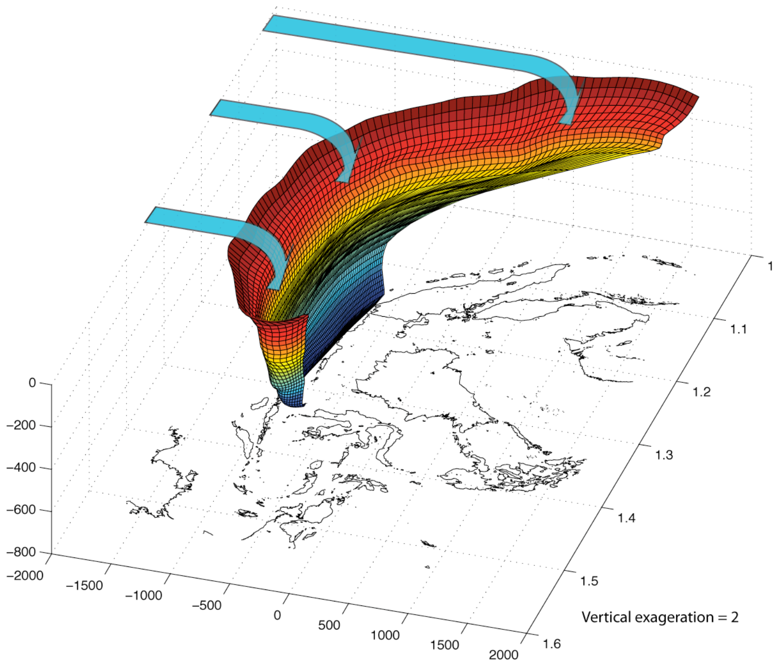
Seismic imaging of fluids and deformation in subduction zones



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Talk overview

1. Seismic imaging of subduction zones
   - 'Classical' pictures of subduction zones
   - The limits of travel-time tomography

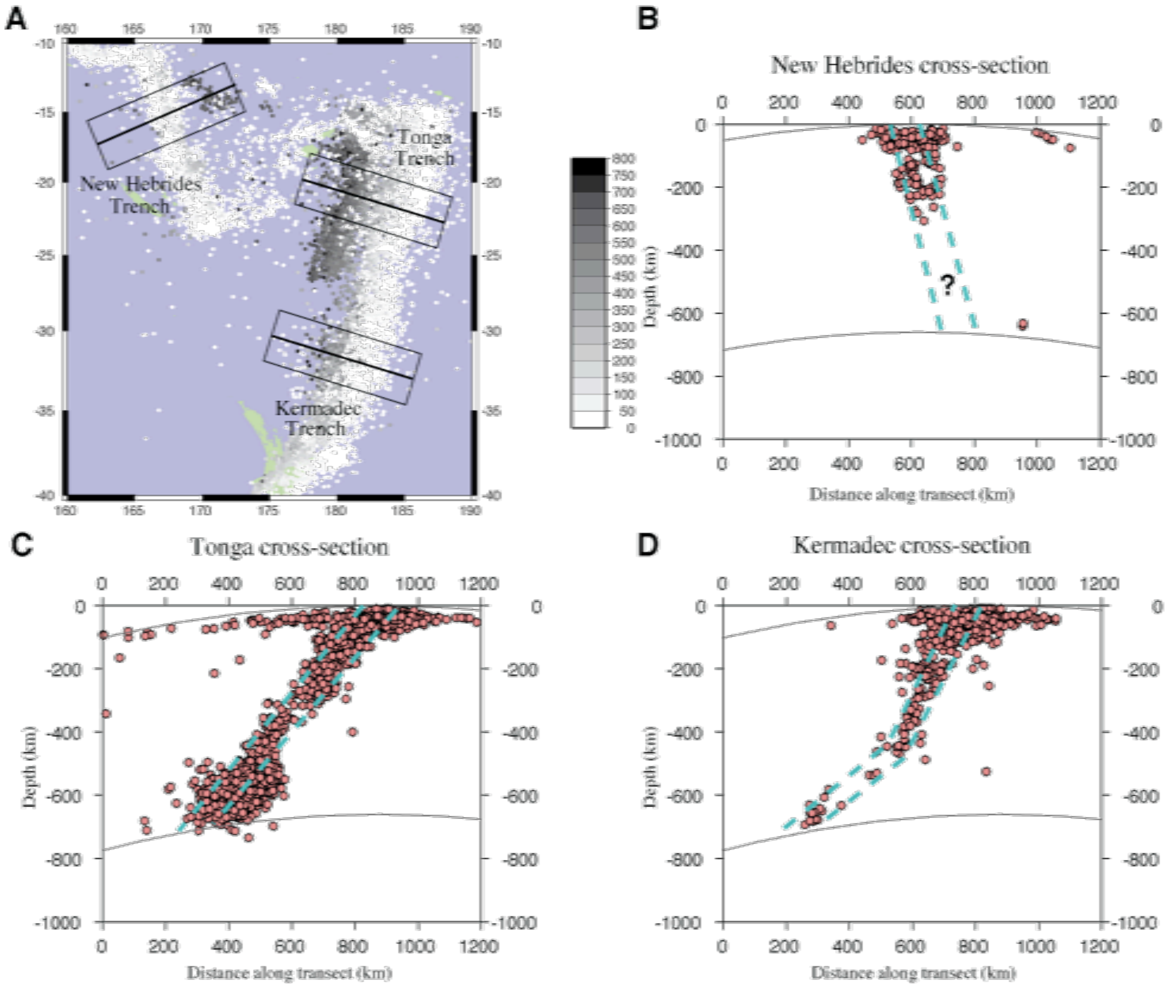
2. Imaging complex processes: fluids and deformation
   - Attenuation
   - Anisotropy

3. Case example: Indonesia

4. Outstanding questions – ESR7

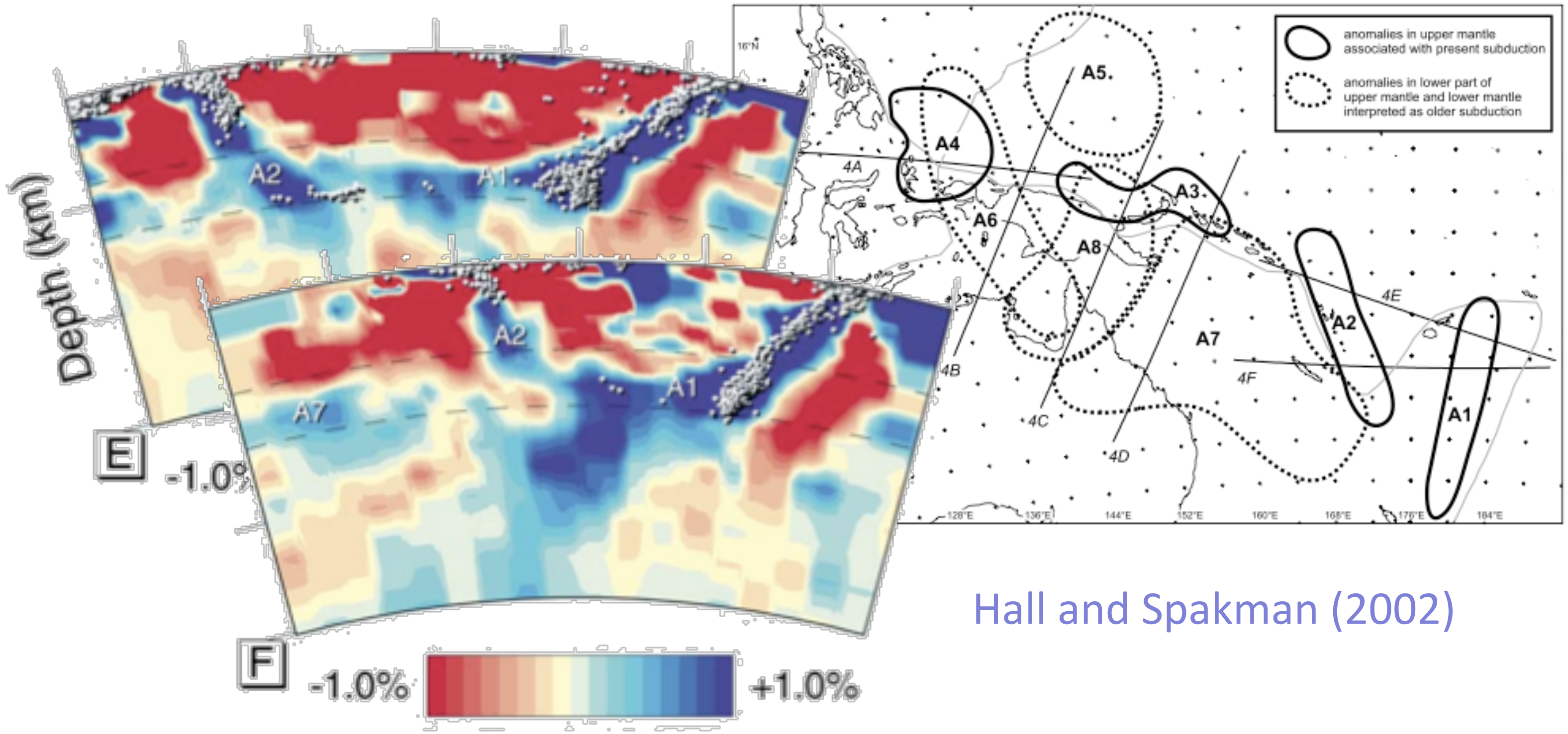
Seismic imaging of subduction zones I

- Subducting plate is seismogenic, sometimes all the way to 660km
- Accurately locating these events (the 'Watadi-Benioff Zone') gives us a first image of the structure of the slab



Seismic imaging of subduction zones II

- Obviously though, this only tells us where the slab is seismogenic
- More information about broader structure comes from travel time tomography
- Travel-time tomography solves for P- and/or S-wave velocity structure:



Hall and Spakman (2002)

Seismic imaging of subduction zones II

- This is very nice: it tells us many things about subduction zones
  - deep structure
  - morphology
  - terminal depth

- However, if we want understand more complex processes like deformation, and the movement of fluids we have a problem …

- P-wave (and S-wave) velocity *are* sensitive to deformation processes, and to the presence of fluids

  but

- They are also sensitive to a host of other parameters
  - mineralogy, temperature, pressure, fine-scale structure …

Seismic imaging of subduction zones II

- Very difficult to disentangle these effects with P- and S-wave velocity alone

- Must look for other, secondary, parameters which can be measured from seismic data:
  - **Attenuation** (fluids)
  - **Anisotropy** (fluids, deformation)

Attenuation

- Attenuation is the frequency-dependent amplitude reduction of seismic waves

$$A \approx e^{-\pi f \tau Q^{-1}}$$

  usually parameterised by the so-called quality factor *Q*.

