Westfälische Wilhelms-Universität Münster

GEOPHYSIK WWU MÜNSTER

# Investigating deformation/flow in the mantle with seismological observations


Christine Thomas (1),
Morvarid Saki (1), Angelo Pisconti (1),
with James Wookey (2), Sébastien Merkel (3), Estelle Ledoux (3)

1: WWU Münster, Germany 2: University of Bristol 3: Université de Lille



University of BRISTOL

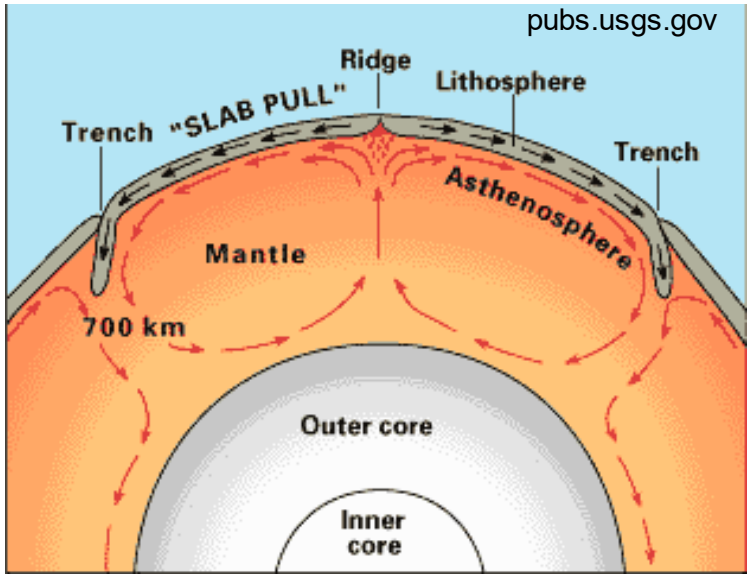
CREEP Horizon 2020 - Marie Sklodowska-Curie Actions Innovative Training Network (ITN) Complex RhEologies in Earth dynamics and industrial Processes

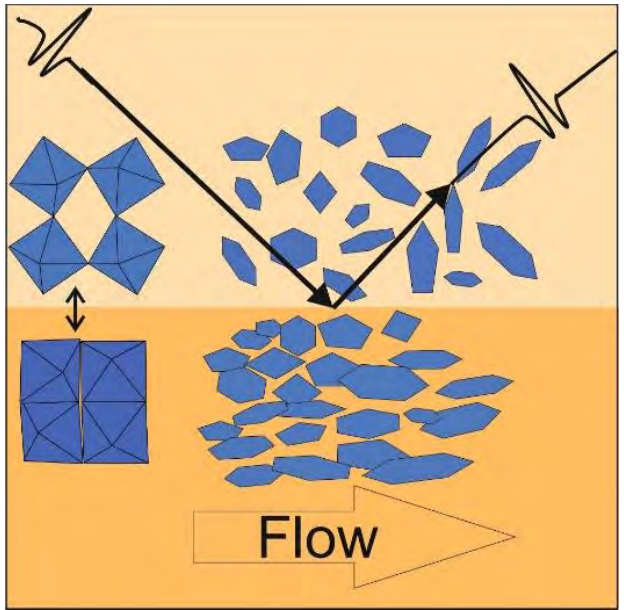
DFG Deutsche Forschungsgemeinschaft

TIMEleSS ANR DFG

Université de Lille

# Imaging mantle flow - Questions for this talk



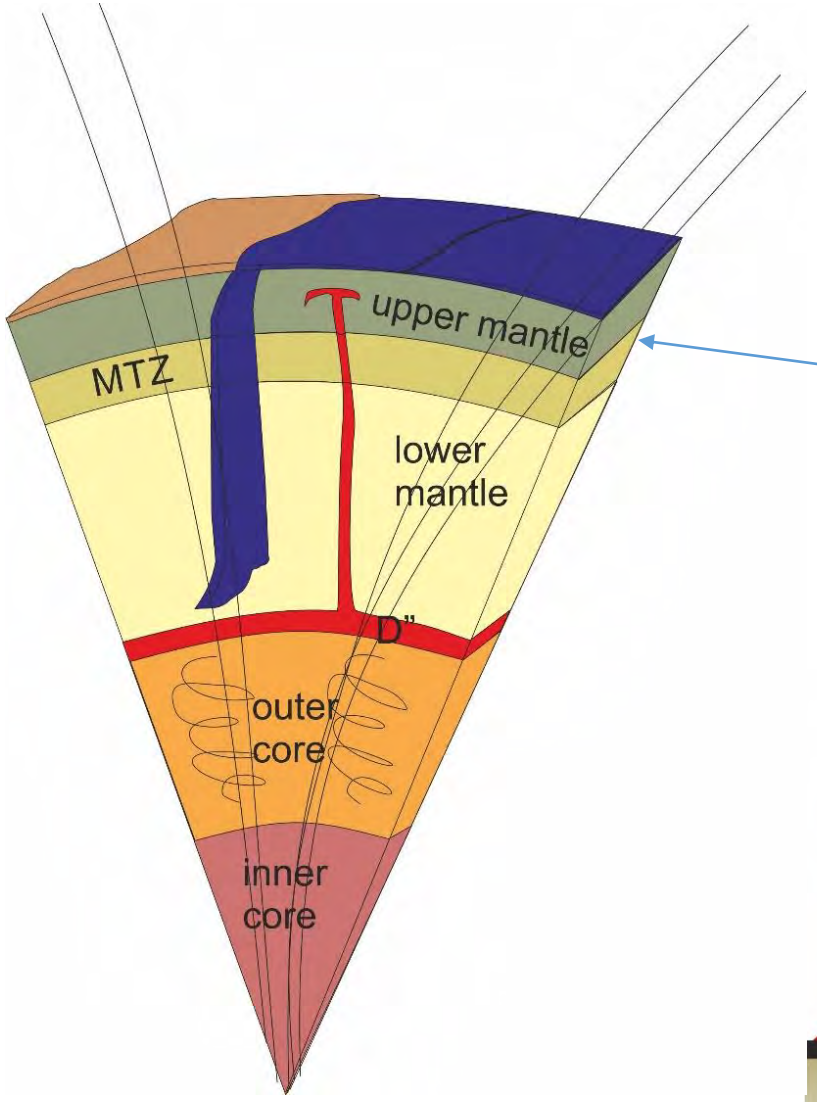




- How can we make dynamic processes visible with seismic methods, i.e., can we "see" convection?
- Can detected anisotropy help to understand processes?
- How important is the knowledge of mineralogy?
- How unique are our interpretations?

**Several ways to image mantle processes**

Here: Flow - Deformation ⟹ Anisotropy

# This talk

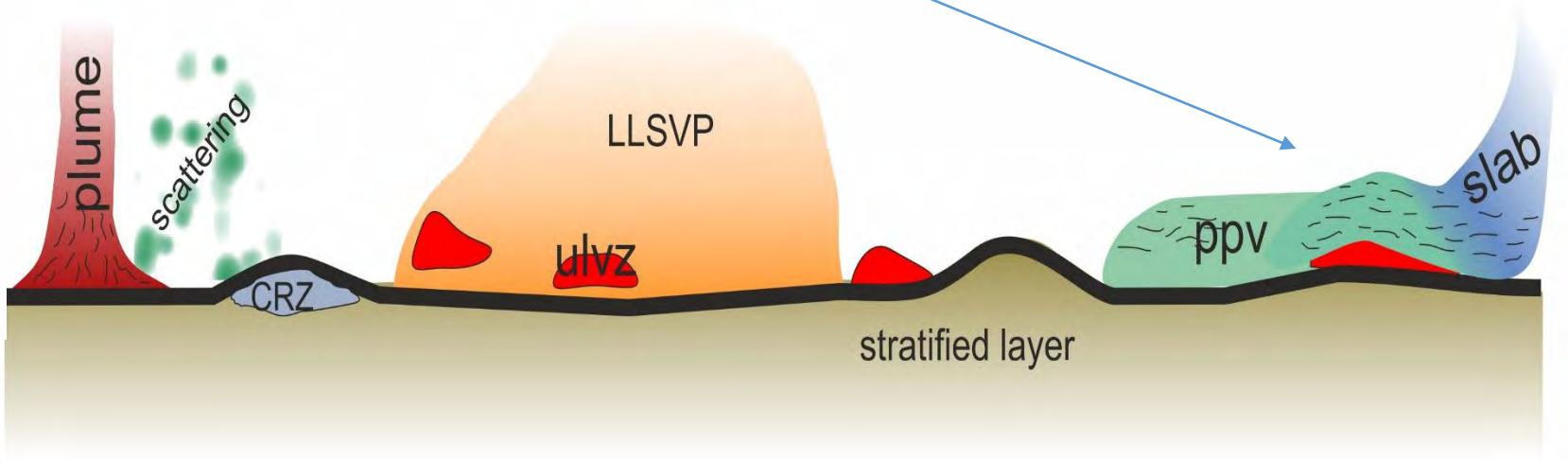



Anisotropy is best detected in boundary layers (J-P. Montagner)

In this talk we will look for anisotropy in:

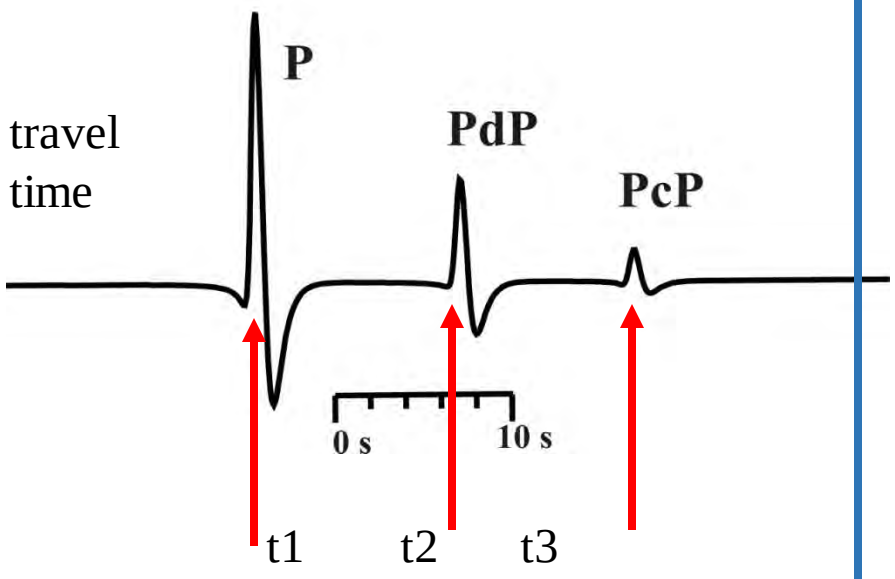
Mantle transition zone (MTZ)

D", lowermost mantle

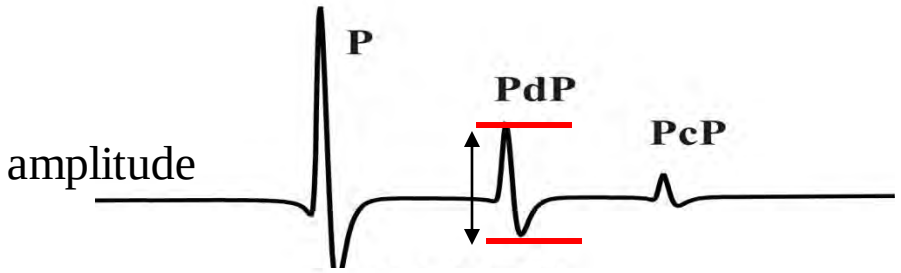


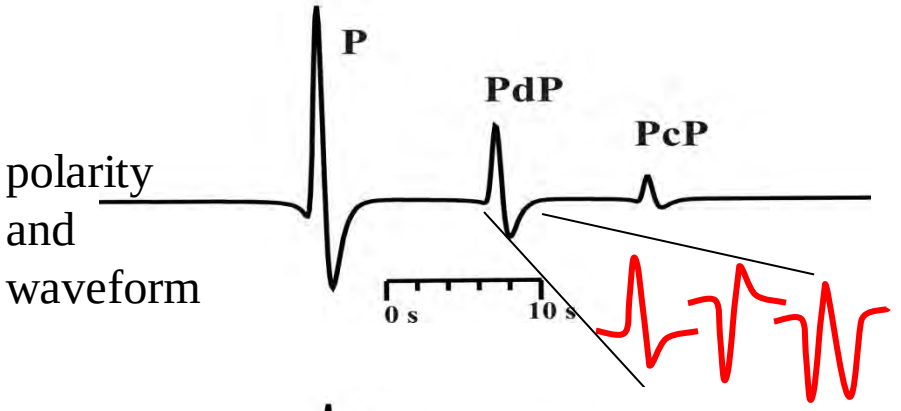
# Information from seismic data

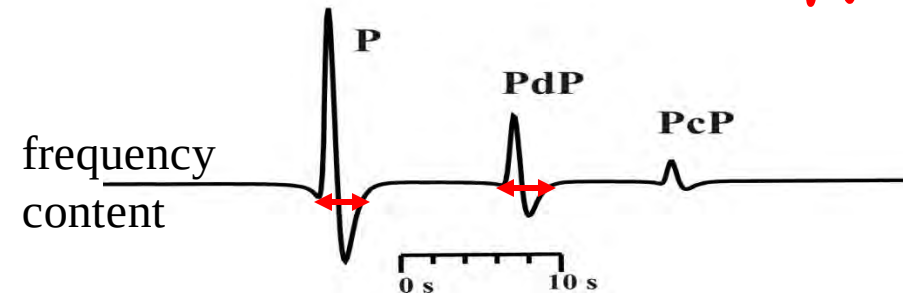
The travel time of reflections provides a measurement for the depth of the reflector
(if the velocity is correct)

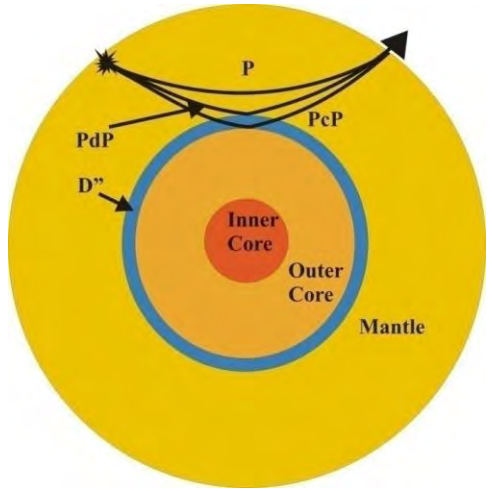



less often used:



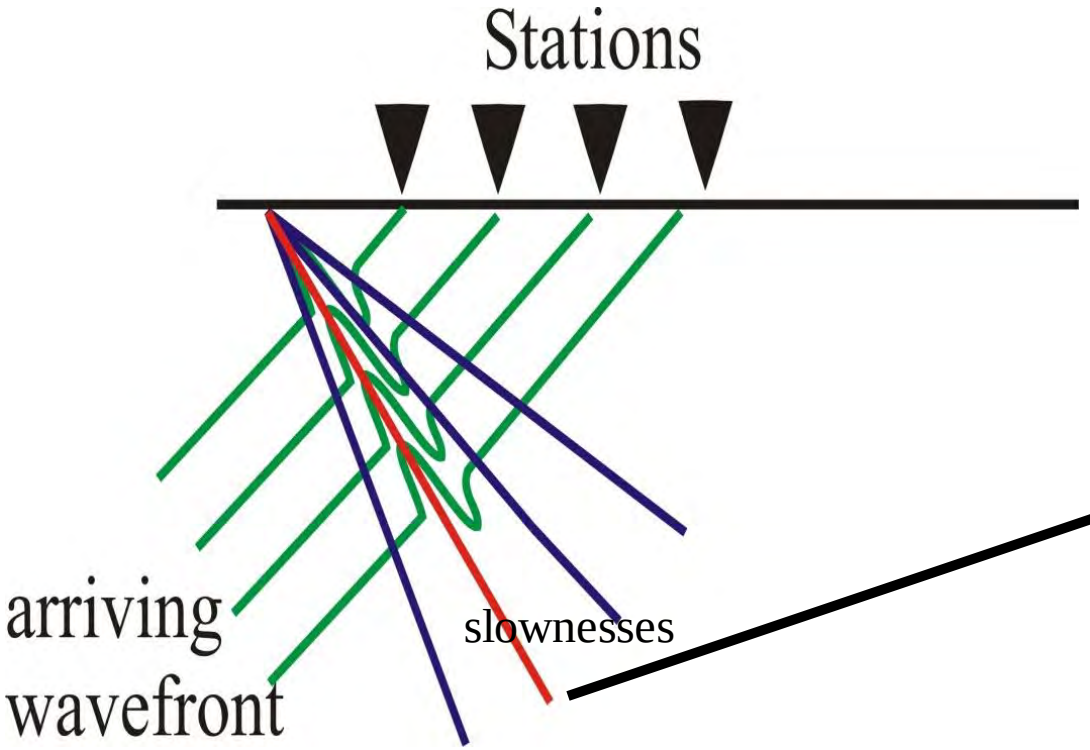



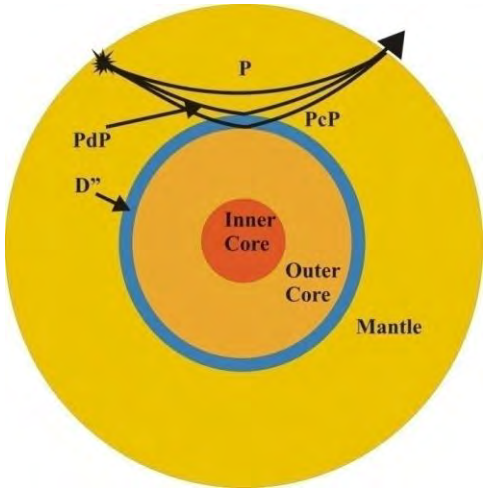



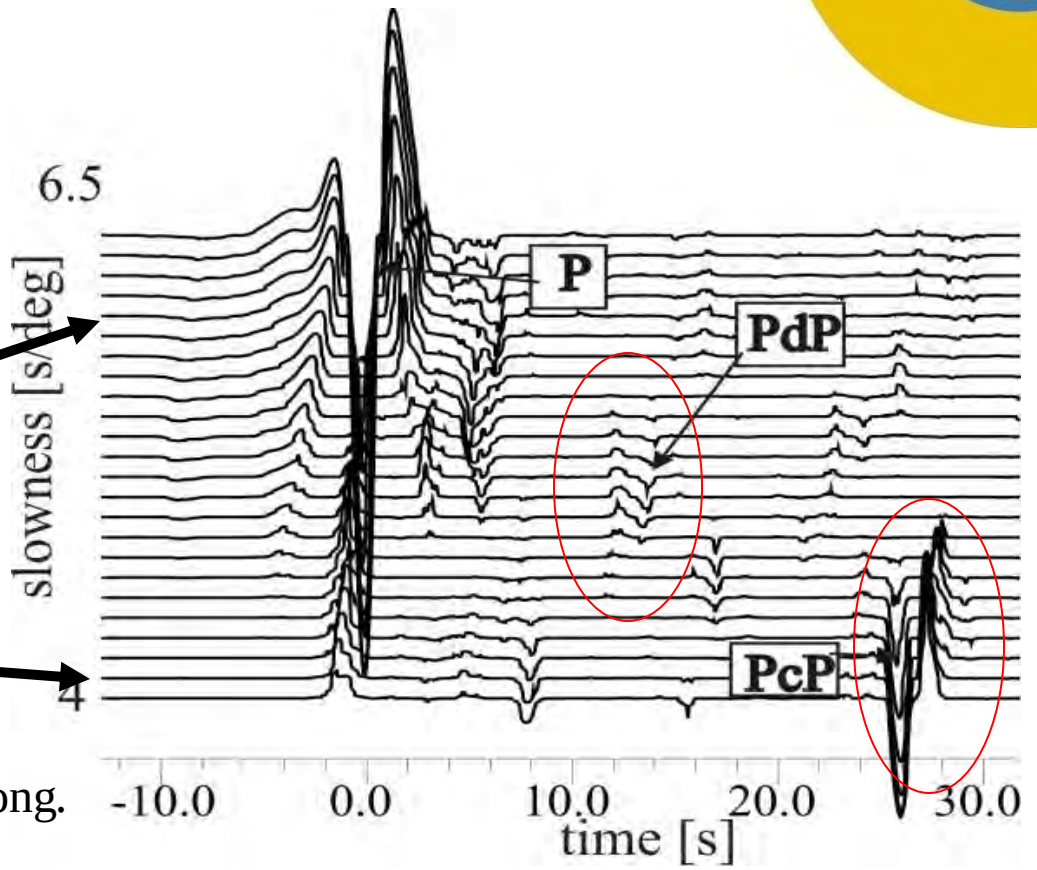



# Stacking of seismic data

Array methods are based on shifting and summing traces

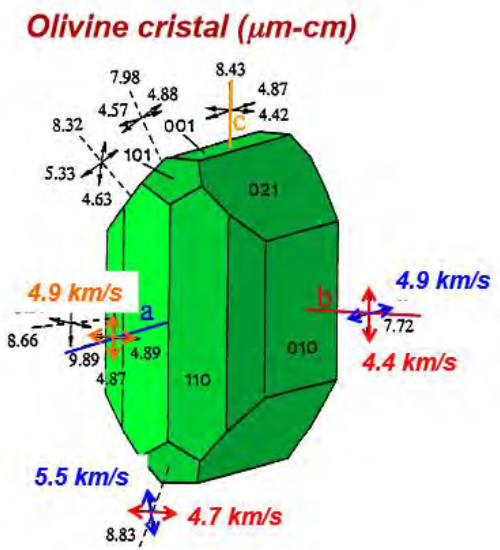



important: backazimuth must be known exactly
otherwise slowness values in the vespagram may be wrong.

