Seismic anisotropy and shear-wave splitting: constraints on mantle deformation and flow

Georg Rümpker,

Miriam Reiss, Ayoub Kaviani, Frederik Link, Ingo Wölbern

Goethe-University Frankfurt

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Outline

- Seismic anisotropy in the crust and mantle - causes and effects
- Effects on receiver functions - with a focus on H-k stacking
- Shear-wave splitting analysis (relies on simple assumptions!)
- Waveform modeling
- Case studies - South American subduction

Definition

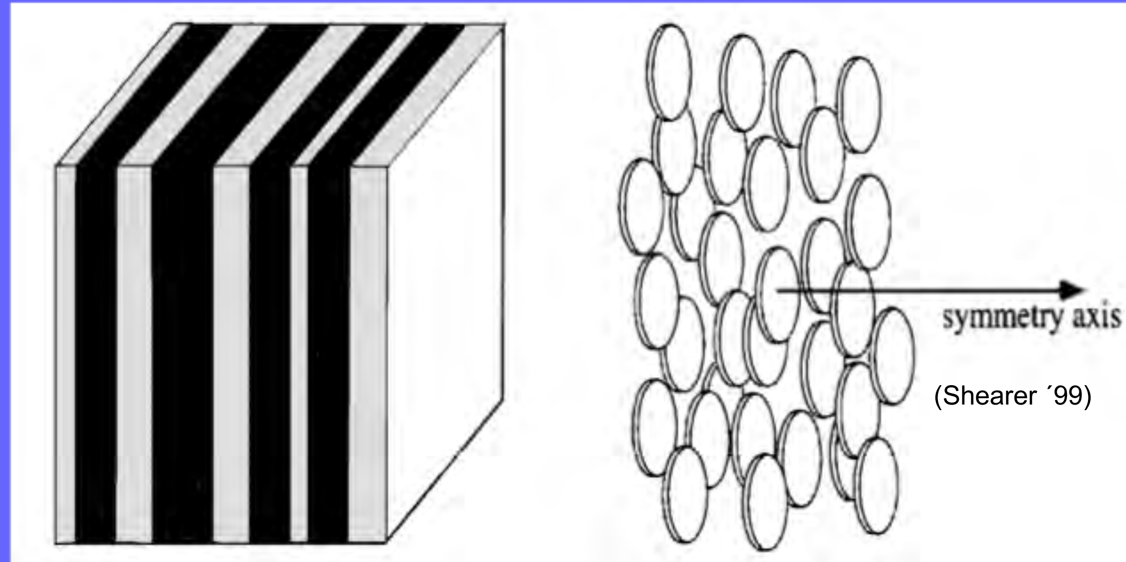
Seismic anisotropy describes the dependence of seismic wave velocities on

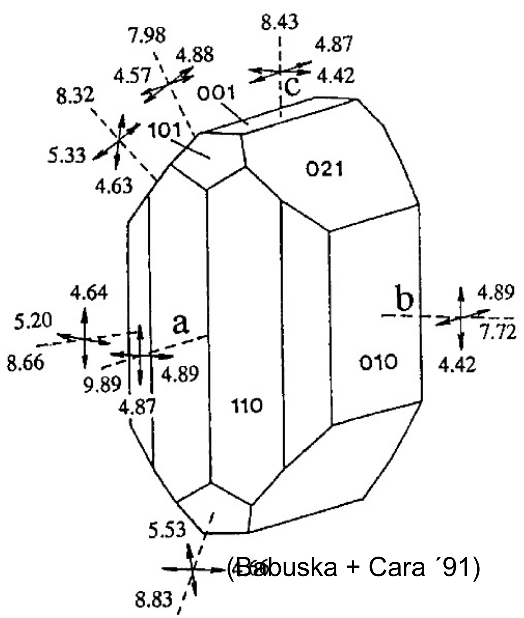
- the direction of propagation or
- shear-wave polarization.

Causes of large-scale seismic anisotropy

Earth's crust

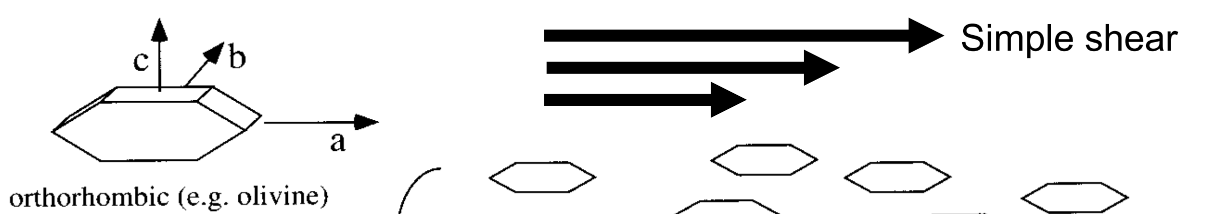
- Periodical sedimentary layering
- Geometrical ordering e.g. due to aligned cracks, magmatic inclusions (Shape-preferred orientation, SPO)
- Anisotropic crystals

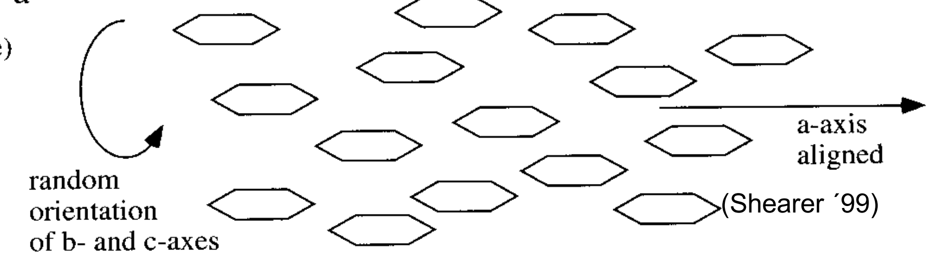




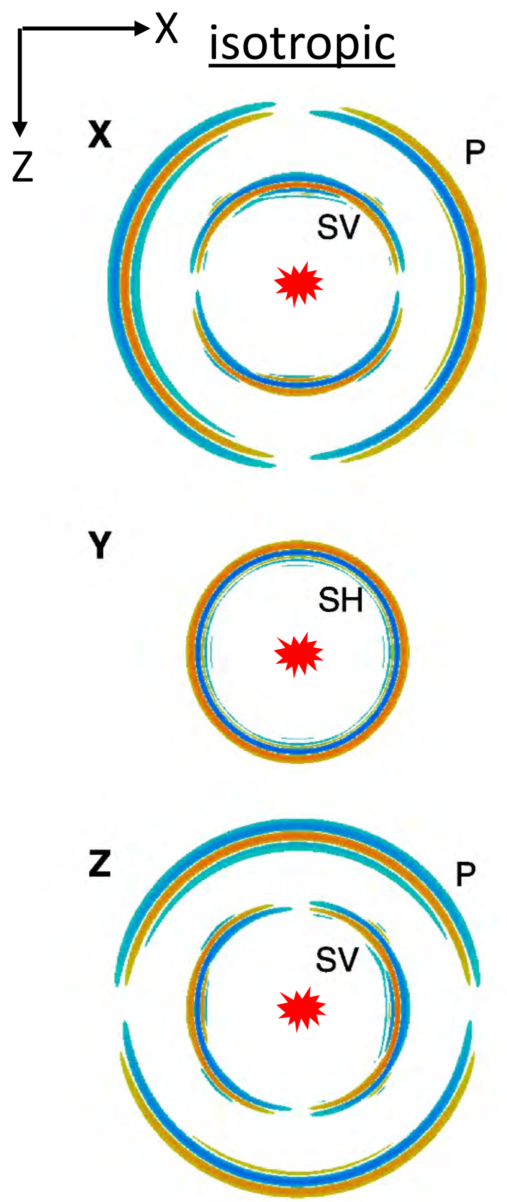
Earth's mantle

Lattice-preferred orientation (LPO) of olivine due to deformation and flow processes