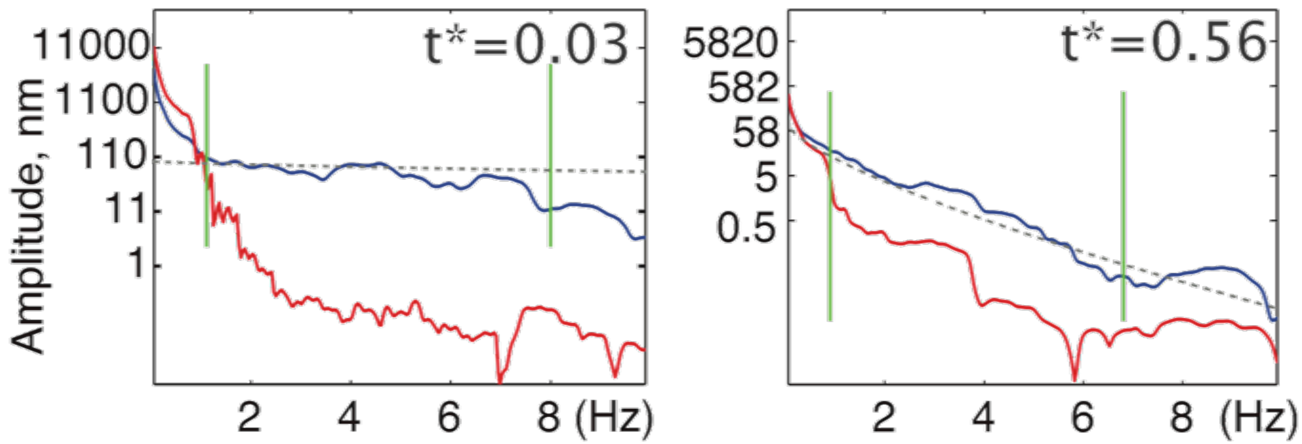
- In 'normal' mantle conditions, attenuation is due to inter- and intragranular processes
  - e.g., Jackson [2007]

- Strongly temperature dependent

- In addition, water and melt significantly effect *Q*

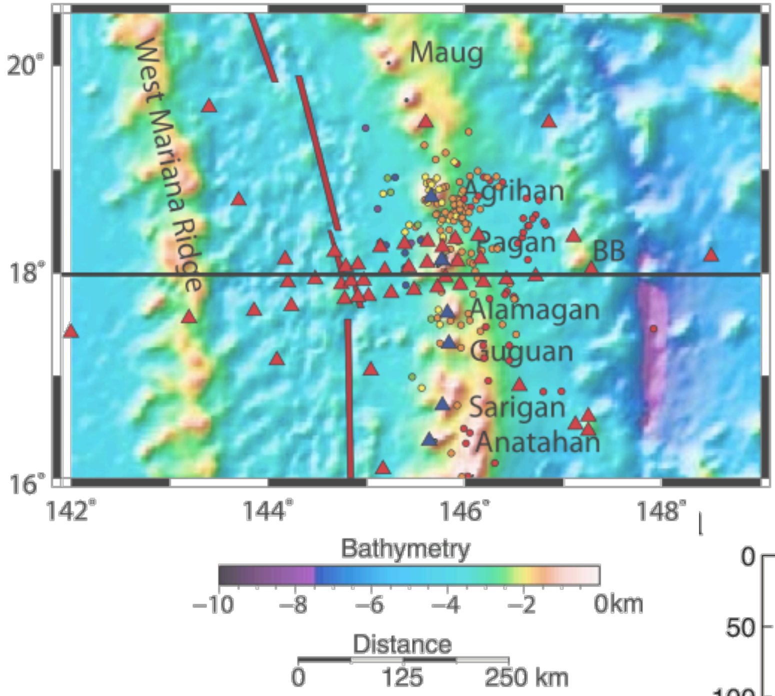
Measuring attenuation in subduction zones

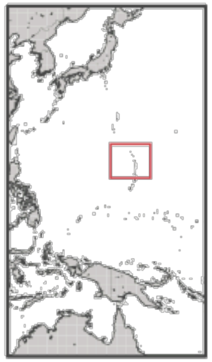
- Attenuation for a seismic phase is usually measured in the form of a t^* operator ($t^*=\tau/Q$)
- Measure for direct P- and S-phases from subduction zone events at local stations
- Calculated using the recorded seismic spectra – *also requires knowledge of source earthquake parameters* (corner frequency and magnitude)
  - See, e.g., Pozgay et al (G3, 2009) for details



- Have a ***t**** operator for each (P and S) raypath

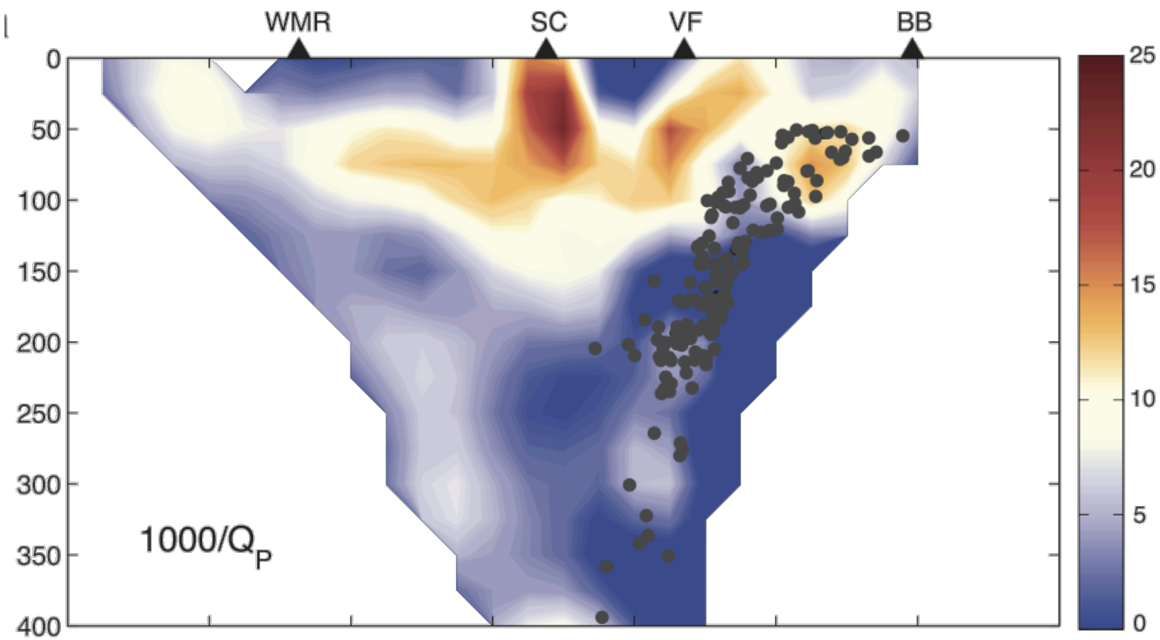
Measuring attenuation in subduction zones





- Can use tomography to make images of the variation of attenuation within the model

- Attenuation appears to be too large to be explained by temperature alone
  - melt?
  - water?



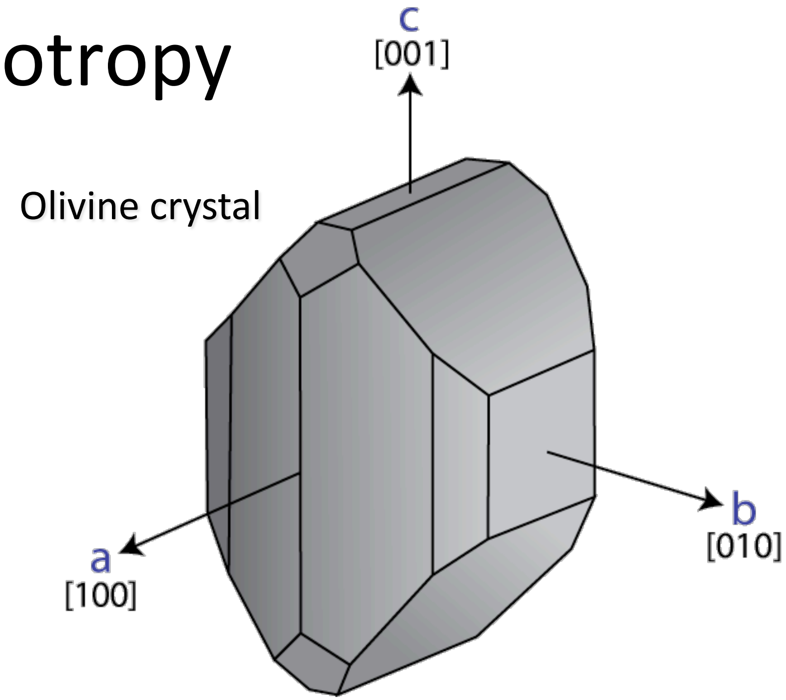
Pozgay et al (G3, 2009)

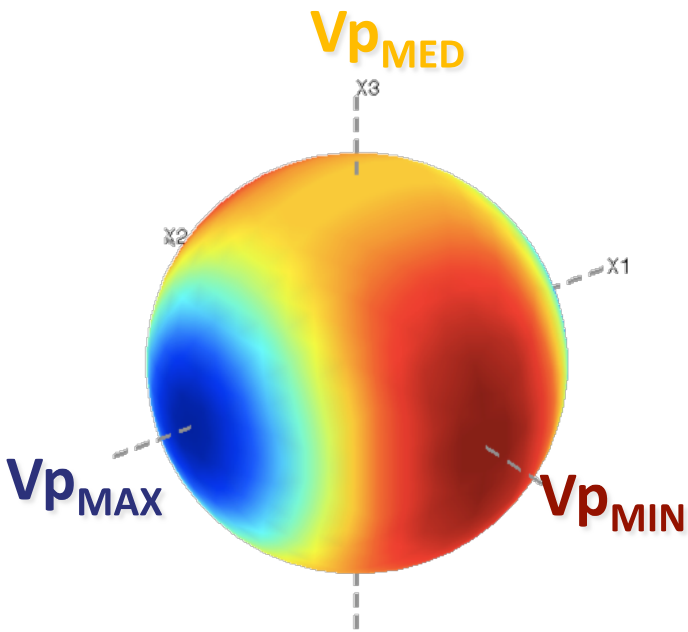
Seismic Anisotropy

- = dependence of seismic wave velocity on direction of propagation

- Can be due to crystal alignment (intrinsic, LPO) or alignment of larger features (grains, fractures, layers …) within the medium (extrinsic, SPO)

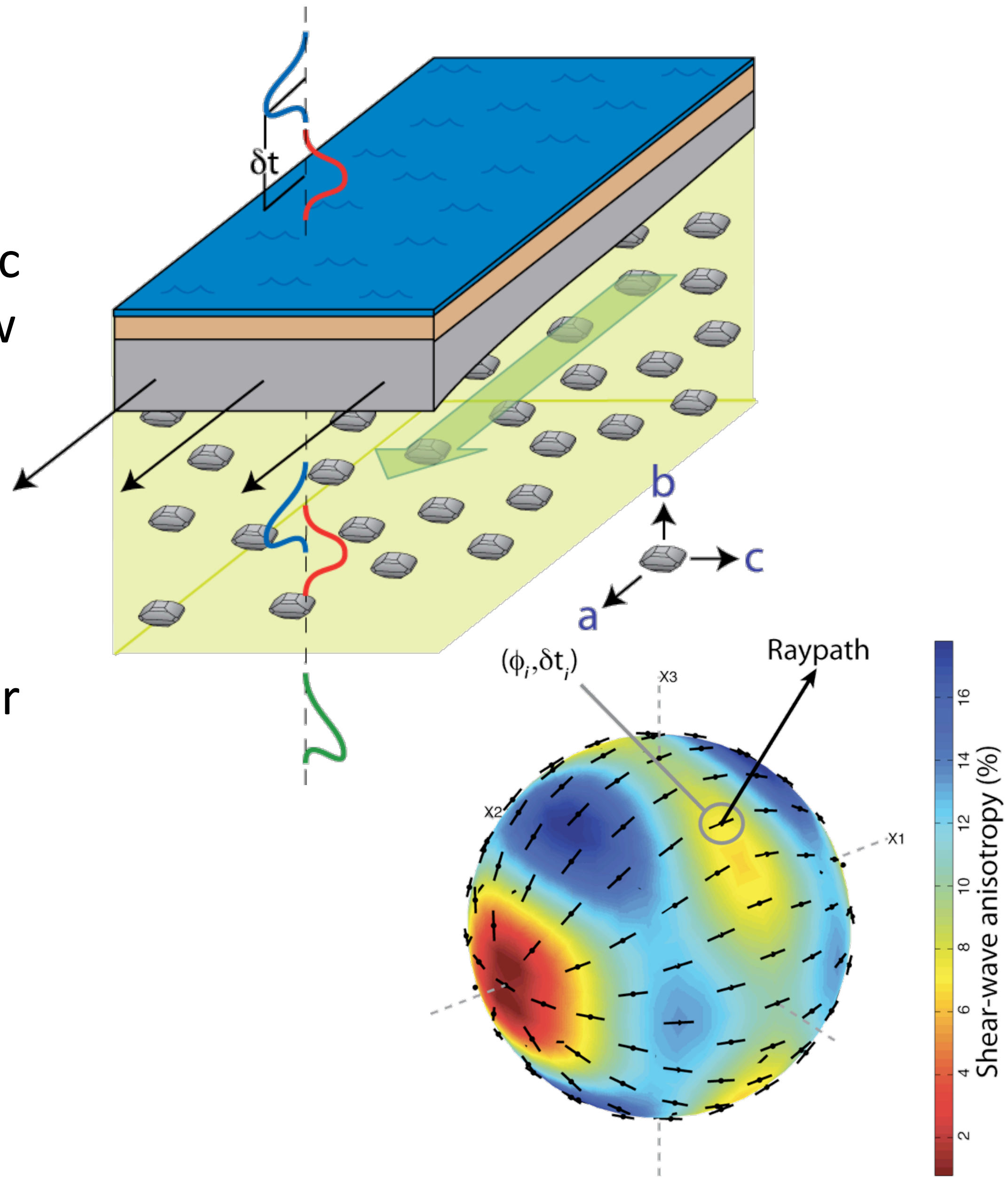
- Indicator of long range order in a material
  - e.g., layering or flow





