Seismology of Core-Mantle Boundary Region of the Earth

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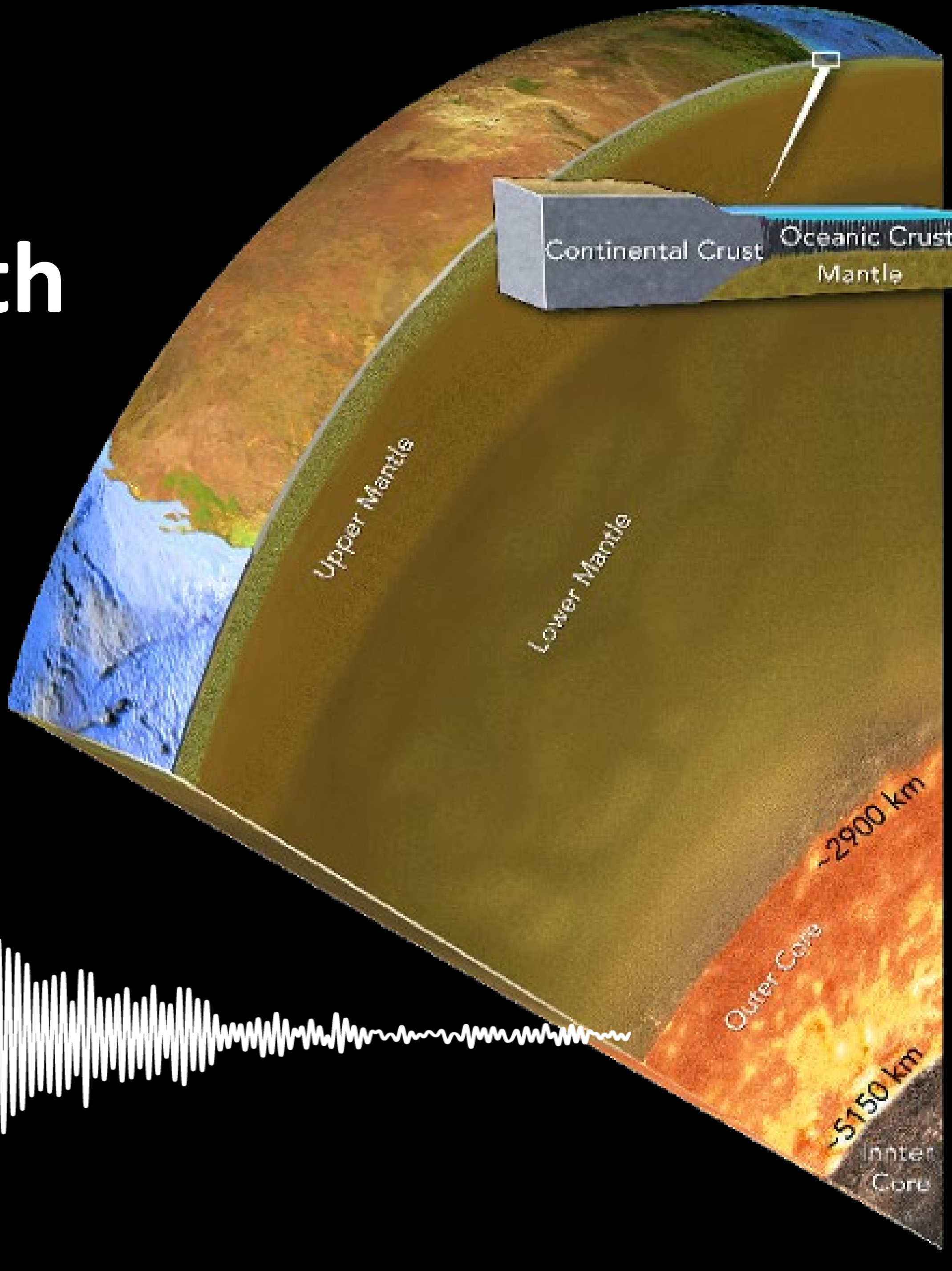
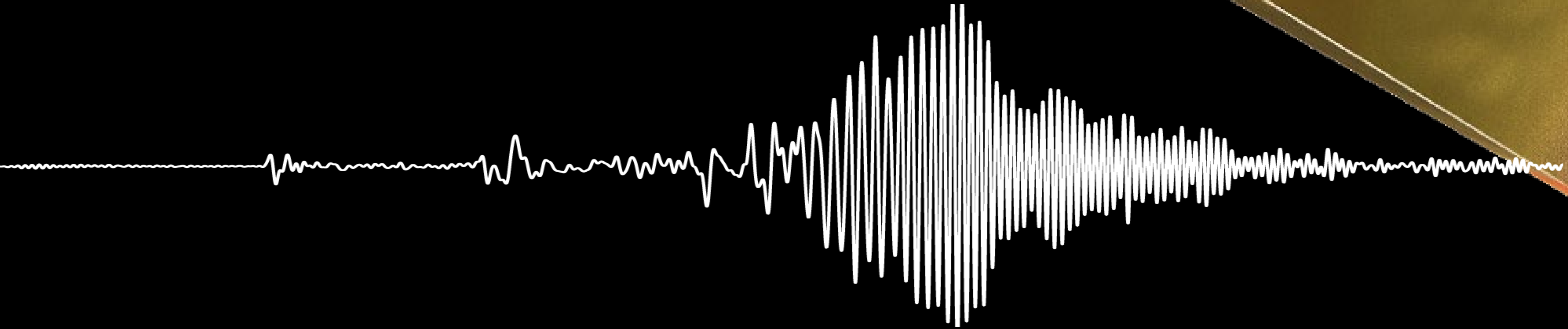
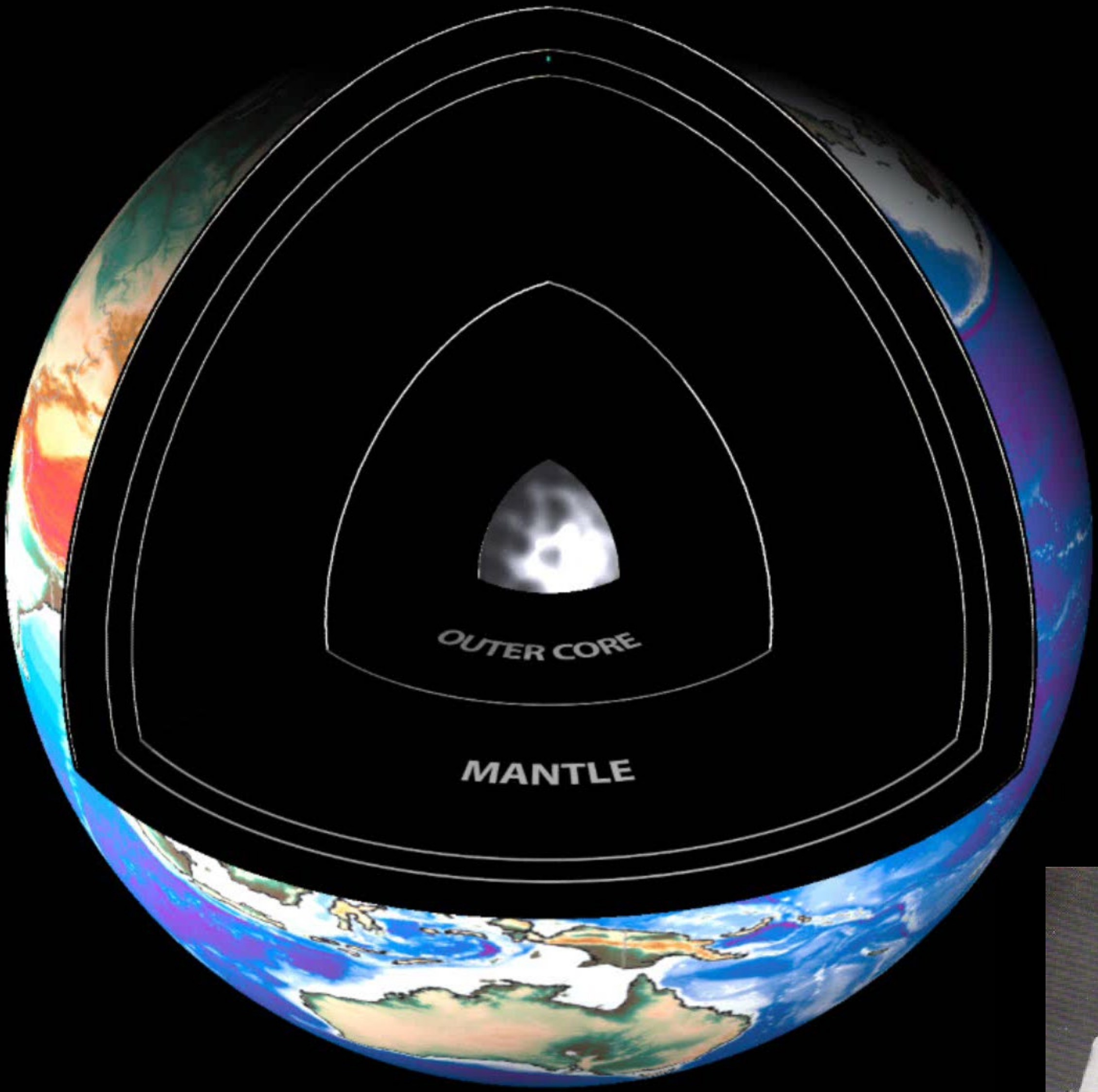
Multi-Messenger Tomography, Paris, 2023