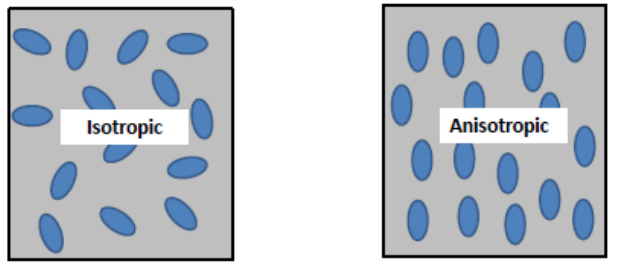
# Deformation




A. Tommasi

Making deformation visible in the deep Earth:

Convective processes in the Earth will align crystals, grains and inclusions => fabric



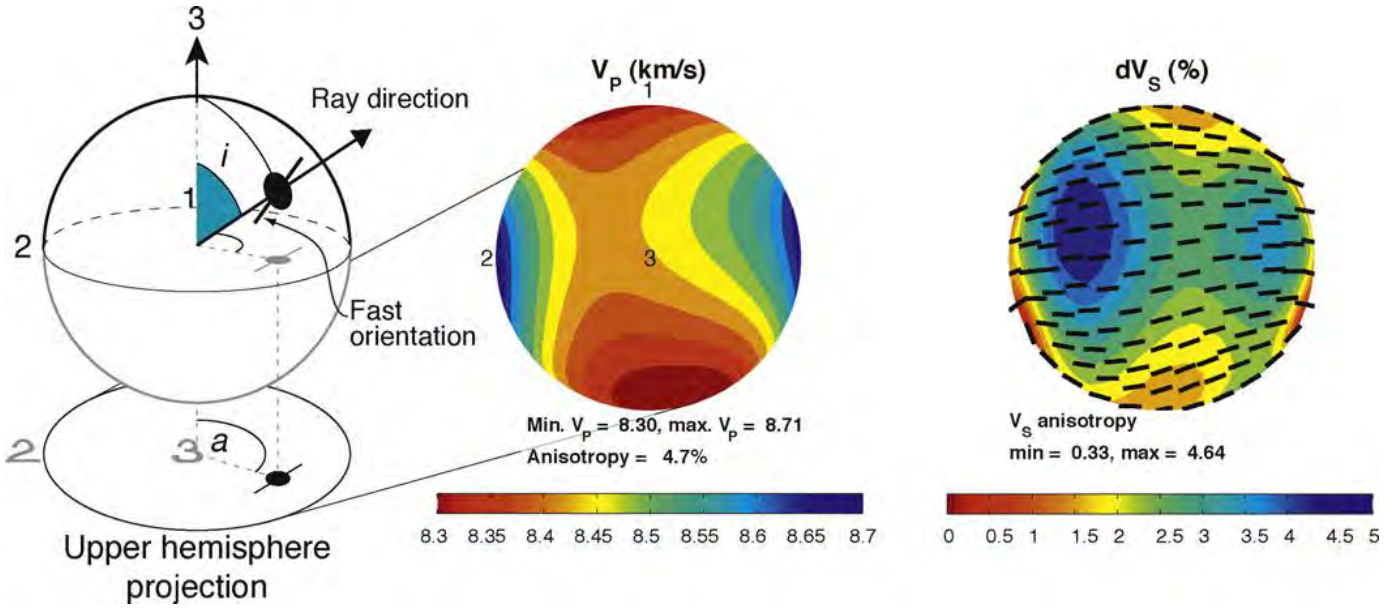

random anisotropic crystals:

aligned anisotropic crystals:

Consequences of anisotropy:

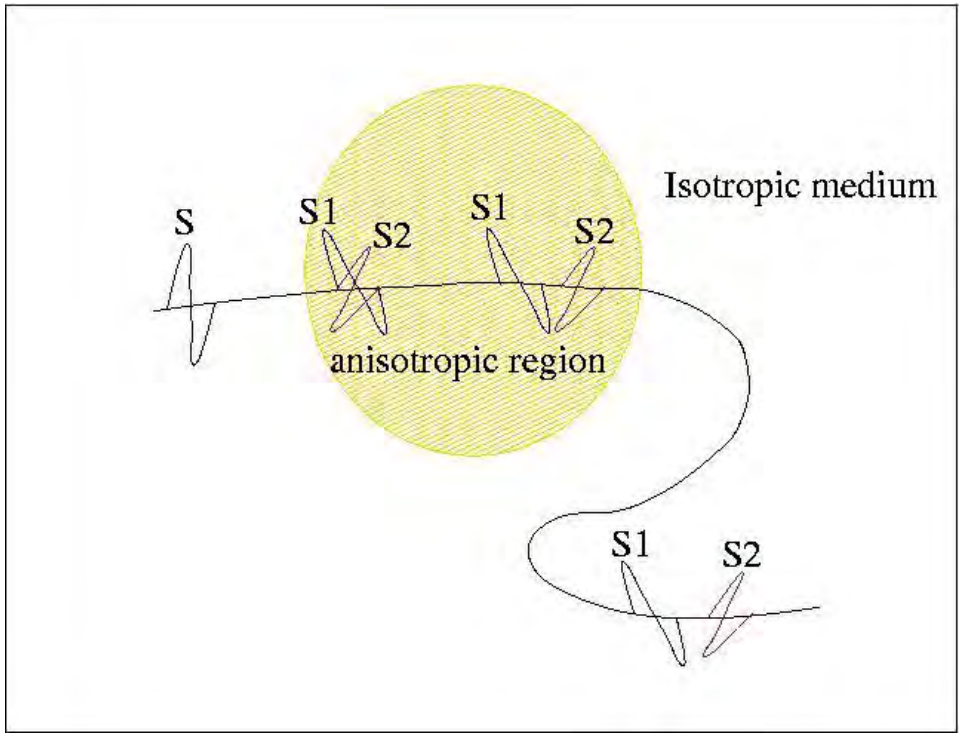
Seismic waves can be polarised

Waves that propagate in different directions travel with different wave speeds




Nowacki et al., 2011

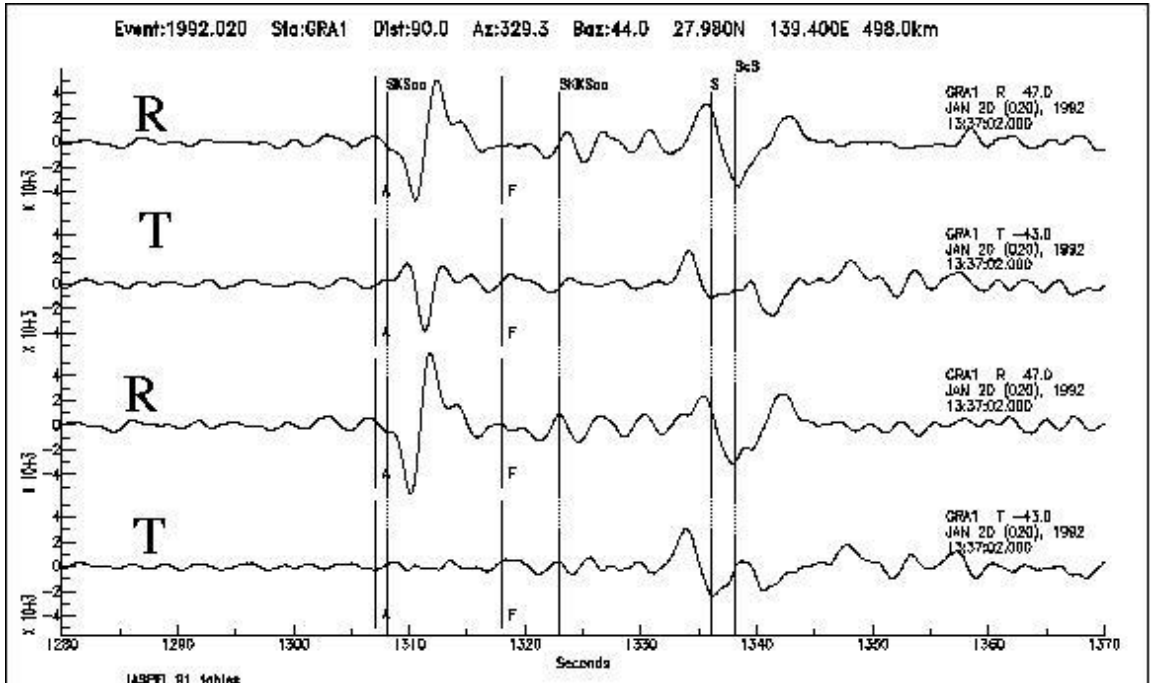
# Shear wave splitting




S-wave in anisotropic medium:
splits up into fast and slow wave (polarised) - the pulses travel with different speeds

=> separation in arrival time

2 Quasi-(S)-waves arrive at surface.
=> Shear wave splitting

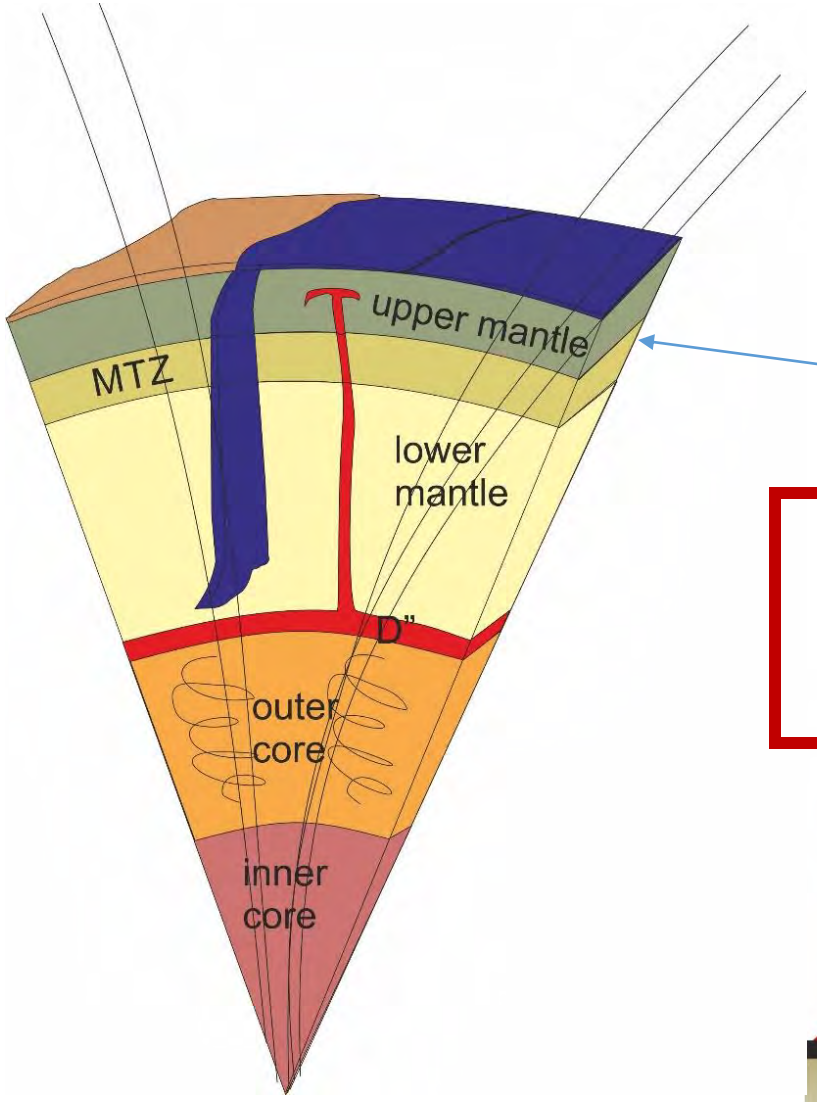



Example: SKS wave (vertically polarised on last leg)

should only be on R component - with anisotropy on the path: energy also on T component

Correction: minimise energy on T component.
Correction parameters (polarisation angle and time shift) provide measurements of anisotropy

# This talk

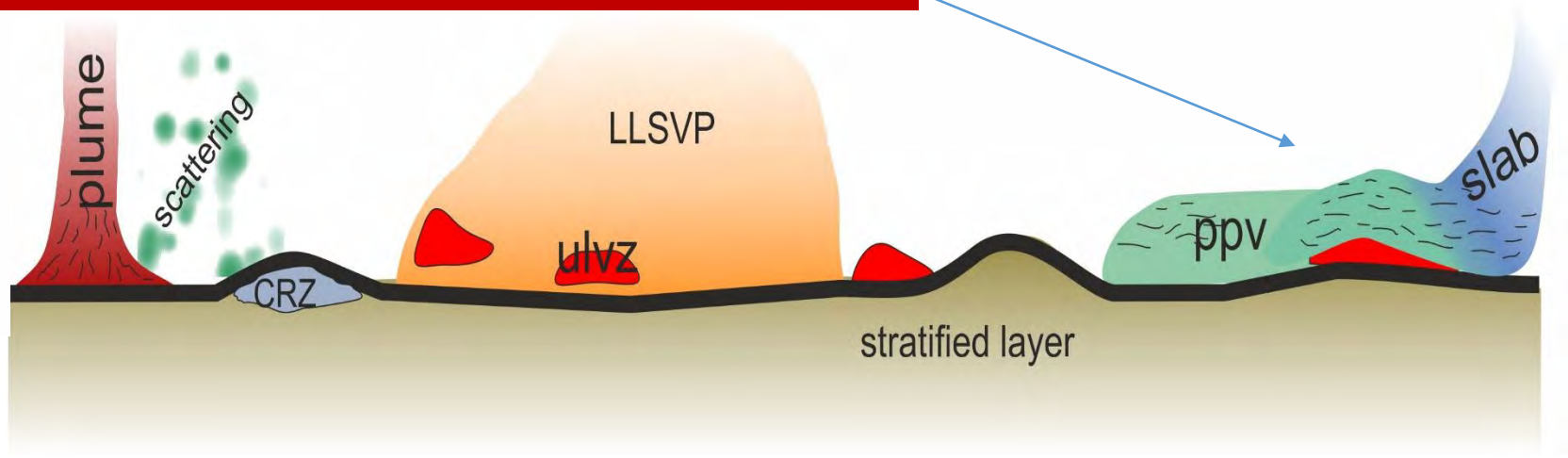



Anisotropy is best detected in boundary layers (J-P. Montagner)

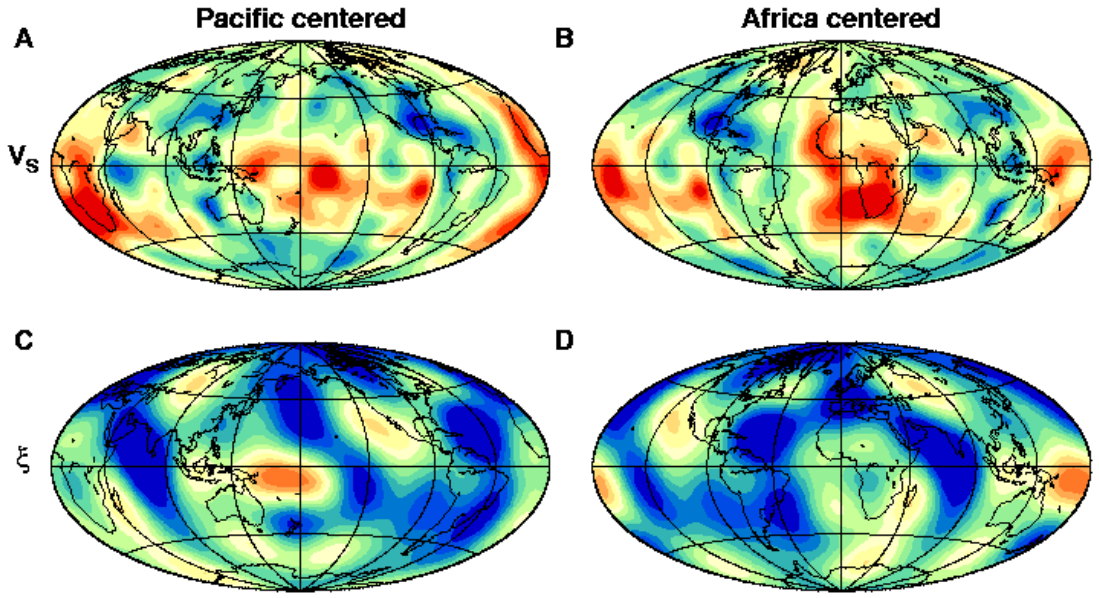
In this talk we will look for anisotropy in:

Mantle transition zone (MTZ)

D", lowermost mantle



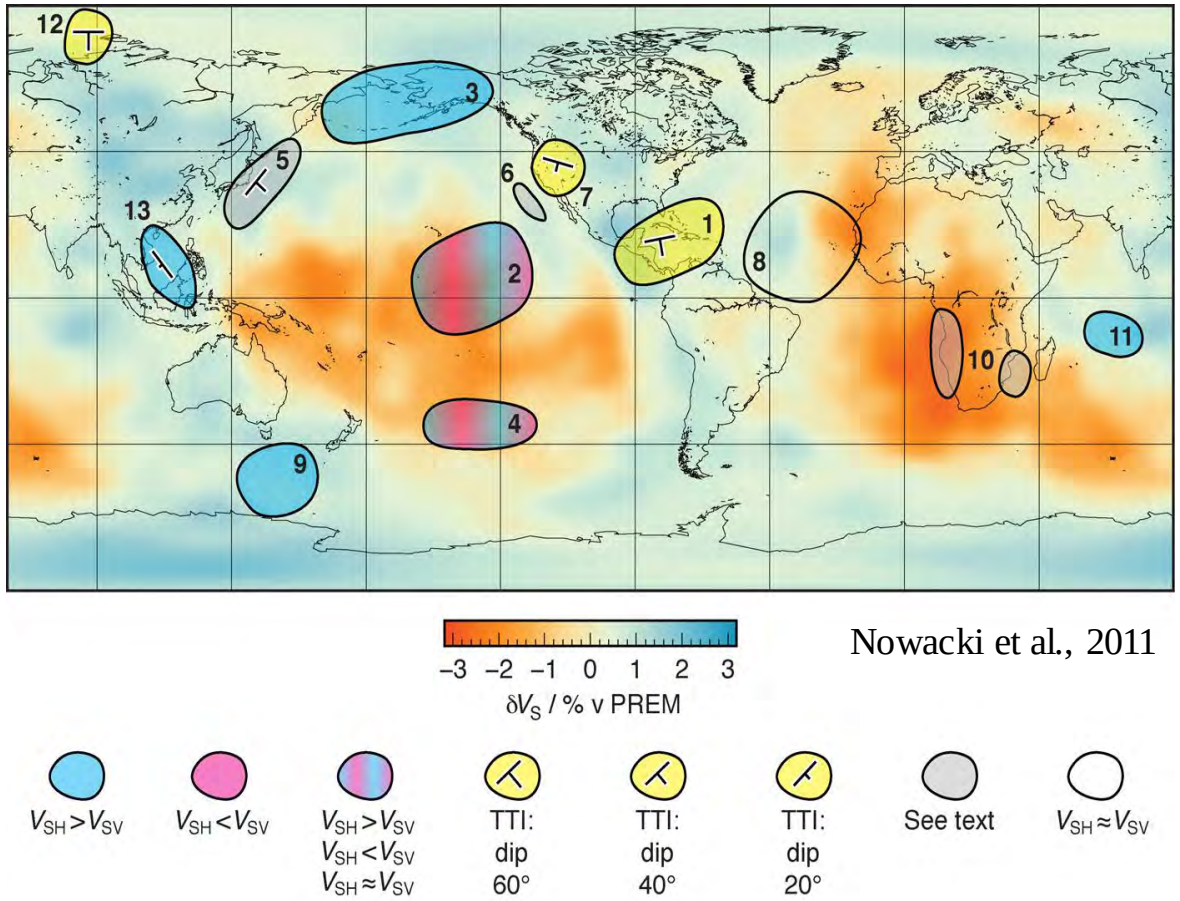
# Anisotropy in the deep Earth




Panning and Romanowicz, 2004

Anisotropy models of the deep mantle show large scale pattern

Anisotropy observations from local studies are variable (compilation from Nowacki et al., 2011)




