Isotropic and Anisotropic Structure of the Upper Mantle, Imaged with Surface and *S* waveform Tomography

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Outline

1. Method and Dataset
2. Empirical Validity of Surface Wave Ray Theory
3. Global anisotropic upper mantle shear velocity model

New generation of seismic Earth models

- Improvements in all aspects of Seismic Modelling
  - Computational Facilities
  - Theoretical and Methodological Advancements
  - Deployment of High-Resolution Large-Scale Seismic Arrays
- Introduced New Challenges to Seismology
  - Management, Distribution, Processing, QC

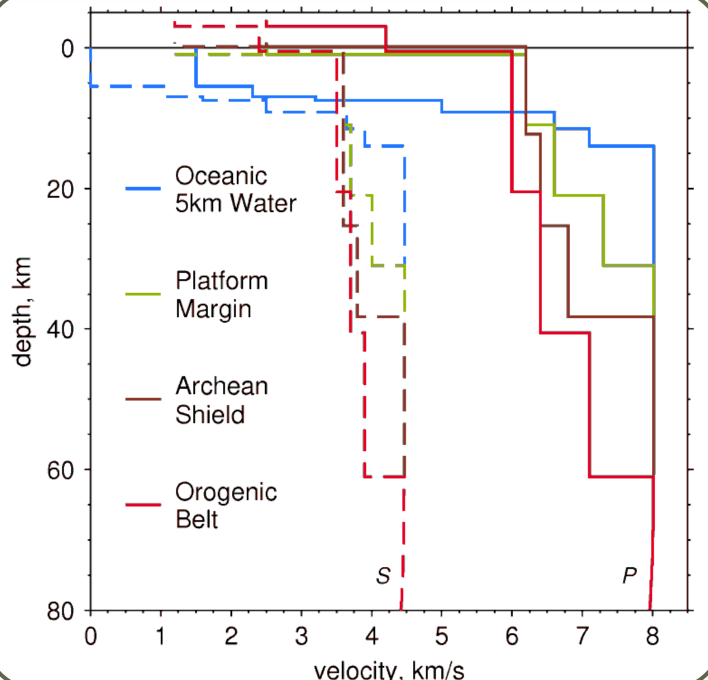
- New generation of seismic Earth models capable of resolving tectonic unit scale features across entire continents

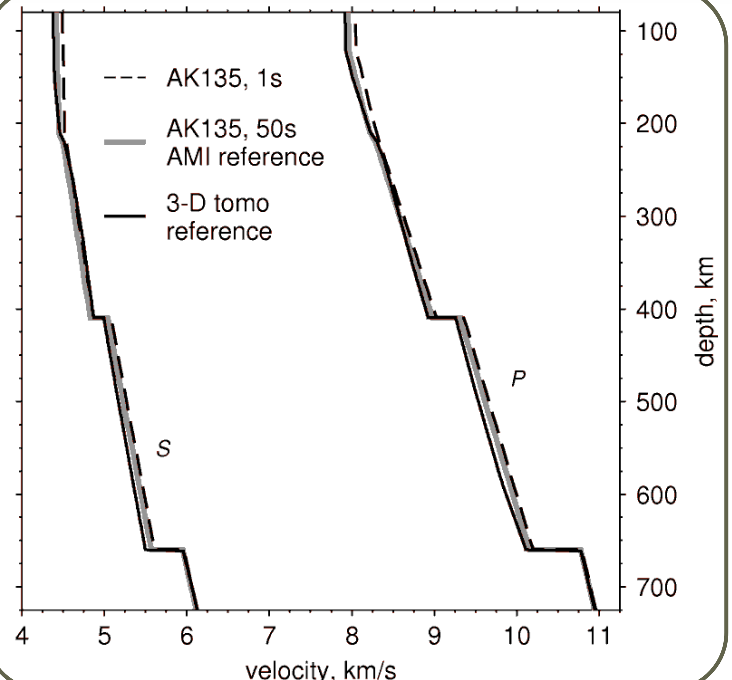
➢ Require accurate and efficient methods to fully exploit each and every seismogram

http://www.ngdc.noaa.gov/mgg/global/global.html

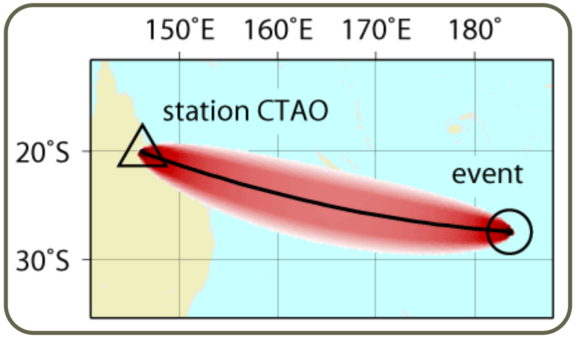
Inversion Technique and Reference Model

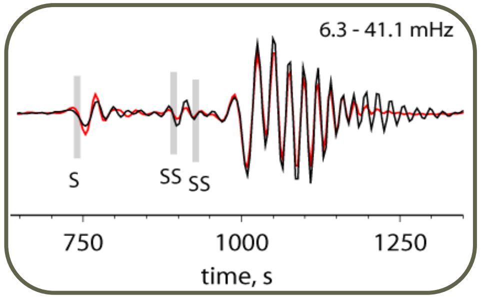
- Two Step Inversion:
  1. Automated Multimode Inversion (AMI) of each seismogram
  2. Linear Tomographic Inversion
- Hybrid 3D Reference Model
  - Crustal model based smoothed Crust2
  - Mantle velocity AK135 recomputed at reference period 50s

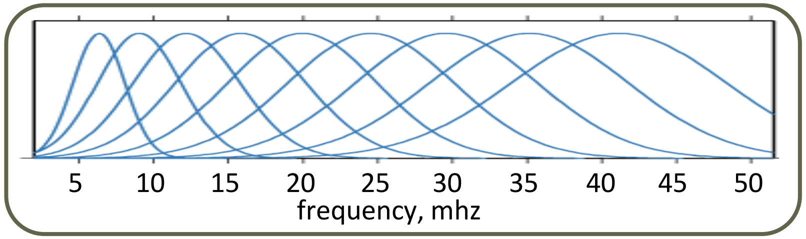




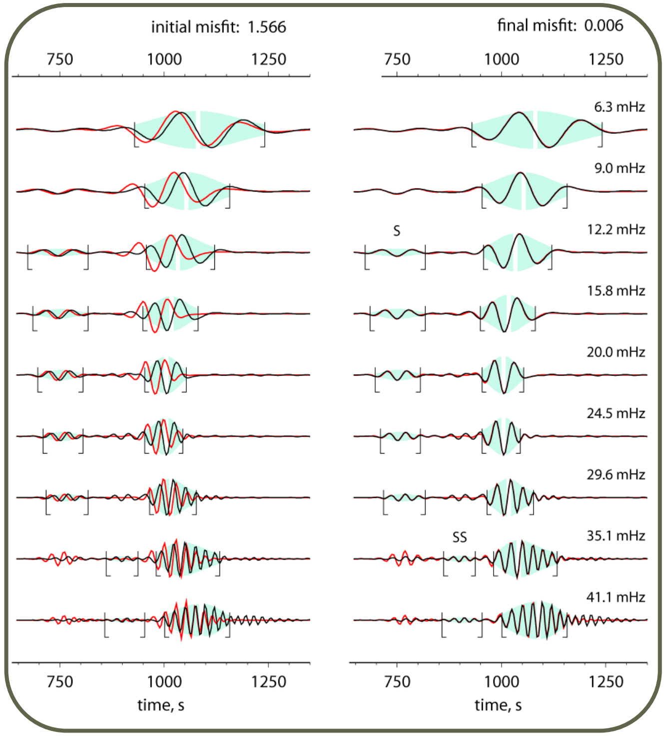
Automated Multimode Inversion







- Sensitivity-volume-average perturbations are extracted by waveform fitting
- Multiple time-frequency windows isolate fundamental and higher modes
- Simultaneous inversion of all windows using synthetic seismograms
- Misfit threshold (5%) to ensure quality fits
- Measure phase velocities for modes with significant contributions

