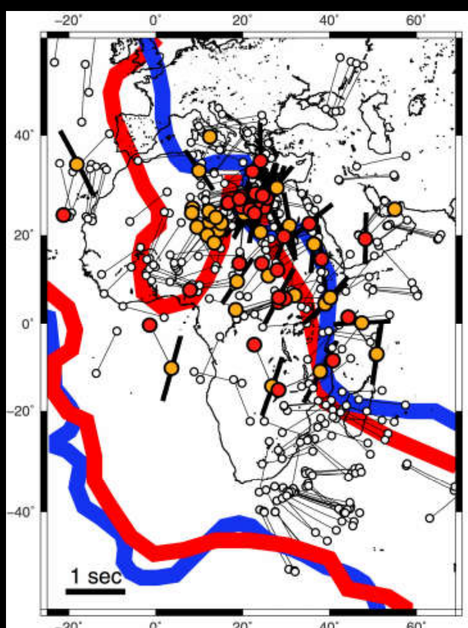
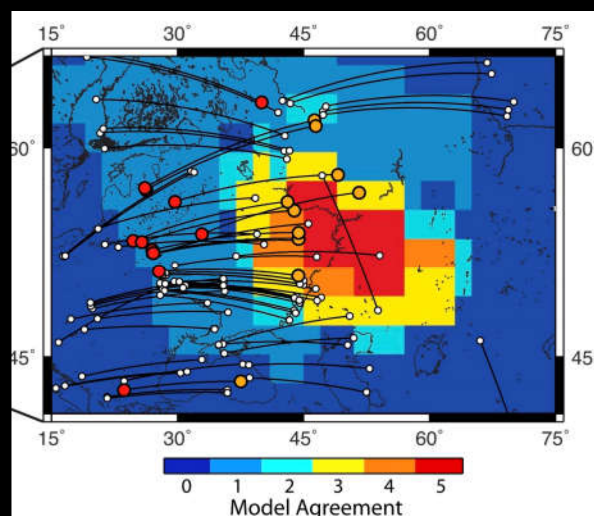
Seismology 5: Body wave anisotropy

what it is, how we study it, and what it can tell us about flow in the deep Earth

Maureen D. Long, Yale University





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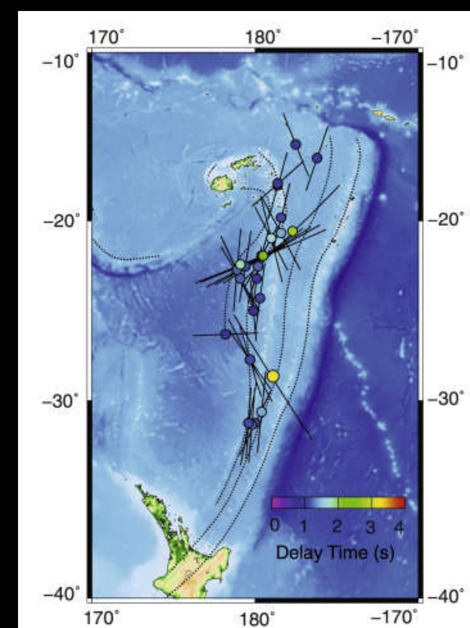


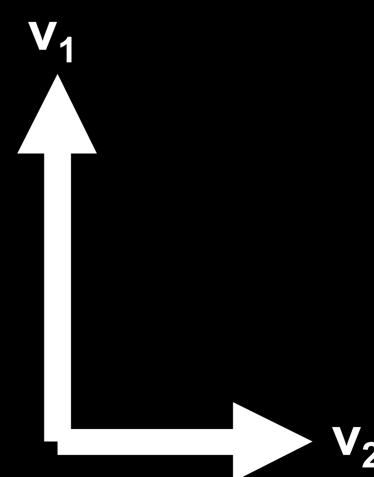
Road map for today's talk

- Part I: Some anisotropy basics, measurement strategies, and caveats
- Part II: Seismic anisotropy in the upper mantle in subduction systems: what does this tell us about subduction dynamics?
- Part III: Anisotropy in the deep mantle and implications for deep mantle flow
  - Transition zone and uppermost lower mantle
  - Lowermost mantle (D") anisotropy

Part I: What is seismic anisotropy, and how do we measure it with body waves?

Olivine: highly anisotropic;
dominant upper mantle constituent

The **speed** at which a seismic wave propagates depends on its **direction** (of propagation, or of polarization).



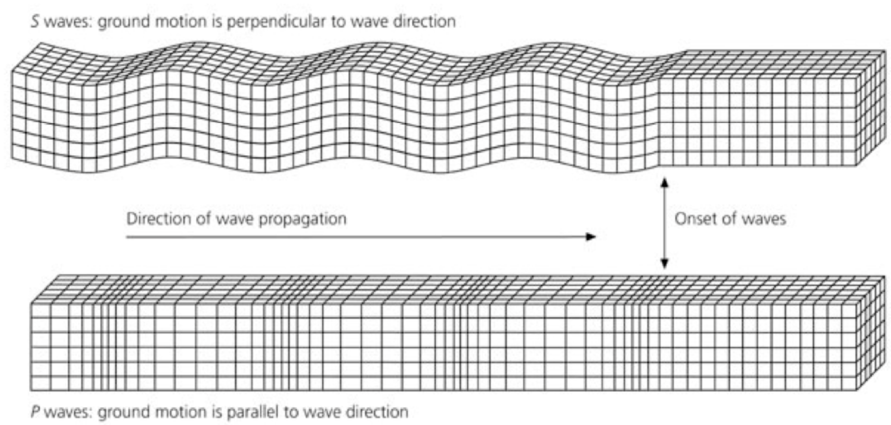
Think back to last week's lectures on body waves…

In an isotropic solid only two elastic moduli are independent, and there are two types of waves, P and S

Figure 2.4-3: Displacements for *P* and *S* waves.

$$\beta = v_S = \sqrt{\frac{\mu}{\rho}}$$

$$\alpha = v_P = \sqrt{\frac{\kappa + \frac{4}{3}\mu}{\rho}}$$



modified from Stein and Wysession, 2009

Slide from Goran Ekstrom, CIDER 2013

If the material is anisotropic…

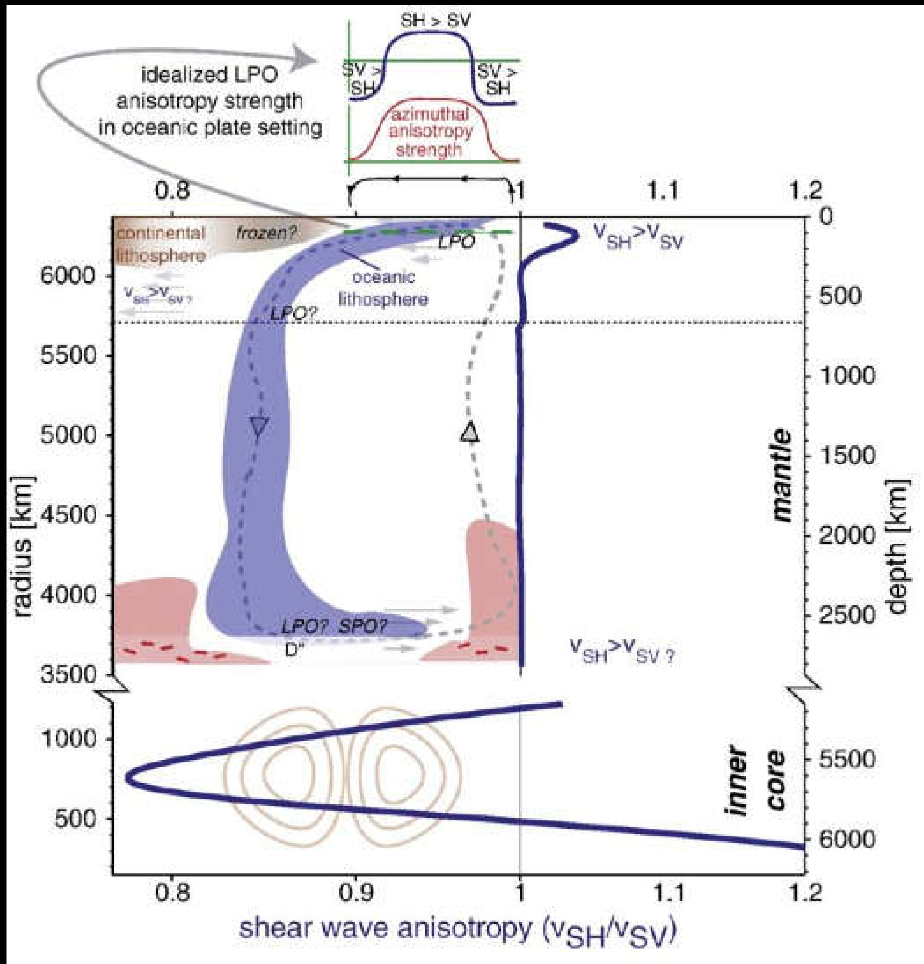
Hooke's law: $\sigma_{ij} = c_{ijkl} e_{kl}$

21 independent terms:

$$C_{mn} = \begin{pmatrix} c_{1111} & c_{1122} & c_{1133} & c_{1123} & c_{1113} & c_{1112} \\ c_{2211} & c_{2222} & c_{2233} & c_{2223} & c_{2213} & c_{2212} \\ c_{3311} & c_{3322} & c_{3333} & c_{3323} & c_{3313} & c_{3312} \\ c_{2311} & c_{2322} & c_{2333} & c_{2323} & c_{2313} & c_{2312} \\ c_{1311} & c_{1322} & c_{1333} & c_{1323} & c_{1313} & c_{1312} \\ c_{1211} & c_{1222} & c_{1233} & c_{1223} & c_{1213} & c_{1212} \end{pmatrix} = \begin{pmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{pmatrix}$$

The equations get quite tricky, but here's the upshot: wavespeed varies with direction; there are now 3 possible polarizations (quasi-P and two quasi-S waves)

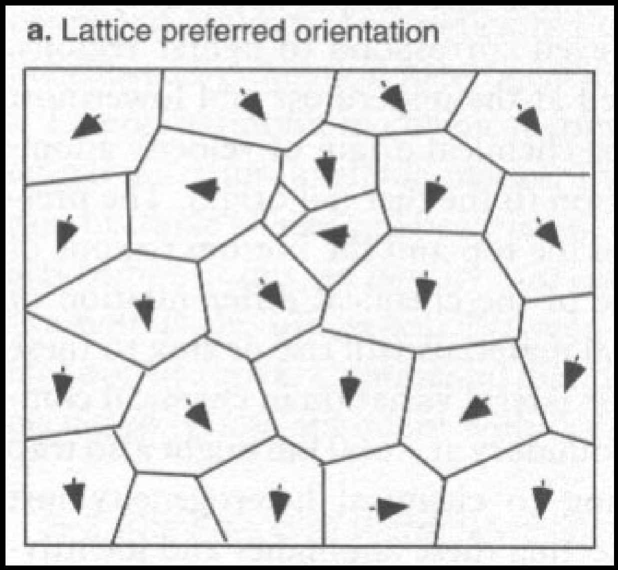
Where in the Earth do we have anisotropy?



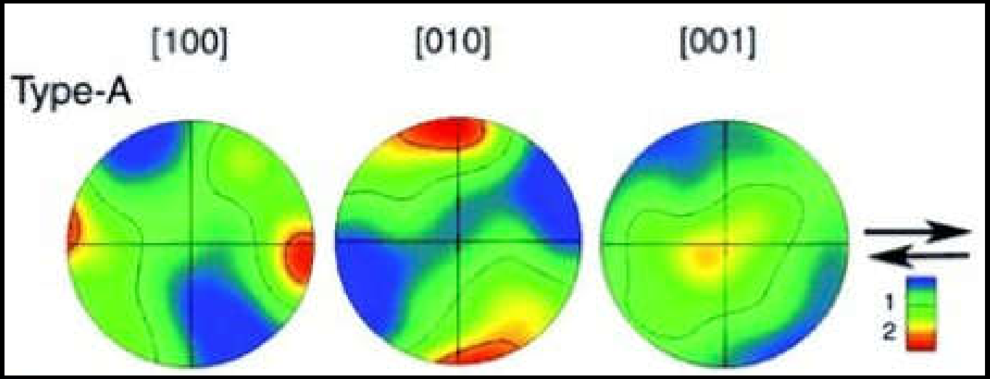
Long, M. D., Becker, T. W., 2010. Mantle dynamics and seismic anisotropy, *Earth Planet. Sci. Lett., 279,* 341-354.

Why is the upper mantle anisotropic?

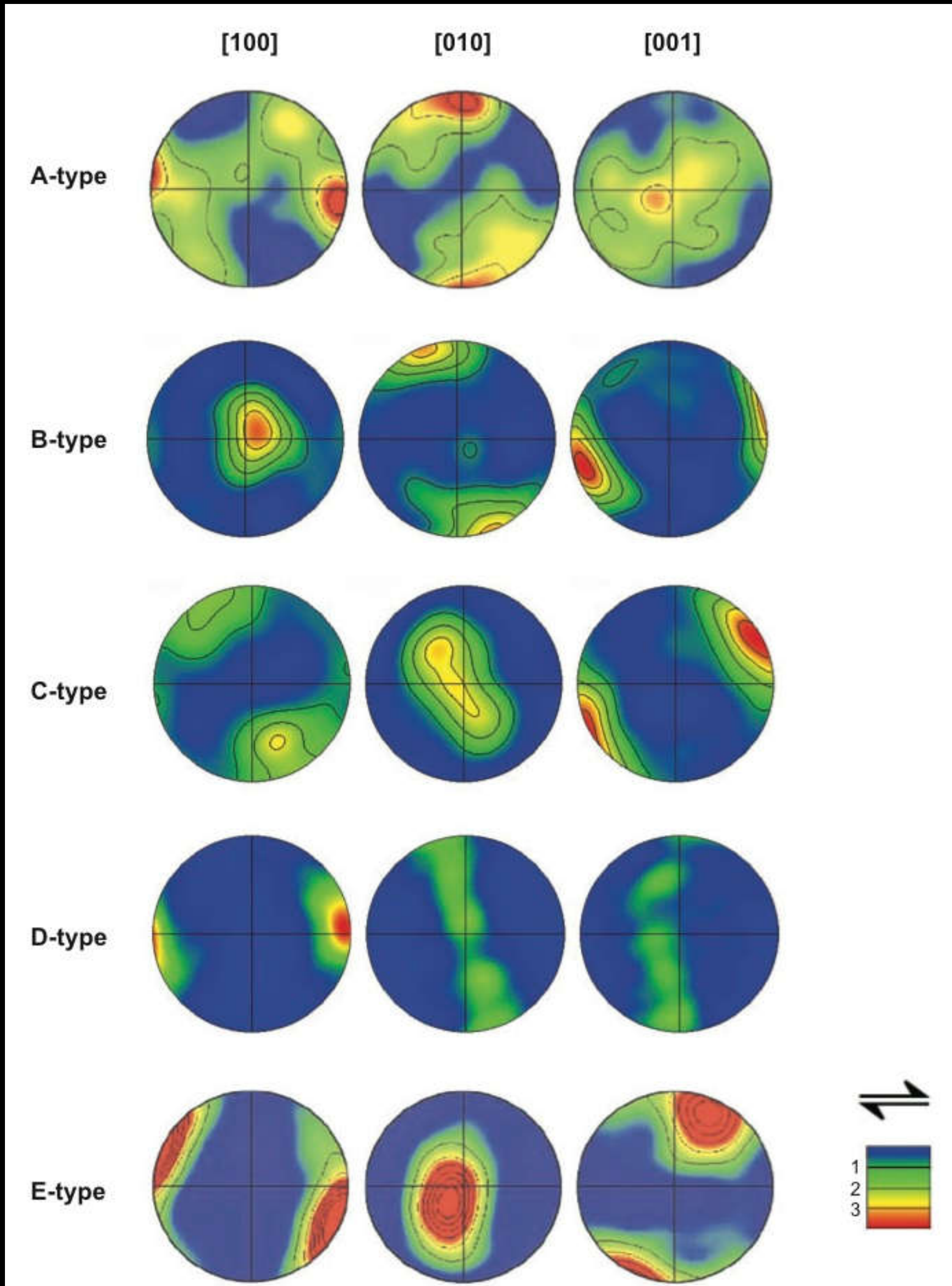
When a collection of mineral crystals (a rock) undergoes **deformation** (under certain conditions), individual crystals tend to align in certain directions. This is known as **lattice preferred orientation** (LPO or CPO) and results in seismic anisotropy that is "felt" by seismic waves.

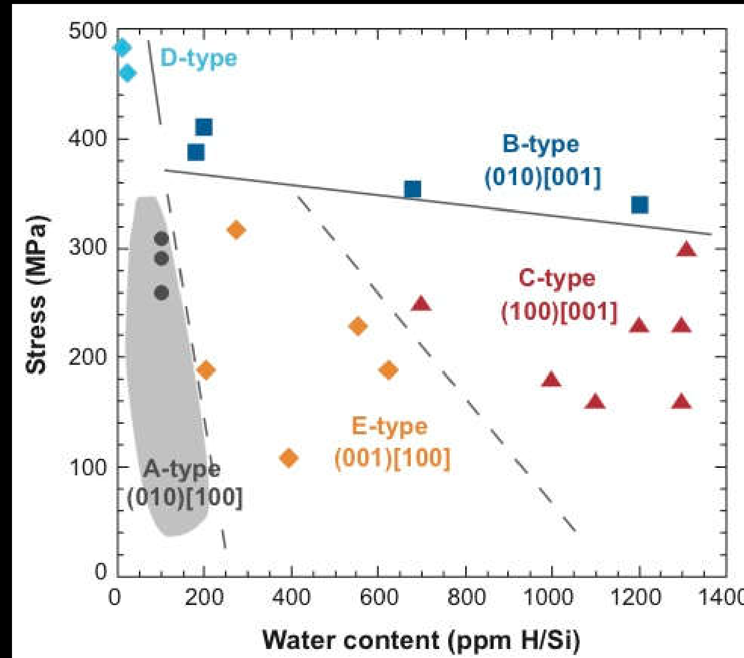


Karato, 2003



Jung and Karato, 2001





Constraints on olivine LPO from laboratory experiments

Karato et al., 2008

Another mechanism for anisotropy: shape preferred orientation (SPO)

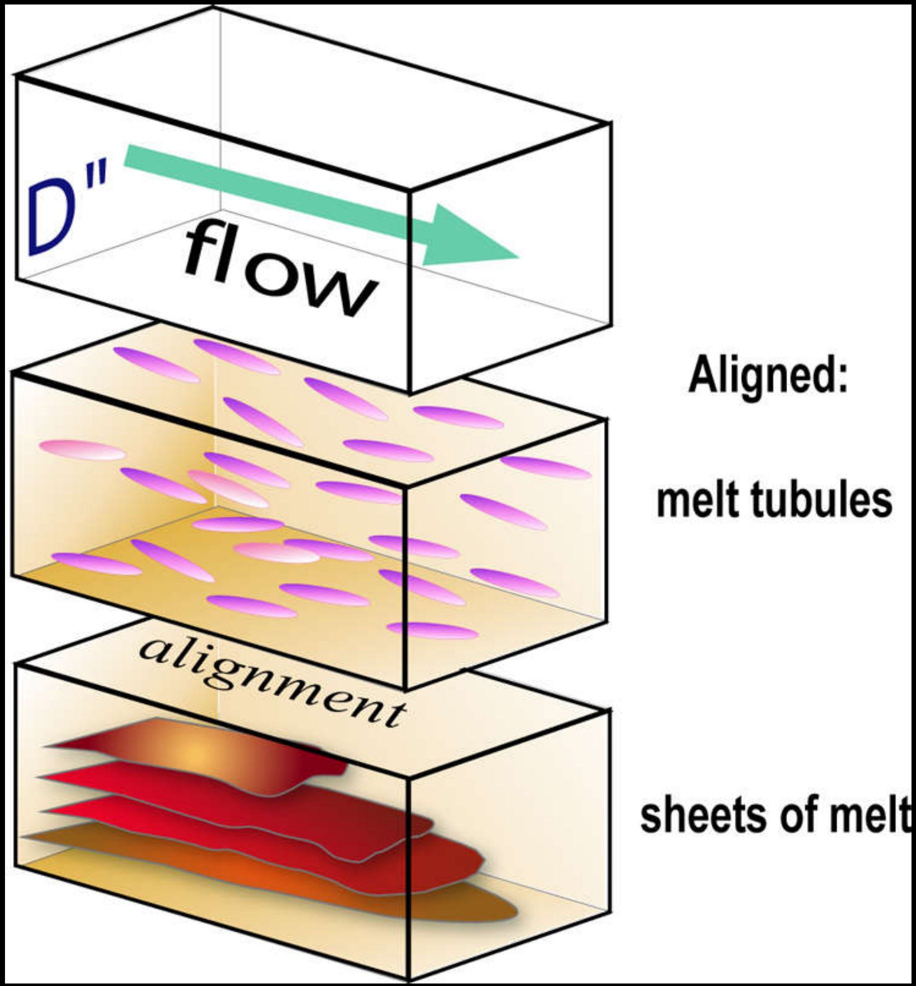
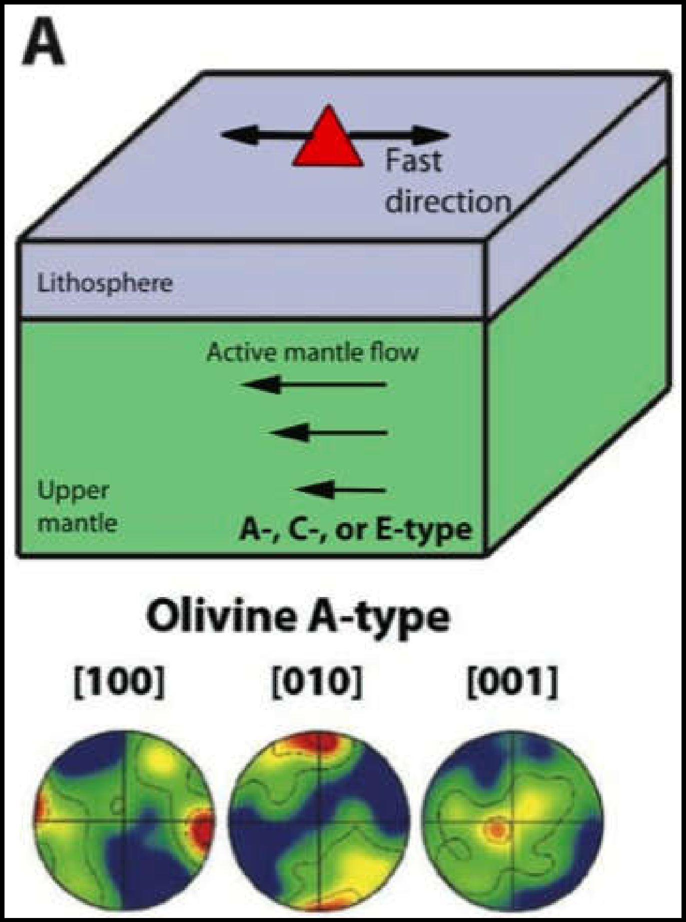
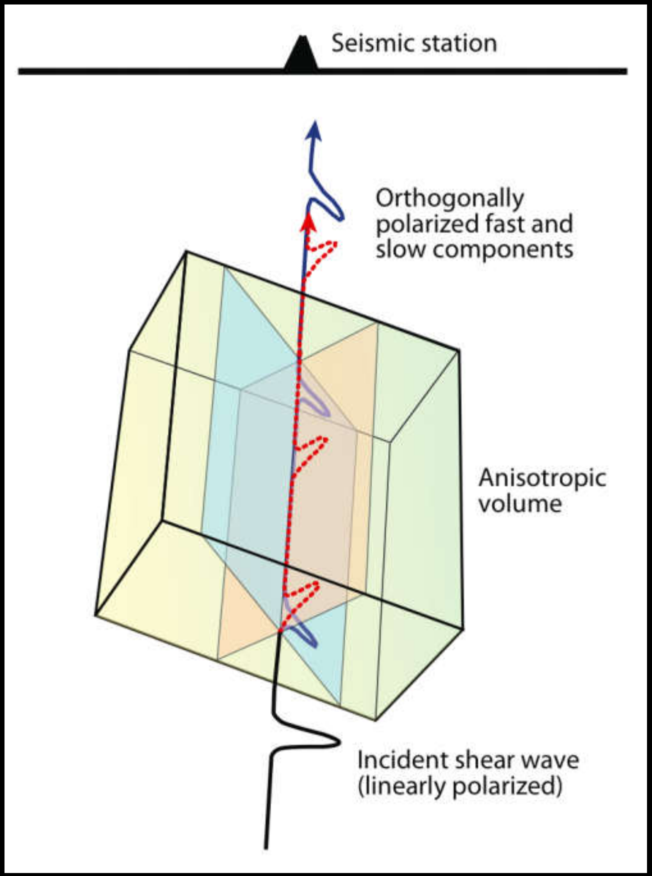


