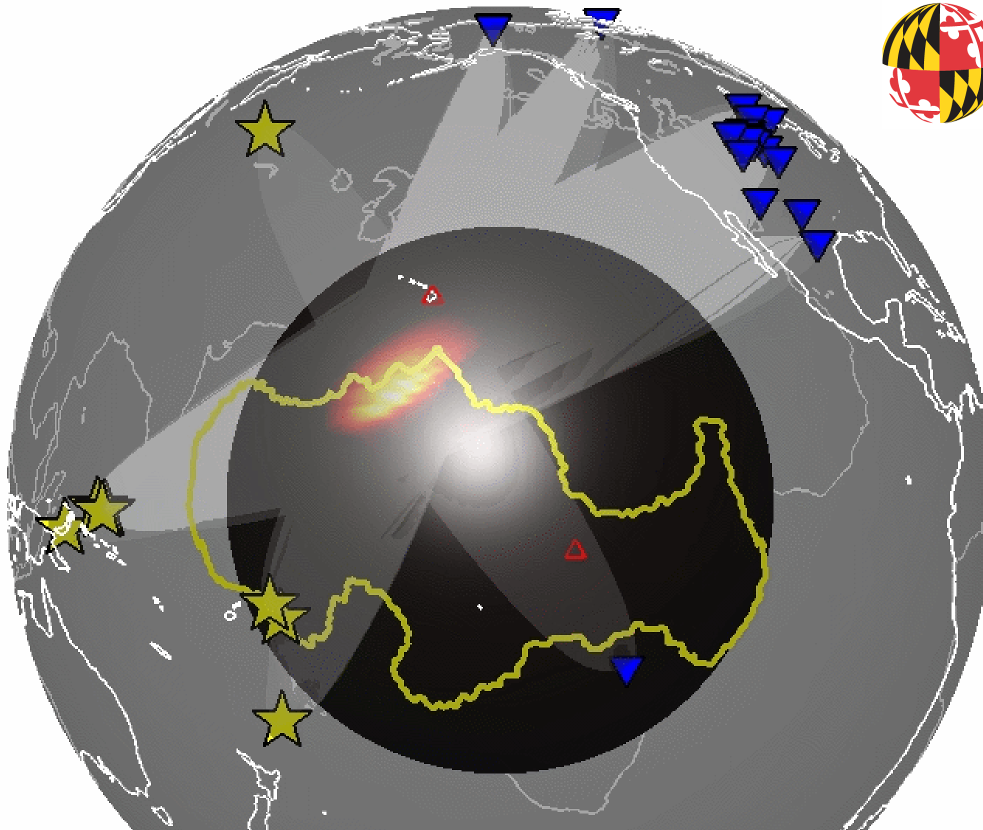


Deep Earth Seismology: Discoveries, Questions, and Challenges

Ved Lekic, University of Maryland, College Park

2020 CIG Community Workshop
Session 3: Long Term Tectonics and Seismology
October 15, 2020

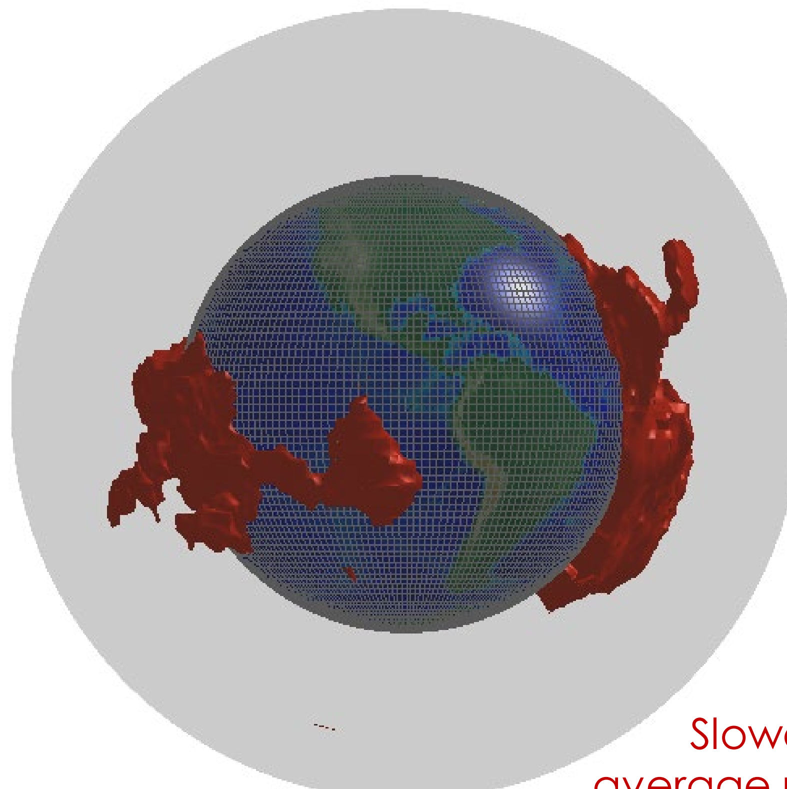
Tomography: Large-Scale Structure

Ritsema & Lekic, AREPS 2020

Fast and Slow Lower Mantle

- To sort out the distribution of slow and fast material in the lower mantle, we classify features across models
  - e.g. Where do **all** models agree → "consensus view"

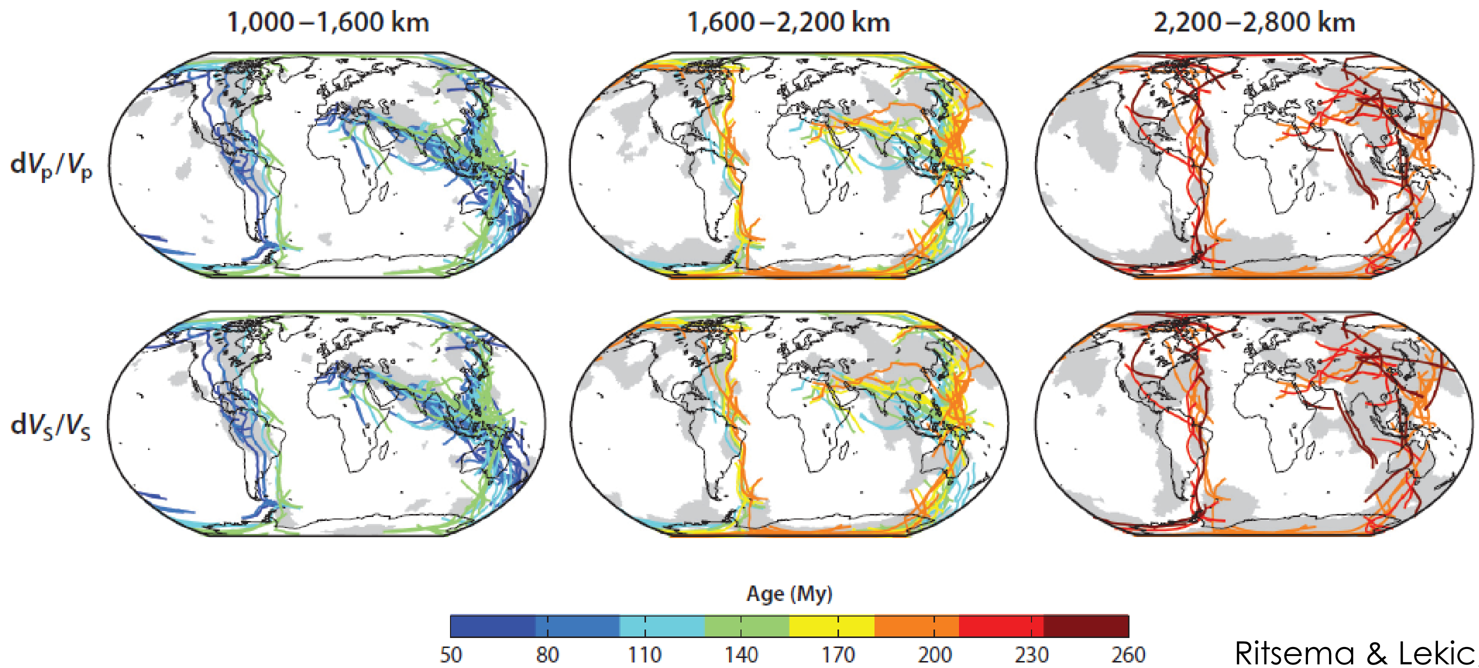
Faster than average regions



Slower than average regions

Fast Regions → Slabs

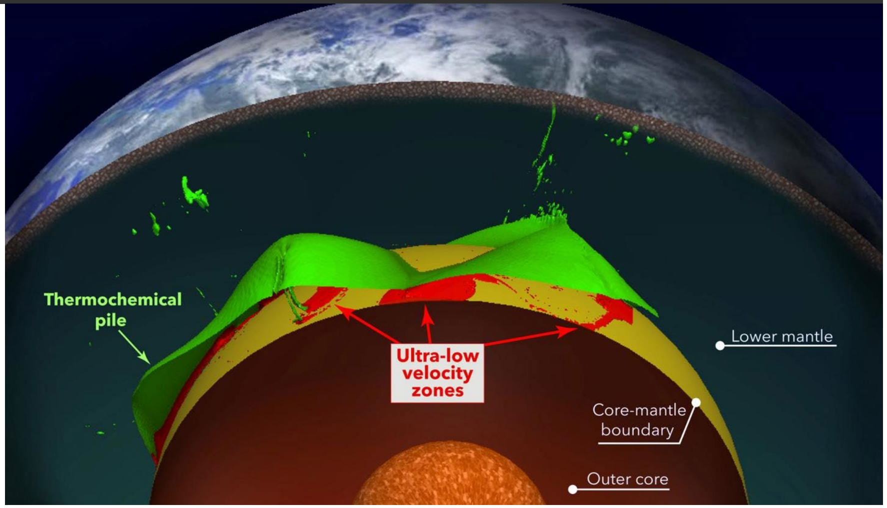
- Excellent correspondence between reconstructed locations of subduction zones and fast regions in lower mantle
  - Informs an "Atlas of the Underworld" (van der Meer et al., 2018)
    - Outstanding question: How far back to go? 130Ma? 240Ma?
  - Reveals previously unknown slabs (e.g. Sigloch & Mihalynuk, 2013)



Ritsema & Lekic, AREPS 2020

Slow Regions → ?