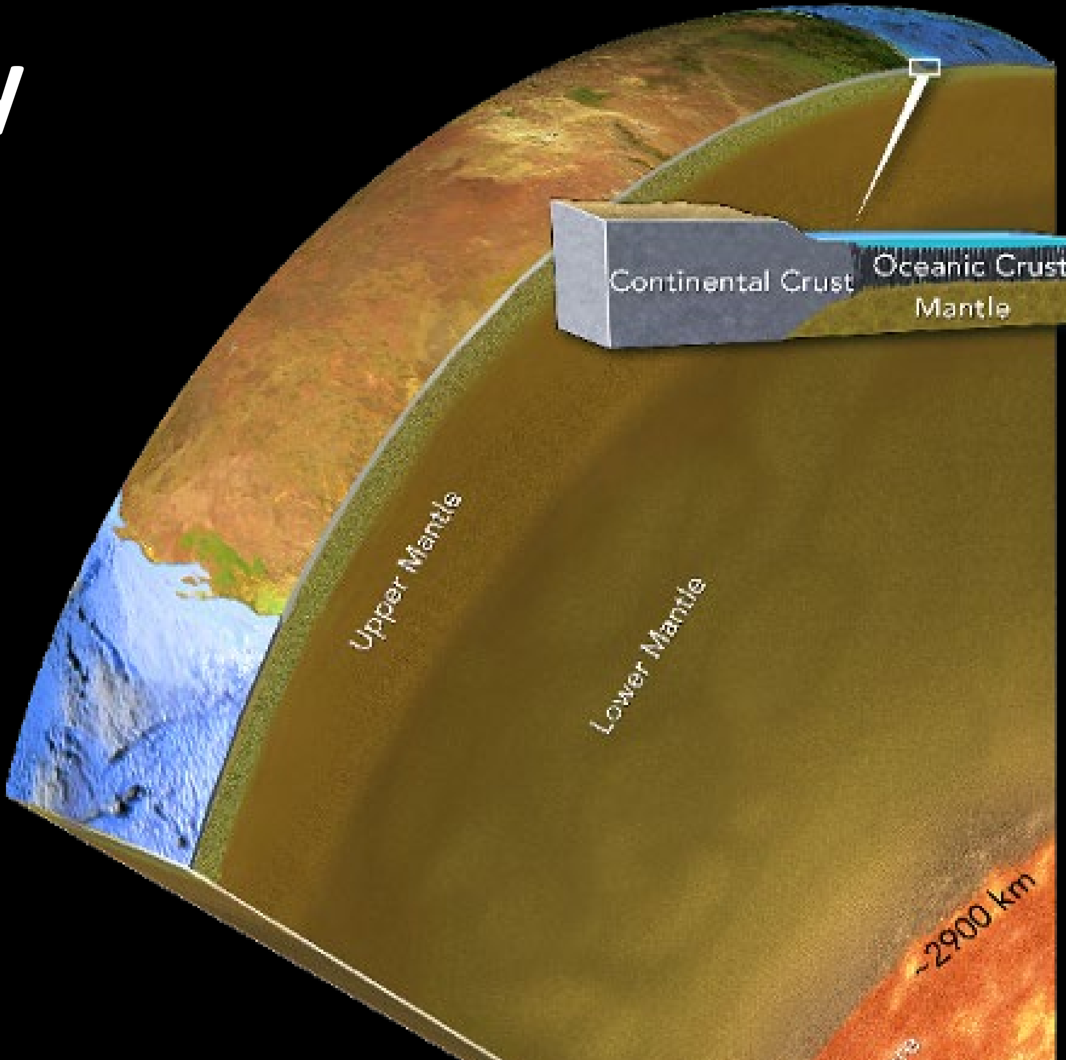


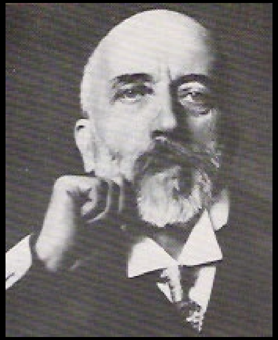


Layers of the Earth / Seismology



Movie by M. Thorne

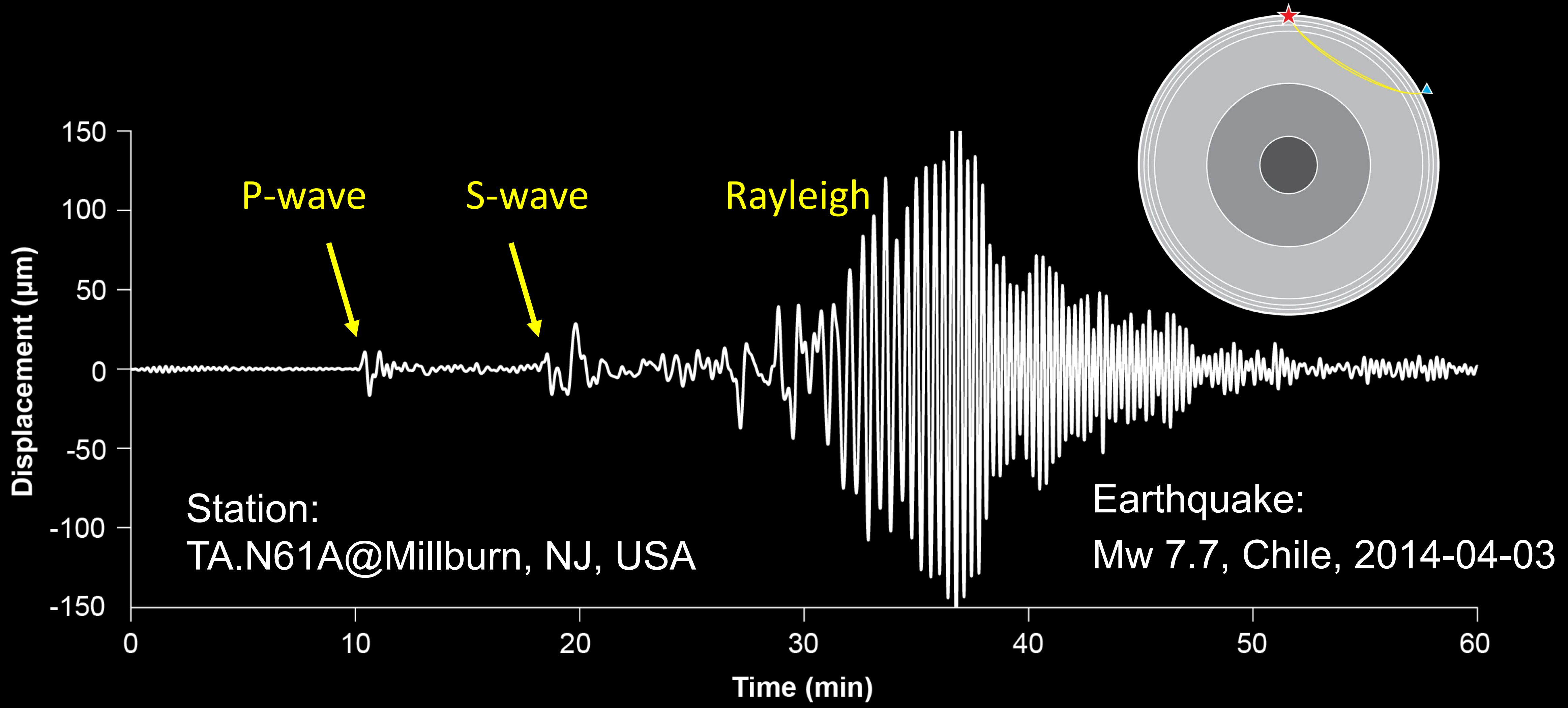




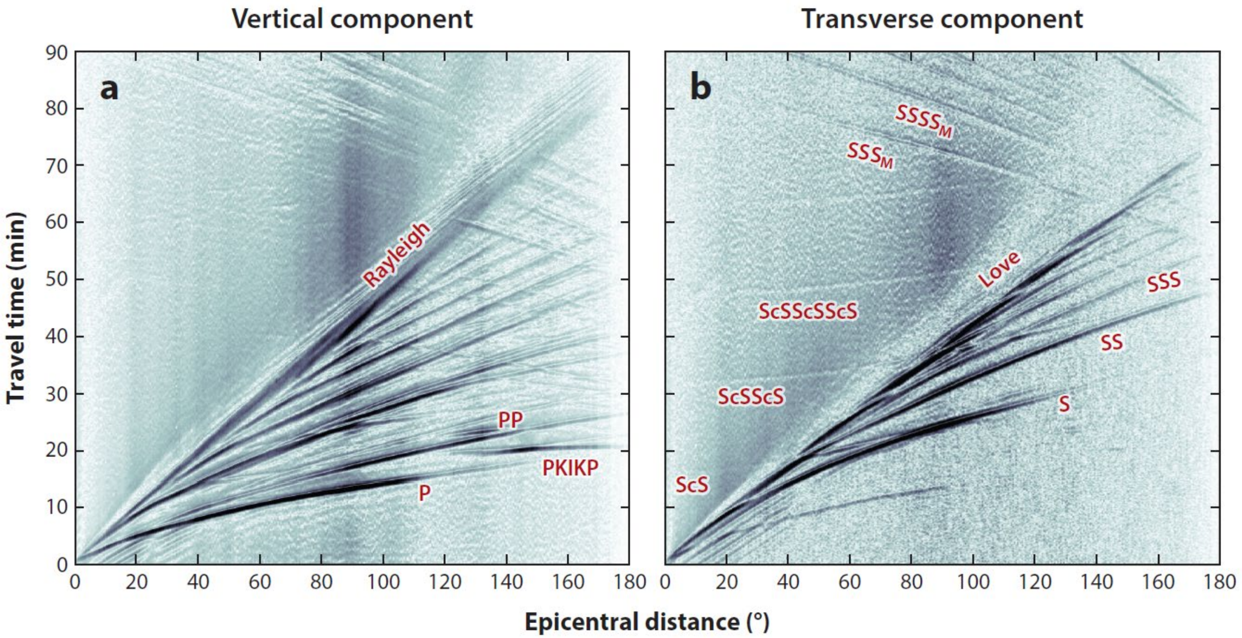
P-waves

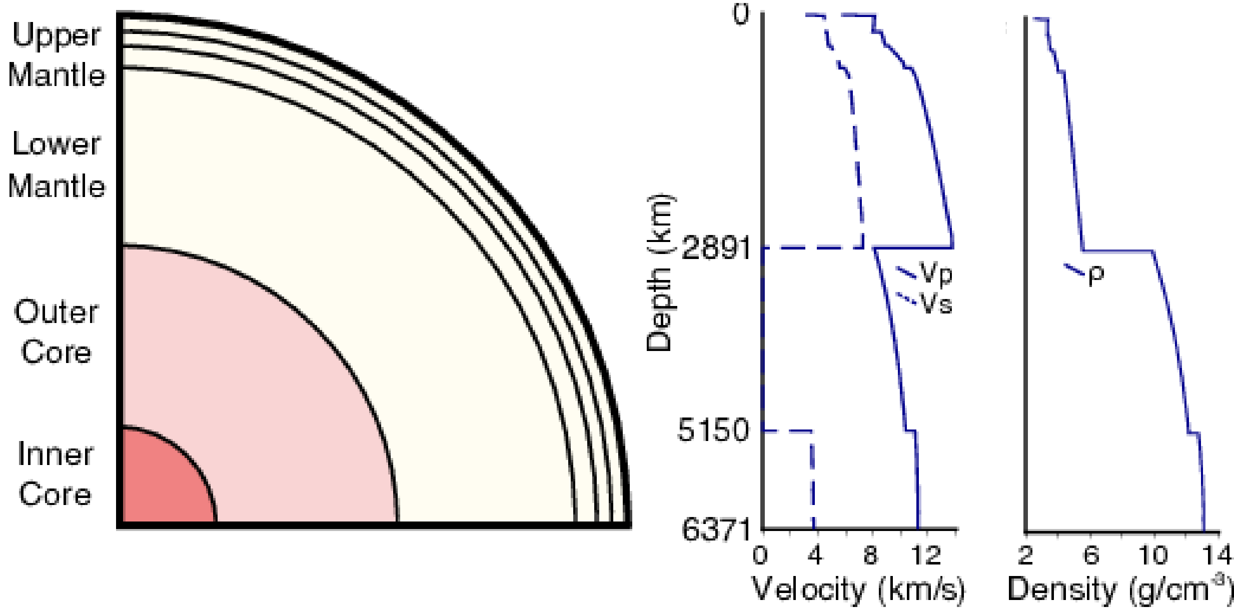
S-waves

Seismogram from a single station



1-D Seismic Structure with Depth

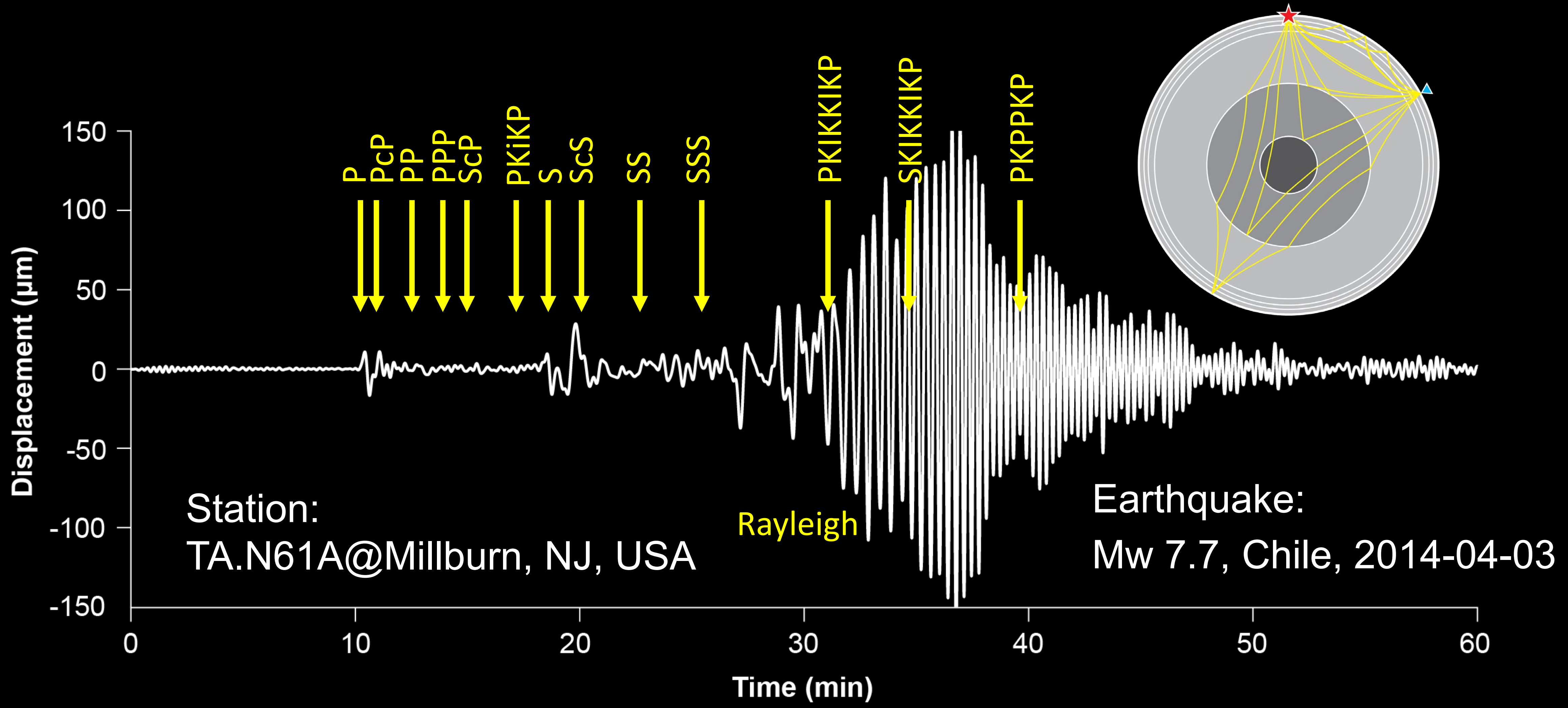




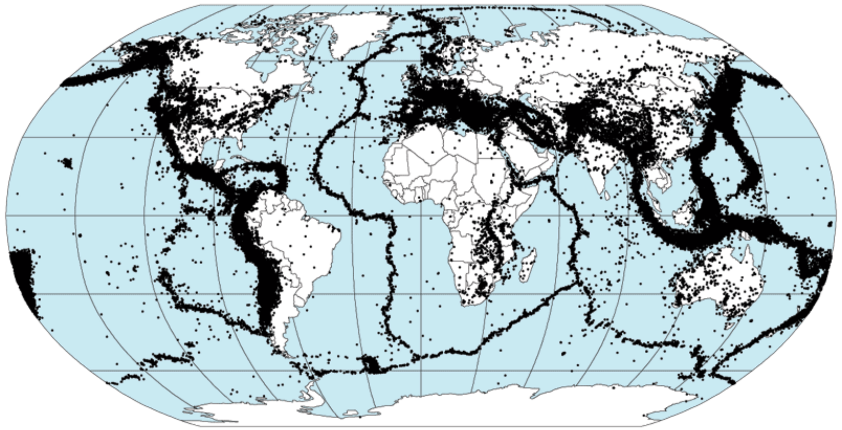
Traveltimes of seismic waves depend primarily on distance