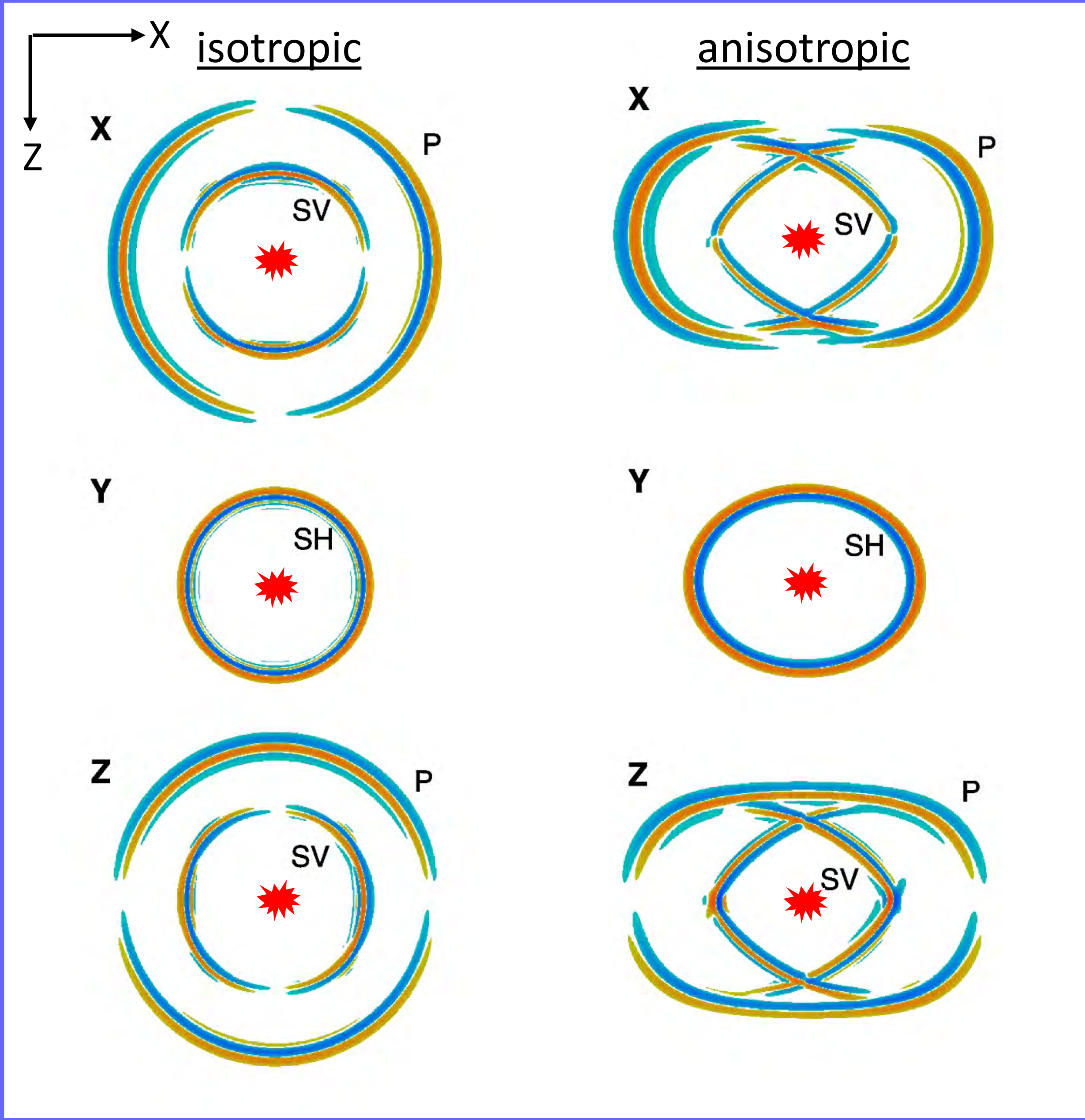




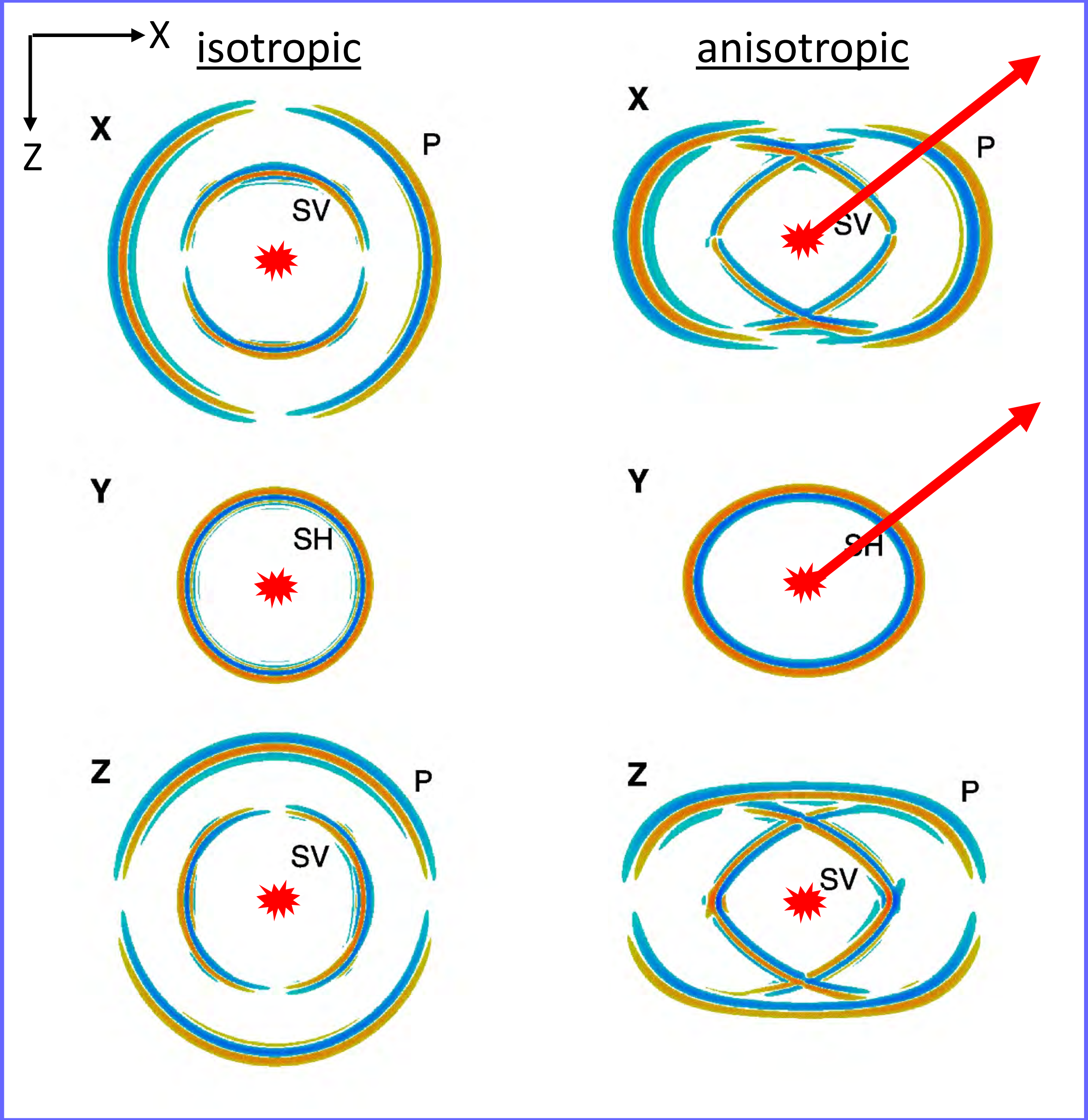
Wave effects of seismic anisotropy



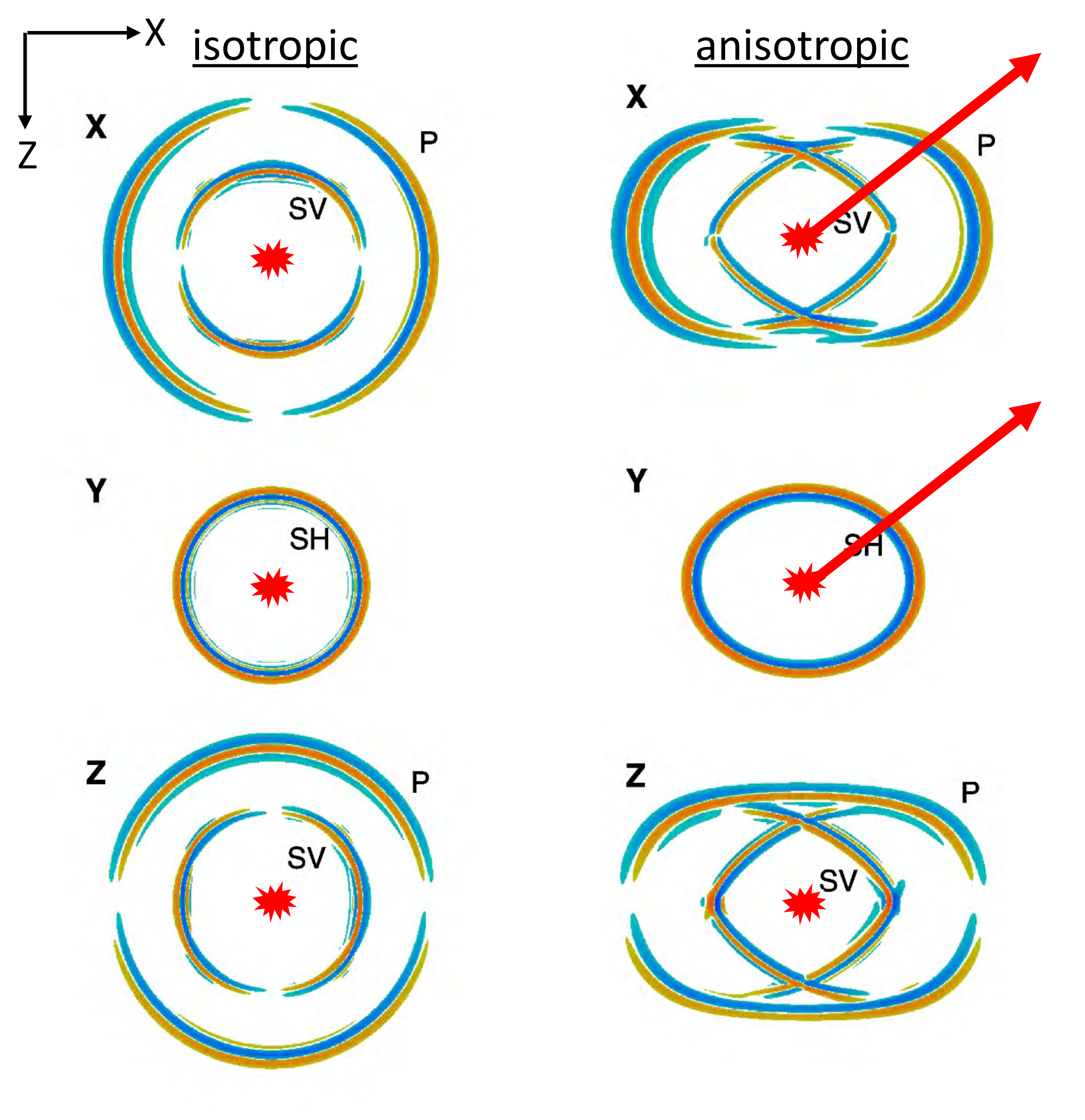
Wave effects of seismic anisotropy



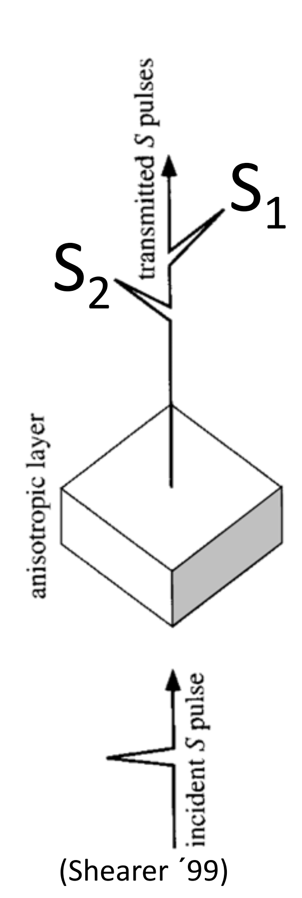
Wave effects of seismic anisotropy



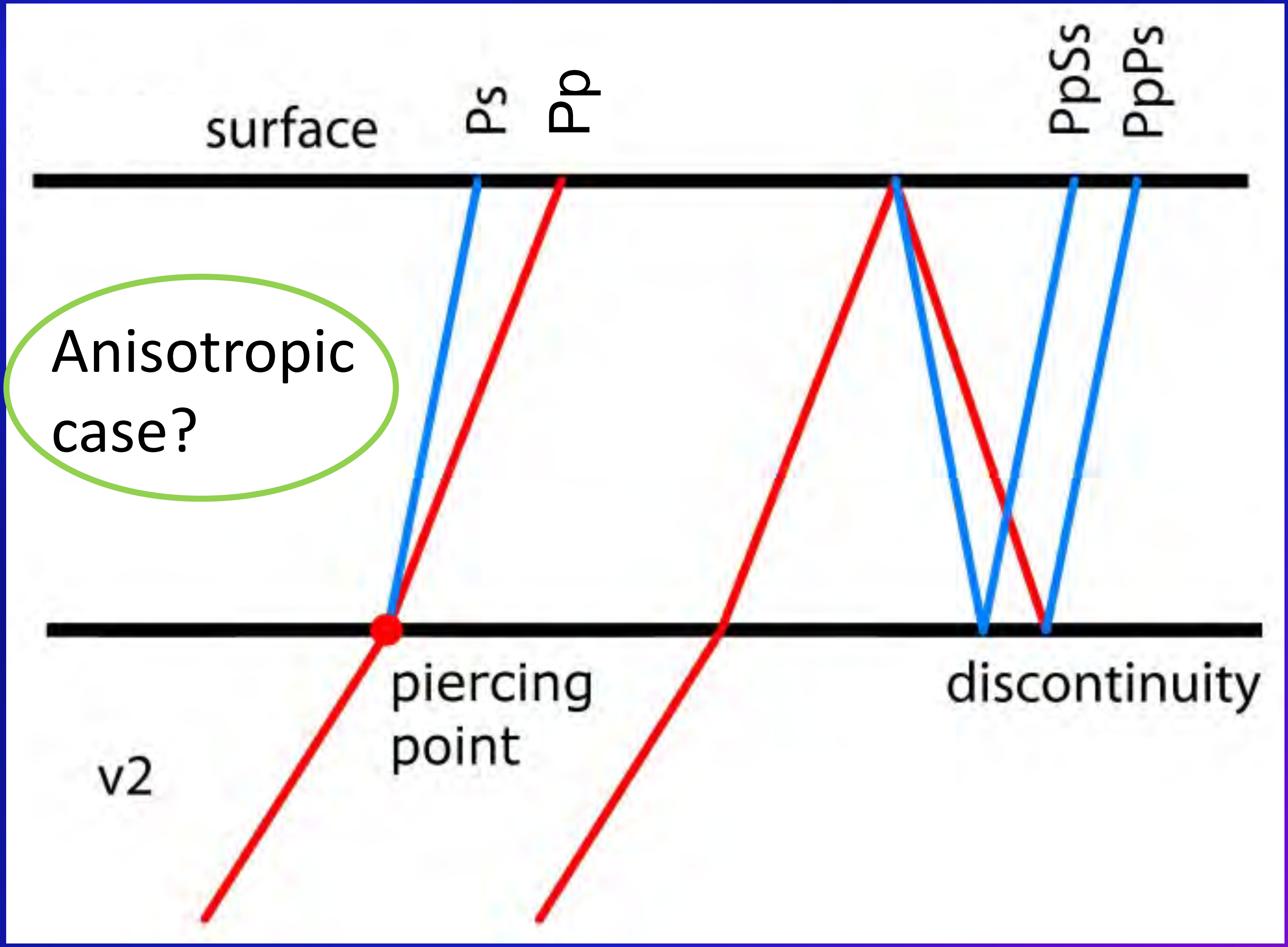
Wave effects of seismic anisotropy



shear-wave splitting:
$V_{SH} \neq V_{SV}$



Receiver functions – converted phases isotropic case



Moho-converted S phases in the anisotropic case

Shear-wave splitting:

- Ps: 2 phases
- PpPs: 2 phases

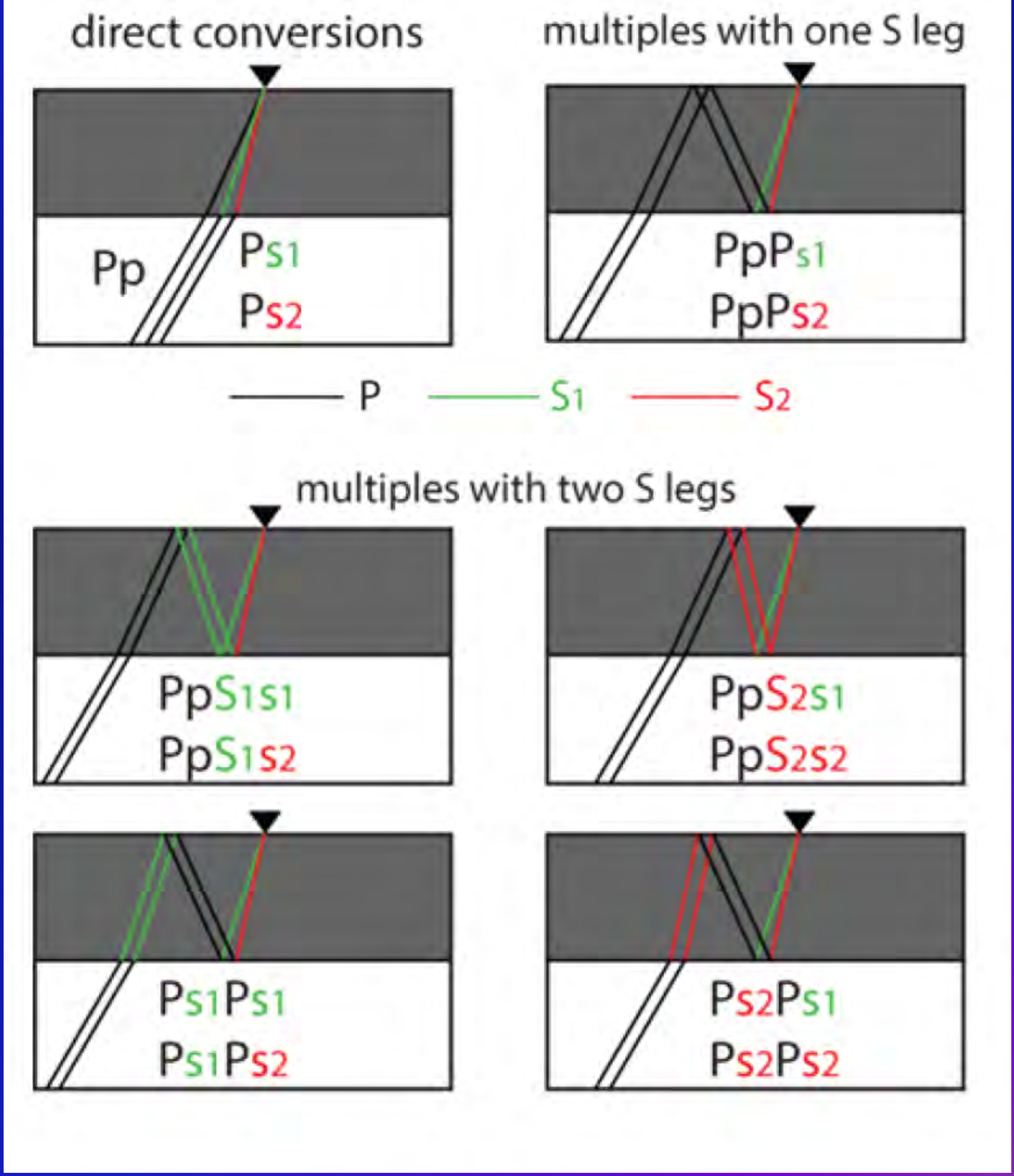
- PpSs: 4 phases
- PsPs: 4 phases

= 12 phases

+ 2^3=8 phases
with three S-legs: PsSs

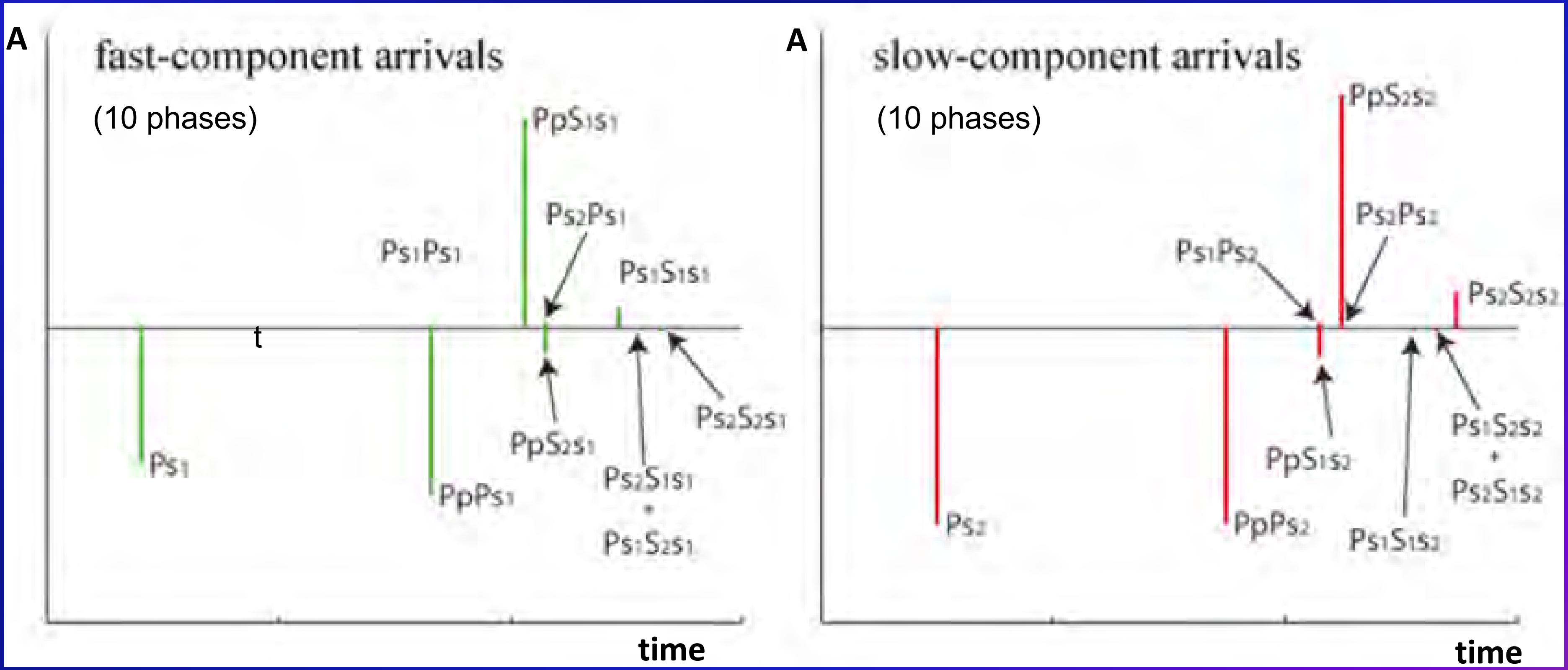
= 20 shear-wave arrivals
in total

… and in the isotropic case?



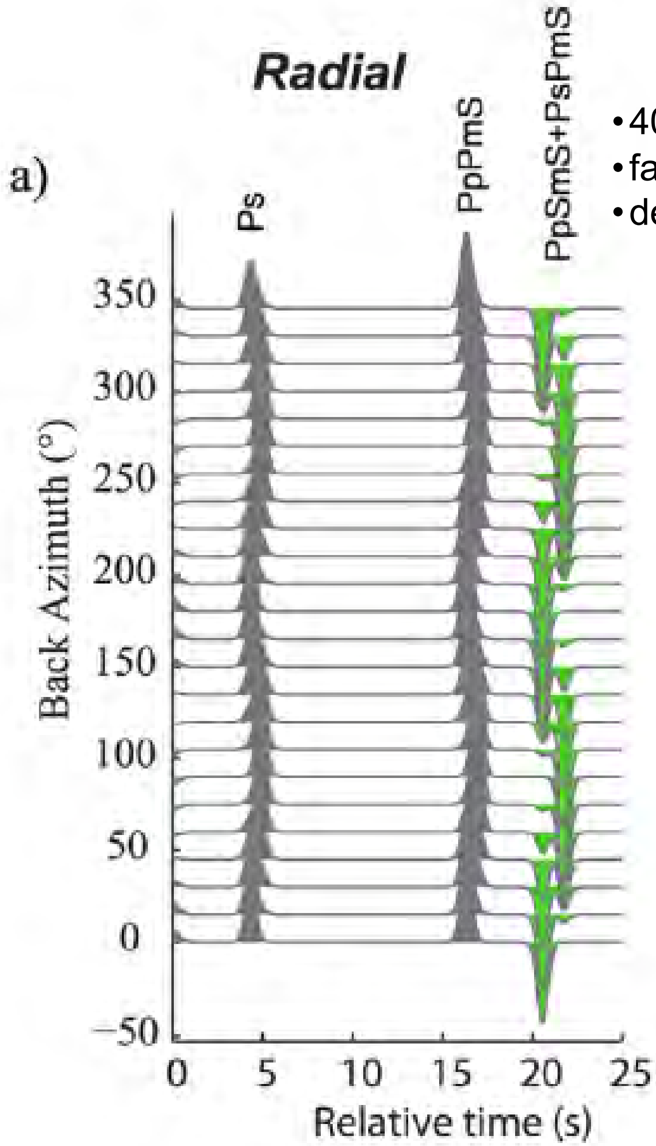
Receiver-functions
arrival times and amplitudes

- anisotropic crust atop isotropic mantle



Azimuthal variations of receiver functions
- anisotropic crust -

(Rümpker et al., 2014)



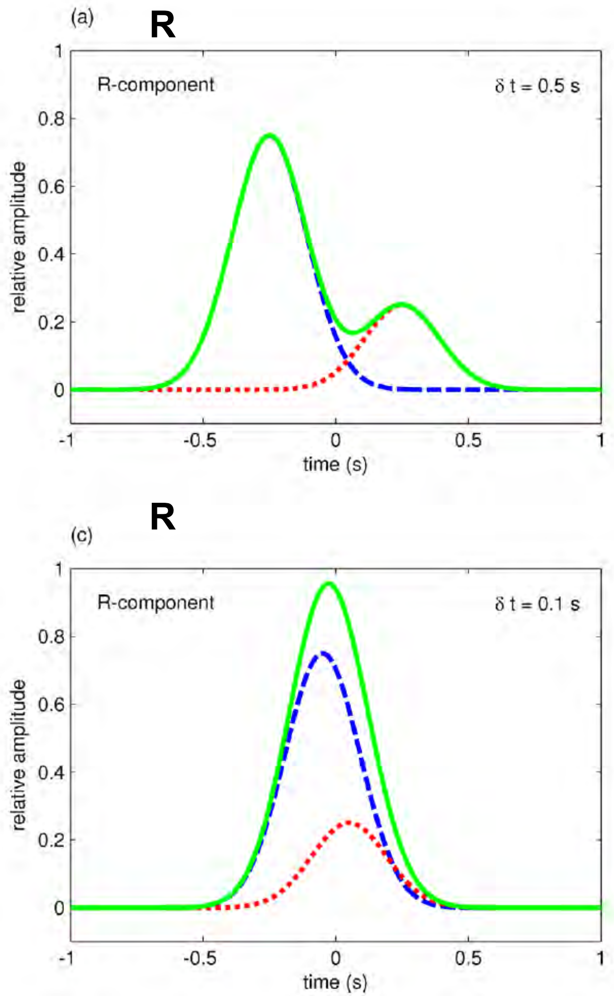
- 40-km anisotropic crust
- fast axis: 0°
- delay time: 0.5 s

Radial and transverse Ps waveforms

Fast, slow, and effective phases

strong anisotropy > 5 %

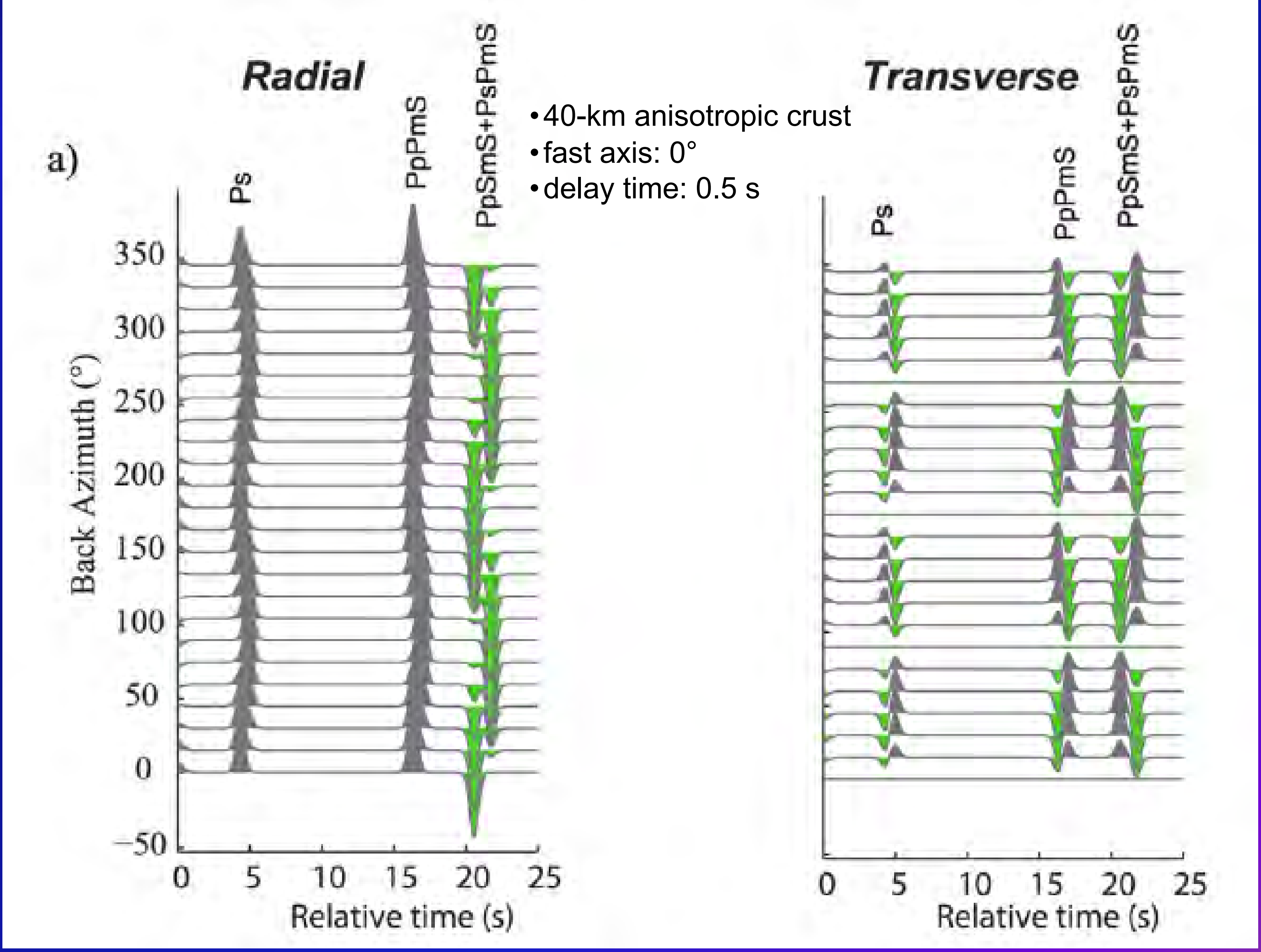
moderate anisotropy < 5 %



the transverse component vanishes in isotropic media

Azimuthal variations of receiver functions
- anisotropic crust -

(Rümpker et al., 2014)