Image from Ed Garnero

Seismic anisotropy: a key tool for understanding mantle flow



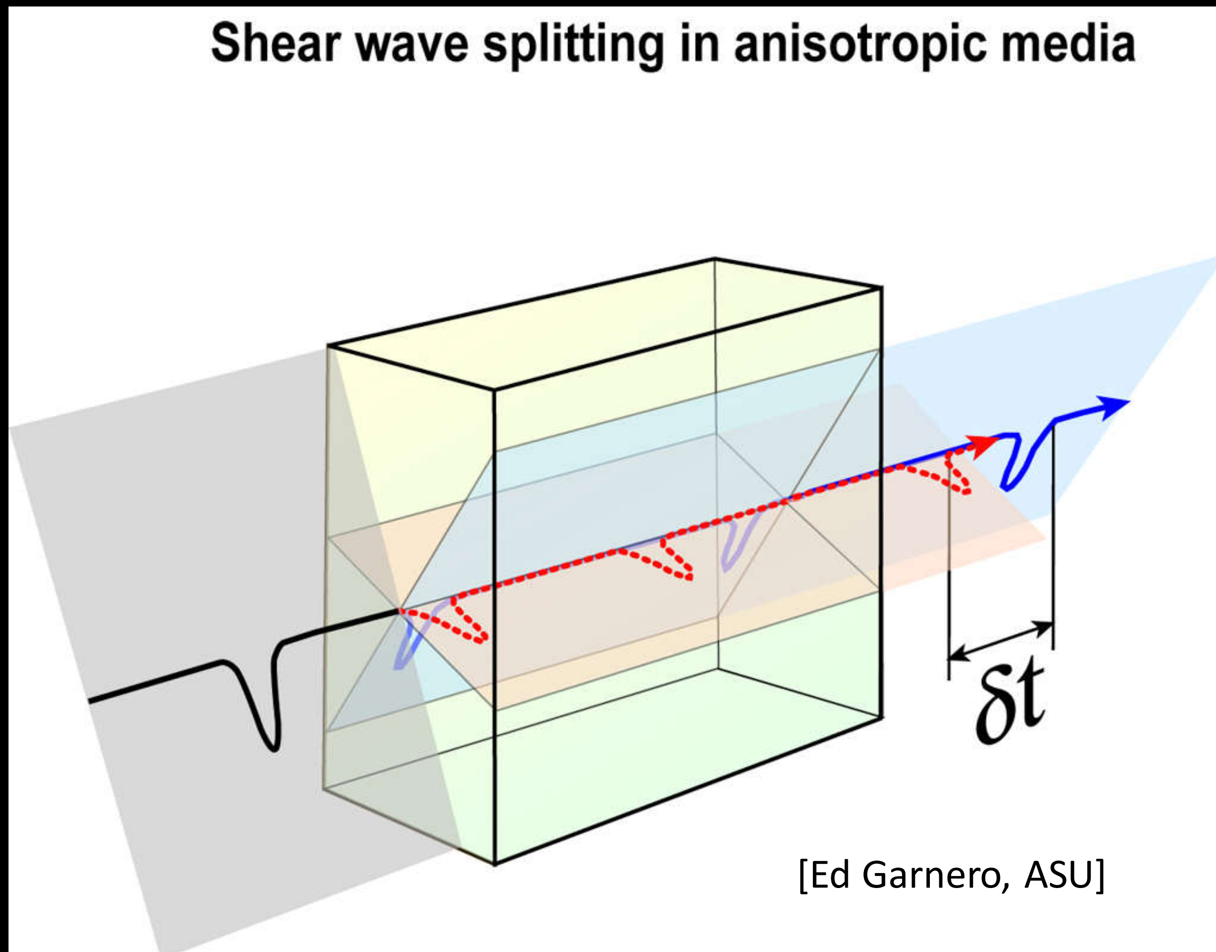
Long & Becker, EPSL, 2010



(OVER)SIMPLIFIED RULE OF THUMB: fast direction = direction of horizontal mantle flow beneath station

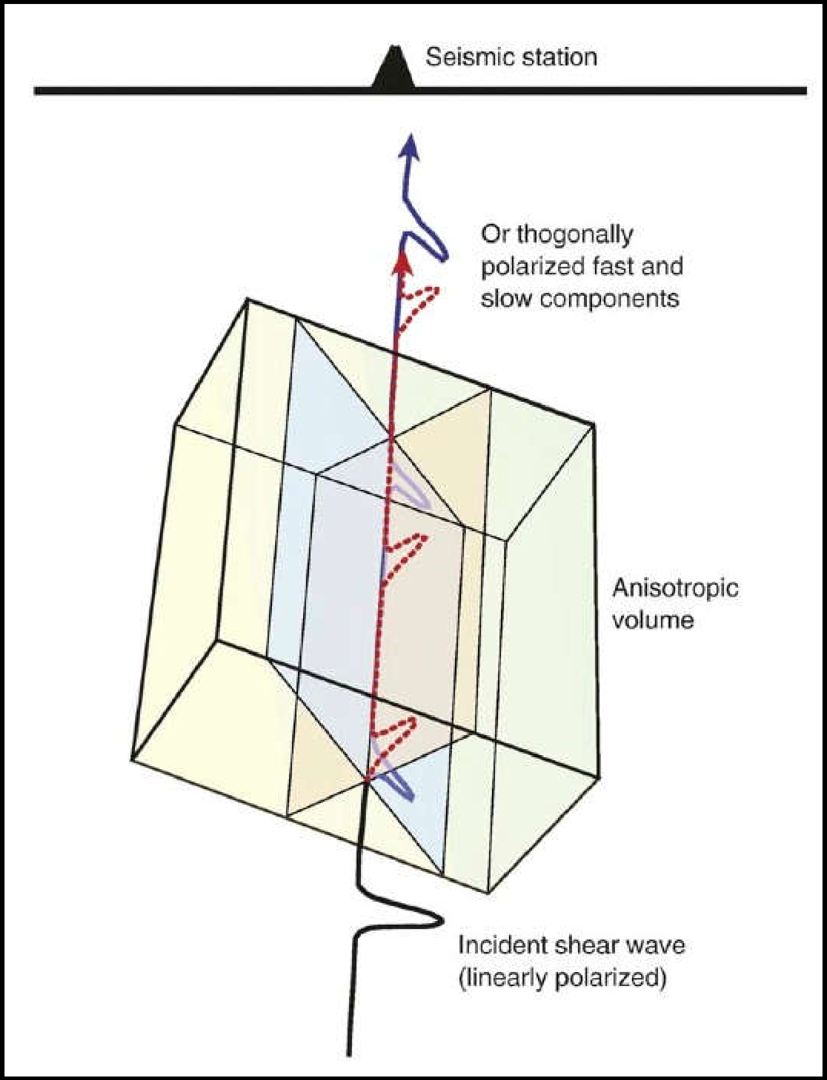
Mantle flow ➔ LPO of anisotropic minerals ➔ seismic anisotropy

What is shear wave splitting?

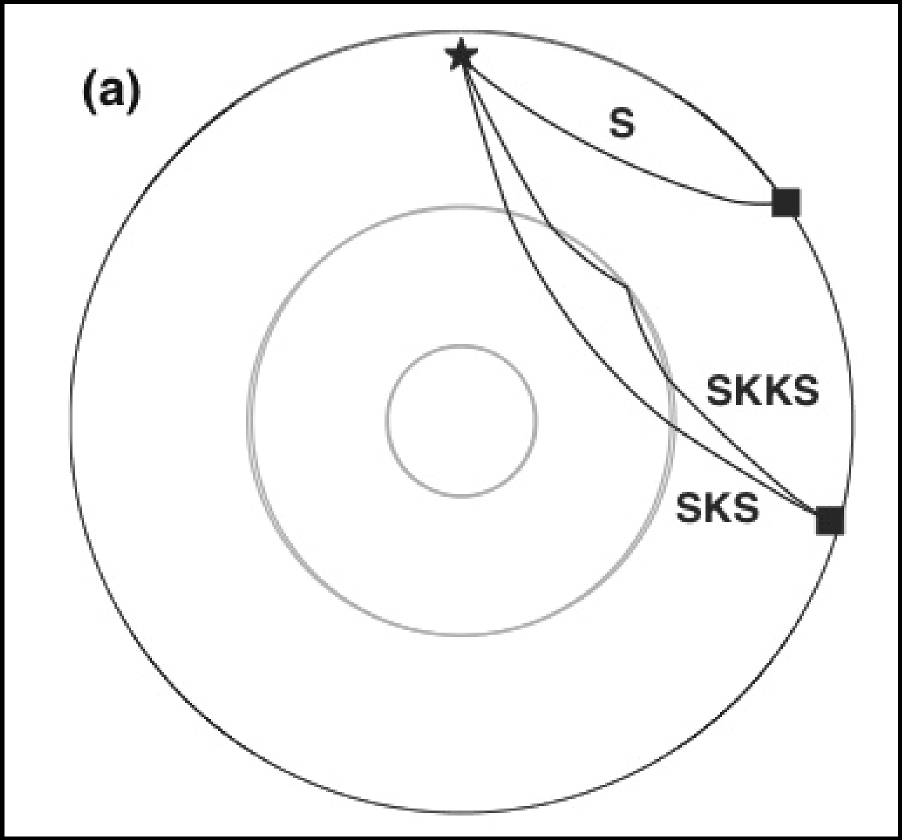


A shear wave is split into two orthogonal components that travel with different wavespeeds. The fast polarization direction (ϕ) and time separation (δt) depend on the characteristics of the anisotropic medium.

What is shear wave splitting?

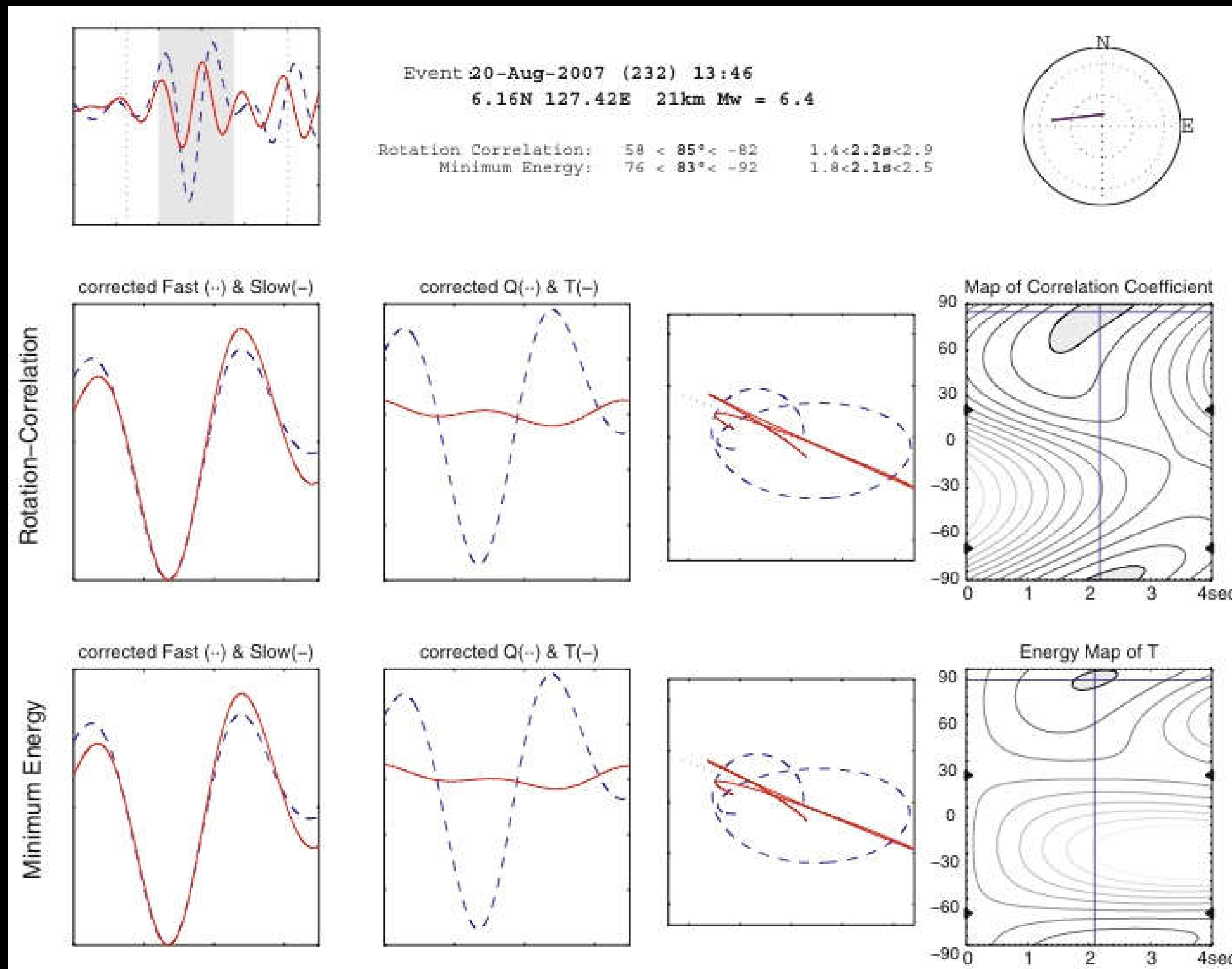


Long & Becker 2010



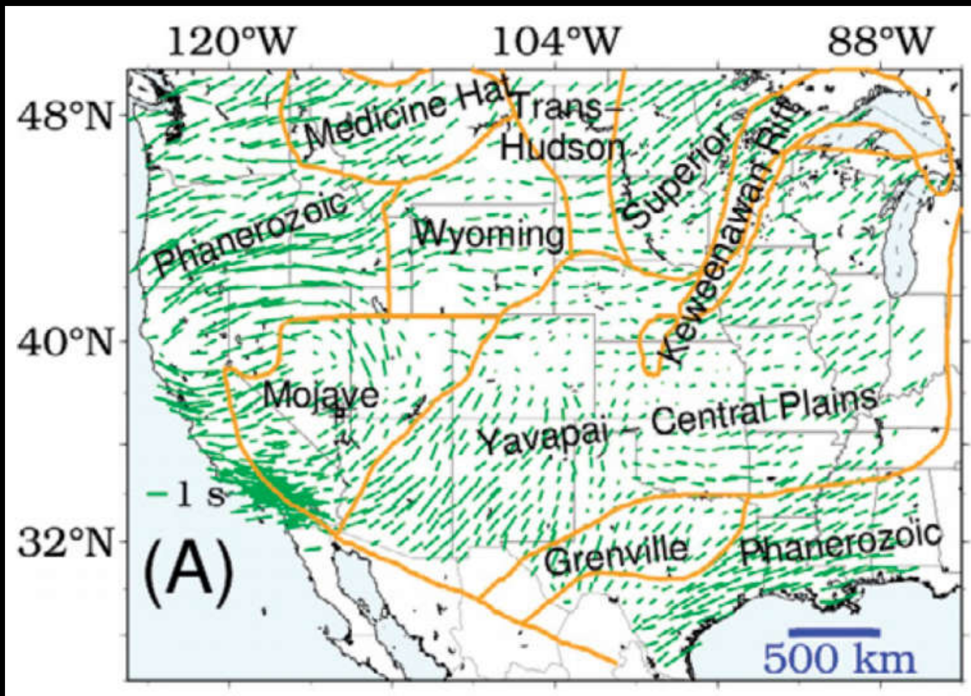
Long & Silver 2009

An example of a shear wave splitting measurement

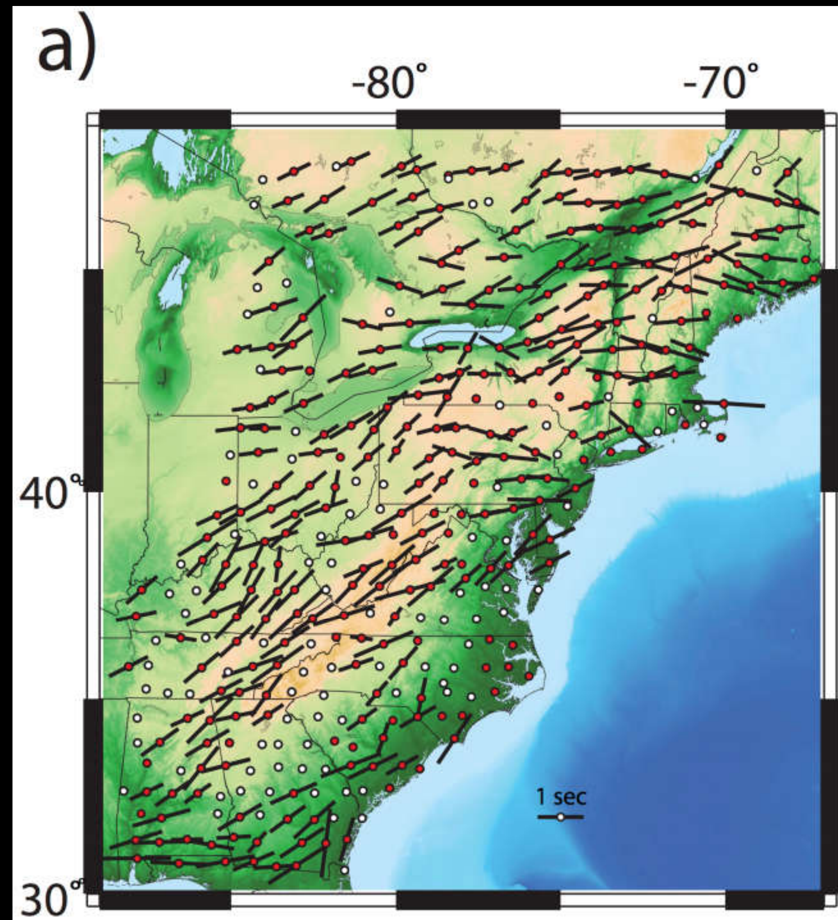


Long & Silver, Surv. Geophys. 2009

Examples of SKS splitting data sets: USArray



Hongsresawat et al., 2015

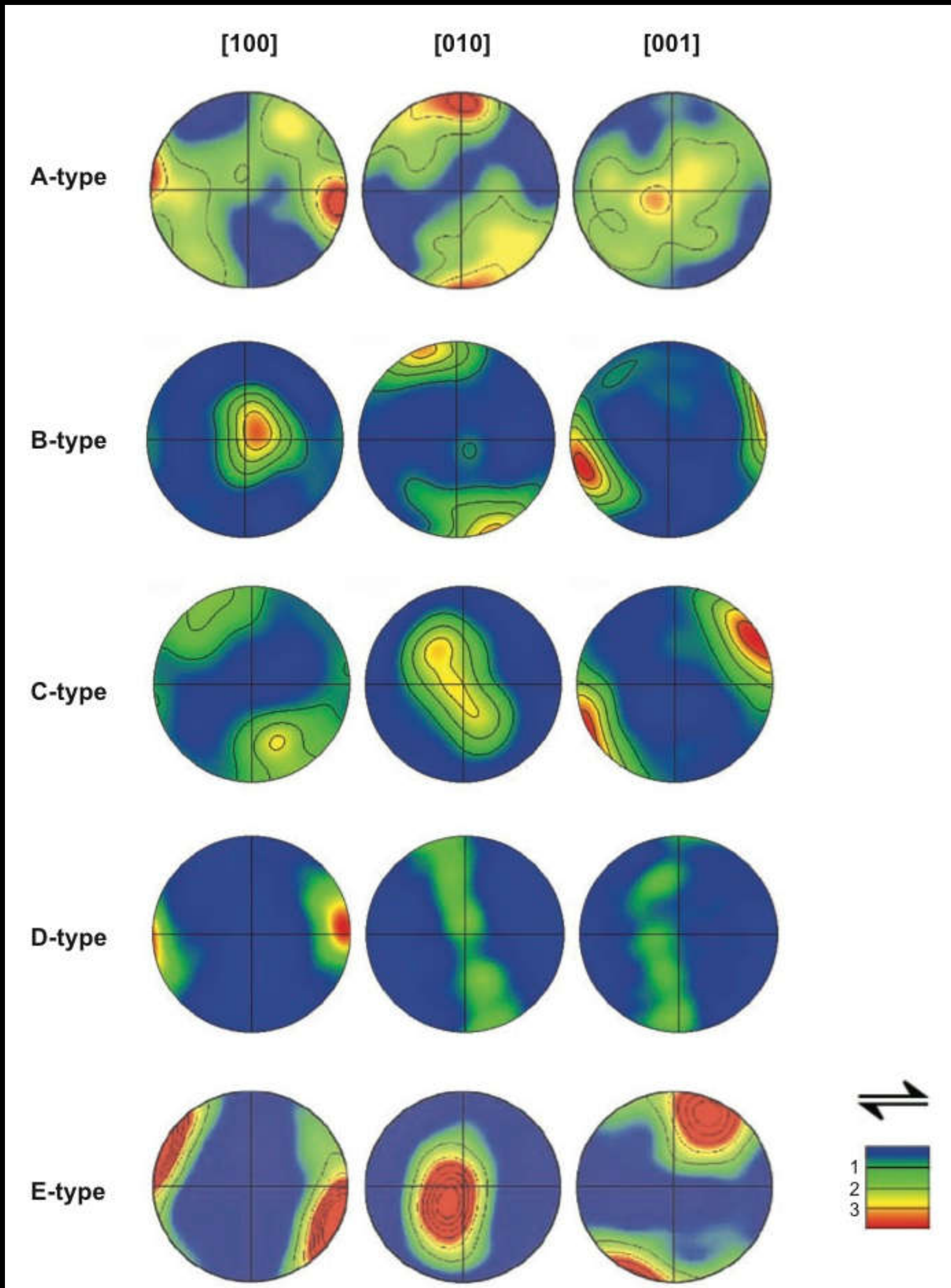


Long et al., 2016

New results from USArray: excellent geographic coverage, can be combined with surface waves/receiver functions to produce joint models (e.g. Romanowicz and collaborators). Key question: contributions from lithosphere vs. asthenosphere? Multiple layers? Present-day mantle flow vs. past lithospheric deformation?

So: observations of seismic anisotropy have the potential to tell us about dynamic processes in the Earth's mantle

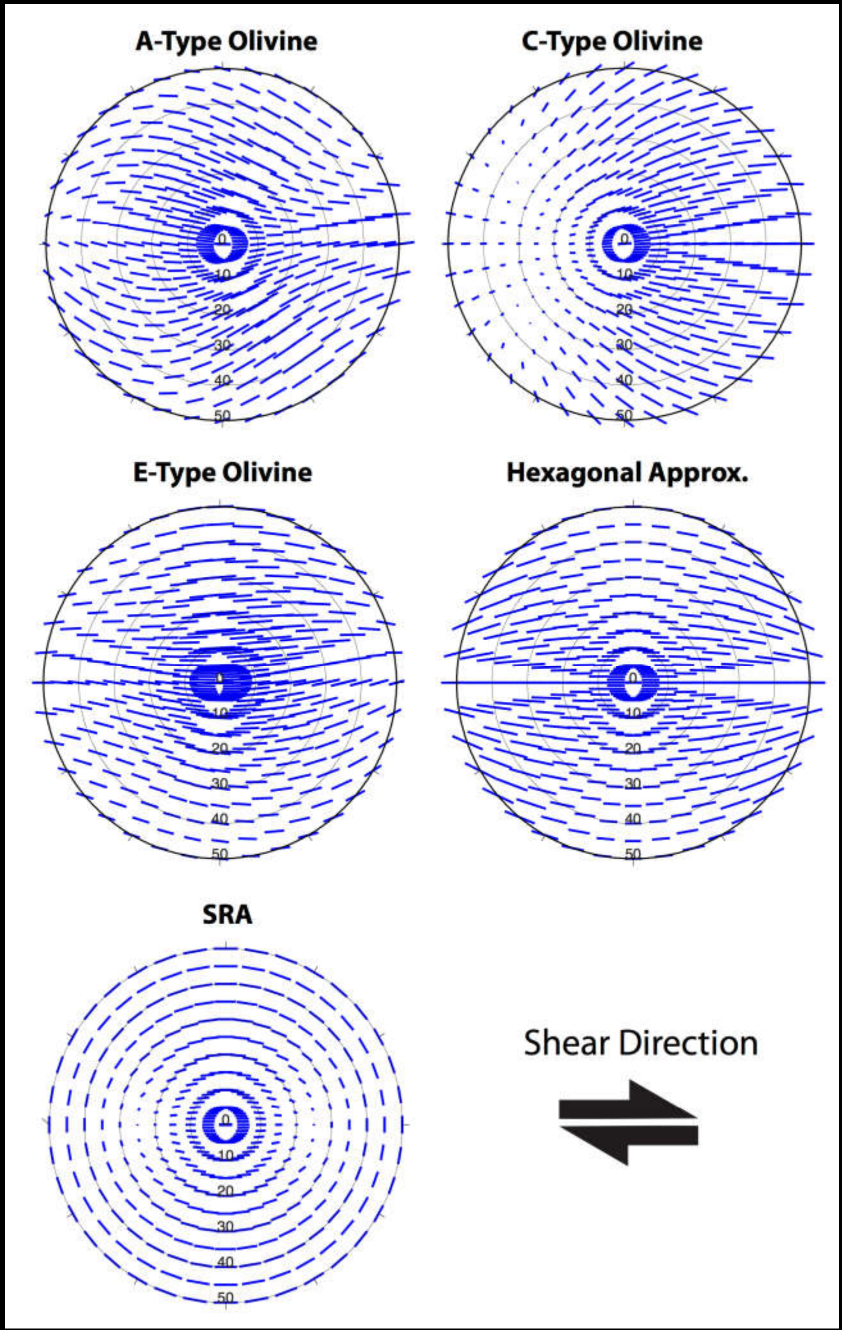
What are the caveats?



Many different olivine fabric types, each of which will have a different effect on the overall anisotropic signature.

Some differences are subtle, others major.

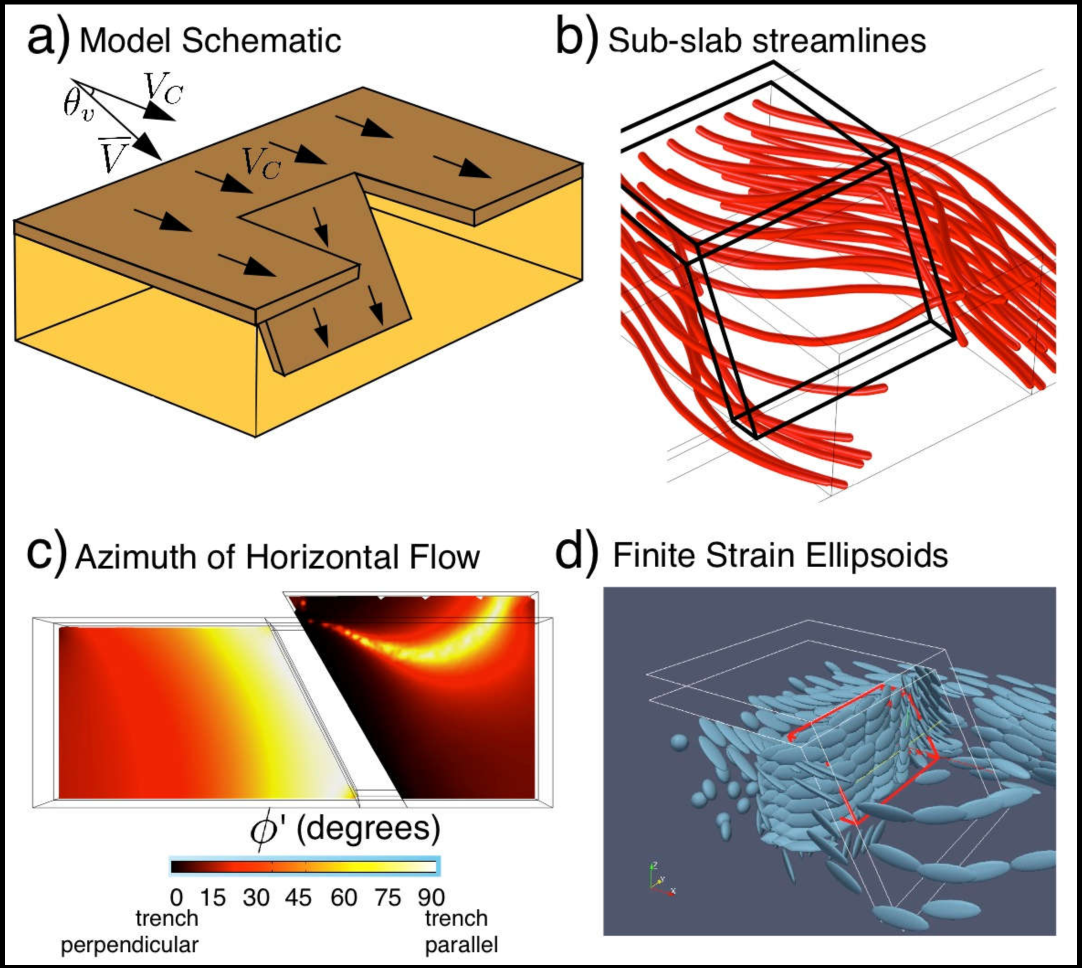
Karato et al., 2008



Many different olivine fabric types, each of which will have a different effect on the overall anisotropic signature.