Nowacki et al., 2011

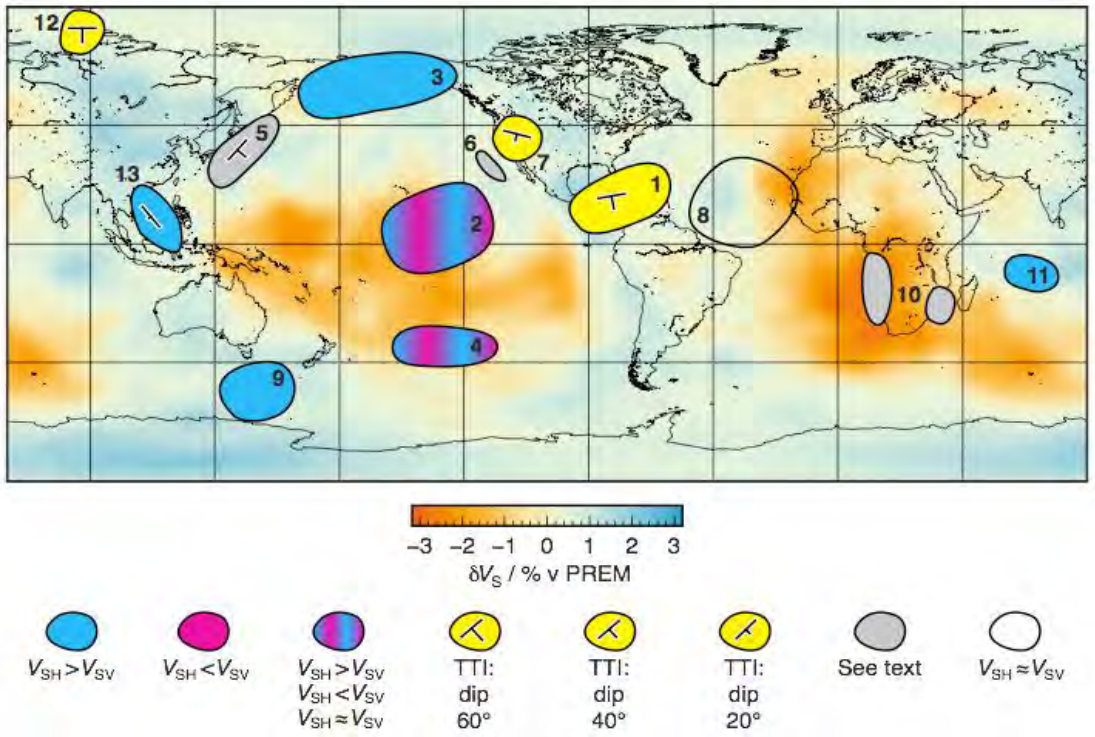
There is still ambiguity about the style of anisotropy -
at least three distinct paths would be necessary to constrain the style of anisotropy

# Mapping mantle flow through anisotropy in D"

Compilation of anisotropy - mostly through shear wave splitting

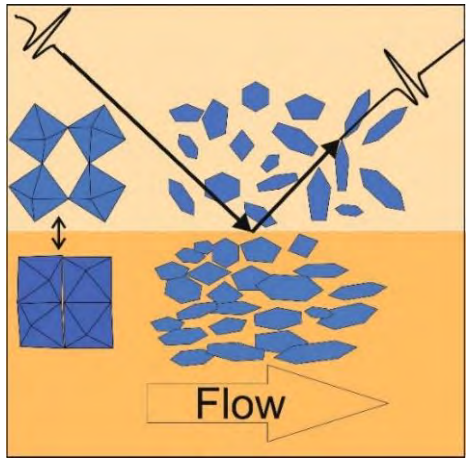
Constraining anisotropy - needs 3 crossing path

splitting observations

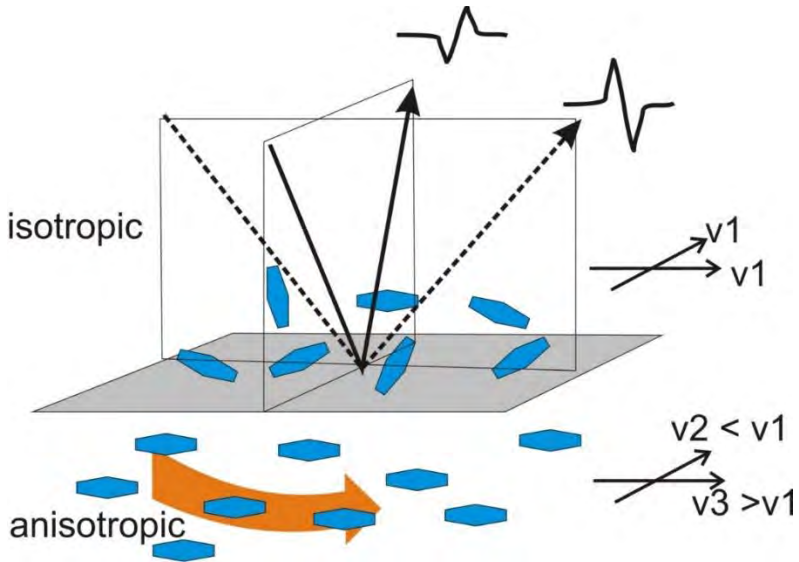



Nowacki et al. 2011

## New approach:



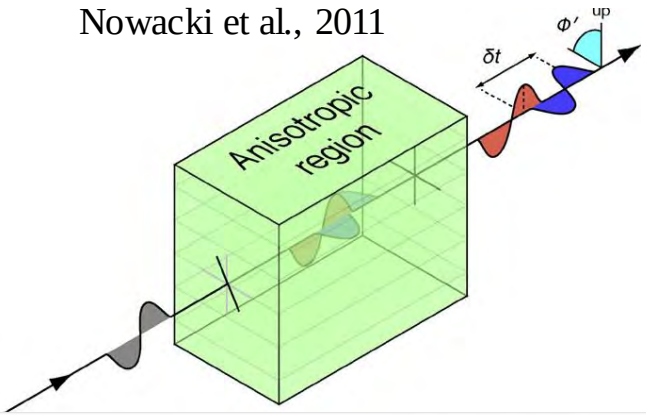

- Minerals (e.g. ppv) align due to mantle flow (Ammann et al., 2009)
- Velocities between layers will change due to alignment.
- Observable through polarities and amplitudes of reflected waves

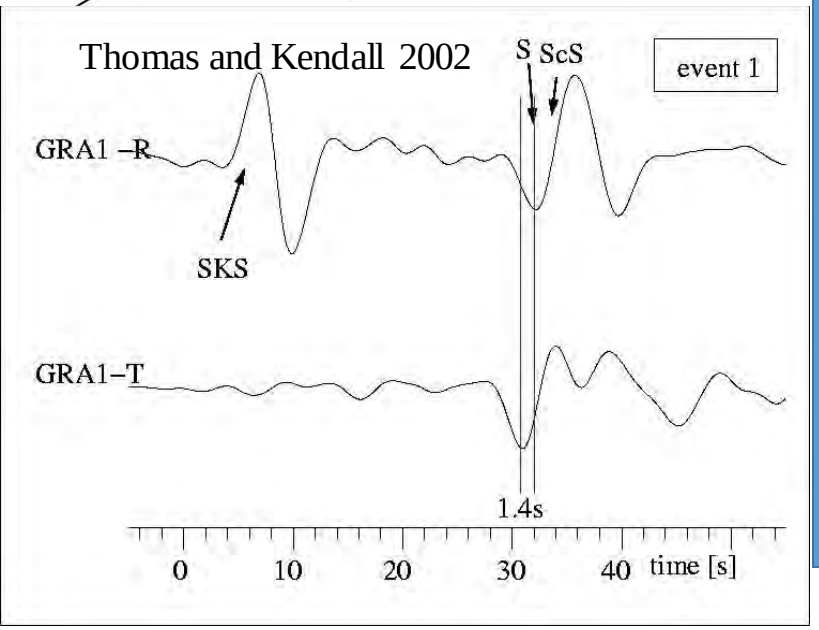


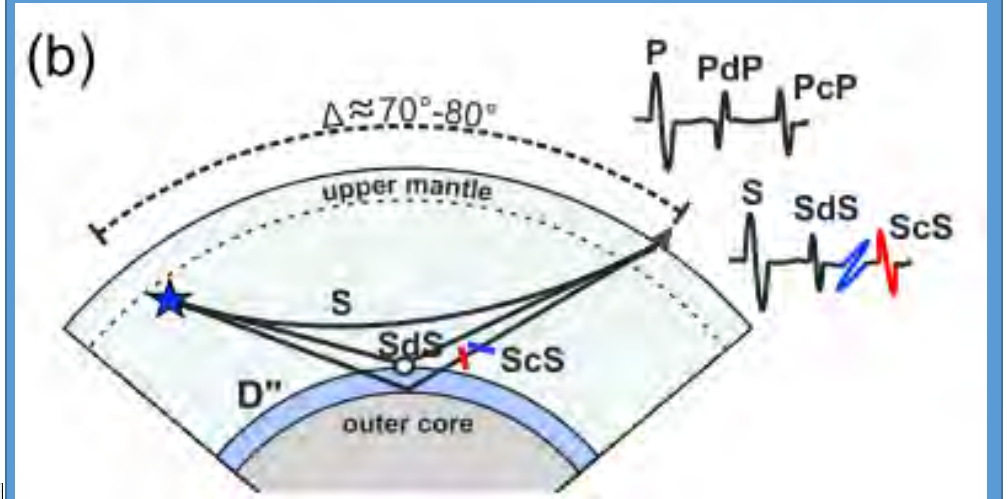
# Splitting and reflections

## Shear -wave splitting

Nowacki et al., 2011



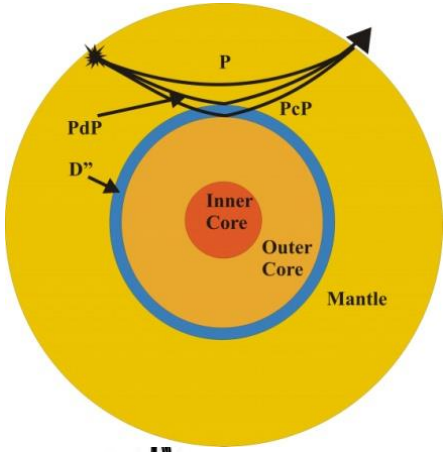



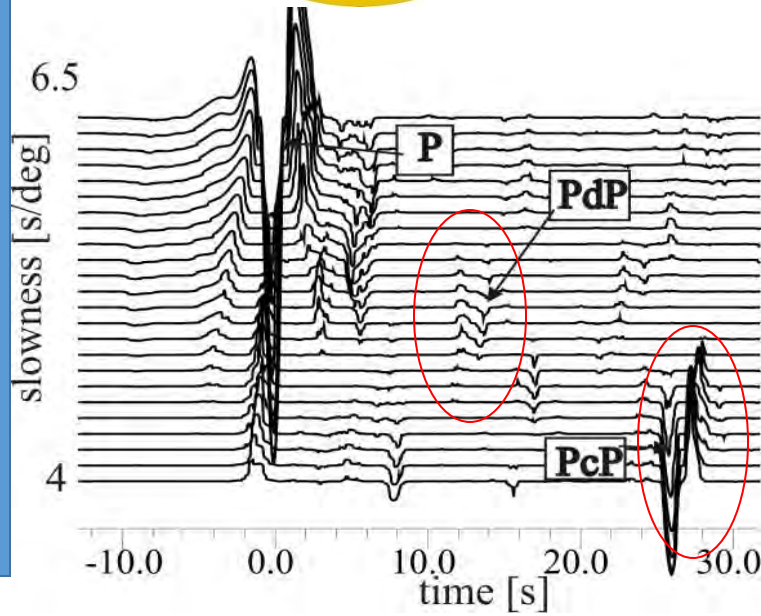

Pisconti et al., 2019

- Reflection polarities **and** splitting
- Only one azimuth
- Knowledge of deformation

allows to discriminate between mineralogical scenarios and determine mantle flow direction (Pisconti et al., 2019).

## Reflection polarities



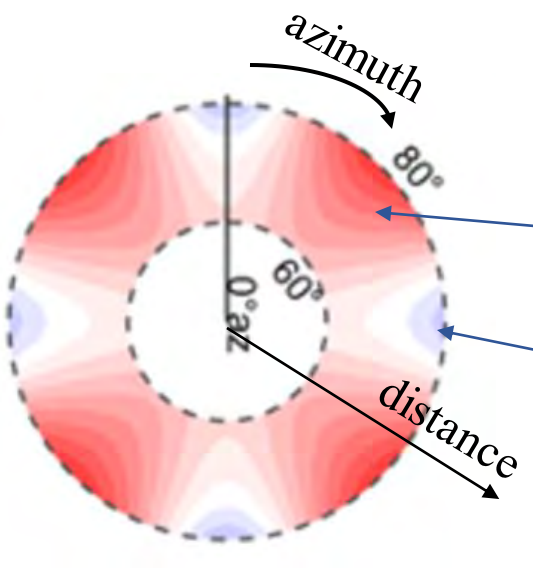

Cobden and Thomas. 2013

# Reflection amplitudes and polarities

We take all possible candidates for D" mineralogy and melt.

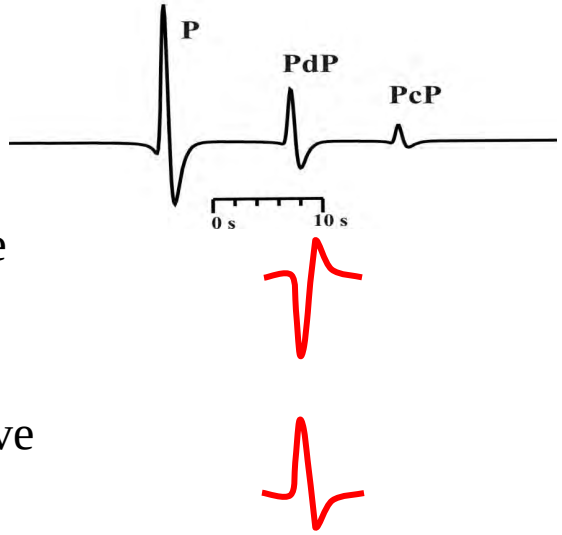
We calculate textures from single crystal elastic parameters and knowing the slip systems of the minerals, we calculate resulting anisotropy.

Using this anisotropy in D", we combine with isotropic materials above D" and calculate reflection coefficients for all directions and distances.




reflection coefficient negative
- opposite polarity

reflection coefficient positive
- same polarity

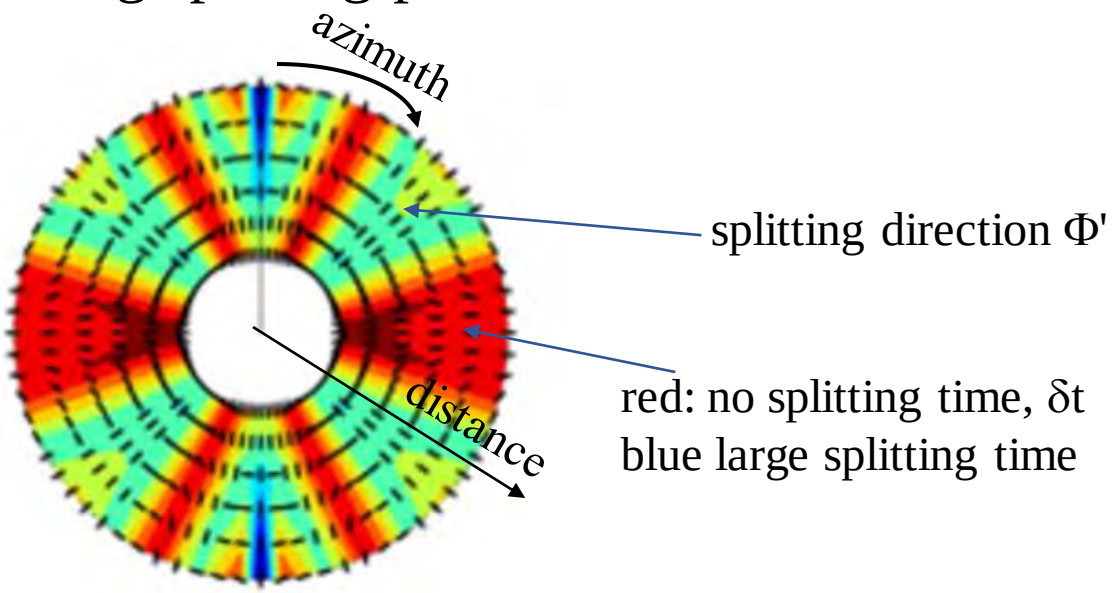


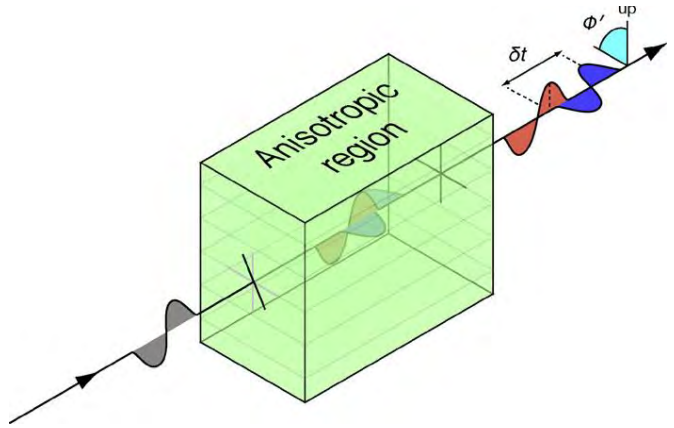
# Splitting measurements

We take all possible candidates for D" mineralogy and melt.