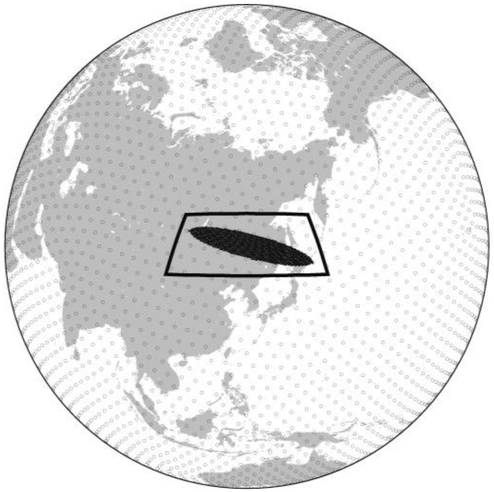


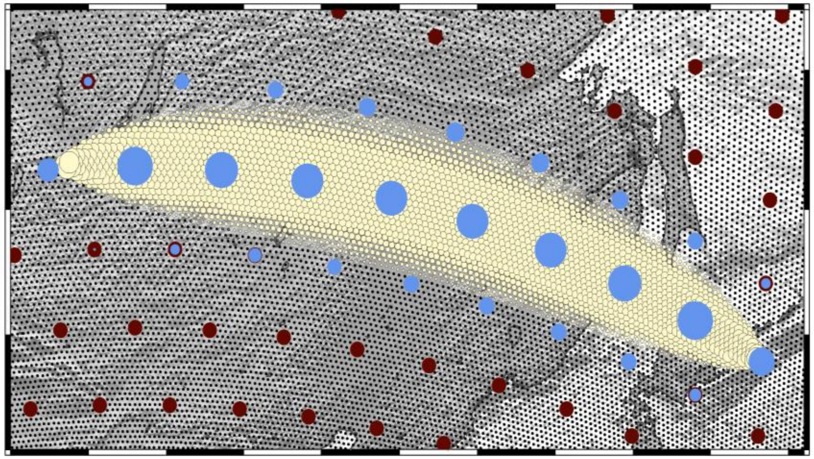
All Figures: Lebedev *et. al.*, 2005 (GJI)

3D Tomographic Inversion

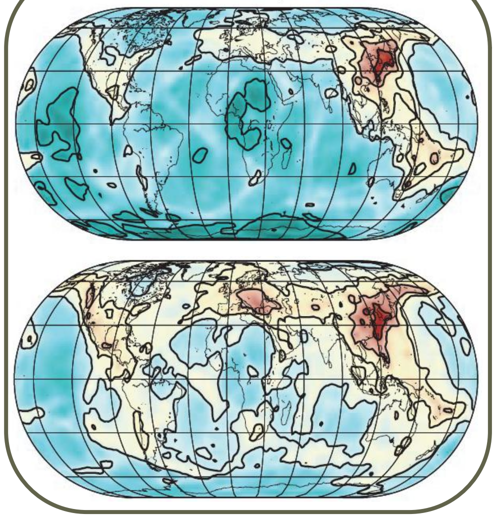
- Linear equations from AMI combined into large system
- Construct 2 co-registered triangular grids (Wang and Dahlen, 1995)
- Sensitivity kernels to map and weight constraints onto grid knots
- Re-weighting common paths to produce more even sampling distribution
- Regularization using Lateral Smoothing, Gradient Damping, Norm Damping
- Outlier Analysis and Removal