Some differences are subtle, others major.

Lynner et al., submitted

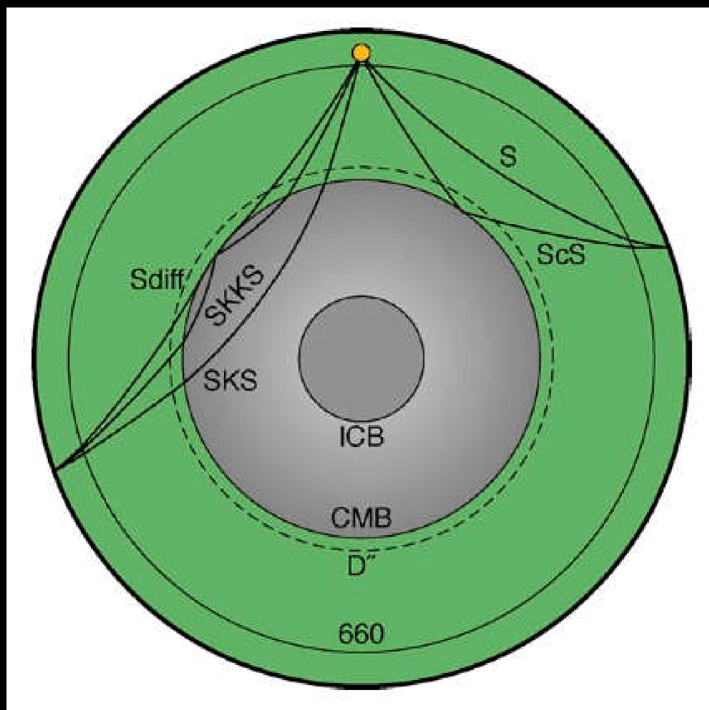


Paczkowski et al., 2014

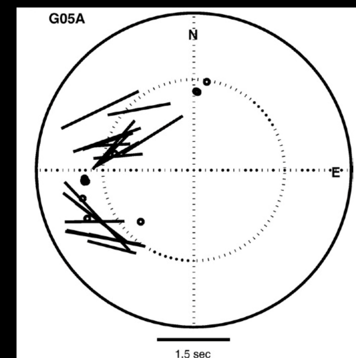
Anisotropy in the mantle is a complicated function of the (time-integrated) mantle strain, fabric type, etc.

"Rules of thumb" relationships between mantle flow direction and fast anisotropy directions are useful to a point, but they are simplifications!

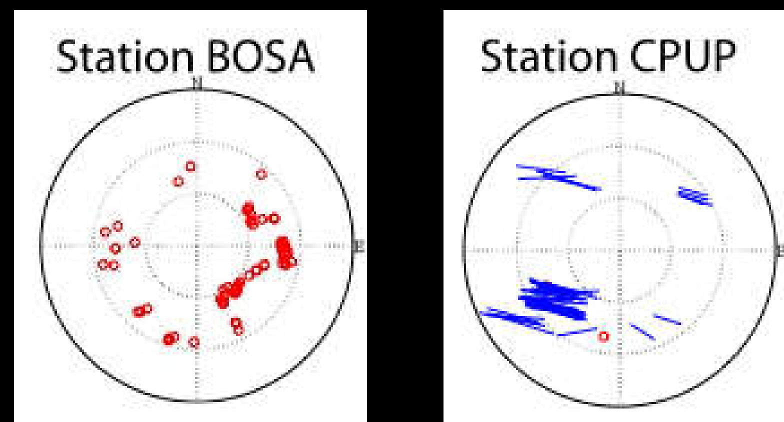
Another major challenge for deep mantle anisotropy: raypath coverage and correcting for the upper mantle



Nowacki et al., JG [2011]



Long et al. [2009]

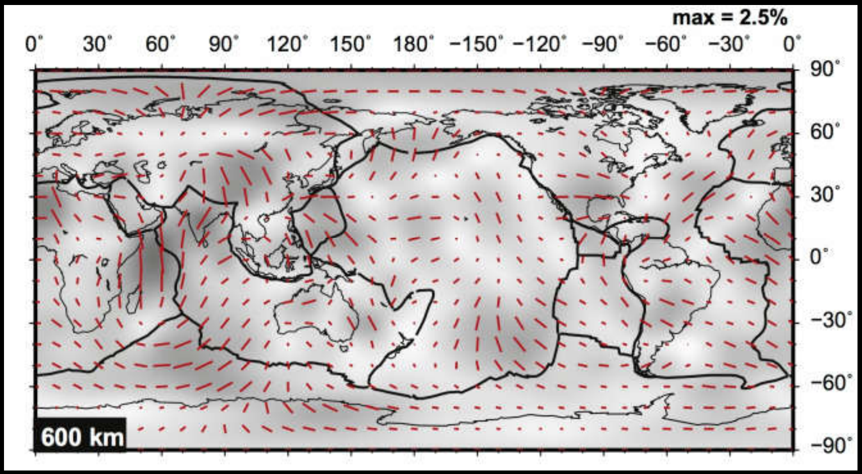


Lynner and Long, G^3 [2014]

All body wave phases suffer from the same limitation: rays have passed through the (anisotropic) upper mantle!

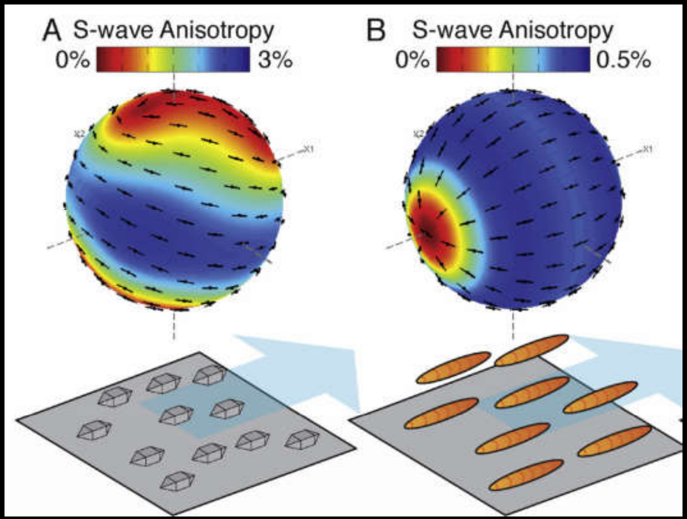
➔ STATION SELECTION extremely important.

And yet another limitation: mechanisms for deep mantle anisotropy (TZ, uppermost lower mantle, D”) poorly known



Yuan and Beghein, EPSL 2013

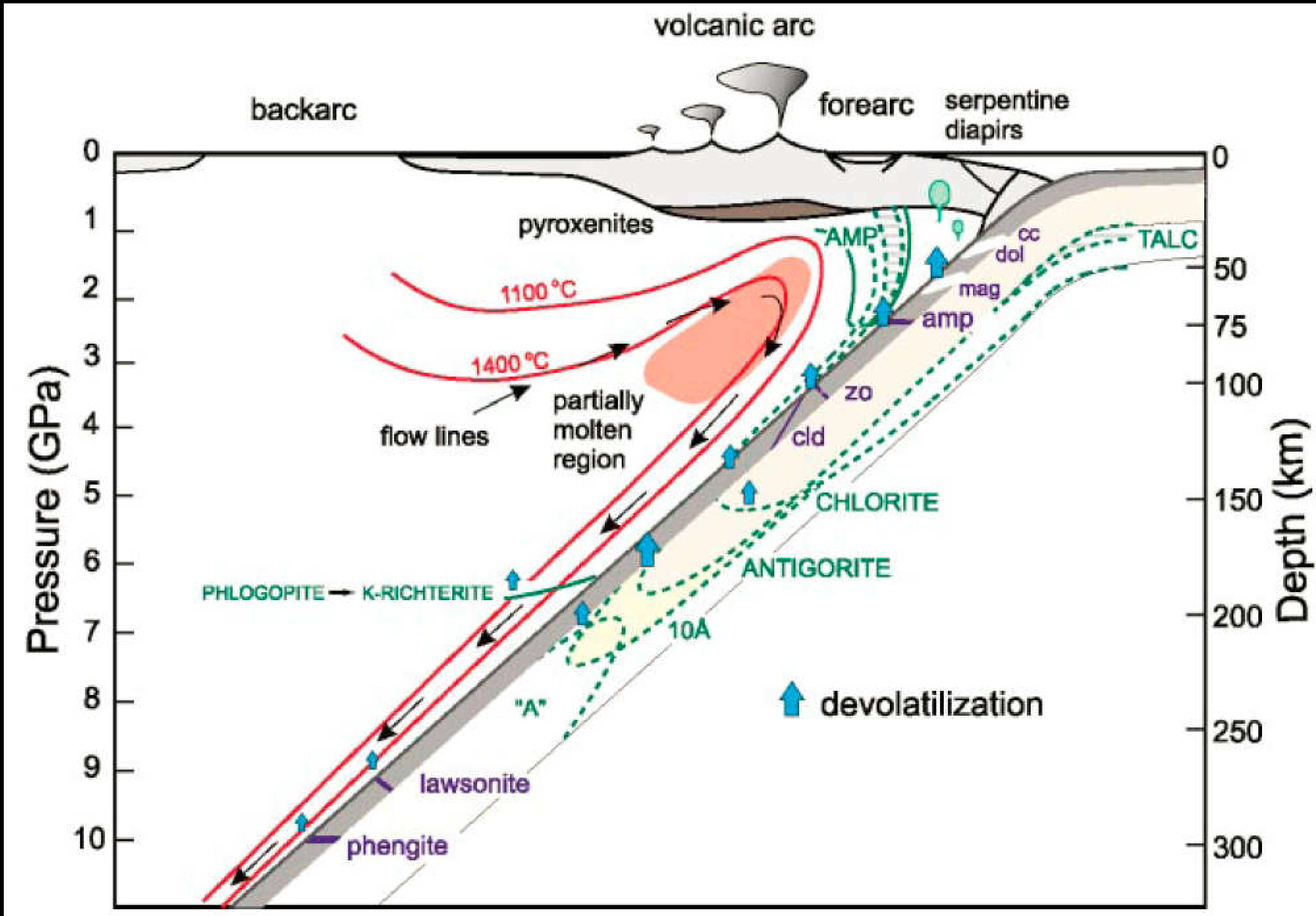
For the mid-mantle: which minerals contribute? What are relationships between strain and resulting anisotropy?



Nowacki et al., JG 2011

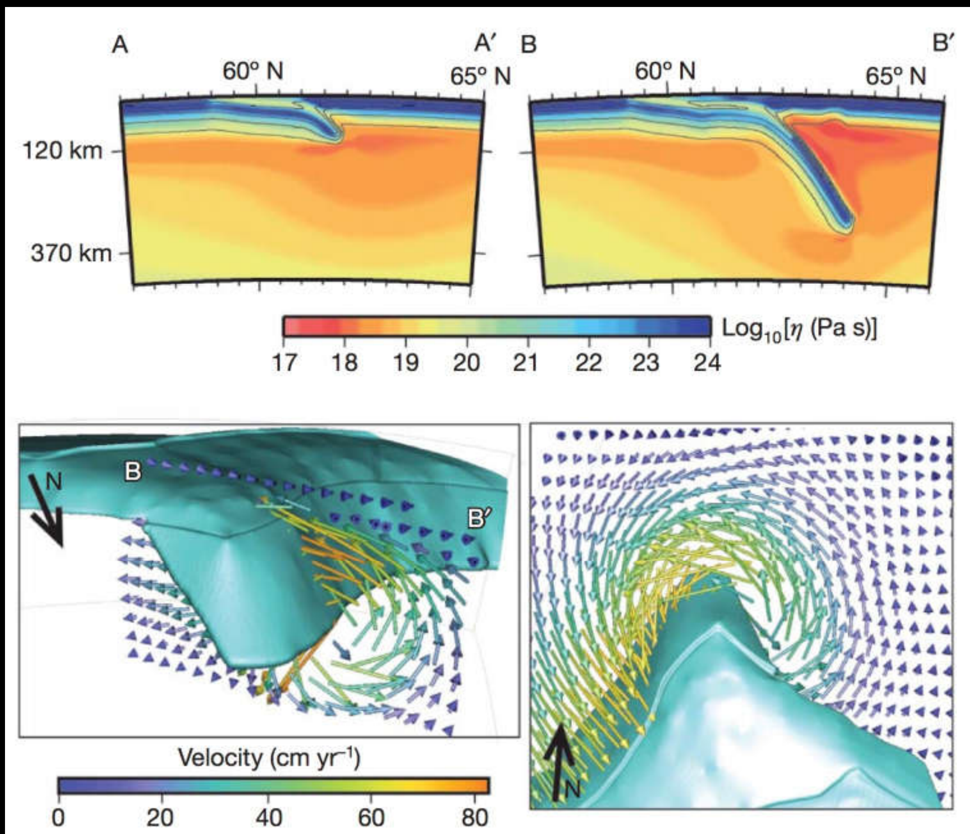
For the lowermost mantle: Is it LPO, SPO, or a combination? Which phases/materials contribute? What are single crystal elastic constants? Dominant slip systems? LPO patterns?

Part II: Anisotropy in subduction systems



Poli & Schmidt, 2002

But: the Earth is 3D, and mantle flow likely is too…



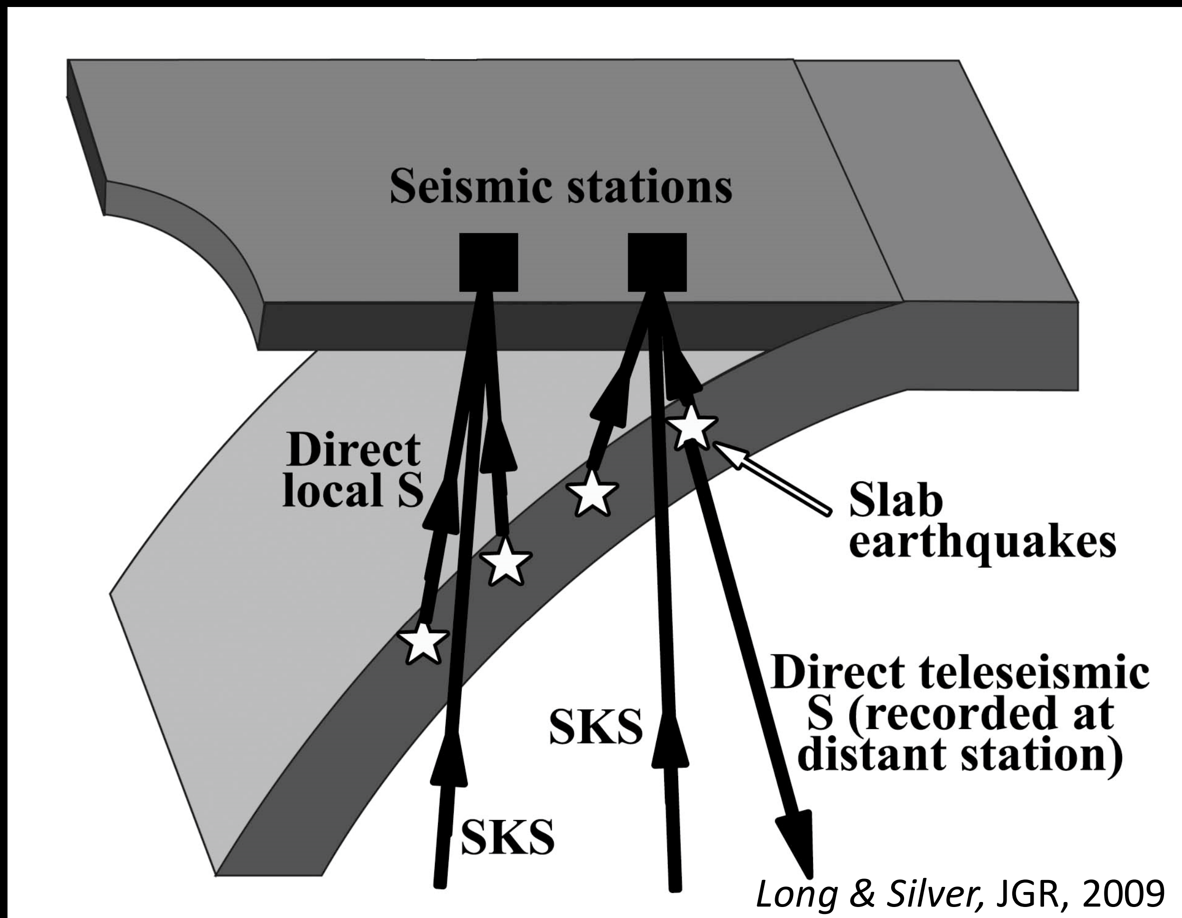
Jadamec and Billen, Nature, 2010

Key questions:

- What are relative importance of 2D flow vs. 3D flow?
- How much along-strike material transport is there? What are implications for melt transport, volatile cycling, etc.?
- What are driving forces for mantle flow in subducting systems?
- How well coupled are slabs to the surrounding mantle?

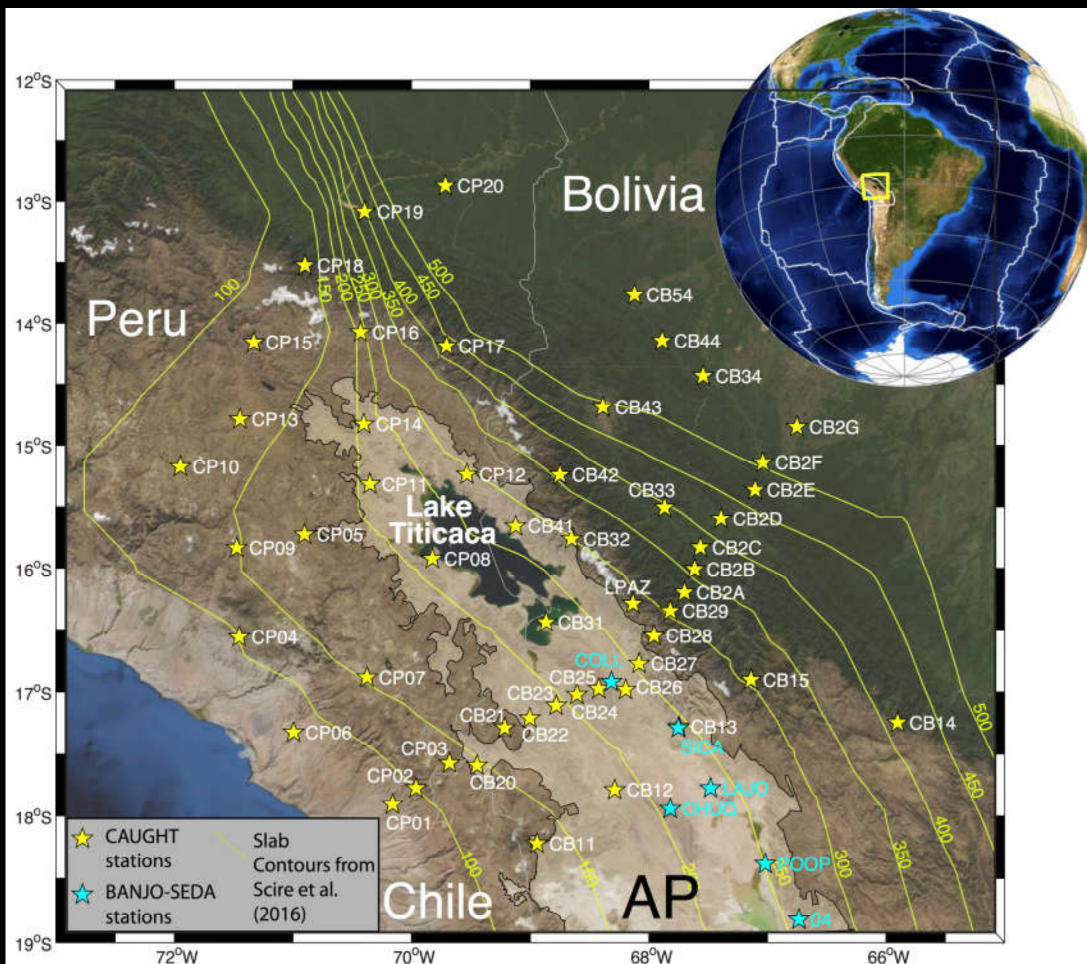
Observations of anisotropy can address these questions!

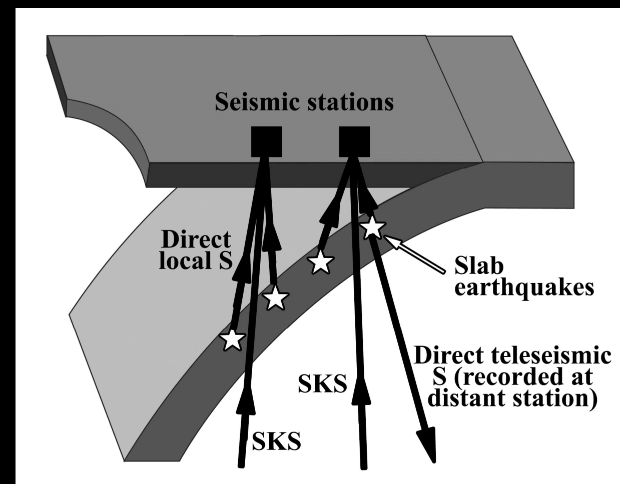
How to observe different parts of the subduction system?



[*NB: Isolating anisotropy in the slab itself is tricky, but see recent work by Eakin et al., Nature Geoscience 2016…*]

An example case study: southern Peru and northern Bolivia

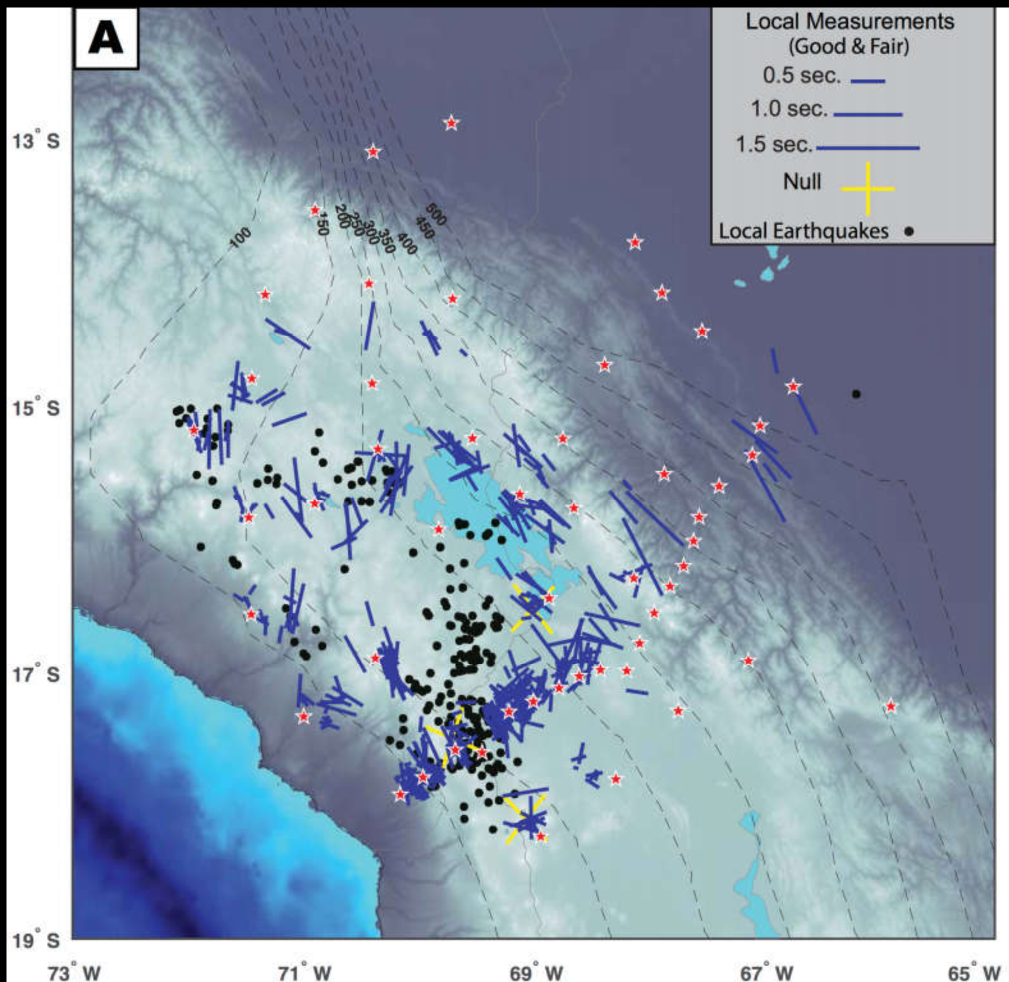




Goal: use different types of phases to constrain anisotropy in different parts of the system (particularly wedge vs. sub-slab)