Velocity (and density) variations in the Earth depend primarily on depth

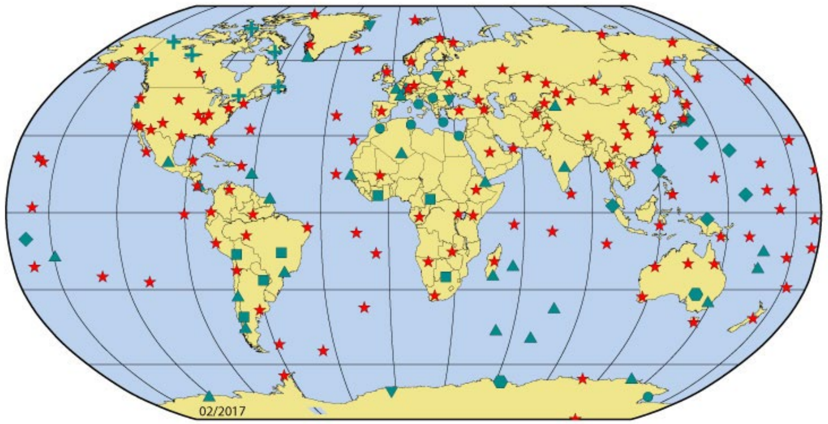
Seismogram from a single station



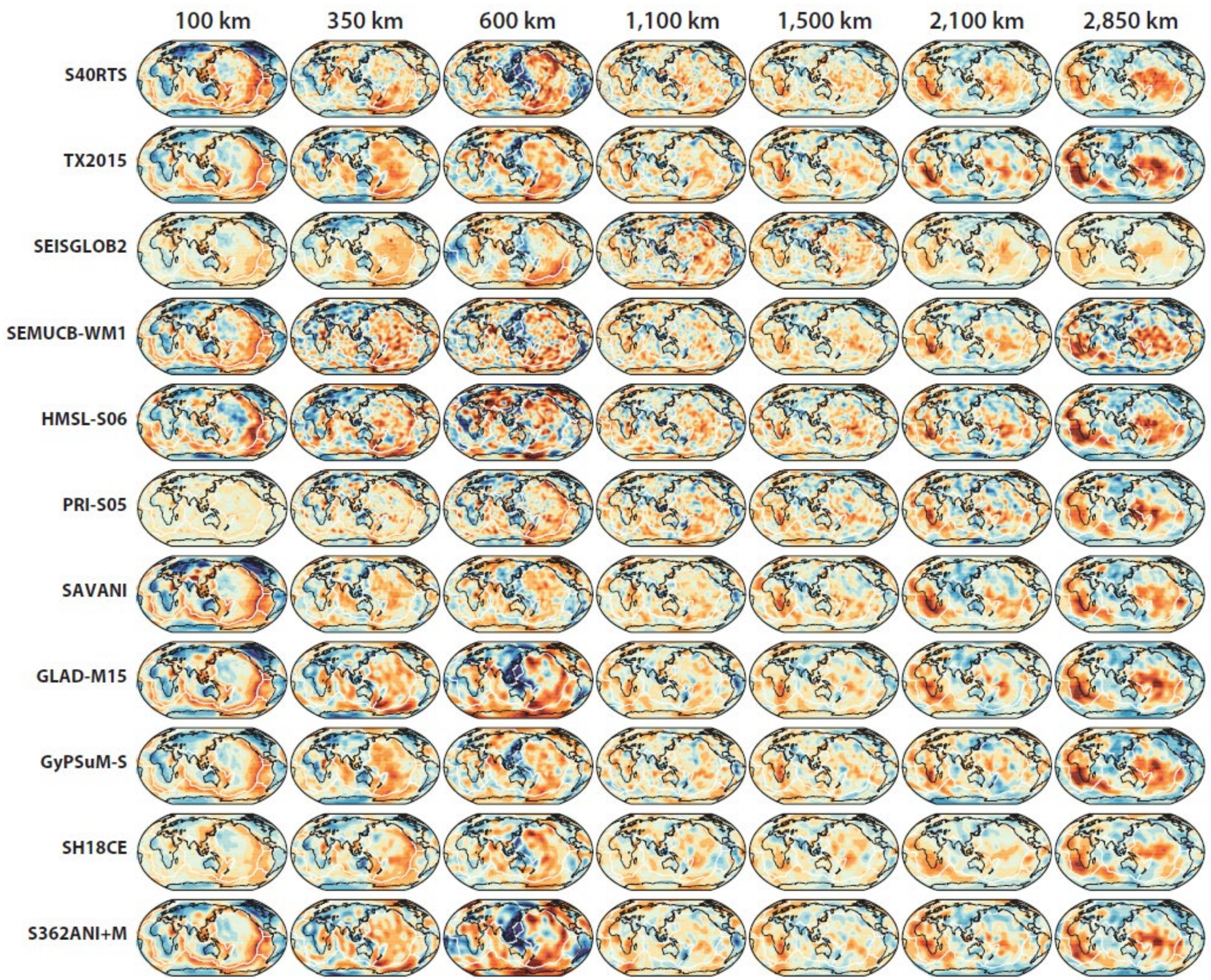
Earthquakes, Seismometers, 3D Earth Structures



We record and locate thousands of earthquakes each year



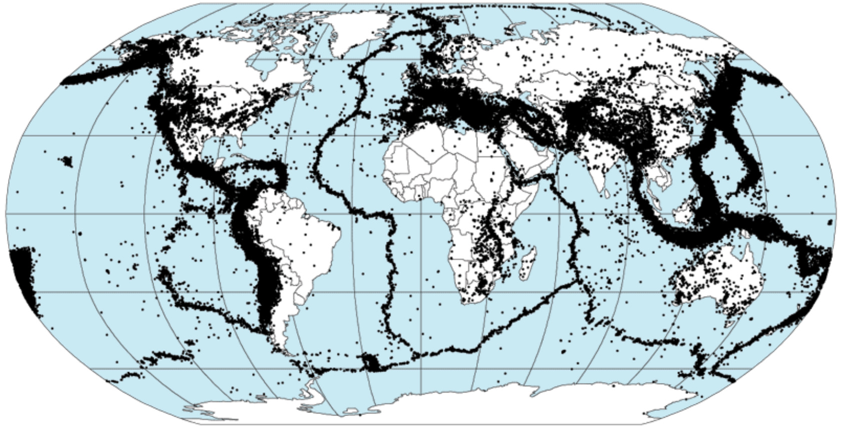
Global seismic networks provide open high-quality data



3D Earth structures from tomographic models

Ritsema & Lekic, AREPS (2020)

Earthquakes, Seismometers, 3D Earth Structures



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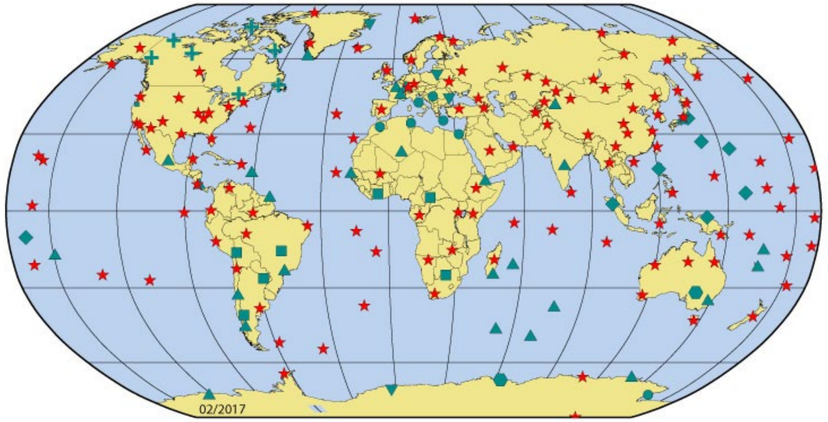

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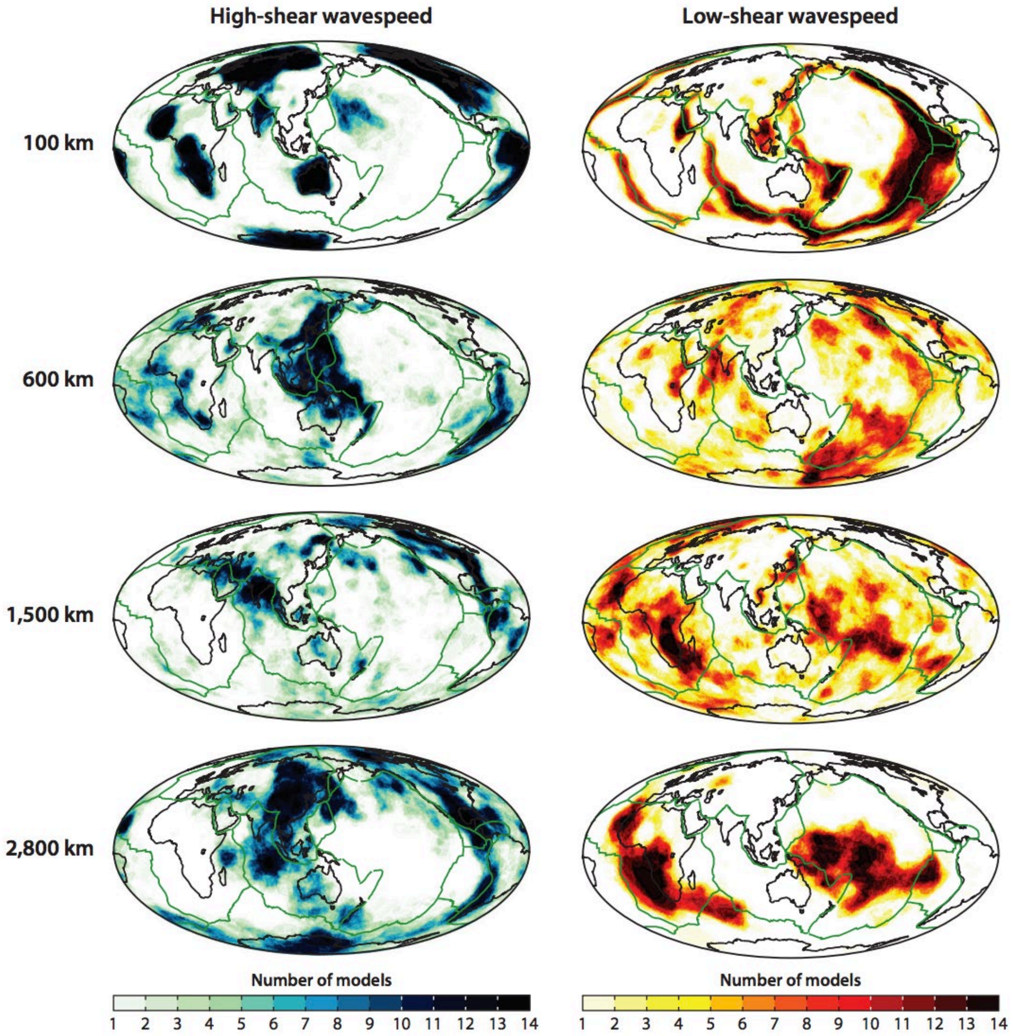

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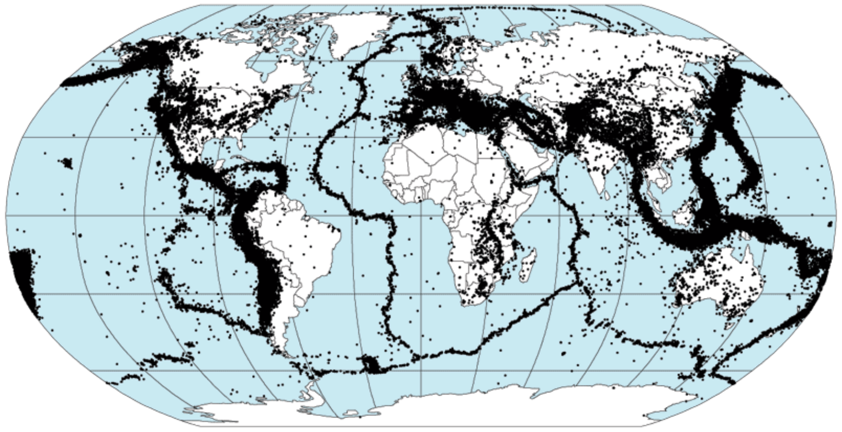

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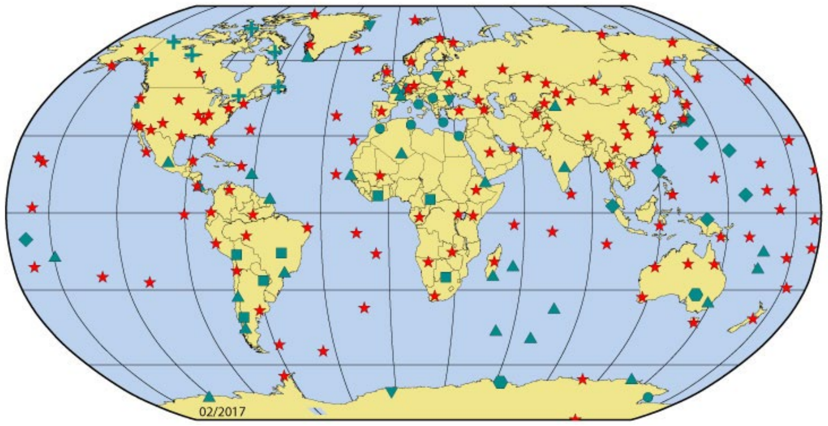

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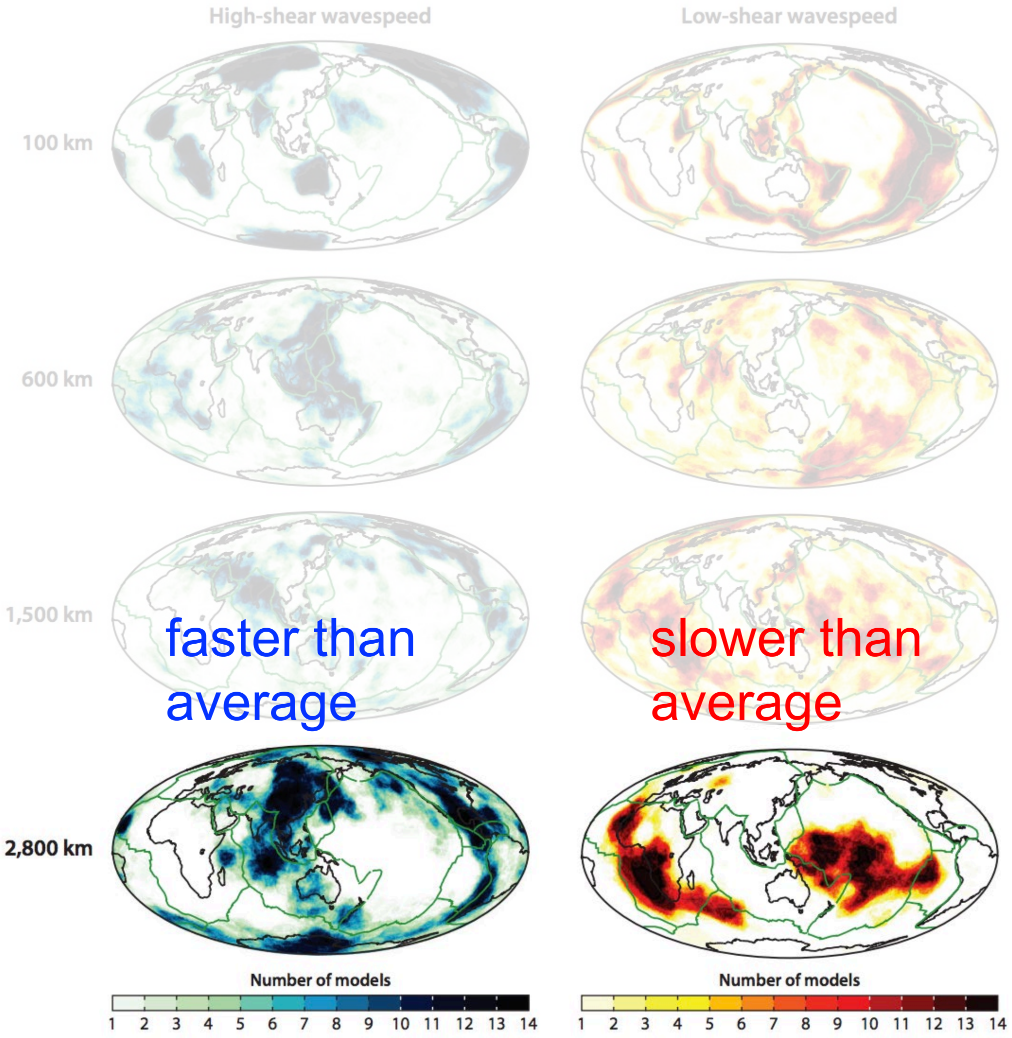
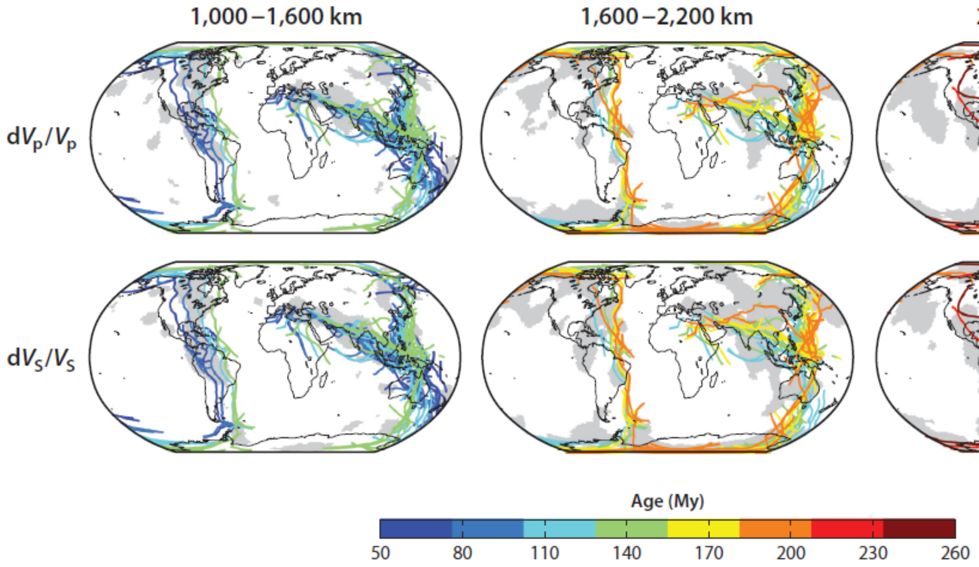