Single crystal to polycrystal

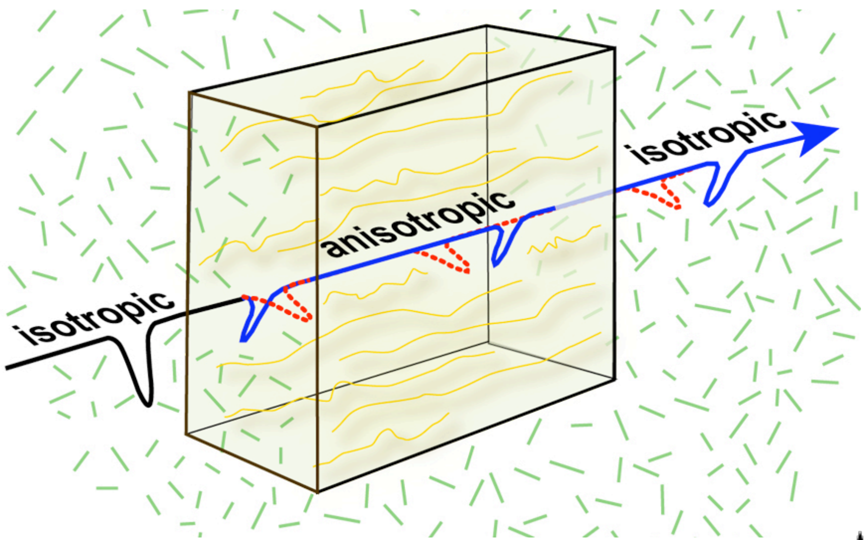
- To predict anisotropy at seismic wavelength, need to know how crystals align with flow (deformation mechanism)
- Classically, in the oceanic upper mantle, olivine aligns with a-axis in flow direction, and b-axis normal to flow plane



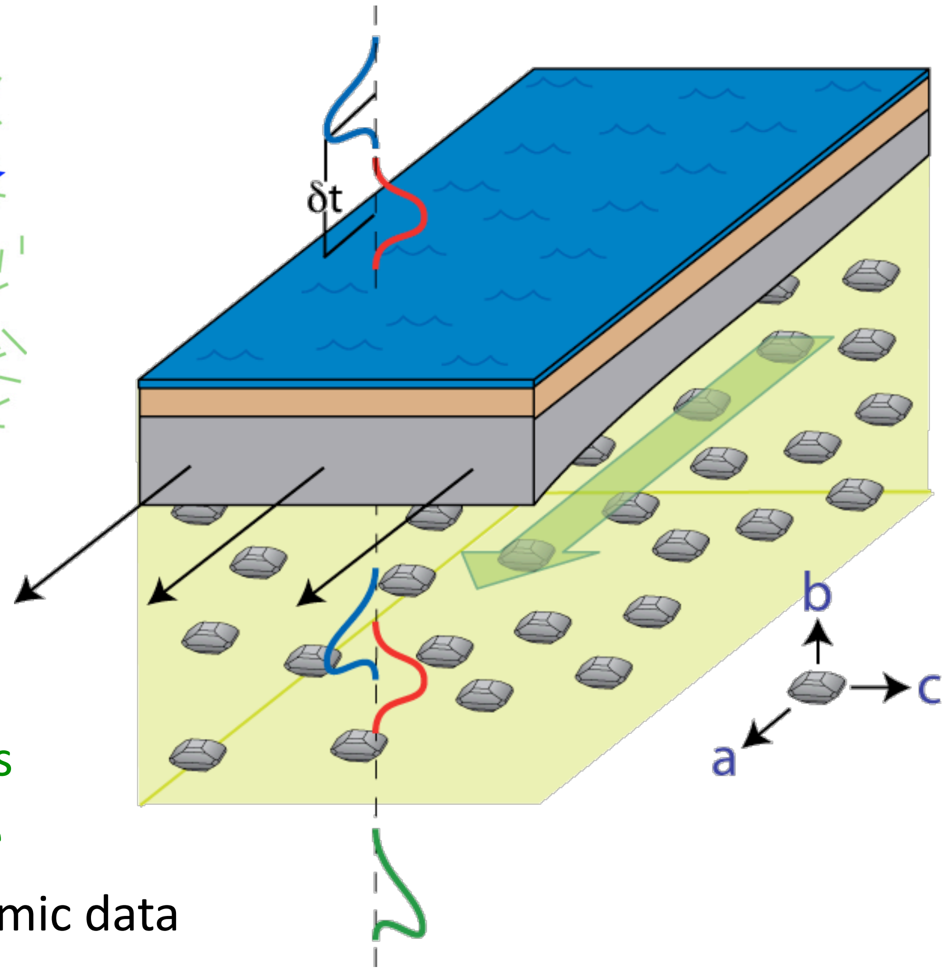
Shear-wave splitting

Shear-wave splitting

- The most unambiguous indicator of anisotropy in seismic data



Courtesy of Ed Garnero



- Described by 2 parameters:

  δt = lag time between shear-waves

  ϕ = polarisation of fast-shear wave

- Measured from 3-component seismic data

Deformation from anisotropy

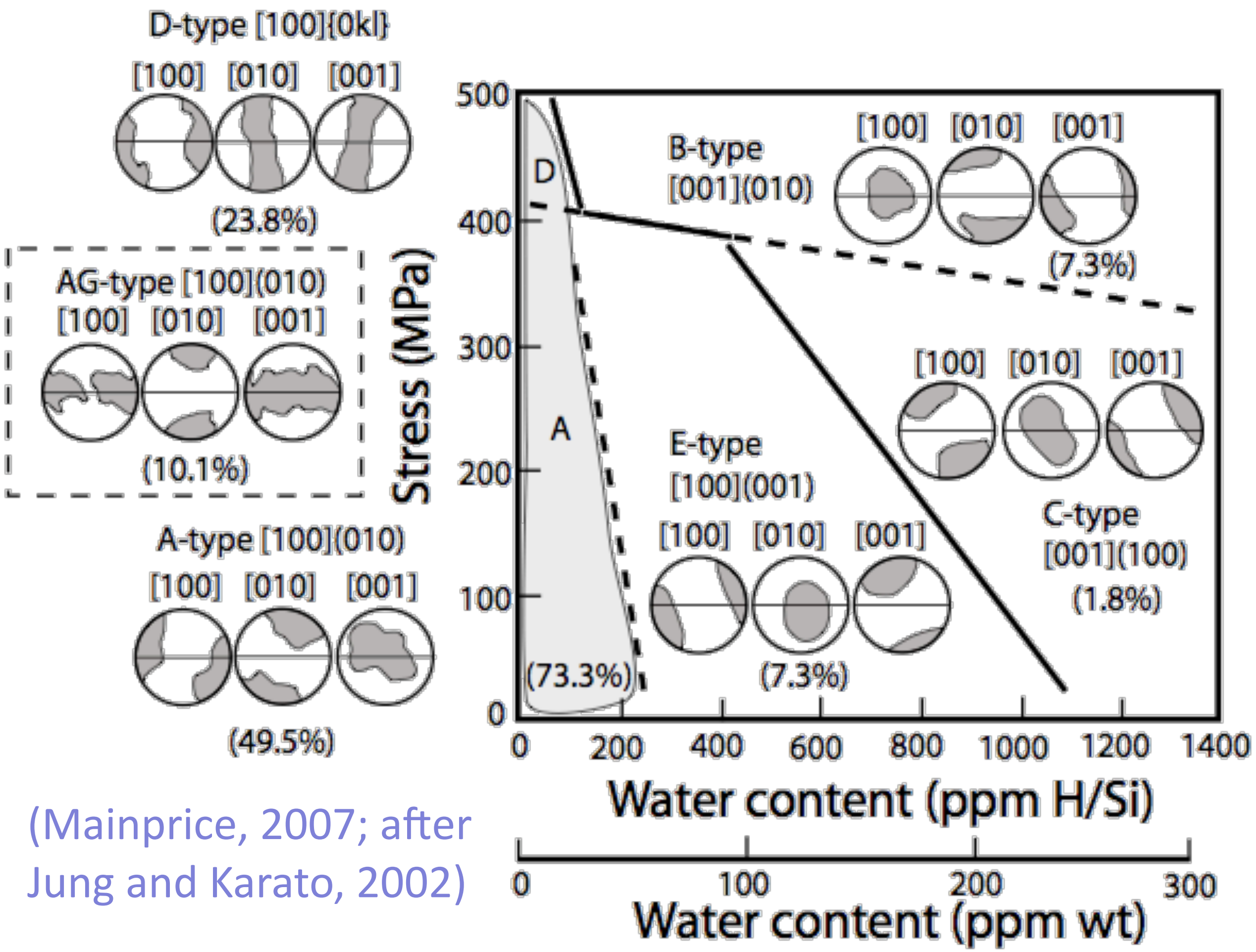
- So, in principle given measurements of the seismic anisotropy (and knowing the mineralogy) we should be able to infer the deformation

- However, once again, deformation is not the only process which effects seismic anisotropy:
  - temperature
  - fluids

- Recent topic of considerable discussion is the effect of water on seismic anisotropy …

Variation of olivine fabric with water content

- Observation in experiment [Jung and Karato, 2002] that alignment of olivine changed in the presence of water



(Mainprice, 2007; after Jung and Karato, 2002)

- Pressure is probably more important for this effect (Mainprice, 2005)

Hydrous phases

- In addition to altering olivine, water in the deep subduction system might cause the presence of other phases, for example the D-phase in the transition zone and deeper

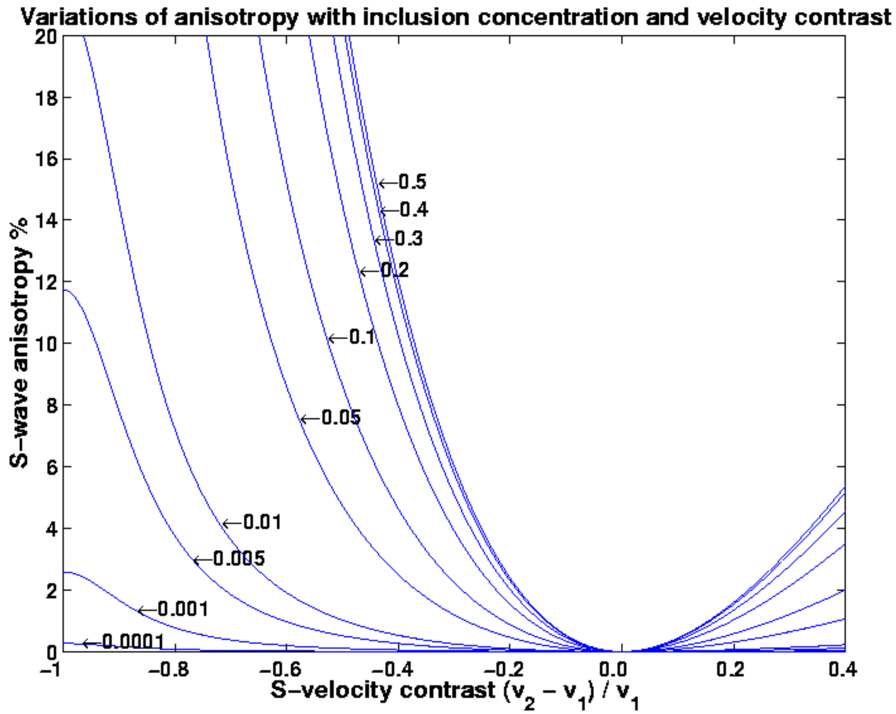
- This phase has a significant shear-wave anisotropy (Mainprice et al, 2007): ~20% maximum c.f. 14% (Wadsleyite) 8% (Ringwoodite)