Integration and Model Grids



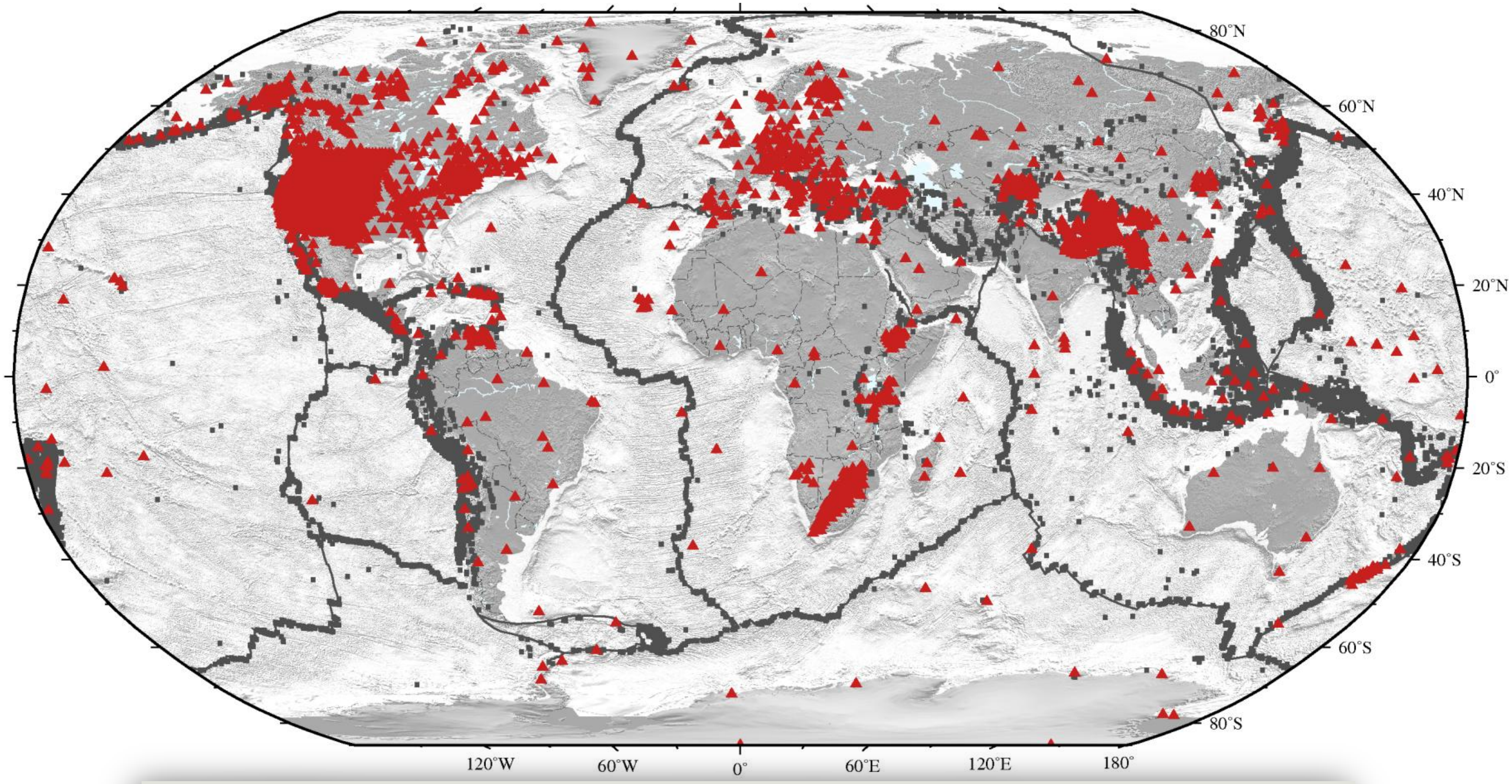


Path Weighting



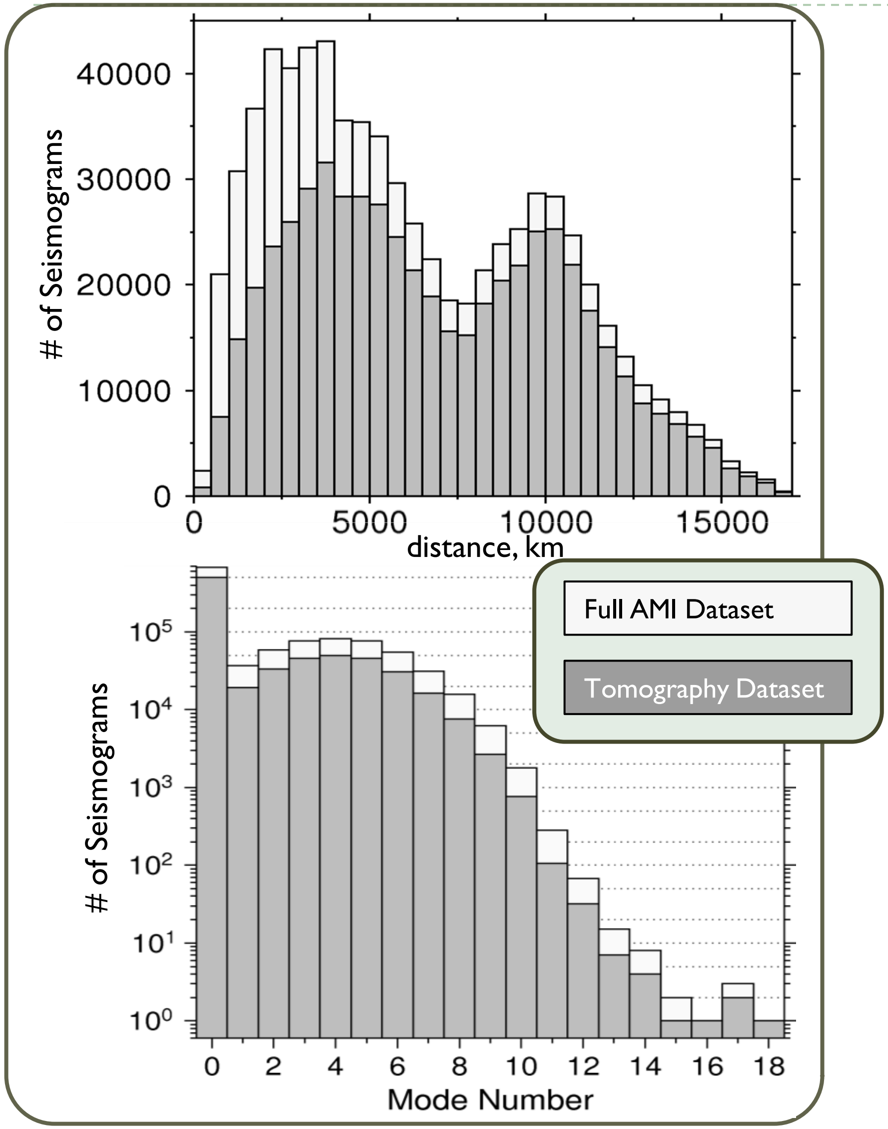
Lebedev and van der Hilst, 2008 (GJI)

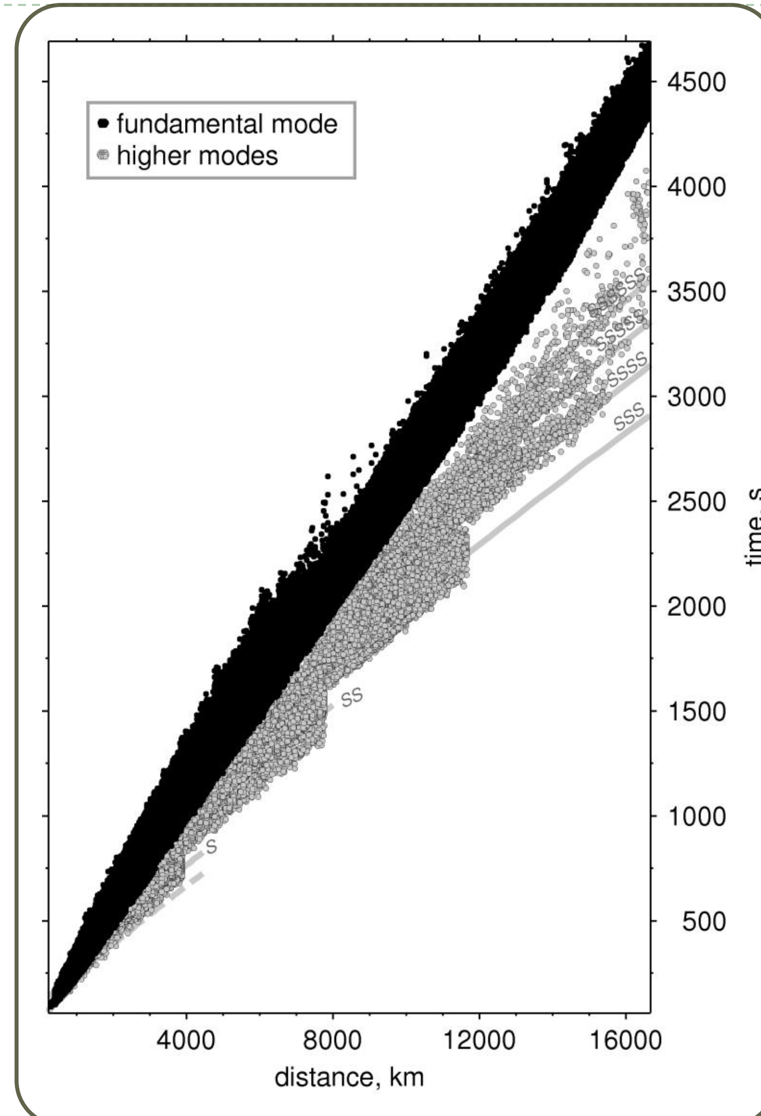
New global model of the upper mantle



- **1 Million** seismograms successfully fit using AMI
  - ~750k vertical and ~250k horizontal components
  - Use 550k of best fitting Rayleigh fits (based on outliers)
- Order of magnitude increase in number of seismograms

What's in the dataset?