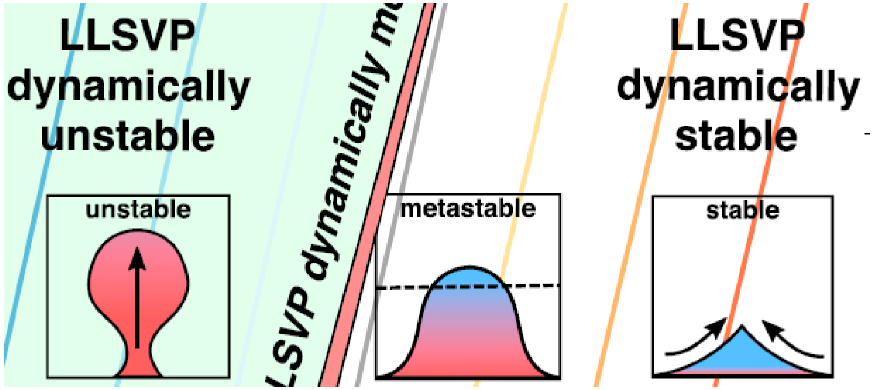
- Large-scale lower mantle low velocity regions remain mysterious:
  - Compositionally distinct or not?
  - Active (plumes) or passive (piles)
  - Primordial or continually created



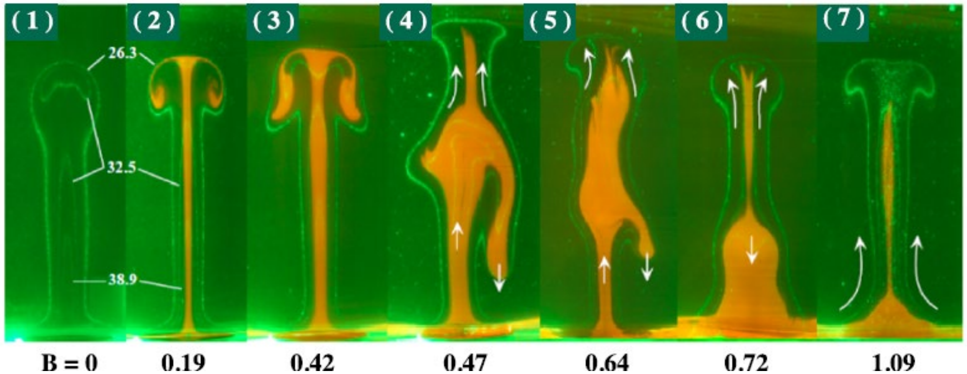
- If LLSVPs are denser than surrounding mantle, then isochemical scenario can be ruled out (e.g. Davies et al. 2015)
  - Most seismic constraints prefer dense LLSVPs (Ishii & Tromp, 1999; Trampert et al. 2004; Moulik & Ekstrom, 2016) as do tidal constraints (Lau et al. 2017)
  - Stonely modes (Koelemeijer et al. 2017) might not, but full coupling calculations are crucial for their interpretations (see Akbarashrafi et al. 2018)

Importance of Morphology

- Mapping small-scale structure within LLSVPs is key for distinguishing between stable thermochemical piles and dynamically unstable domes/plumes
- Intrinsic density of LLSVP material will affect their morphology whether they are primordial piles or clusters of thermo-chemical plumes



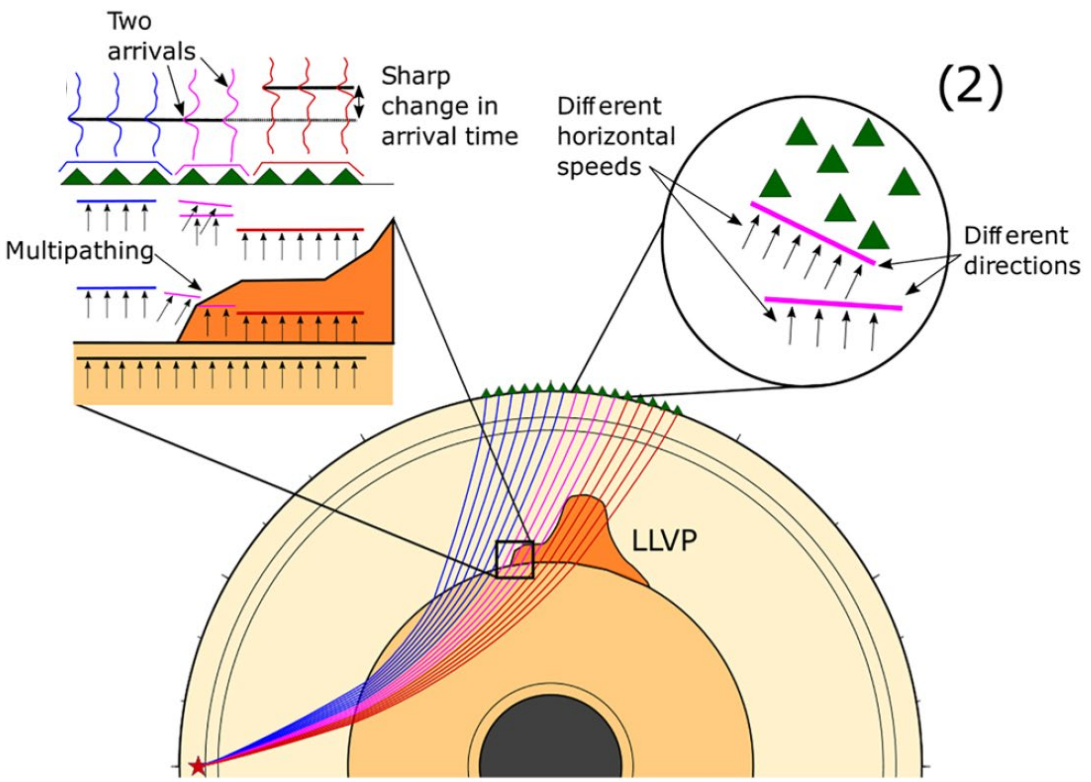
Wolf et al. 2015



Davaille & Romanowicz, 2020

Waveform and Array Constraints

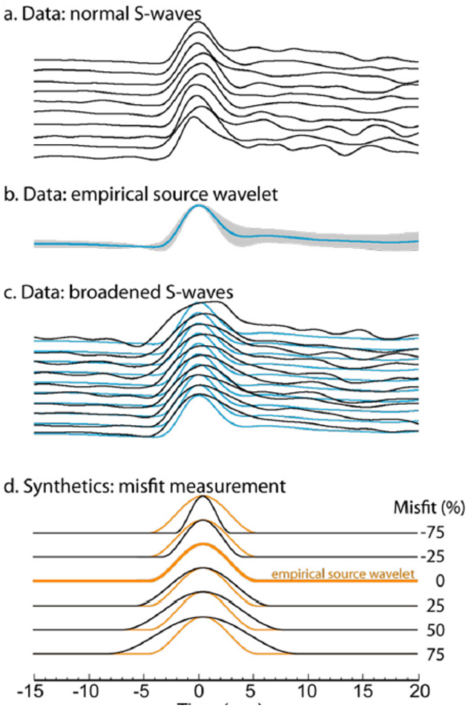
- Waveform shape becomes complex or broadened
- Arrays detect multiple arrivals with different slowness