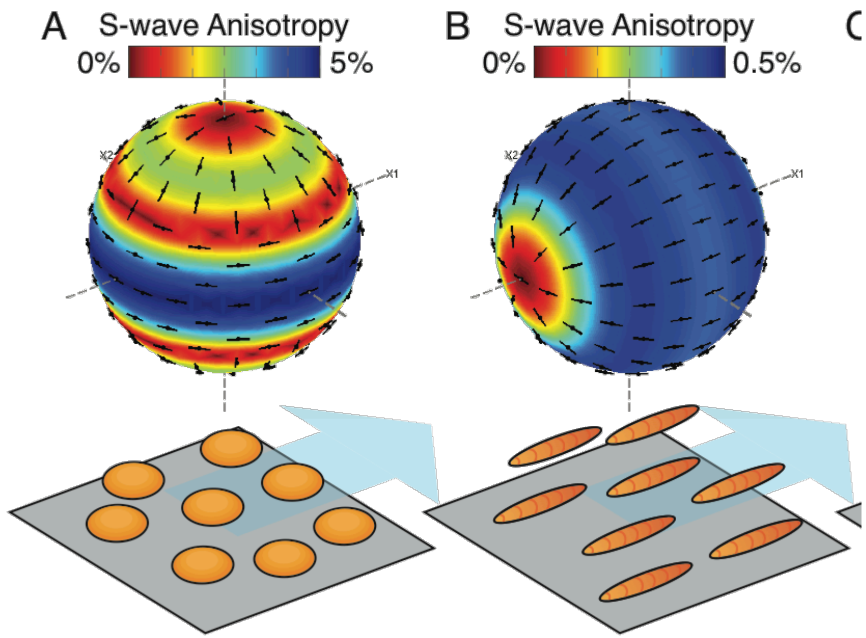
- Especially significant in the midmantle region?
  - Don't see much anisotropy globally, but some locally?

Effects of melt on anisotropy

- So far discussed LPO – anisotropy is at the crystal scale
- Also potentially have at larger (though still sub-seismic wavelength) scales
  - inclusions where the fill material has different elastic properties than that of the matrix (fluids)

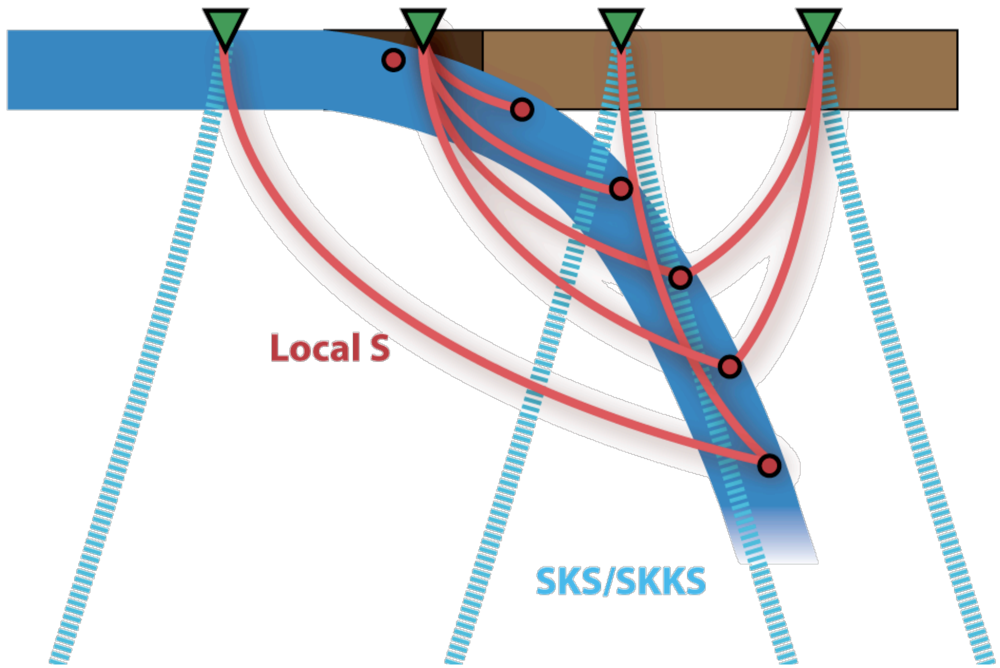
- These are very effective at generating anisotropy …





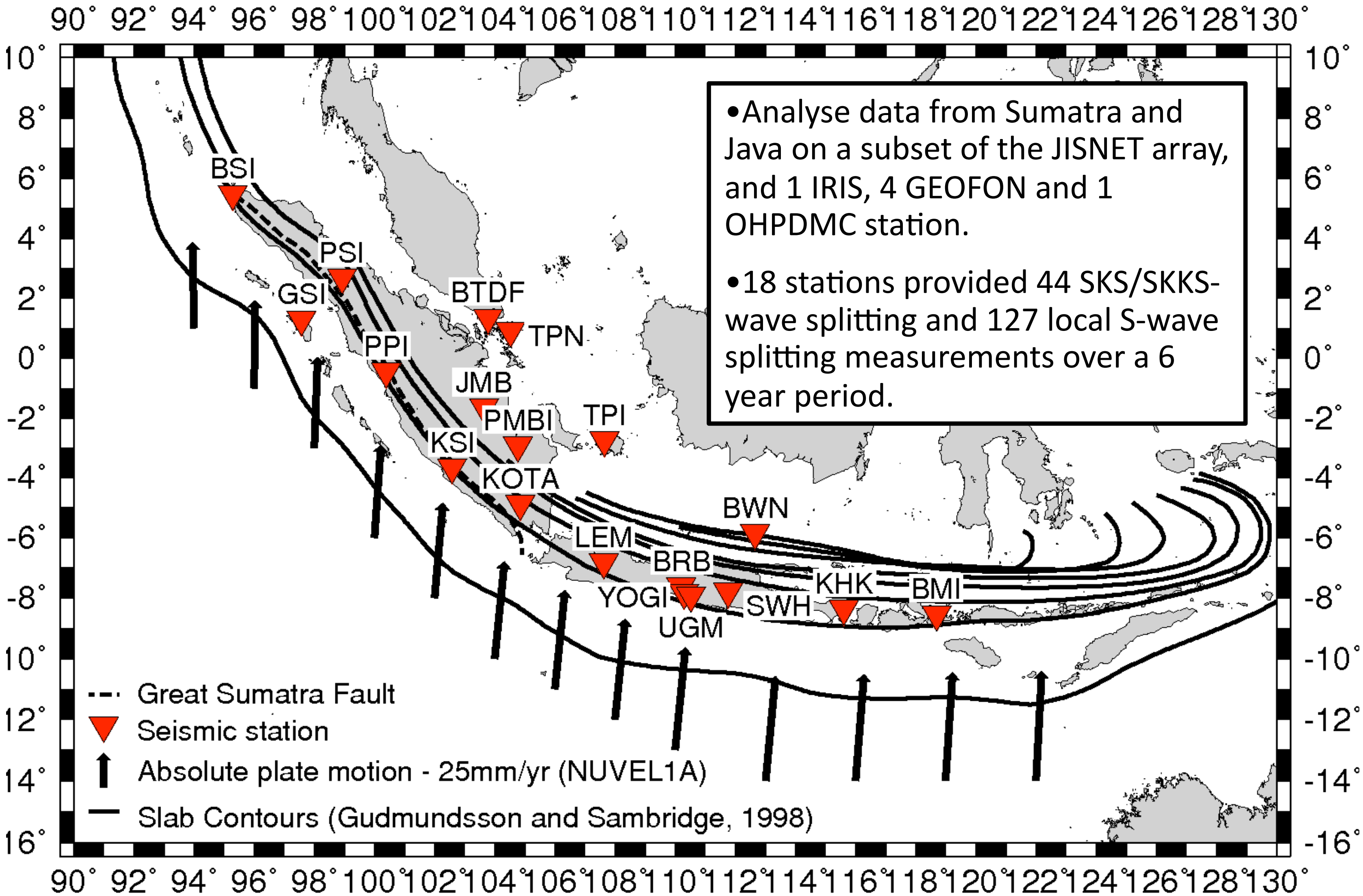
Measuring anisotropy in subduction zones

- Once again, advantage in subduction zones over other tectonic settings: events!
- Can use local events between the surface and 700km, as well as teleseismic phases such as SKS



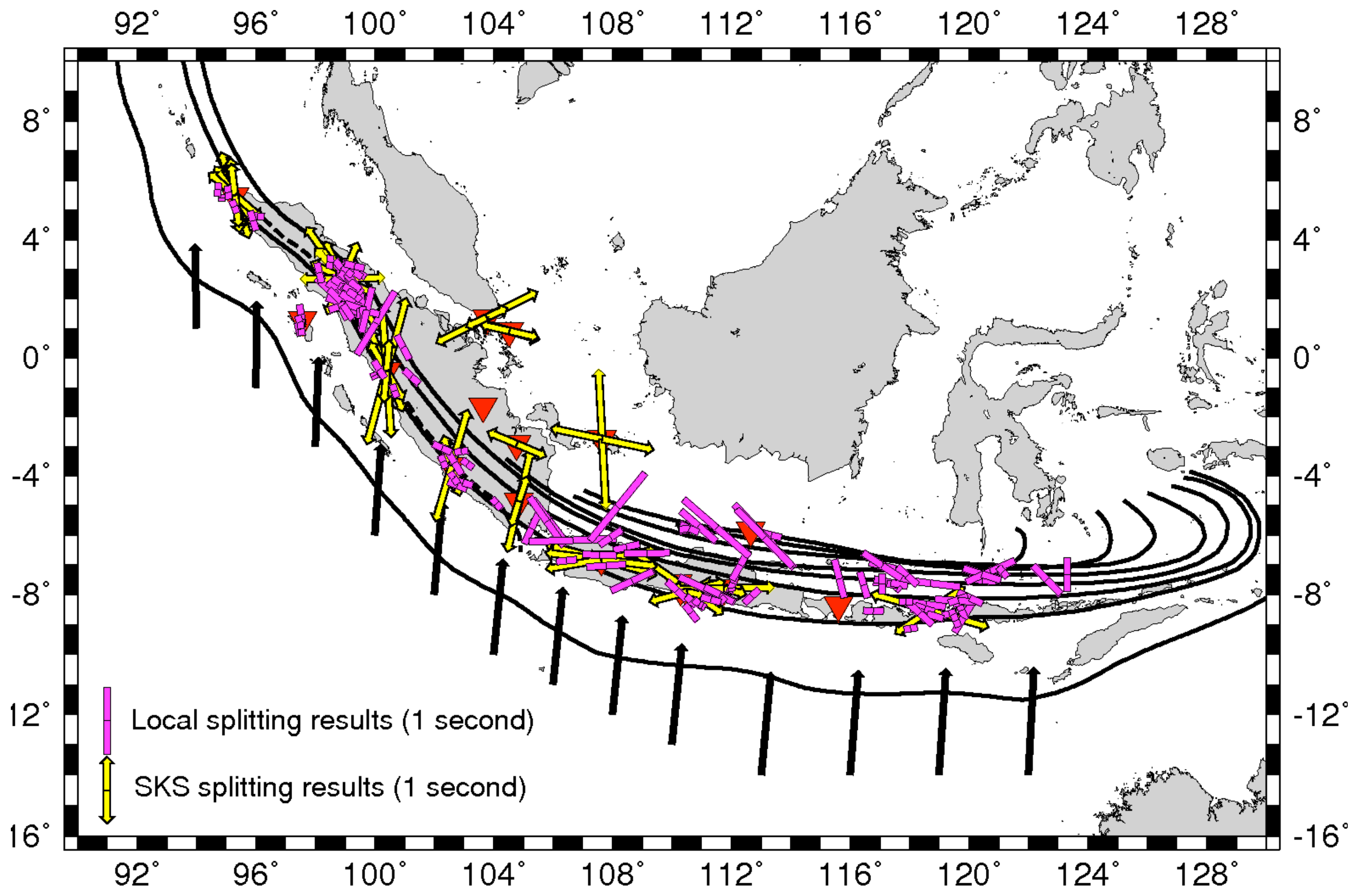
- This provides the opportunity of separating anisotropy by depth/region

