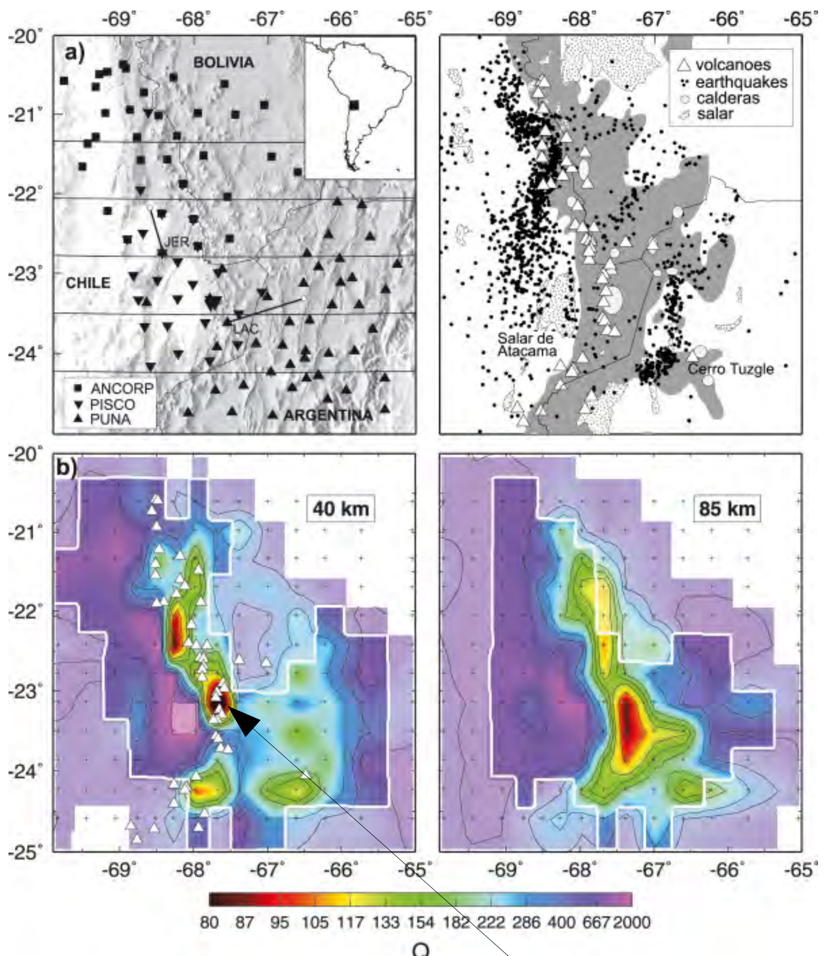


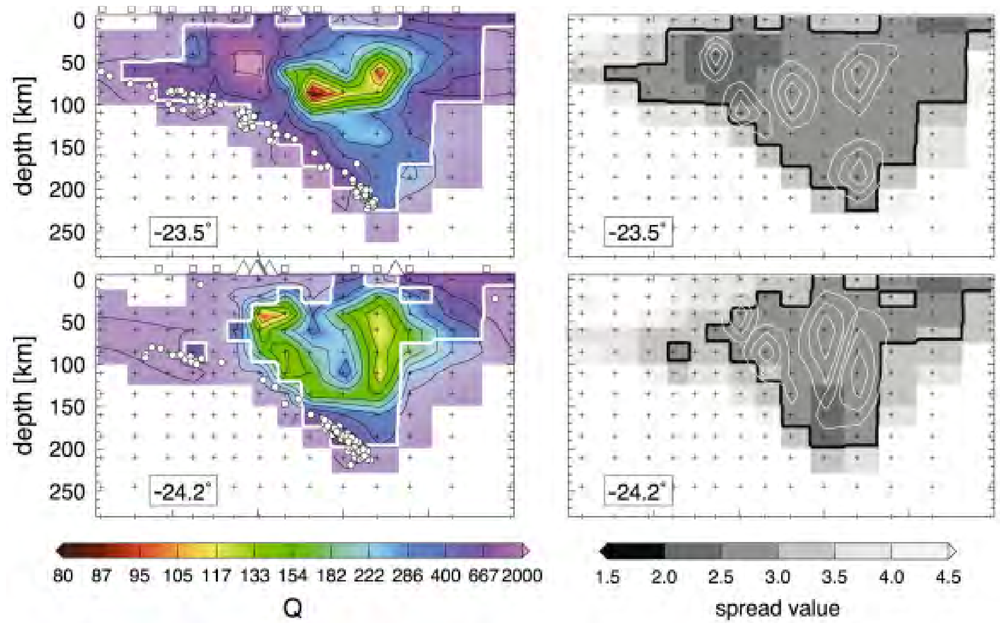


1: low vp in Kendeng Zone (sed. basin) and beneath magmatic arc (-35% vel. reduction)
2: moderate/low vp in Java crust
3: high vp south of magmatic arc
4: low vp south of „3“
5: high vp in deeper marine forearc

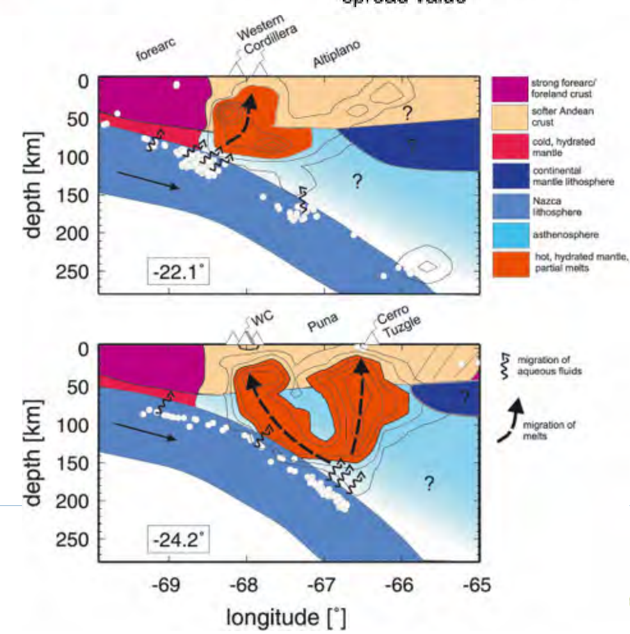
Haberland et al., 2009

Applications / Interpretation





Imaging fluid and melt (transport) in subduction zone



Low Q → partial crustal melting?

Schurr et al., 2003

Conclusions

- Robust and mature method to study structure of crust and lithosphere
- Classic approach through linearization and DLSQ inversion (e.g. simul2000); improvements (tomoDD, fat rays,
- Simultaneous inversion for 3D seismic structure and hypocenter
- Assessment of solution quality/resolution is essential
- Use of permanent and temporary local/regional network data
- Excellent tool to image 3D subsurface structure, geodynamical processes and temporary variations
- Outlook: full-waveform, later phases, Monte Carlo approaches
- Restricted to seismically active regions