Long et al., G^3, in press

An example case study: southern Peru and northern Bolivia

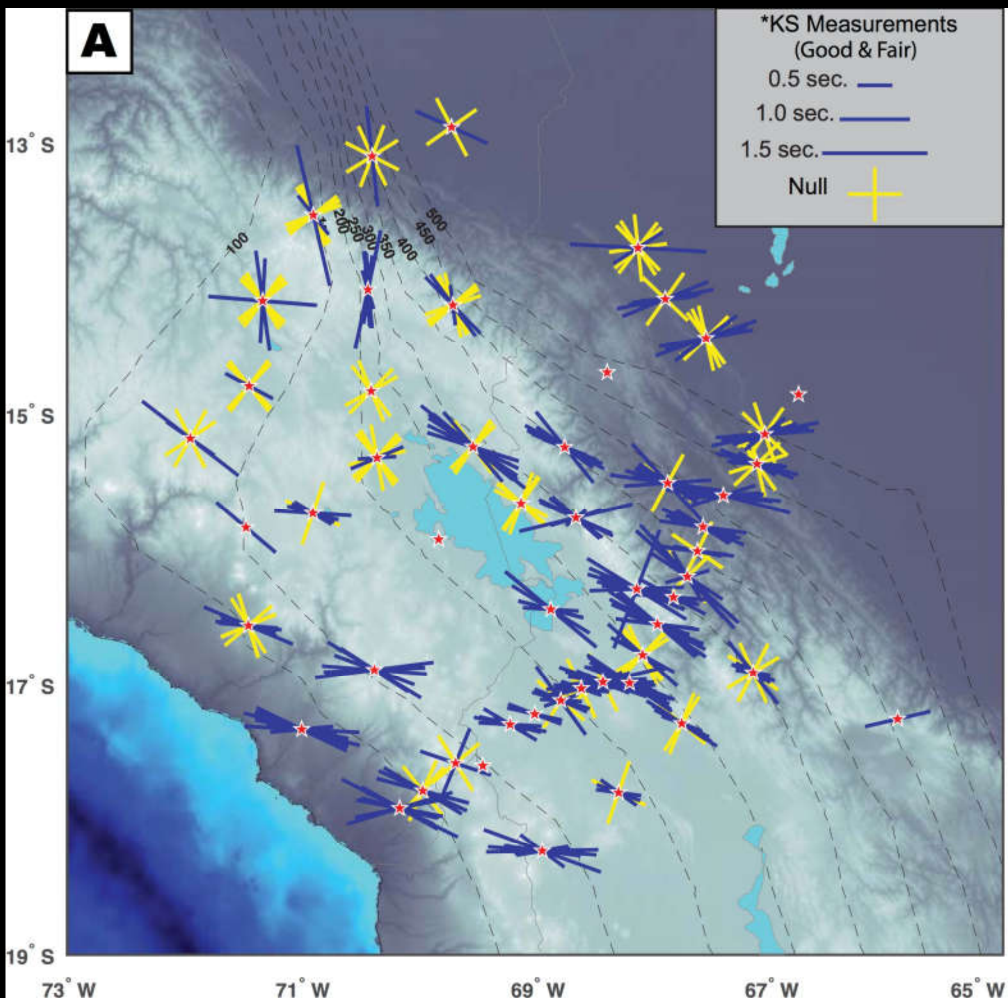


Long et al., G^3, in press

Local S splitting – mostly reflects mantle wedge anisotropy (+ overriding plate, which seems to be small here)

Patterns are complex, but lots of nearly slab-parallel fast directions

An example case study: southern Peru and northern Bolivia

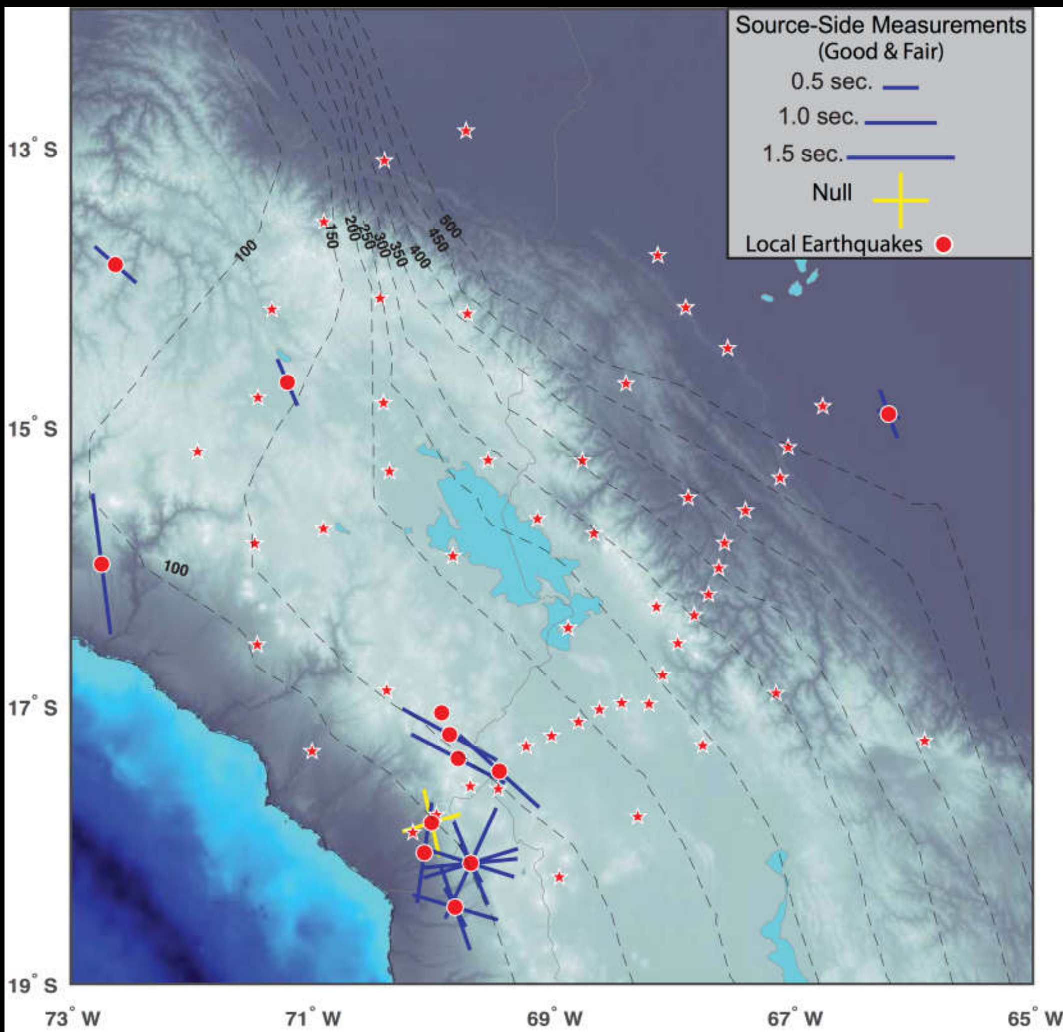


Long et al., G^3, in press

SKS splitting – reflects signal integrated over entire upper mantle

Dominated by slab-parallel fast directions, with region in north dominated by null (non-split) SKS arrivals

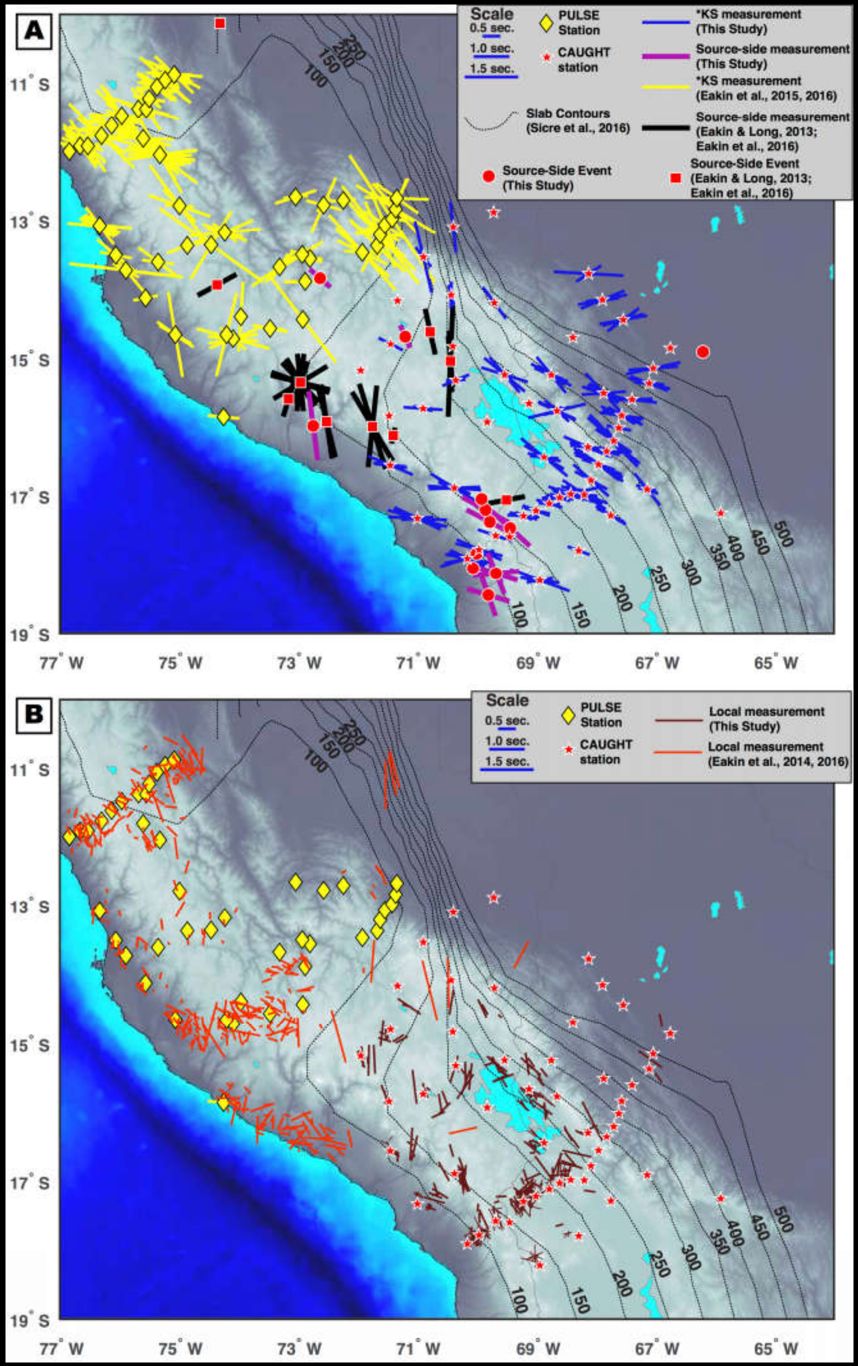
An example case study: southern Peru and northern Bolivia



Long et al., G^3, in press

Source-side splitting – mainly reflects anisotropy beneath the subducting slab

Fewer measurements with plenty of scatter, but lots of fast directions parallel to slab contours – not consistent with simple 2D entrained flow.s

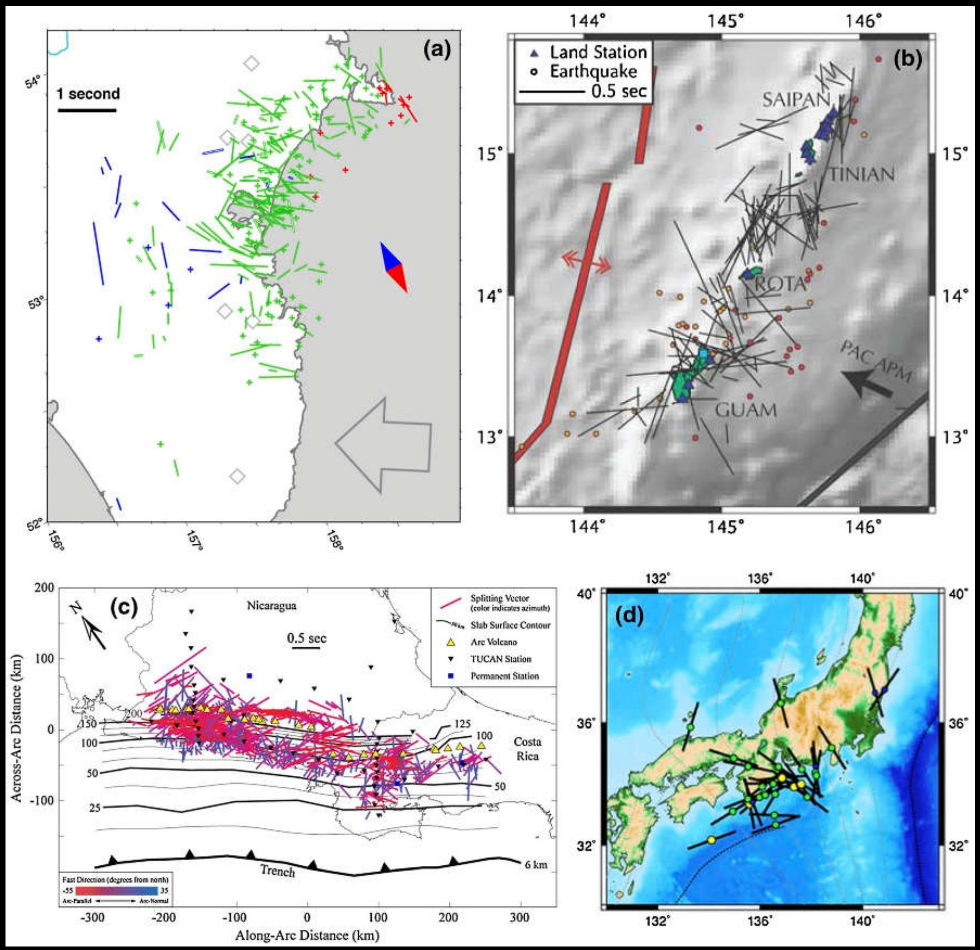


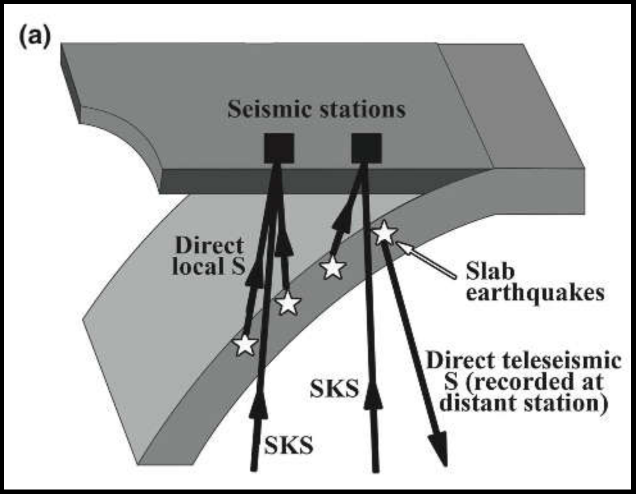
Key observations:

- SKS delay times much larger than local S, implies contribution from sub-slab mantle
- Lots of trench-parallel fast directions in all parts of the system. A few potential explanations (perhaps B-type fabric or serpentinized mantle in shallow mantle wedge?), but seems to require some component of along-strike flow.

Long et al., G^3, in press

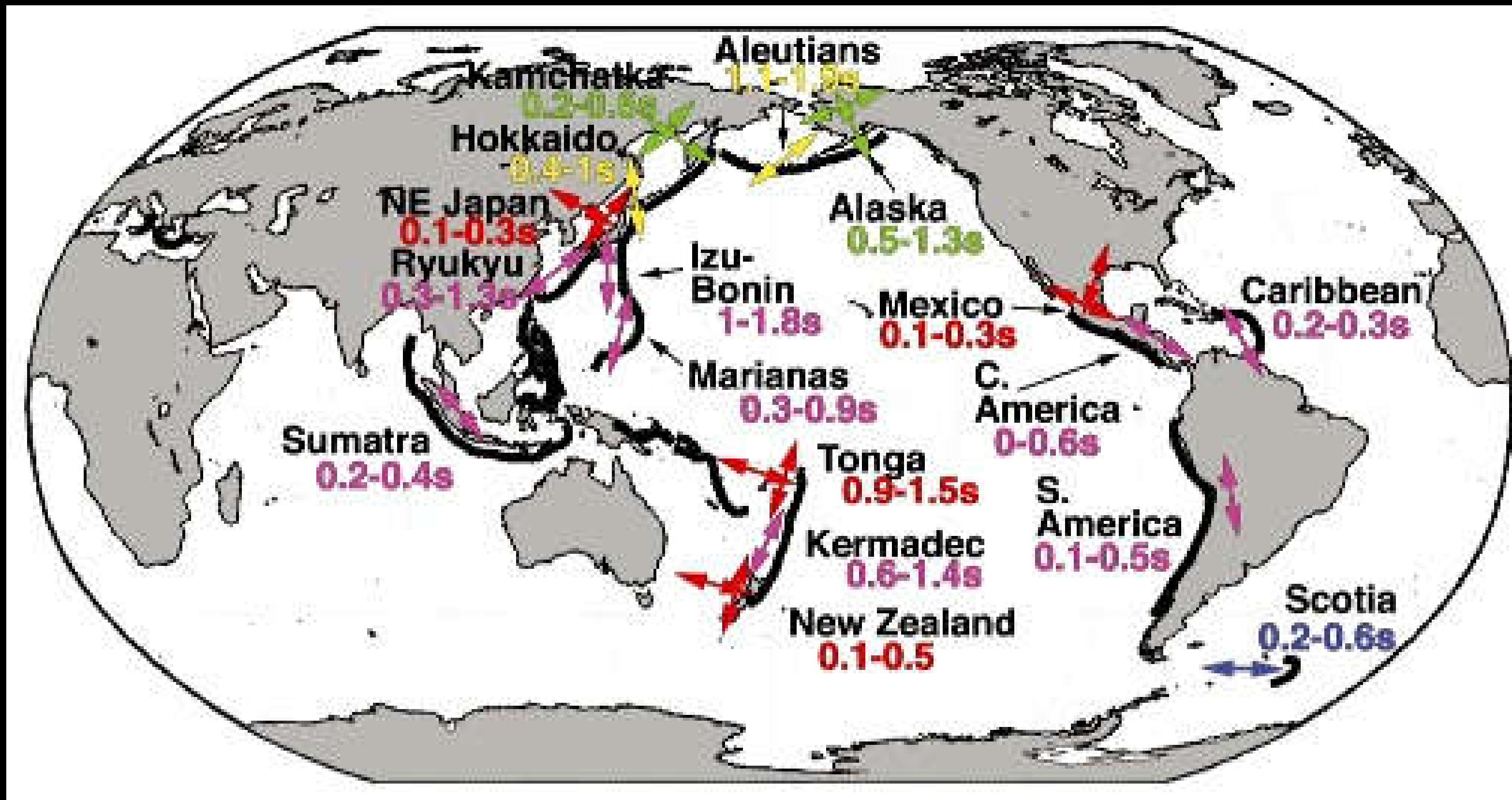
Anisotropy in subduction systems: The mantle wedge





Kamchatka: Levin et al., 2004; Marianas: Pozgay et al., 2007; Central America: Abt et al., 2008; Japan: Wirth and Long, 2010

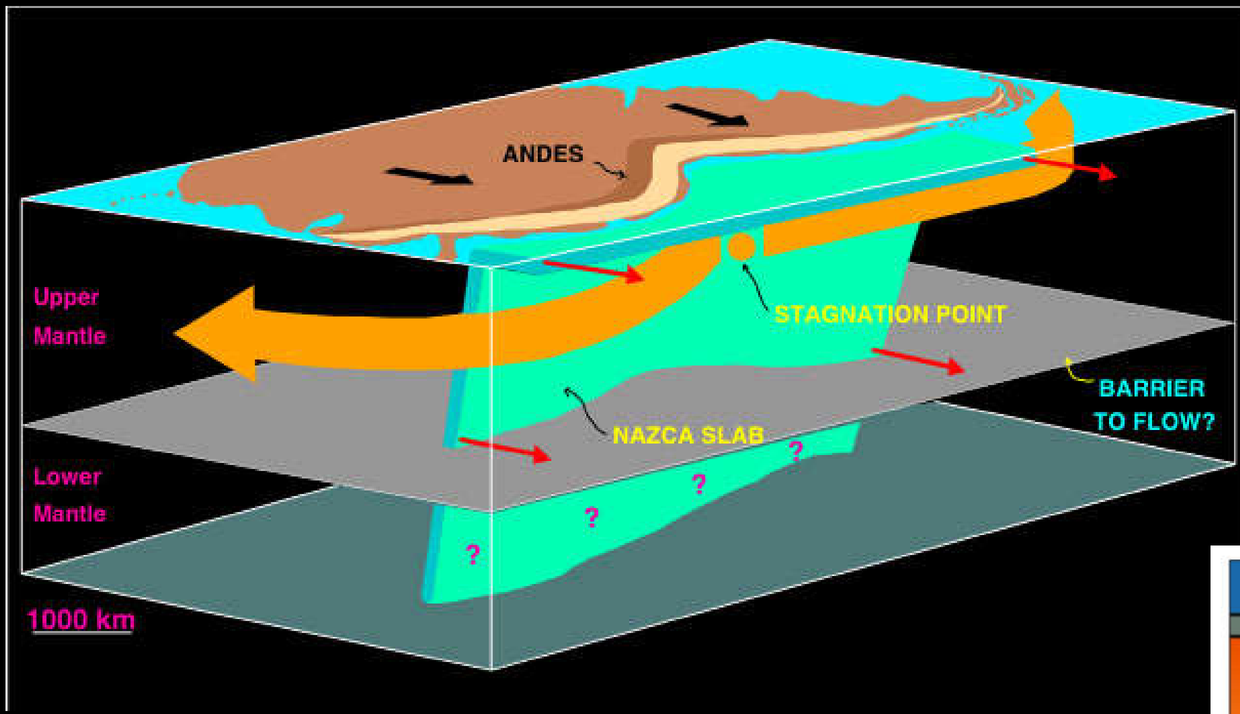
Anisotropy in subduction systems: The mantle wedge



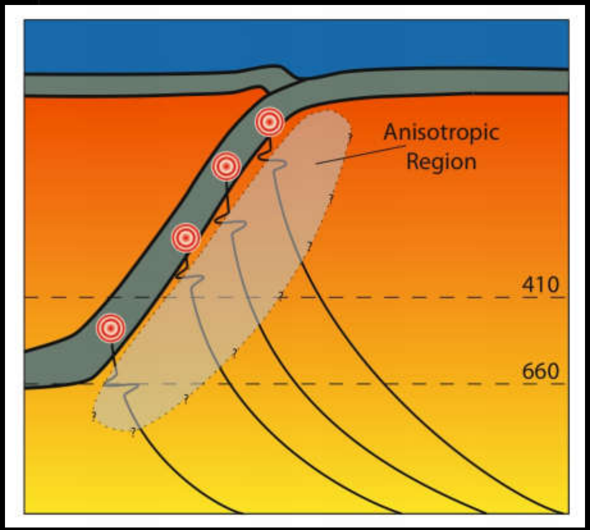
Long and Wirth, 2013

MANY processes might contribute: Corner flow, along-strike flow, edge flow, B-type fabric, serpentinization, flow affected by complex slab morphology, lower crustal foundering, etc.