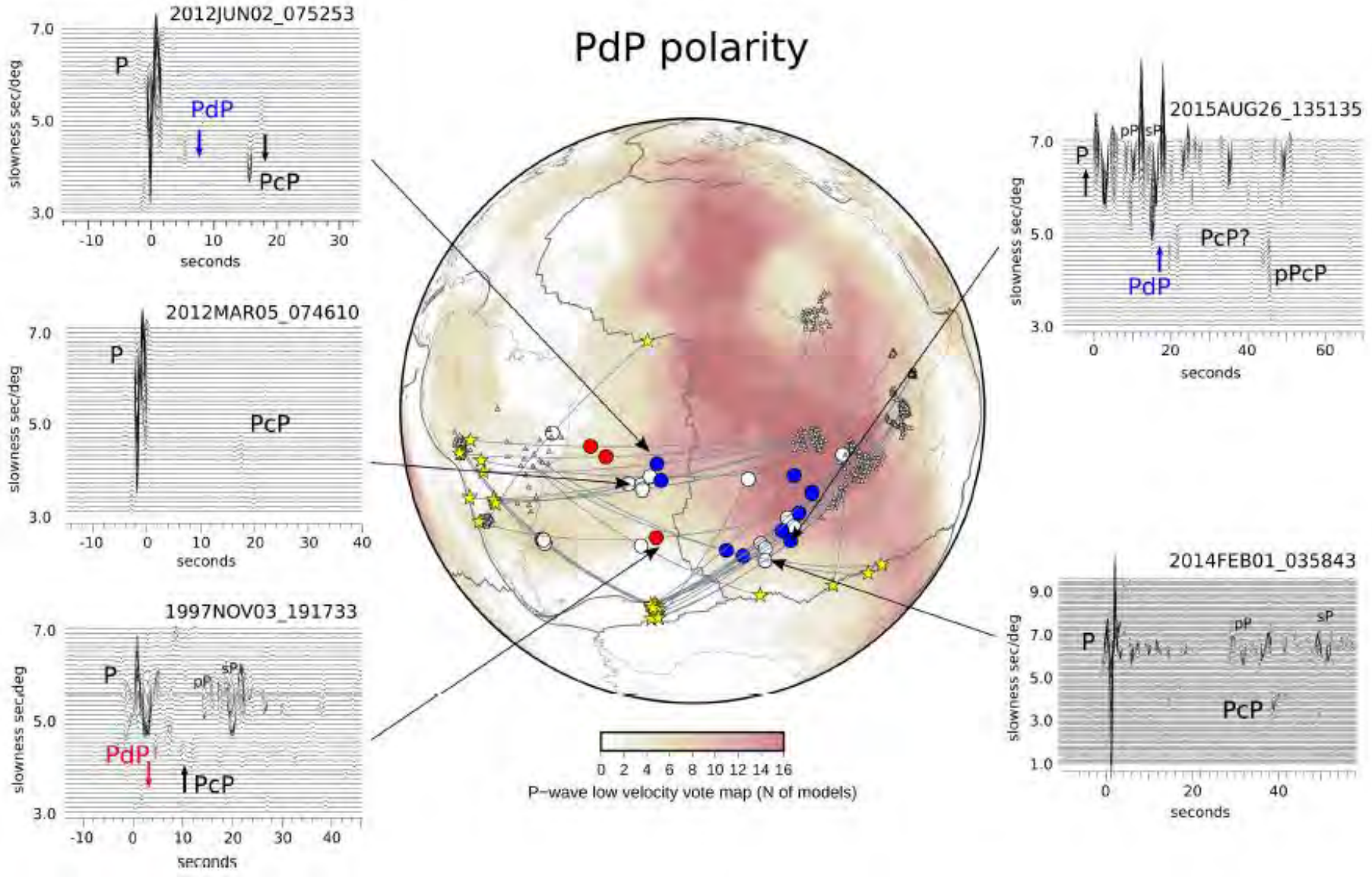
We calculate textures from single crystal elastic parameters and knowing the slip systems of the minerals, we calculate resulting anisotropy.

Using this anisotropy in D", we combine with isotropic materials above D" and calculate reflection coefficients for all directions and distances.
We also calculate resulting splitting predictions



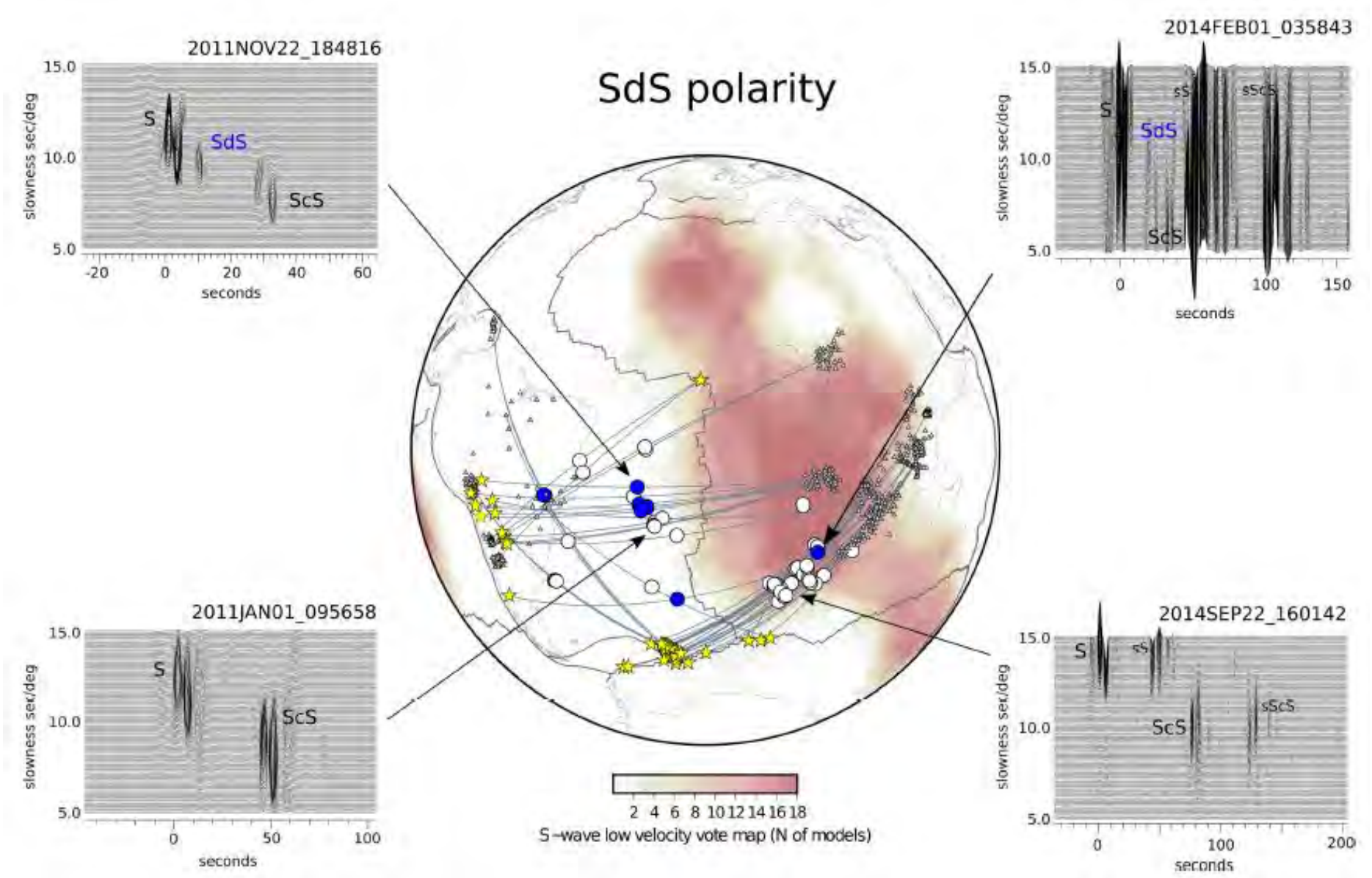
# Case study -Atlantic




Pisconti et al., 2021

Using Reflection polarities and splitting measurements for the South Atlantic (Pisconti et al., 2019 and 2021)

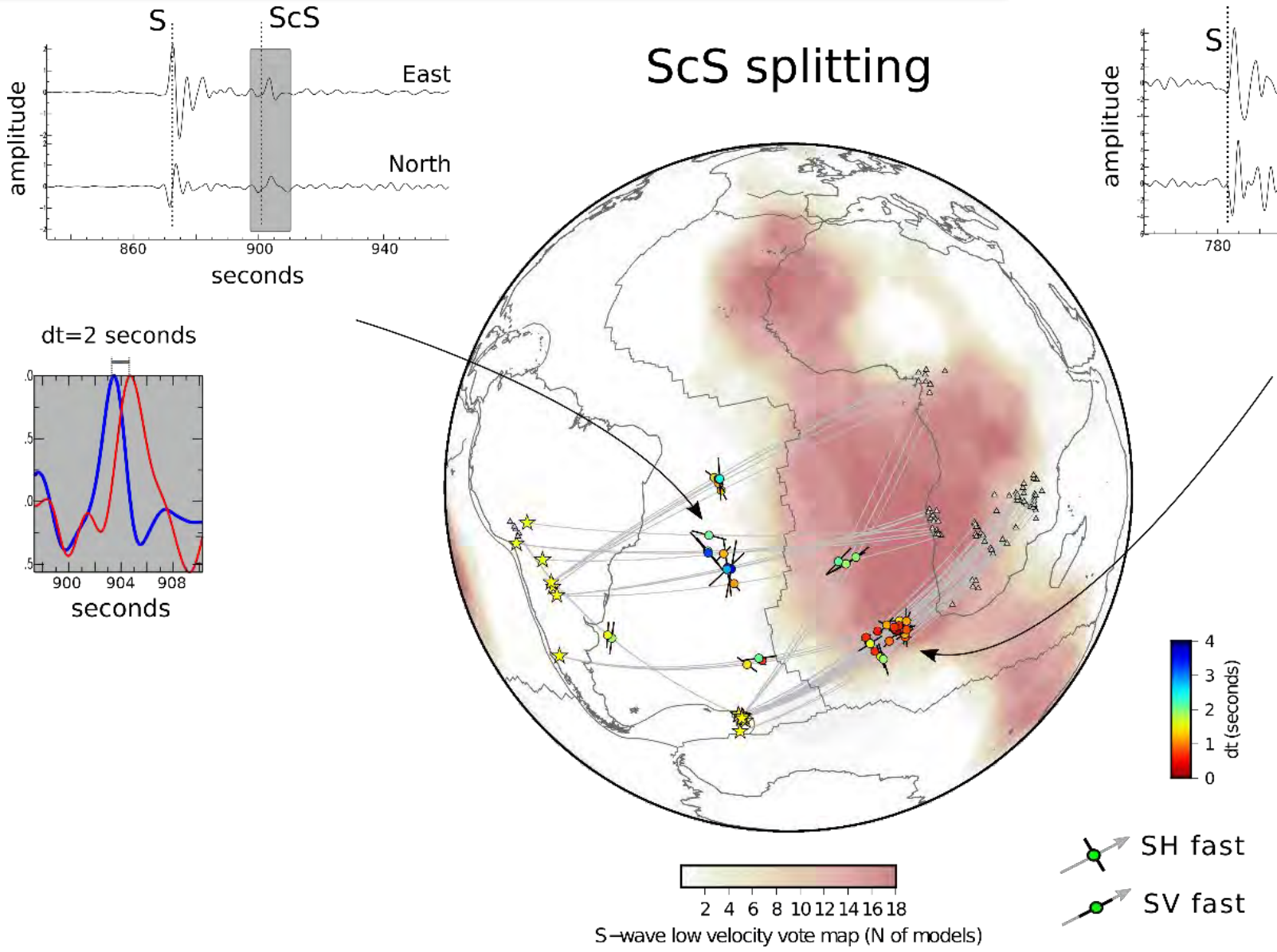
# Case study -Atlantic




Pisconti et al., 2021

Using Reflection polarities and splitting measurements for the South Atlantic (Pisconti et al., 2019 and 2021)

# Case study -Atlantic

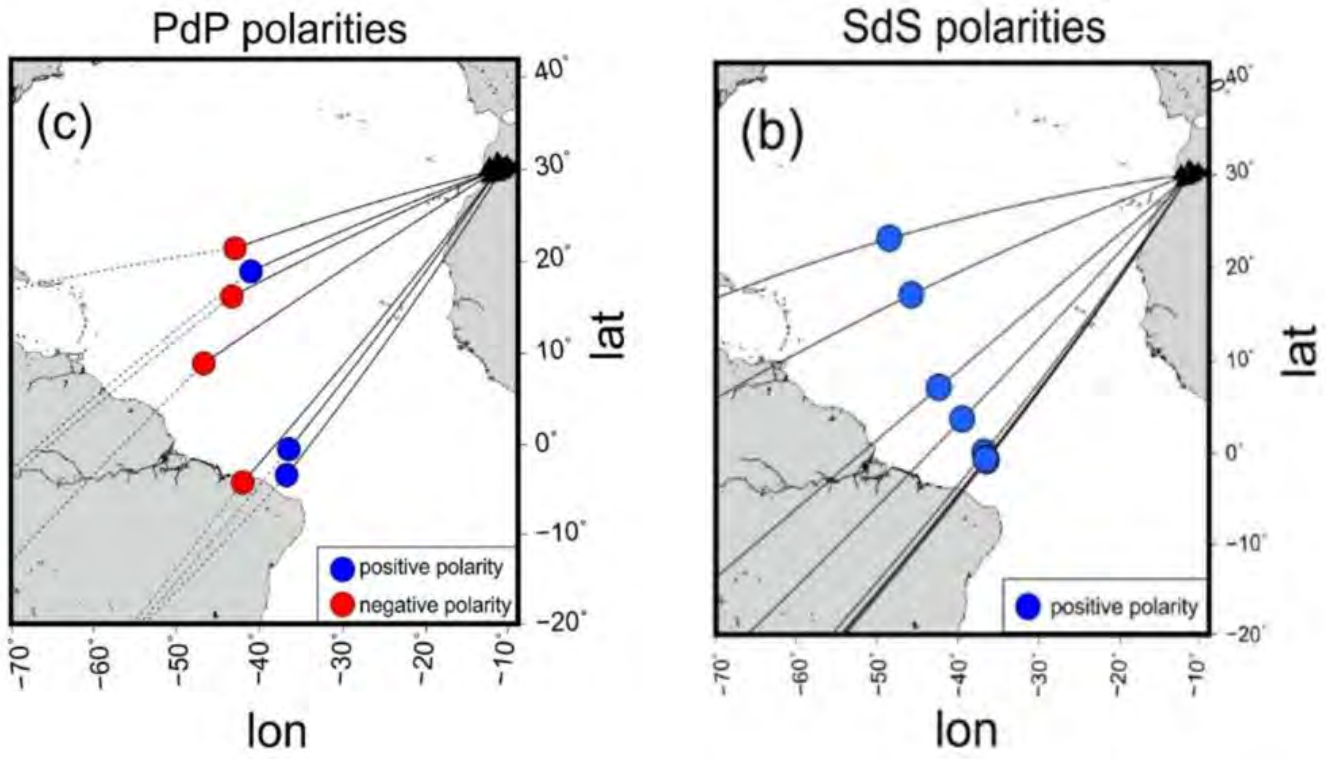


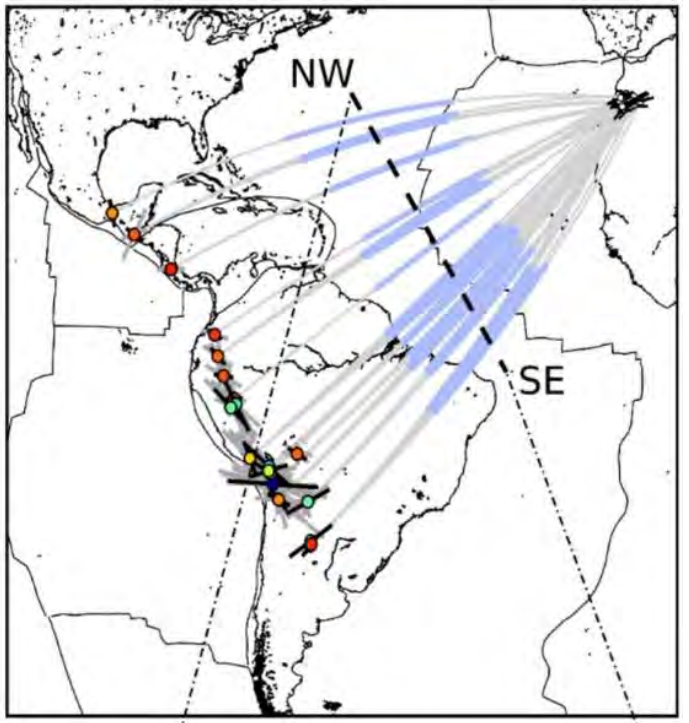

Pisconti et al., 2021

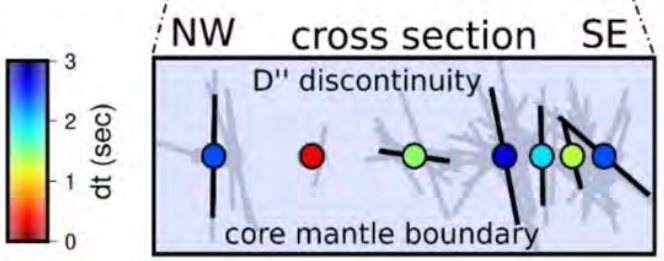
Using Reflection polarities and splitting measurements for the South Atlantic (Pisconti et al., 2019 and 2021)

# Case study - adding the Central Atlantic

Pisconti et al., 2019




...and combining with reflection polarities and splitting measurements for the Central Atlantic

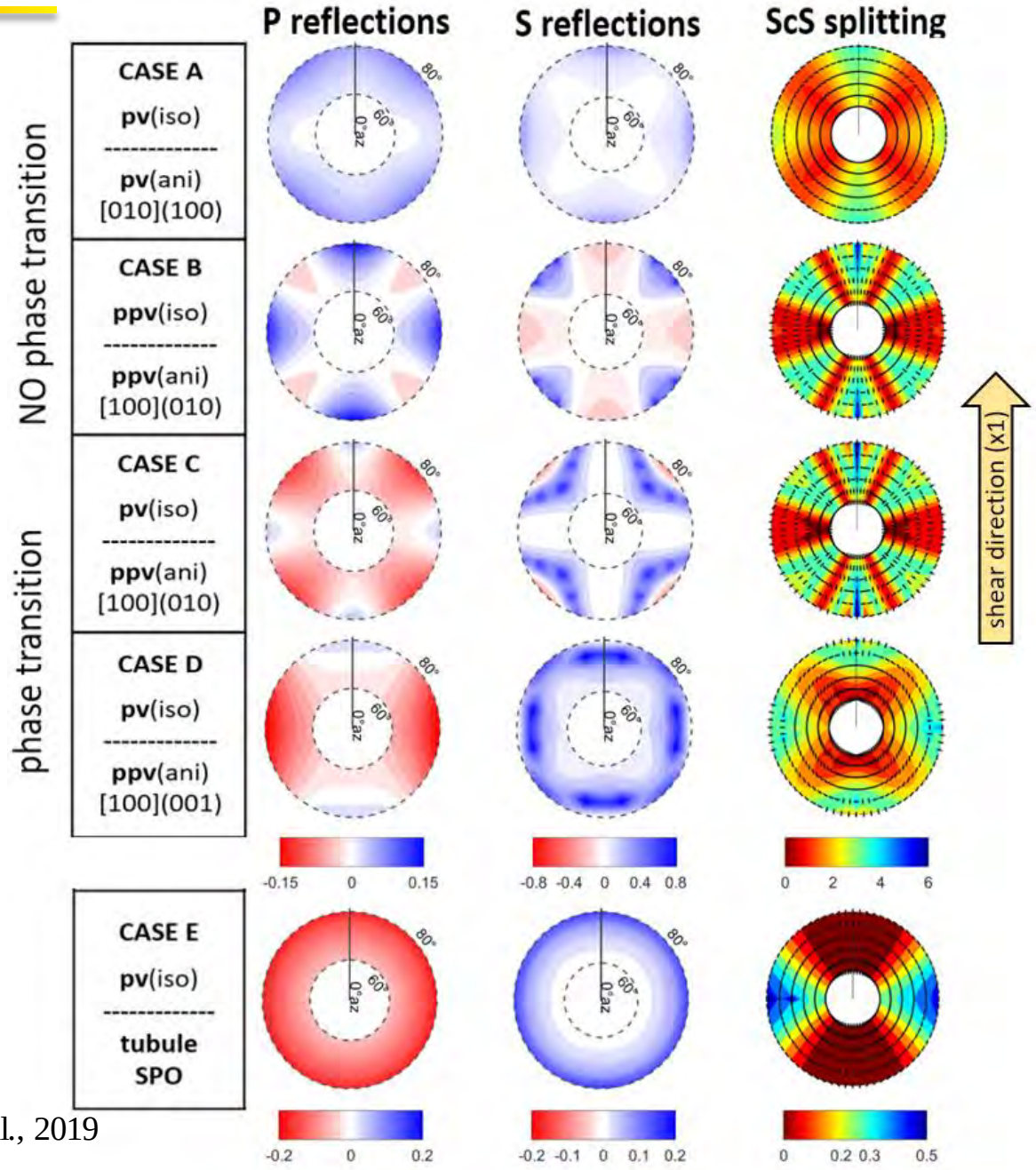
# Modelling of reflections and splitting

Testing of several cases: including change in mineralogy, with and without anisotropy

different slip systems

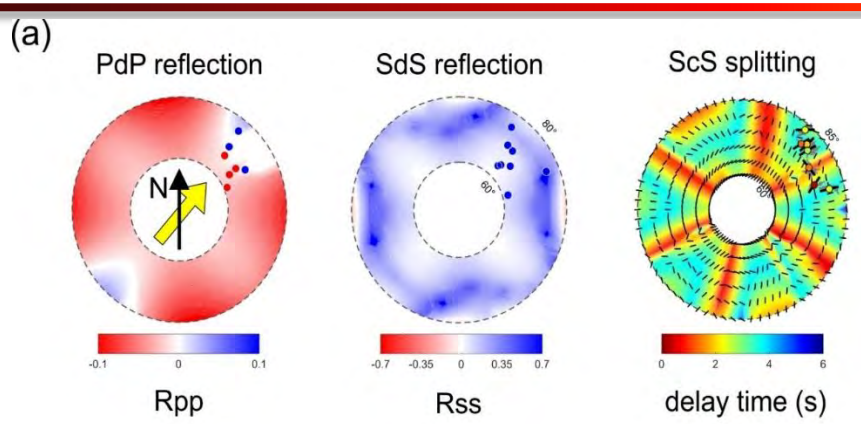
including SPO, e.g., melt

and all possible rotations of anisotropy are considered.