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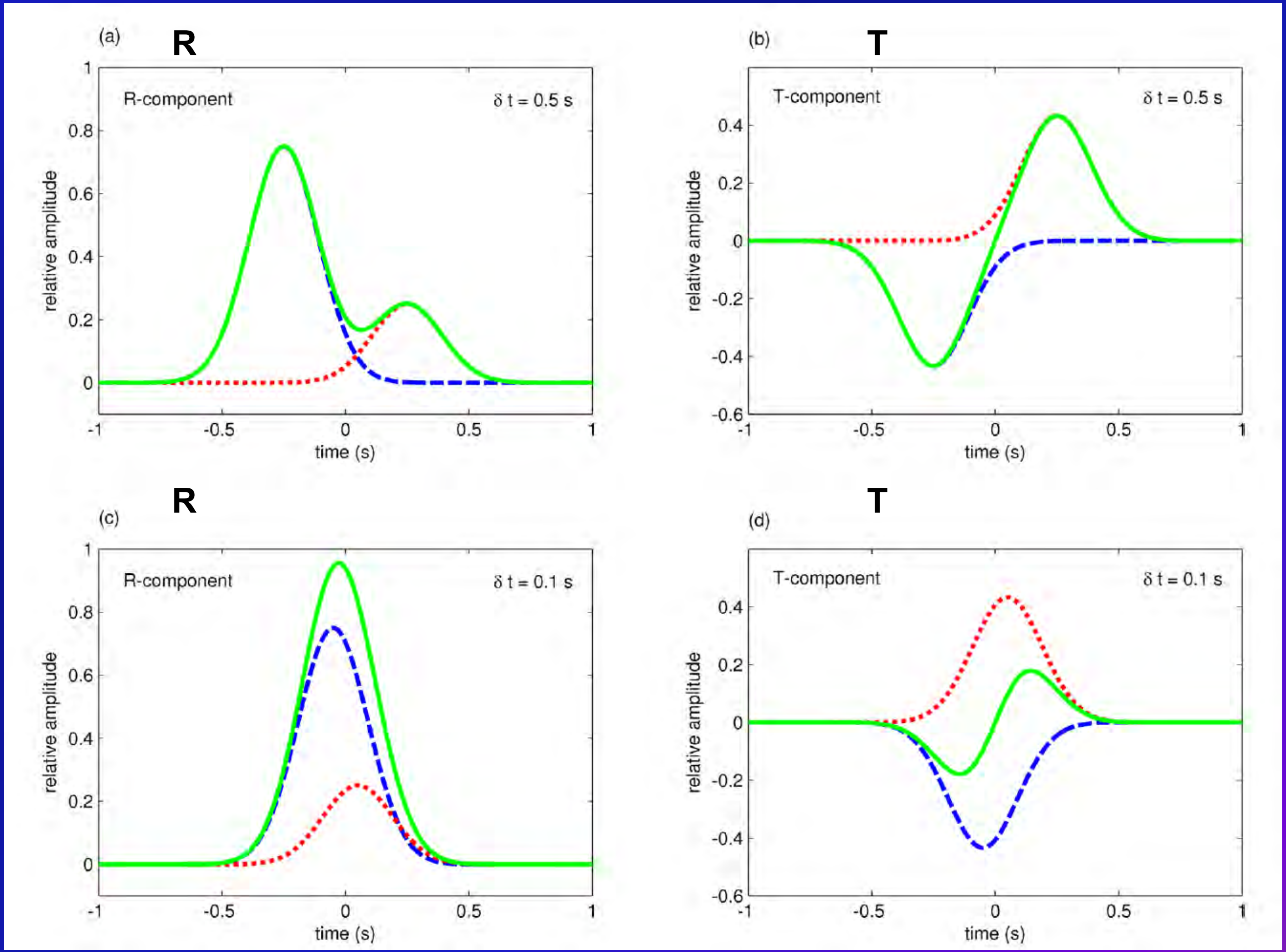
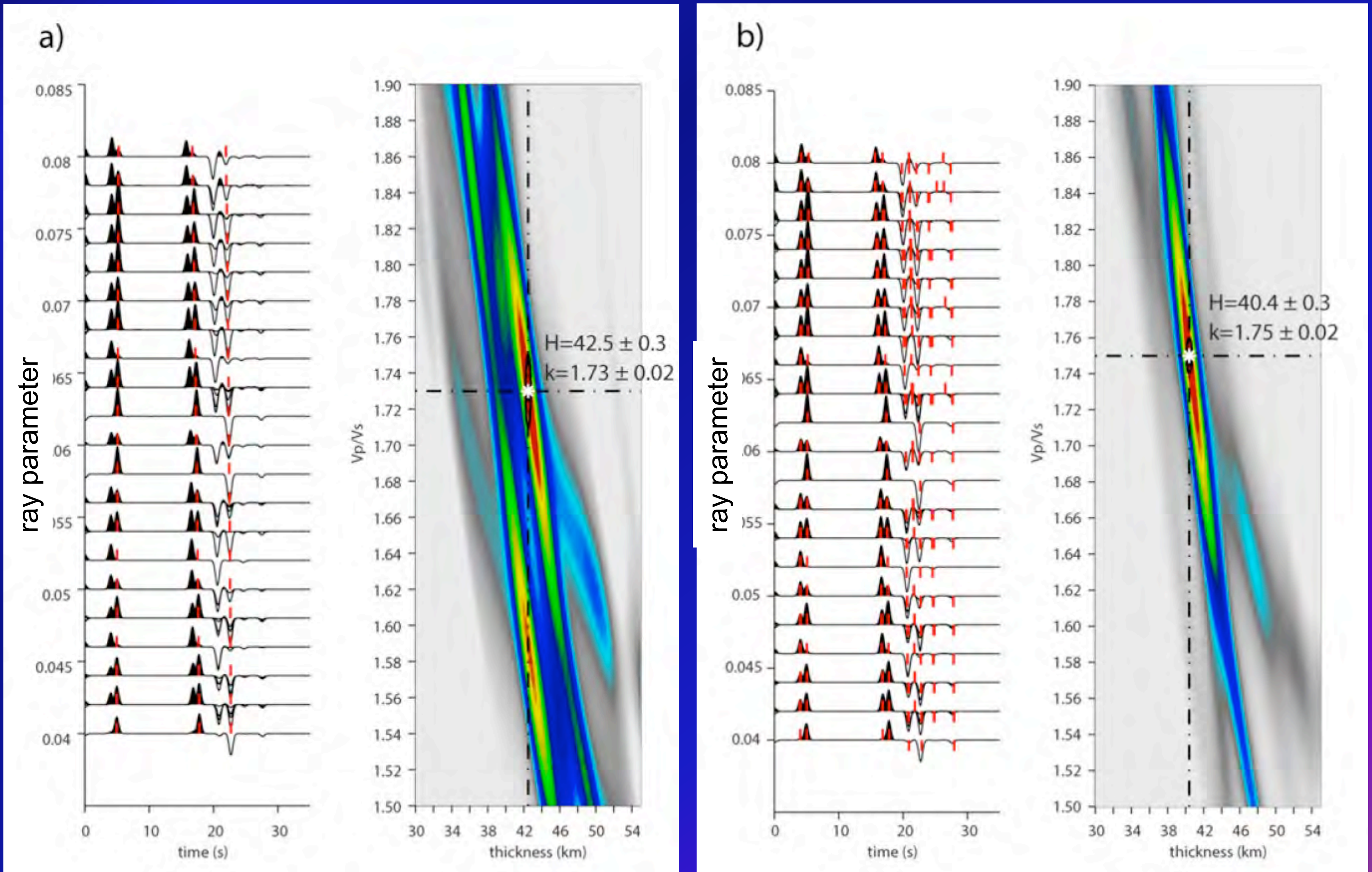


the transverse component vanishes in isotropic media

H - k stacking procedure
(a) isotropic vs. (b) anisotropic version

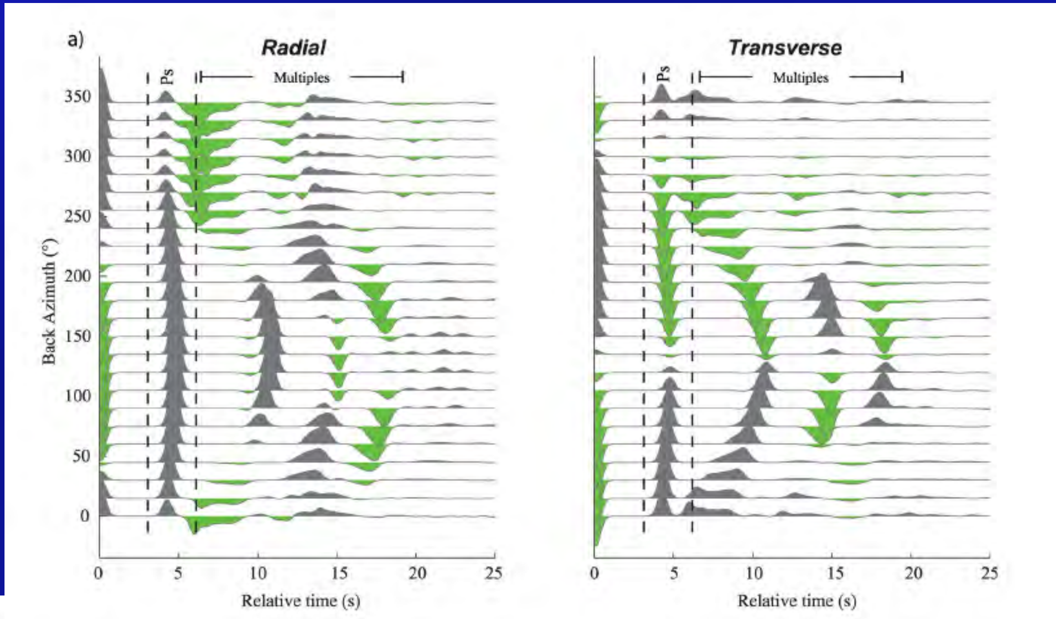
8% anisotropy

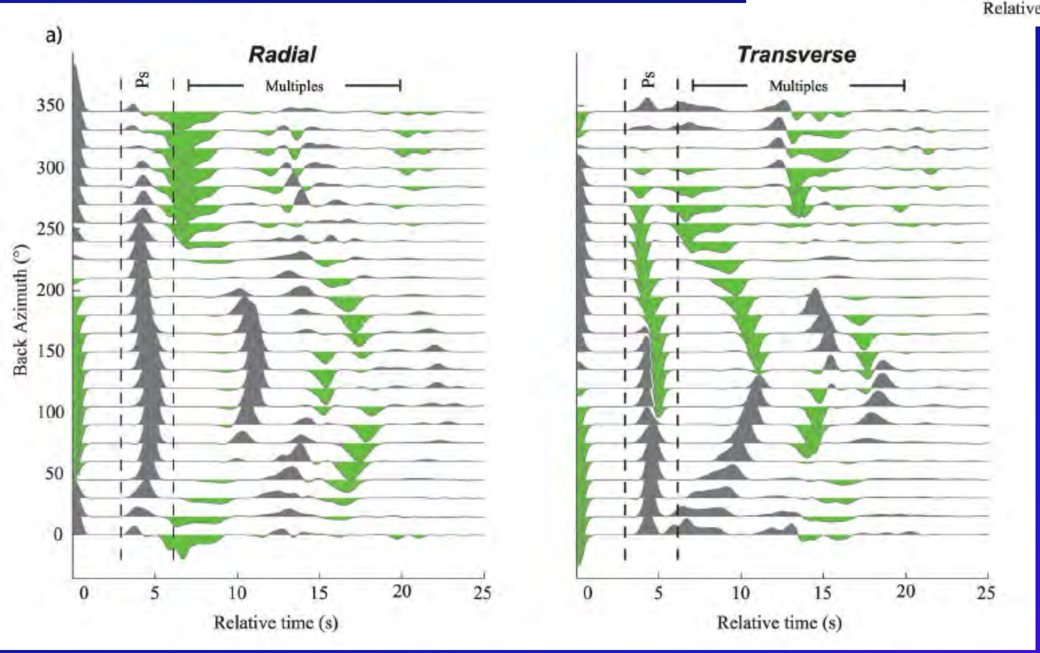
(Kaviani & Rümpker 2015)



Azimuthal variations of receiver functions - dipping Moho

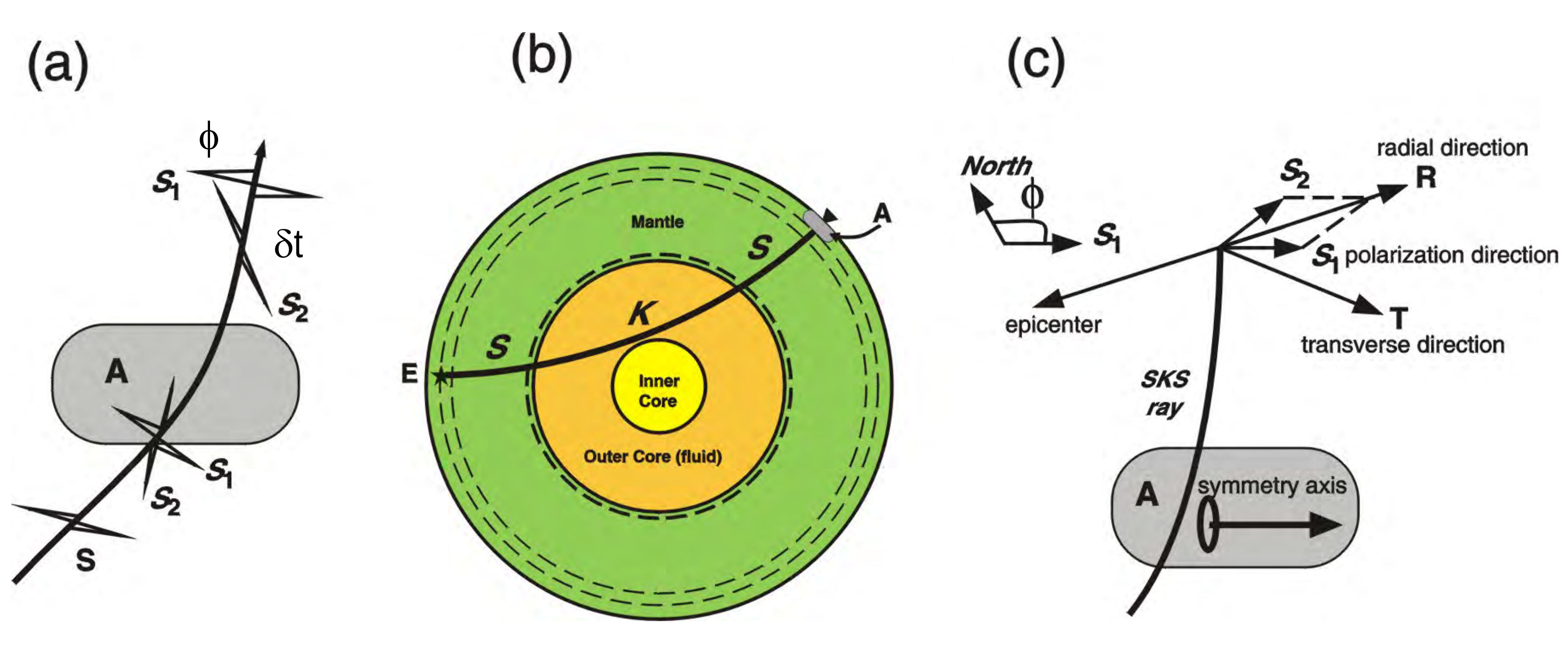
- isotropic crust





- anisotropic crust

Seismic anisotropy and teleseismic shear-wave splitting analysis



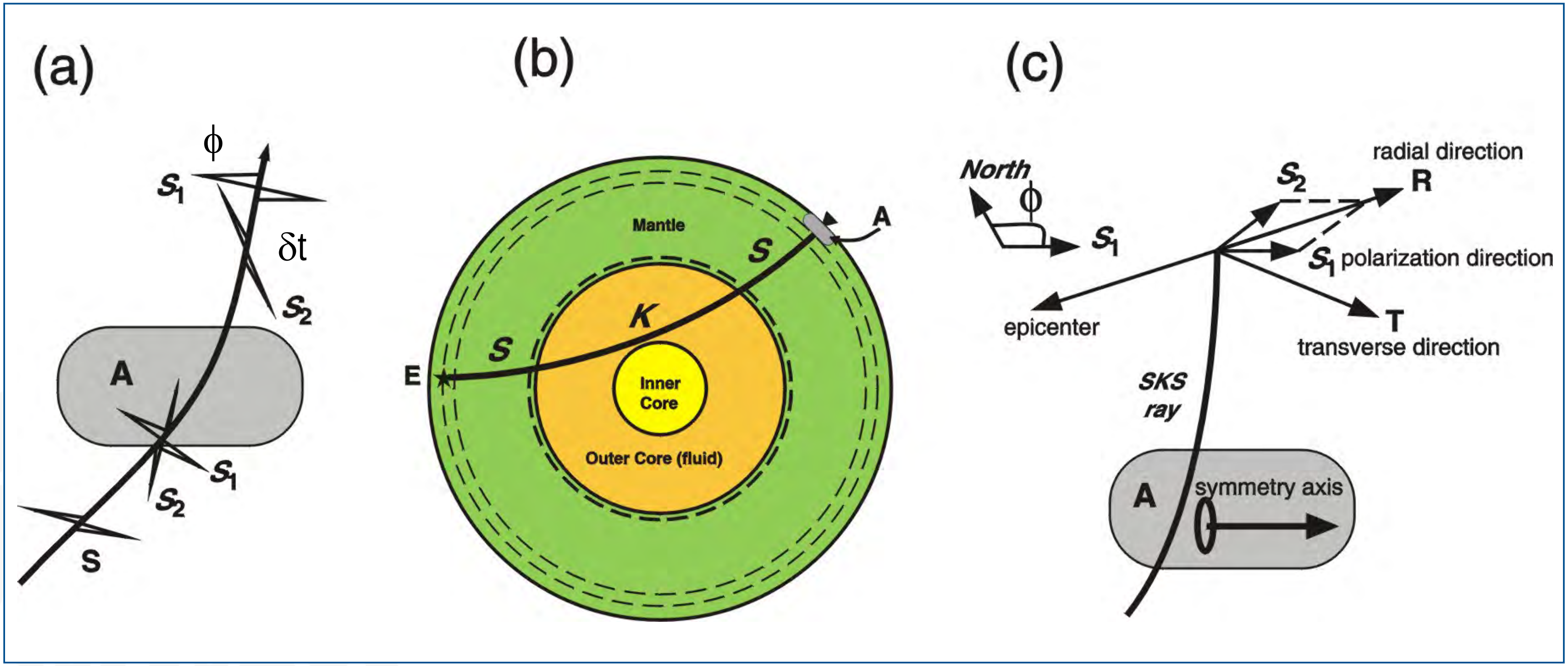
Effect of shear-wave splitting -- two splitting parameters:

ϕ: “Fast-polarization direction” ↔ crystal orientation

(e.g. a-axis of olivine in the mantle)