Anisotropy in subduction systems: The sub-slab mantle

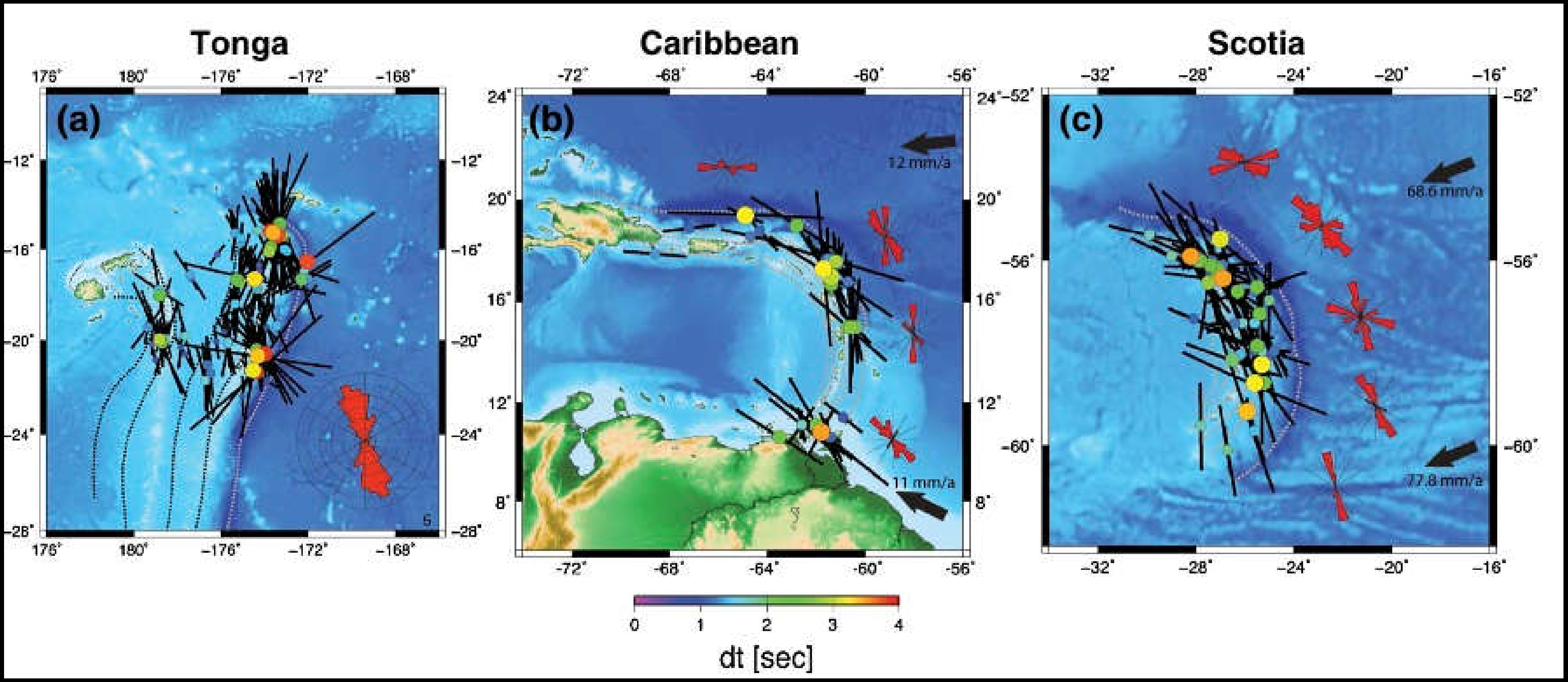


Russo and Silver, Science, 1994



Foley and Long, GRL, 2011

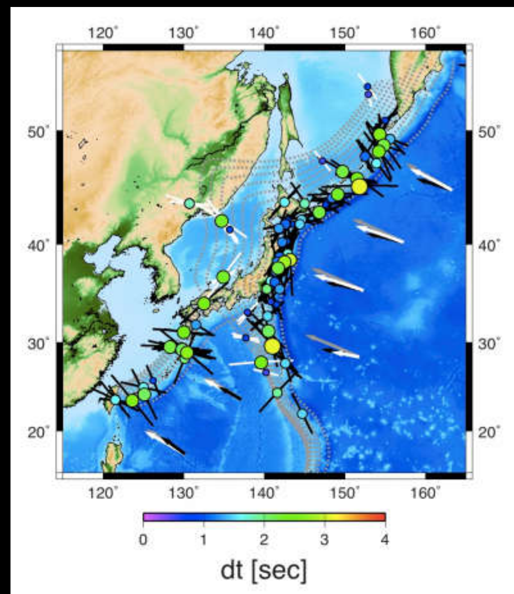
Anisotropy in subduction systems: The sub-slab mantle

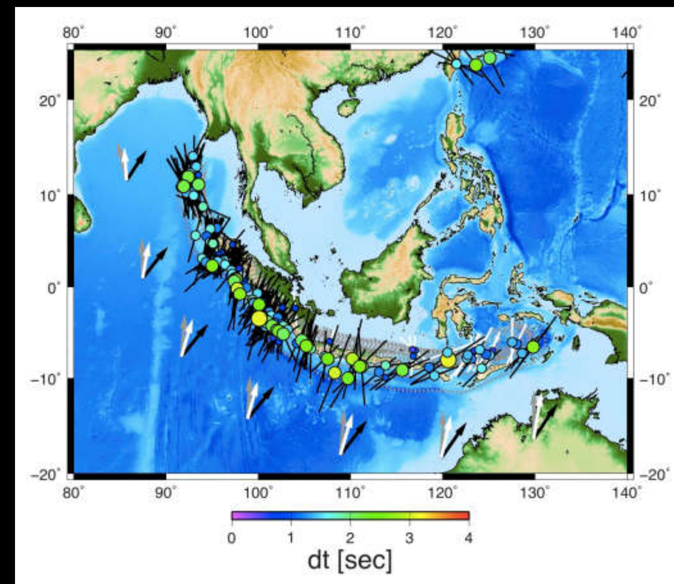


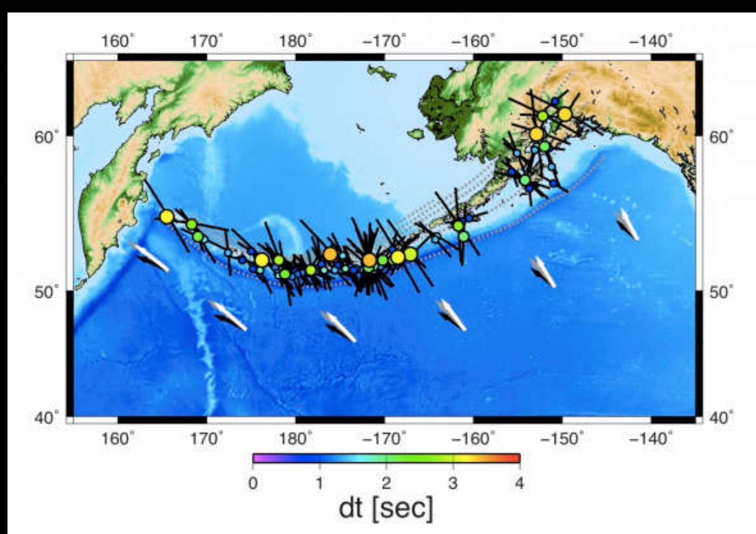
Foley and Long, GRL, 2011*; Lynner and Long, EPSL,* 2013

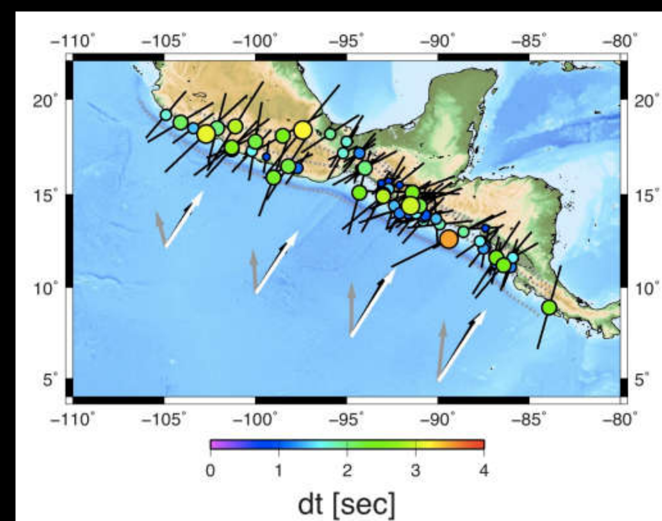
Anisotropy in subduction systems: The sub-slab mantle

Lots of variability! Trench-parallel sub-slab fast directions are common, but not ubiquitous. How to explain different patterns in different regions?



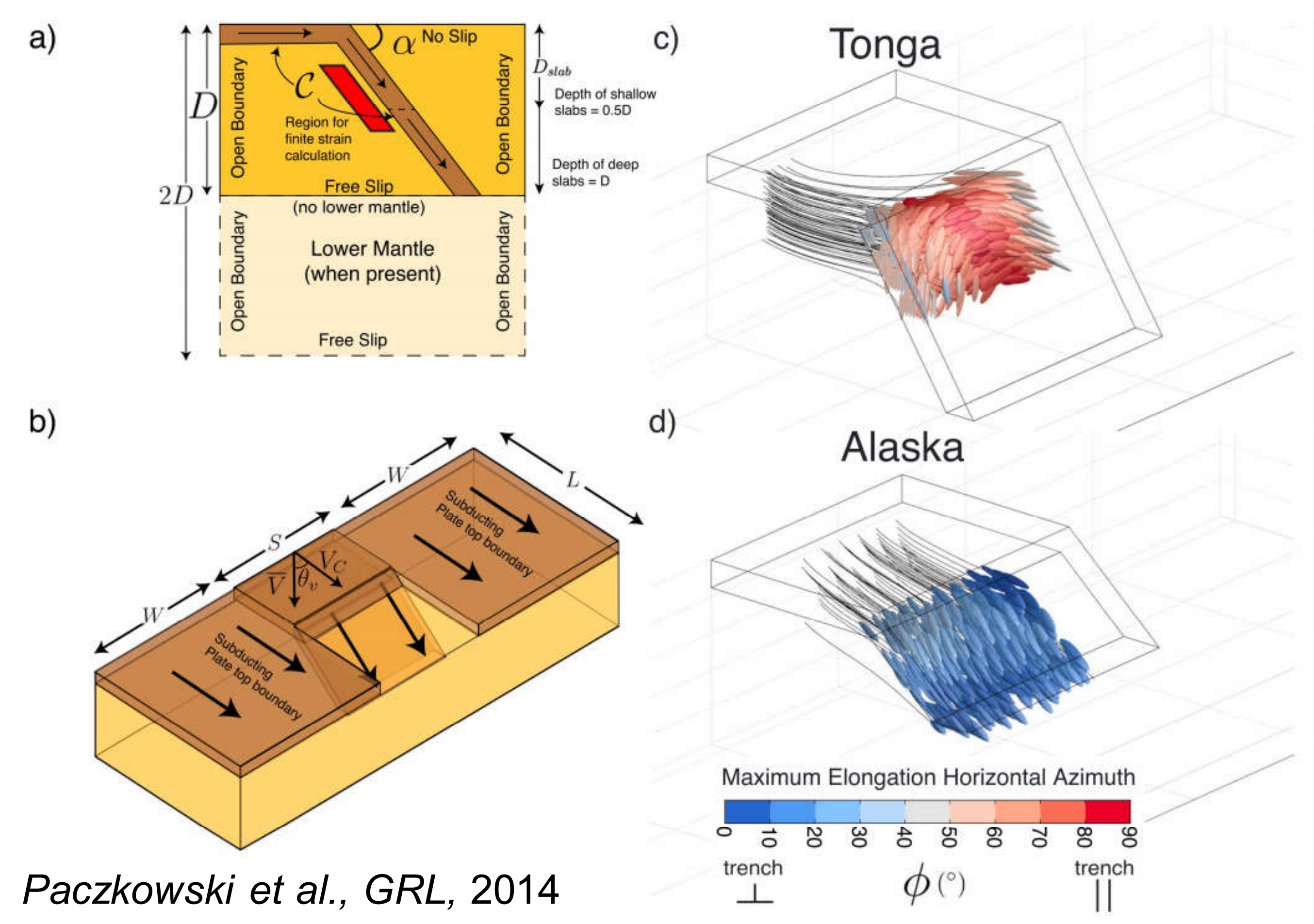






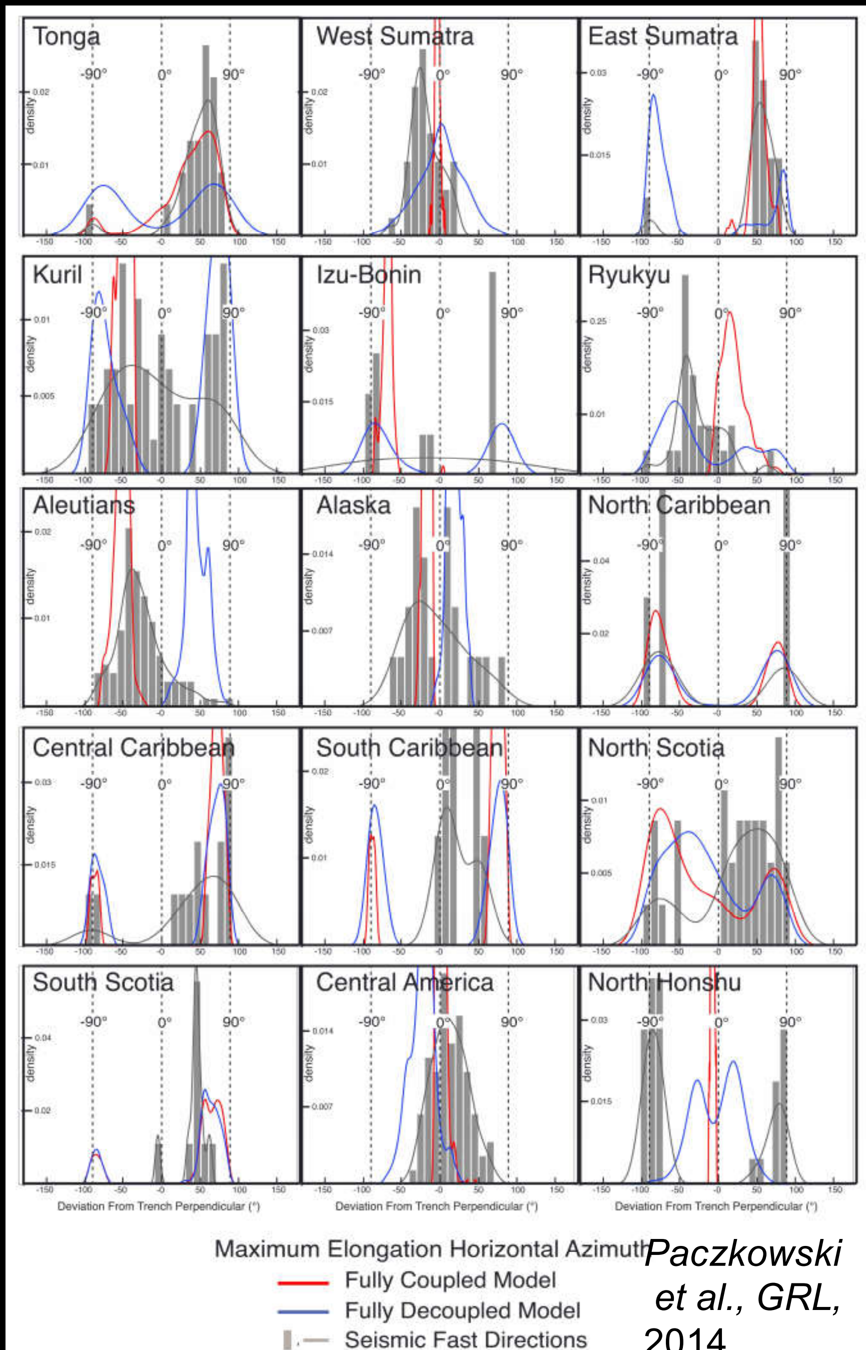
Lynner and Long, G^3, 2014

Can we model this variability?



Paczkowski et al., GRL, 2014

A series of numerical experiments to test the idea of 3D toroidal flow beneath subducting slabs



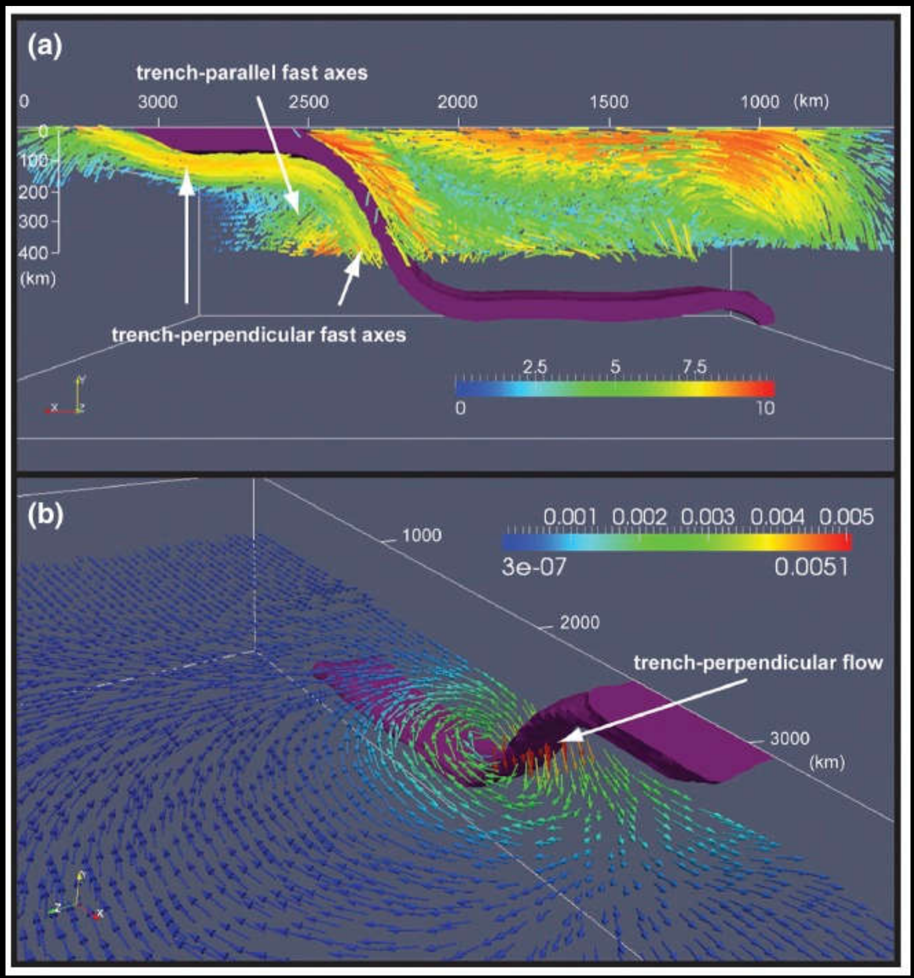
Paczkowski et al., GRL, 2014

A comparison (highly simplified!!) between model finite strain geometries and sub-slab splitting measurements is generally favorable.

So: conclusion is that some, though not all, subduction systems may be dominated by toroidal flow beneath the slab.

Alternative explanations possible: strong radial anisotropy beneath slabs (Song & Kawakatsu)?

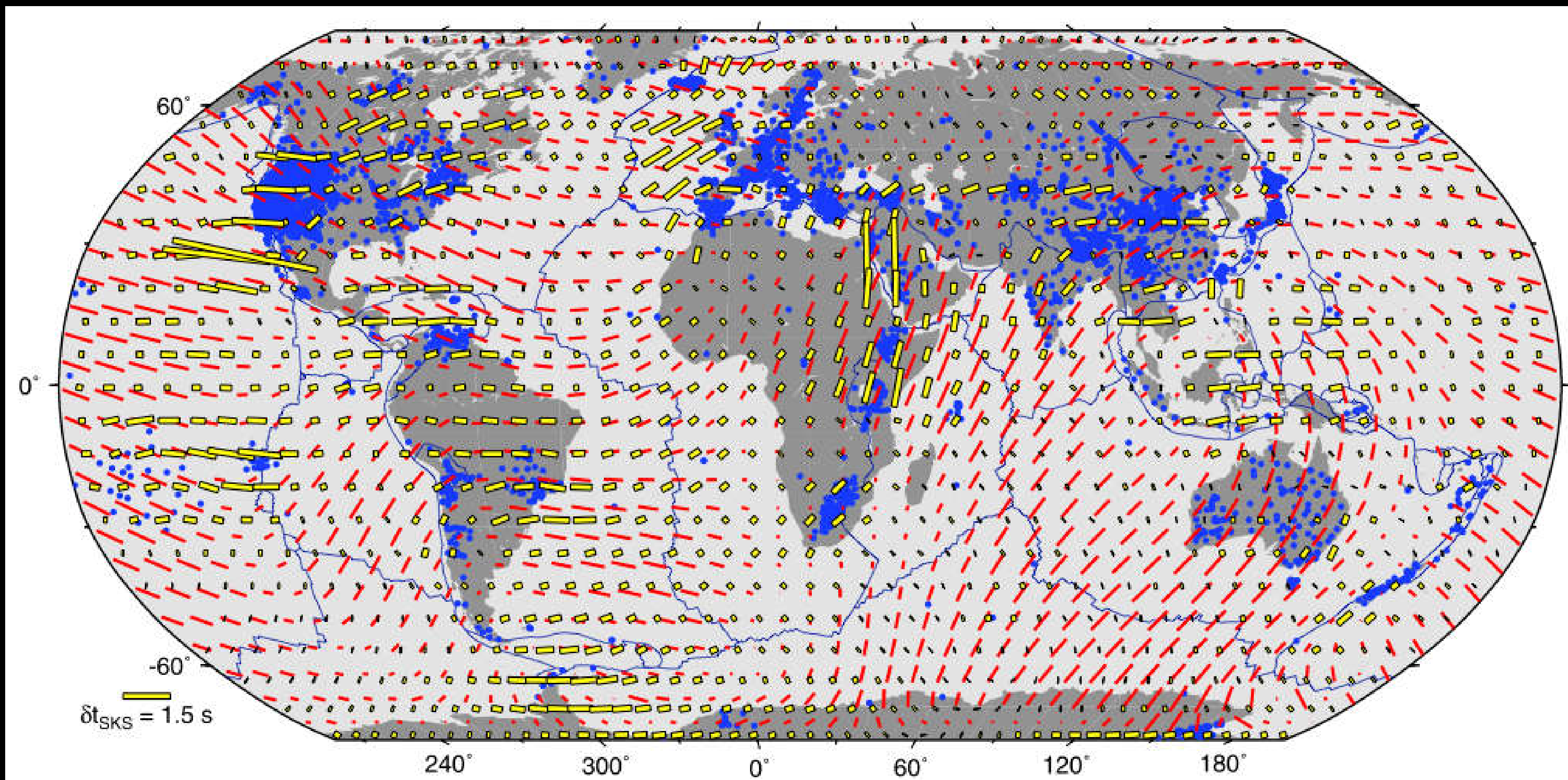
End of Part II



Faccenda and Capitanio, G^3, 2012

BOTTOM LINE: Anisotropy in subduction systems often does not conform to the predictions of a simple 2D flow model. There are many potential complications and and untangling the many possible contributing processes is a challenge. However, this is important, because understanding the deviations from predictions of simple models presumably will tell us a lot about subduction zone geodynamics.

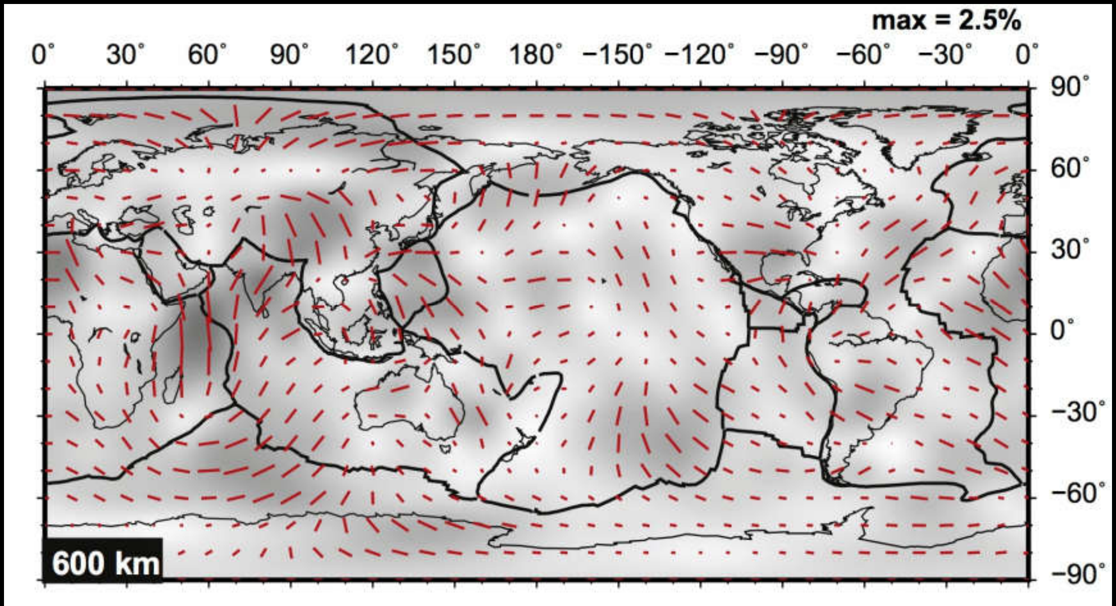
Part III: Anisotropy in the deep mantle



Becker et al., JGR, 2012

For the upper mantle, we have well-established frameworks for interpreting anisotropy in terms of dynamic processes. For the deep mantle (transition zone, uppermost lower mantle, D”), this is less true.

Transition zone and uppermost lower mantle anisotropy

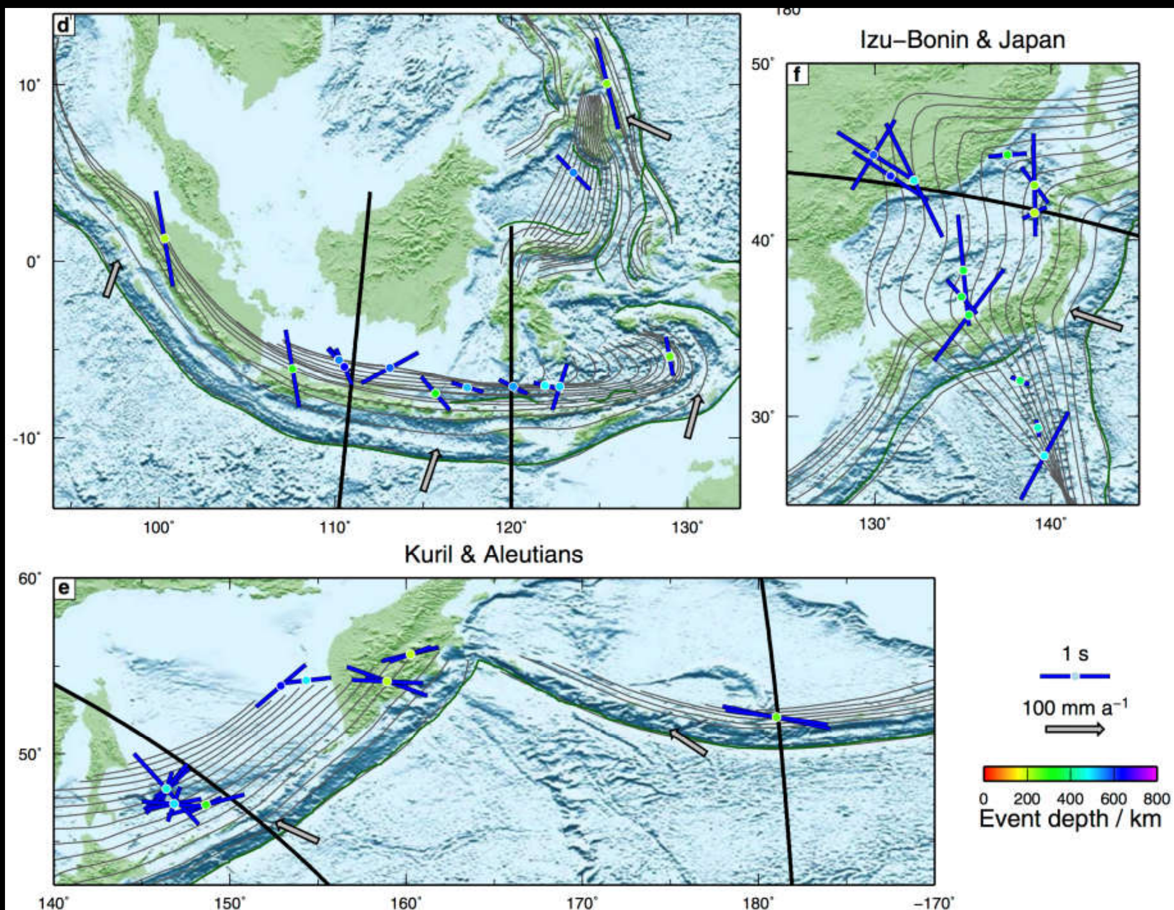


Yuan and Beghein, EPSL 2013

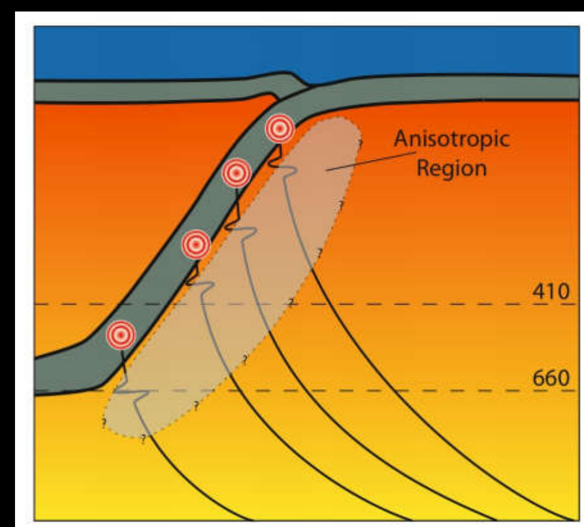
Also work by Montagner, Trampert, others…

There are robust constraints from surface waves for azimuthal anisotropy throughout the transition zone and in the uppermost lower mantle (implications for deformation mechanism!). With body waves, we can probe subduction systems more specifically, and ask, how do slabs deform the mantle around them in the mid-mantle?