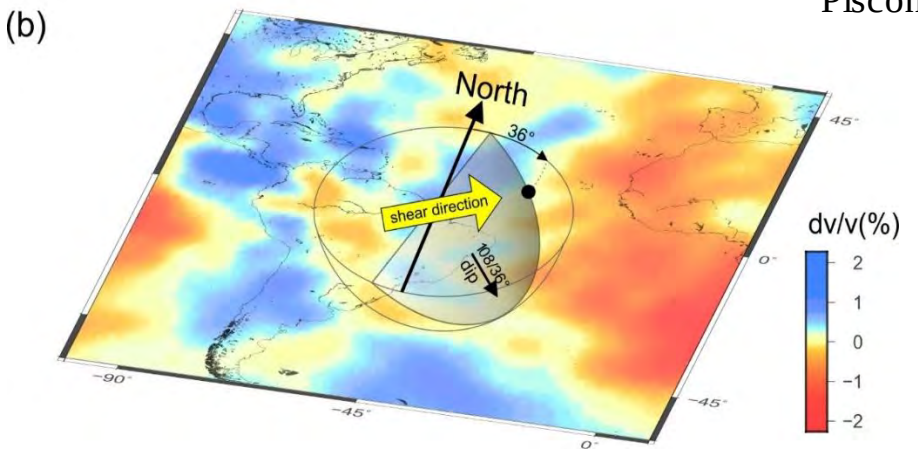



Pisconti et al., 2019

# Modelling of reflections and splitting

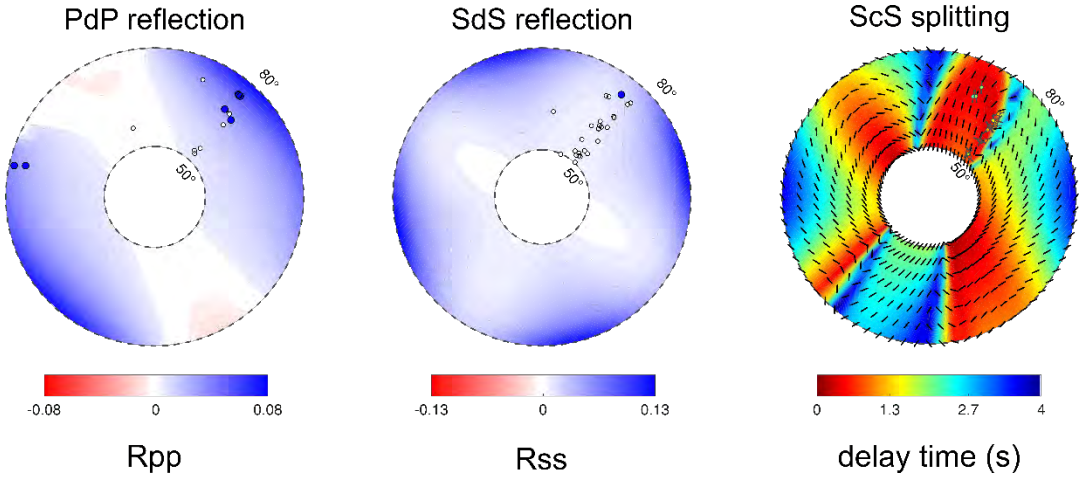



Pisconti et al., 2019




Beneath Central Atlantic:

- best fitting model has an inclined shear plane along a shear direction of 36 degrees from North.
- model includes a phase transition from bridgmanite to post-perovskite and alignment accommodated by the [100](010) slip system

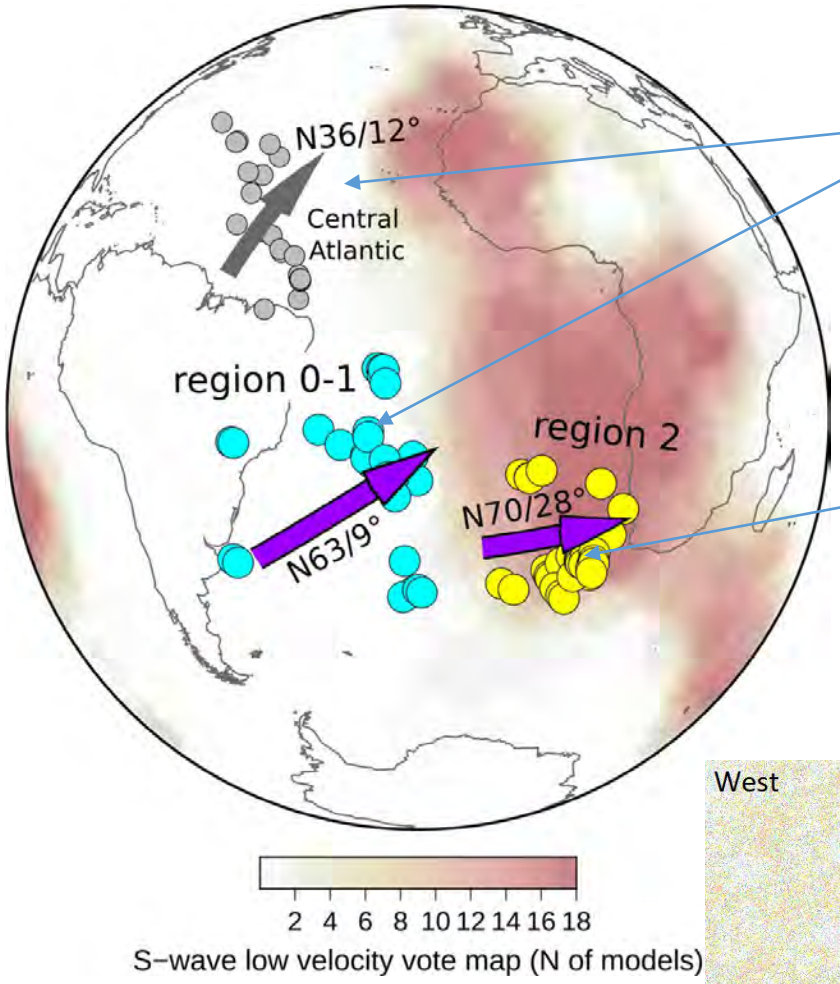



Pisconti et al., 2021

Beneath Africa (inside the LLSVP):
best fitting model has an deformation direction 75 deg from N, tilted shear plane dipping 30deg

the model includes only bridgmanite, with [010](100) slip system beneath the reflector.

# Results

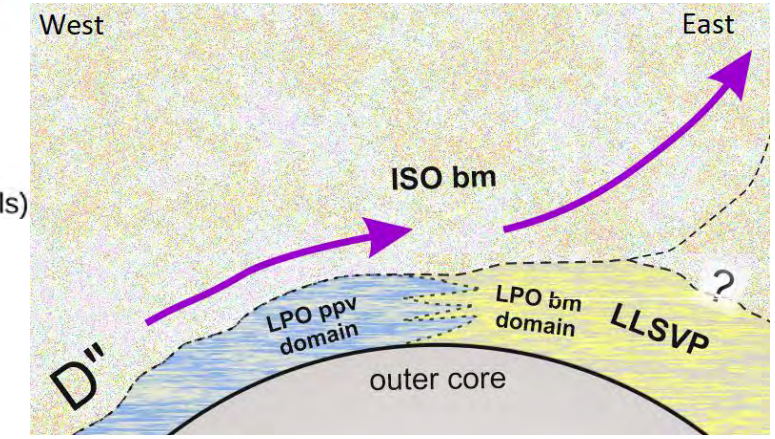


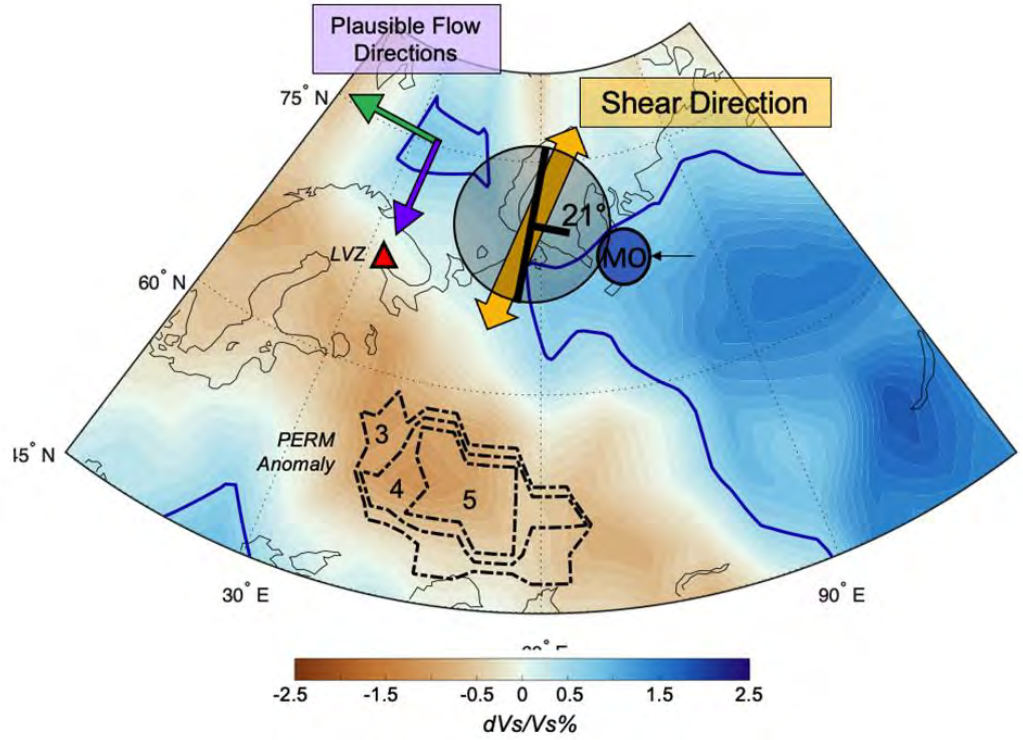

ppv
[100](010)

bridgmanite
[010](100)

Pisconti et al., 2021

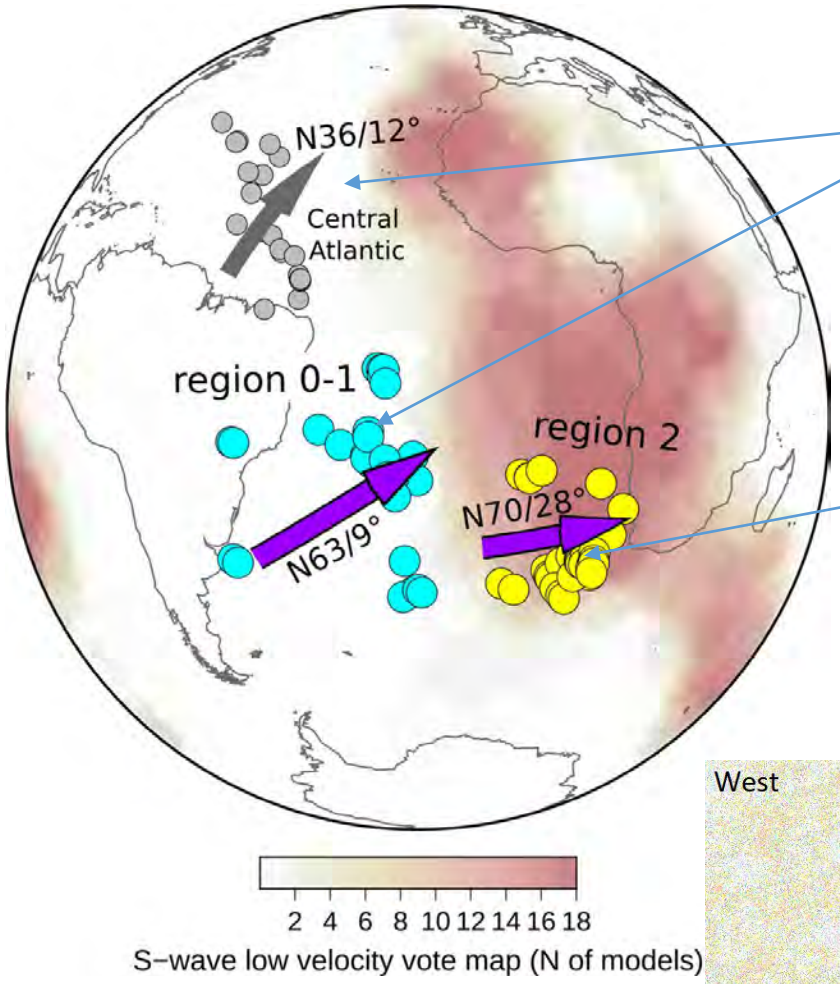
Extending this combination of splitting and reflections to the south Atlantic and part of the LLSVP and Siberia




Creasy et al., 2021

# Results

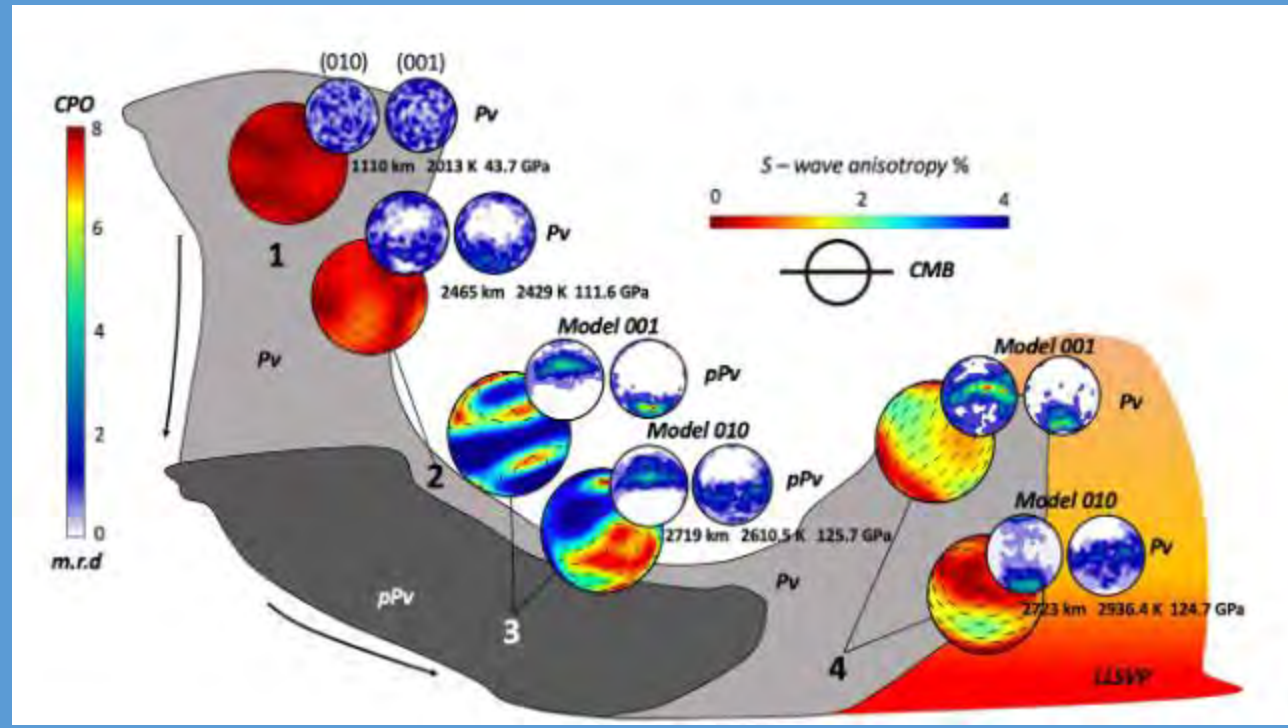



ppv
[100](010)

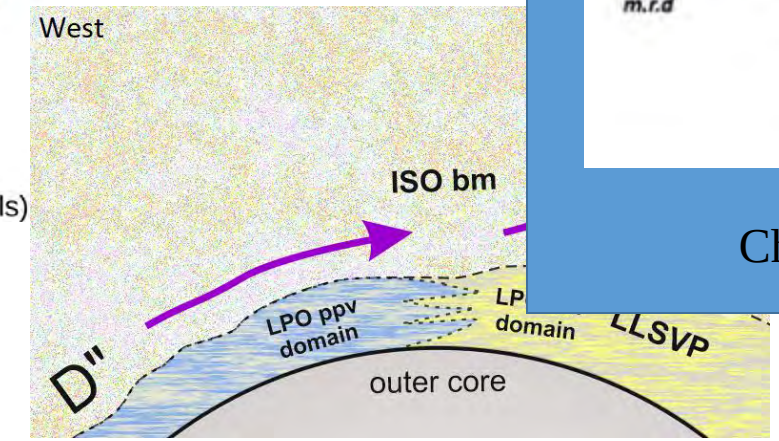
bridgmanite
[010](100)

Pisconti et al., 2021

Extending this combination of splitting and reflections to the south Atlantic and part of the LLSVP and Siberia

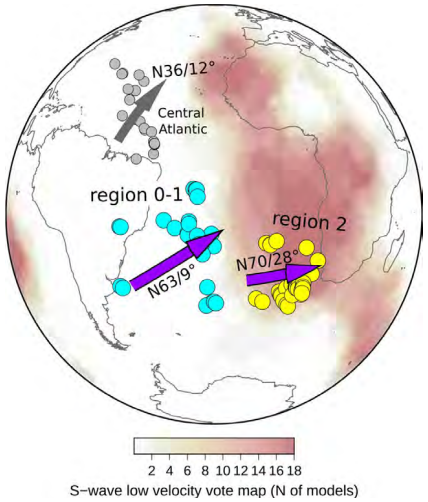



Chandler et al., 2021




Creasy et al., 2021

# Implications



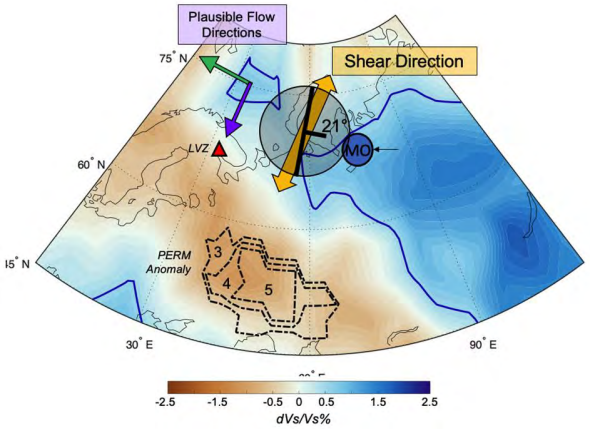

Pisconti et al., 2021

Anisotropy in D'' allows to image flow in the lowermost mantle

Using splitting and reflections (as well as different waves) reduces ambiguity.