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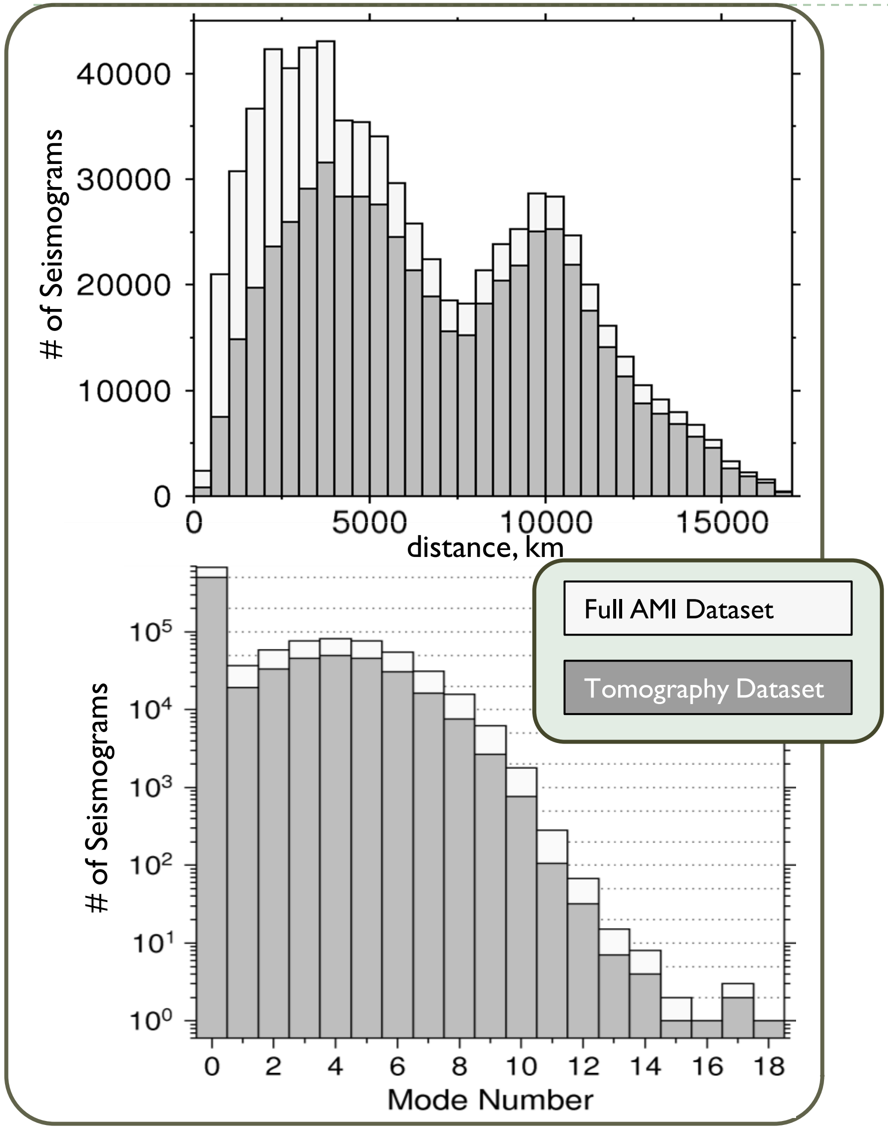
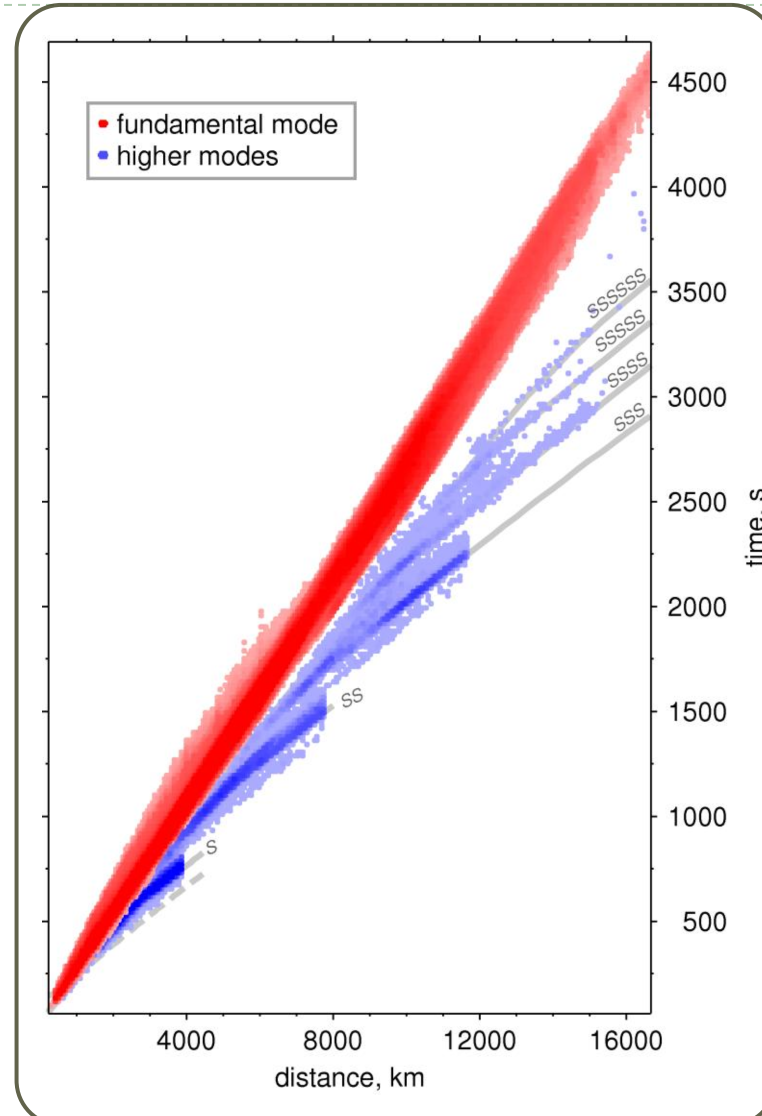
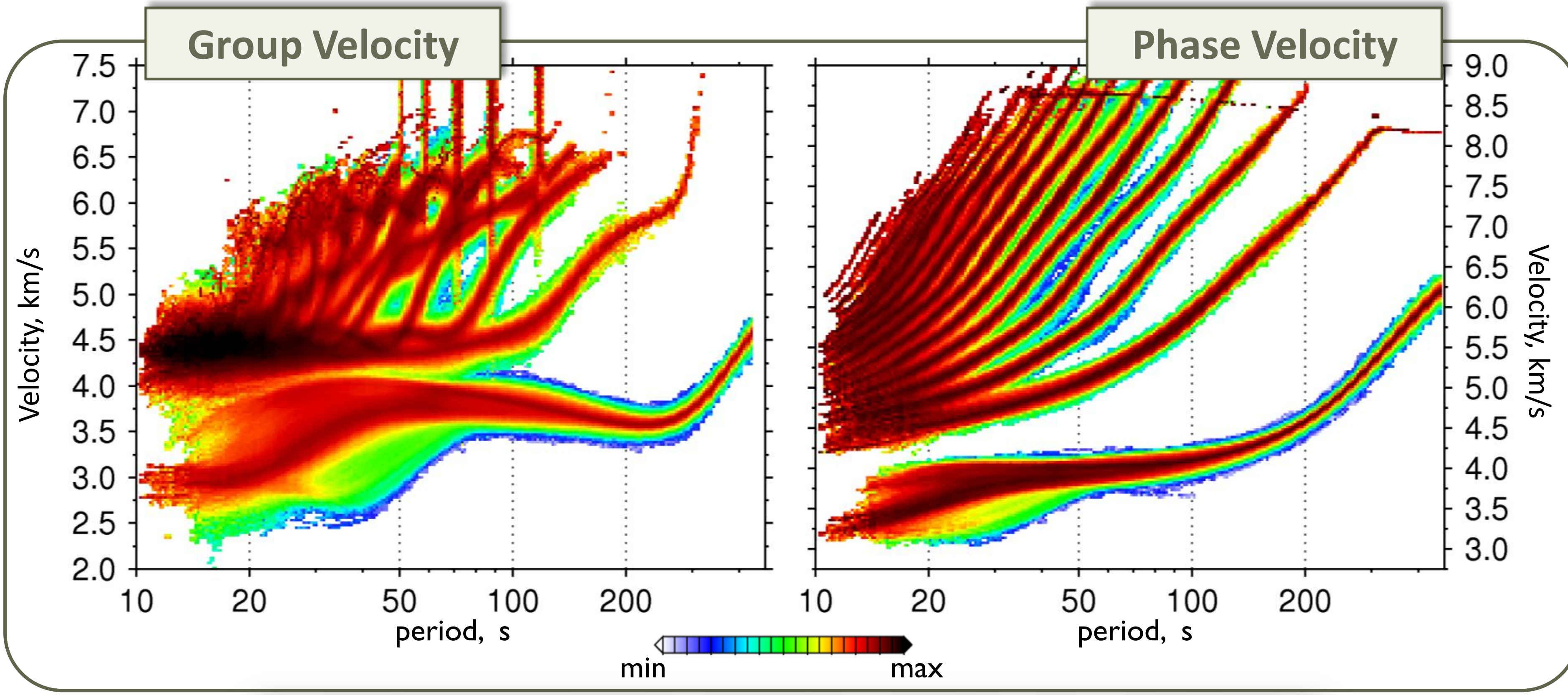




Empirical dispersive structure of the upper mantle



- Fundamental and Higher mode phase velocities measured by AMI
- Group Velocities computed from phase velocities
  - Modes 0 through 16
- Computed dispersion curves for for AK 135

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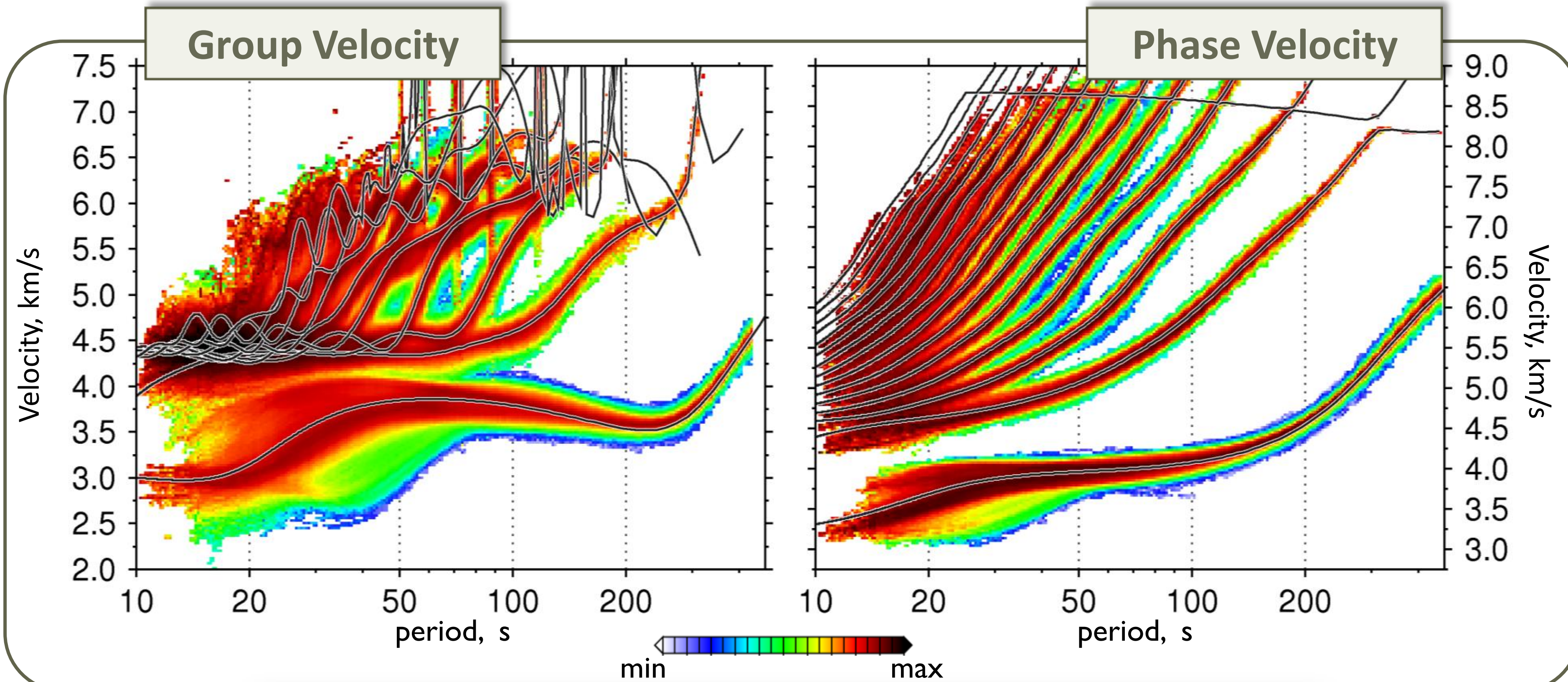