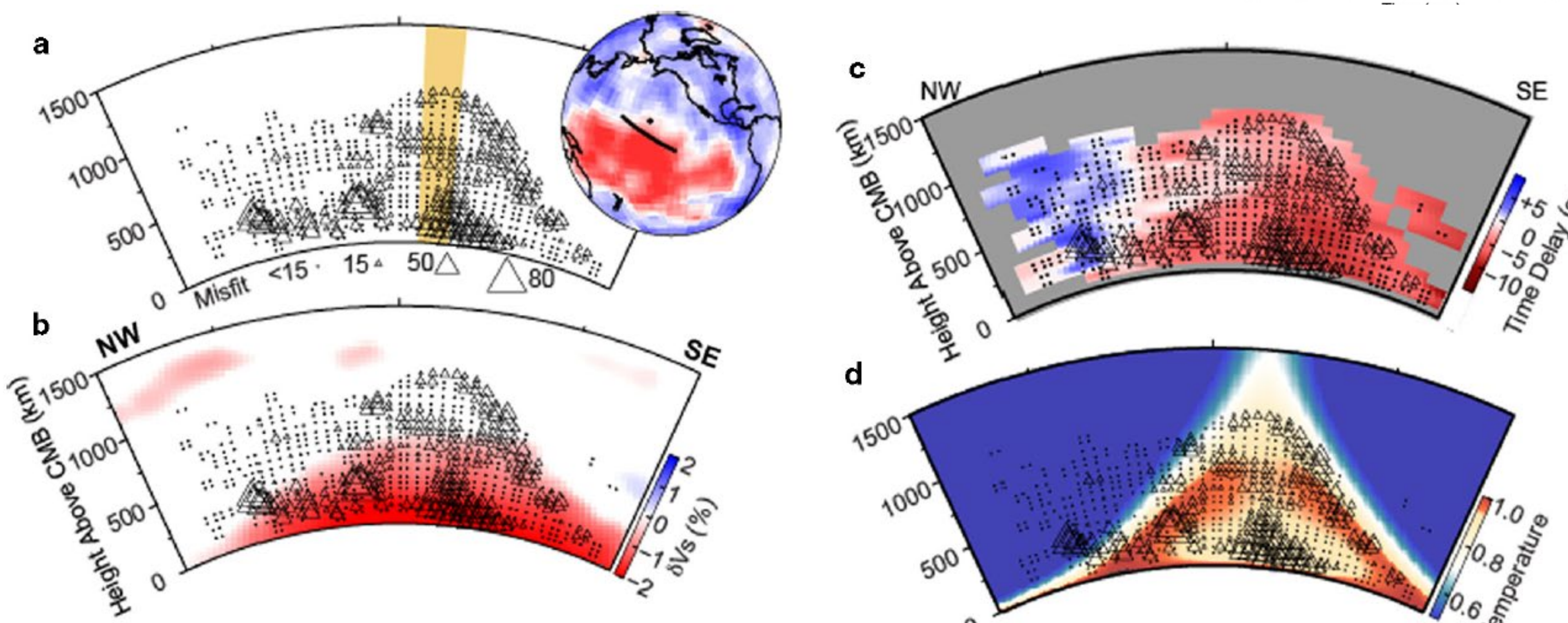


Ward et al. 2020

Pulse Broadening

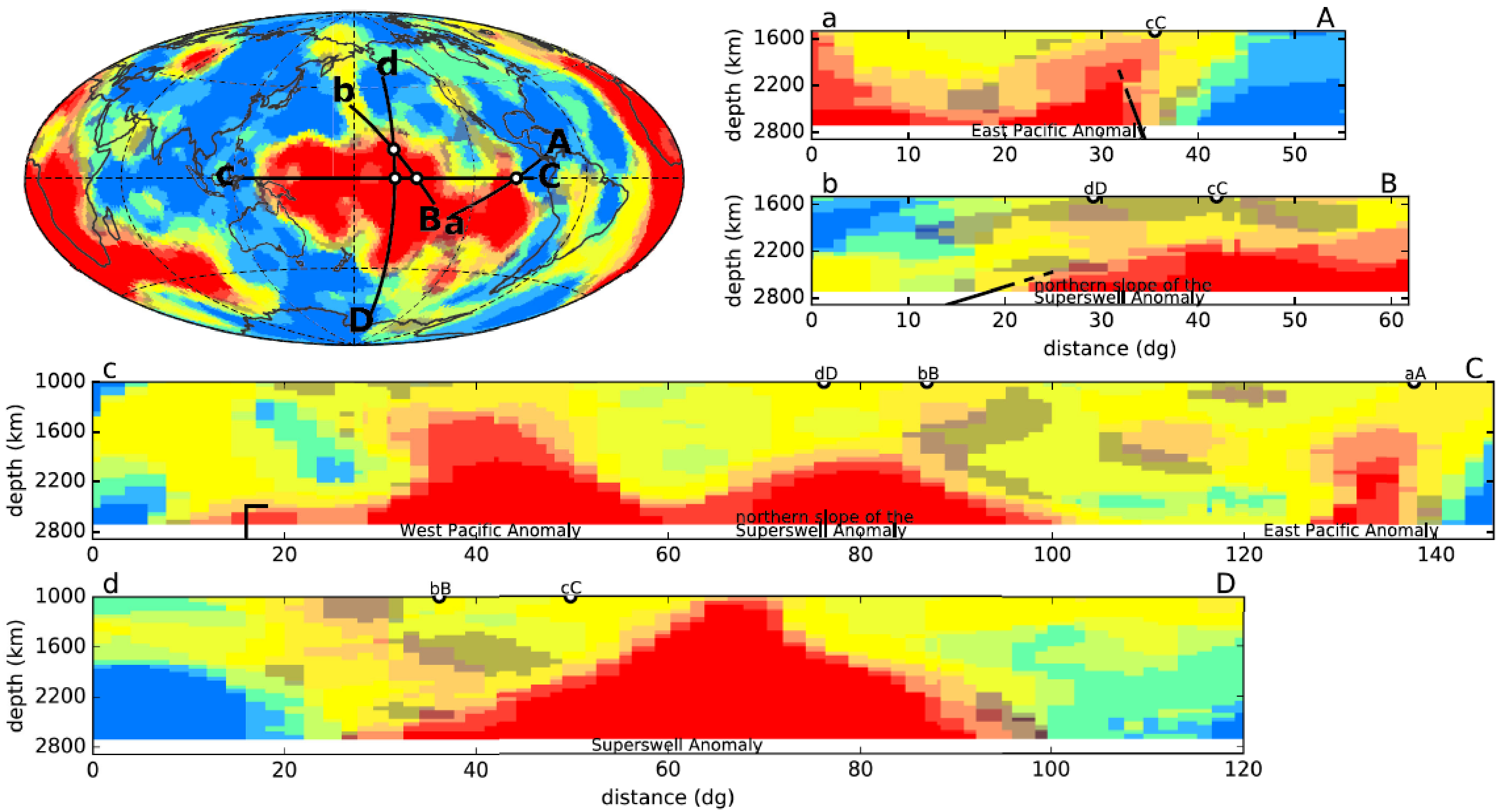
- Measurements of S-wave broadening can map areas of abrupt Vs changes
- Mapped back to likely origin, they reveal an anomalous, conical region beneath Hawaii





Zhao et al. 2015

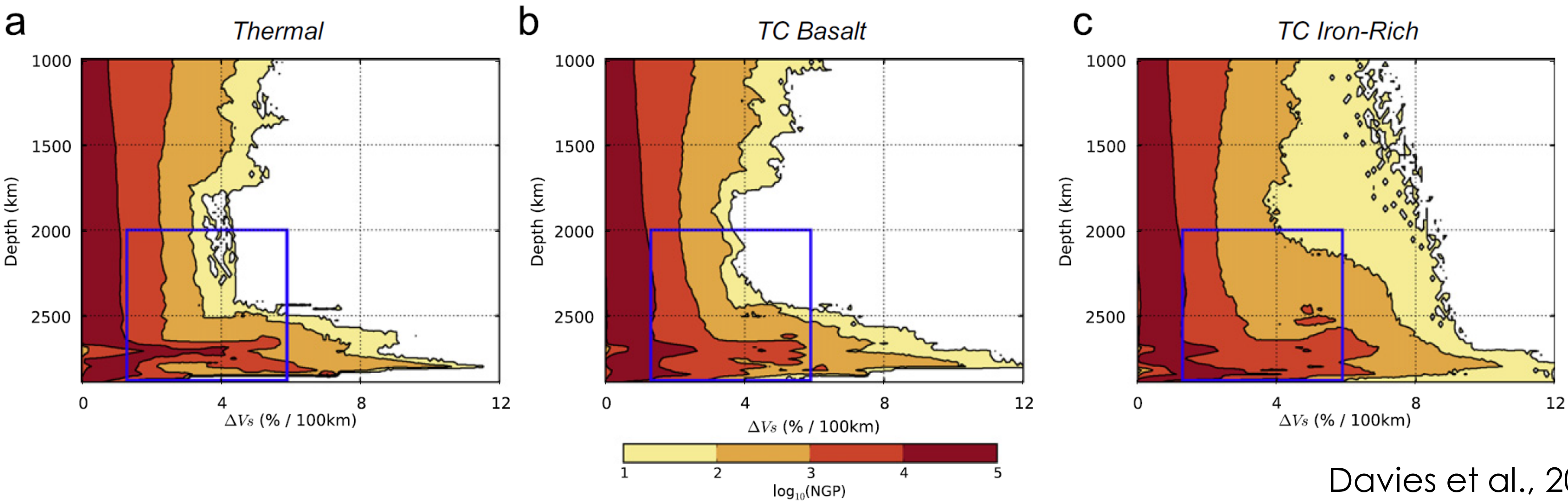
Conical "Pile-Like" Structures



Cottaar & Lekic, 2016

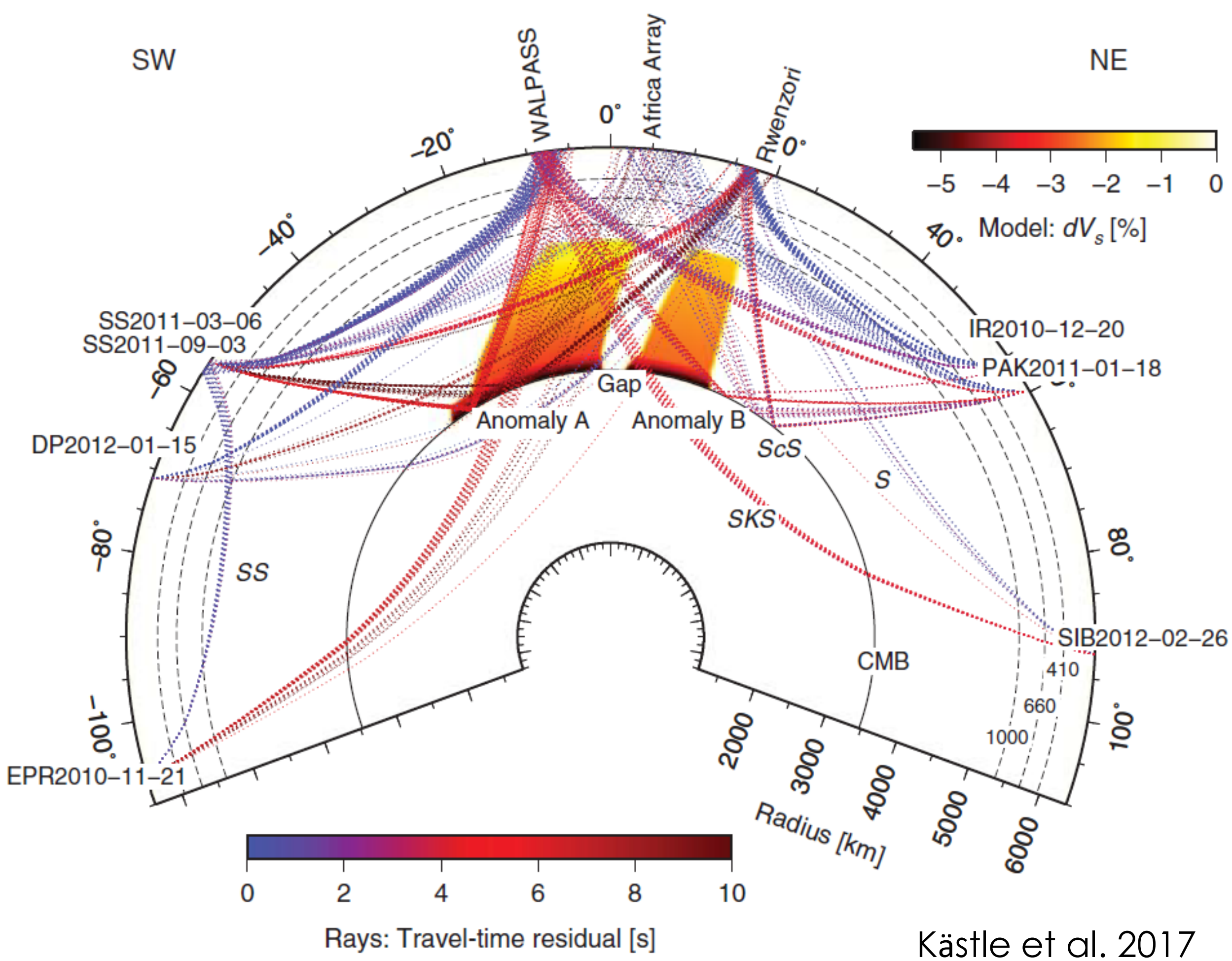
Sharp Edges

- Sharp lateral gradients (1.5-6% δVs/100km) have been interpreted to imply chemical heterogeneity (e.g. Wen, 2001; Ni et al. 2002; To et al., 2005).
- Can purely thermal gradients (800-1000K/100 km) in a compressible flow + post perovskite explain the gradients?
- Recent studies suggest that perhaps even smaller gradients (~0.7 % δVs/100 km) are sufficient to produce multipathing (Ward et al. 2020)