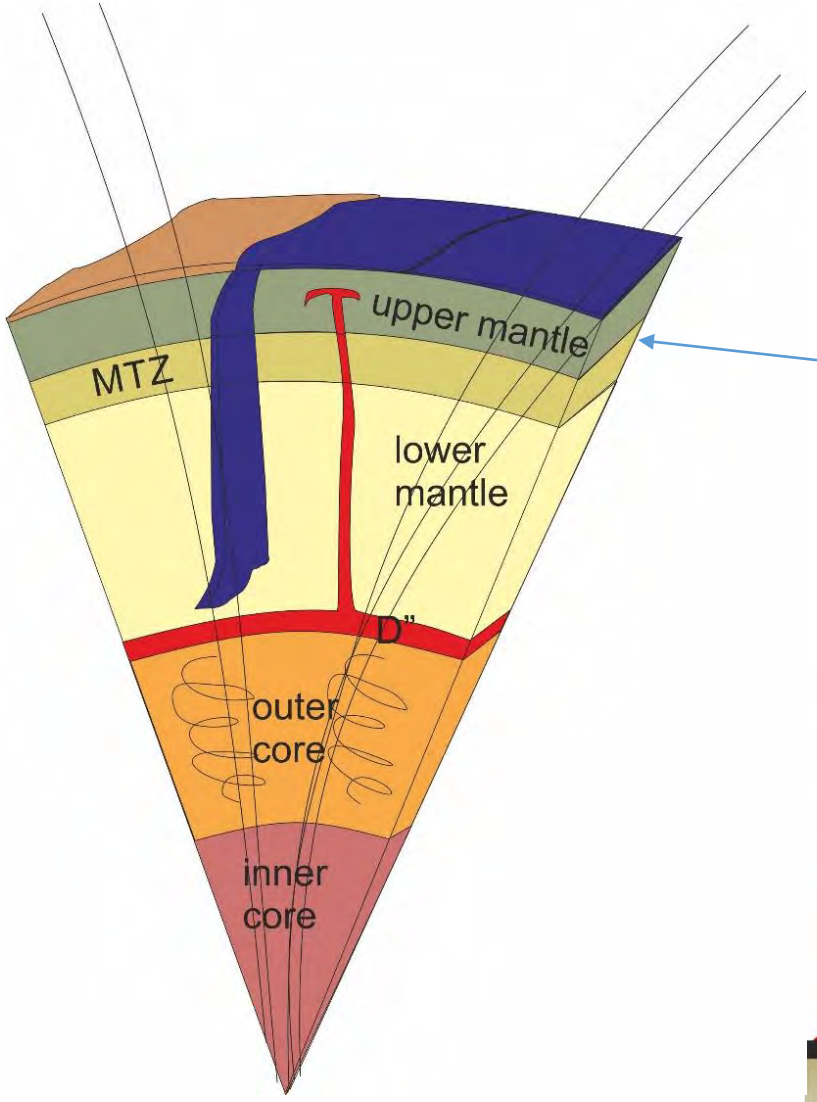
This approach also allows to constrain mineralogy and slip systems.

Crossing raypaths are not needed to constrain anisotropy if splitting and reflections are combined (but can still help to confirm results)




Creasy et al., 2021

# This talk

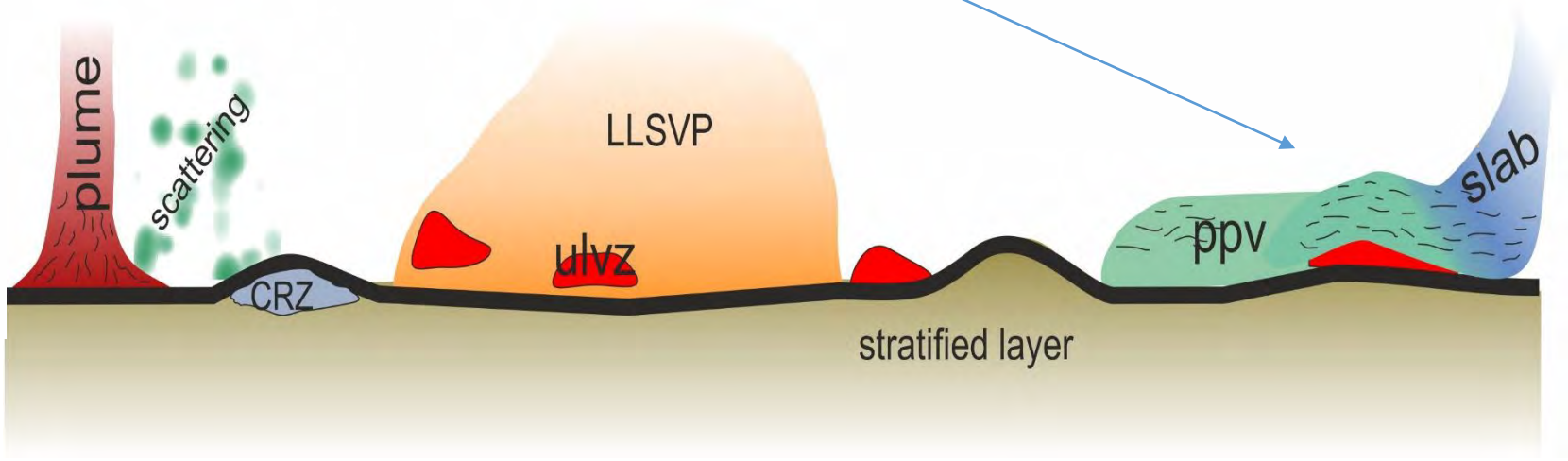



Anisotropy is best detected in boundary layers (J-P. Montagner)

In this talk we will look for anisotropy in:

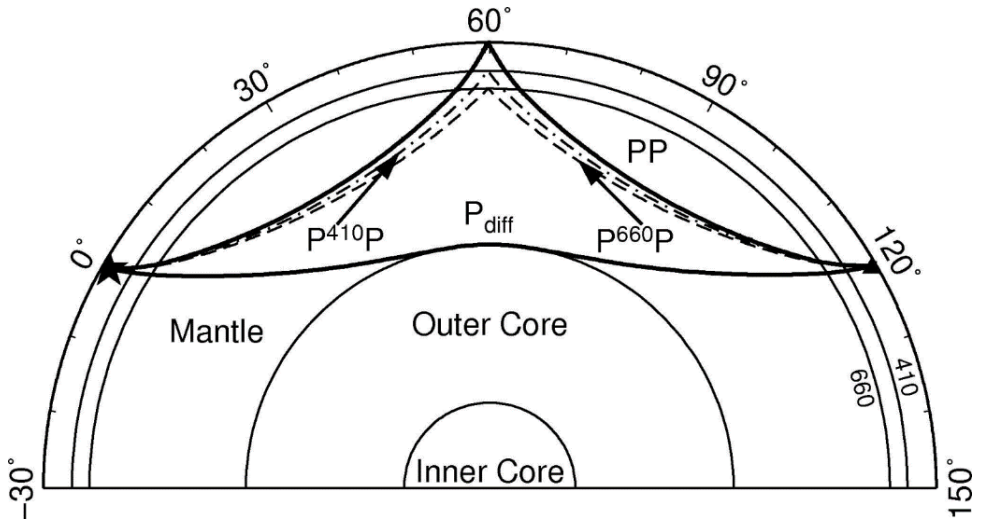
Mantle transition zone (MTZ)

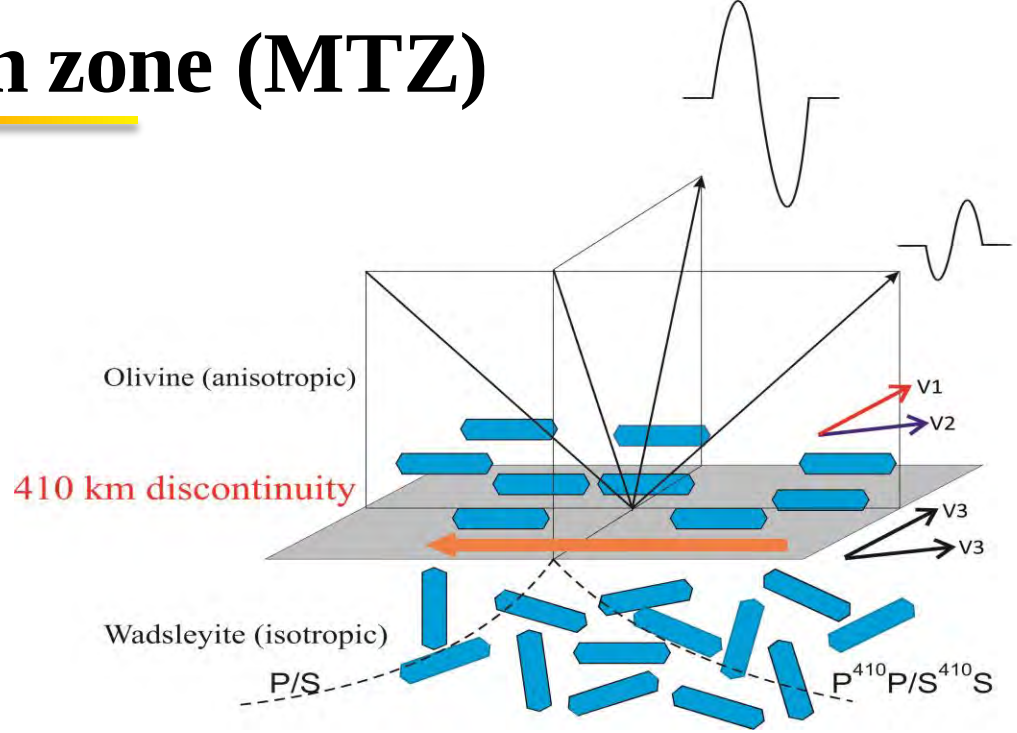
D'', lowermost mantle



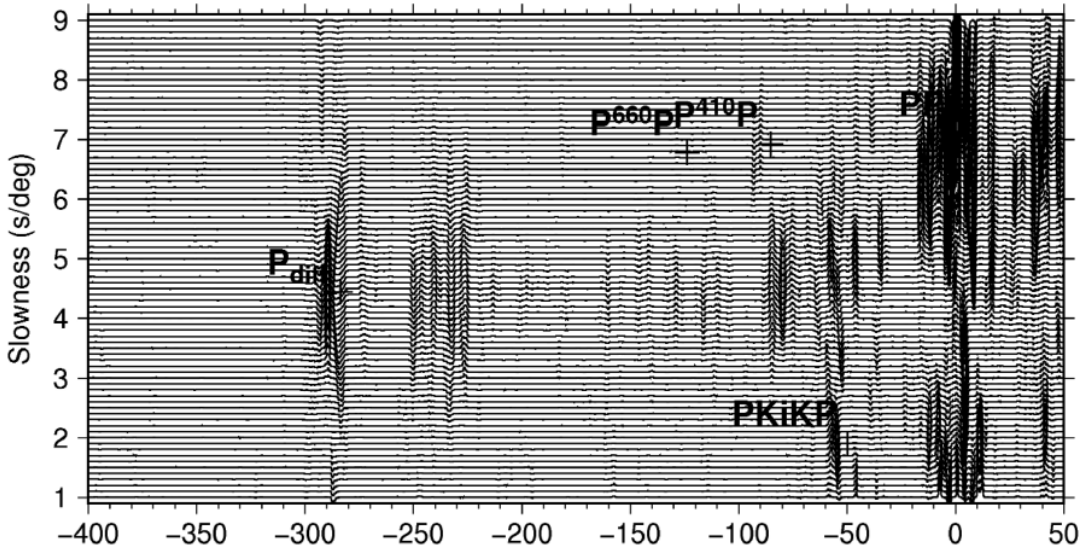
# Anisotropy in the mantle transition zone (MTZ)

Same approach as for D'', but using
PP and SS underside reflections (without splitting)



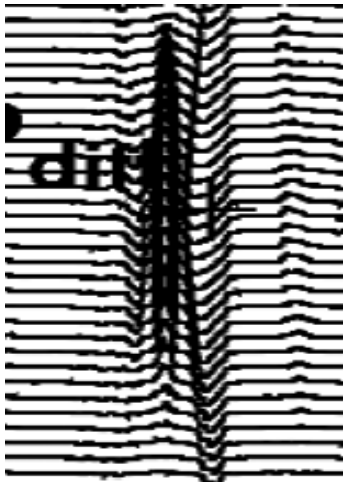




**A theoretical study:**
is it possible to see polarity changes of PP and SS precursors for different deformation systems?



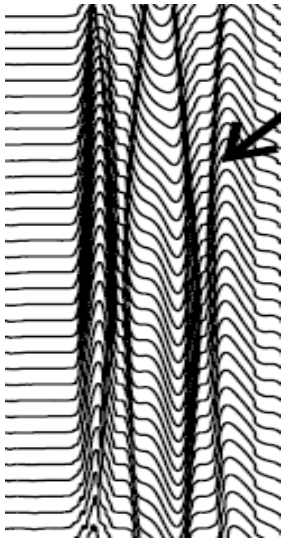
# PP precursors - polarity observations

Pdiff

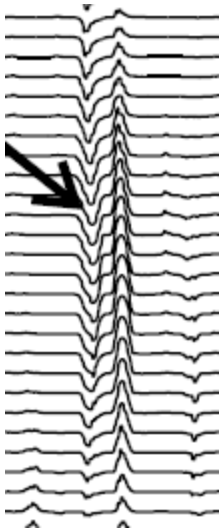


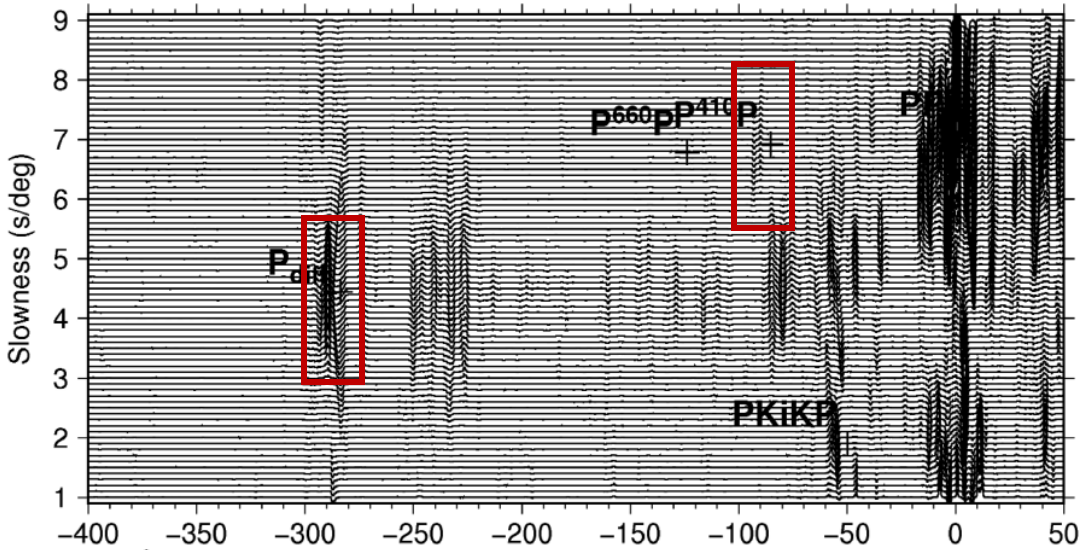
precursor

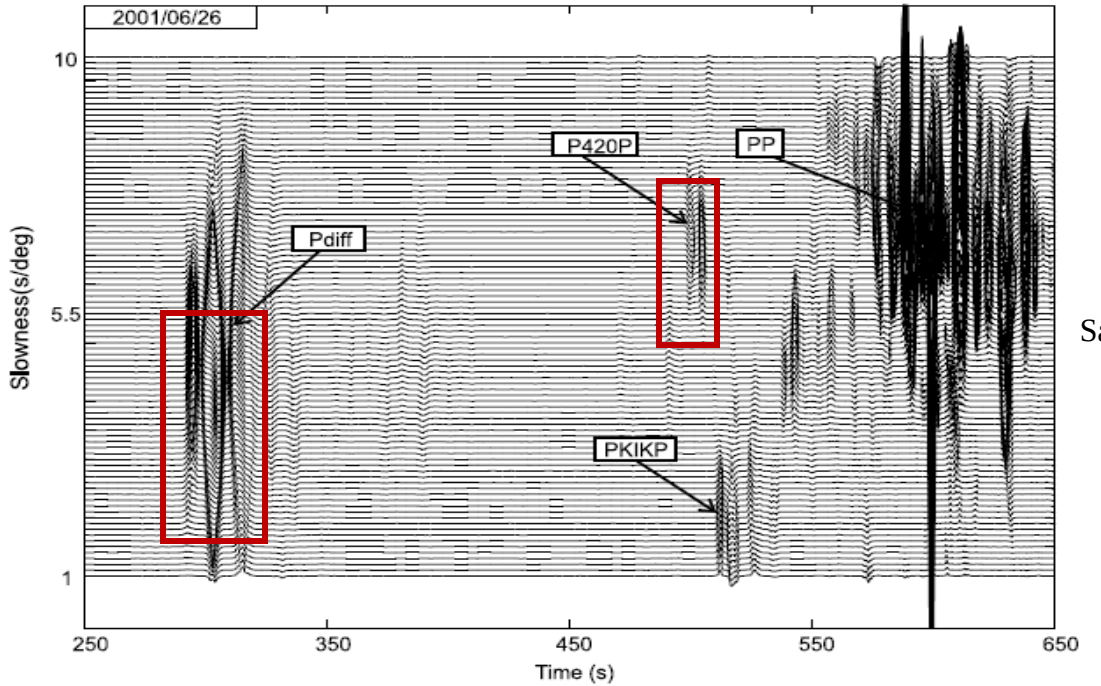
Pdiff

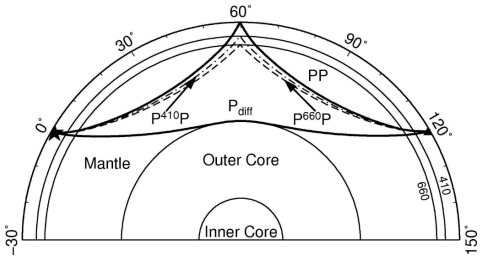


precursor





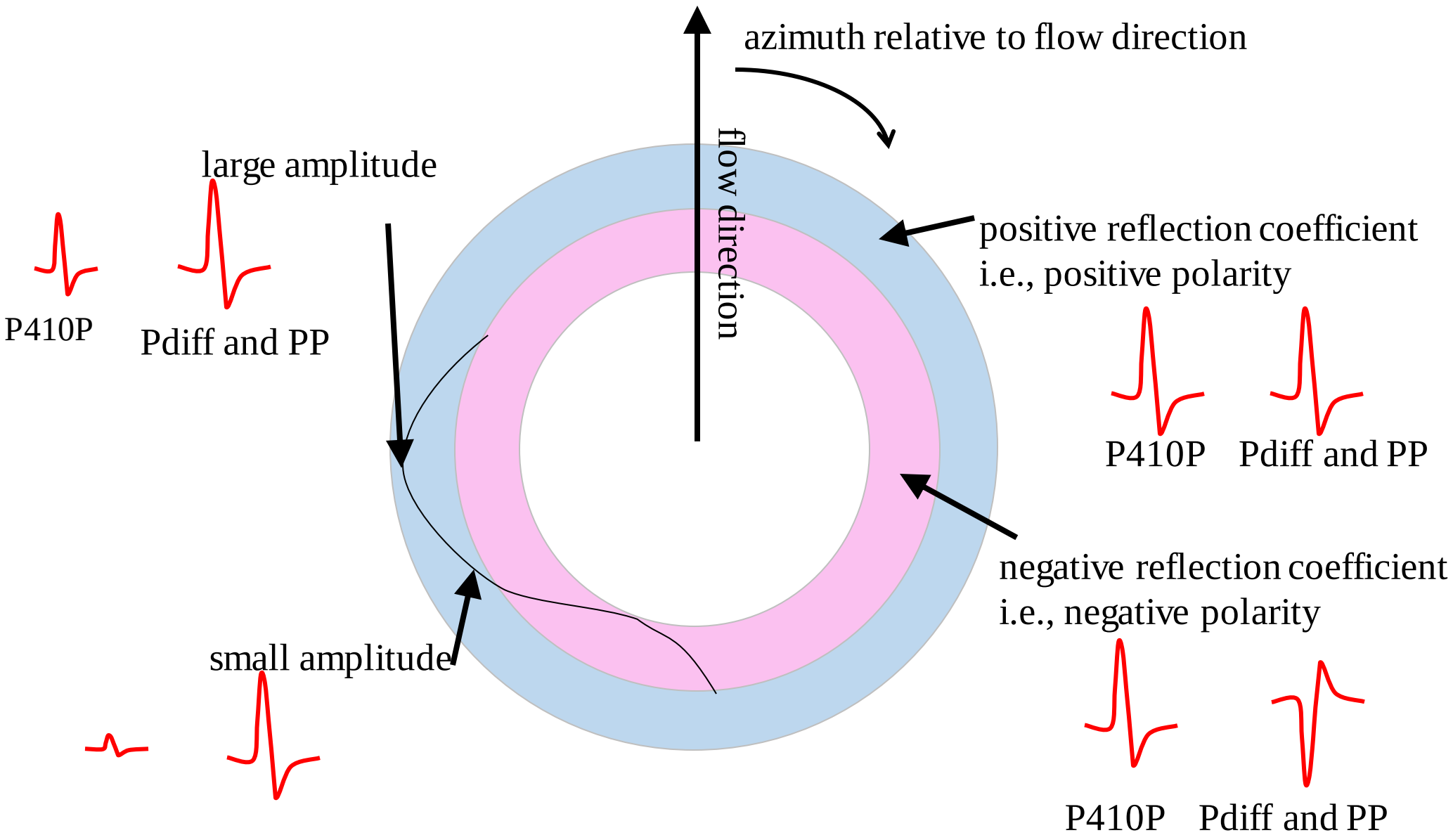

Lessing et al., (2014)

opposite polarity PP precursors can be seen in a number of seismograms

(here beneath Tibet (top) and the Atlantic (bottom)