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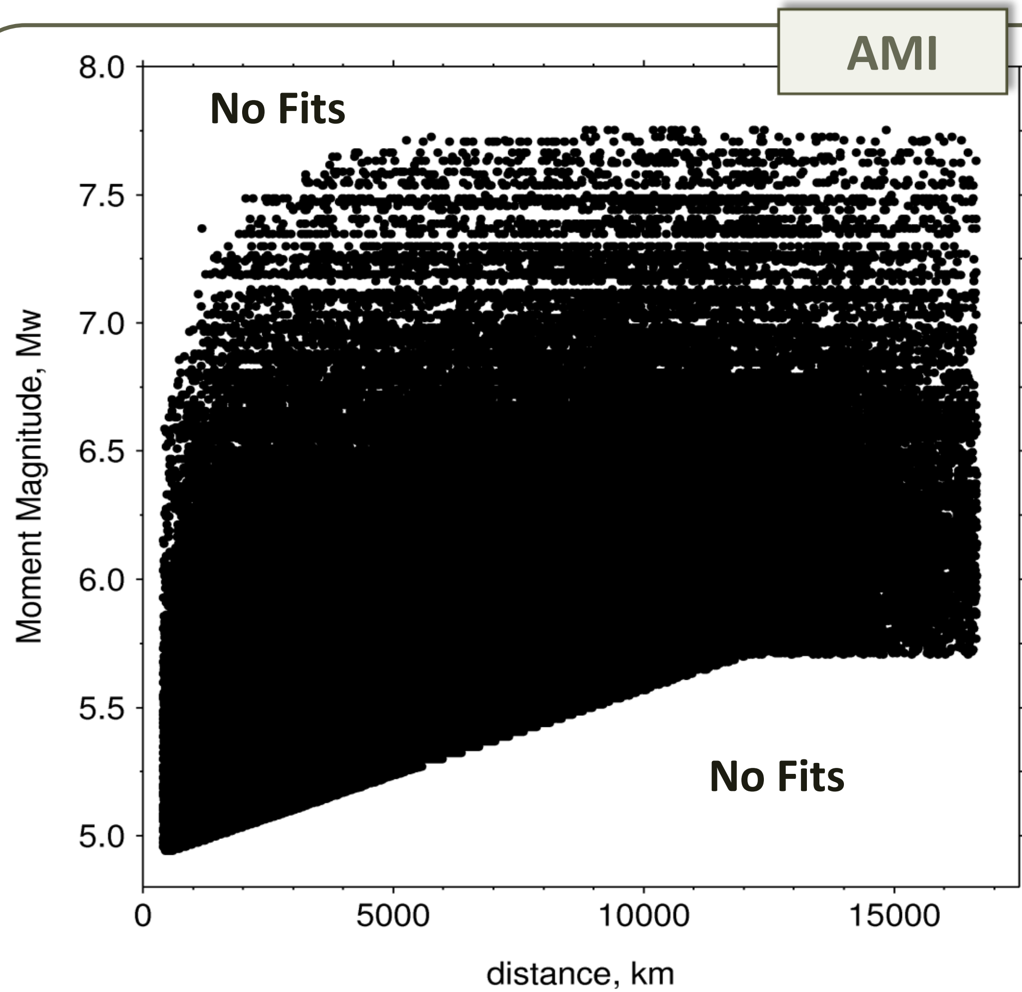
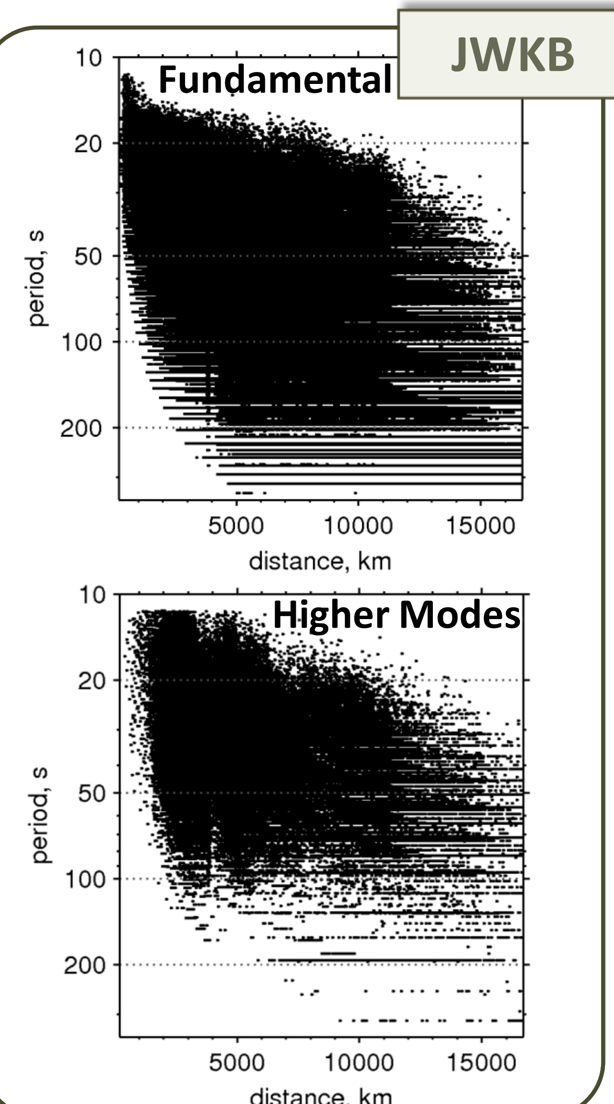
Empirical Validity for Surface Wave Ray Theory