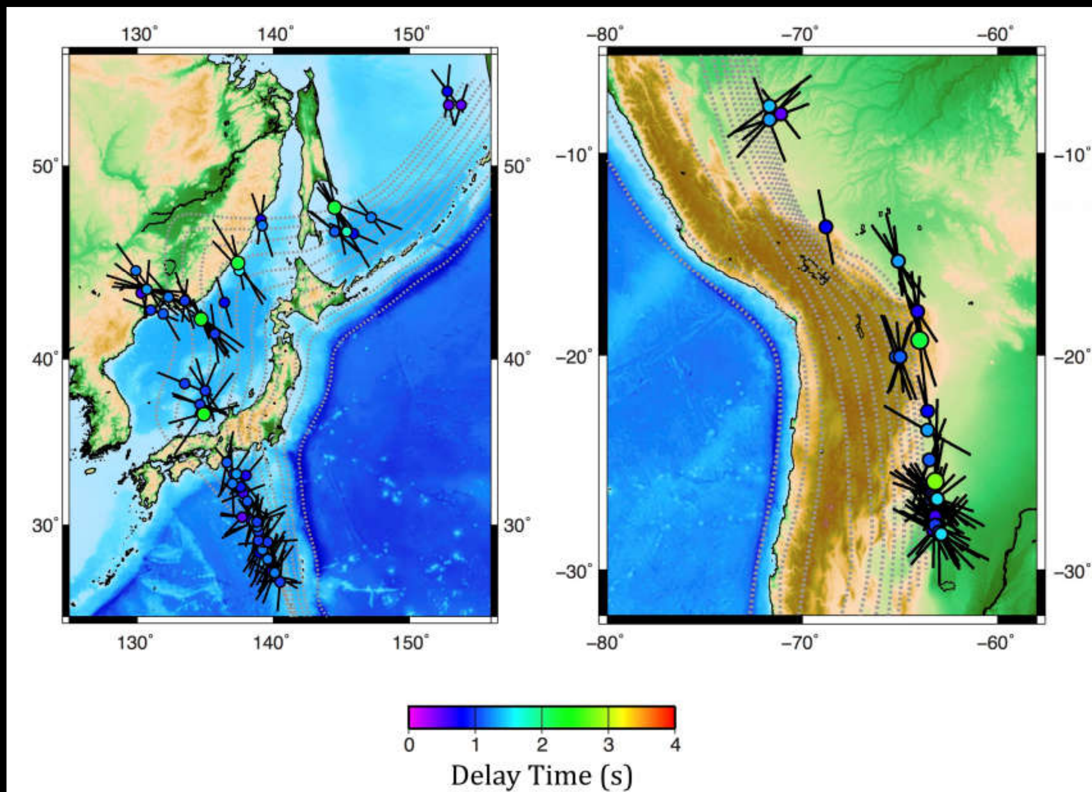
Transition zone and uppermost lower mantle anisotropy: splitting from deep earthquakes



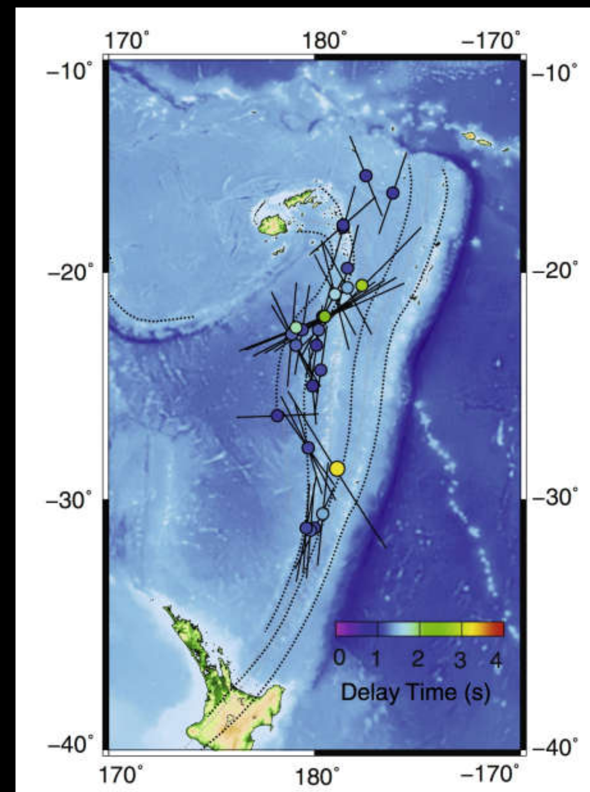
Nowacki et al., G^3, 2015



Transition zone and uppermost lower mantle anisotropy: splitting from deep earthquakes



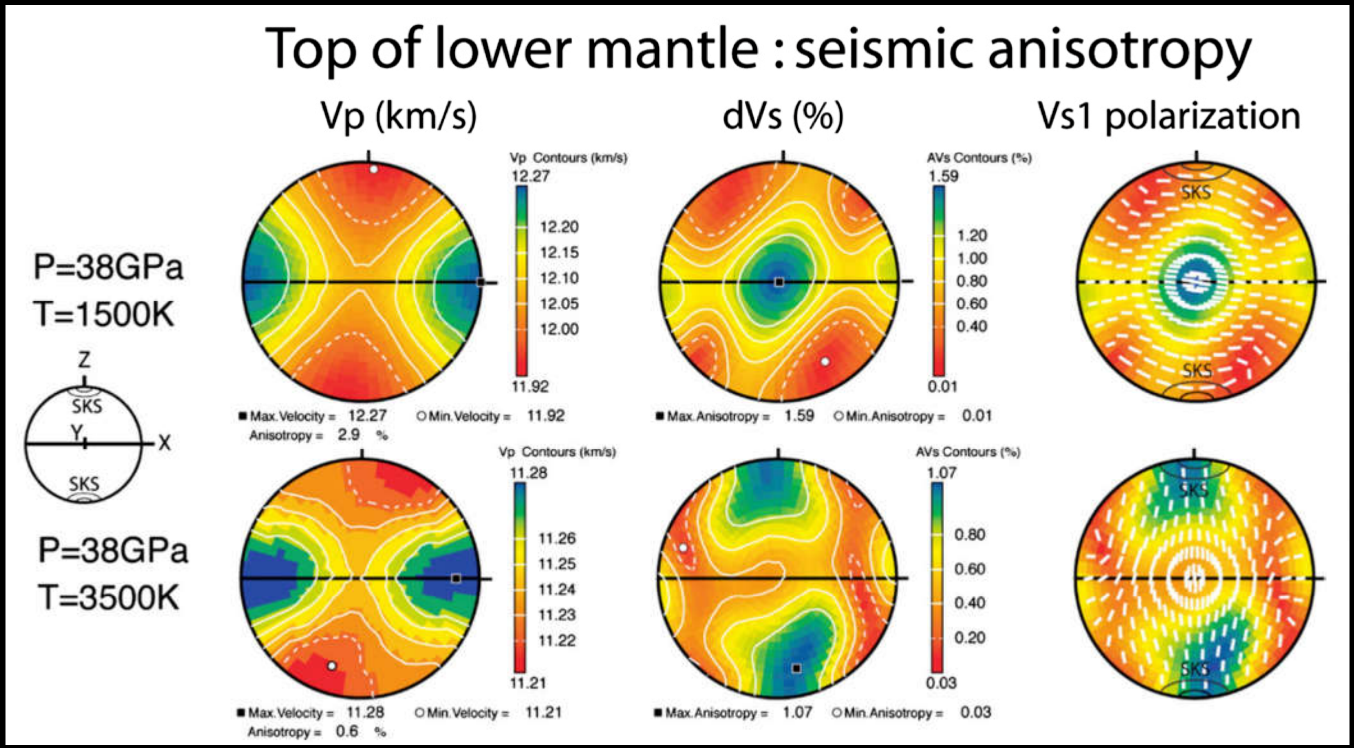
Lynner and Long, GJI, 2015



Mohiuddin et al., PEPI, 2015

BOTTOM LINE: Substantial shear wave splitting associated with mid-mantle anisotropy. Splitting from deepest events (~660 km) requires contribution from uppermost lower mantle. Patterns are complex…

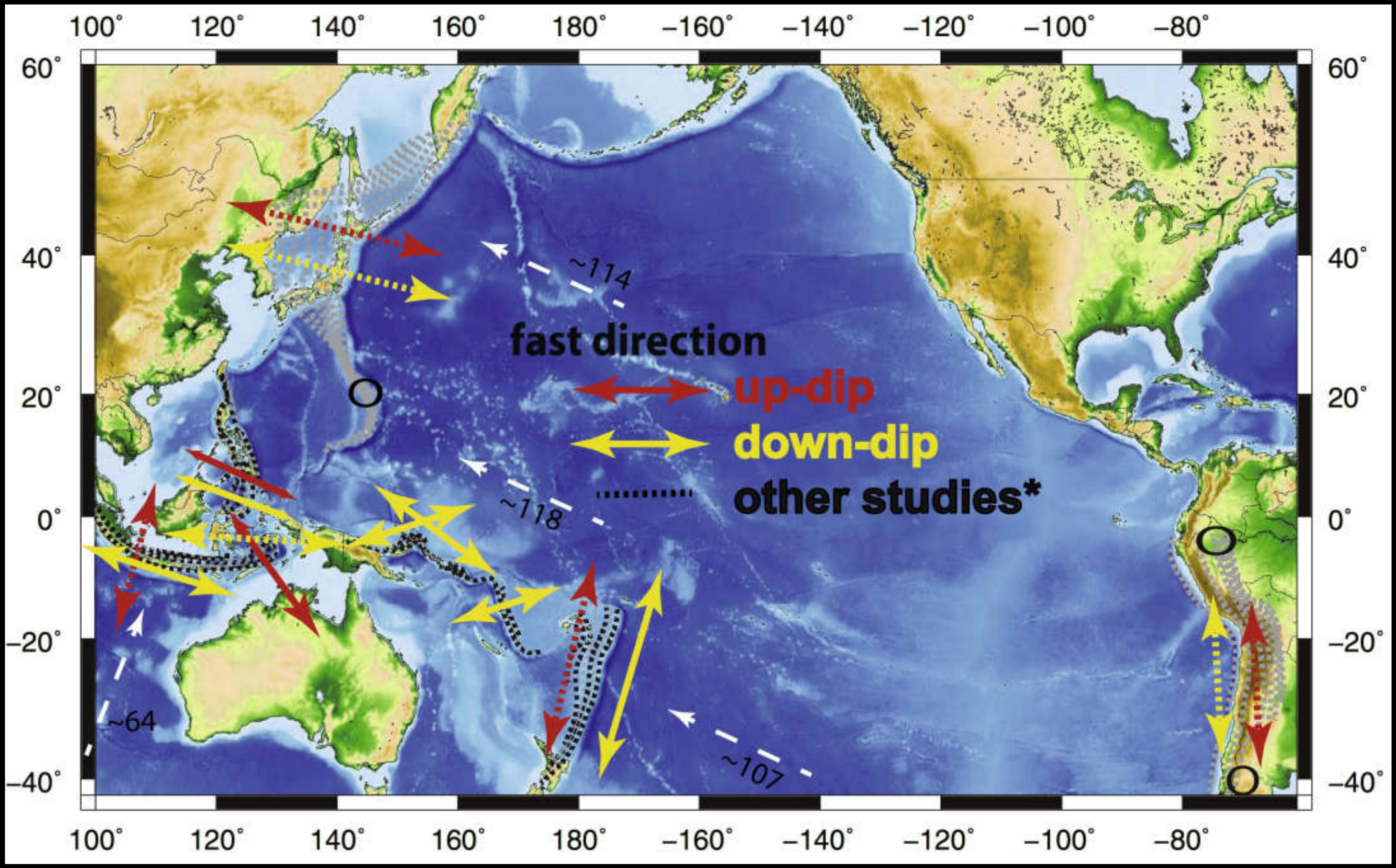
Transition zone and uppermost lower mantle anisotropy: Geodynamic implications



Mainprice et al., EPSL, 2008

How to interpret in terms of deformation geometry? Difficult; few constraints on LPO development in wadsleyite/ringwoodite/bridgmanite. As ability to do high-P deformation experiments improves, so will our knowledge of LPO formation. Regardless, important implication is that the uppermost lower mantle is deforming via dislocation creep.

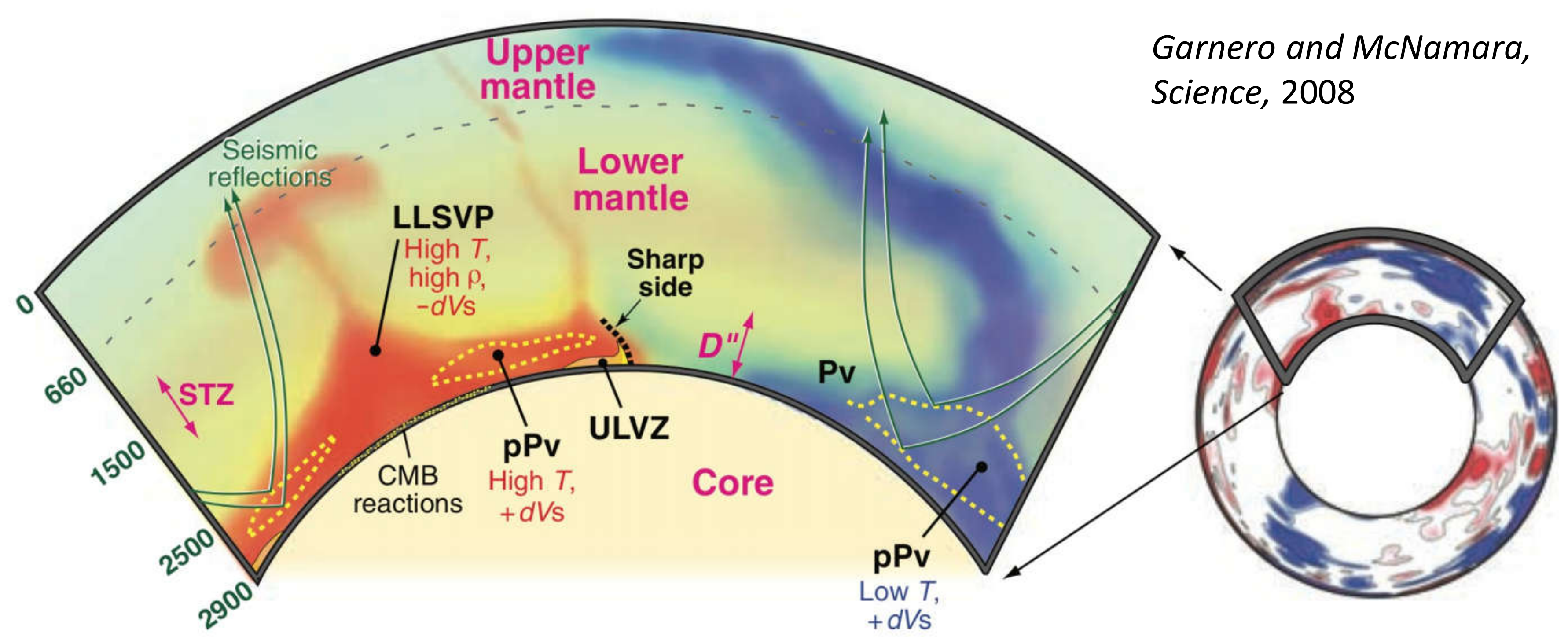
Are there any discernable trends in the global patterns of fast directions?



Mohiuddin et al., PEPI, 2015

Short answer seems to be not really, but I am open to suggestions!

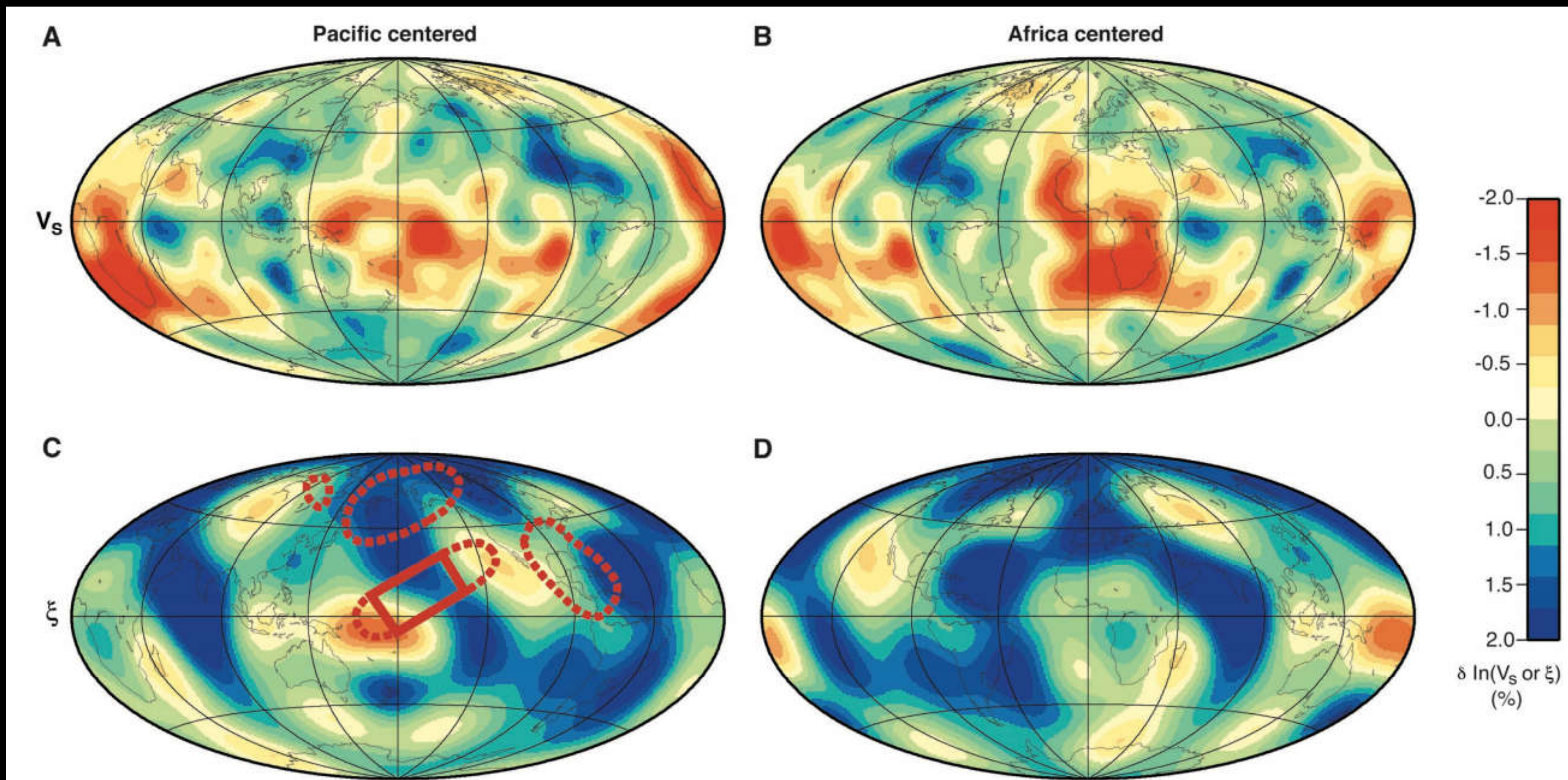
Anisotropy in the lowermost mantle



Garnero and McNamara, Science, 2008

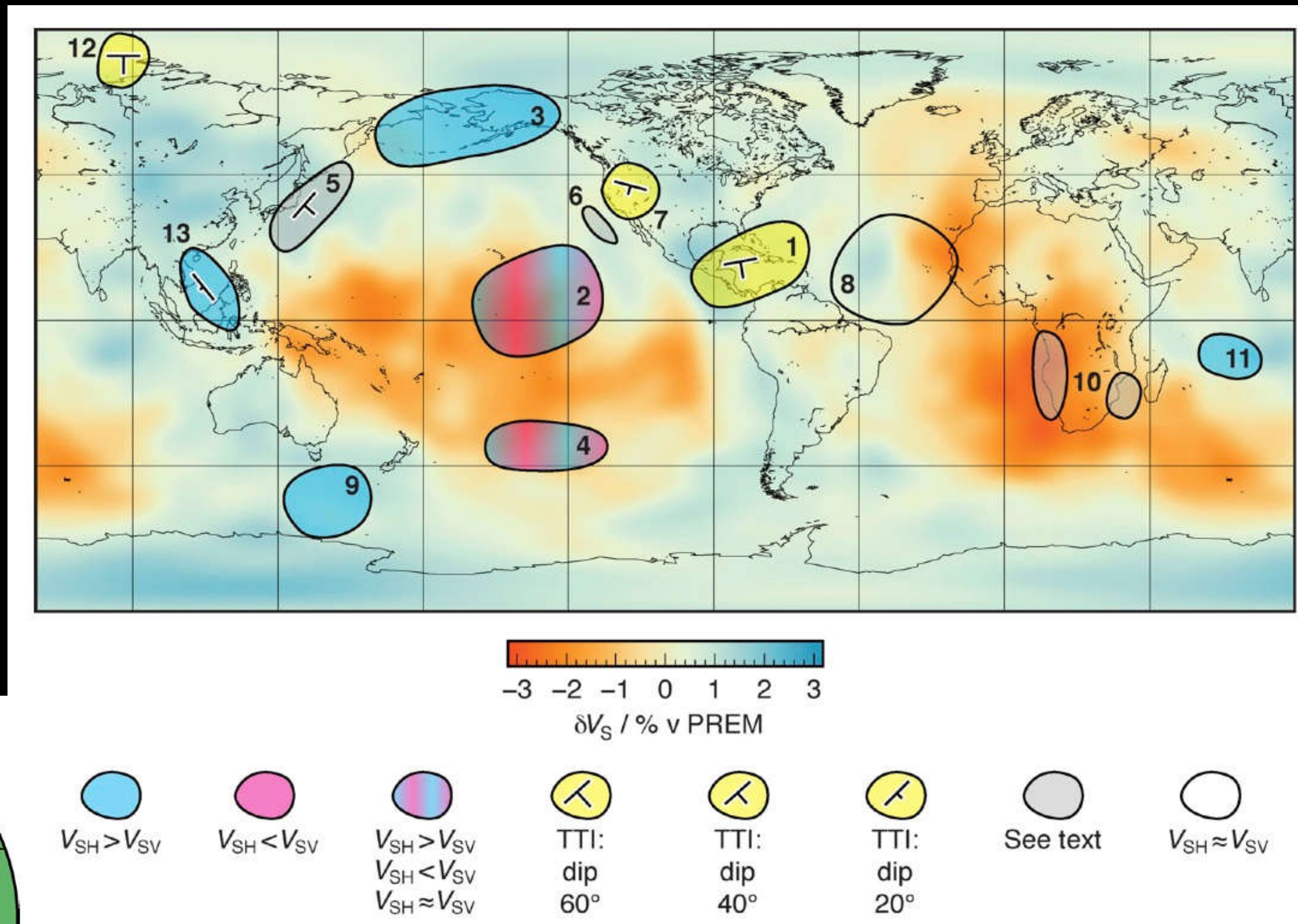
Processes at the base of the mantle play a critical role in Earth's thermal evolution, pattern of mantle convection, generation of upwellings, chemical evolution of mantle, and tectonic features we see at the surface. If we knew the **pattern of flow** at the base of the mantle, we would understand these processes better. Can we constrain this pattern of flow using seismic anisotropy?

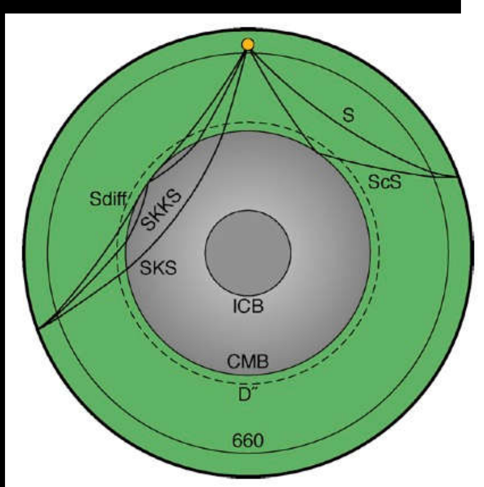
Constraints on D” anisotropy



Early work by Lay, Vinnik, others… Global model of radial anisotropy (c and d) from Panning and Romanowicz (2004): mostly $V_{SH} > V_{SV}$ (reflecting mostly horizontal flow), with some deviations. What about regional studies?