Saki et al., (2019)

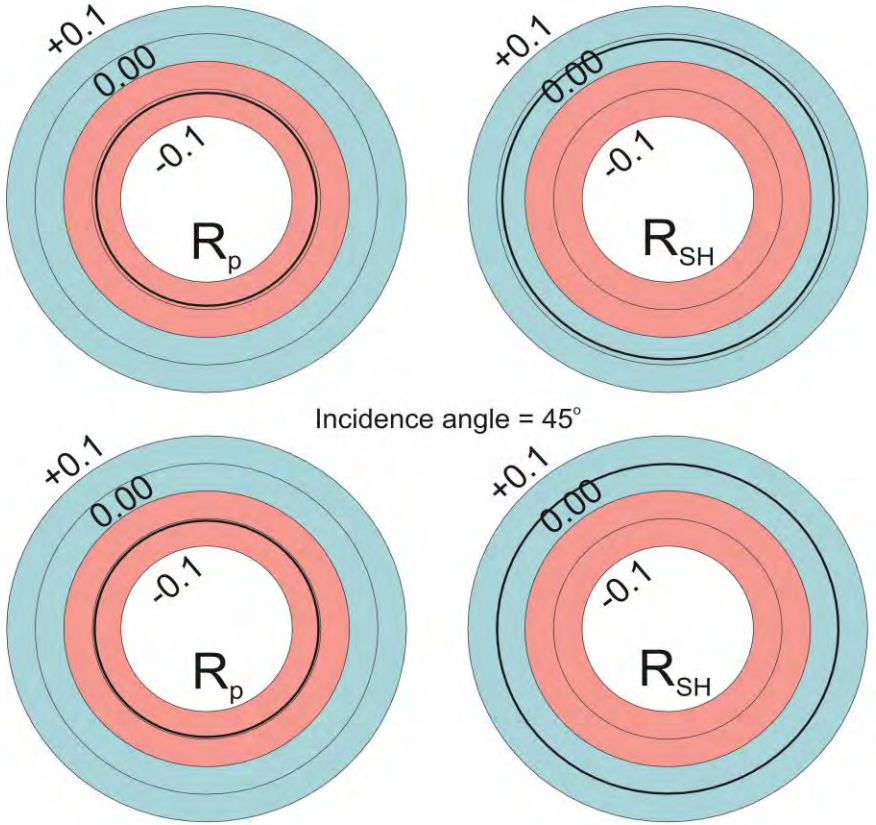
# Explanation of graph - for one distance:

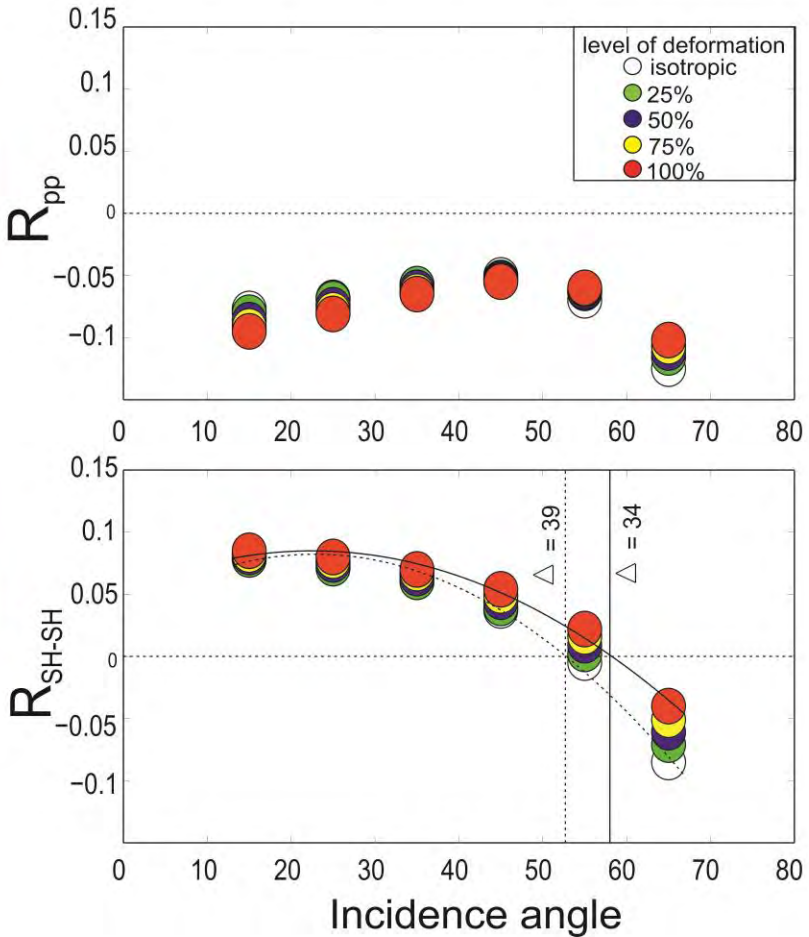


# Reflection coefficient axial deformation

## Assumption: only olivine deforms - axial deformation

Reflection coefficient for PP-waves for one distance and varying azimuth



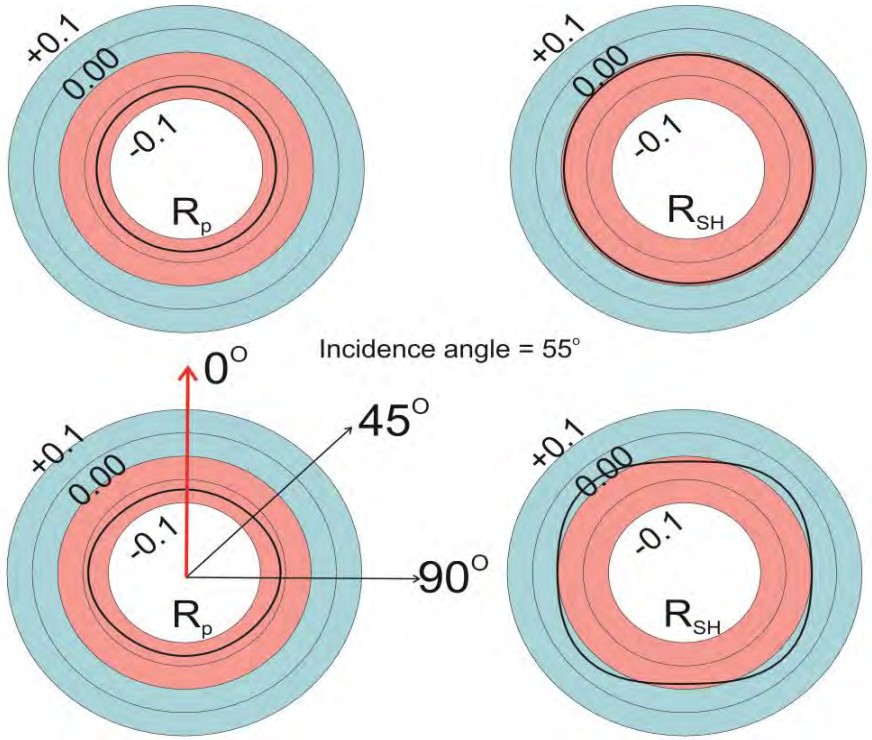



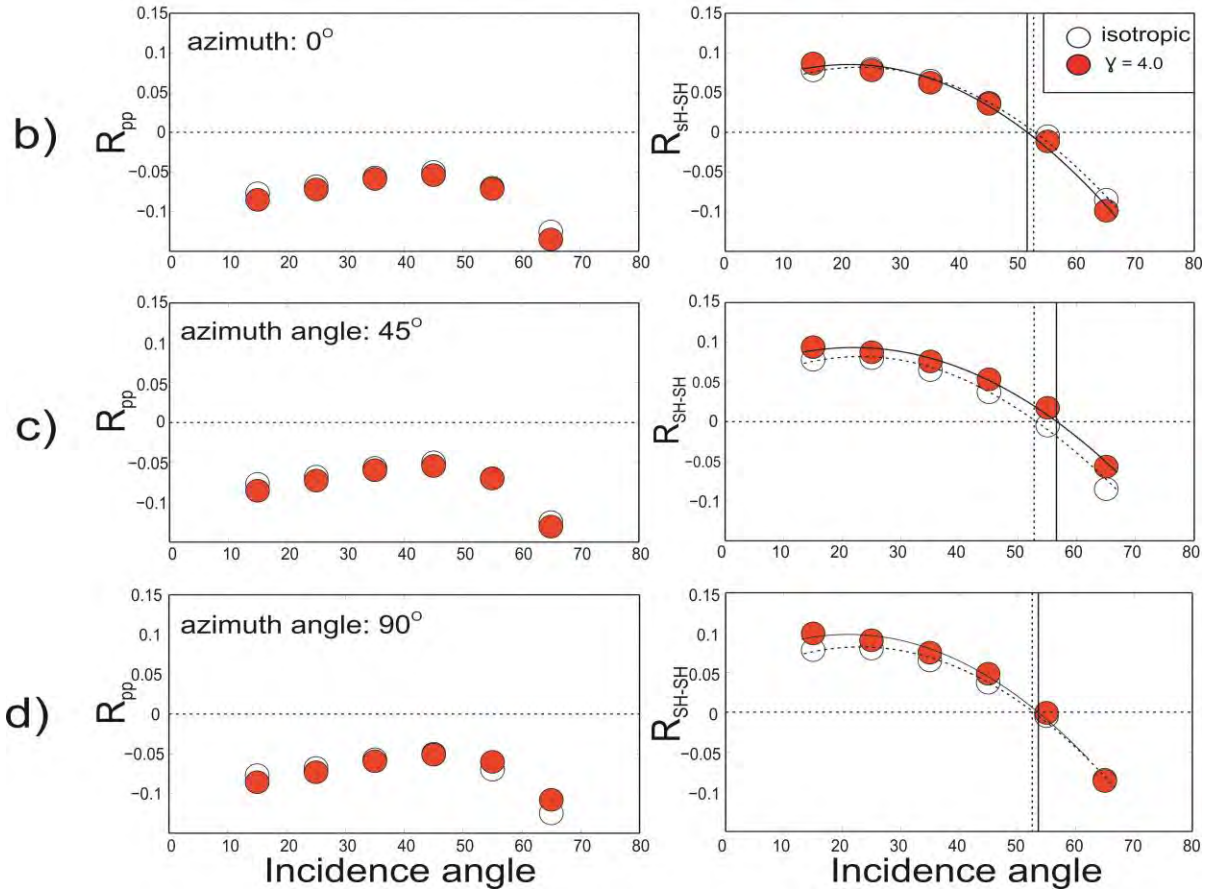

axial deformation does not generate any changes in polarity with direction of travel

Saki et al., 2018

# Shear deformation

**shear** deformation introduces variation of reflection coefficient with azimuth



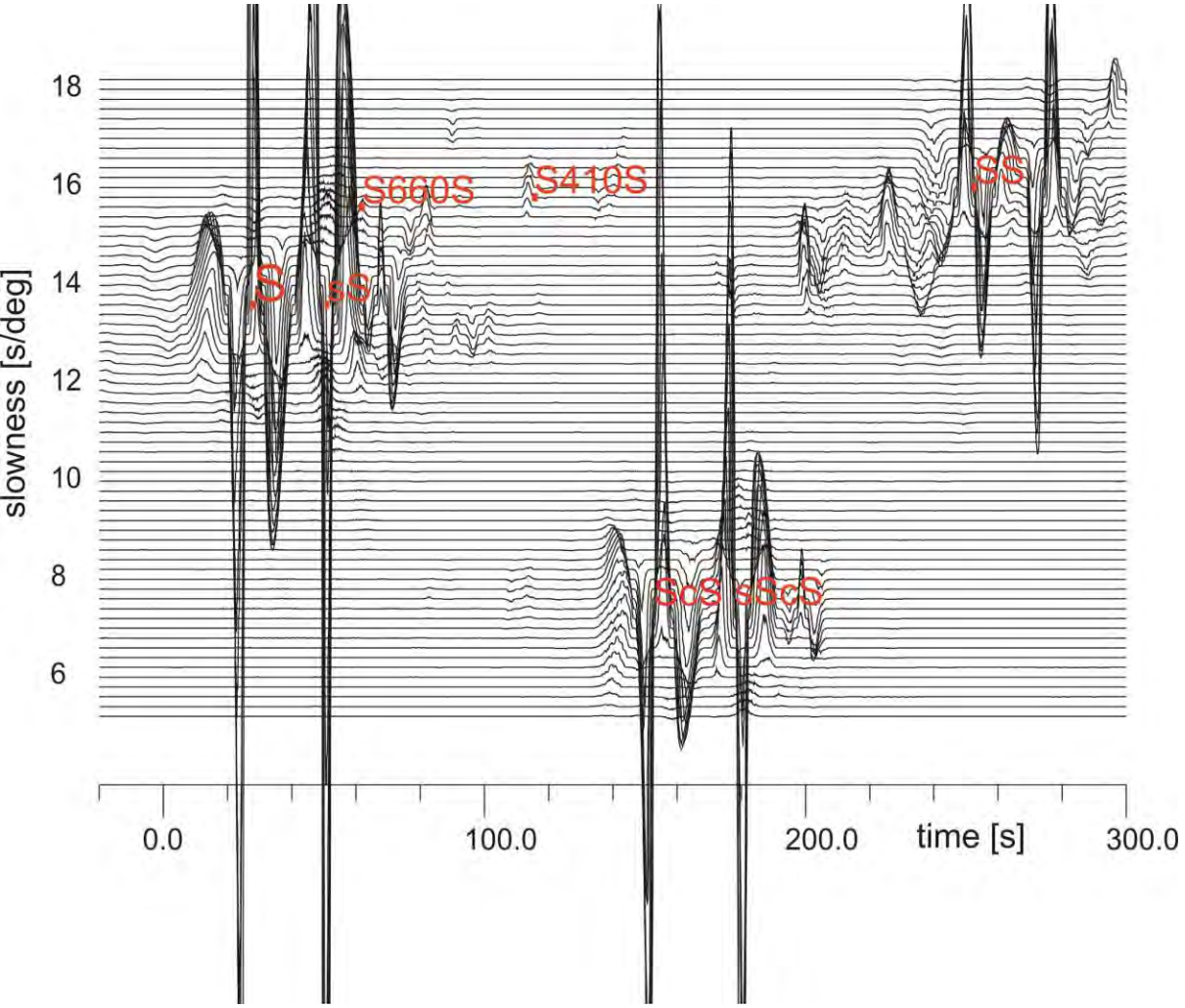




**A problem:**

The polarity change is only visible at short epicentral distances

And only for S-waves

# Short distance PP precursors

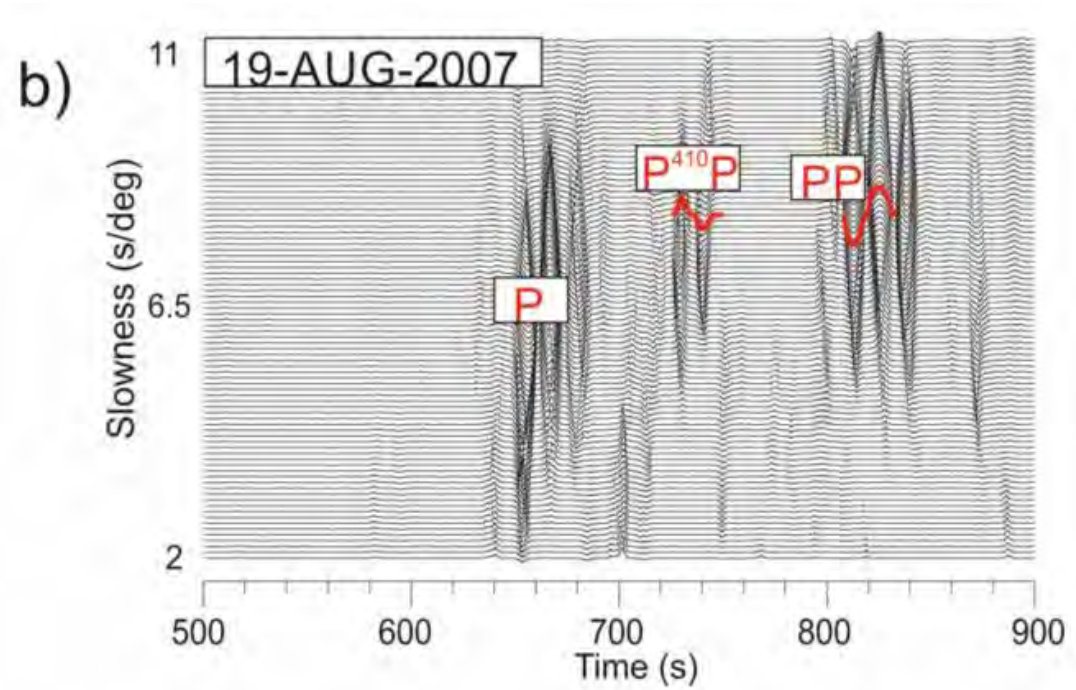



Saki et al., 2018

Modelling shows that effects are visible at short epicentral distances

But -most studies are at distances Δ >100 deg

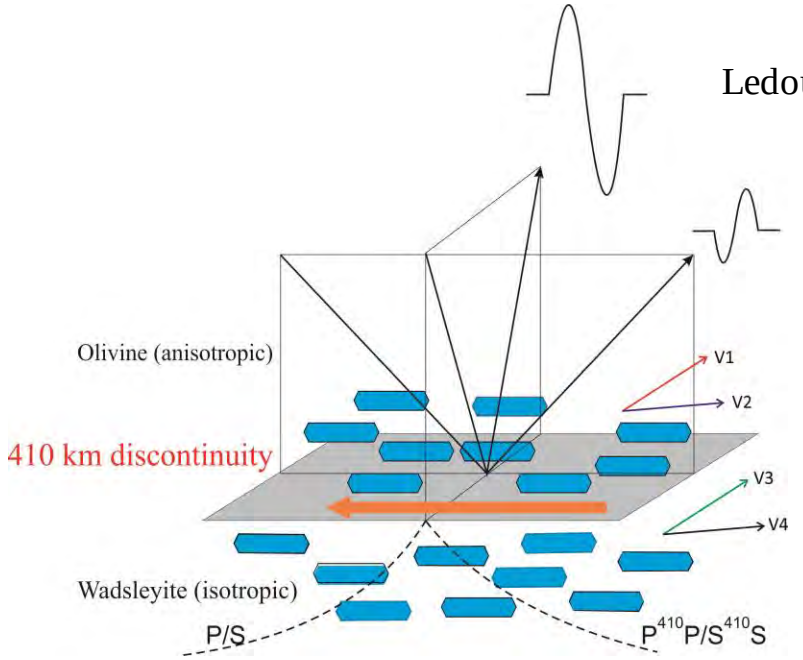
Synthetic data show possibility to observe SS and PP precursors at shorter epicentral distances