Example study – Java-Sumatra



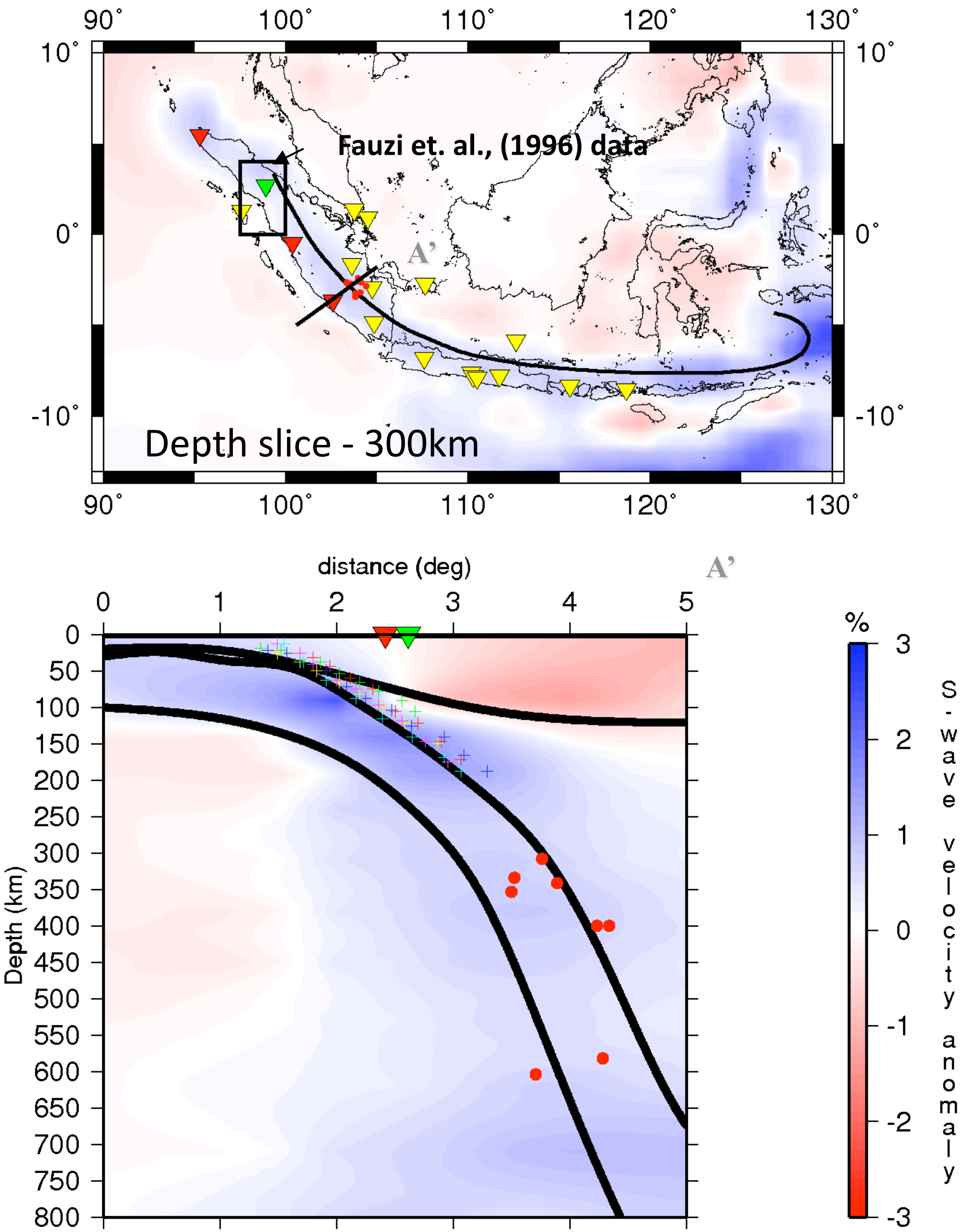
- Analyse data from Sumatra and Java on a subset of the JISNET array, and 1 IRIS, 4 GEOFON and 1 OHPDMC station.
- 18 stations provided 44 SKS/SKKS-wave splitting and 127 local S-wave splitting measurements over a 6 year period.

Hammond, Wookey, Kaneshima, Inoue, Yamashina and Hajardi (2009, in revision)



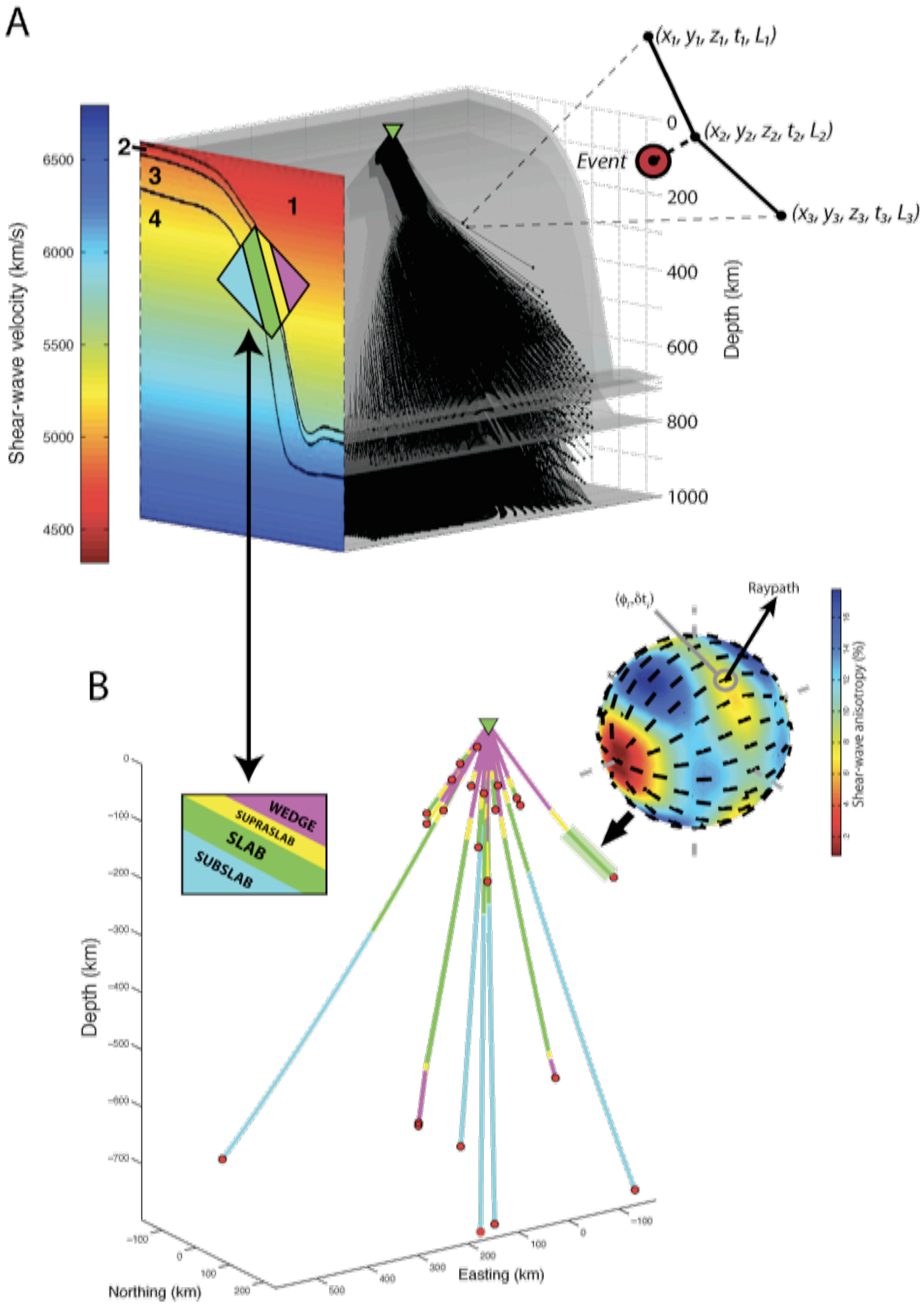
- Complicated pattern of splitting
- Splitting is an aggregate measurement
- Need modelling to understand how anisotropy varies within the system

- Forward model the local/SKS splitting results
- Build 2.5-D model for each station, constrained by:
  1. Local seismicity (Gudmunsson and Sambridge, 1998)
  2. Local re-located seismicity (Fauzi et al, 1996)
  3. Regional tomographic models (Gorbatov and Kennett, 2003)
- Forward model using ATRAK (Guest and Kendall, 1993)
- A ray tracer capable of tracking seismic rays in multilayered 3-D media



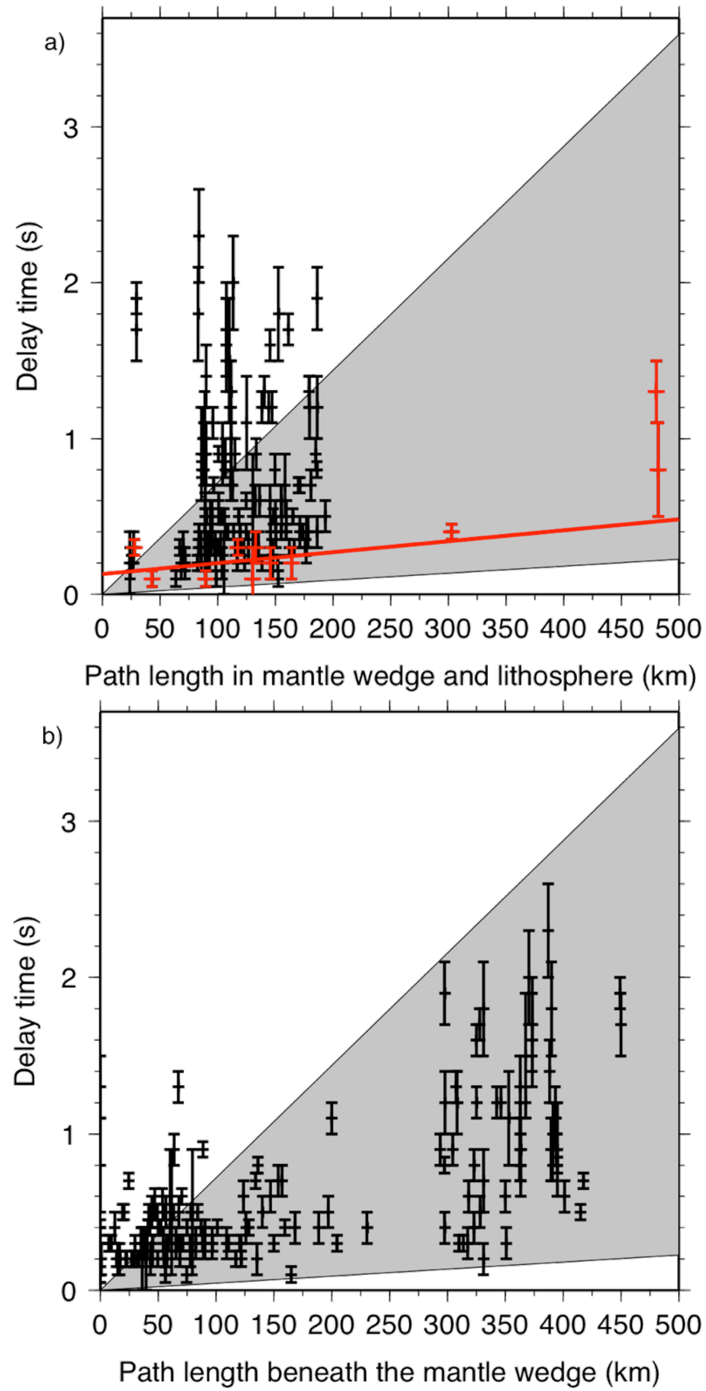
Forward modelling

- Model raypaths in isotropic medium (assume anisotropy is only a small perturbation to the raypath)
- Appeal to reciprocity, and shoot rays from the station to saturate the model (>12,000 rays per station)
- Match each event to the nearest point on a ray (for SKS assume an event depth of 800km) to get raypath
- Have realistic raypaths for every event, with direction and distance in each part of model