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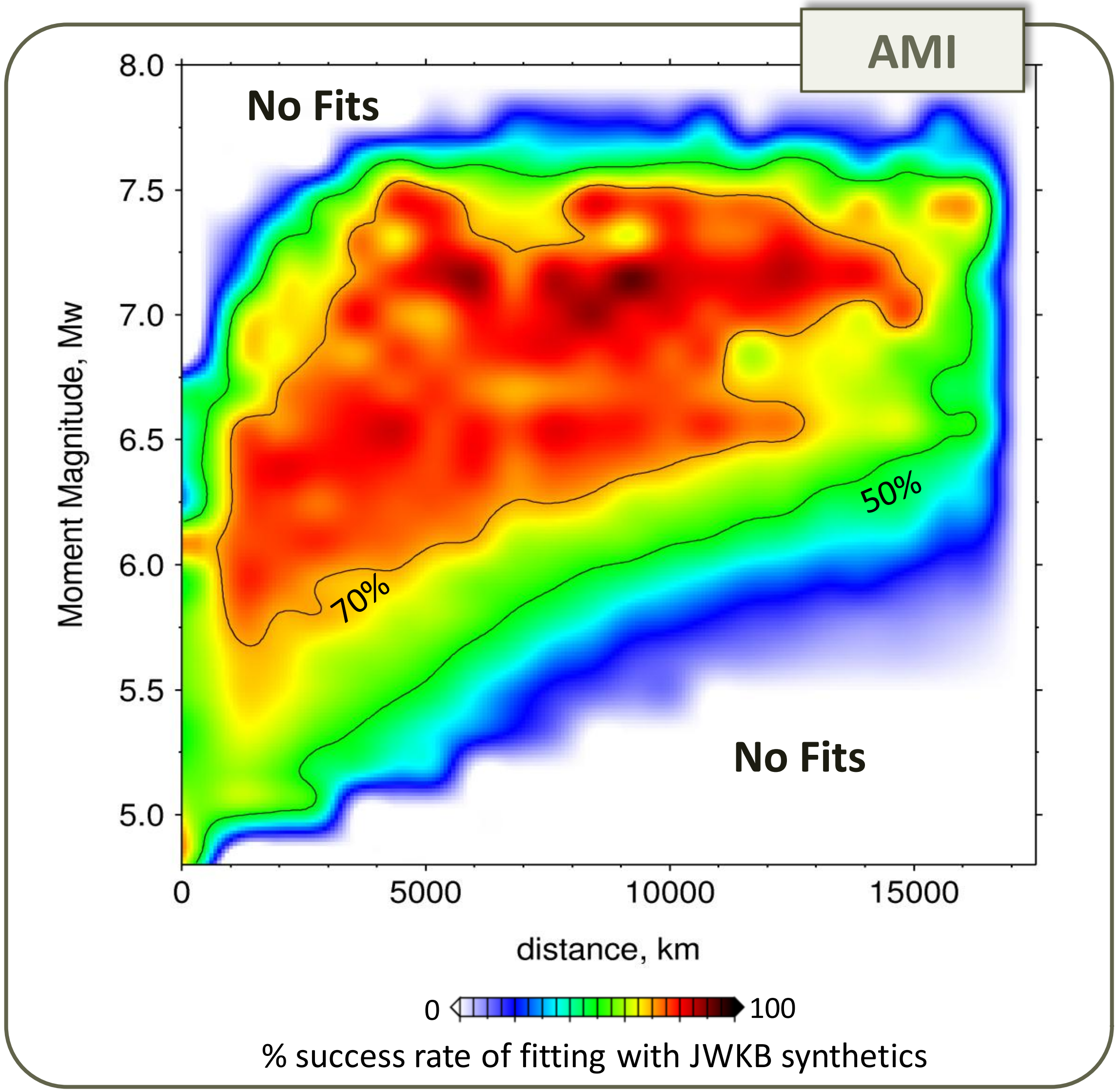