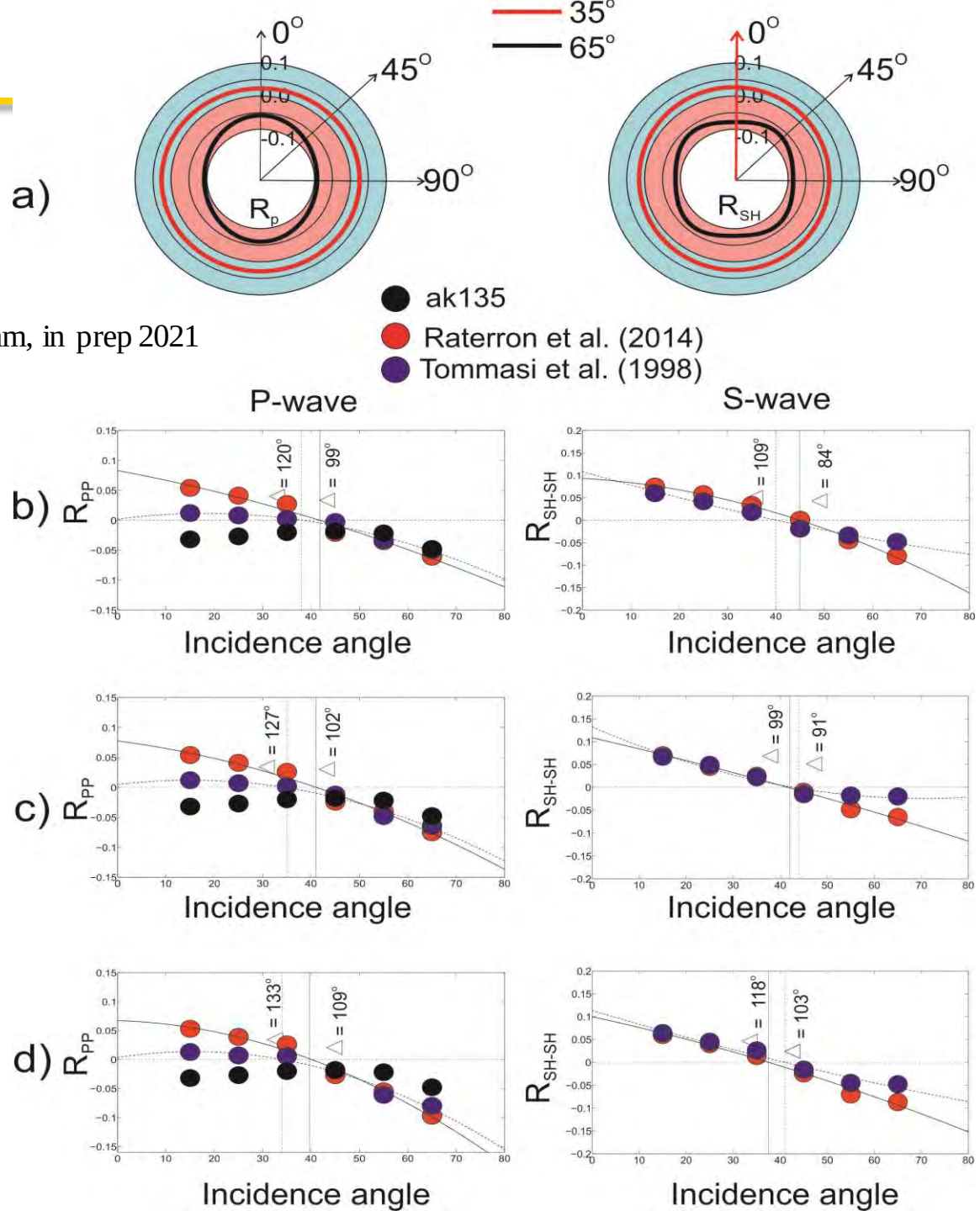

Saki and Thomas, 2021 in prep

# Deformed olivine and wadsleyite

## what about anisotropic wadsleyite?




Ledoux, Saki and TIMEleSS team, in prep 2021

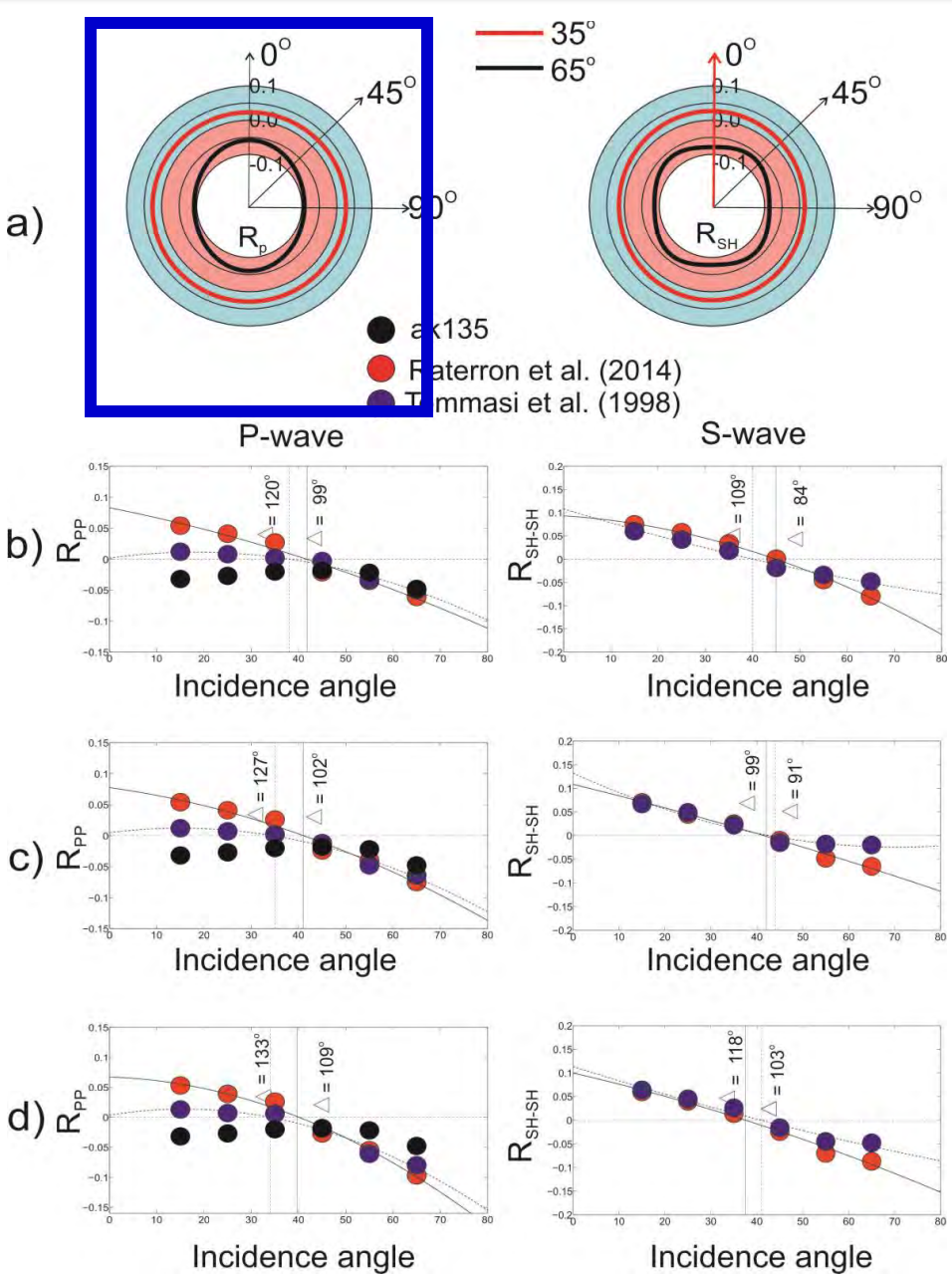


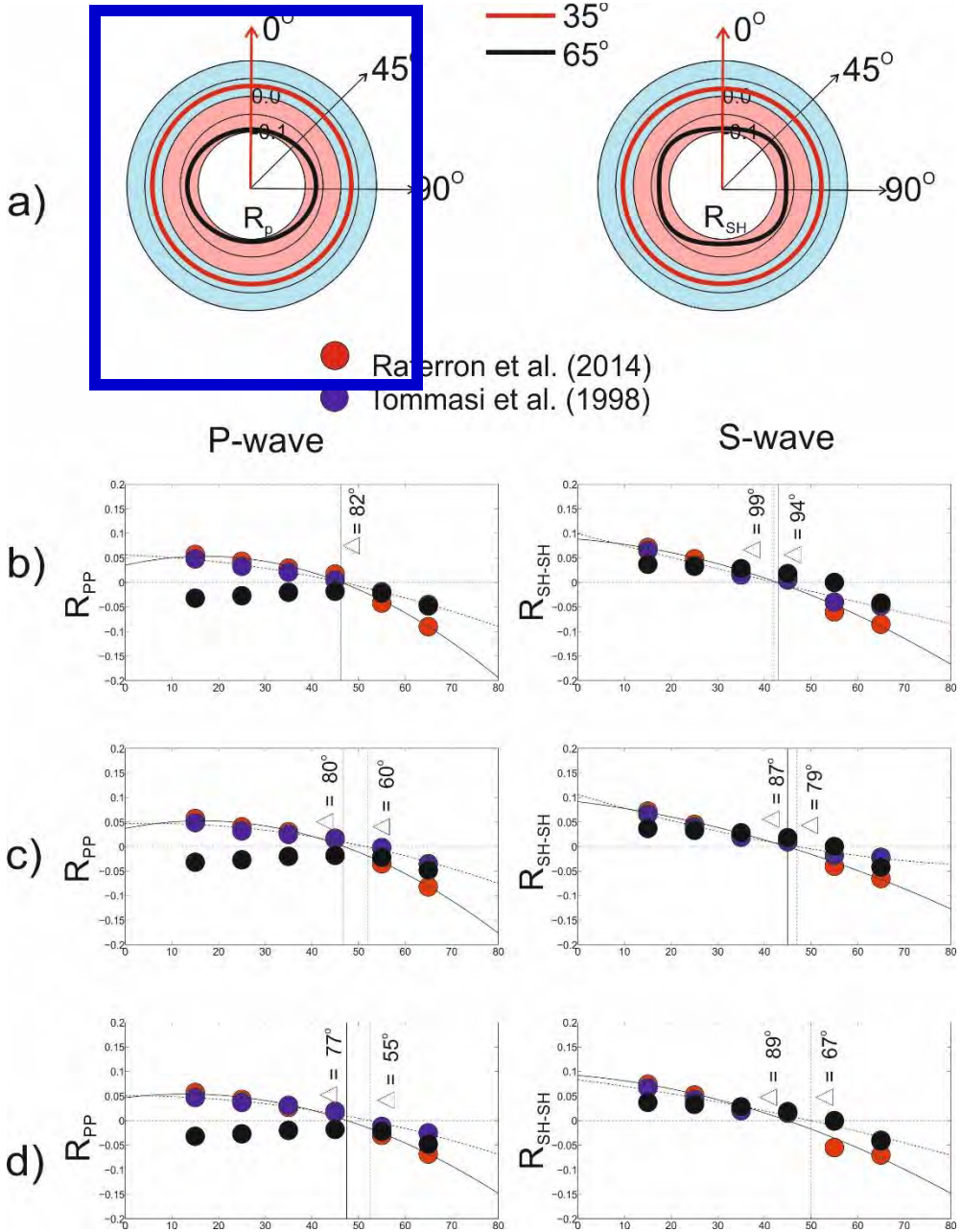

Effects for shorter epicentral distances
at longer epicentral distances no change with direction.

But new values for velocities from (Ledoux, Saki et al., 2021) in combination with olivine values by Tommasi et al, 1998 or Raterron et al., 2014 show a polarity reversal for P-waves as well.

# Vertical and horizontal shear

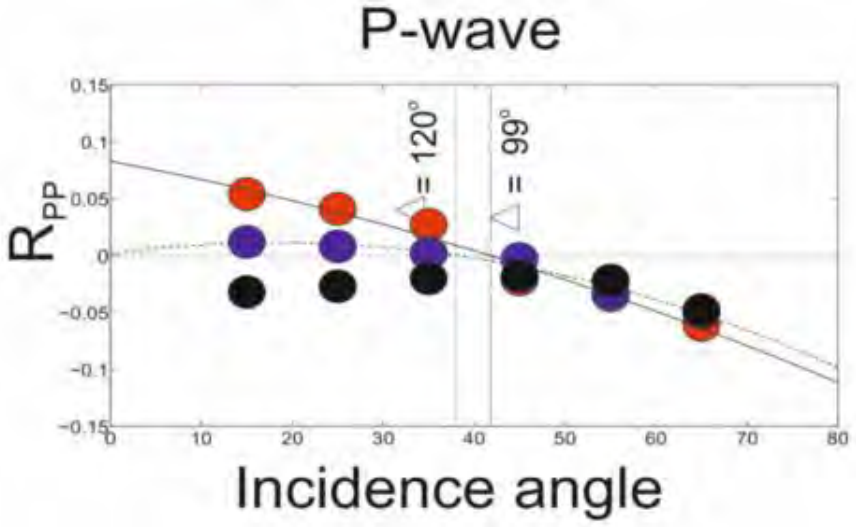
Ledoux, Saki and TIMEleSS team, in prep 2021



# Implications

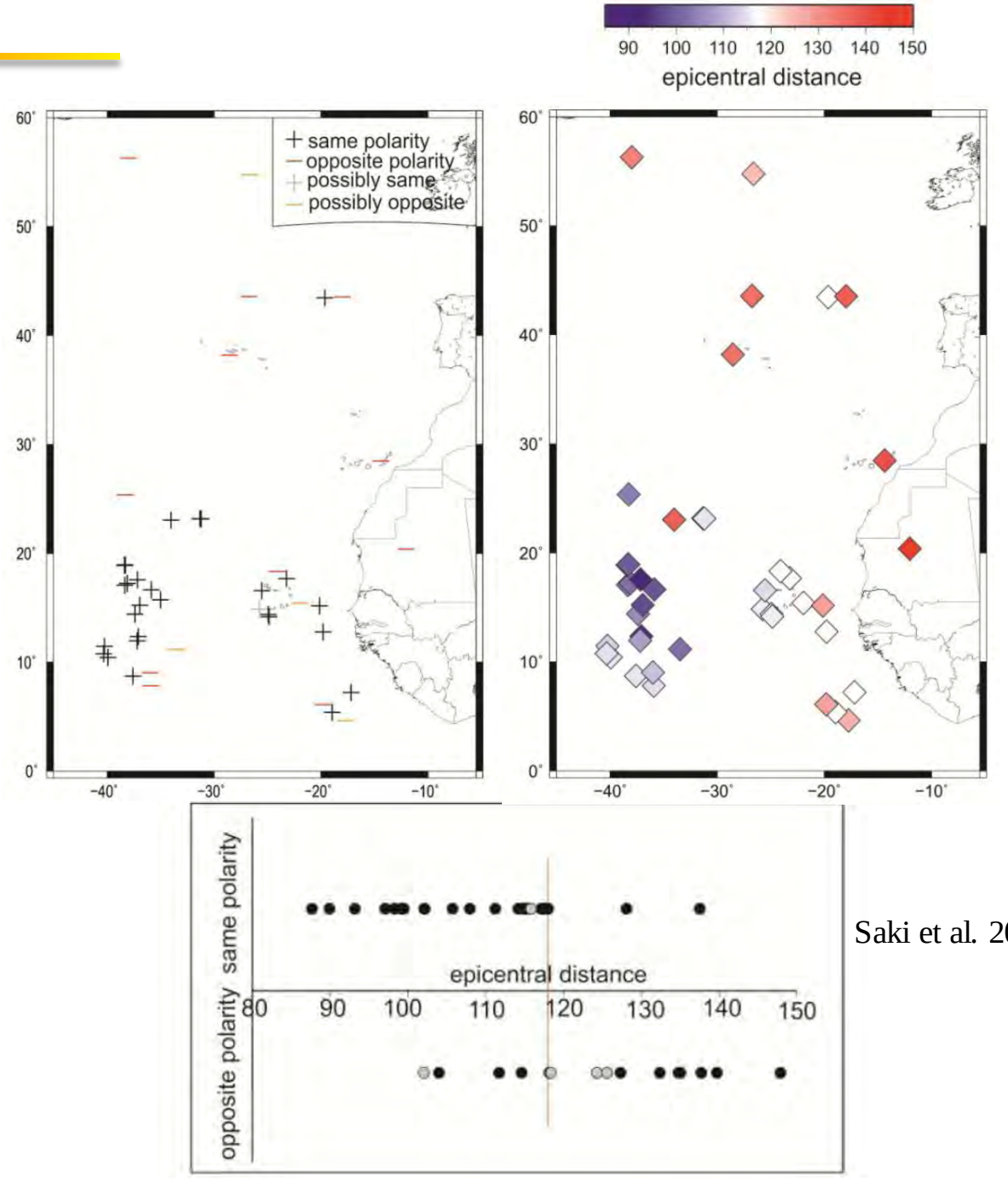
Ledoux, Saki and TIMEleSS team, in prep 2021




Polarity changes with direction only for short distance (PP and) SS precursors.

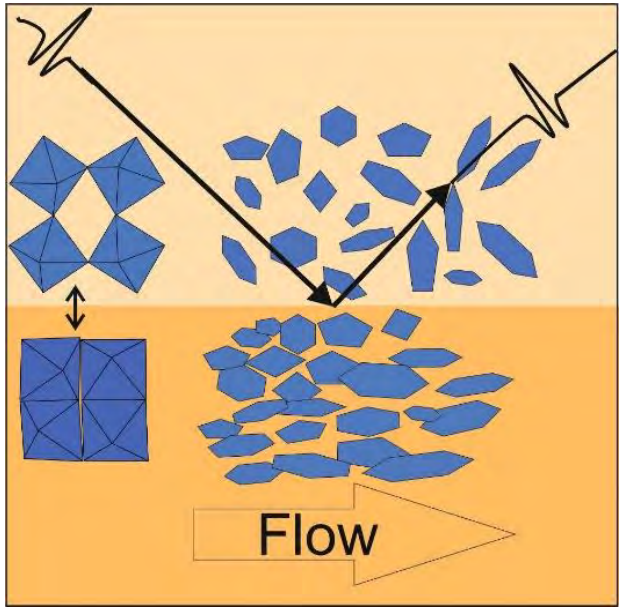
At larger distances no variation of reflection coefficient visible (only very small amplitude changes).

But: New results (Ledoux, Saki, TIMEleSS team, 2021) in combination with values for Olivine (Tommasi et al, 1998 or Raterron et al., 2014) provide a possibility to explain observed polarity variations with distance (e.g. Saki et al, 2019) not predicted with ak135.




Saki et al. 2019

# Summary




- How can we make dynamic processes visible with seismic methods, i.e., can we "see" convection?

yes - through Anisotropy

- Can detected anisotropy help to understand processes?

For D'': the slip system and tilt provides a measure of deformation (and with that may indicate mantle flow).
For MTZ: horizontal and vertical shear can be distinguished, esp. with short distance PP-precursors (not possible for long distance PP and SS precursors)

- How important is the knowledge of mineralogy?

different mineralogy gives different splitting/reflections predictions.
for upper mantle new results provide a different result for polarities than ak135.

- How unique are our interpretations?

Good for D'', because of the use of different waves and methods.
MTZ: for PP and SS precursors potentially only for short distances.
But crossing paths are necessary here.