Davies et al., 2012

Small-Scale Intra-LLSVP Structure

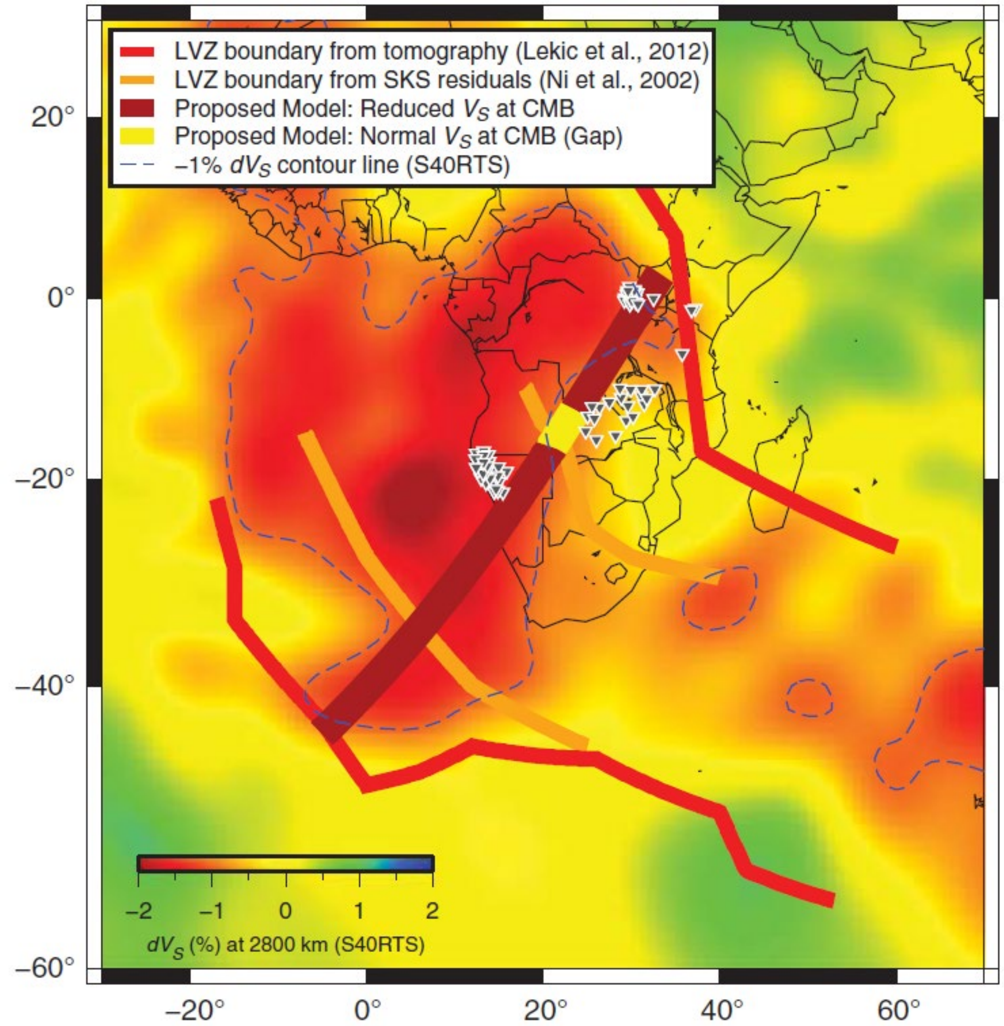


Kästle et al. 2017

- Small-scale structure within LLSVPs may yield clues
- Seismologists can leverage various illumination geometries and seismic phases to probe detailed structure
- Often, such studies find stronger overall δVs drops compared to global tomography

Gap In the African LLSVP

- Abrupt differences in SK(K)S travel-time residuals reveal a 300 km gap in African LLSVP:
  - Undulation in the LLVSPs boundary, or
  - Signature of individual plumes, rather than one large homogeneous structure.



Kästle et al. 2017

Gap In the African LLSVP

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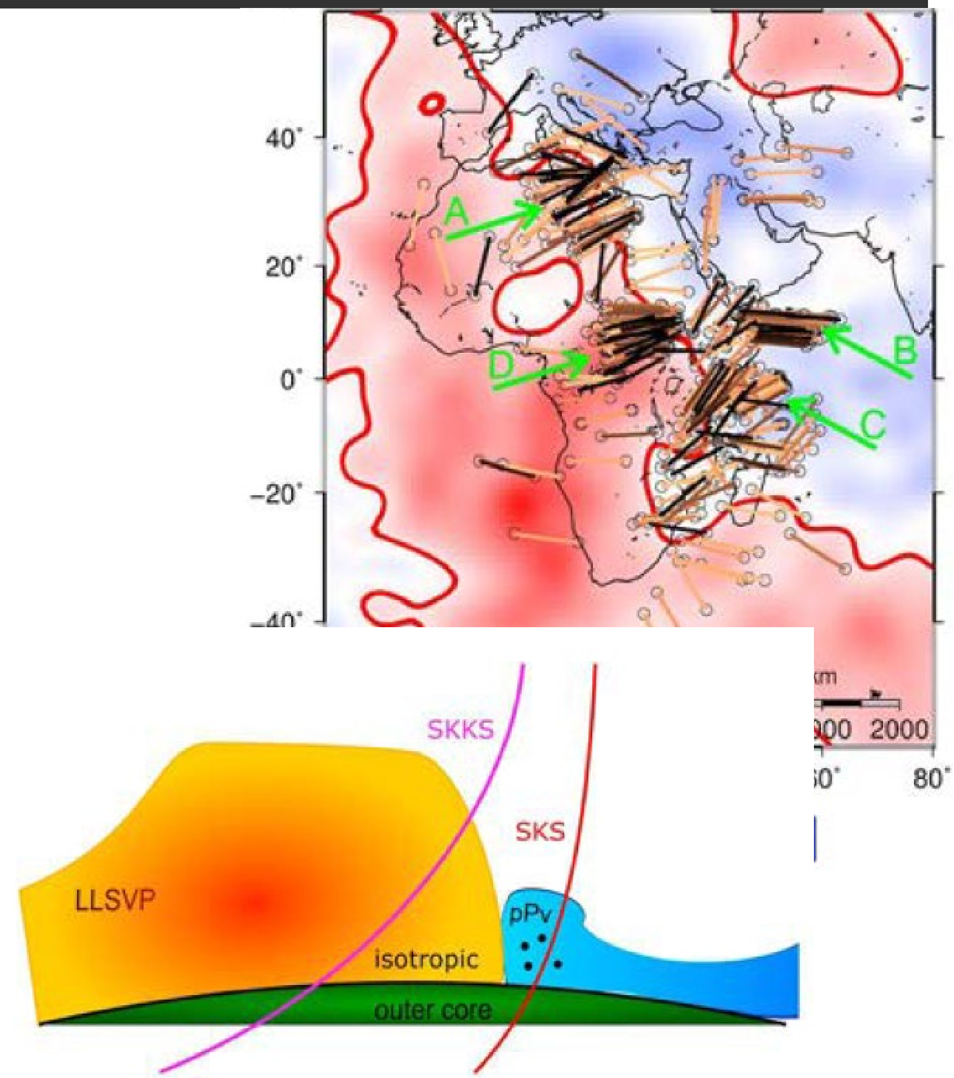
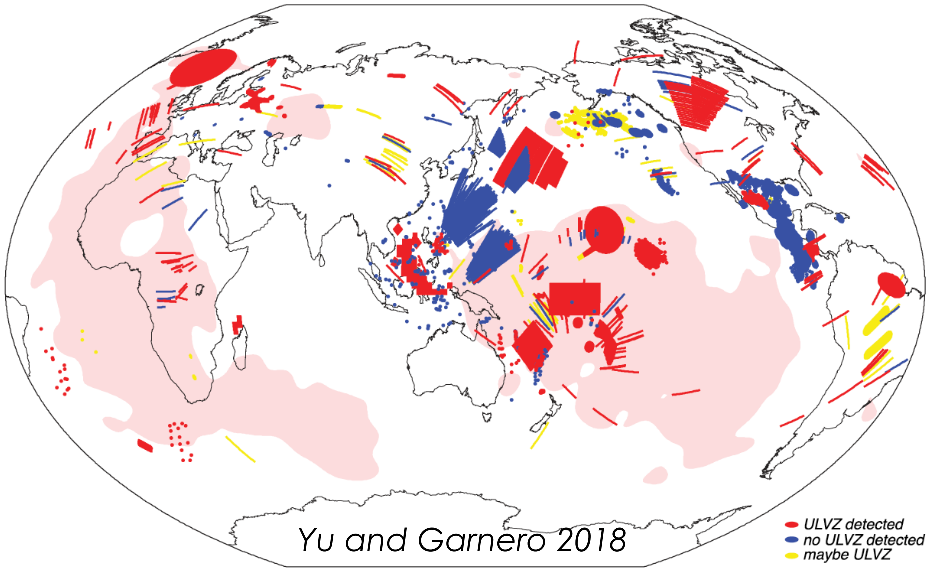
  - Undulation in the LLVSPs boundary, or
  - Signature of individual plumes, rather than one large homogeneous structure.
- Combined seismic-geodynamic modeling of splitting / anisotropy should provide insights



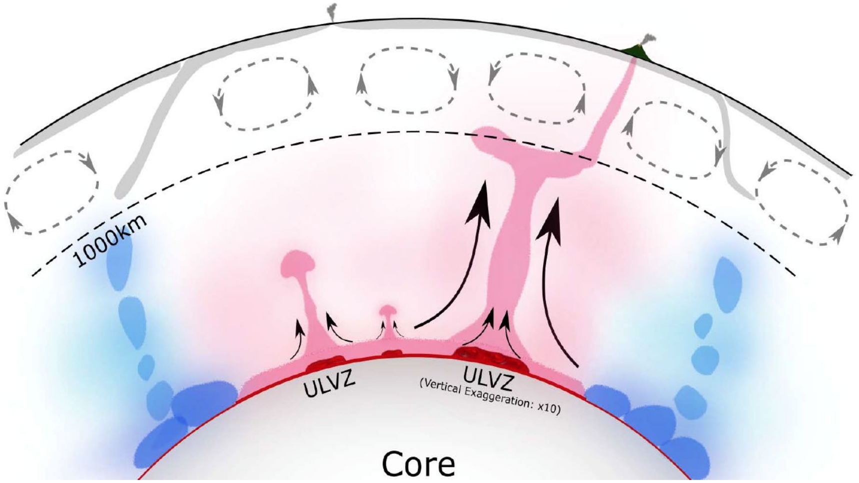
Reiss et al. 2019

Smaller-Scale Structure: ULVZs

- **ULVZs** are small (~10 km tall, ~100 km across), dense (~10%), ultra-slow (>10% δVs) anomalies
- "**Huge**" or "**Mega**" ULVZs (~1000 km across) have been discovered beneath Hawaii (Cottaar & Romanowicz, 2012), Samoa (Thorne et al. 2013), Iceland (Yuan and Romanowicz, 2017), Galapagos (Cottaar et al., in prep), and Marquesas (Kim et al. 2020)
  - Locally thickened global layer of melt (Williams & Garnero, 1996)? Or iron-enrichment (Wicks et al. 2010)?
  - Associated with anomalous 182-W and high 3He/4He isotopic signatures from the early Earth (Mundl et al. 2017, 2020)