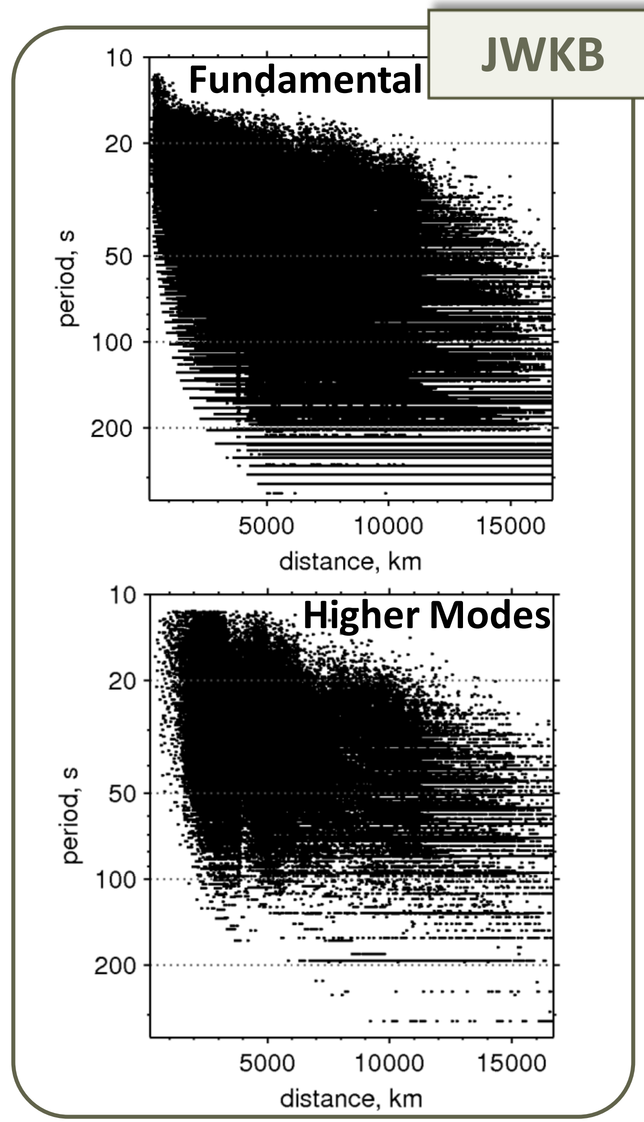

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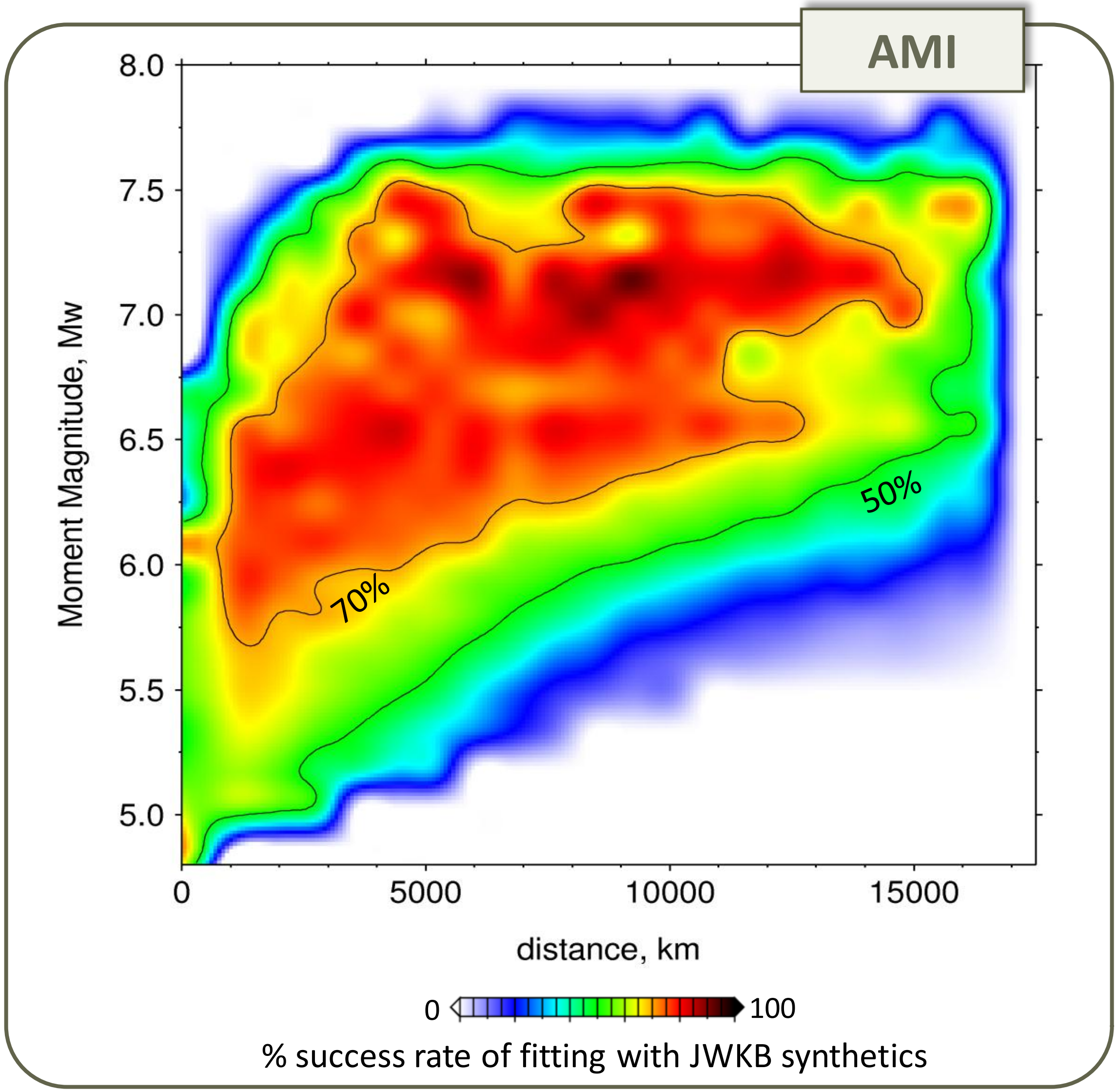
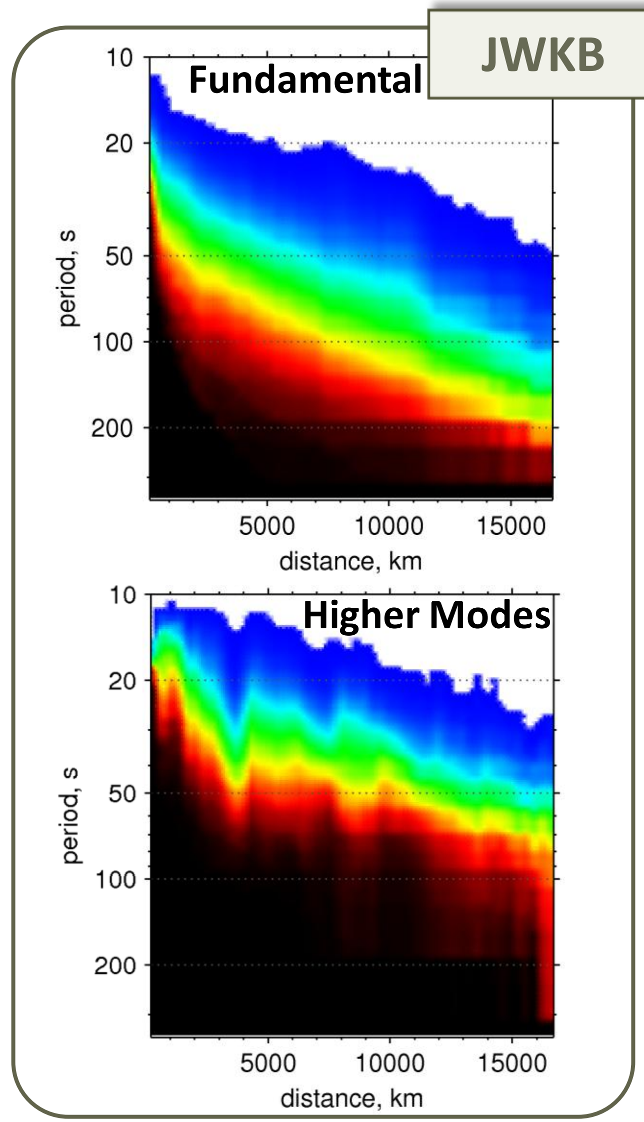
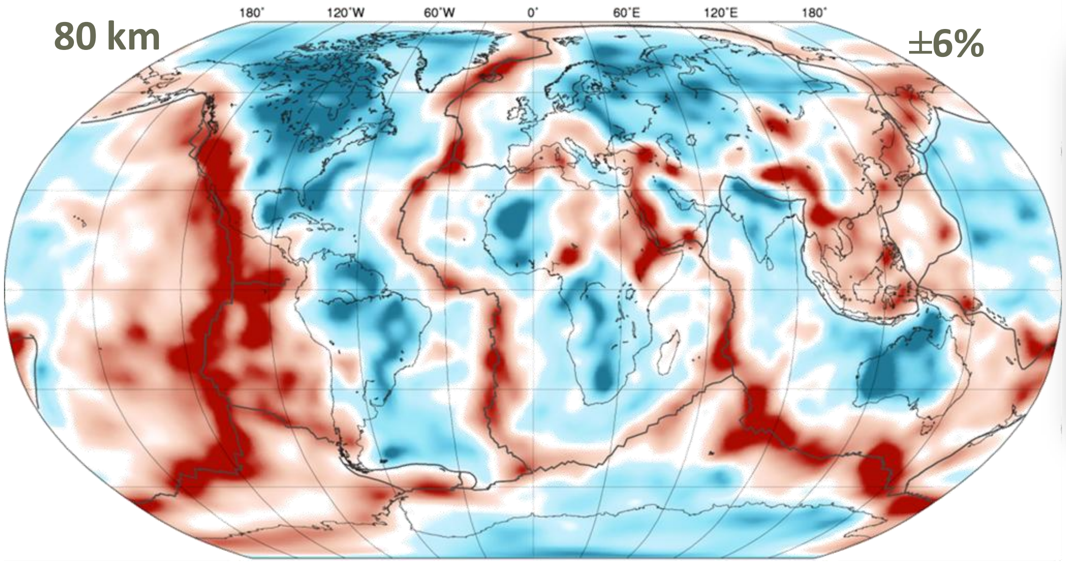




Shear velocity structure of the upper mantle

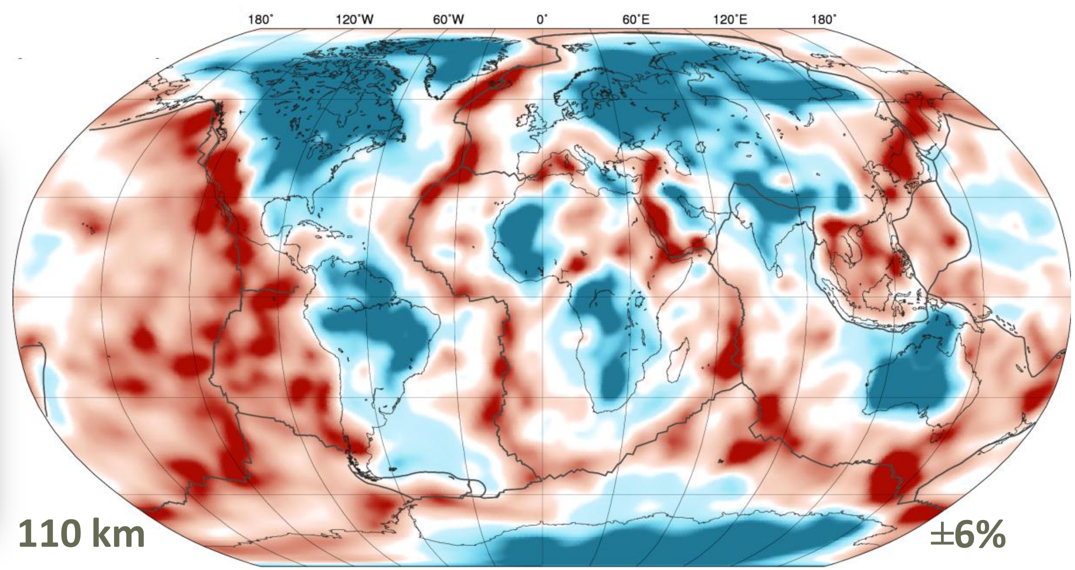


← Horizontal slice at 80km

- Striking low velocity anomalies associated with spreading ridges
- Strong contrasting high velocity anomalies indicating shallowest portions of cratonic cores

Horizontal slice at 110km →

- Dichotomy between oceans and continents
- Spreading ridges still evident
- India-Asia collision
- Cameroon Line Volcanic belt