3D Earth structures from tomographic models

Ritsema & Lekic, AREPS (2020)

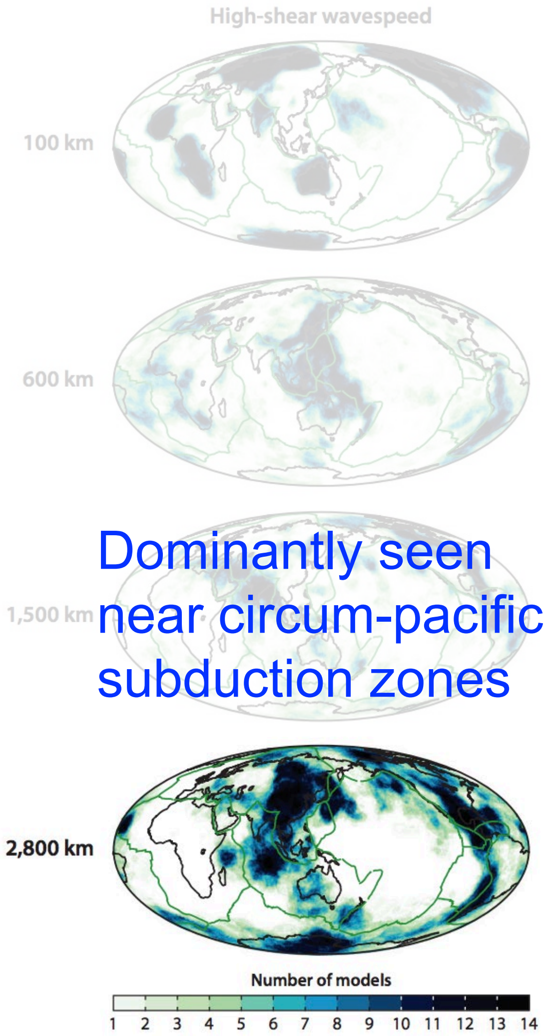
Large-scale Structures [~5000 km]: fast anomaly



Young et al, Nature (2019)

Subducted slabs in P- and S-wave models

Excellent correspondence between reconstructed locations of subduction zones and fast regions in lower mantle



Dominantly seen near circum-pacific subduction zones

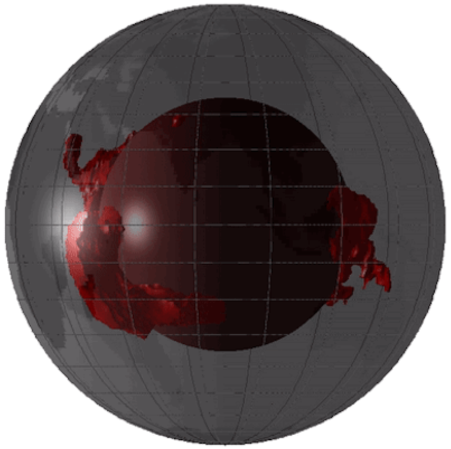
-Tomographic models reveal slabs of oceanic lithosphere subducting through the mantle

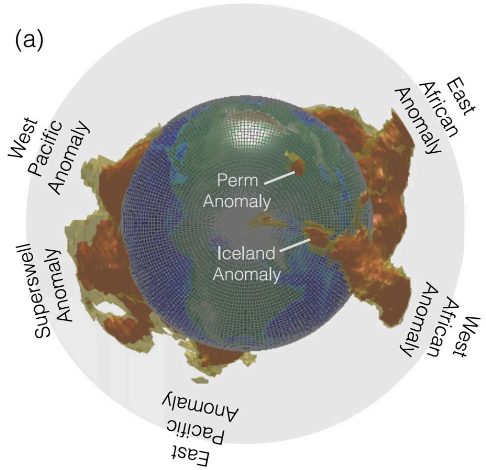
-Consistent between P- and S-wave models

-Well explained by past 200 Myr subduction history

-When did the subduction begin? How far back to go? 130Ma? 240Ma?

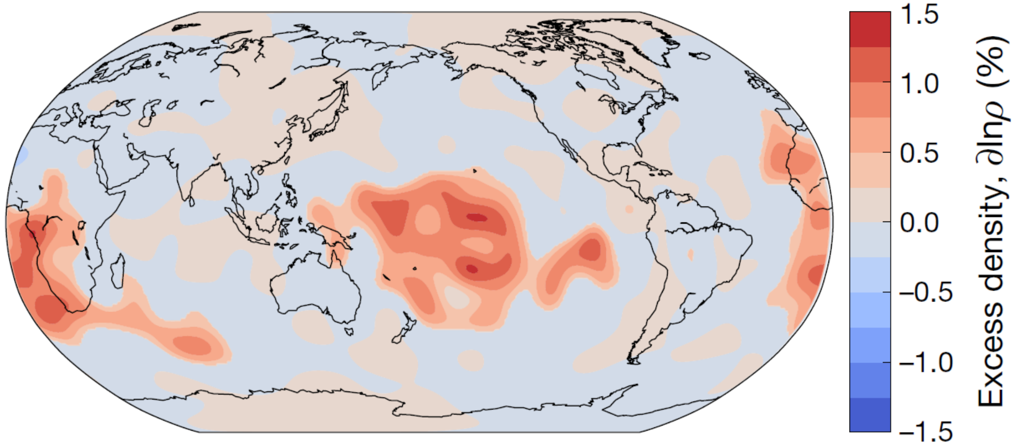
Large-scale Structures [~5000 km]: slow anomaly





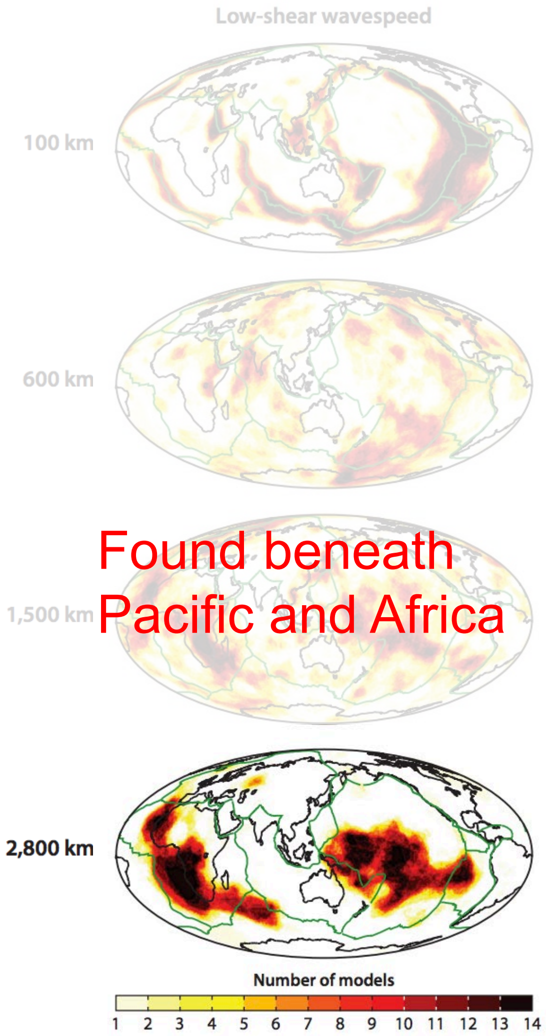
Cottaar & Lekic, GJI (2016)

Large low shear velocity provinces (~9% of whole mantle mass)



Dense but seismically slow regions

Lau et al, Nature (2017)



Found beneath Pacific and Africa

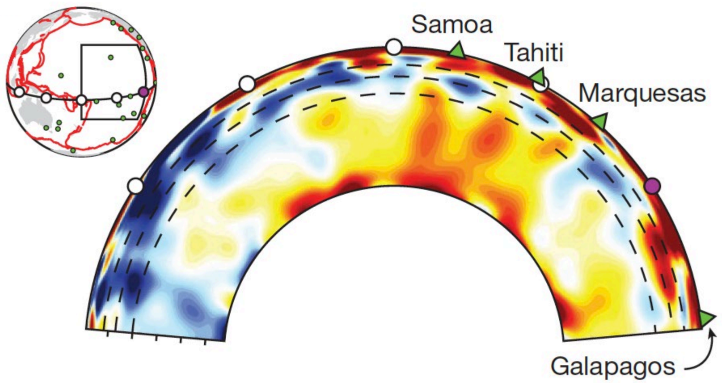
Extend no more than ~900 km above the CMB

-Traditionally viewed as mantle upwelling regions, “Super plumes”: isochemical?

-More recently observed in P-wave models / sharp edges support a compositional heterogeneity (~ +/- 3-5% out of ~2%)

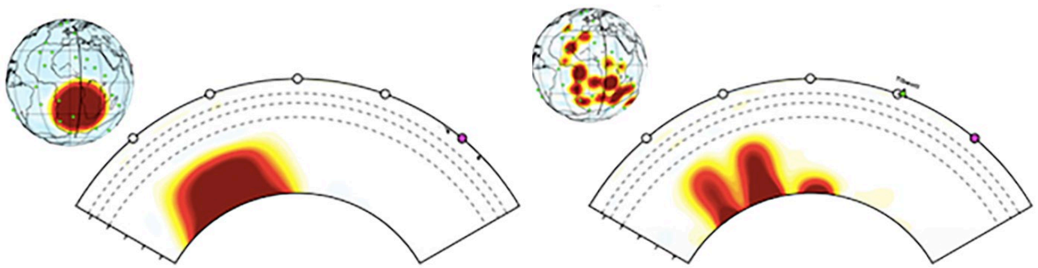
-Geophysical constraints (tidal response, normal modes, dynamic topography, CMB ellipticity, gravity) prefer denser material (~1%) at the base (~200 km) (e.g., Ishii & Tromp 1999; Trampert et al., 2004; Lau et al., 2017; Richards et al., 2023)

Large-scale Structures [~5000 km]: complexities

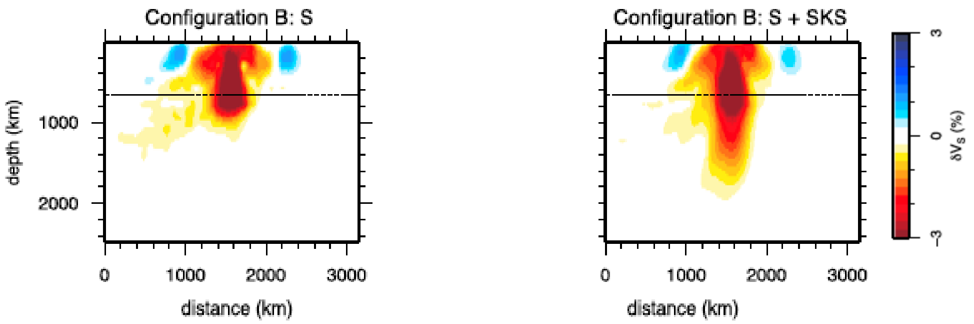


French & Romanowicz, Science (2015)

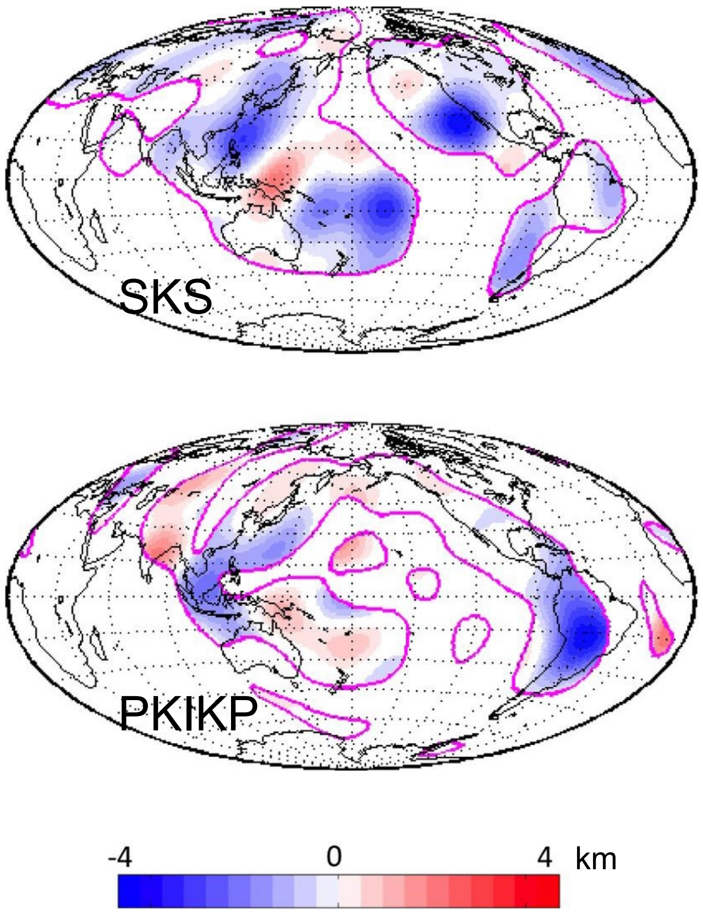
Seismic anomalies and resolution at the base of the mantle