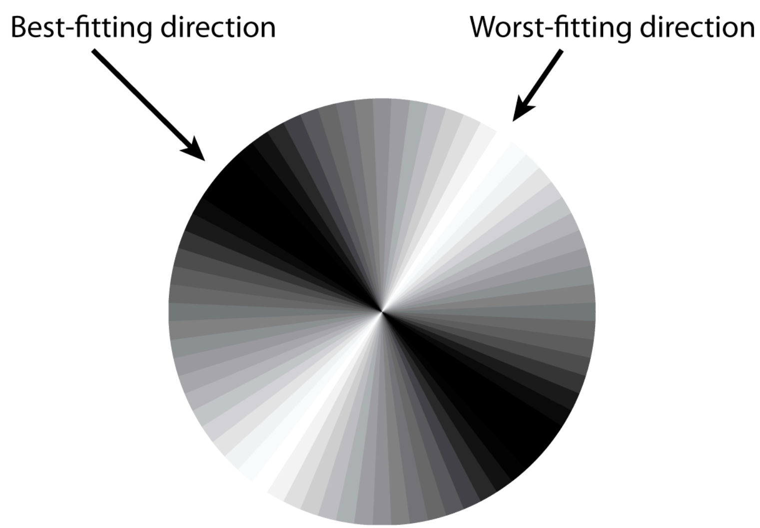


Analysis of anisotropy distribution

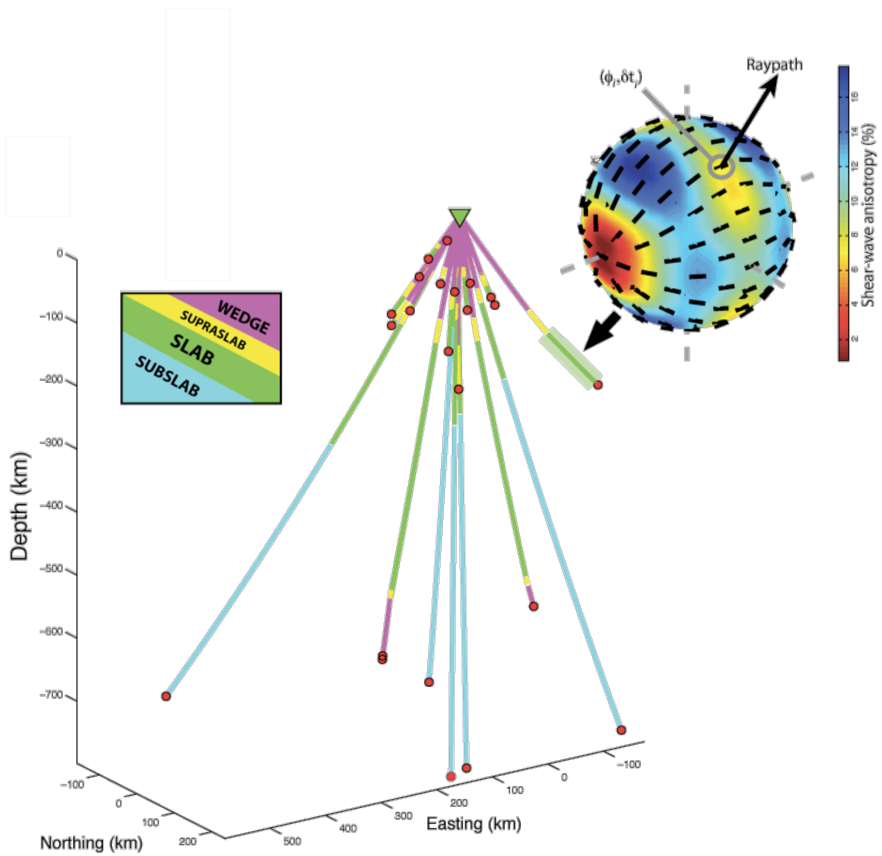
- Upper panel is the delay time as a function of the path length in the wedge and lithosphere (above the slab)
  - No apparent correlation
  - Red results have no travelled no significant outside this region
  - 1.8% in the lithosphere or 0.3% in the wedge
  - **Wedge is (approximately) isotropic**
- Lower panel shows the path outside the wedge
  - better correlation
  - anisotropy probably mostly deep, but also significant shallow
  - Need to model 2 layers
- Divide events into shallow (<300km) and deep (>300km, including all SKS)

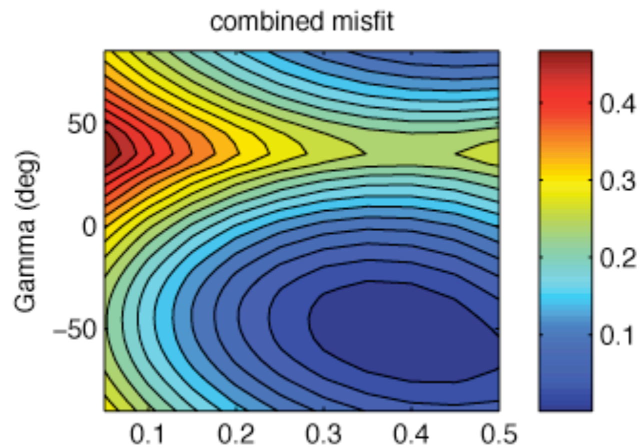


- Add anisotropy to a specified region
- Grid search over orientation and anisotropy strength (by Voigt-Reuss-Hill dilution of the olivine tensor)
- Minimise misfit between predicted (ϕ,δt) and data
- Represent direction using a polar density plot:



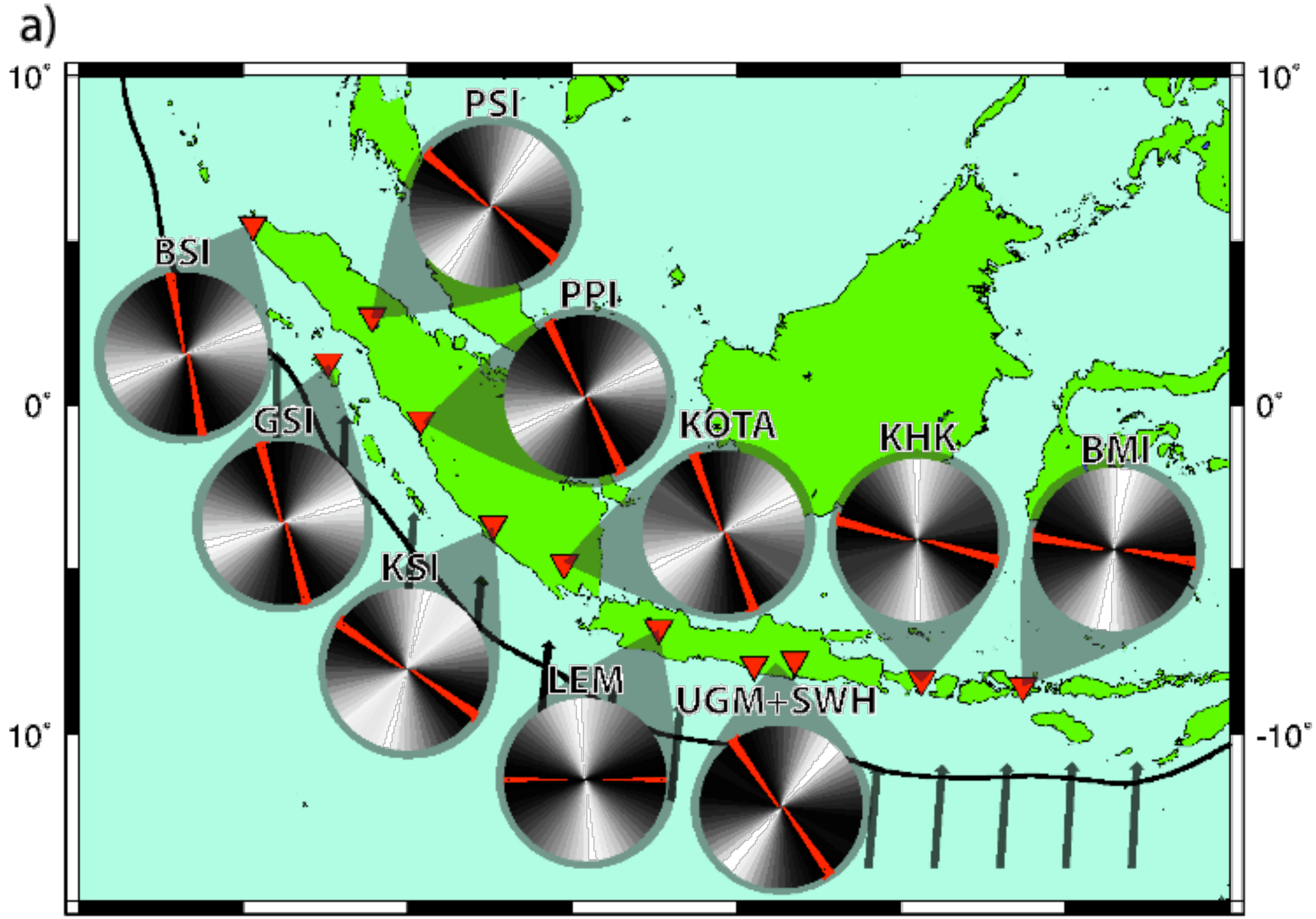
- Given the inference of a (largely) isotropic mantle wedge, divide events into shallow (<300km) and deep (including SKS) to resolve different layer





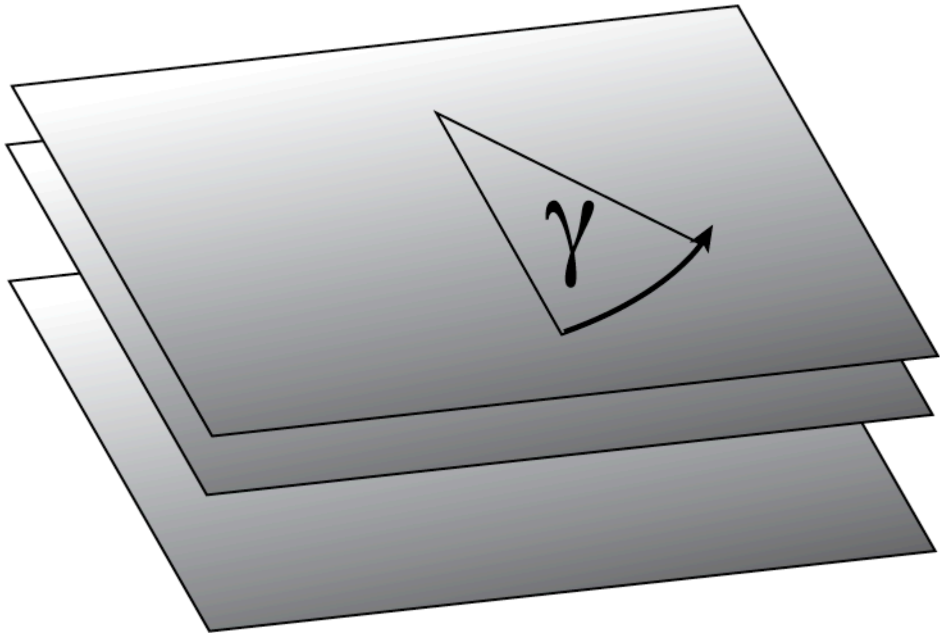
Shallow model

- Assume lithospheric layer 40km thick (though not necessarily constrained to be mantle, could be crustal)
- Constrain the direction of (horizontal) alignment of olivine a-axis