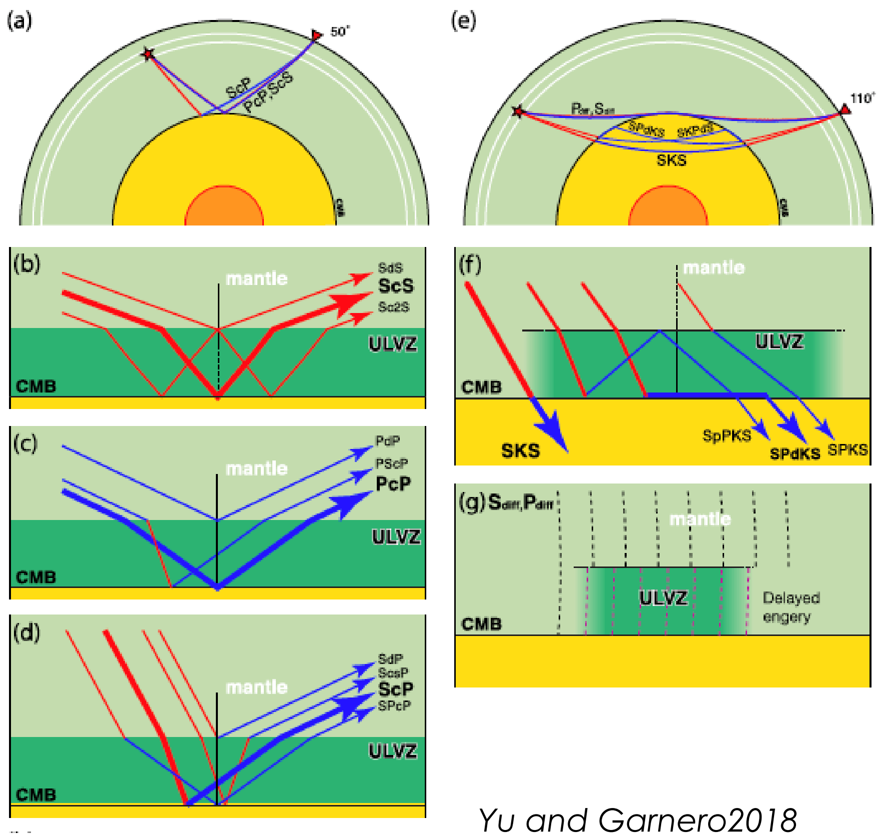


Yu and Garnero 2018



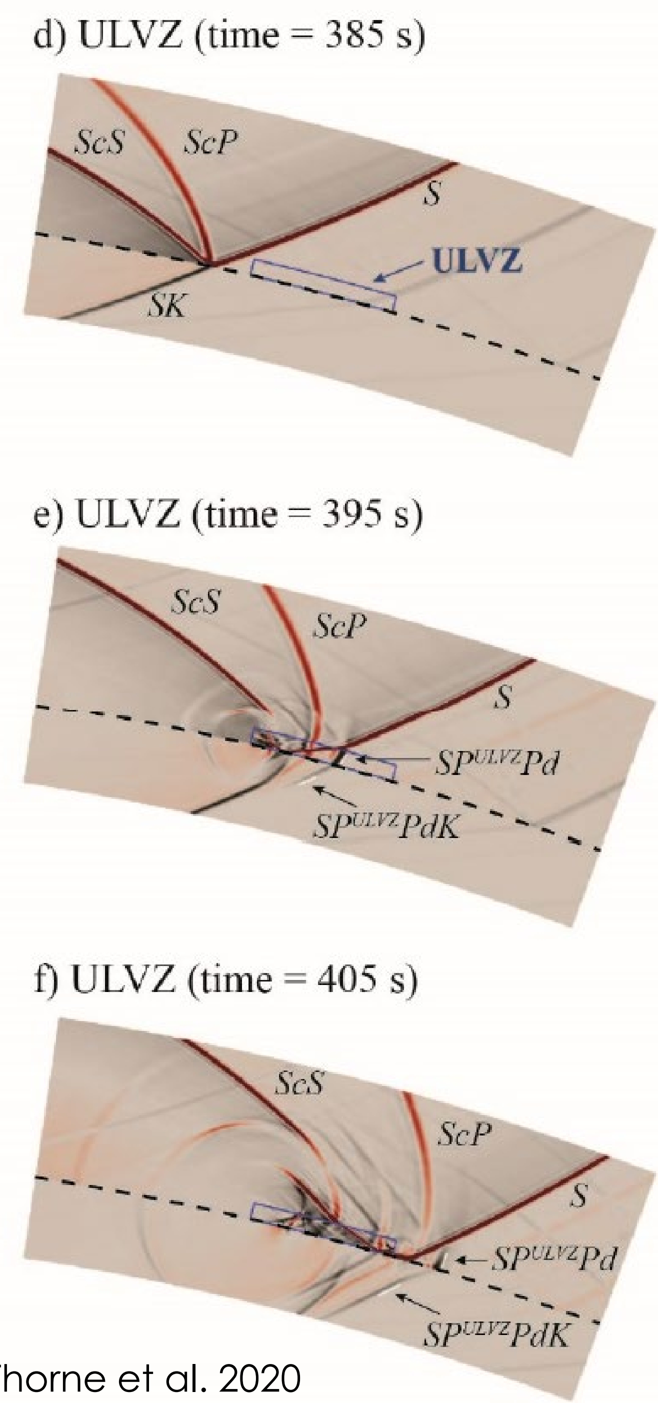
Yuan and Romanowicz 2017

Probing ULVZs



Yu and Garnero2018

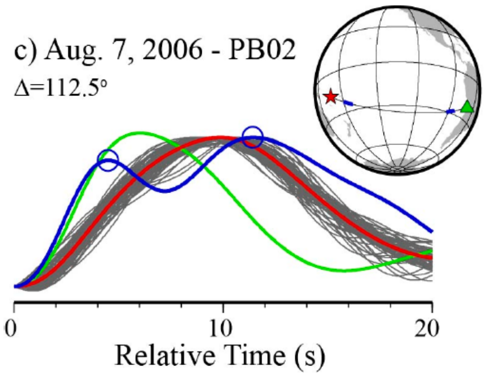
A host of clever uses of body wave phases

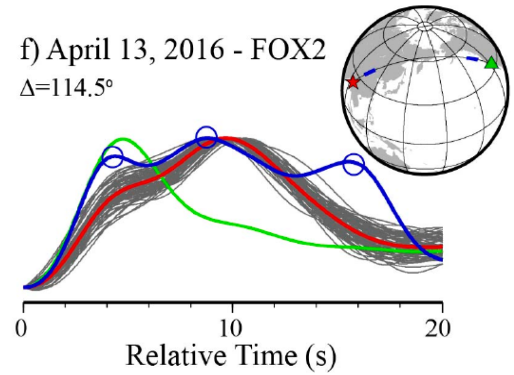


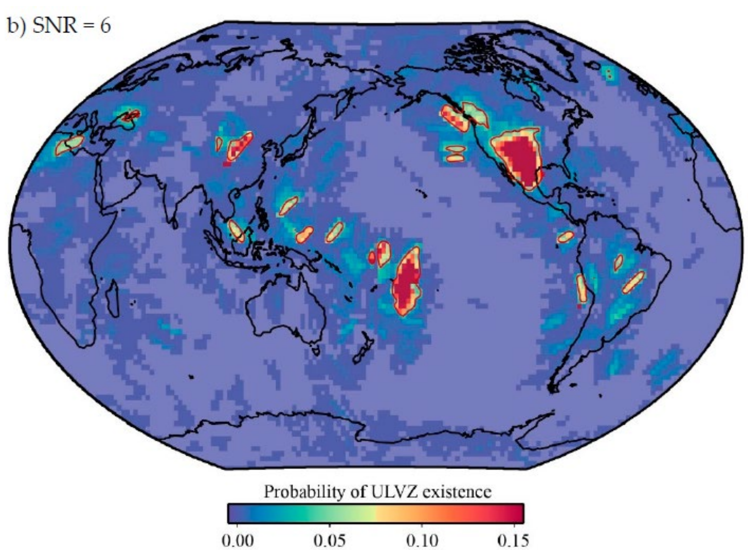
Thorne et al. 2020

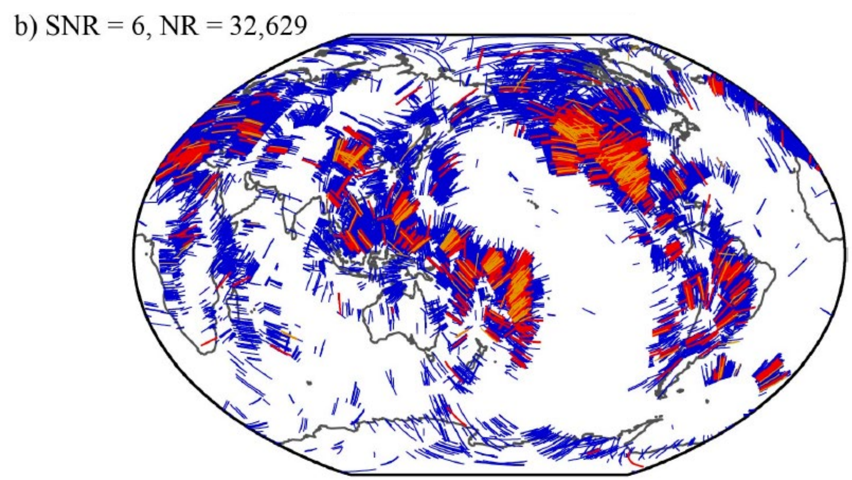
Mapping ULVZs

- >58,000 waveforms of SPdKS
- Cover >50% of CMB
- New ULVZs discovered beneath north Africa, east Asia, and Papua New Guinea



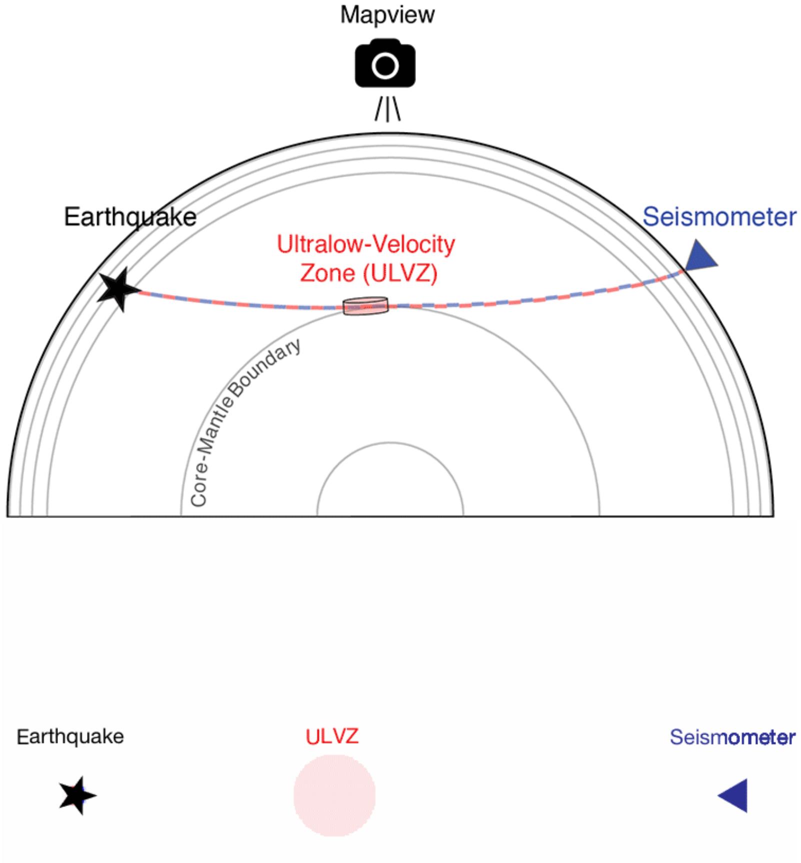






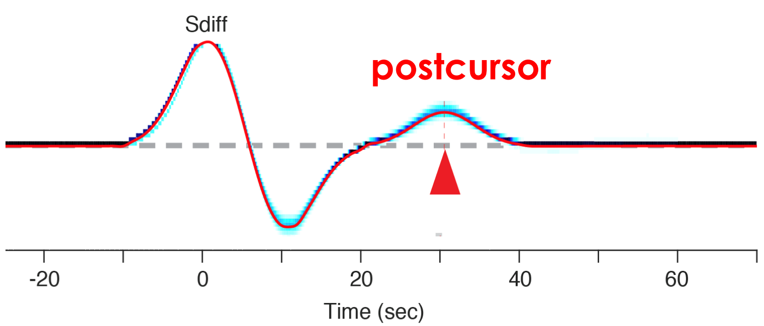
Thorne et al. 2020

Sdiff & Sdiff "postcursors"