Davaille & Romanowicz, Tectonics (2020)



Maguire et al., GRL (2017)



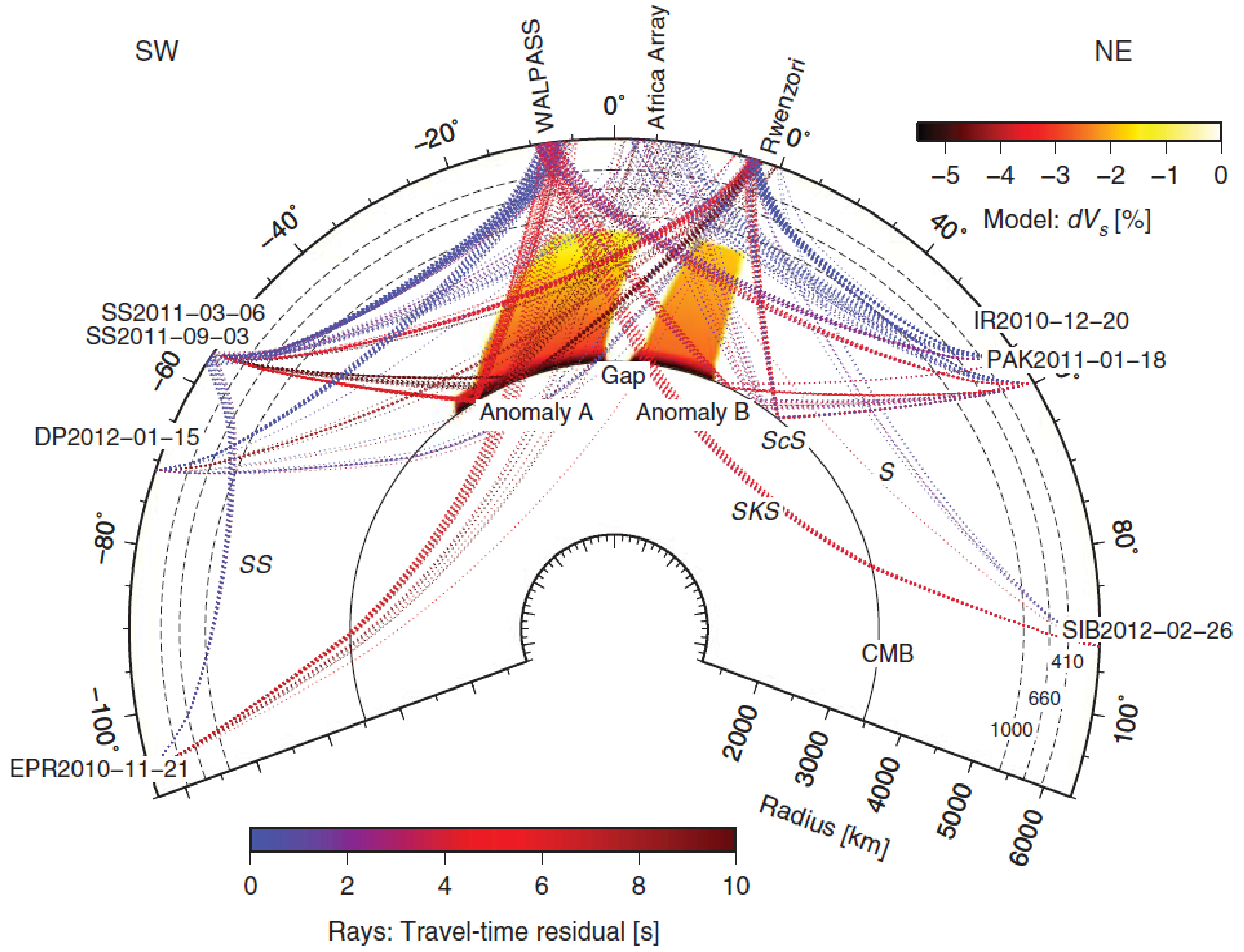
CMB topographic patterns with varying lateral wavelengths

Colombi et al., GJI (2014)

-Limited resolution: regularizations in tomographic inversions can generate blurred images and it is a challenge to robustly image structures smaller than ~1000 km scale

-Complexities with other existing structures: difficult to decouple mantle heterogeneity vs. CMB topography

Large-scale Structures [~5000 km]: complexities

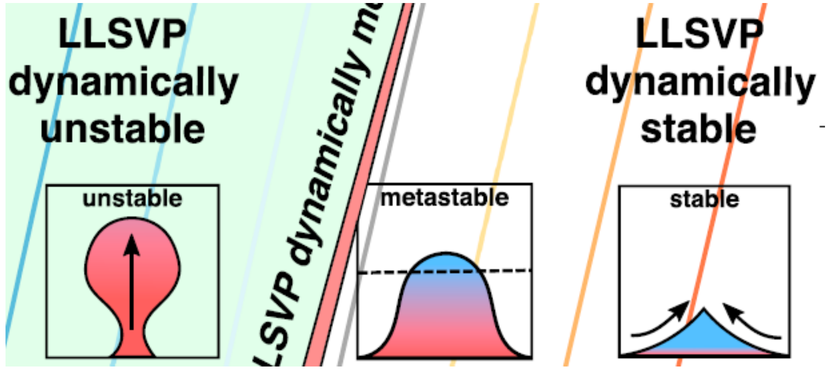


Kästle et al. (2017)

-Probing detailed morphology and small-scale intra-LLSVP structures are needed

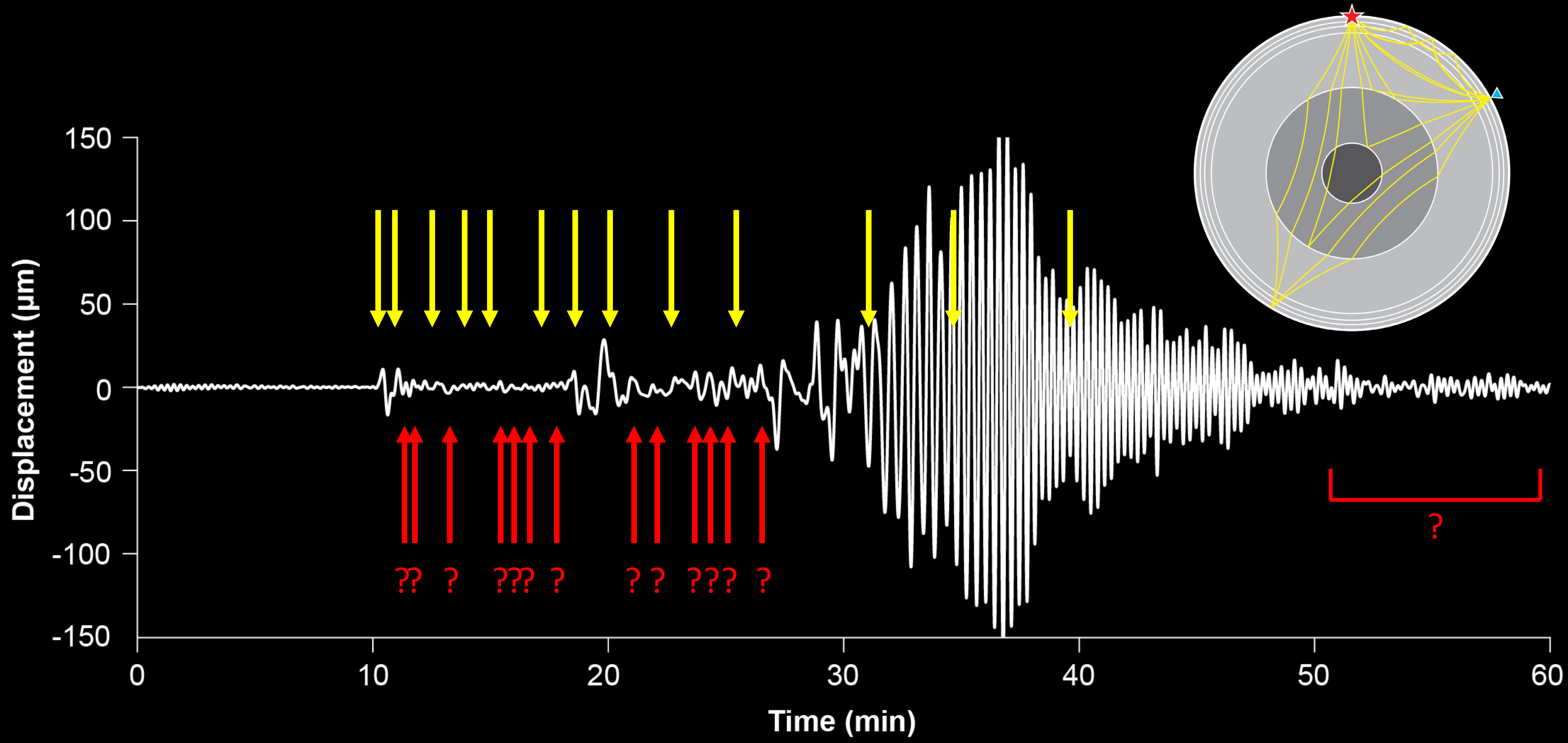
-Gap within African LLSVP: signature of individual plumes or piles boundary undulation?

-Often, such studies find stronger overall δVs drops compared to global tomography



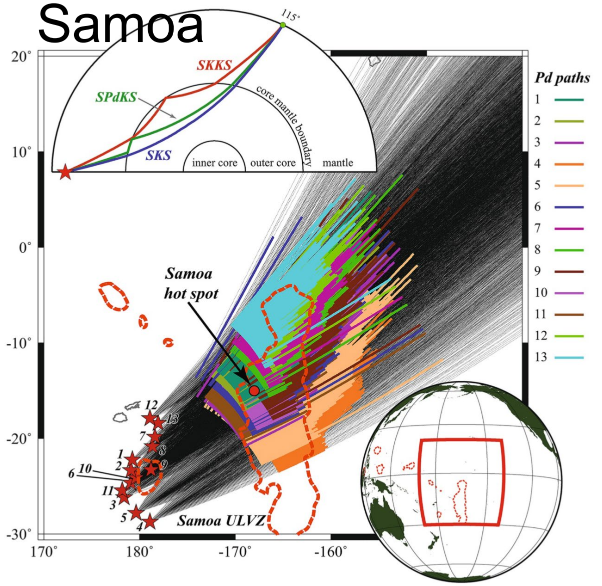
Wolf et al. (2015)

Holy Grail in Seismology: understading coda wiggles



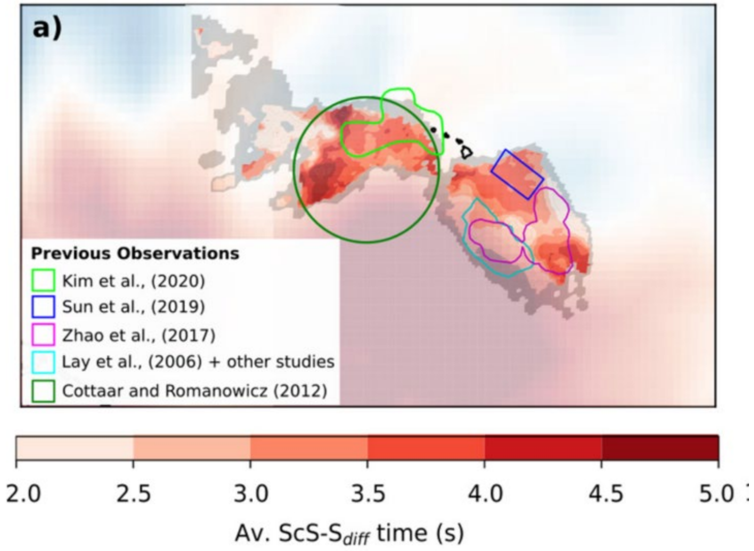
Meso-scale structures [~1000 km]: mega-ULVZs

Samoa



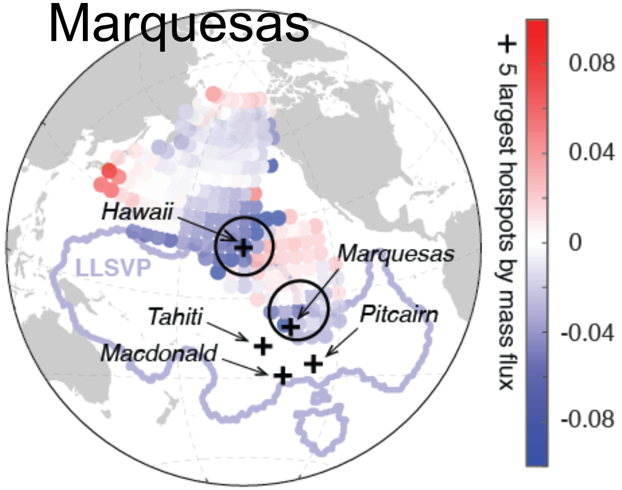
Krier, et al., JGR (2021)

Hawaii



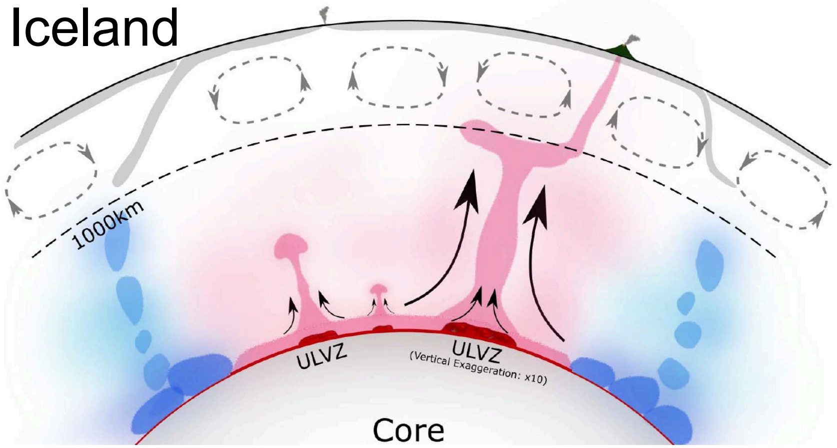
Jenkins et al., EPSL (2021)

Marquesas



Kim et al., Science (2020)

Iceland



Yuan & Romanowicz, Science (2017)