δt: “delay time” ↔ extent/strength of anisotropy

Anisotropy and XKS-phases



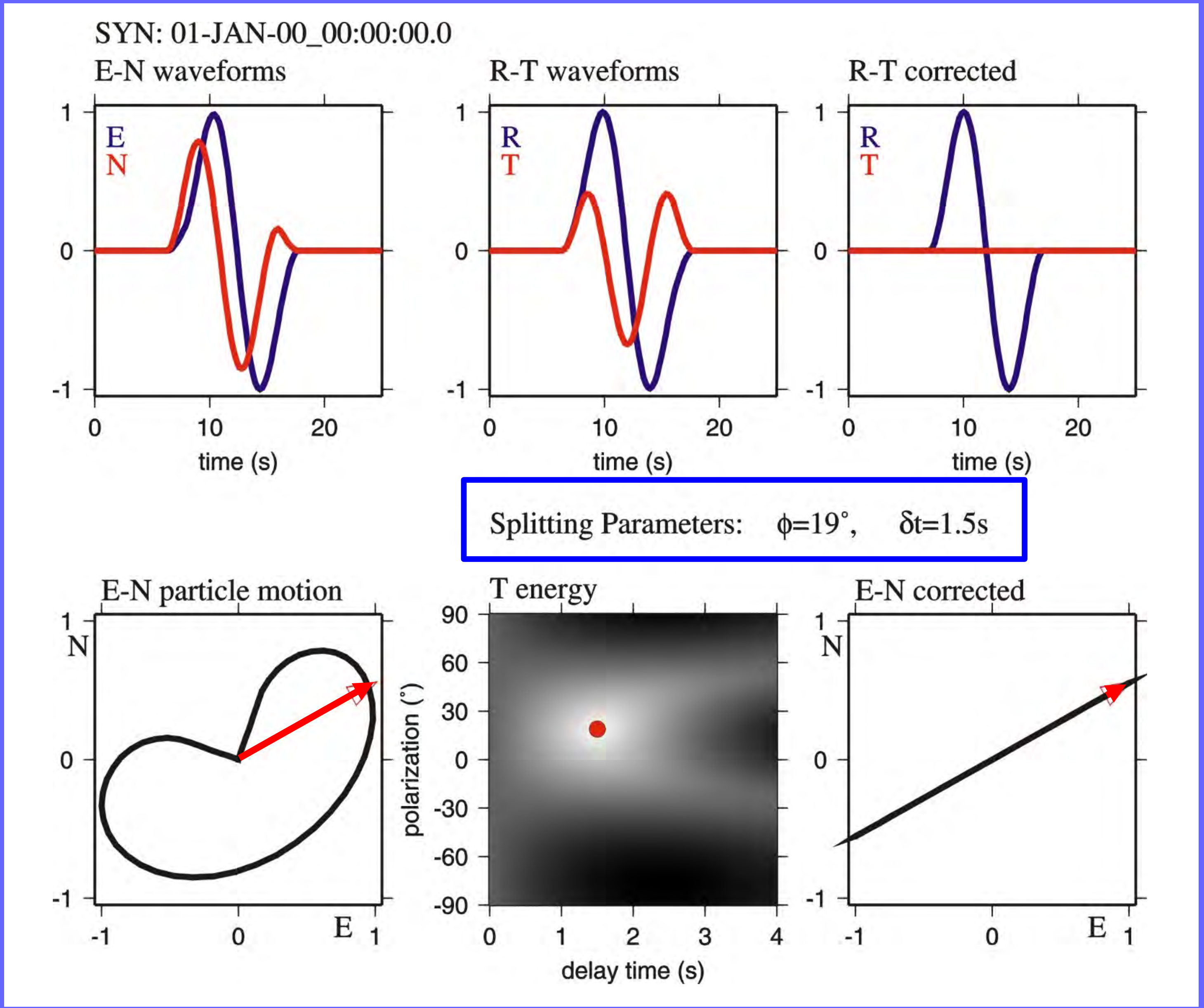
Isotropic Earth and V=V(z):

SKS, XKS phases are purely radially polarized (linear particle motion)

Anisotropic Earth:

XKS phases exhibit transverse component

SKS splitting analysis: synthetic example

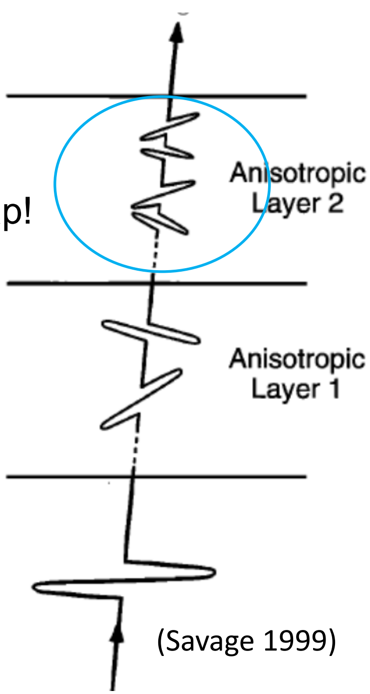


Splitting Parameters: ϕ=19°, δt=1.5s

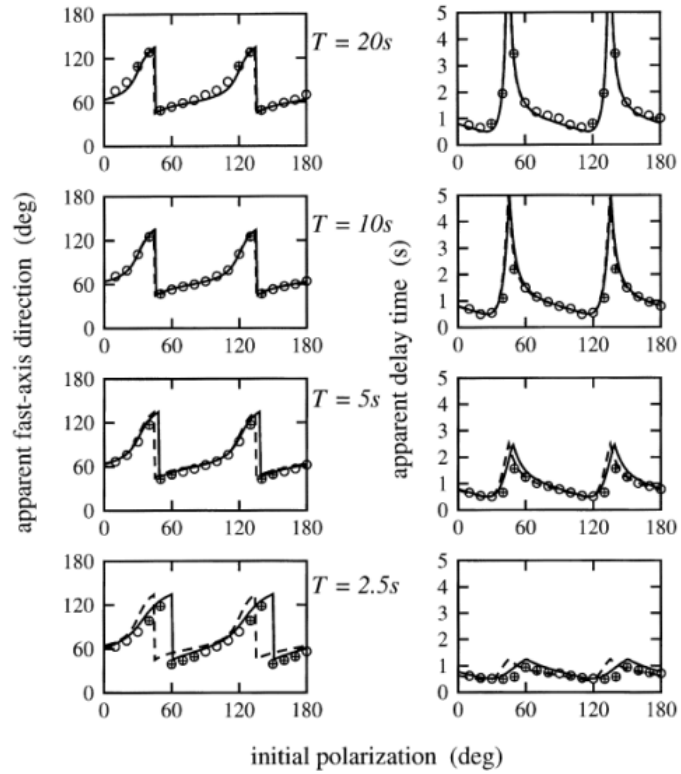
2 and N-layer splitting parameters

- “apparent” parameters vary as function of backazimuth and frequency

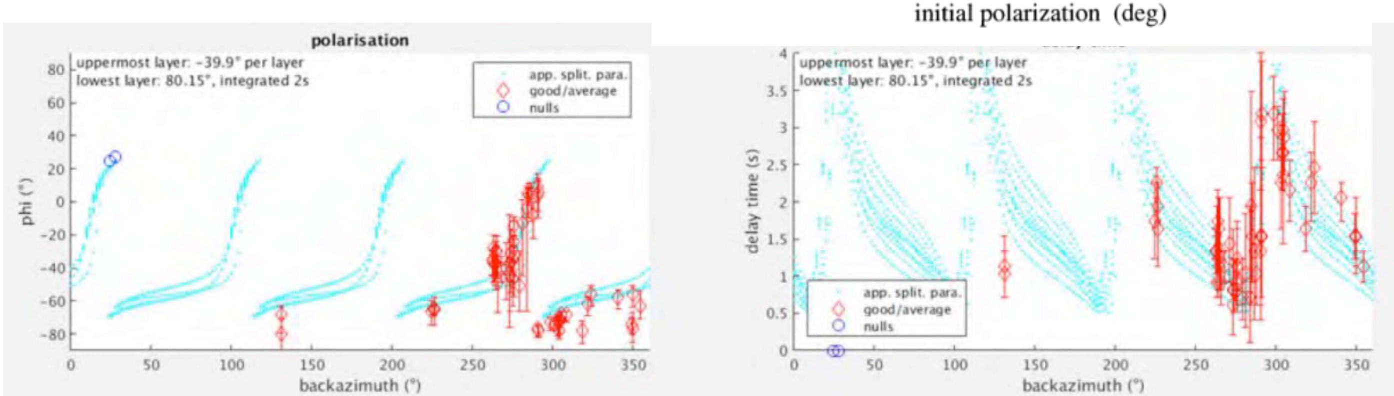
in reality:
phases overlap!



(Savage 1999)

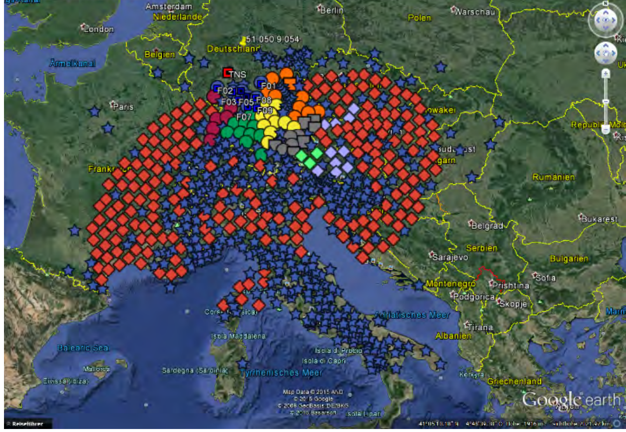


(Rümpker & Silver 1998)



(Reiss & Rümpker 2017)

SplitRacer – code:
Shear-wave splitting analysis and interpretation



Download Data
(or import)

↓

Pre-Processing
(automatic & visual)

↓

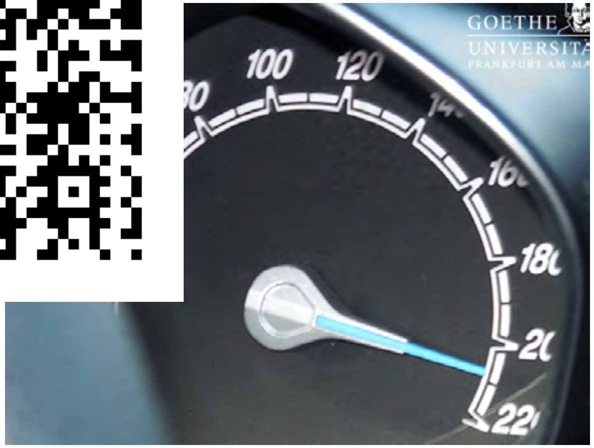
Splitting Analysis
(Single & Multi-event)

Reference & Program Download

Miriam Christina Reiss & Georg Rümpker (2017)

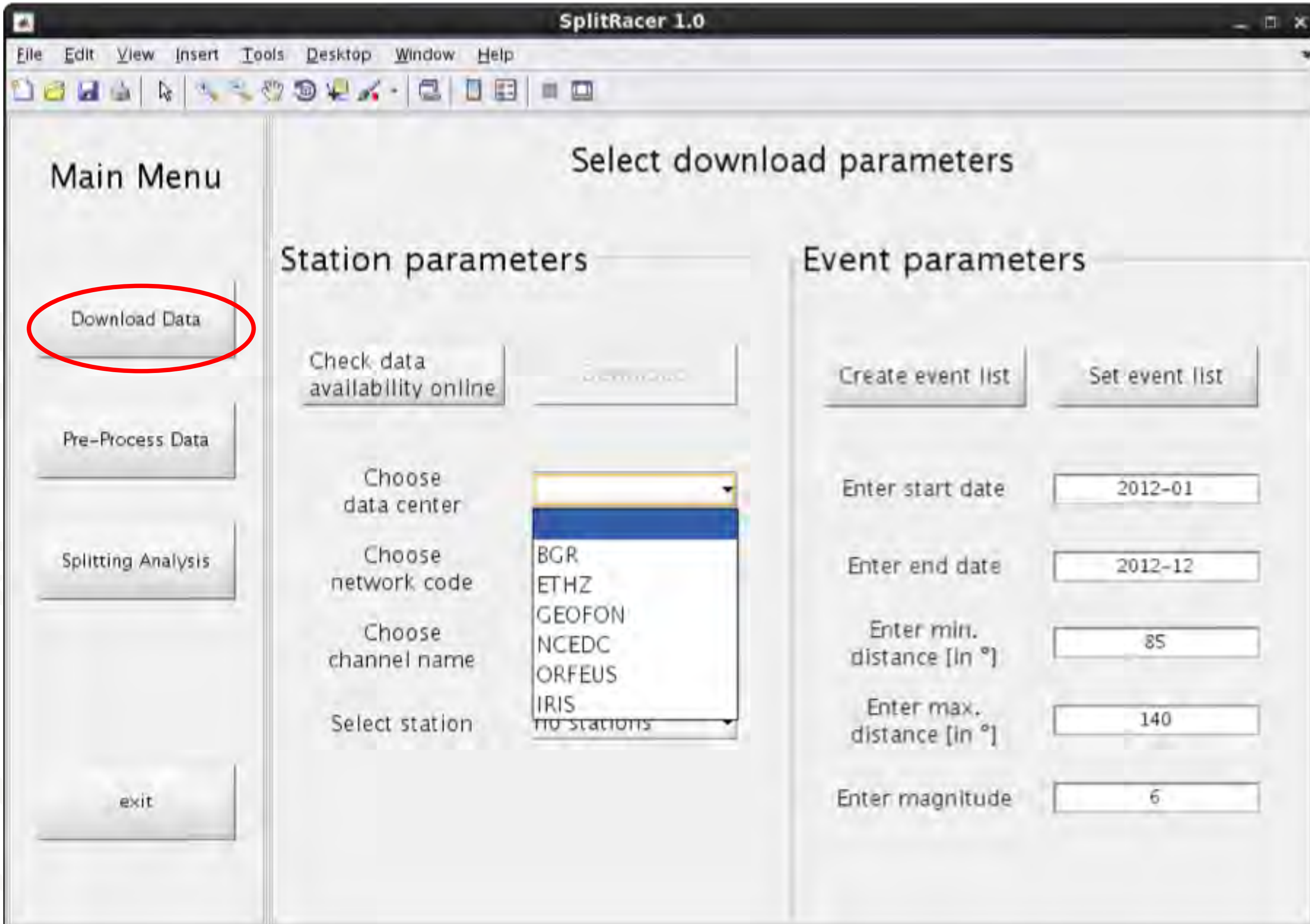
SplitRacer: MATLAB Code and GUI forSemiautomated Analysis and Interpretation of Teleseismic Shear-Wave Splitting, Seismological Research Letters, v. 88, i. 2A, p. 392-409, doi:10.1785/0220160191.