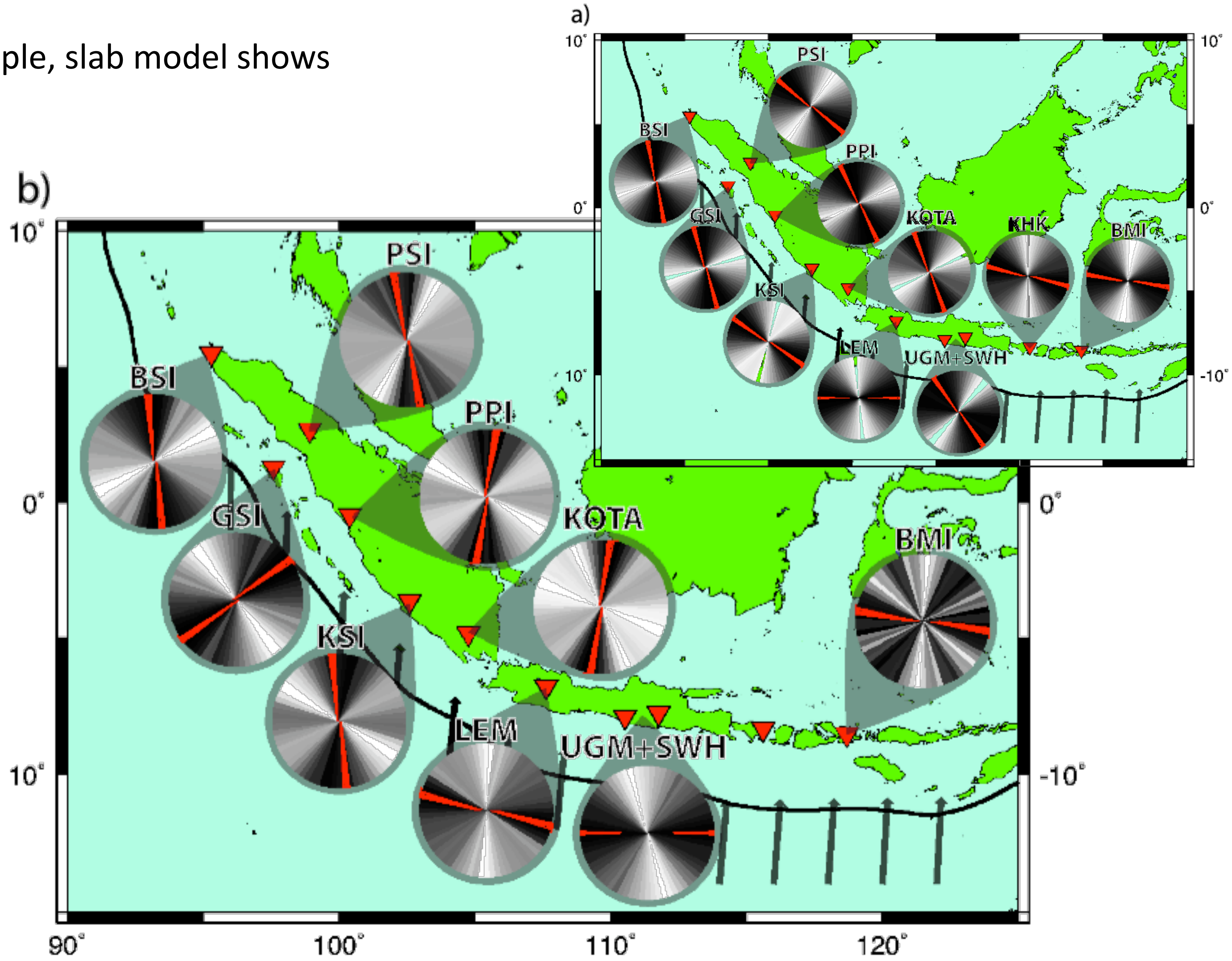
Deeper models

- Deeper models have a flow direction in the dipping plane of the subduction zone
- All also incorporate the shallow lithospheric anisotropy
- Tried models with anisotropy: (i), in the slab; (ii), in a thin layer above the slab; (iii), beneath the slab
- Thin layer above the slab fits poorly, but **cannot distinguish between the slab and subslab**



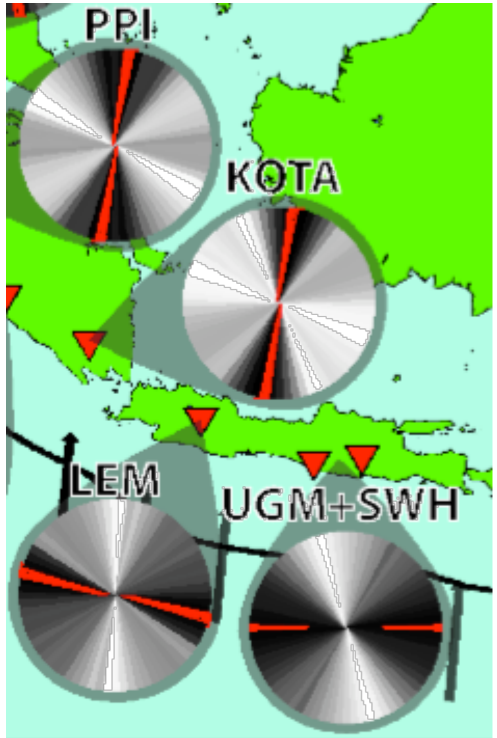
Deeper models

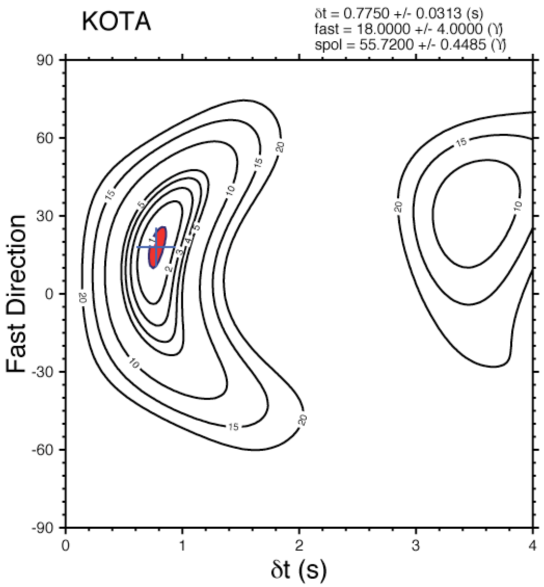
- For example, slab model shows

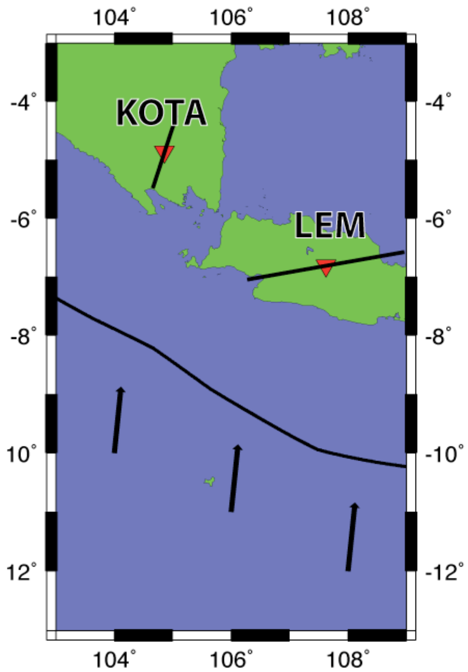


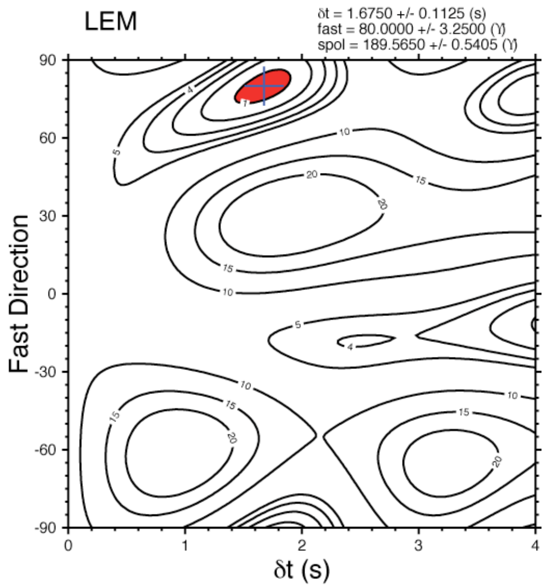
Results

- All deep anisotropy models show a marked change of anisotropic alignment between Java and Sumatra
- Sumatran stations are predominantly N-S in orientation, similar to APM of subducting Australian plate
- In contrast, Javan models show a dominant E-W orientation. This is also apparent directly in the data:



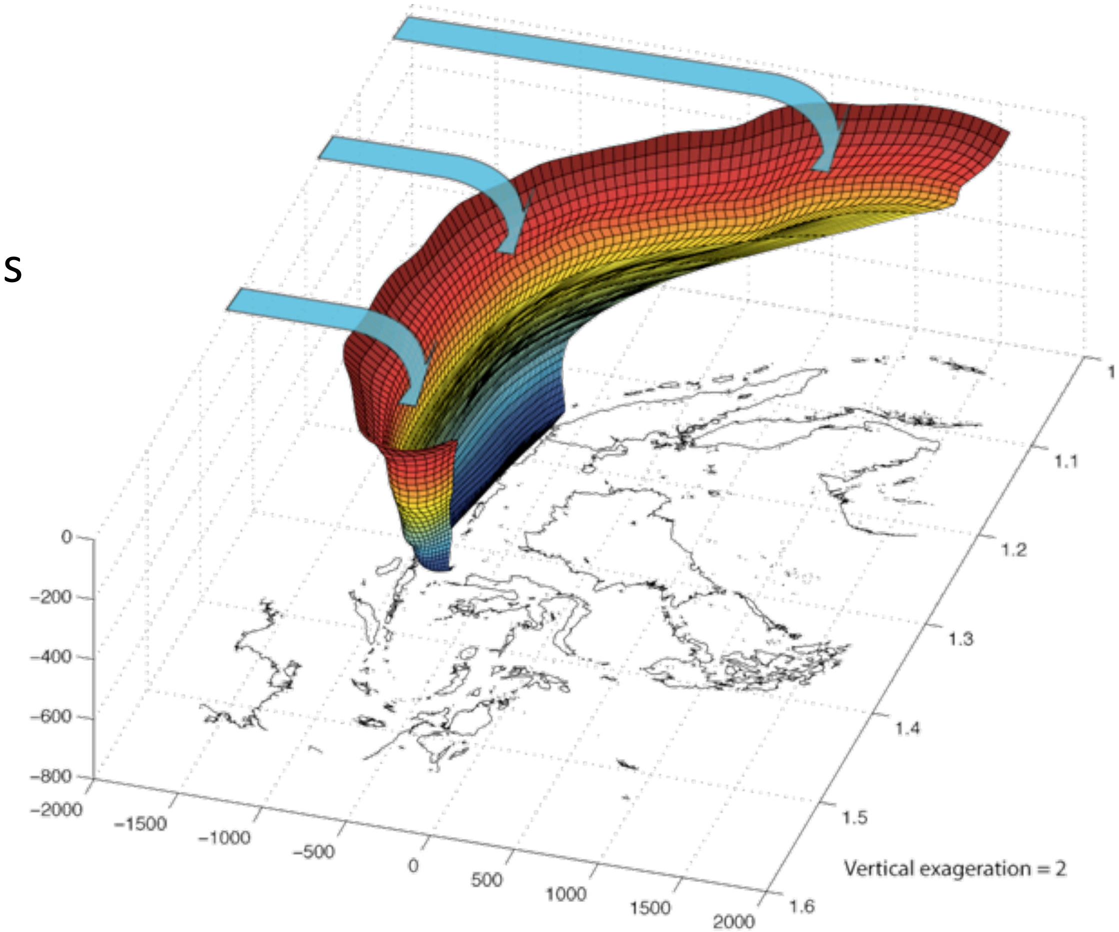






Interpretation

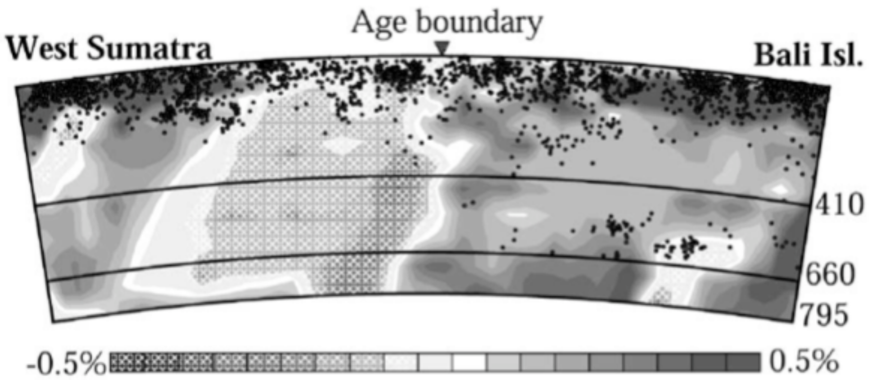
- Change in geometry reason for difference between Java and Sumatra?
  - Change in fast direction is very rapid (almost 90 degrees over a few 100s of km)
  - Flow geometry changes much more gradually around the arc (?)
  - **Seems an unlikely explanation***