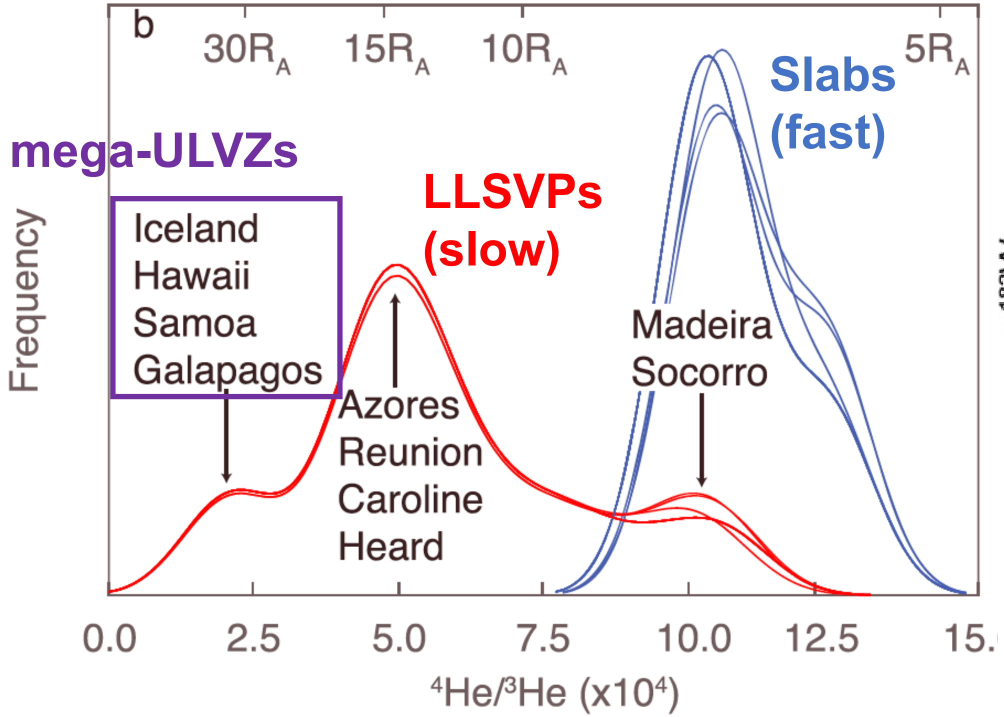
-Unresolved by tomographic inversions so largely inferred from distortions in the seismic wavefield (except for Perm / Kamchatka)

-Reduced S-wave speed up to 40%; P-wave constraints are relatively less explored

-Mega-ULVZs are only discovered below a few hotspot volcanoes (e.g., Cottarr & Romanowicz 2012; Thorne et al., 2013; Yuan & Romanowicz, 2017; Kim et al., 2020; Cottar et al., 2022) Hawaii/Samoa/Iceland/Marquesas/ Galapagos

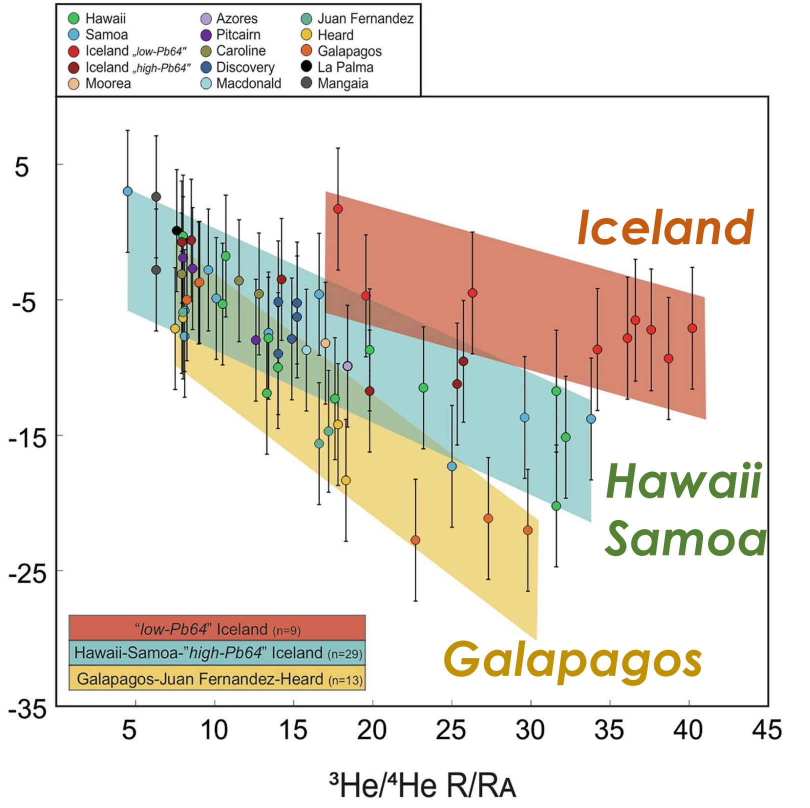
-Origin and composition of these structures are largely unknown

Geochemical Characteristics of Mega-ULVZs



Normal *Tungsten* & high ^{3}*He*/^{4}*He* suggests relatively un-degassed material that is associated with LLVPs

Williams et al., Science (2019)



Negative correlation of *Tungsten* vs. ^{3}*He*/^{4}*He is seen at nearly all mega-ULVZs*

Mundl-Petermeier et al., Geochimica et Cosmochimica Acta (2020)

Some isotope system provides an important temporal constraint for primordial geochemical reservoirs

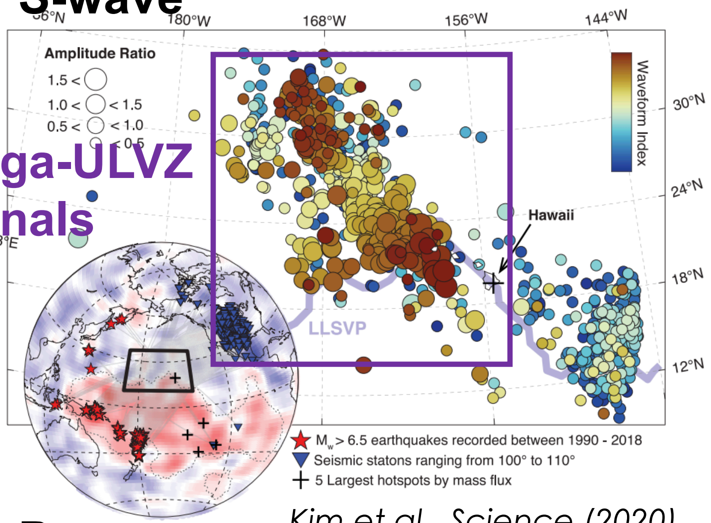
Mega-ULVZs may host primitive geochemical signatures?

If mega-ULVZs are associated with partial melt, this will facilitate core-mantle isotope equilibration

One of a kind: Hawaiian mega-ULVZ

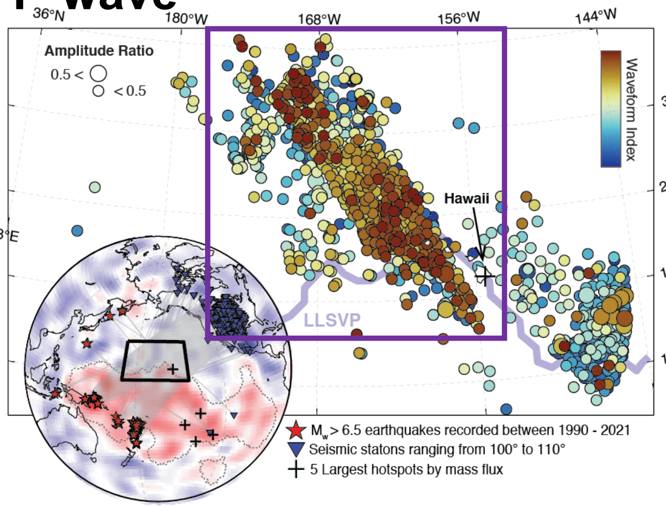
A joint analysis using Pdiff and Sdiff datasets

S-wave

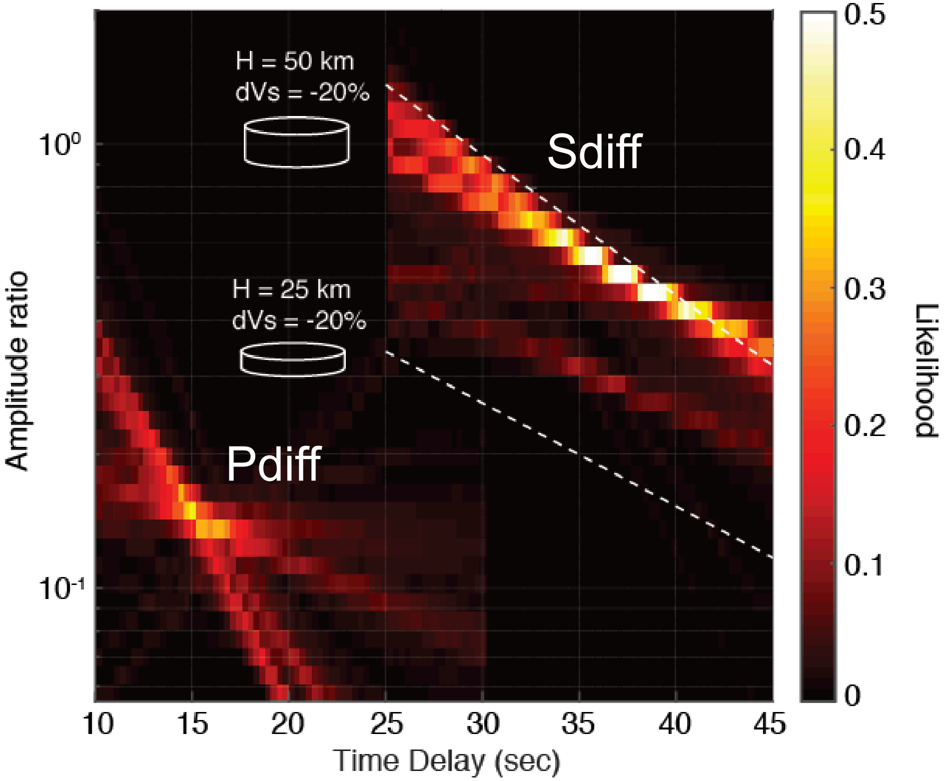


Kim et al., Science (2020)

P-wave

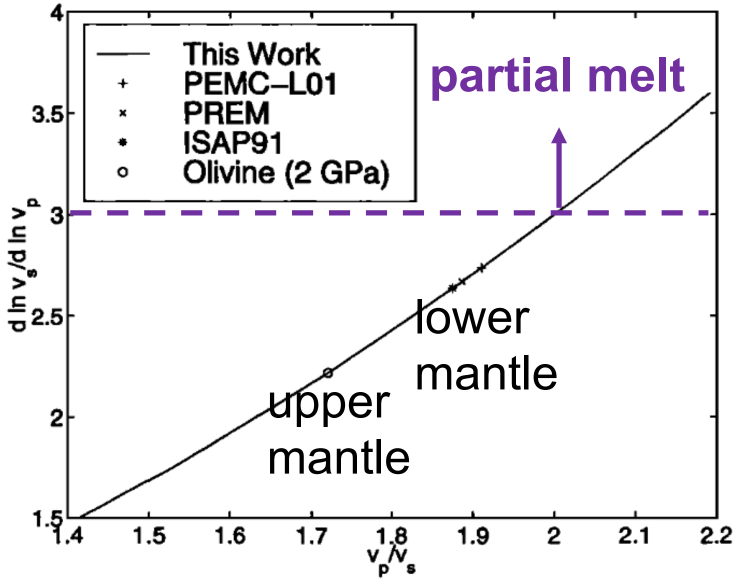


Kim et al., AGU meeting (2021)



P-wave amplitudes being much weaker (*dlnVs/dlnVp* = 2-4) but showing similar spatial pattern compared to the S-wave

dlnVs/dlnVp vs. Vp/Vs



Berryman, GRL (2000)

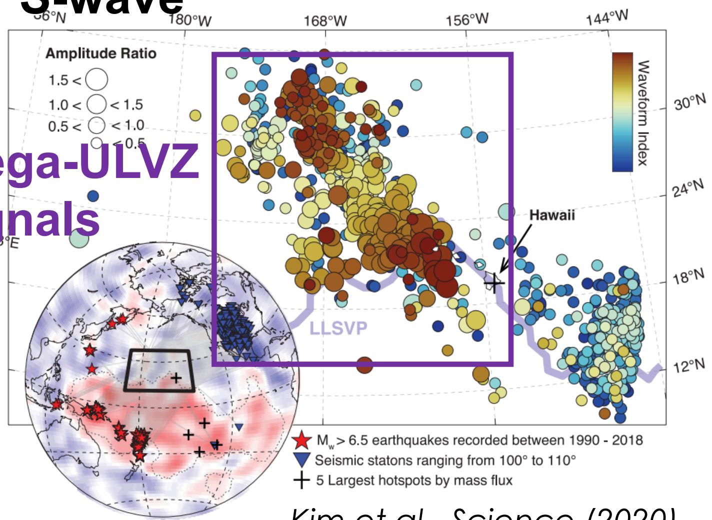
Observed dlnVs/dlnVp is close to what we would expect for partially molten materials at the CMB