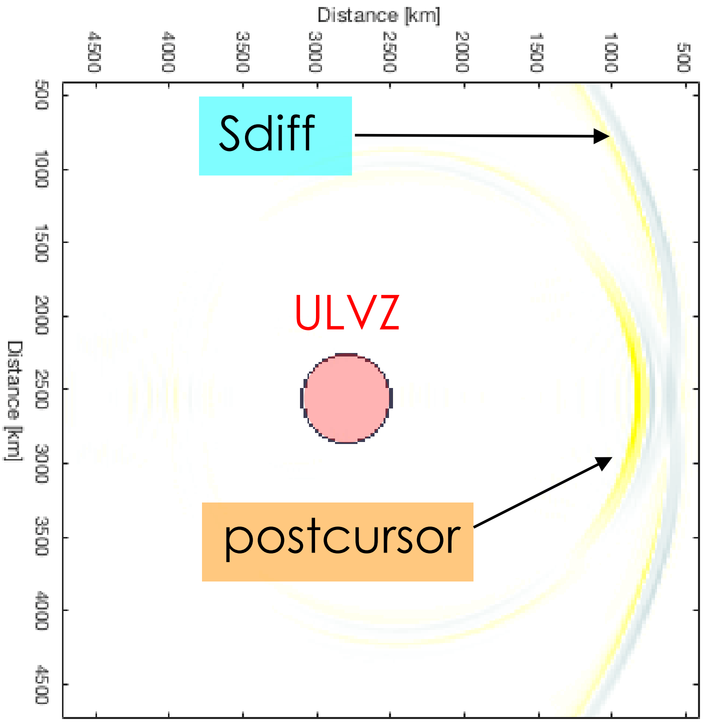
-What can we observe:

- Seismic waves either **transmit through** or **scatter off from** the anomaly, e.g., Sdiff postcursors
- **Amplitude** and **delay time** of the postcursors vs. the main Sdiff arrivals

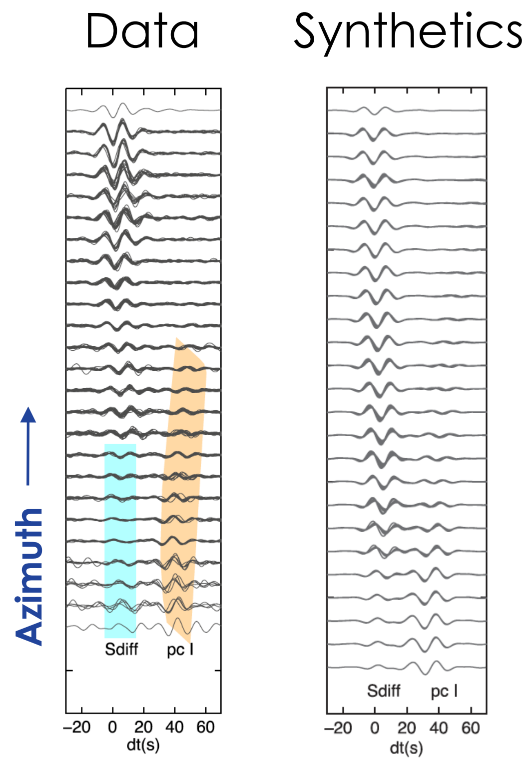


Kim et al. 2020

Detecting Postcursors



Traditionally, we use **geometrical parameters** such as **azimuth** or **epicentral distance** and focus on specific target areas



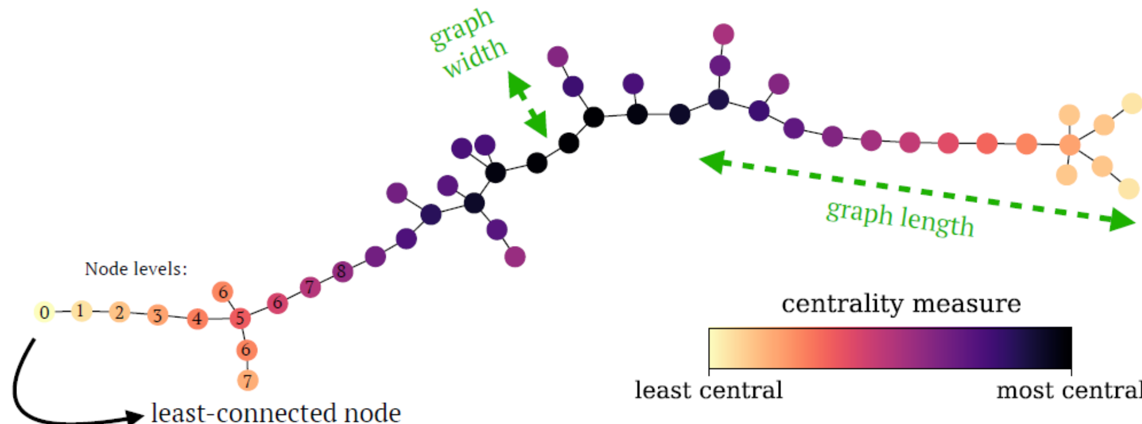
Cottaar and Romanowicz, 2012

Kim et al. 2020

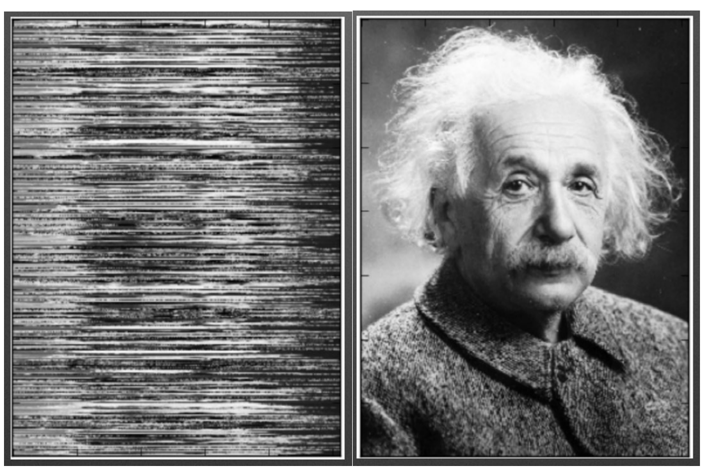
Sequencing Seismograms

We can arrange seismograms in a way that maximizes similarity along them → **optimal arrangement**

www.sequencer.org



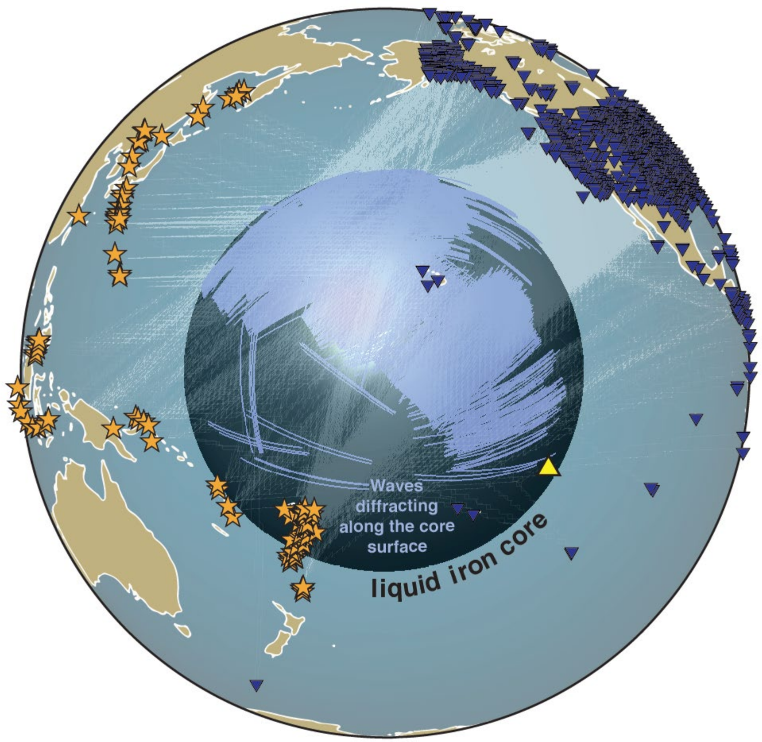
Baron & Menard, 2020

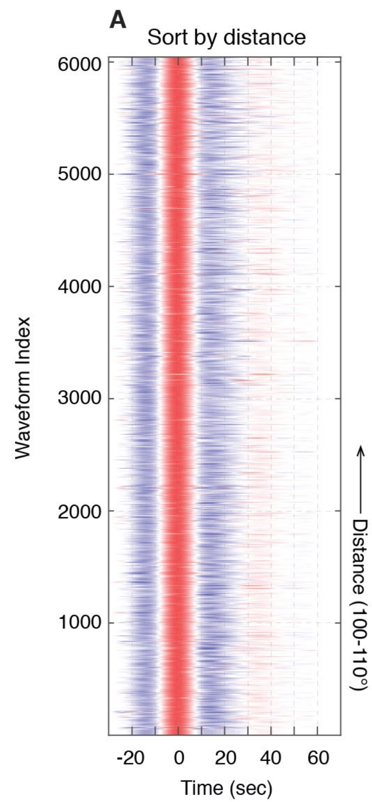


- By **sequencing** seismograms we can contextualize and interpret signals even in poorly-sampled regions
- We can simultaneously analyze structure across a whole ocean basin or even globally!