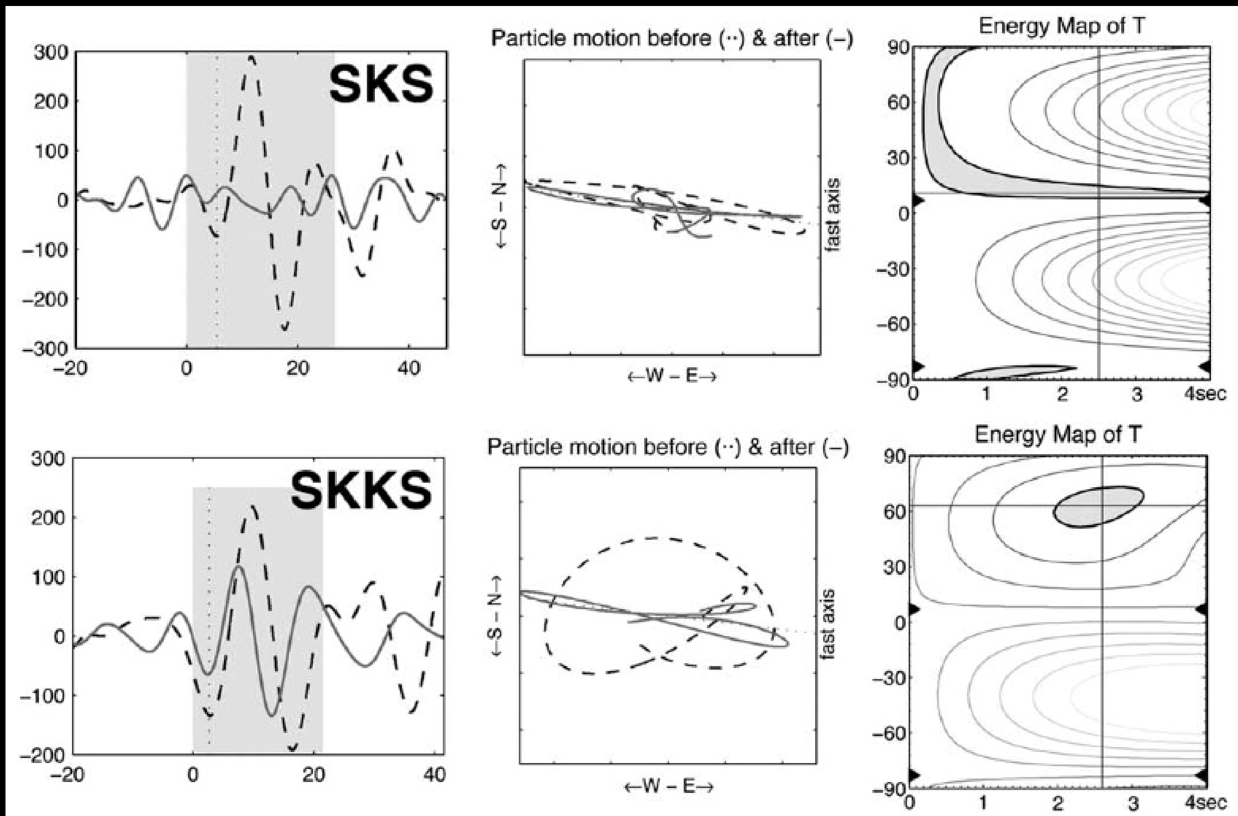
Results from regional studies (as of 2011)



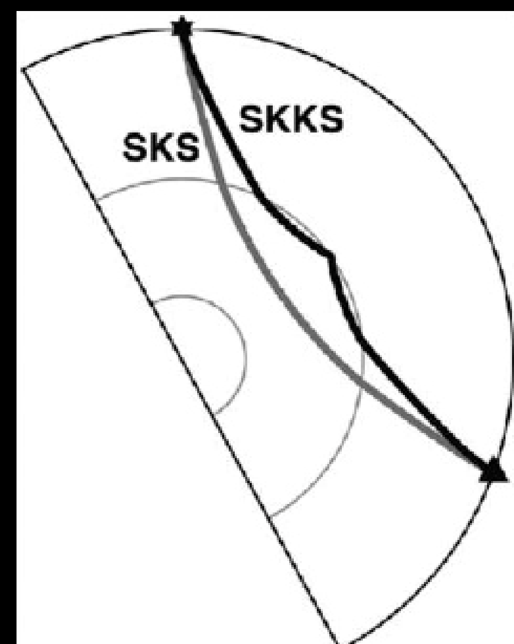


Nowacki et al., JG, 2011

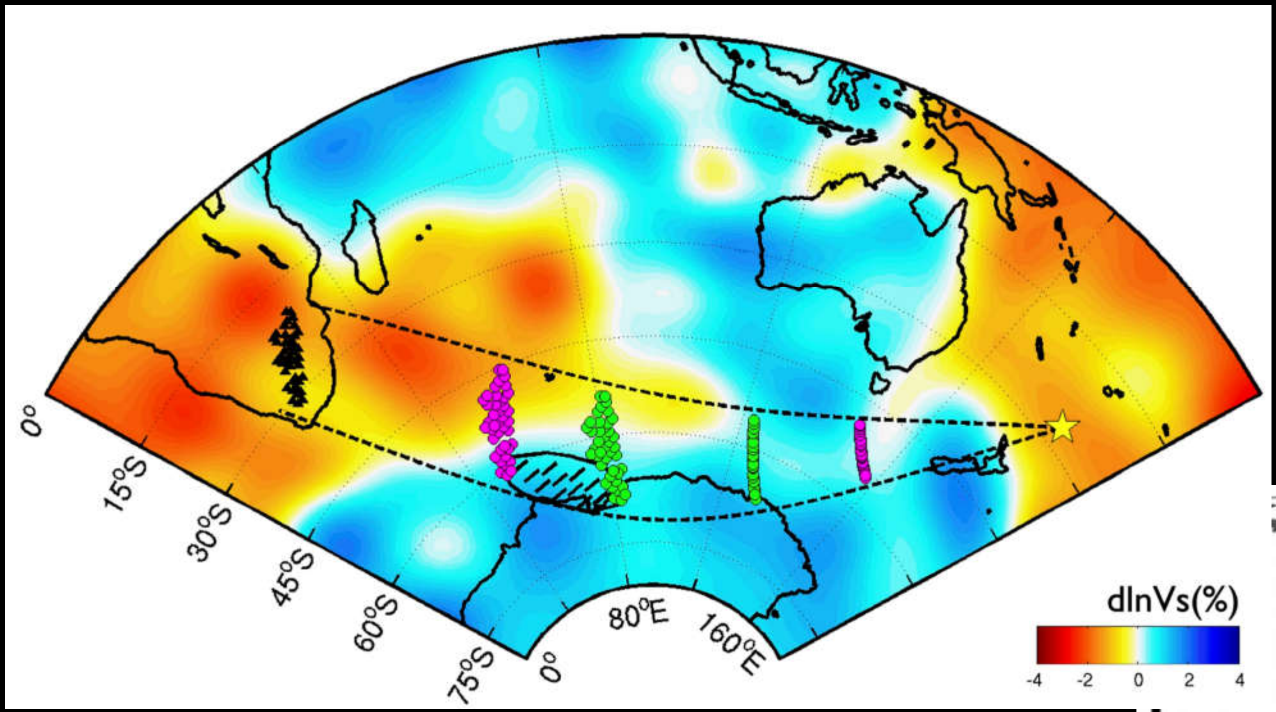
A quick tangent: the SKS-SKKS splitting discrepancy method: Sometimes SK(K)S phases reflect lowermost mantle anisotropy!



Long, EPSL, 2009

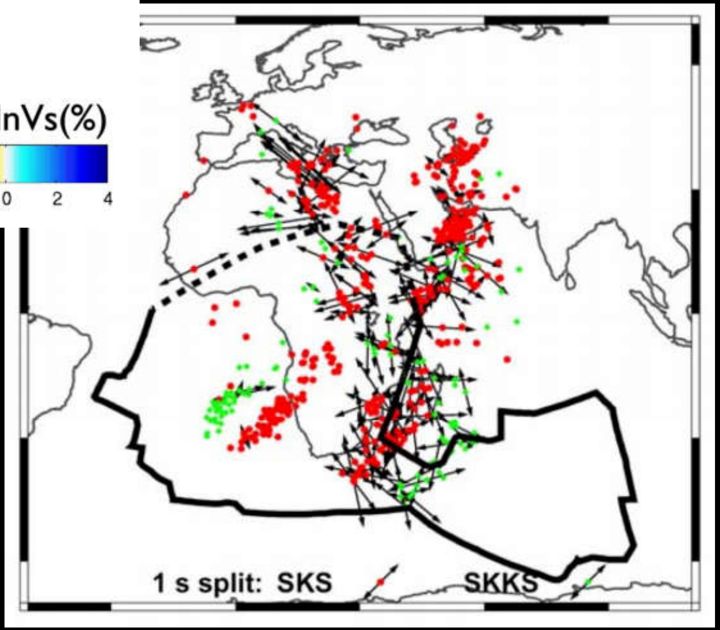


An interesting observation: Strong anisotropy concentrated at the edges of LLSVPs



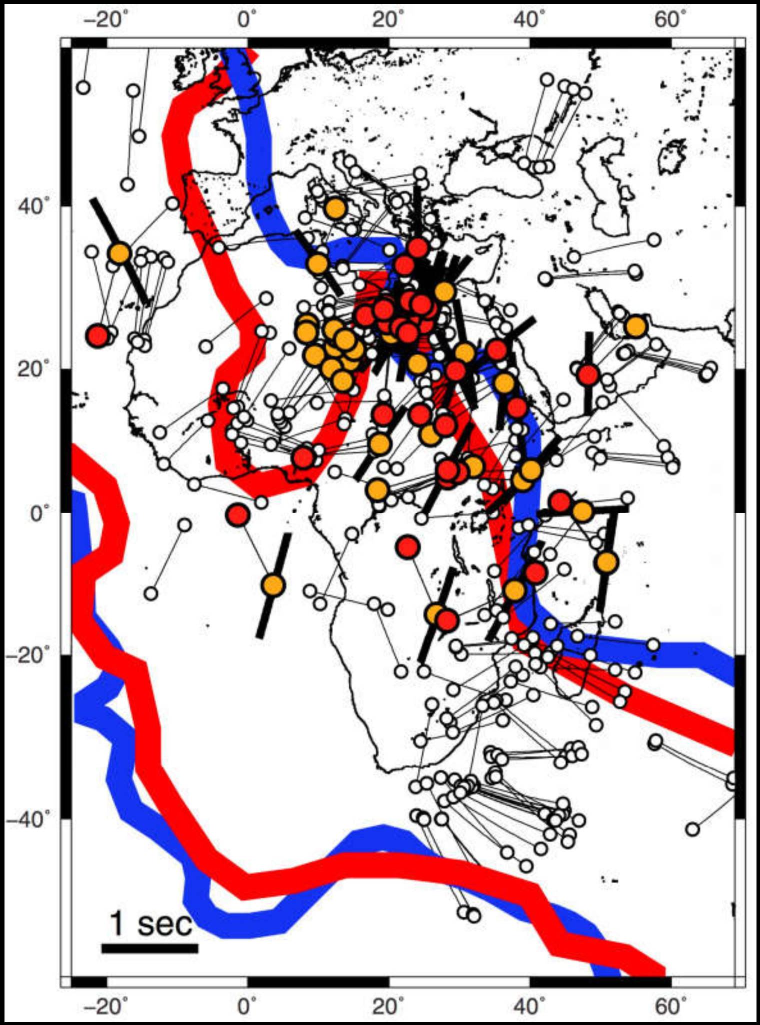
Cottaar and Romanowicz, GJI, 2013

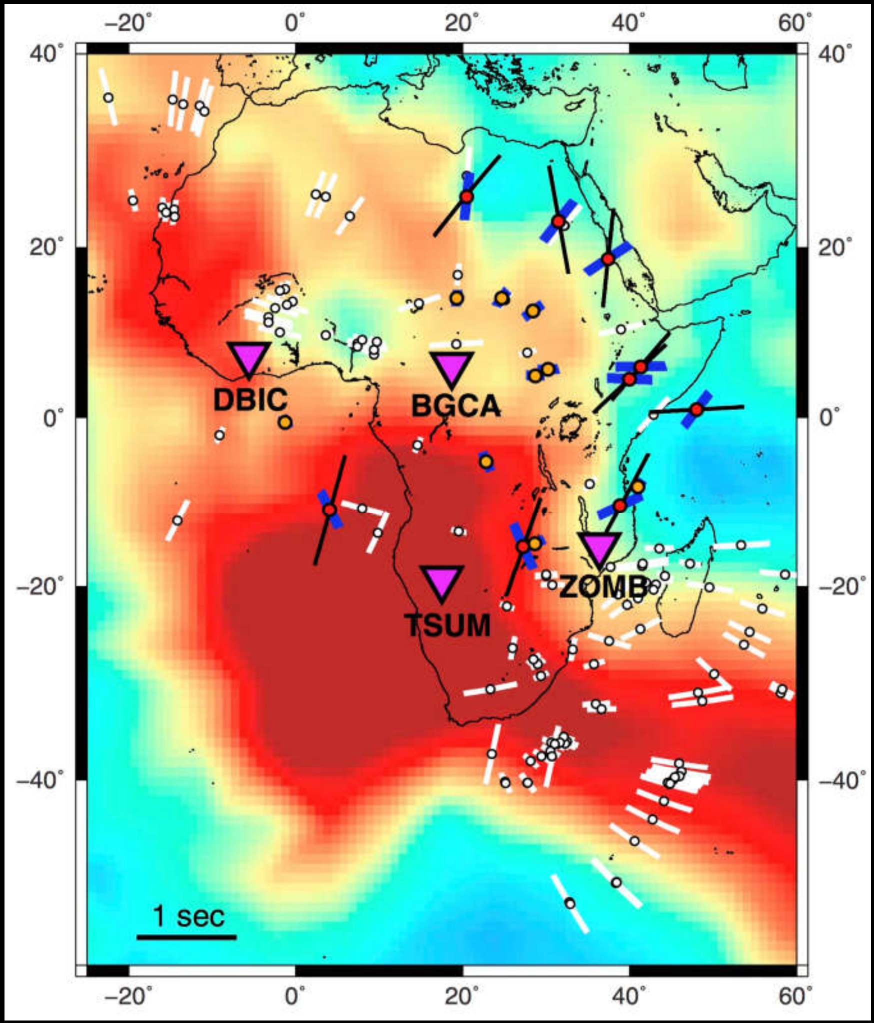
Wang and Wen, JGR, 2007



Observations of S_{diff} (above) and SKS/SKKS phases (right) suggest seismic anisotropy along the southern and eastern margins of the African LLSVP.

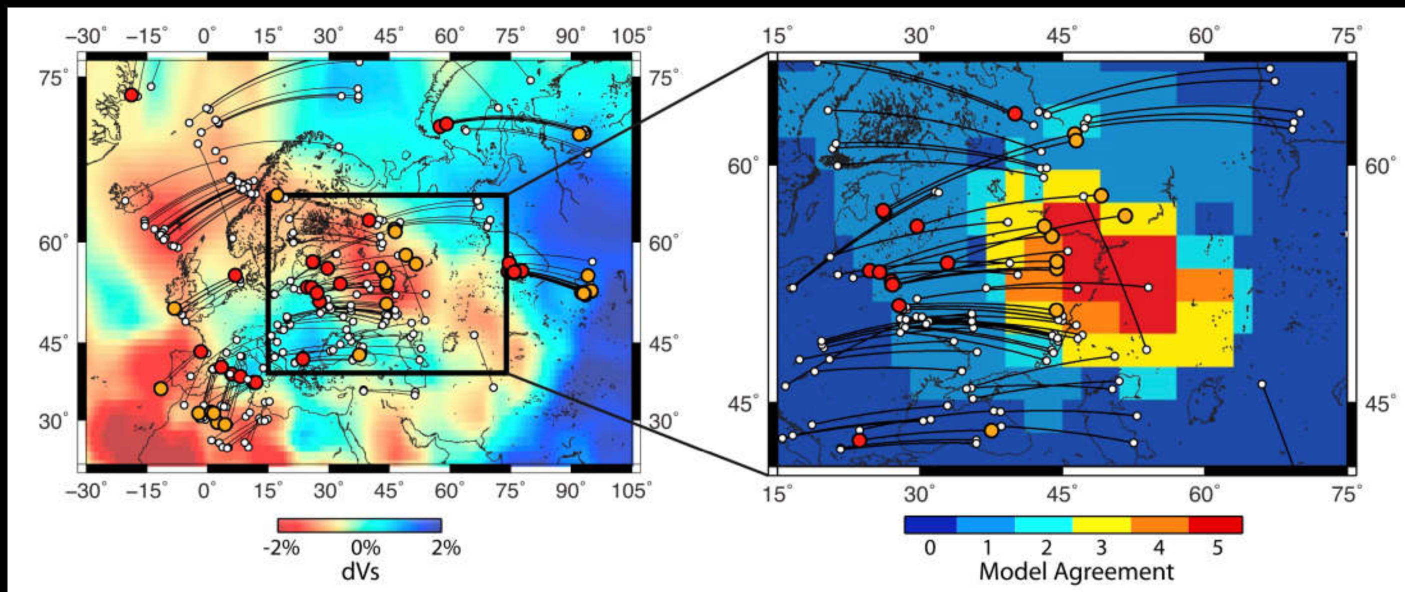
An interesting observation: Strong anisotropy concentrated at the edges of LLSVPs

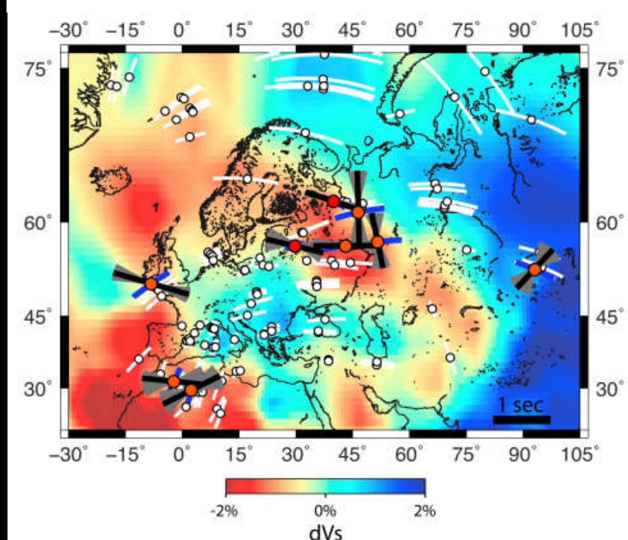




Lynner and Long, GRL, 2014

What about the Perm Anomaly? Is it associated with lowermost mantle anisotropy?

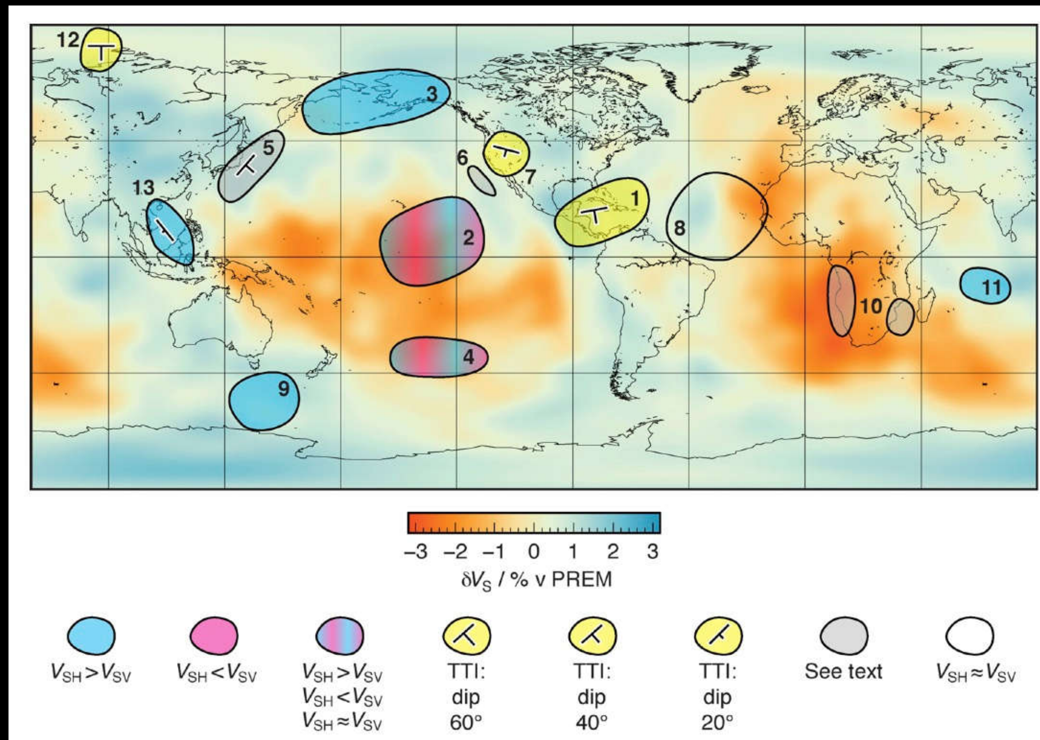




Long and Lynner, GRL, 2015

Yes! Perm Anomaly is very well-sampled using SKS-SKKS measured at stations in Europe; there is evidence for anisotropy associated with Perm Anomaly.

What have we learned so far from studies of D” anisotropy?



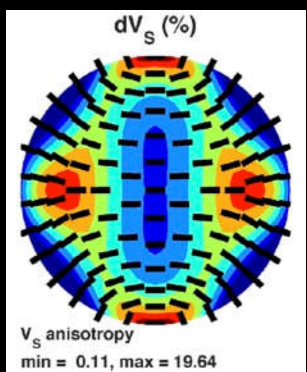
Quite a lot: they suggest that lowermost mantle may be deforming via dislocation and/or contain elastically distinct material; we know that structures such as LLSVPs have a distinctive signature; we know there are interesting regional variations.

BUT: WE STILL DON’T HAVE THE MECHANISM NAILED DOWN, SO CANNOT RELATE TO FLOW GEOMETRY. How to move forward?

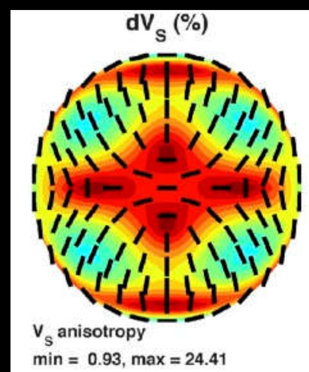
What candidate mechanisms may play a role in generating D” anisotropy?

LPO due to dislocation creep

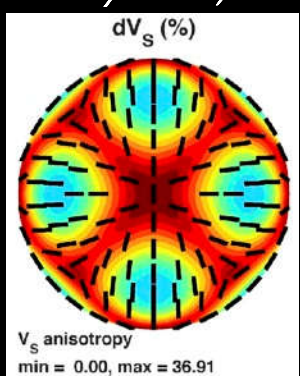
Candidate minerals:



Perovskite
Wookey et al., 2005

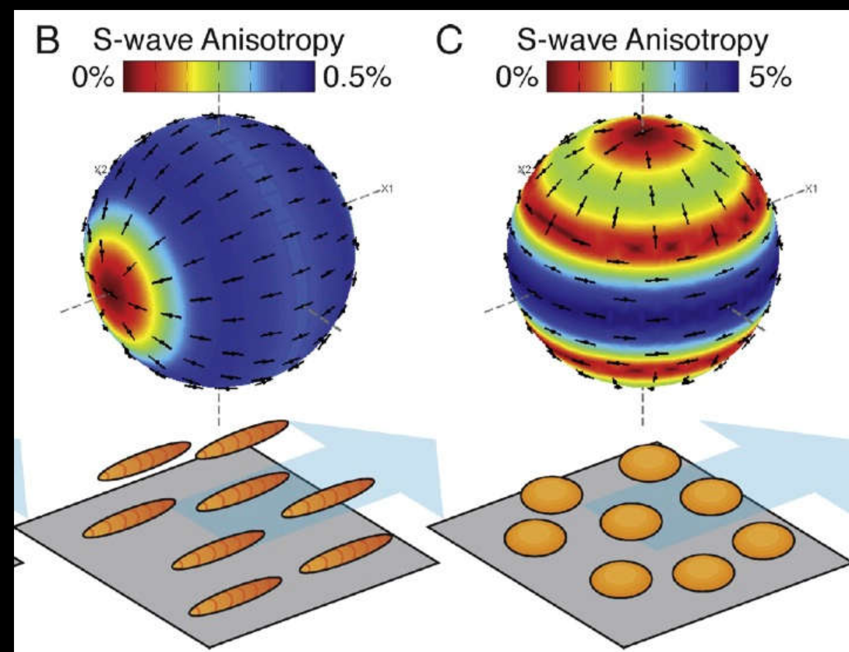


Post-perovskite
Stackhouse et al., 2005



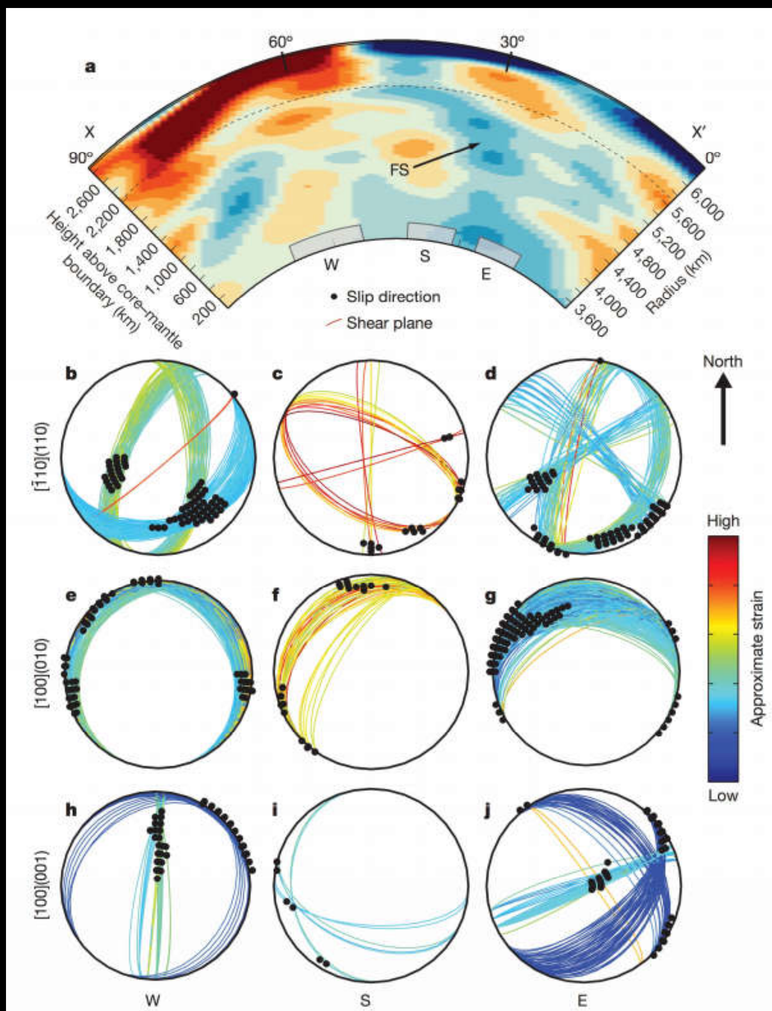
MgO
Karki et al., 1999

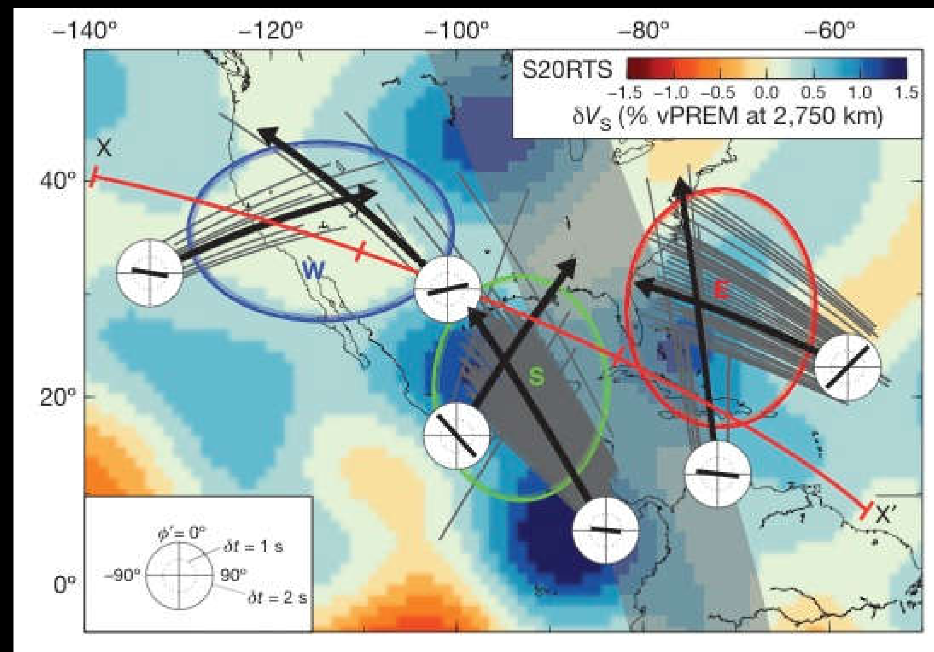
SPO due to melt/slab remnants



Nowacki et al., J. Geodyn., 2011

Can we build data sets that can distinguish among the candidate mechanisms/anisotropic geometries?