http://www.geophysik.uni-frankfurt.de/64002762/Software



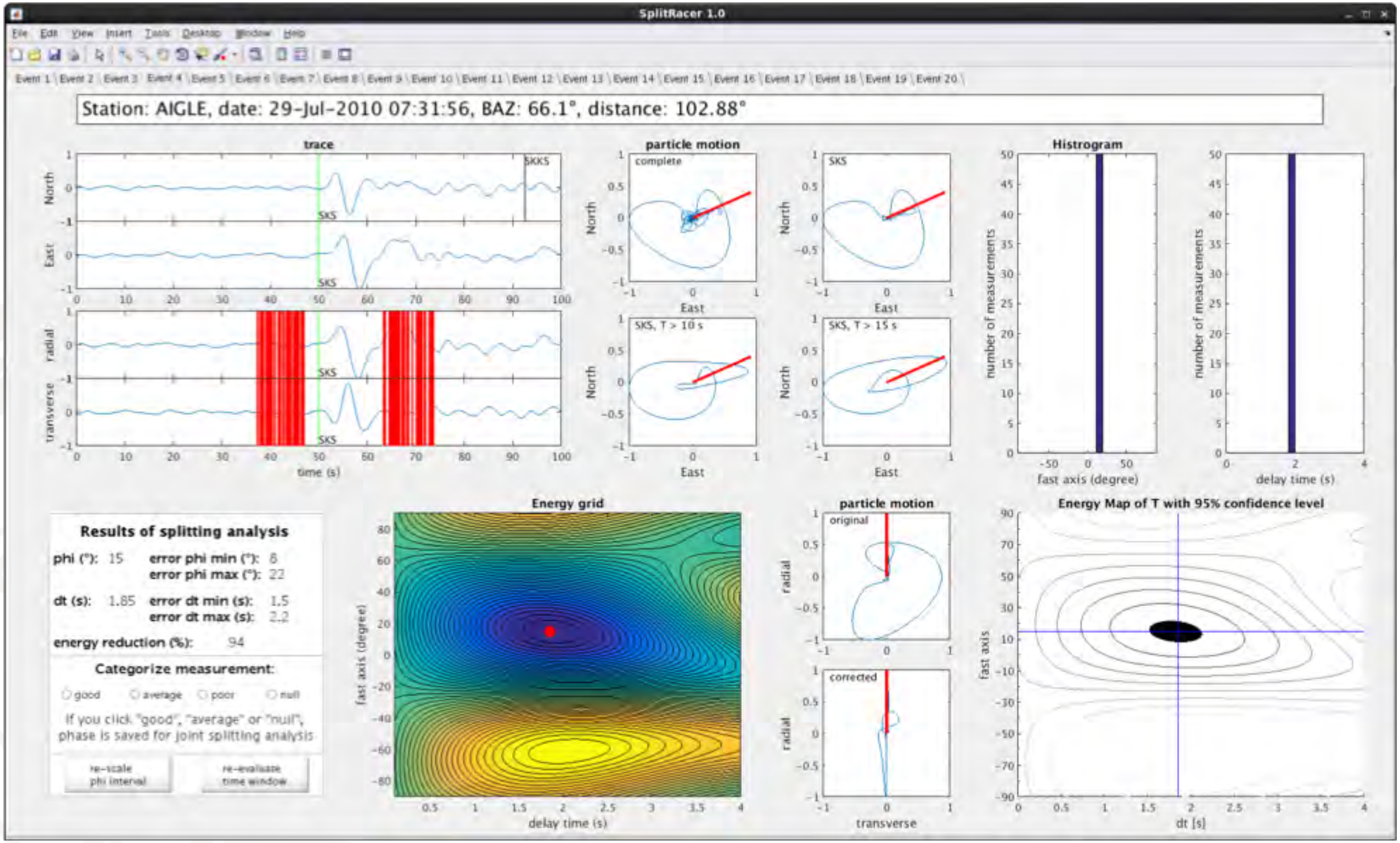
Main Menu - Download Data

- **Select stations and earthquakes**



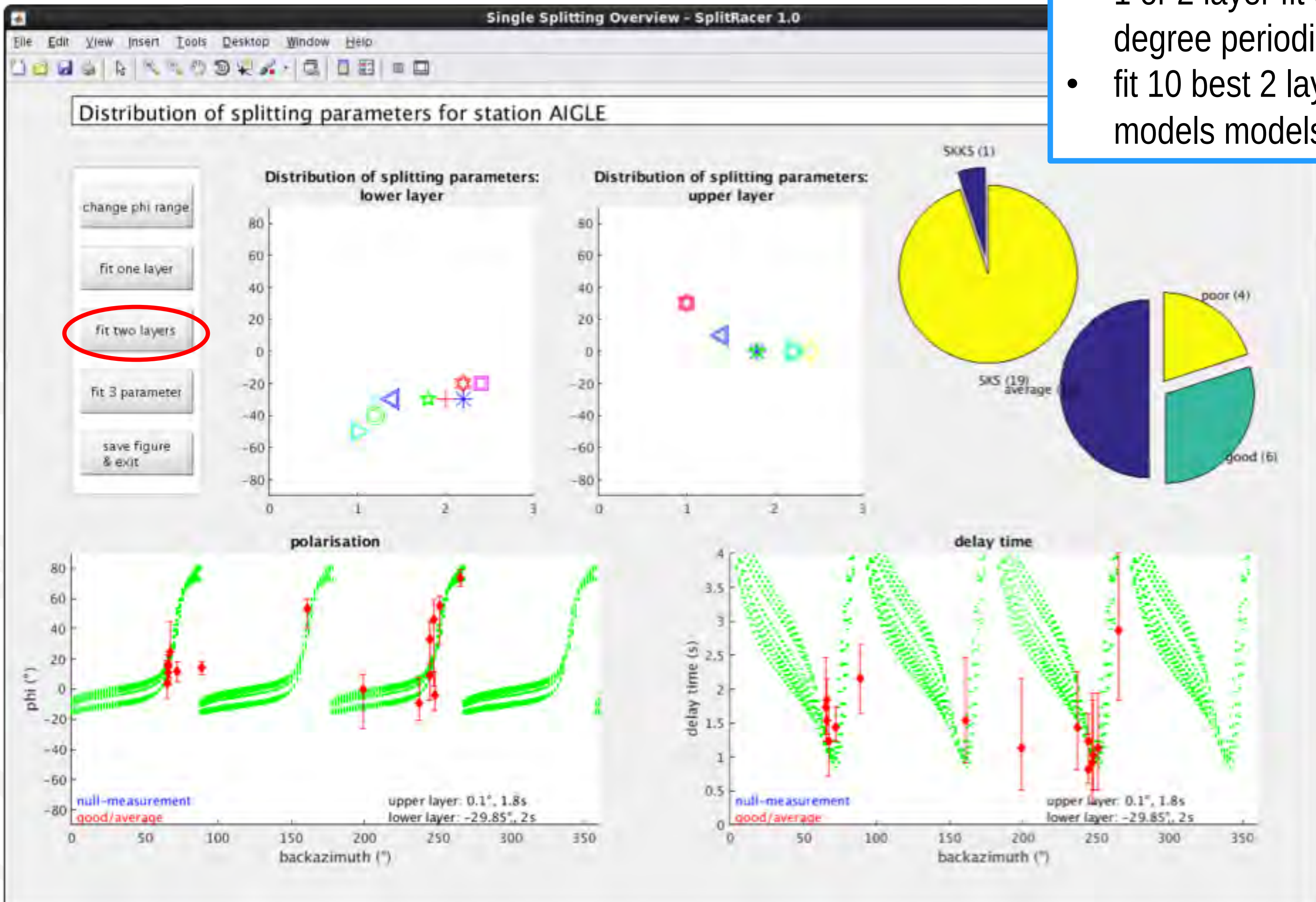
Splitting Analysis – Single event

for all events at 1 station



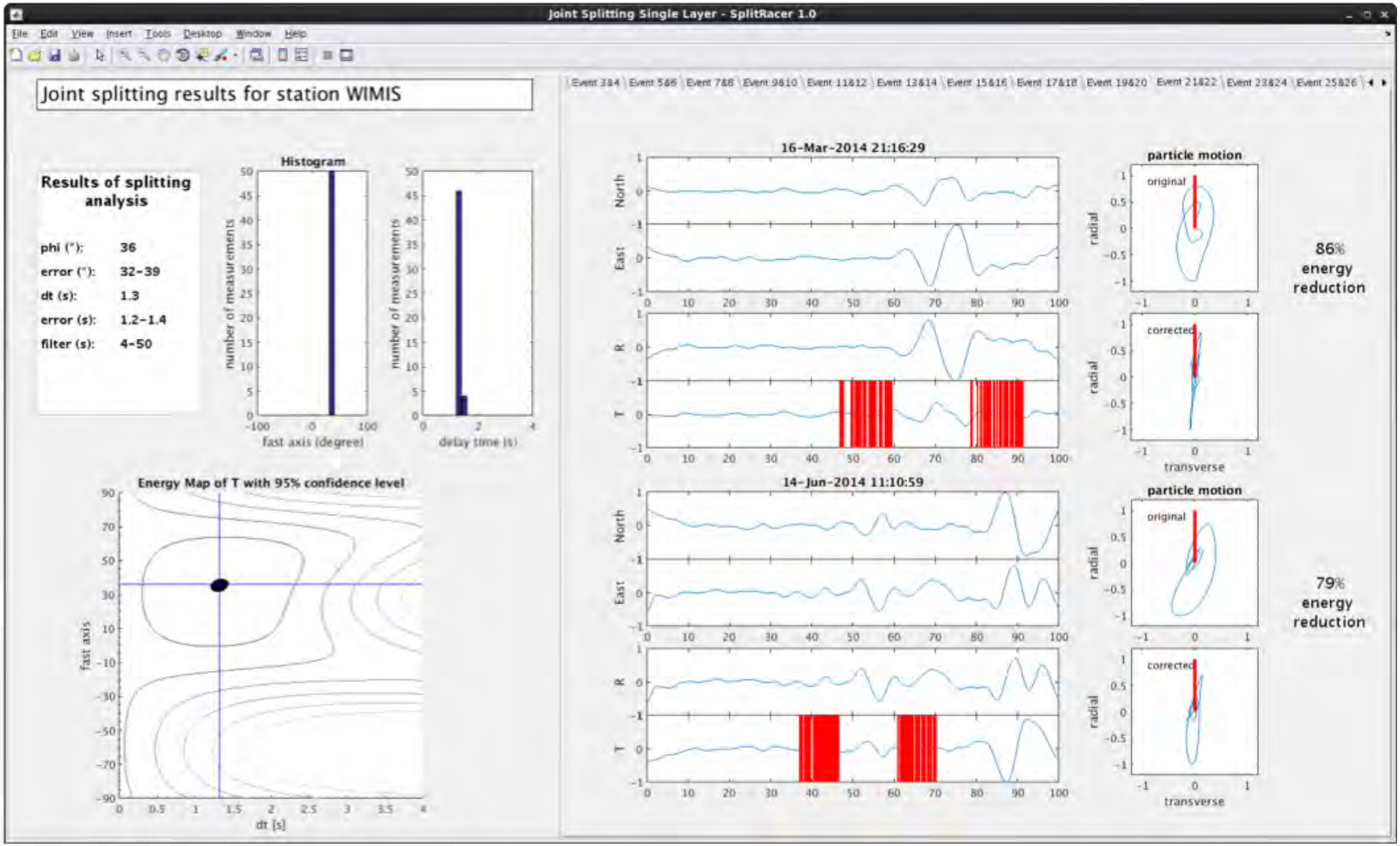
Interpretation – 1, 2 layers, continous variations

- 1 or 2 layer fit (90 degree periodicity)
- fit 10 best 2 layer models models



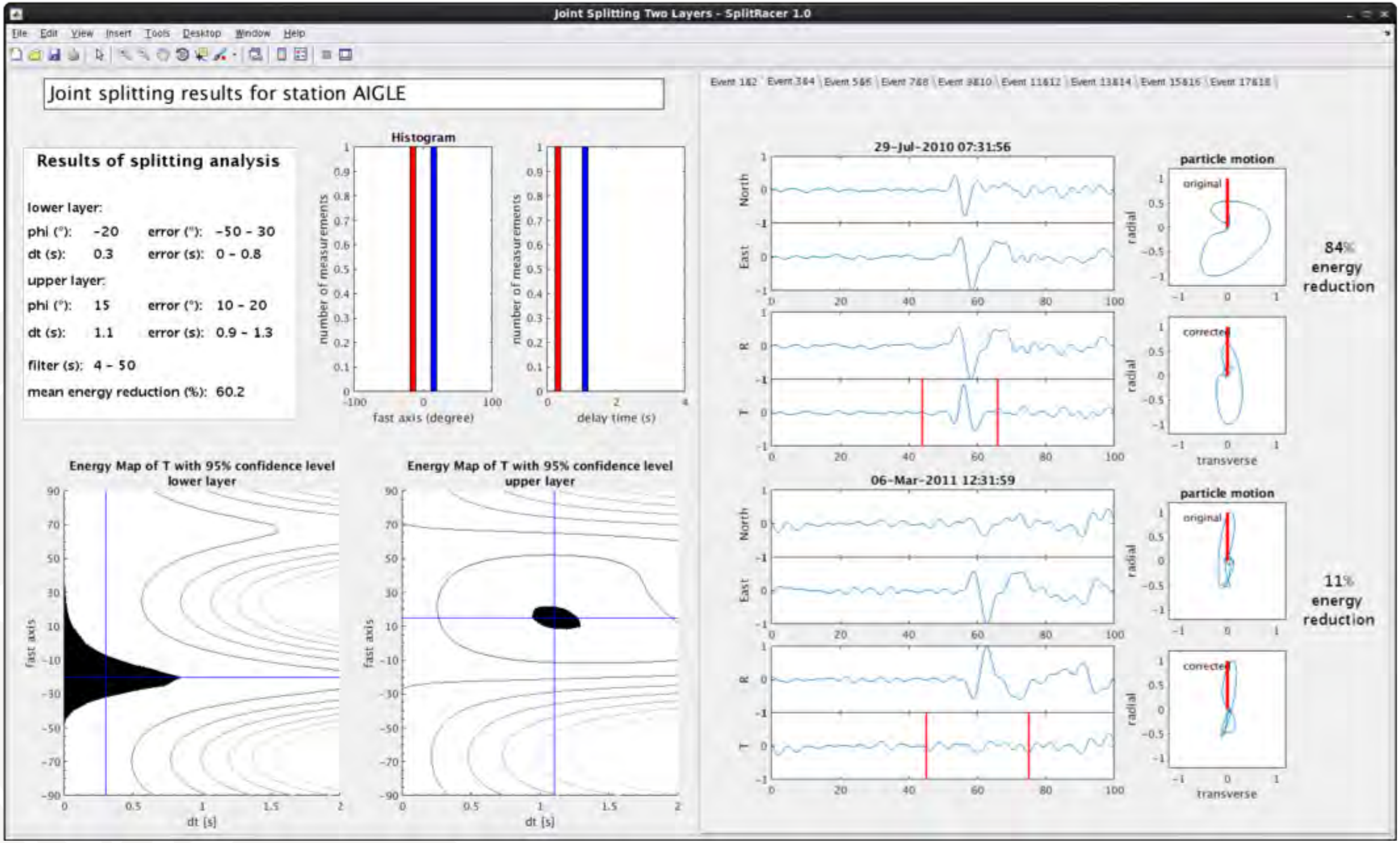
Joint-Splitting Analysis – Single Layer

- minimize transverse components for all events

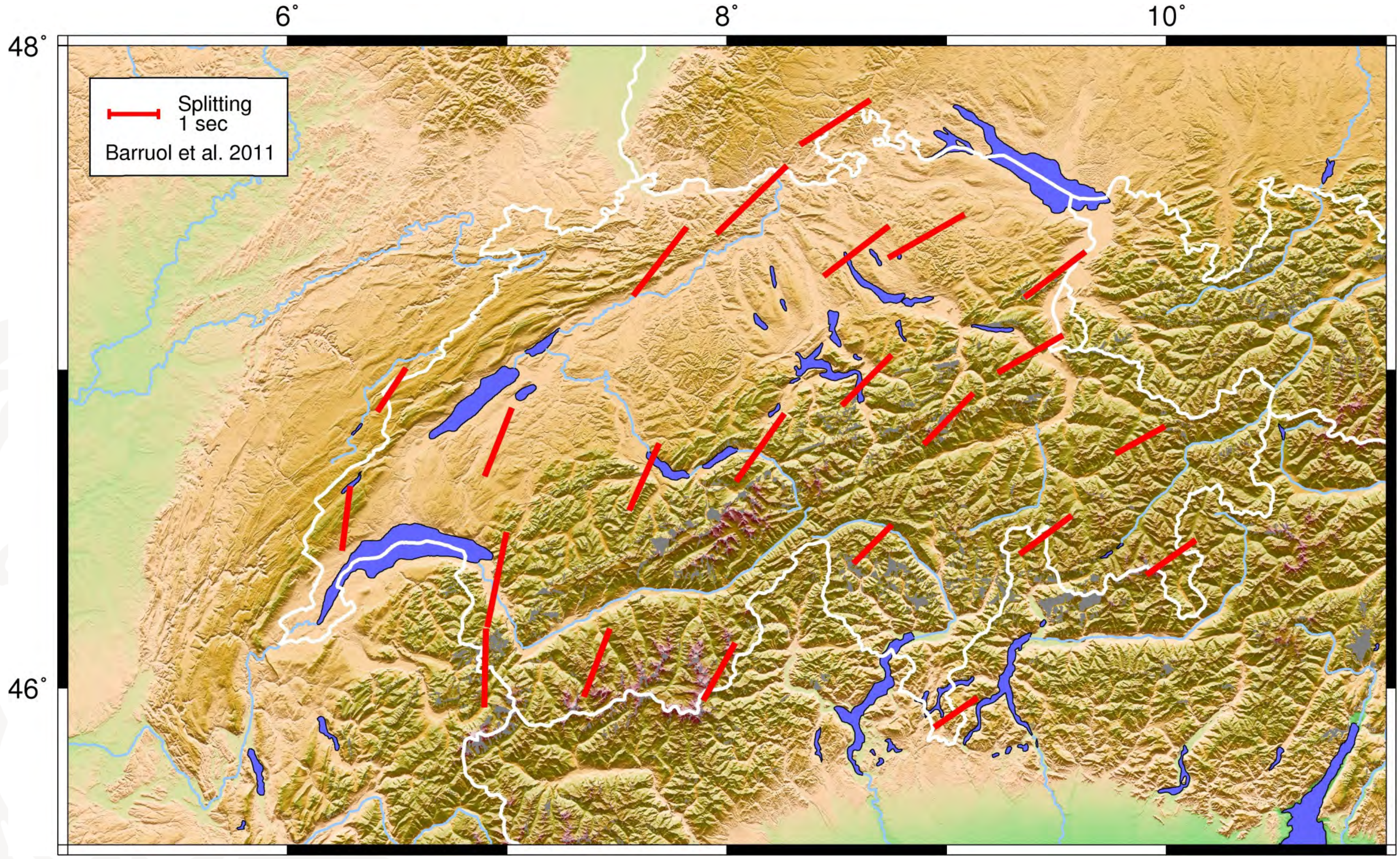


Joint-splitting analysis – 2 layers

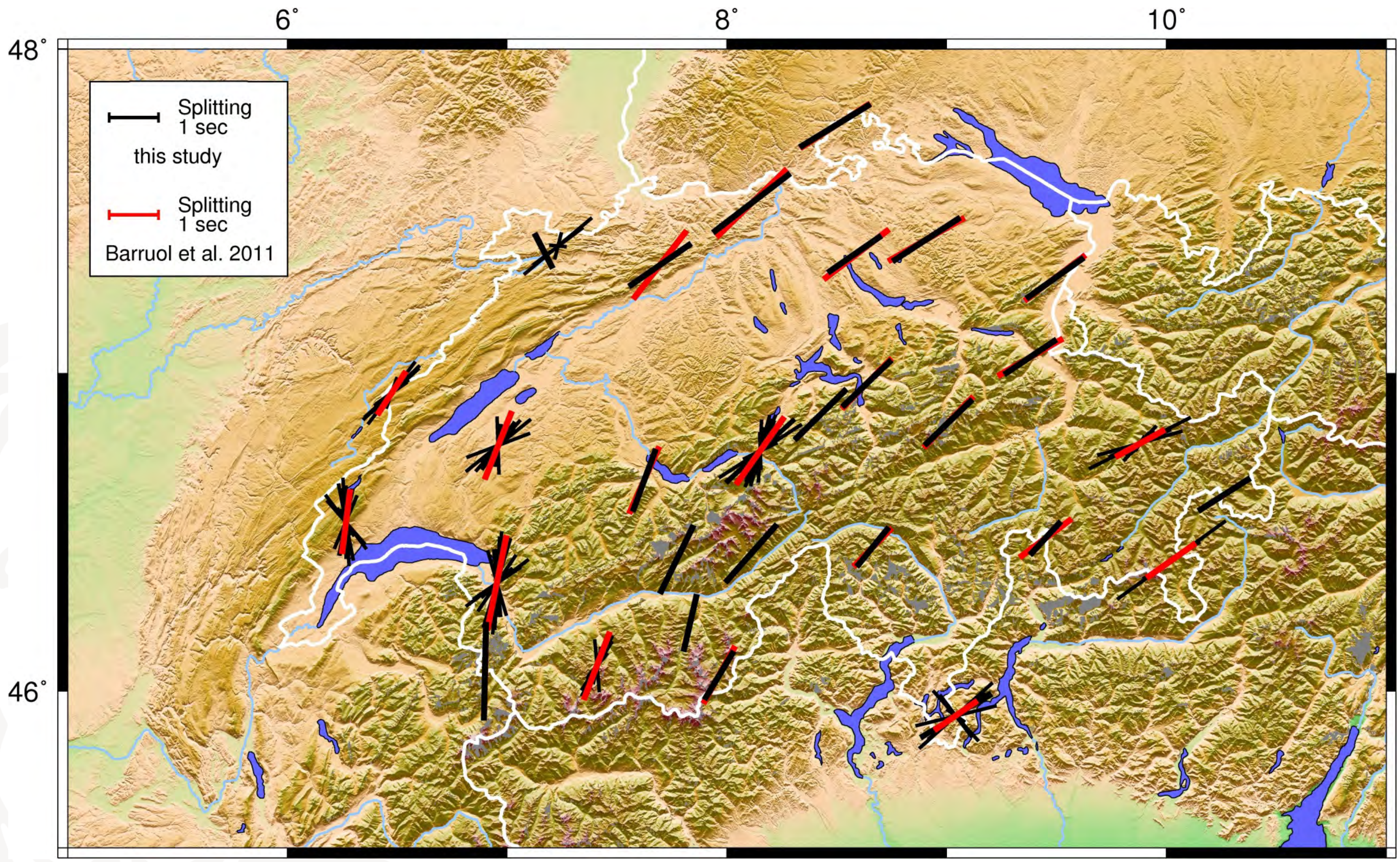
- minimize transverse components for all events



Test: results for the Swiss permanent network

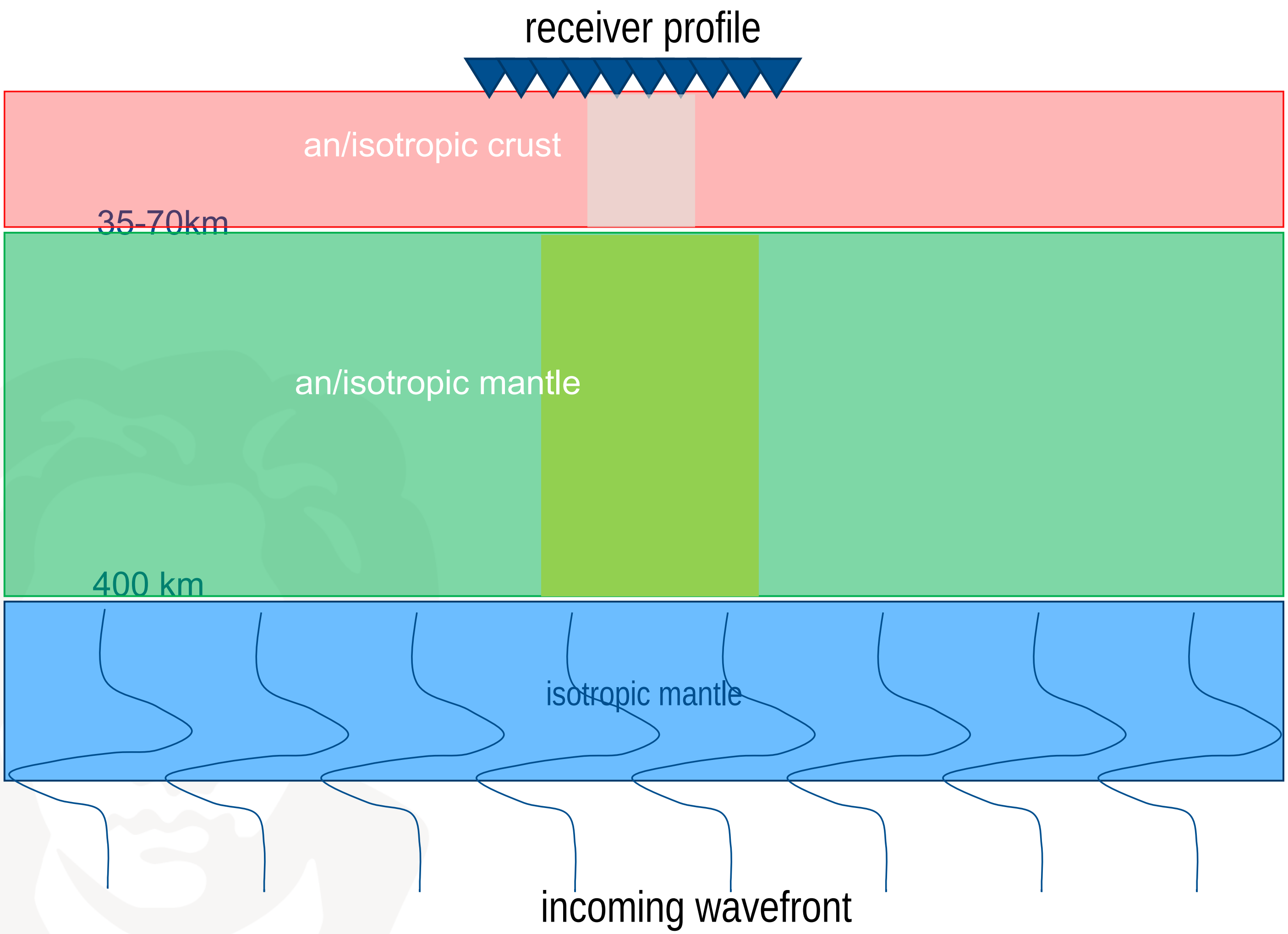


Comparison



6˚
8˚
10˚
48˚
46˚
Splitting
1 sec
this study
Splitting
1 sec
Barruol et al. 2011

Improve interpretation: FD waveform modeling

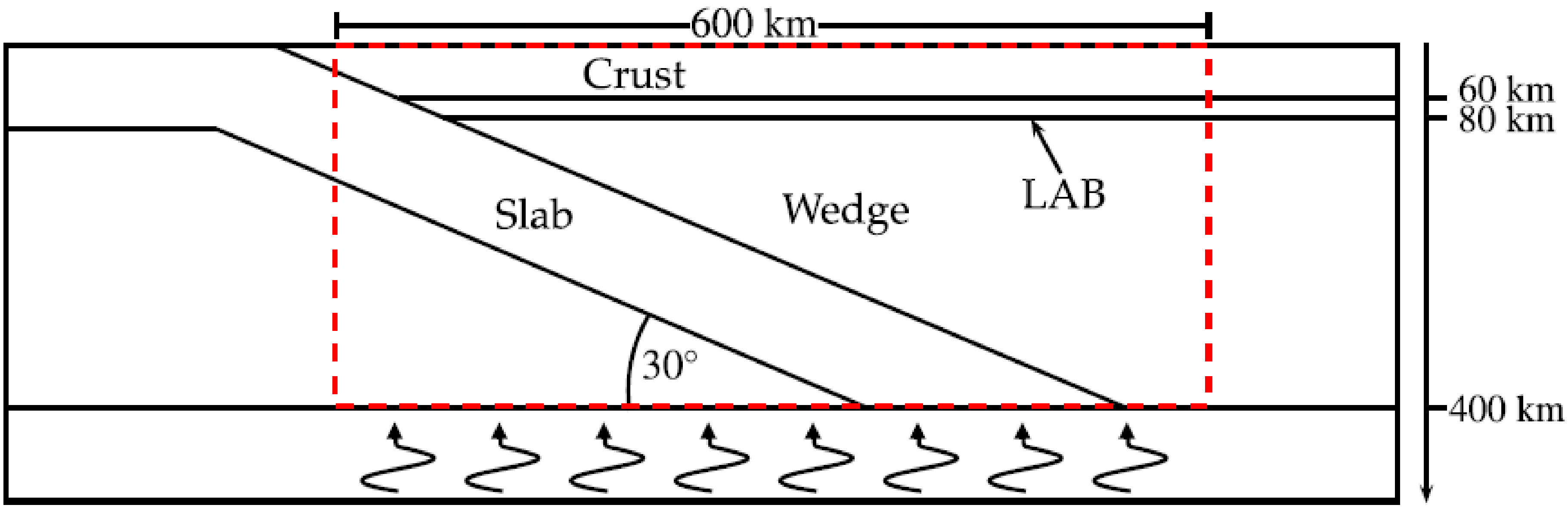


- 2D Finite-Difference modeling
- explicit second-order FD scheme
- plane-wave initial conditions, defined in the isotropic mantle