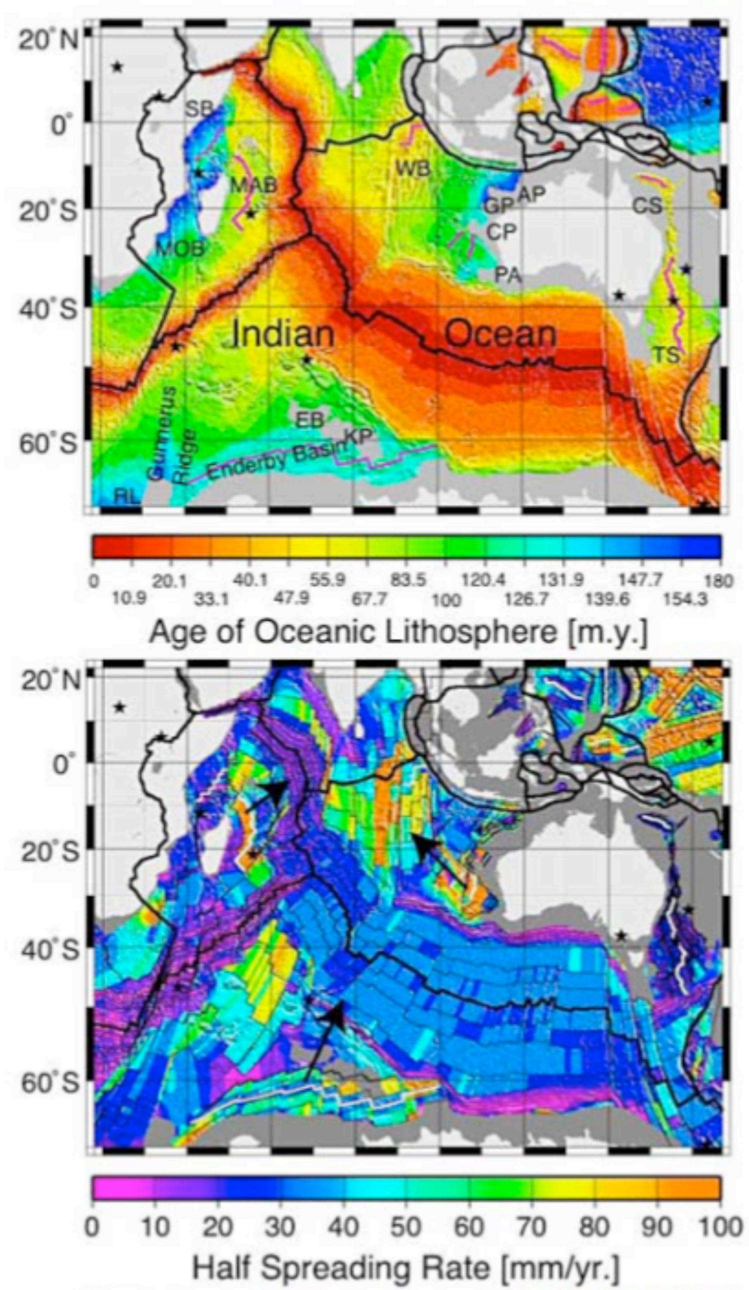
Slab geometry from Gudmundsson and Sambridge (1998)

Interpretation

- Change in slab?
  - Depth of seismicity (<400km beneath Sumatra; down to 660km beneath Java)
  - Seafloor characteristics (age, spreading rate, crustal accretion)
  - Tomographic characteristics



(Gorbatov and Kennett; EPSL, 2003)

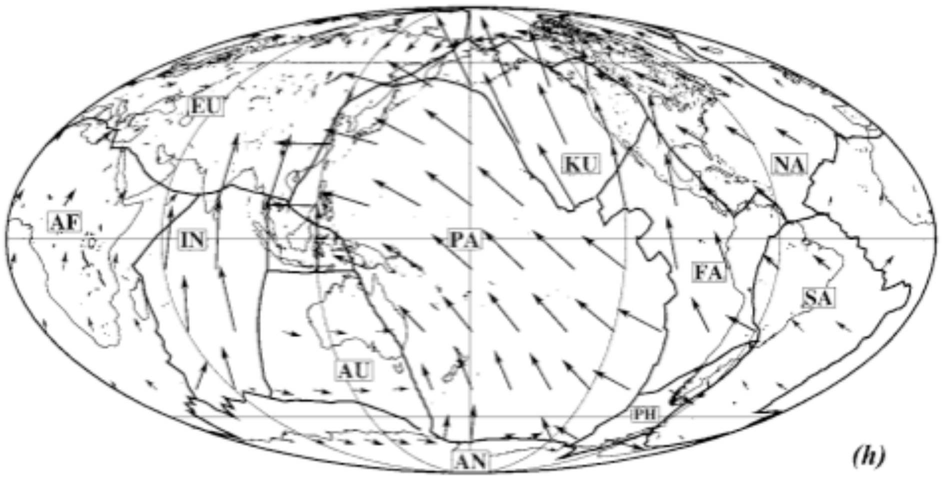


Muller et al (G3, 2008)

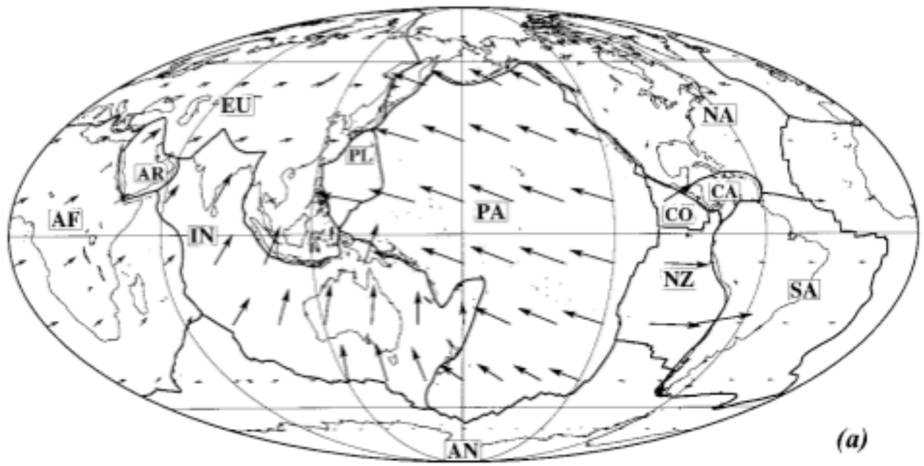
Interpretation

- Change in slab characteristics coincides with change in anisotropy characteristics; reasonable to assume that anisotropy is related to the slab in this region (?)
- Possible causes of anisotropy difference
    - Difference in mineralogy? (Javan slab is older, colder)
    - Fossil anisotropy (reconstructions suggest that early plate motions of the material being subducted beneath Java were East-West)

~80Ma



Present day



[Lithgow-Bertelloni and Richards; JGR, 1998]

Outstanding questions

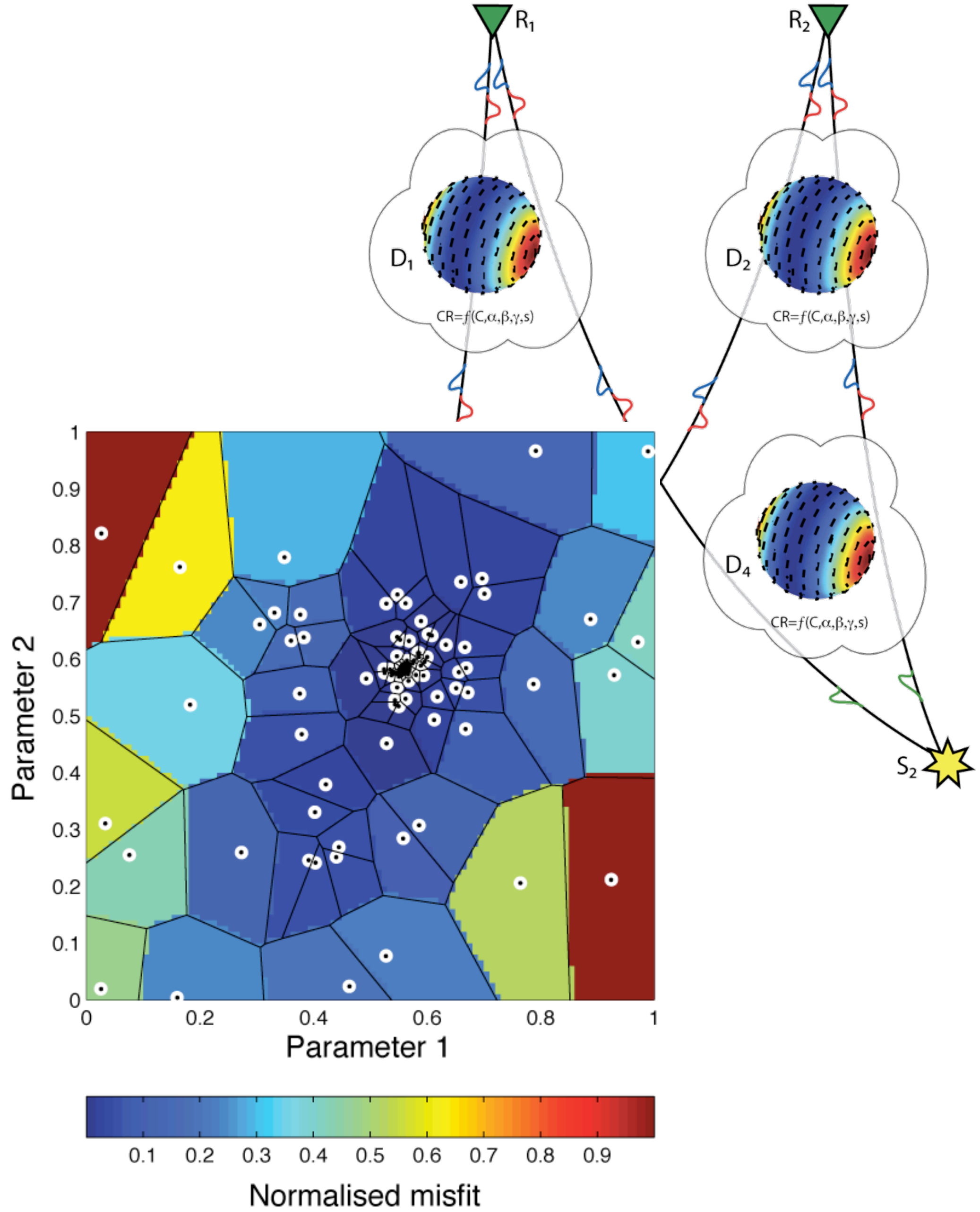
- Data and modelling suggest strong difference between the slab beneath Java and Sumatra

- Reason is still unclear
  - Geometry?
  - Age/History?
  - Other factors (fluids, mineralogy)?

- Plenty of scope to improve modelling …
  - Incorporation of better petrophysics
  - Incorporation of geodynamic constraints

… and observation

- tomographic approach to analysis of shear-wave splitting
  (e.g., Abt and Fischer, 2008)
- allows more flexibility in anisotropic model
- Method modified to use the data themselves (Wookey, 2009, in prep)
  - More robust objective function
  - Better incorporation of uncertainties
- Neighbourhood algorithm to make nonlinear parameter space search efficient



ESR7 - *Imaging the distribution of fluids and of the deformation above the active Indonesian subduction zone*

Jenny Di Leo

- Data analysis
  - Receiver functions
  - Tomography (+ attenuation?)
  - Extension of shear-wave splitting, and SWS tomography

- Incorporation of better constraints into the model
  - Plasticity modelling, better strain
  - Geodynamic constraints (effect of slab geometry)

- Answer some of the outstanding questions
  - Why the sharp transition between Java and Sumatra?
  - Role of fluids in the system?
  - How does this compare with further round the arc