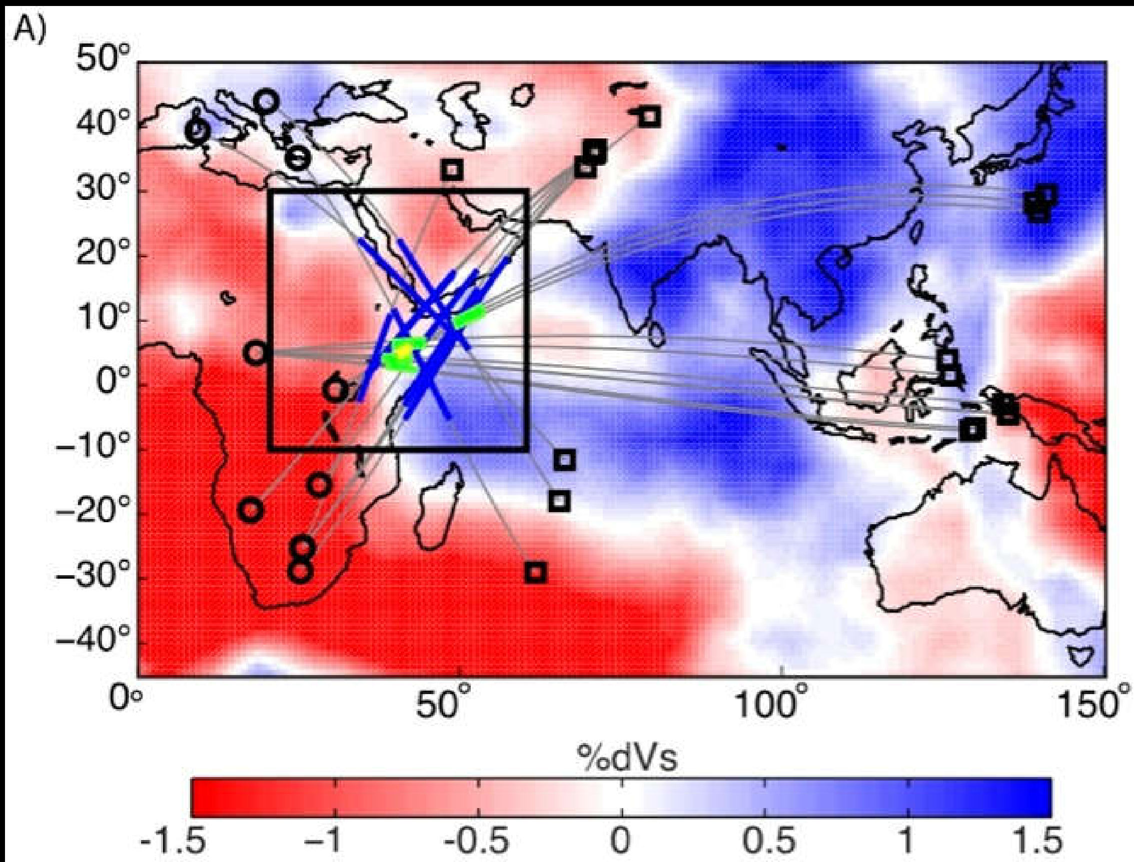




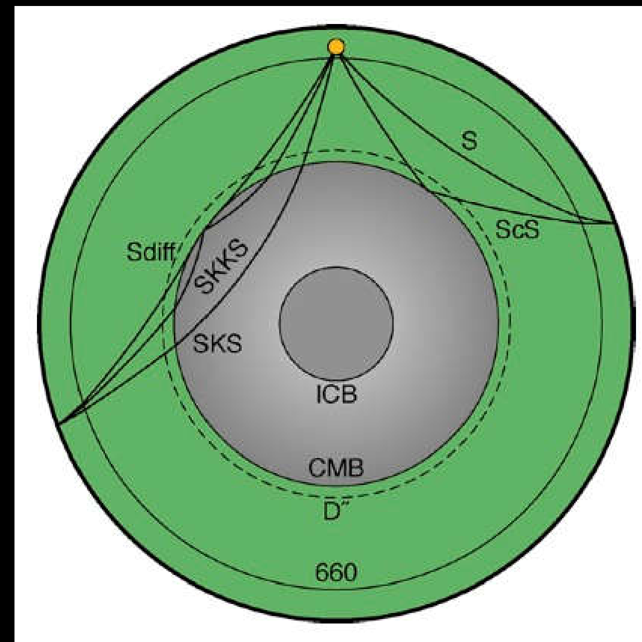
Nowacki et al., Nature, 2010

With splitting measurements for multiple raypaths, can start to test hypotheses (in this case, horizontal shear of ppv).

A similar approach: a detailed dataset and mineral physics based forward modeling

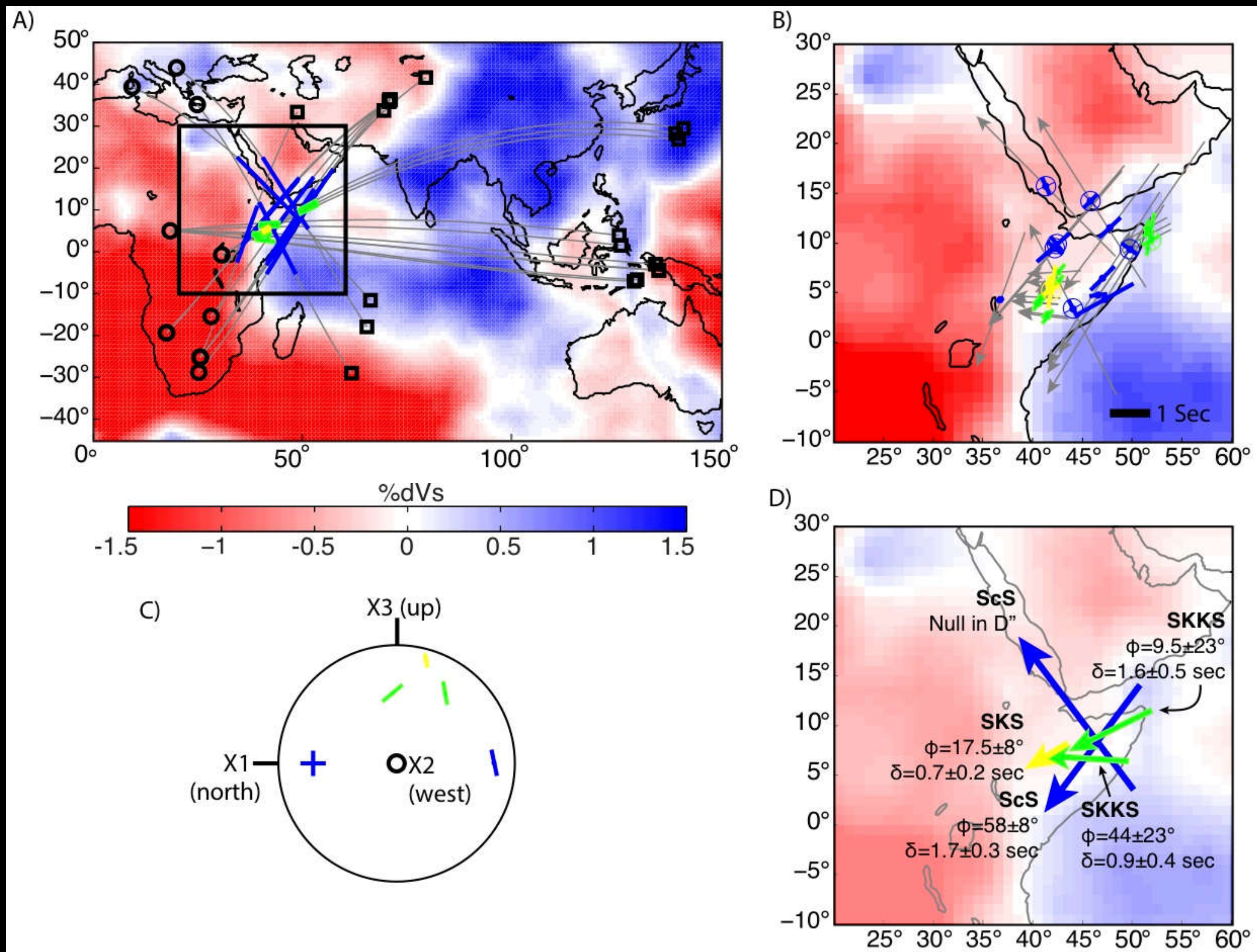


Ford et al., EPSL 2015



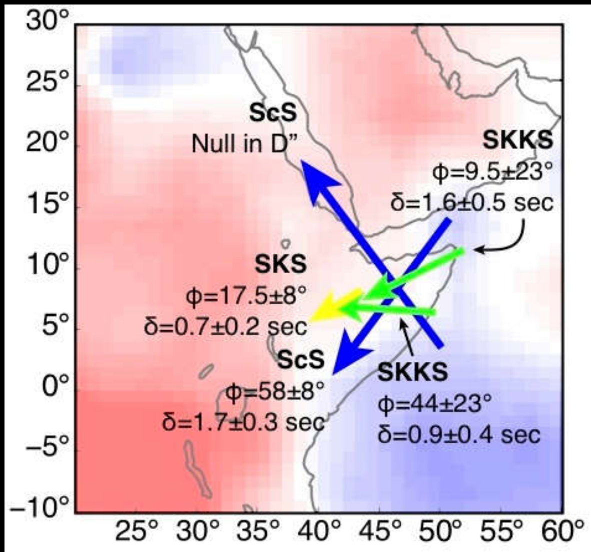
Combination of 2 types of data: SKS-SKKS and ScS-S

The approach: a detailed dataset and mineral physics based forward modeling



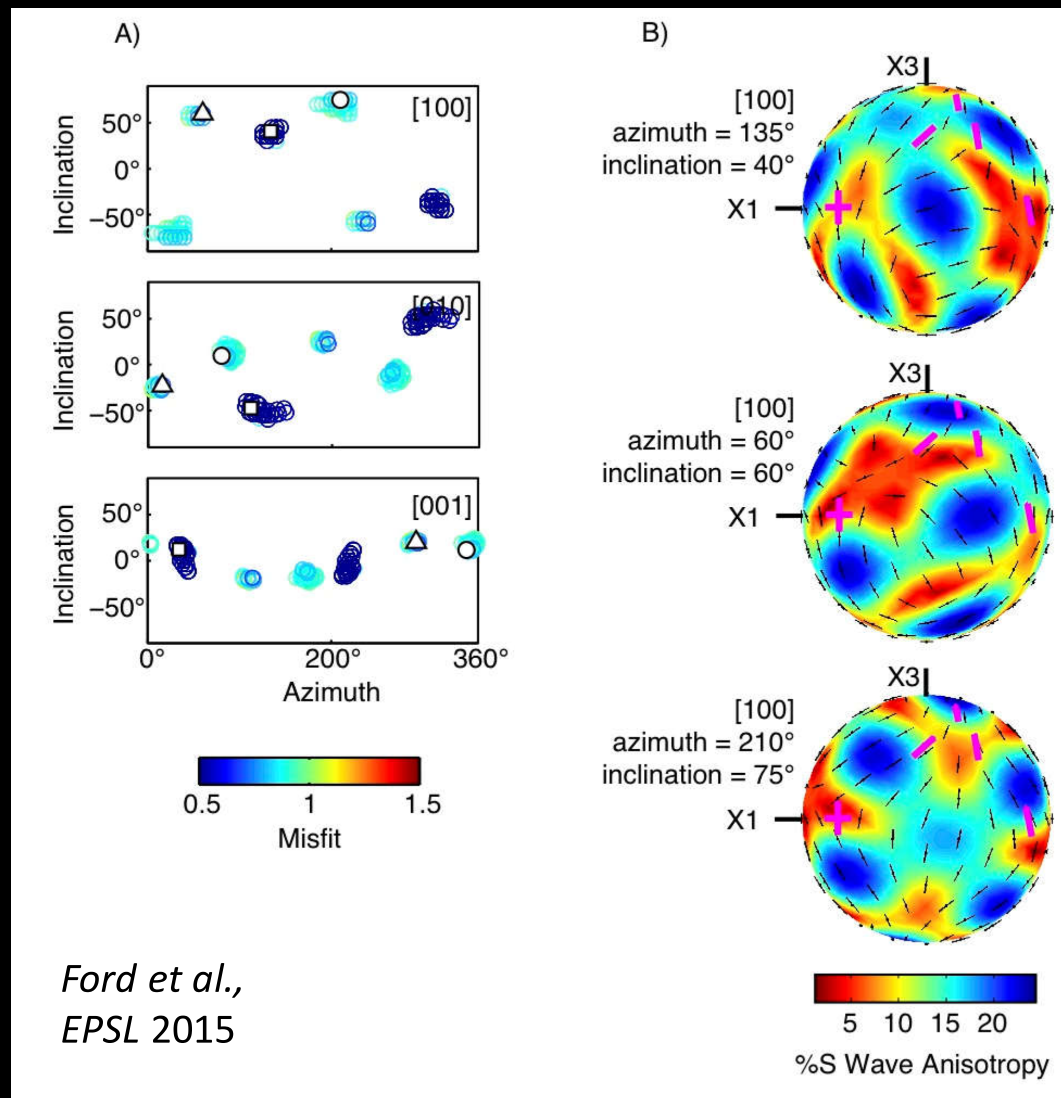
Ford et al., EPSL 2015

Testing plausible anisotropic scenarios against our splitting observations



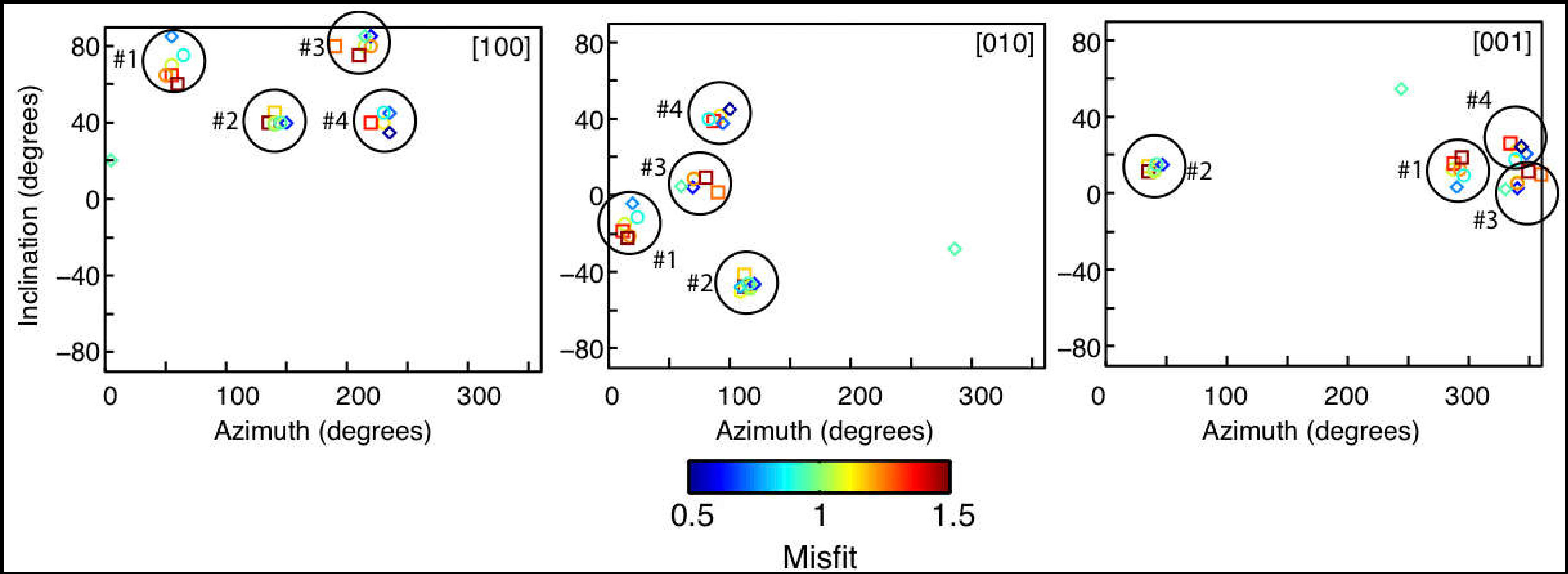
The approach: use single-crystal elastic constants (as a start!) for different minerals and carry out forward modeling for all possible orientations.

Check: which minerals/ orientations are consistent with the splitting data?



Ford et al., EPSL 2015

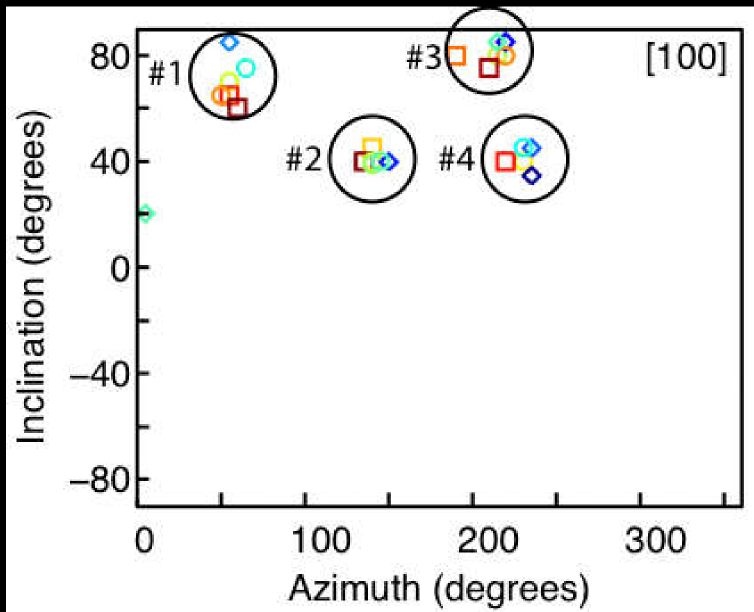
Testing plausible anisotropic scenarios against our splitting observations



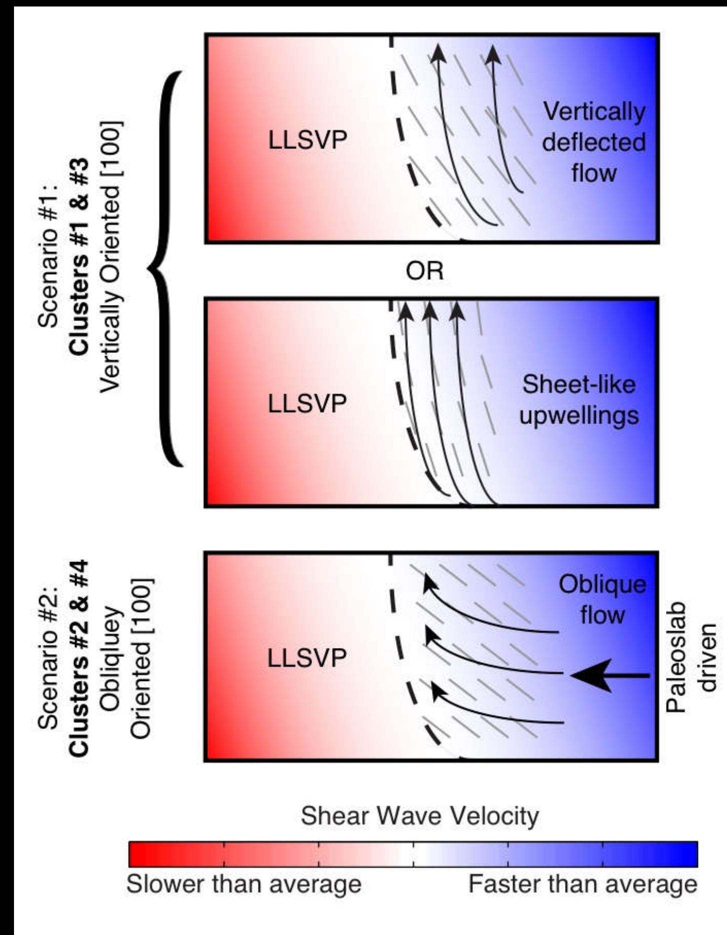
Ford et al., in review

Our measurements are able to dramatically narrow down the possibilities. Specifically: can rule out any melt SPO scenario. MgO and perovskite also very poor fits to the data. Most likely: LPO of post-perovskite, with a few (~4) plausible orientations.

Testing plausible mantle flow scenarios: Which (simple) models are consistent with the data?



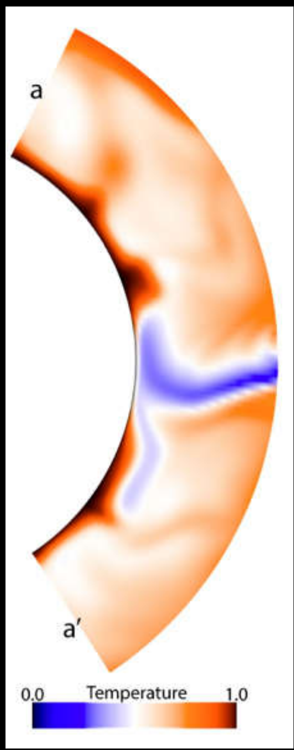
Ford et al., EPSL, 2015

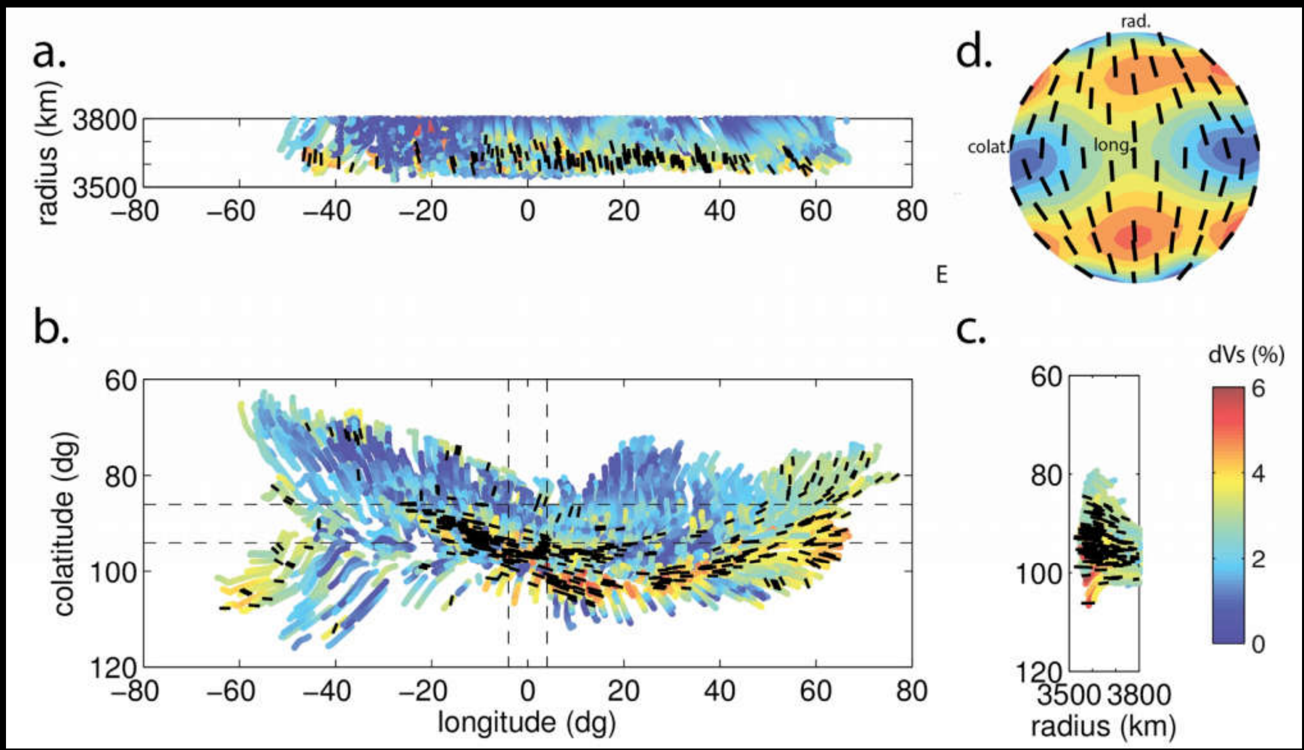


IF [100] is most likely slip direction for dislocation creep of post-perovskite (slip plane less well known), *THEN*:

- We can (mostly) rule out horizontal flow.
- Most likely simple flow scenario involves some component of vertical flow at LLSVP edge

There are MANY assumptions made in this approach. Can we do better?





What is needed: better consensus on single-crystal elasticity and LPO development in lowermost mantle minerals, more realistic geodynamic scenarios to test, integration of additional observational constraints…

Summary of take-home points

- Shear wave splitting provides robust constraints on anisotropy in the upper, mid-, and lowermost mantle, but care is needed to isolate signal from deeper portions.
- Anisotropy in subduction systems is complicated, reflecting a complex mix of physical processes, and at least sometimes requiring departures from simple 2D flow.
- There is significant anisotropy in the transition zone and uppermost lower mantle, both globally and in subduction systems. Can we learn about mid-mantle deformation near slabs by interpreting these measurements?
- Lowermost mantle anisotropy: an exciting frontier. Relationships between anisotropy and structures such as LLSVPs. Moving towards a framework for relating D” anisotropy to flow – exciting!