One of a kind: Hawaiian mega-ULVZ

A joint analysis using Pdiff and Sdiff datasets

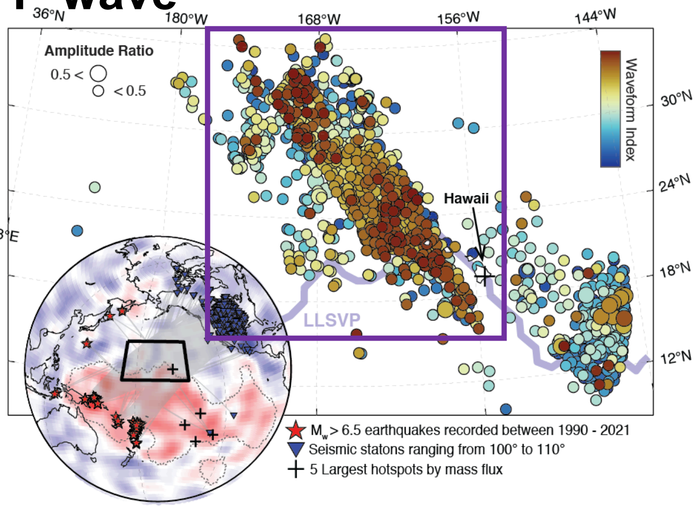
S-wave

mega-ULVZ signals

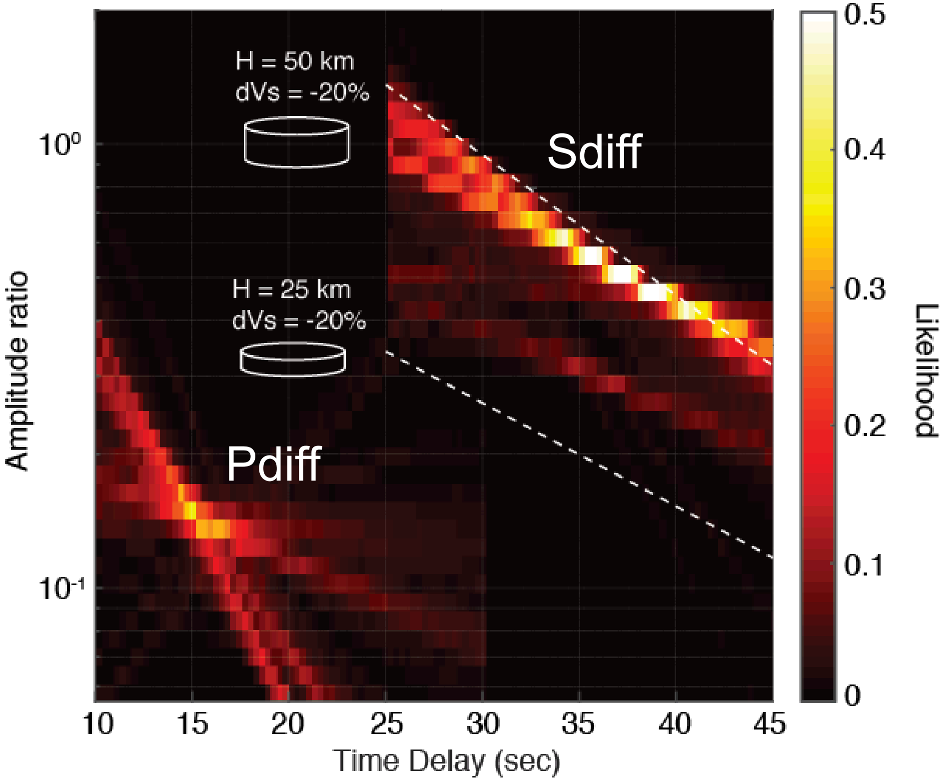


Kim et al., Science (2020)

P-wave



Kim et al., AGU meeting (2021)



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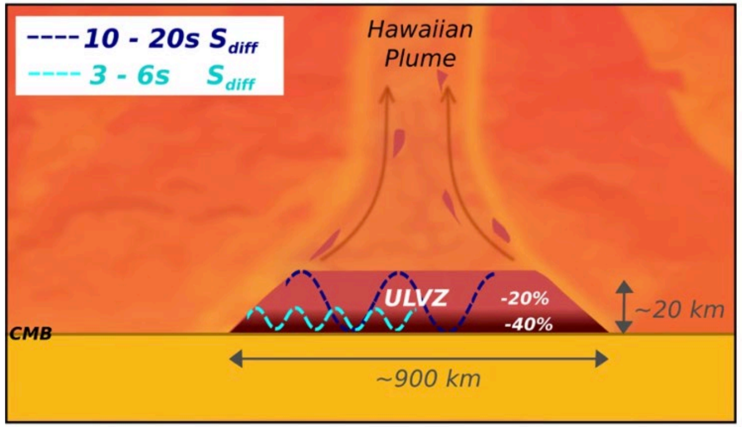
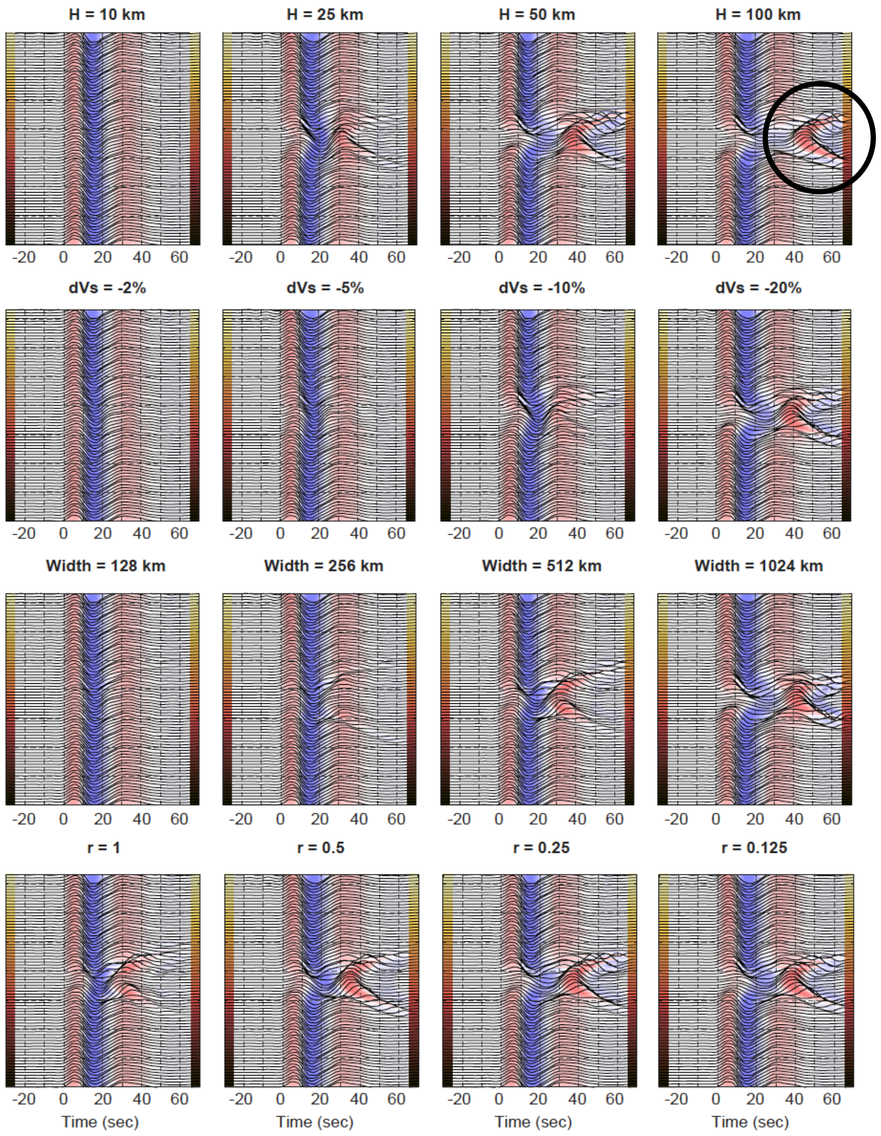
km-scale structures within the mega-ULVZ



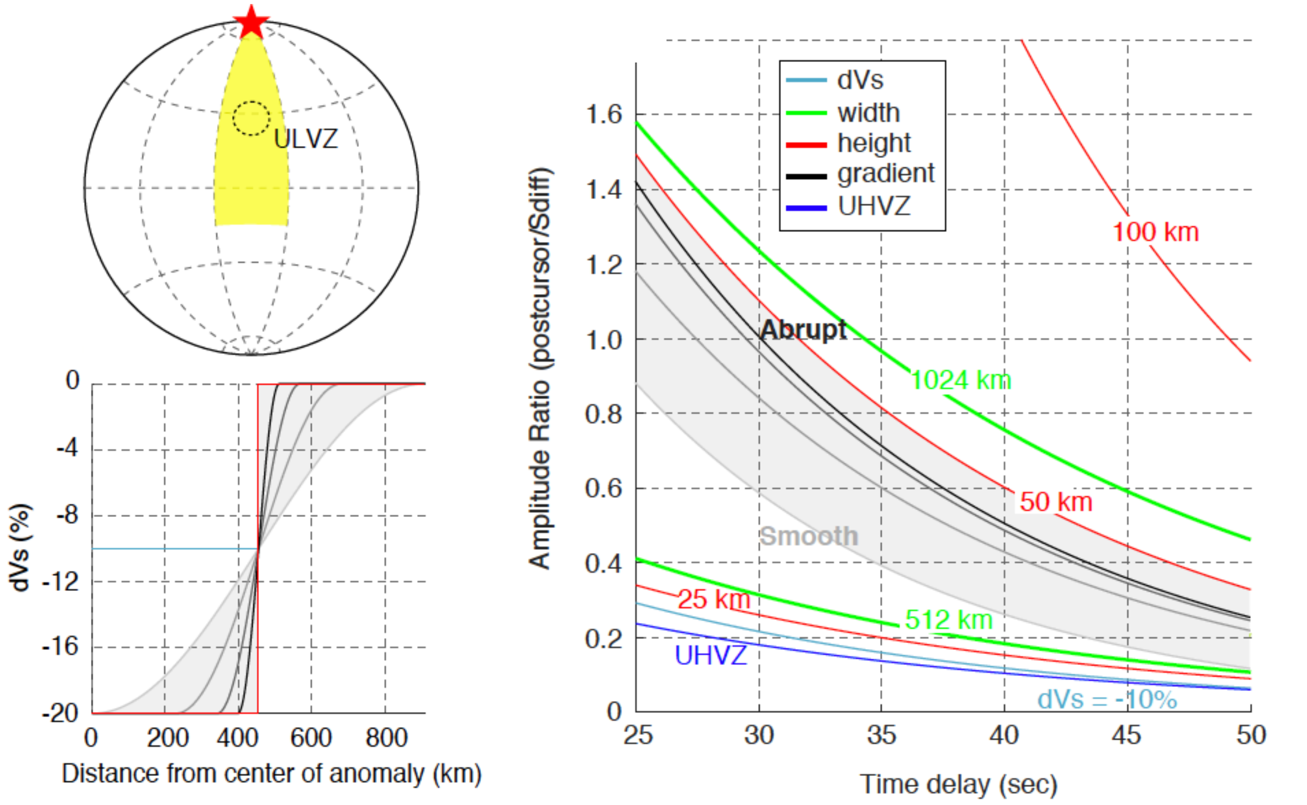
Li et al., Nat. Comm. (2022)

New seismic evidence supports a partially molten or chemical distinct material with increasing iron content towards the base of the CMB

Meso-scale structures [~1000 km]: challenges



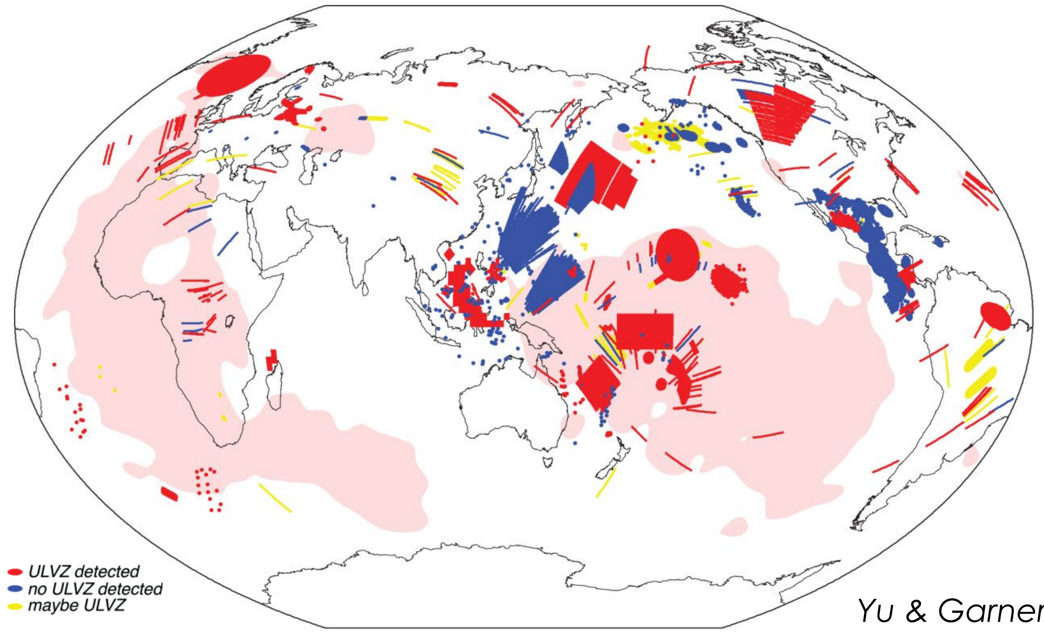
Waveform simulations of S-wave diffracting the CMB



-Tradeoffs exist among physical parameters (velocity, density, size, shape, etc.) in waveform modeling
-Modeling with other seismic phases also suffer from non-uniqueness

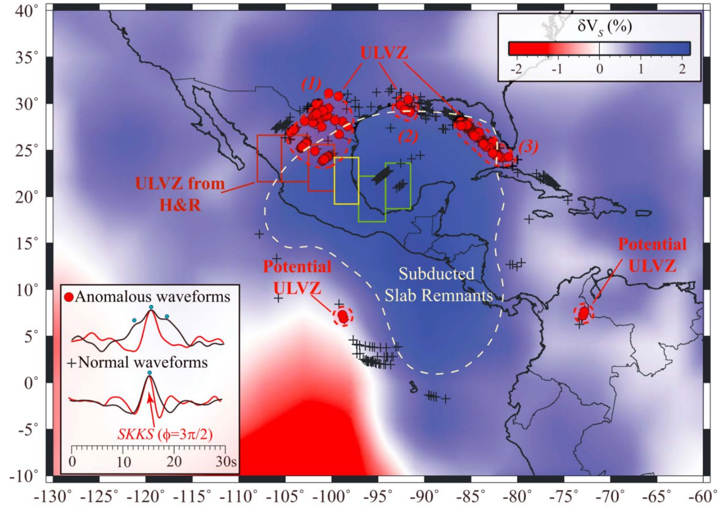
Small-scale Structures [~10-**100 km**]: ULVZs

A global assessment of ULVZ studies until 2018



Yu & Garnero, G3 (2018)

Some ULVZs may be associated with slabs



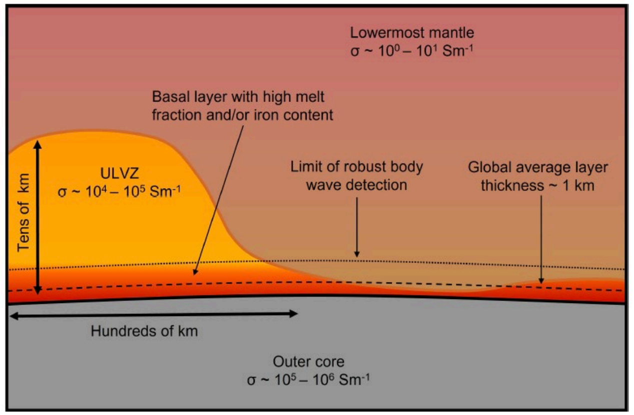
Thorne et al., GRL (2019)

-The total percentage of CMB area sampled by past ULVZ studies since 2018 is 17.1%

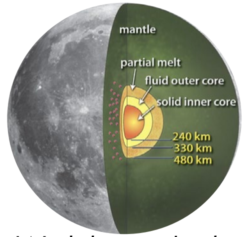
-Shows no spatial correlation between observed ULVZ locations and large-scale structures / hotspot volcanoes

-Studies using reflected / converted seismic data advocate a density increase

Globally molten layer at the CMB?