Subduction-zone geometry and waveform modeling

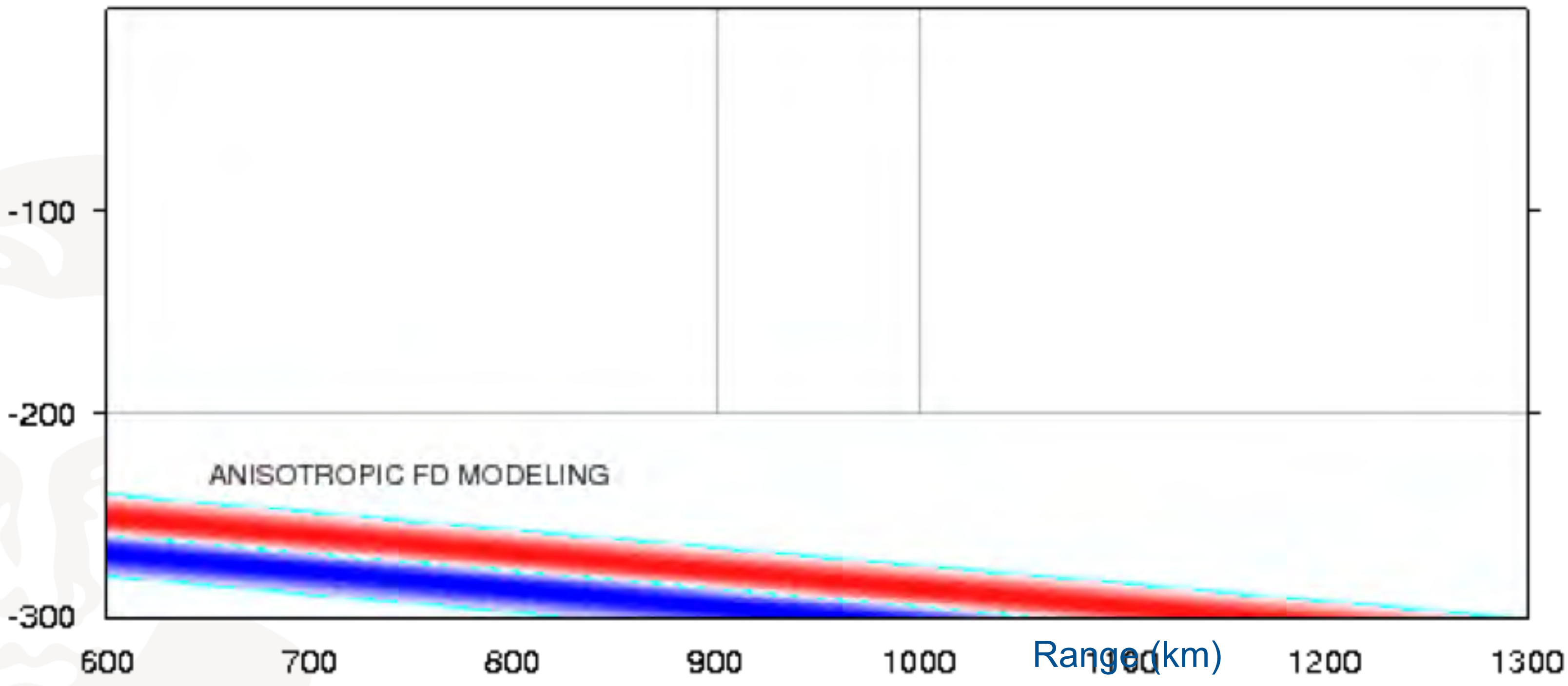
- **comparsion of synthetic and observed waveform effects**

  - 2D Finite-difference method
  - anisotropic elastic tensor
  - finite-frequency effects



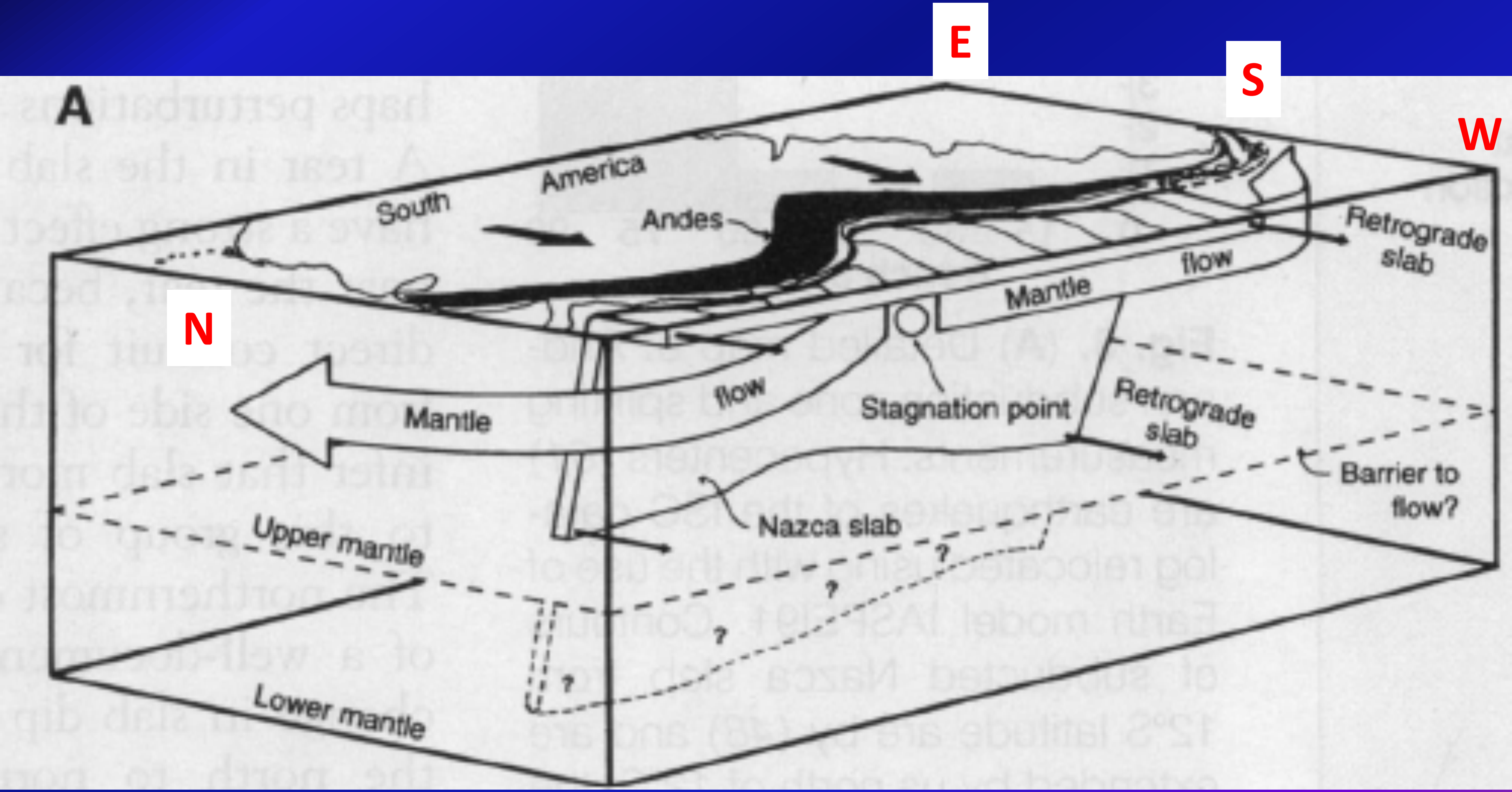
FD waveform modeling

displacement in X_1-direction; period: 10 s

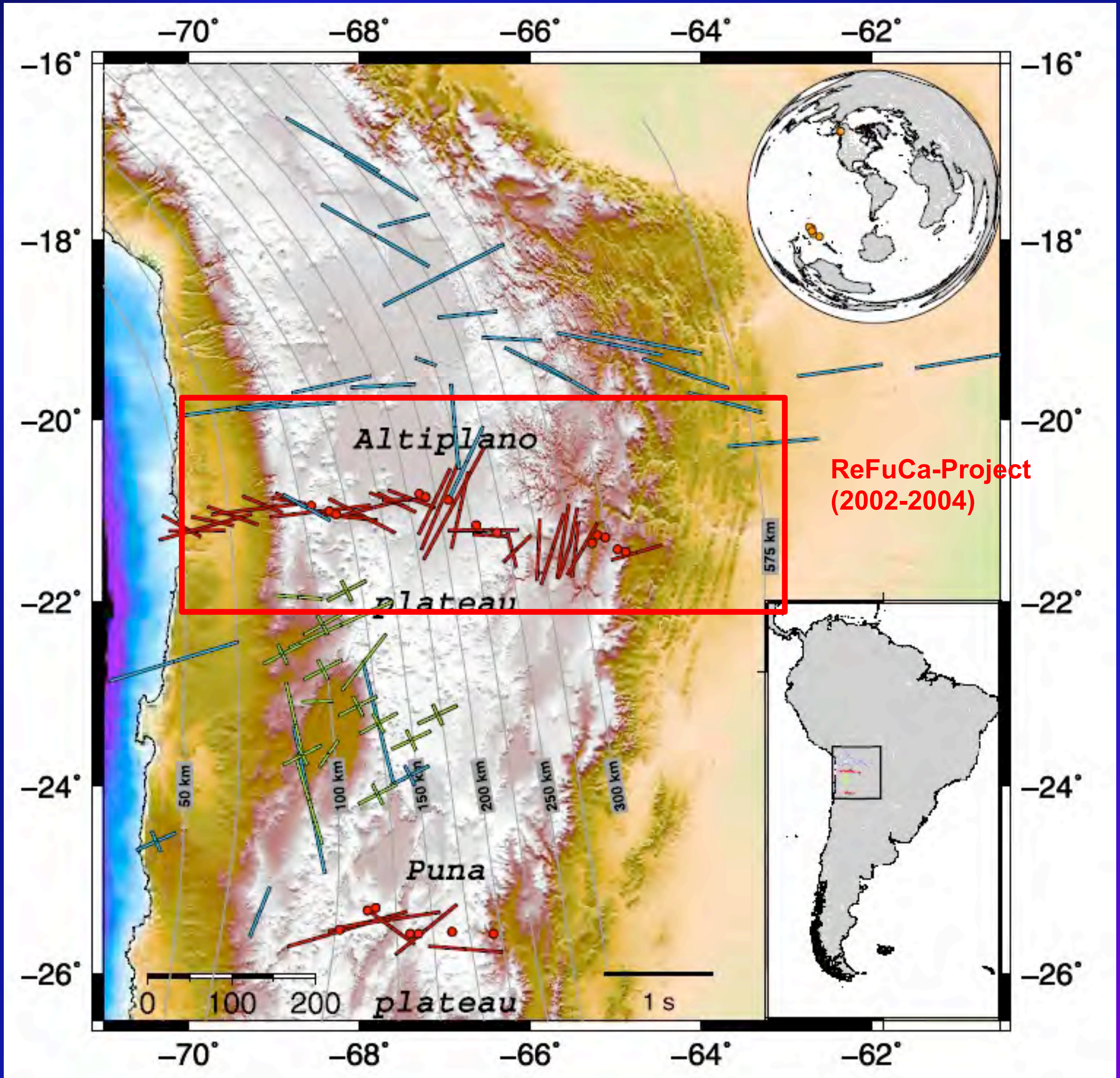


Case studies from South America

- Trench-parallel mantle flow (Russo & Silver, 1994)



SKS-splitting measurements from the Altiplano



red: Wölbern, Kees, Rümpker, 2014, EPSL

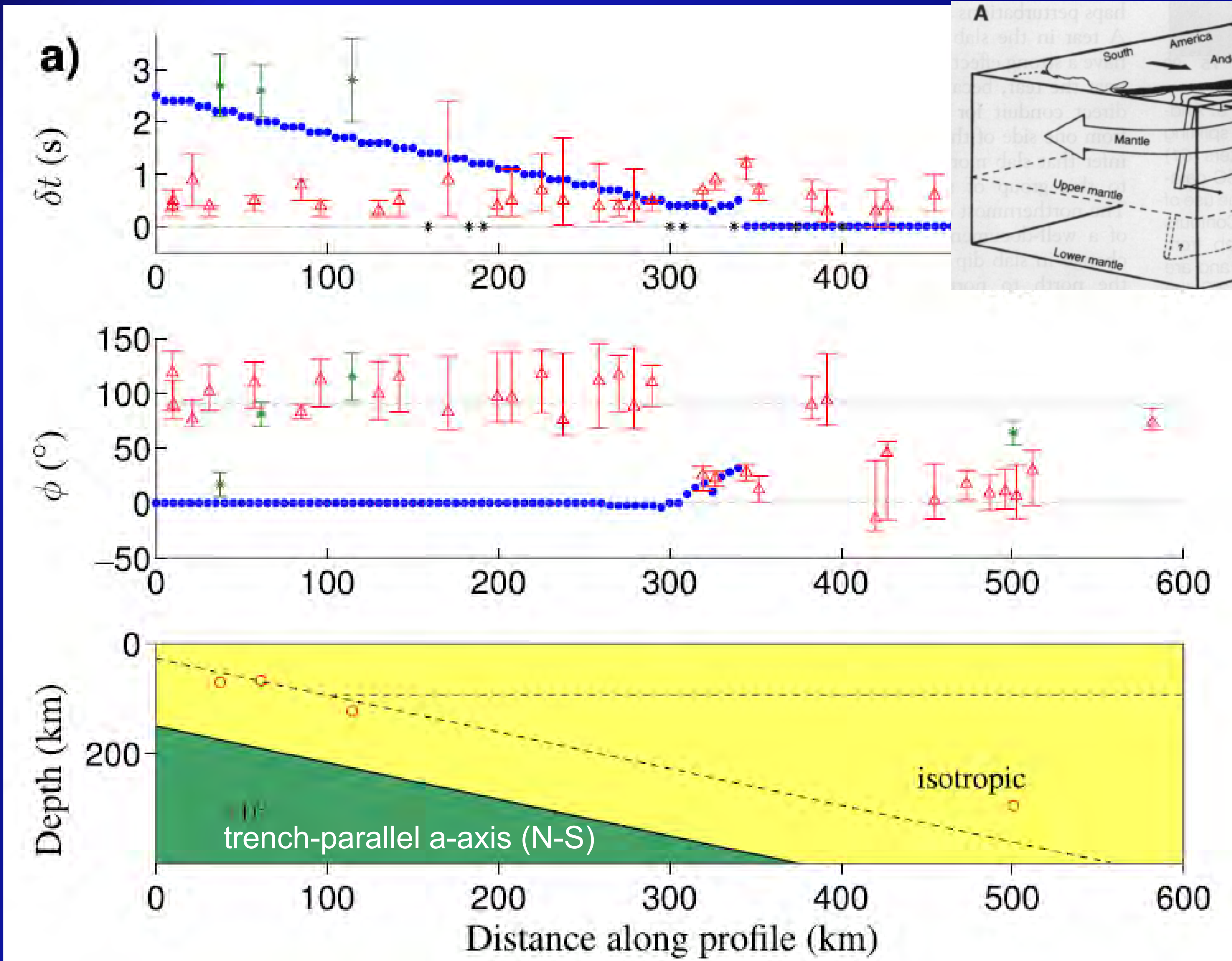
blue: Polet et al.(2000)

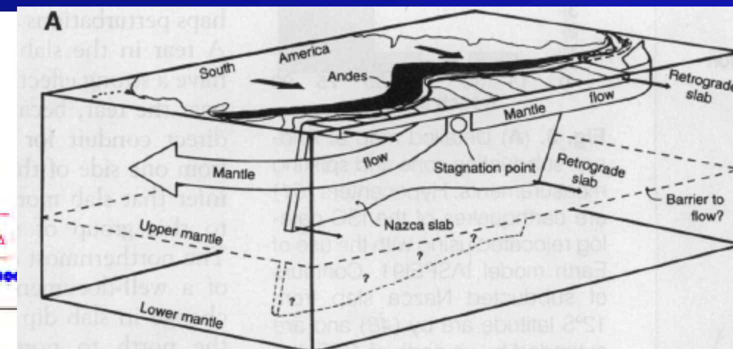
green: Bock et al. (1998)