Kim et al. 2020

Sequencing Postcursors

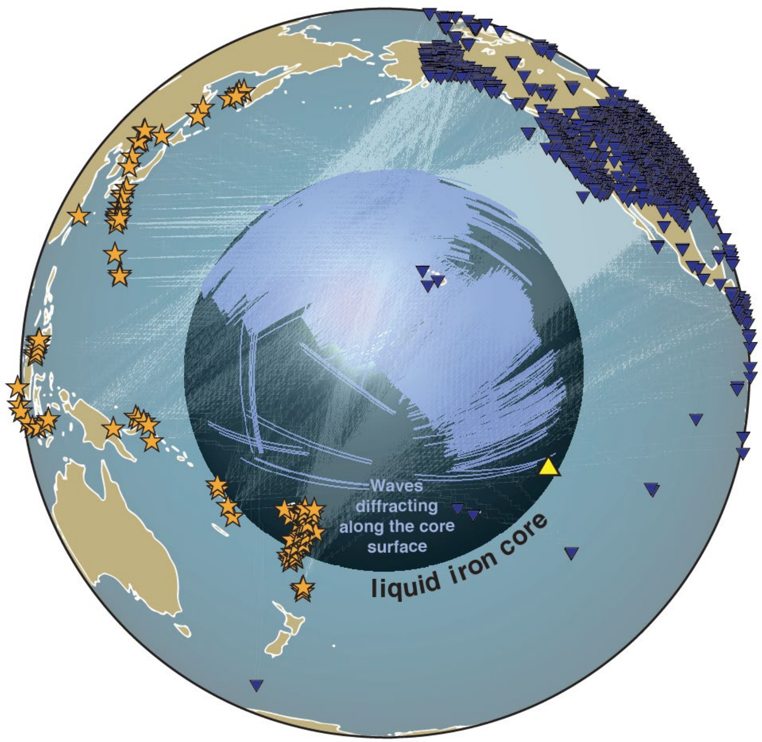


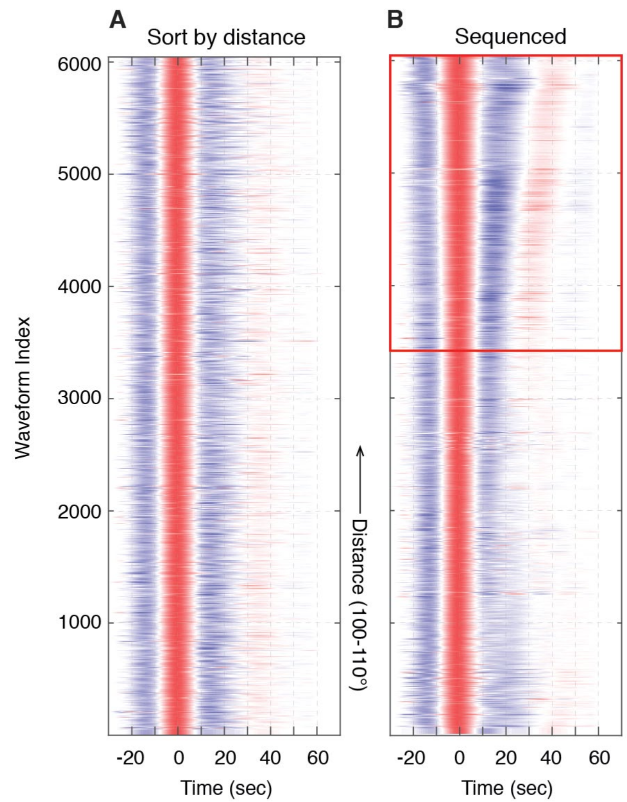


Sorting waveforms by geometrical parameters doesn't work anymore …

Kim et al. 2020

Sequencing Postcursors



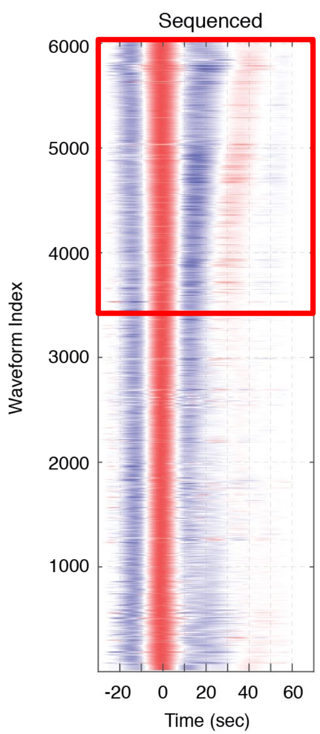


postcursor detected

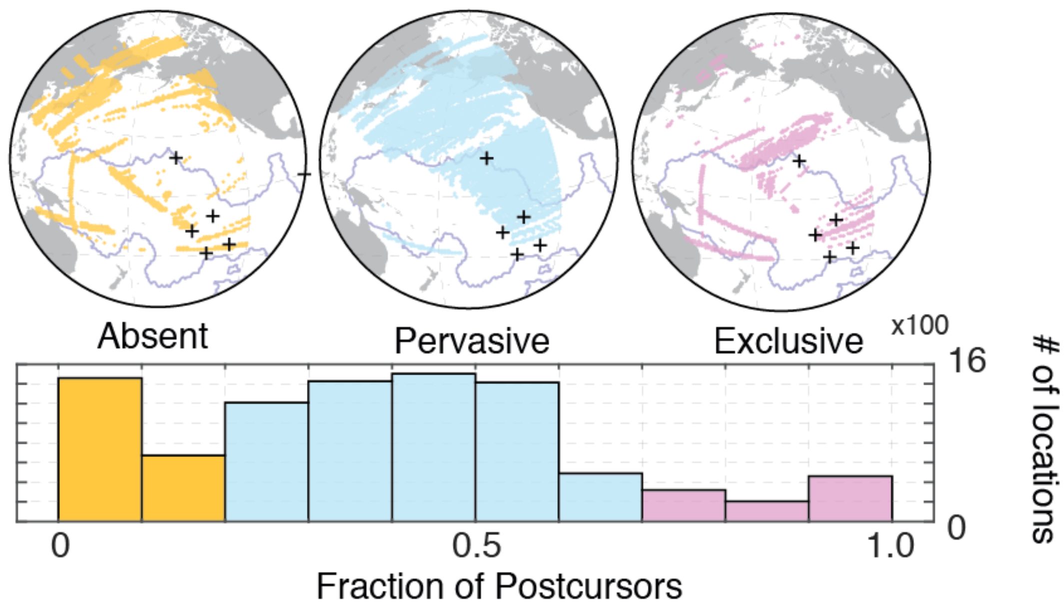
Postcursors are found in nearly 40% of all of the waveforms

Kim et al. 2020

Pervasive Postcursors in the Pacific



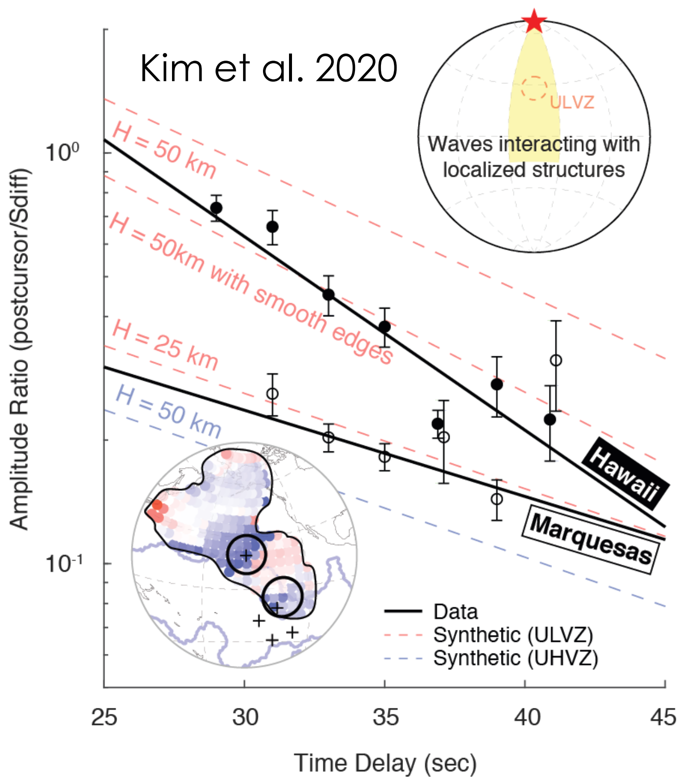
Identify postcursors in **more than 40%** of waveforms, **far more common** than previously thought

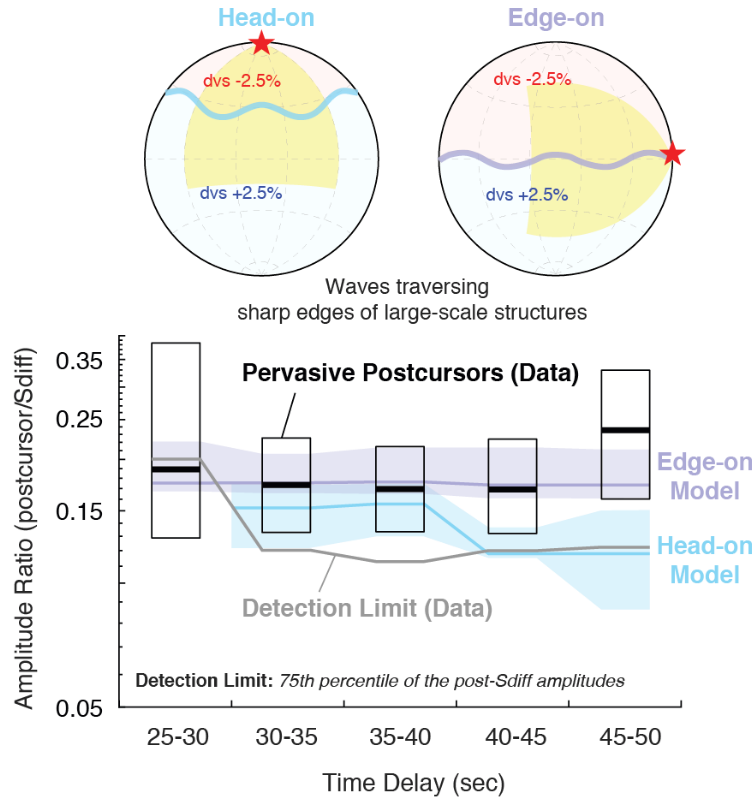


Pervasive: most locations
Absent: on paths that do not cross LLSVP boundaries, instead being confined either in their interior or outside
Exclusive: nearly all Sdiff waves sampling near Hawaii and Marquesas show postcursors