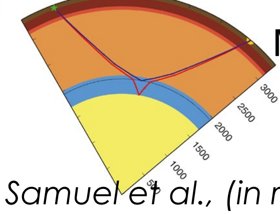


Russell et al., GRL (in revision)



Lunar core

Webber et al., Science (2011)

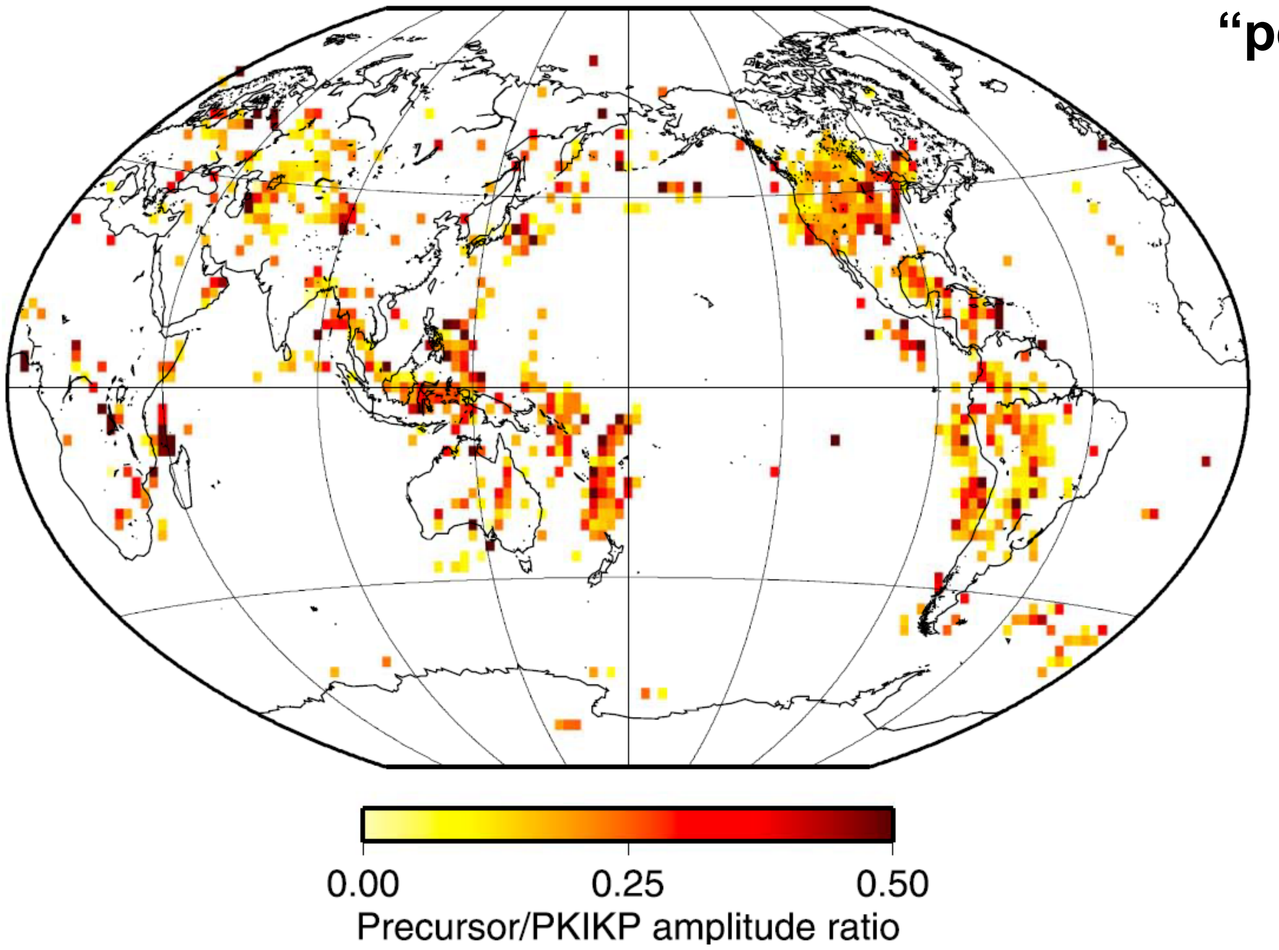


Martian core

Samuel et al., (in revision)

Small-scale Structures [**~10**-100 km]: scatterers

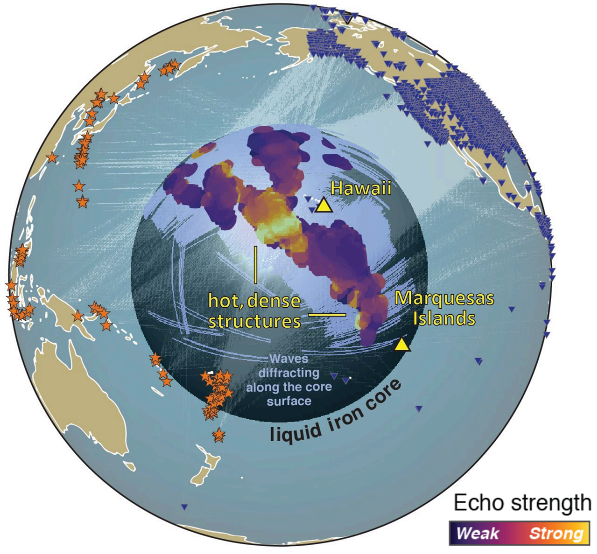
Global CMB scatterers from core-traversing phases



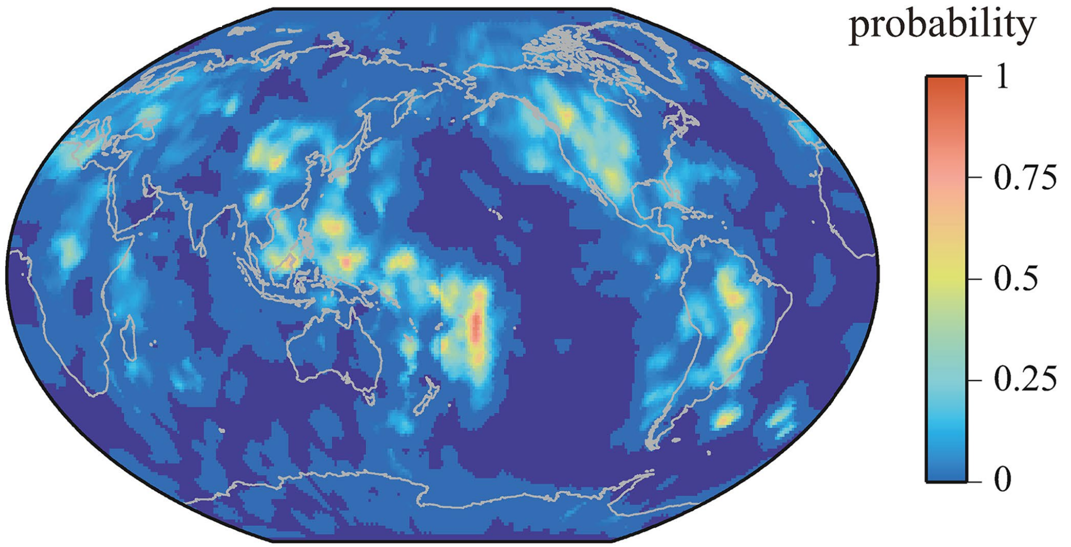
Waszek et al., GRL (2015)

"pervasive postcursors"

No strong correlation is found with known large lower mantle structures but may be related to widespread scattering ?

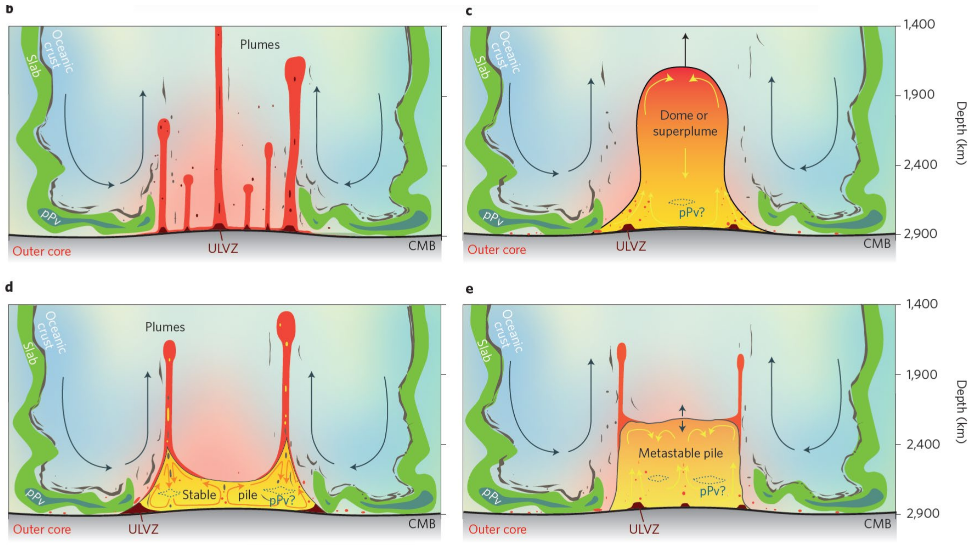


Kim et al., Science (2020)



Thorne et al., G3 (2021)

Key Takeaways



Garnero et al., Nat. Geo. (2017)

-Lower mantle hosts anomalous structures in various scales:

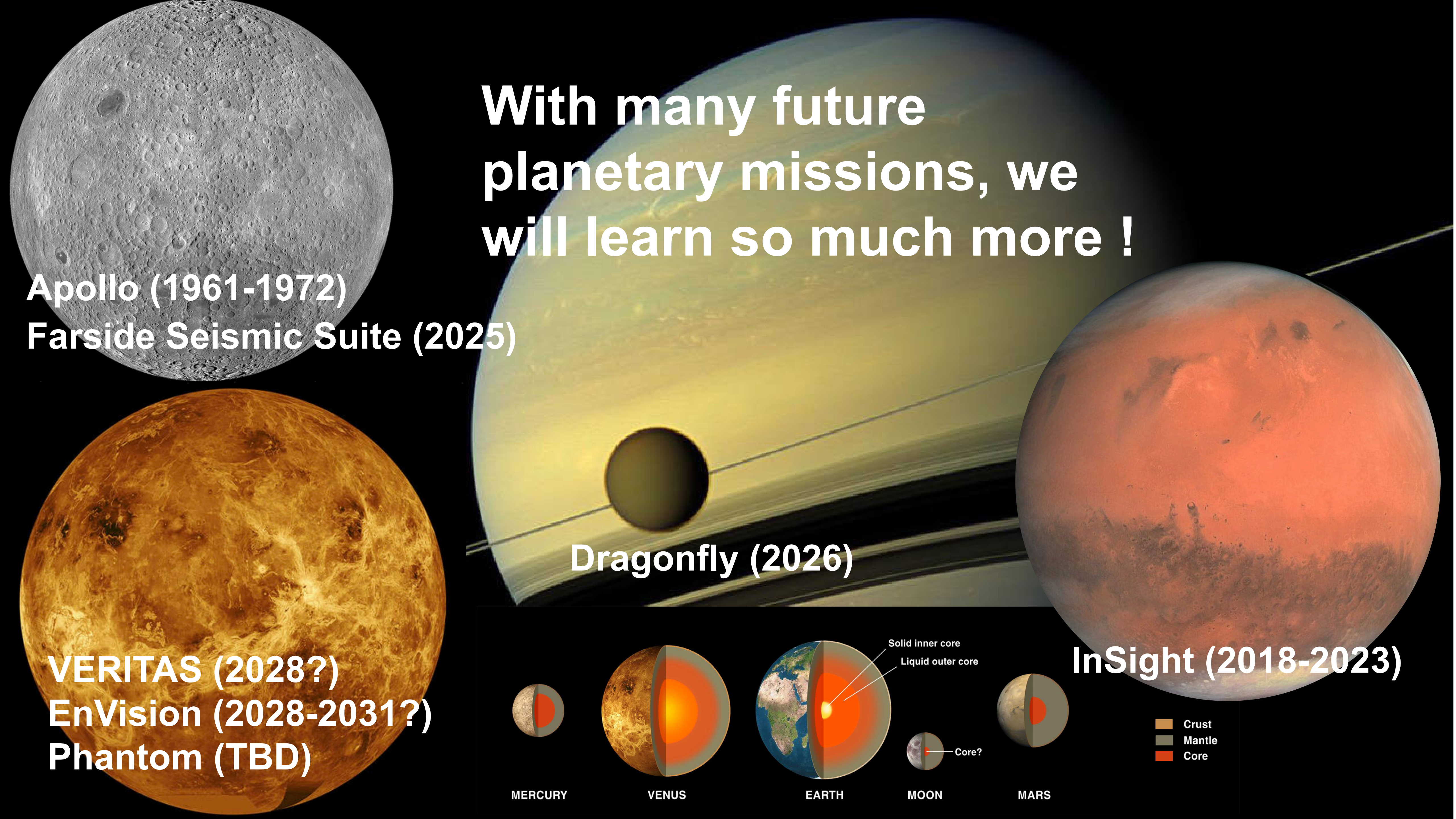
- -LLSVPs [5000 km]
- -Mega ULVZs [1000 km]
- -ULVZs [100 km]
- -CMB topography, unknown scatterers

-These structures are intimately tied to the fate of subducted slabs, origin of plumes, and nature of primitive geochemical reservoirs with many open questions to be answered

-Robustly imaging the lower mantle structure requires different types of seismic waves and multiple approaches

-Much of the lowermost mantle / CMB region remains unexplored (e.g., physical coverage illuminated by seismic waves, anisotropy, attenuation, etc.)

-Seismologists continue to work together with the larger terrestrial / planetary science community to uncover various mysteries of the deep planetary interior structures and dynamics


With many future planetary missions, we will learn so much more !
Apollo (1961-1972)
Farside Seismic Suite (2025)
Dragonfly (2026)
InSight (2018-2023)
VERITAS (2028?)
EnVision (2028-2031?)
Phantom (TBD)
Solid inner core
Liquid outer core
Core?
Crust
Mantle
Core
MERCURY
VENUS
EARTH
MOON
MARS