Waveform modeling of splitting parameters

- sub-slab mantle flow parallel to the trench

W E



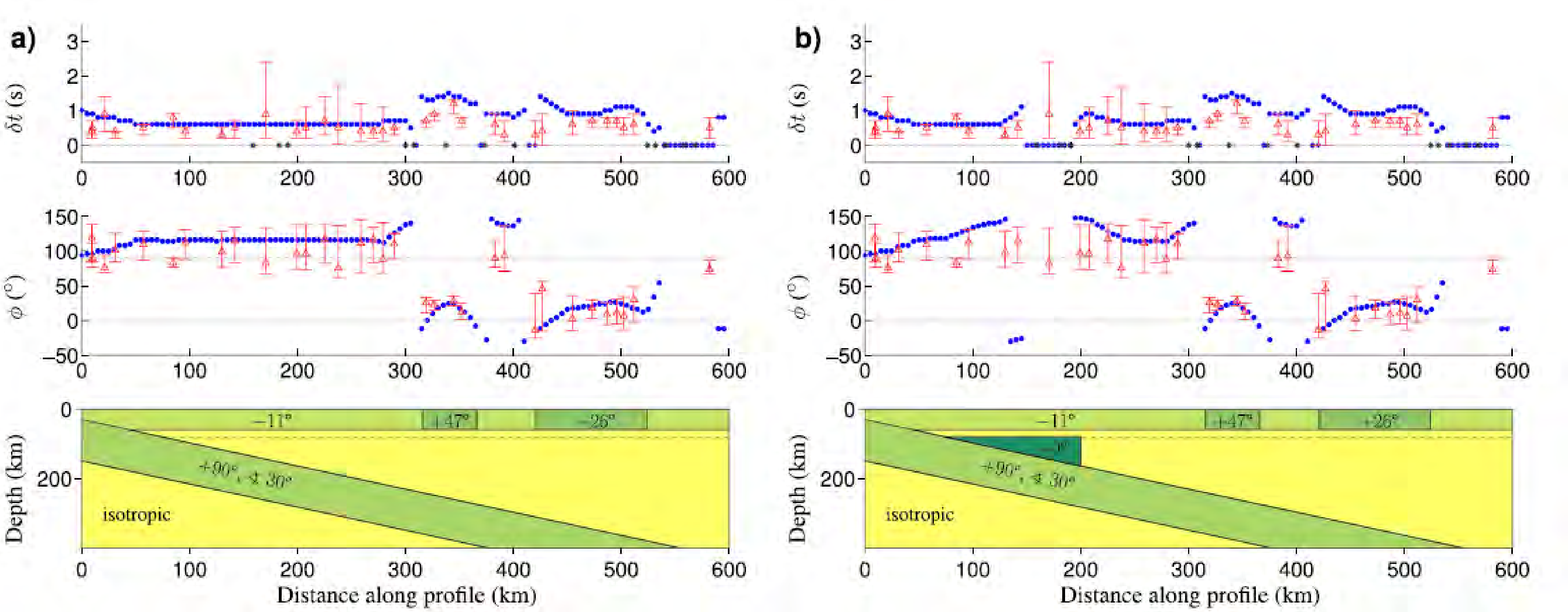


(Russo & Silver 1994)

Waveform modeling of splitting parameters

- trench-perpendicular intra-slab anisotropy
  + trench-parallel crustal anisotropy

W E W E



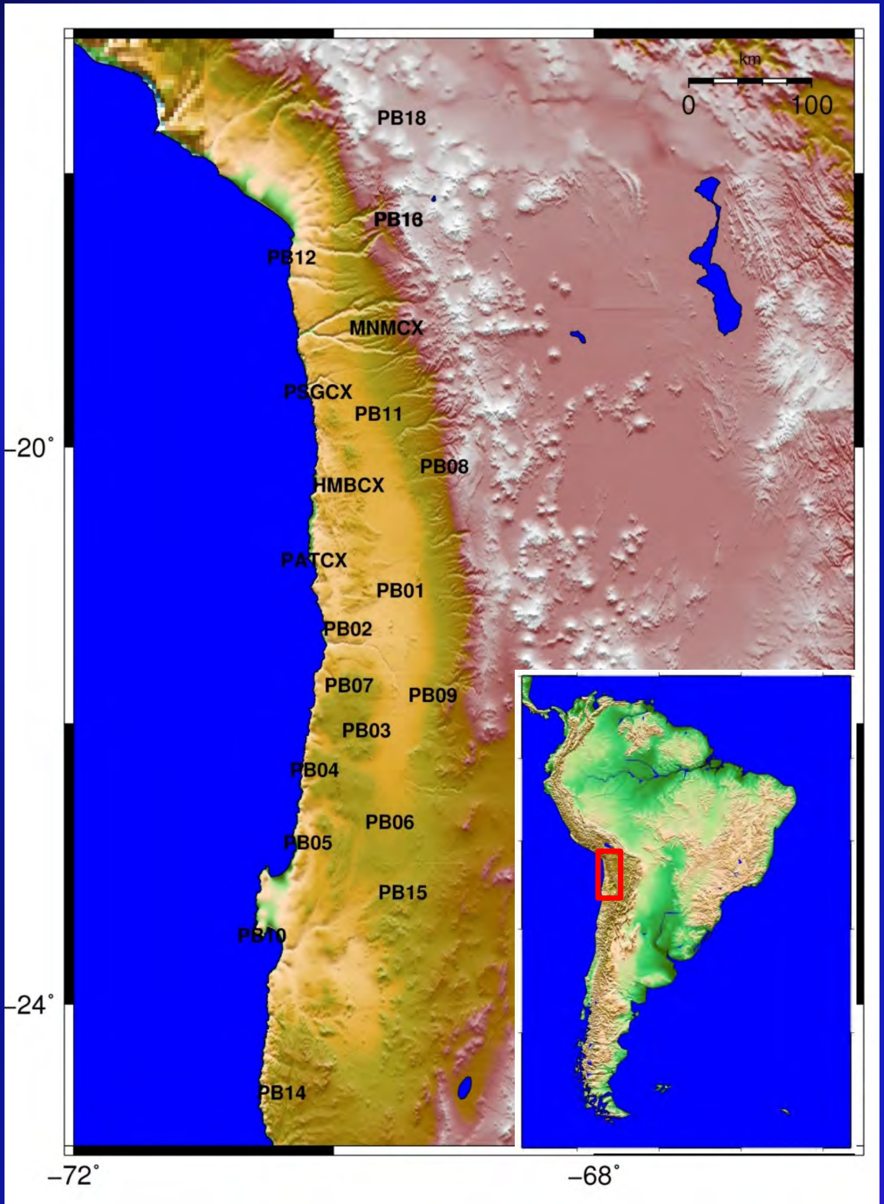
B-type olivine under water-rich conditions
(Jung et al., 2009; Ohuchi et al., 2012)

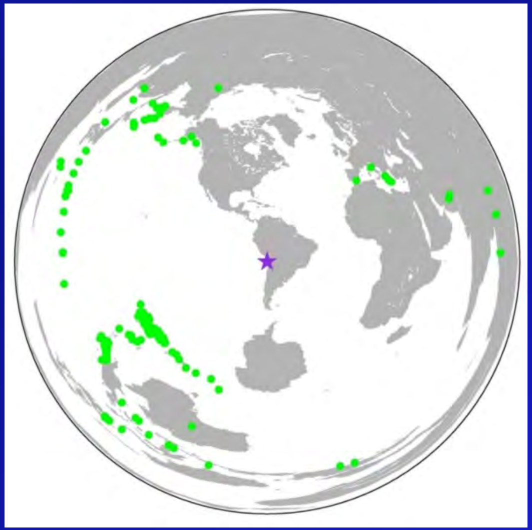
possible source of crustal anisotropy:

- ductile flow in the lower crust (Gerbault et al., 2005)
- fluid-fulled cracks within the Altiplano-Puna volcanic zone (Leidig & Zandt, 2003)

Large-scale trench-perpendicular mantle flow beneath northern Chile

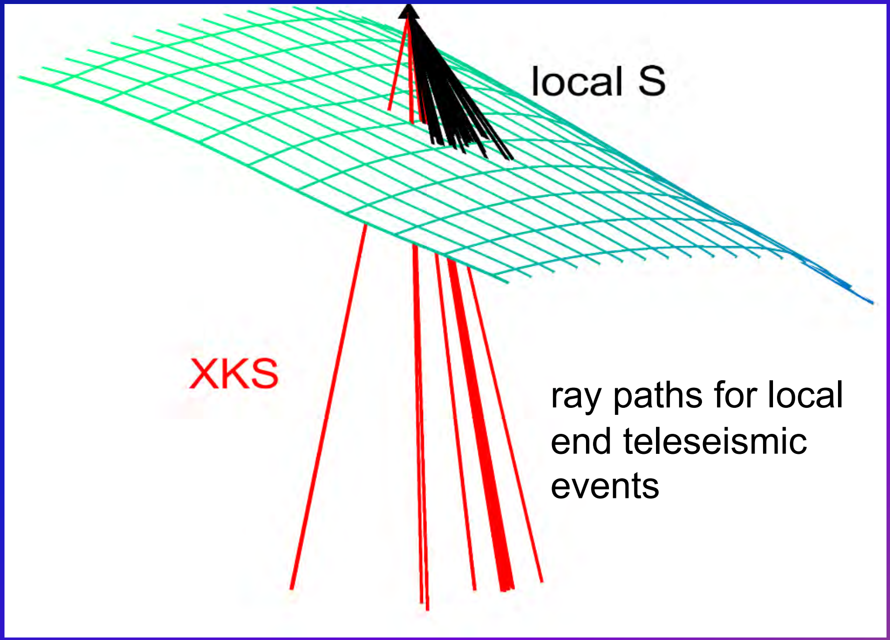
IPOC network





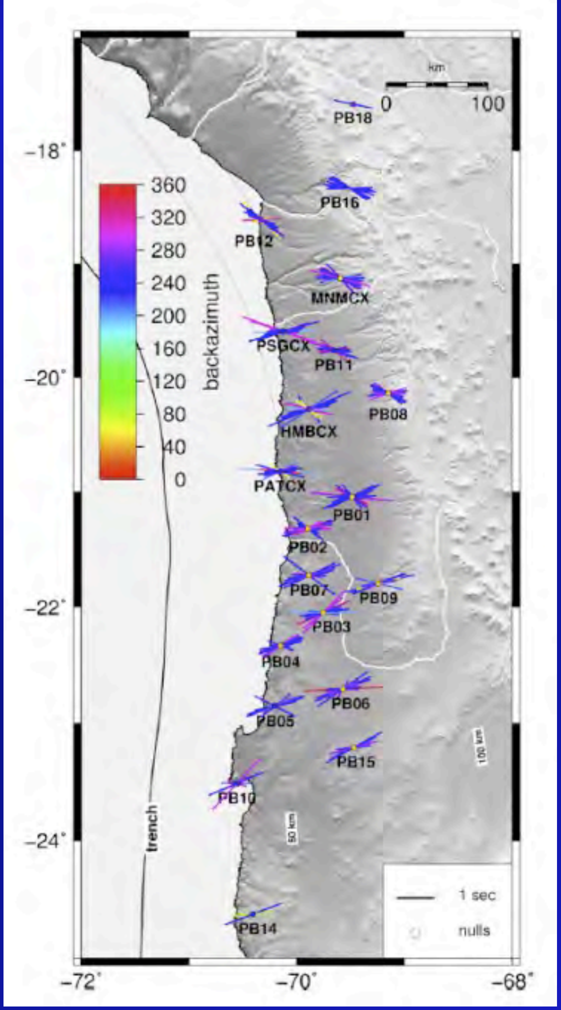
event distribution

(Reiss, Rümpker, Wölbern 2018, EPSL)