Kim et al. 2020

Local vs. Distributed Anomalies



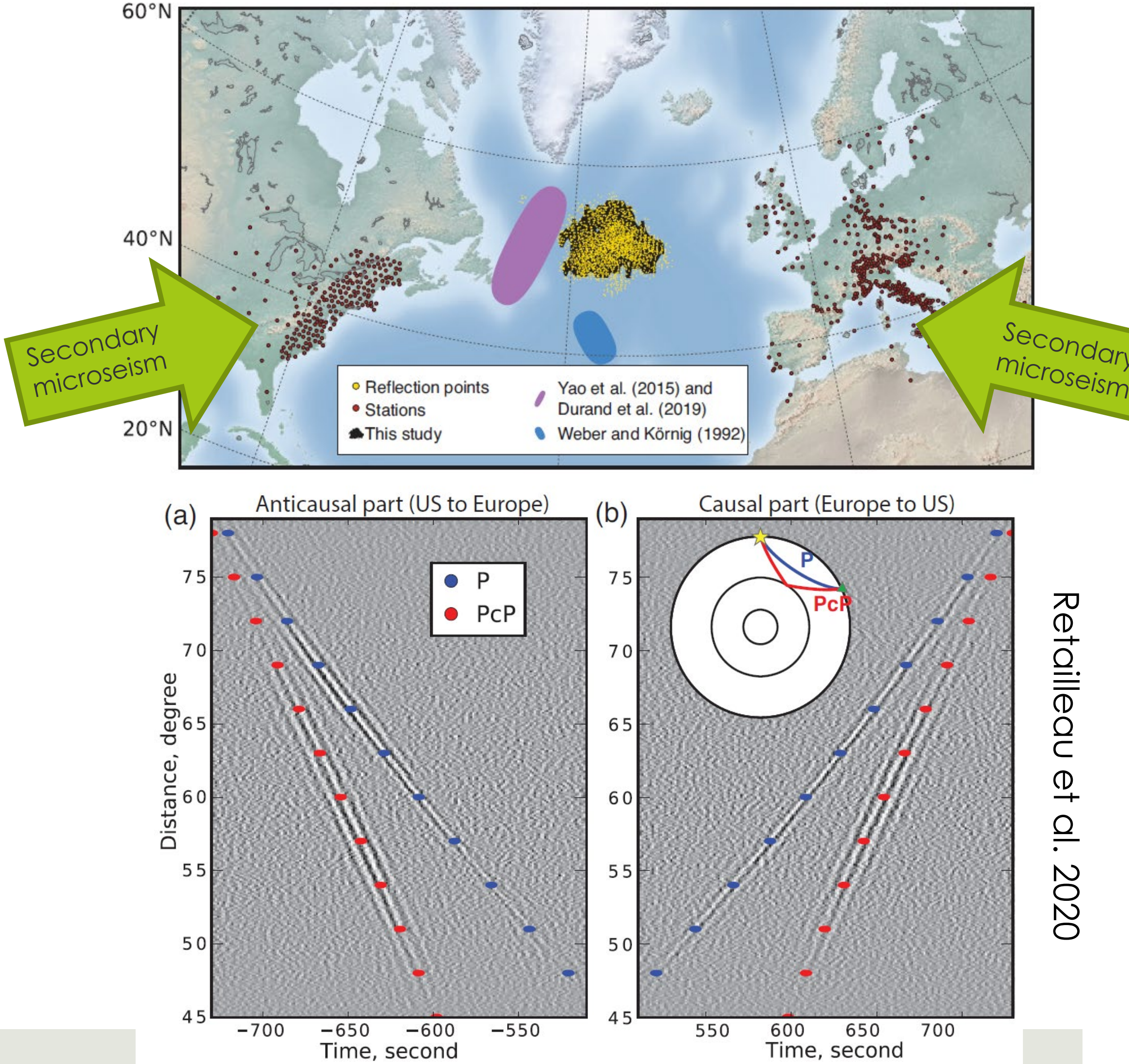


Localized structures beneath **Hawaii** and **Marquesas** Islands

Edges of Large-scale structures or scatterers **widespread** in CMB region

A Bright Future!

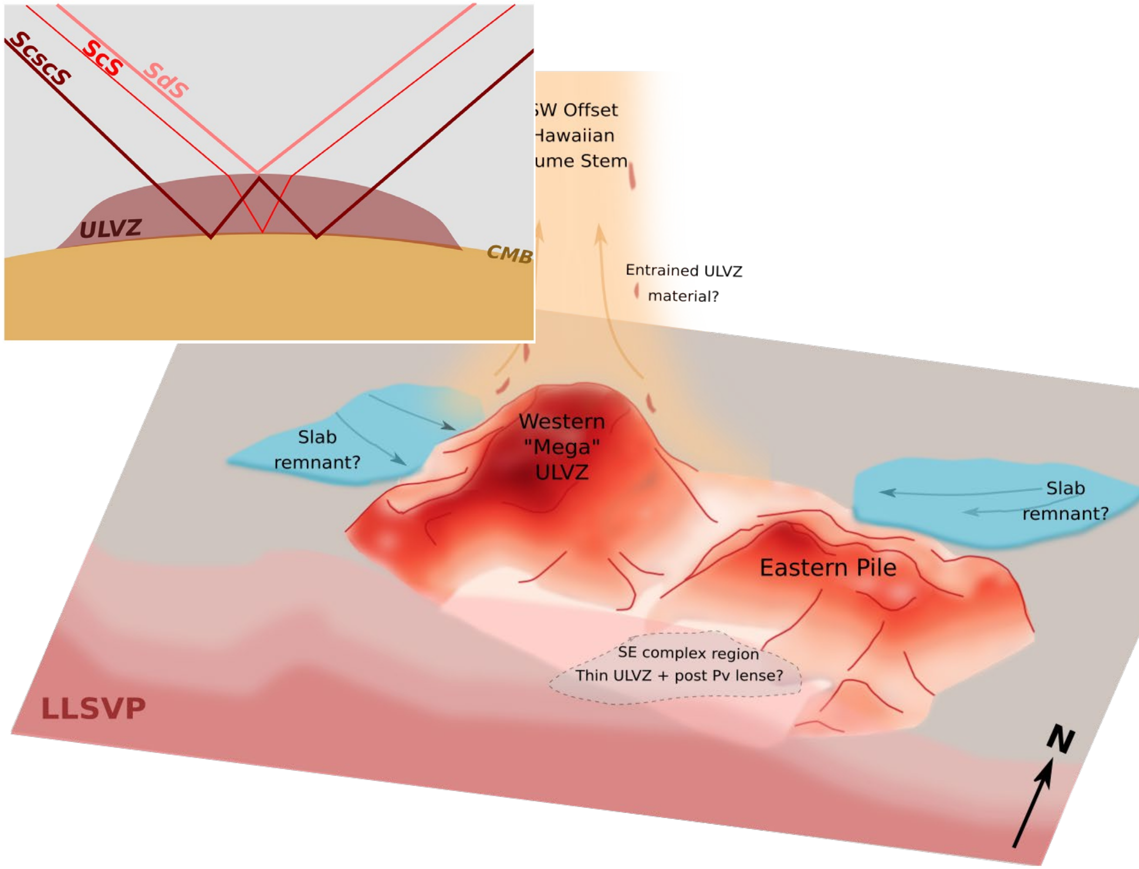
- In addition to new ways of analyzing existing data to discover anomalous signals…
- As of 2020, bodywave phases identified from ambient noise correlations have successfully targeted lower-mantle structures!



Retailleau et al. 2020

A Bright Future!

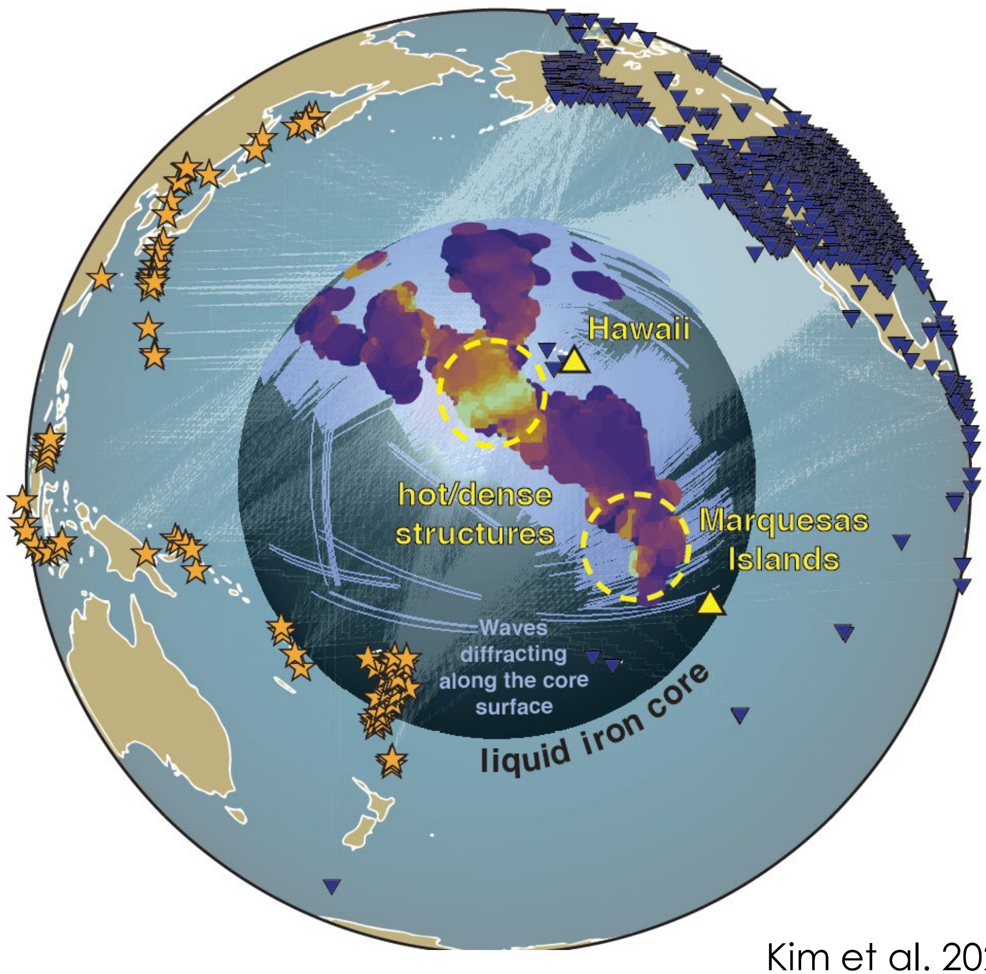
- In addition to new ways of analyzing existing data to discover anomalous signals…
- As of 2020, body-wave phases identified from ambient noise correlations have successfully targeted lower-mantle structures!
- Detailed studies of ULVZ and LLSVP morphology



Jenkins et al., in review

Takeaways and Questions?

- Origin and nature of LLSVPs remains mysterious
- Detailed studies of LLSVP morphology and internal structure are now possible
- ULVZs span a wide range of sizes → largest found beneath hotspots!
- New techniques and datasets reveal a highly heterogeneous CMB region



Kim et al. 2020