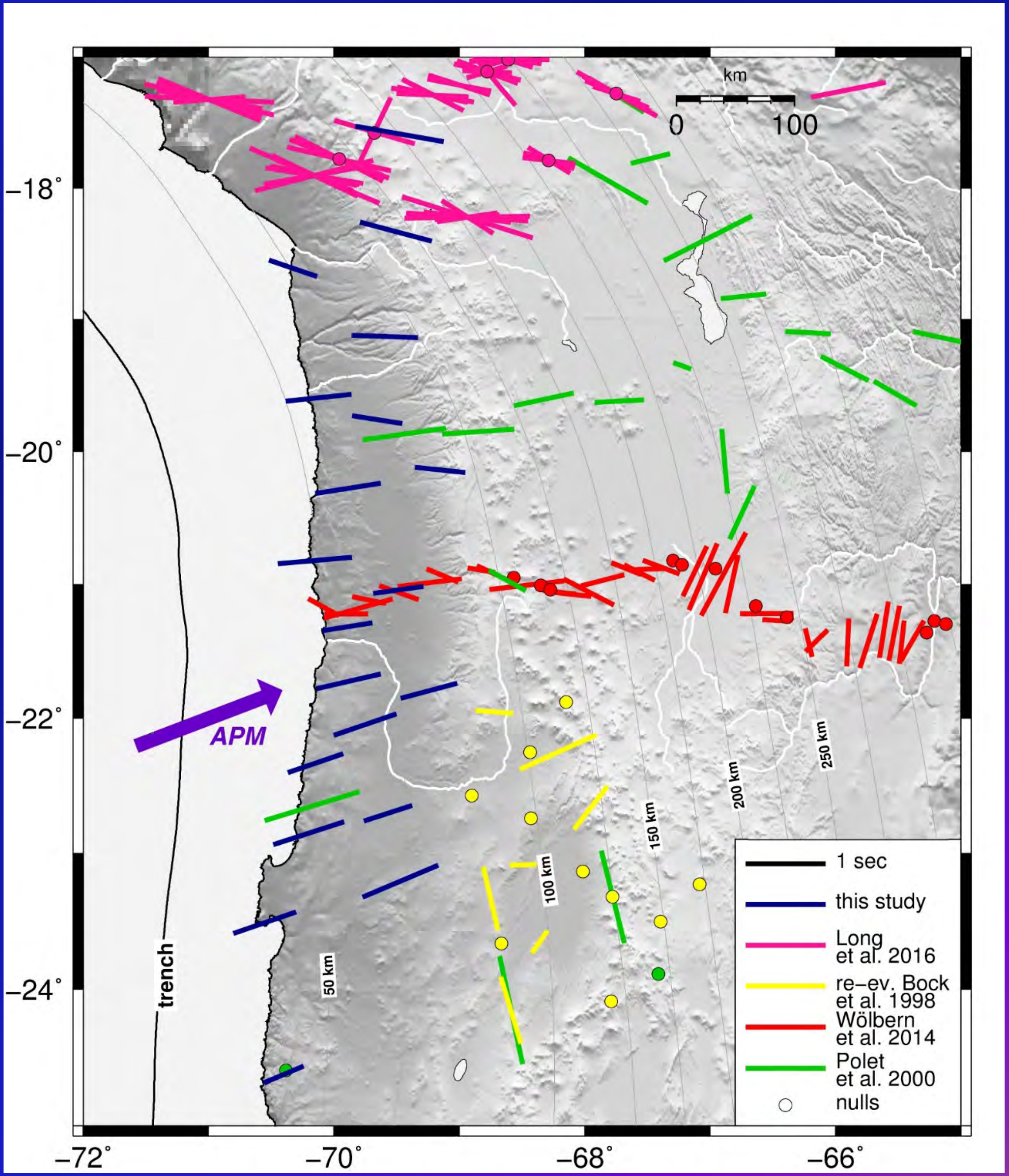


Splitting parameters obtained from teleseismic events

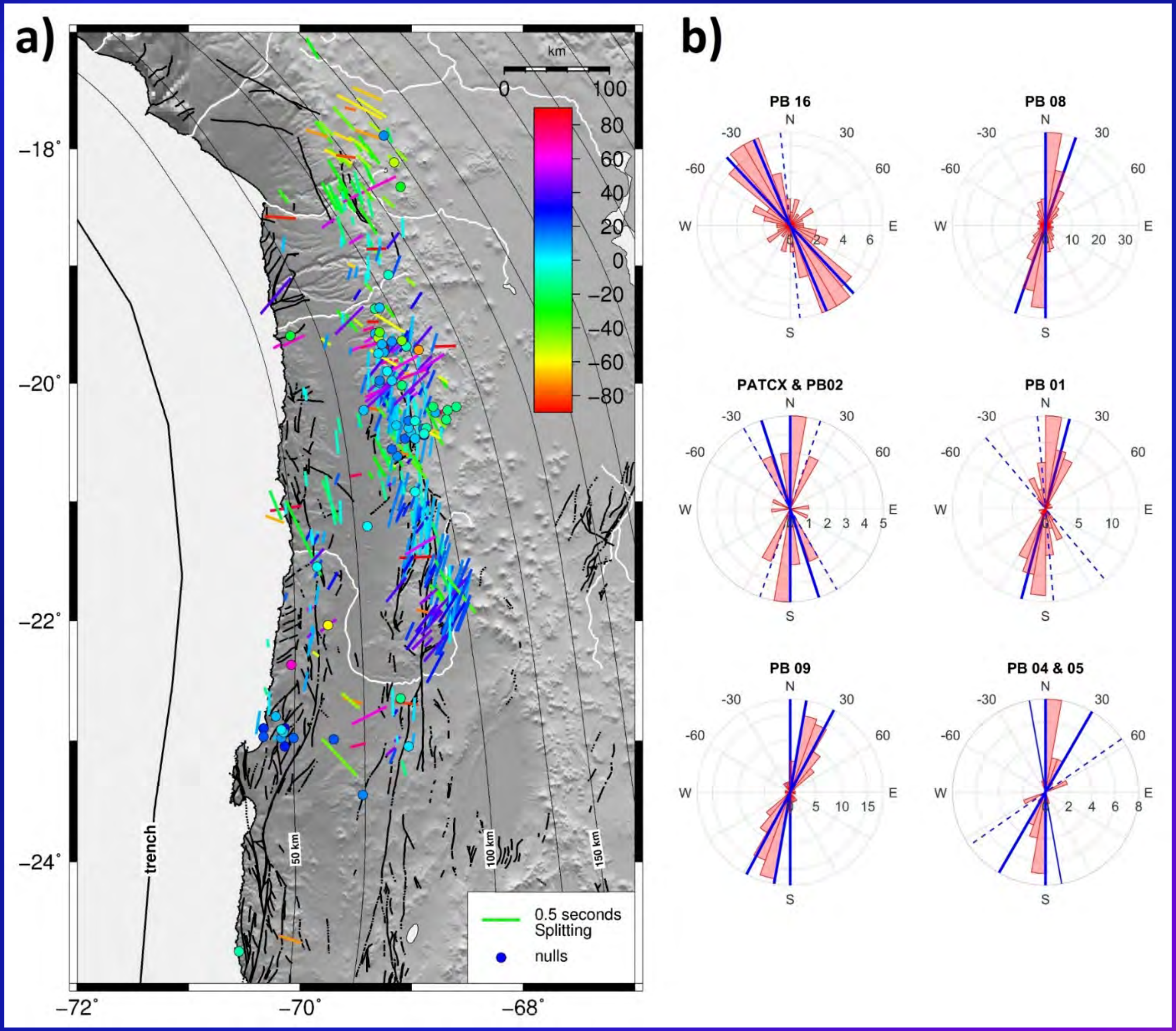
IPOC



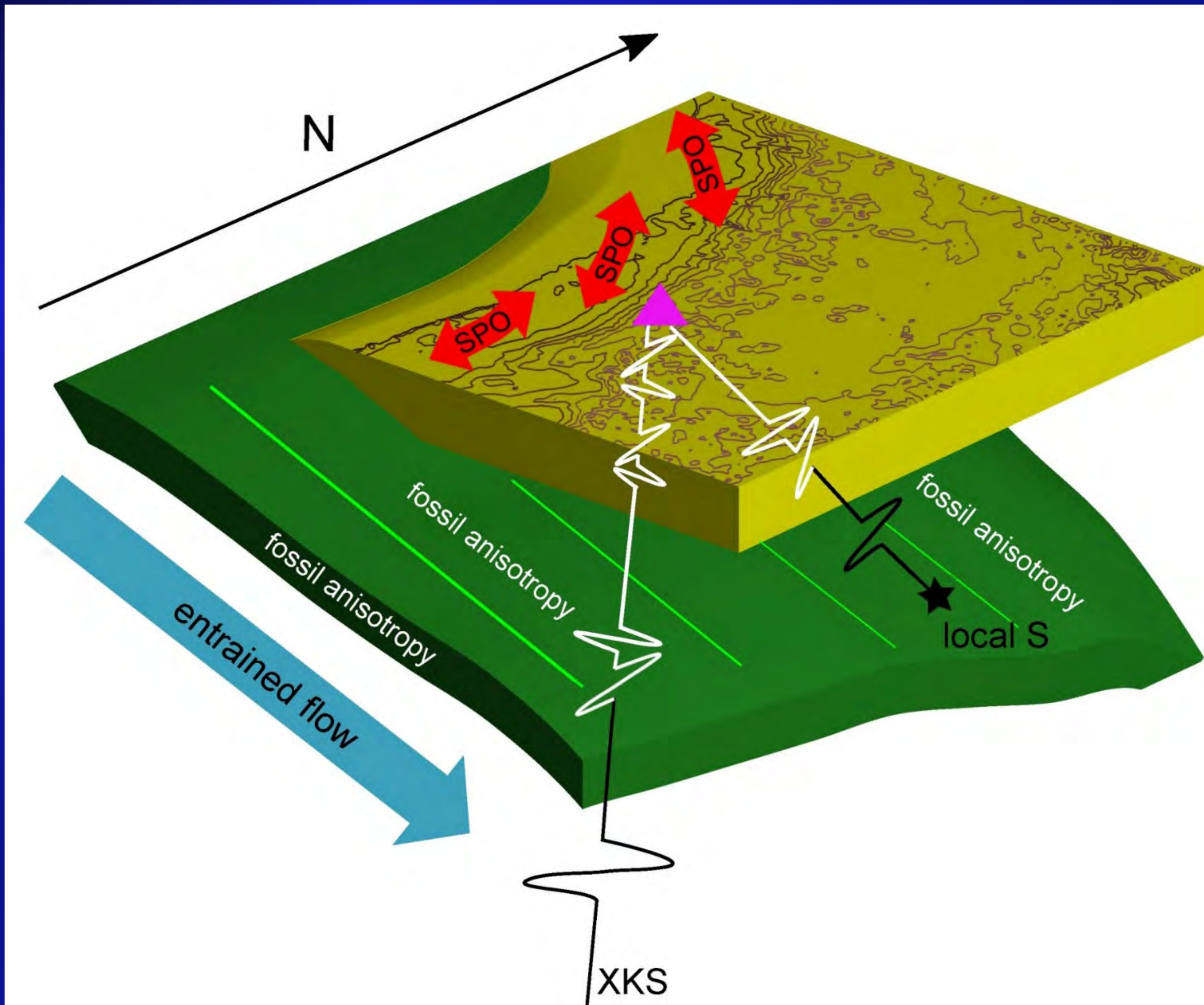
Summary



Splitting parameters from local events and fault-zone orientations



Model of anisotropy beneath the central South America

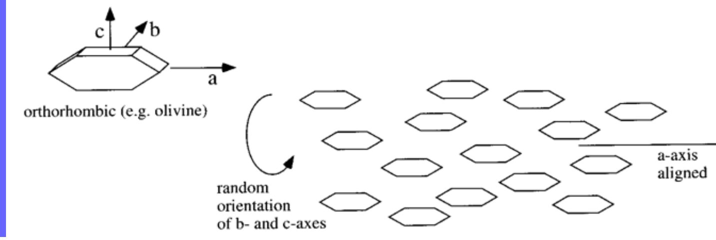


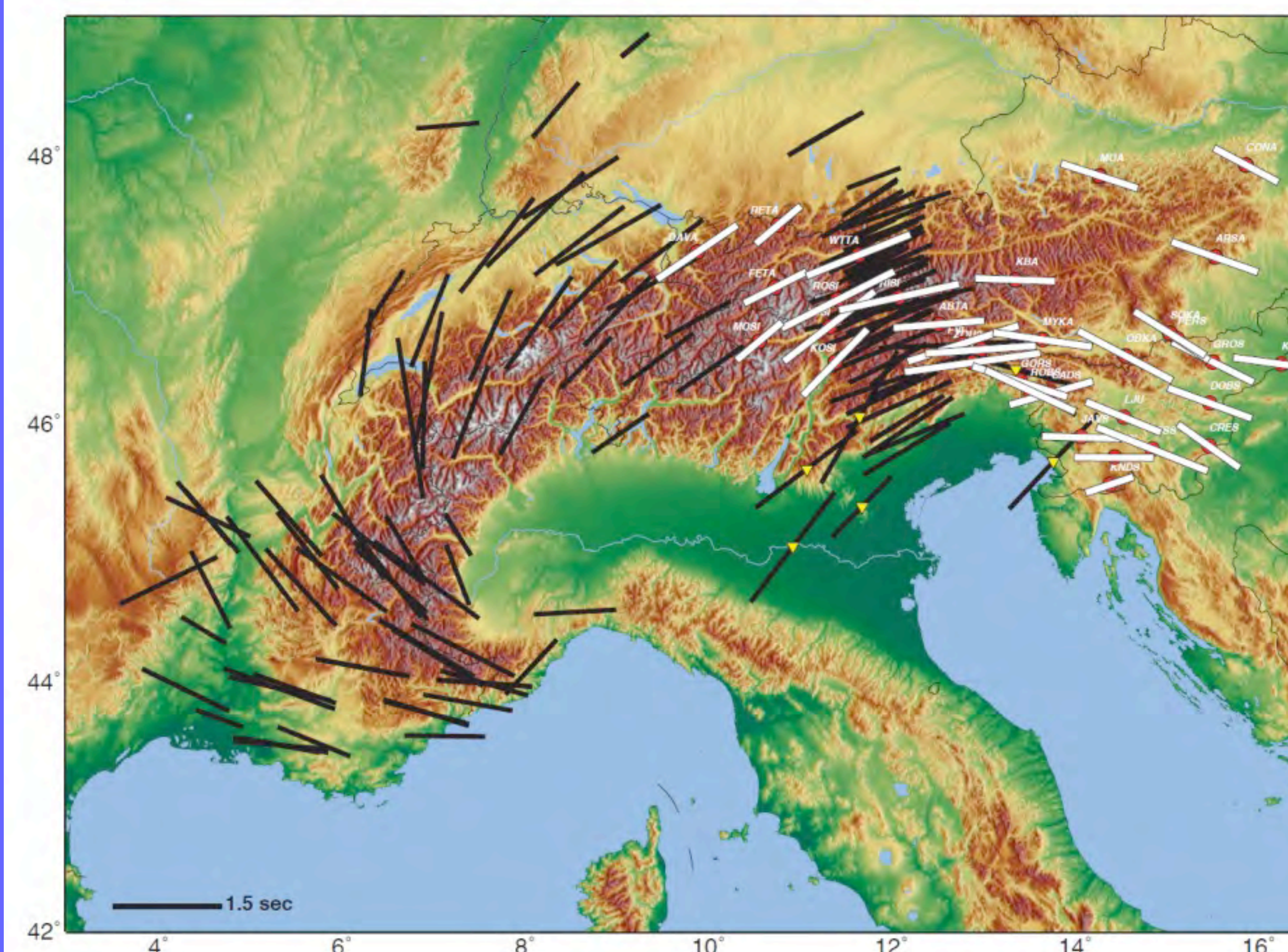
- Crust: Shape-preferred orientation (SPO) related to locally varying faults in response to the strain through crustal shortening.
- Mantle: Lattice-preferred orientation (LPO) of olivine crystals caused by fossilized anisotropy (within the slab) from plate formation and possibly entrained mantle flow.
- There is no evidence for trench-parallel flow beneath the subducting Nazca plate as previously suggested

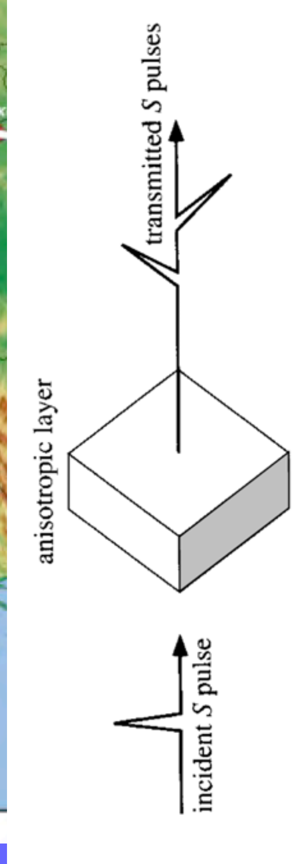
(Reiss, Rümpker, Wölbern 2018, EPSL)

What about the Alps?

(compilation by Qorbani 2015, Vienna)







References

Reiss, M. C., Rümpker, G. & Wölbern, 2018, I., Large-scale trench-normal mantle flow beneath central South America, Earth Planet. Sci. Lett., 482, 115–125, DOI: 10.1016/j.epsl.2017.11.002

Reiss, M. C. & Rümpker, G., 2017, SplitRacer: MATLAB Code and GUI for semiautomated analysis and interpretation of teleseismic shear-wave splitting, Seism. Res. Lett., 88(2), DOI:10.1785/0220160191.

Kaviani, A. & Rümpker, G., 2015, Generalization of the H-κ stacking method to anisotropic media, J. Geophys. Res. Solid Earth, 120, 5135–5153, DOI:10.1002/2014JB011858.

Rümpker, G., Kaviani, A. & Latifi, K., 2014, Ps-splitting analysis for multi-layered anisotropic media by azimuthal stacking and layer stripping, Geophys. J. Int., 199 (1), 146-163, DOI:10.1093/gji/ggu154.

Wölbern, I., Löbl. U. & Rümpker, G., 2014, Crustal origin of trench-parallel shear-wave fast polarizations in the Central Andes, Earth Planet. Sci. Lett., 392, 230-238, DOI:10.1016/j.epsl.2014.02.032

Rümpker, G. & Silver, P.G., 1998, Apparent shear-wave splitting parameters in the presence of vertically-varying anisotropy, Geophys. J. Int., 135, 790-800.

Seismic anisotropy (SA)

Definition: SA describes the dependence of seismic wave velocities on

- the direction of propagation or
- shear-wave polarization.

Causes
- preferred alignment of intrinsically anisotropic minerals
- the layering / geometric ordering of isotropic materials with contrasting elastic properties

Effects
- shear wave splitting or birefringence
- azimuthal dependence of body and surface wave propagation speed
- discrepancy between propagation speeds of Love and Rayleigh waves

SA is often assumed to have hexagonal symmetry (i.e., transverse isotropy) with an axis of symmetry that is either horizontal (azimuthal anisotropy) or vertical (radial anisotropy), but other orientations may occur.

SA in the upper mantle is mainly due to strain-induced crystallographic or lattice preferred orientation (CPO, LPO) of intrinsically anisotropic mantle minerals, principally olivine.

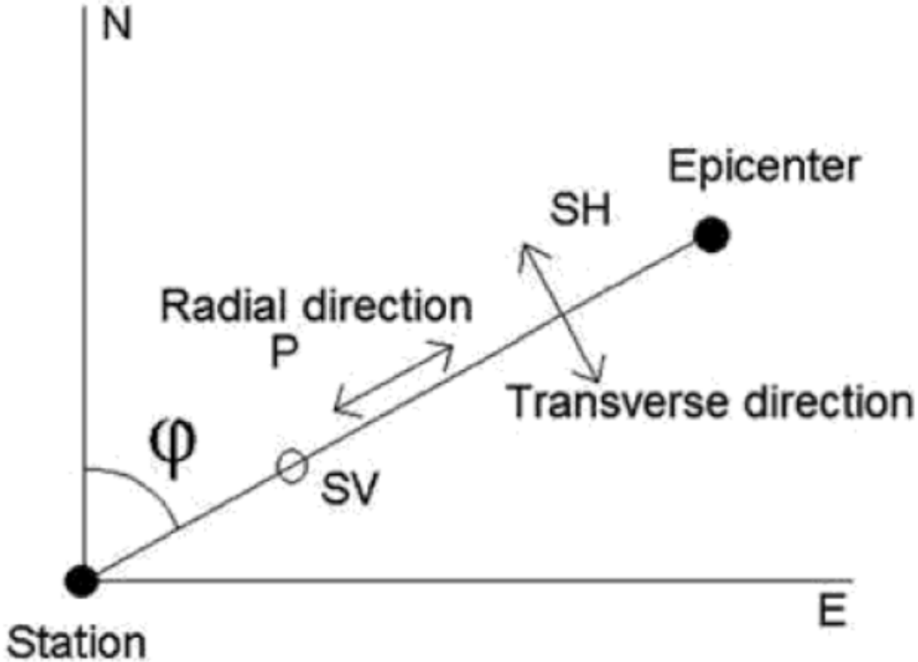
Radial anisotropy is required in the uppermost mantle to reconcile Love and Rayleigh wave dispersion.

Azimuthal anisotropy occurs when seismic wave velocity changes with the azimuth of propagation.

(see http://www.virtualuppermantle.info)

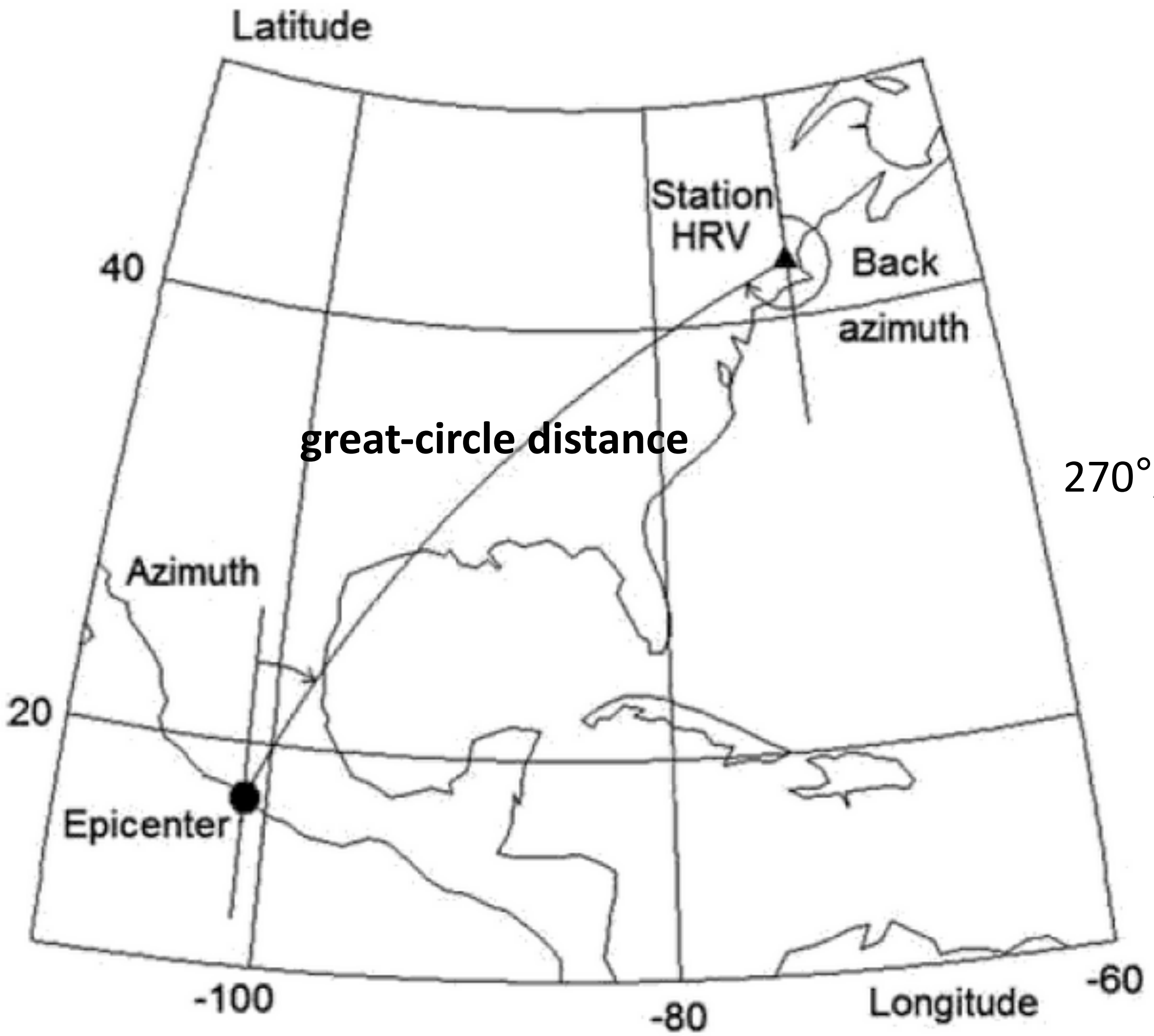
Waves and their polarizations

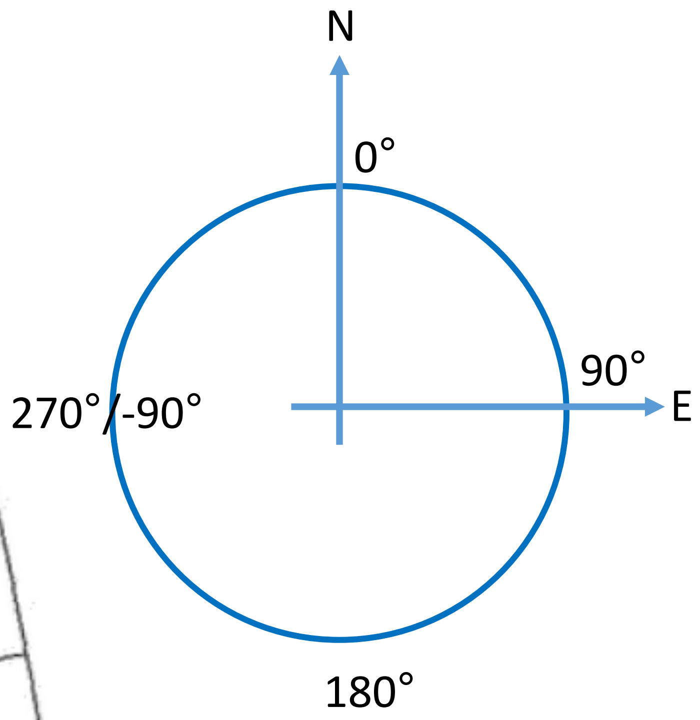
φ : back-azimuth



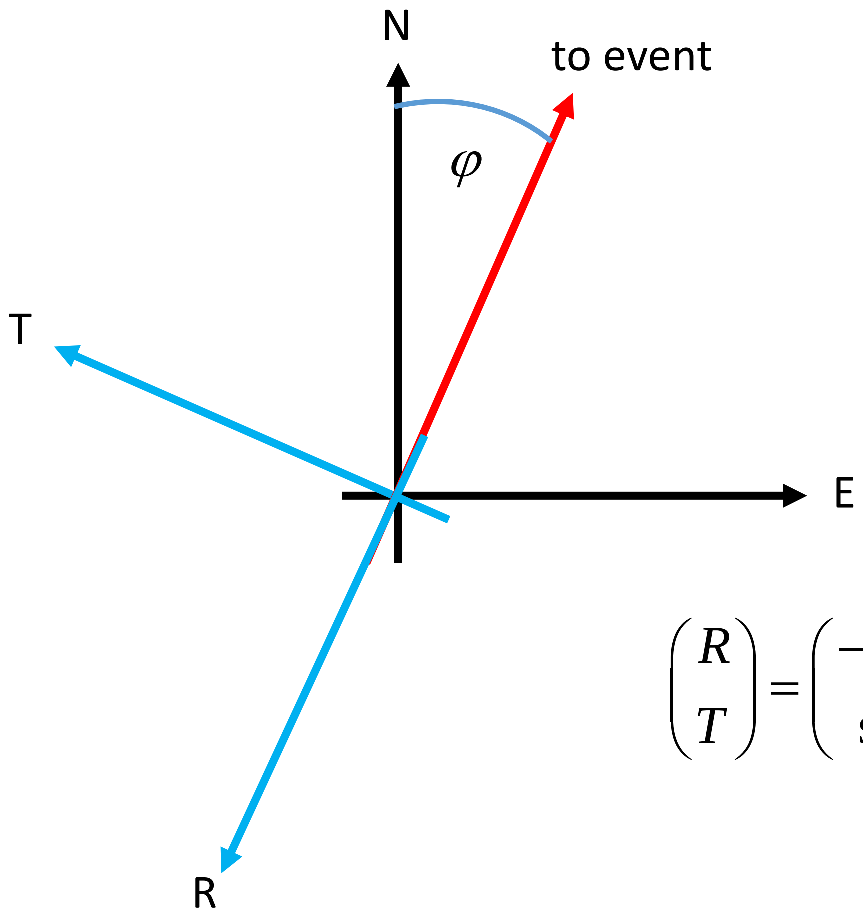
- P-waves: Linear in radial and vertical plane.
- SH waves: Linear in the transverse direction.
- SV waves: Linear in the radial and vertical plane.
- Rayleigh waves: Elliptical in the radial and vertical plane.
- Love waves: Linear in the transverse direction.

Azimuth and Backazimuth





Transformation from NE to RT coordinates



φ : back-azimuth

$$\begin{pmatrix} R \\ T \end{pmatrix} = \begin{pmatrix} -\cos\varphi & -\sin\varphi \\ \sin\varphi & -\cos\varphi \end{pmatrix} \begin{pmatrix} N \\ E \end{pmatrix}$$