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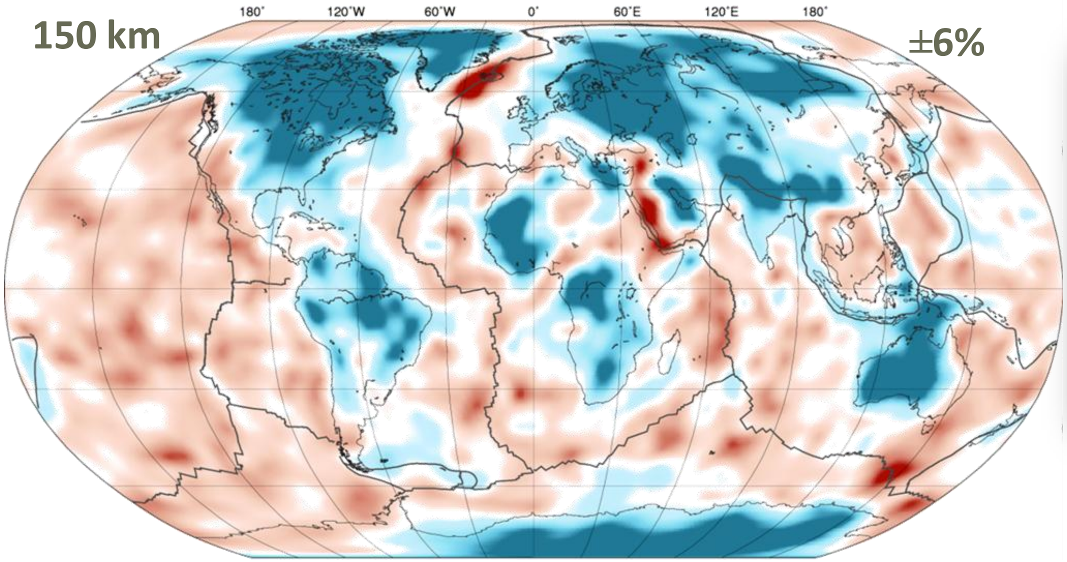
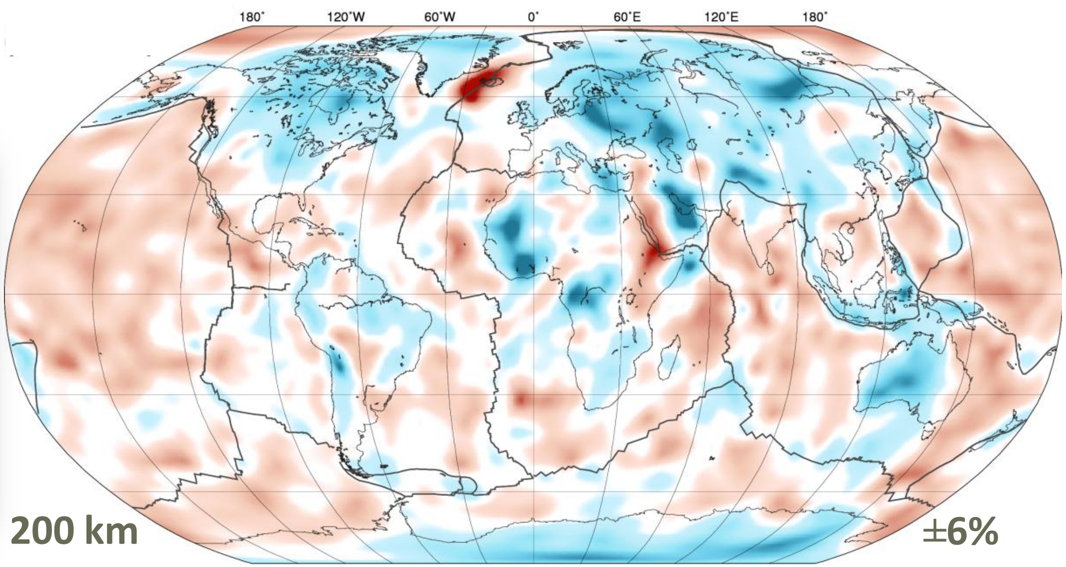


← Horizontal slice at 150km

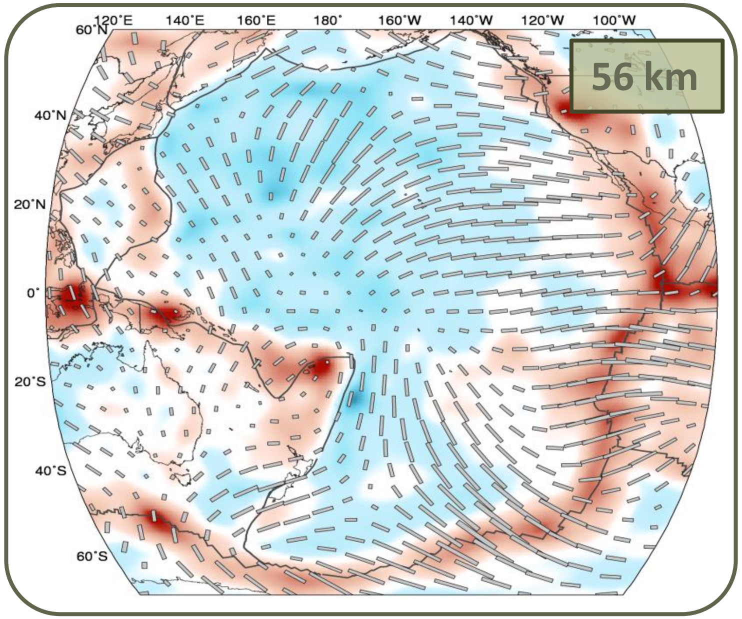
- Spreading ridge anomalies terminated at shallower depths
- Dominated by fast, cold roots of continental cratons

Horizontal slice at 200km →

- Strength of heterogeneity weakened
- High velocity anomalies at the base of continental roots
- Evidence for subduction zones

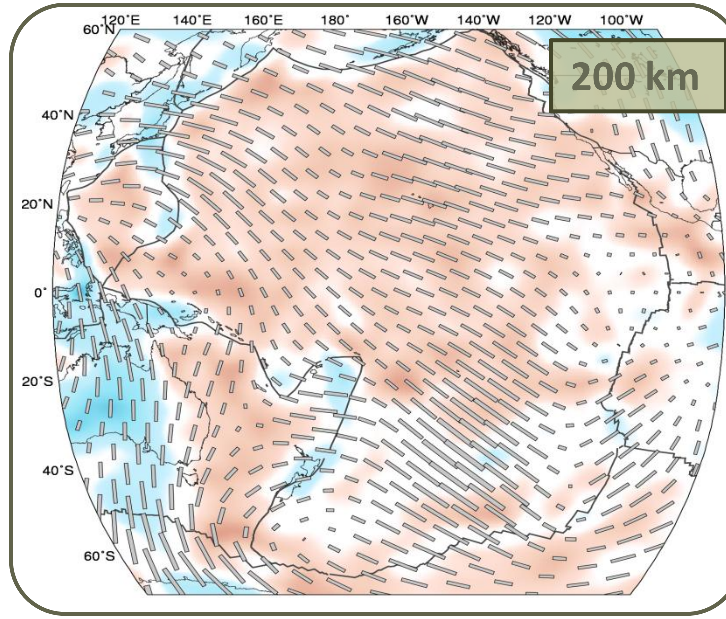


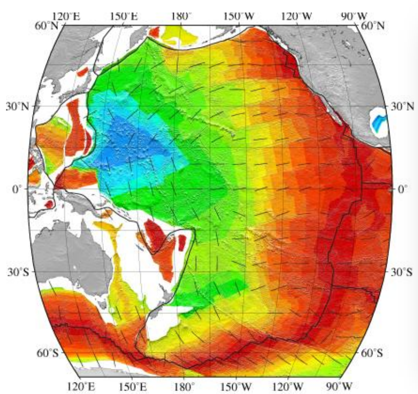
Azimuthal Anisotropy



±8% ± 5%

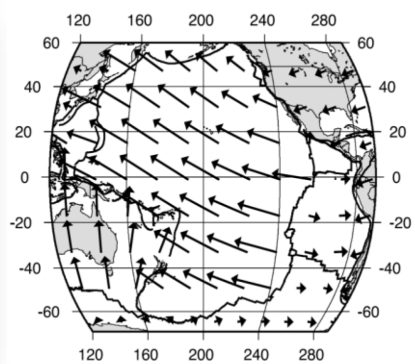
±2.5% | ±1.0%





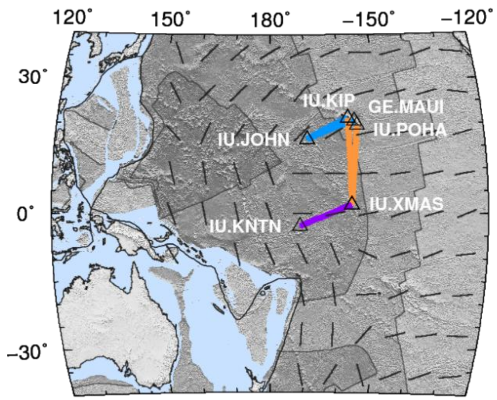
Pacific Ocean Anisotropy Stratification

- Fast axis of azimuthal anisotropy aligned with spreading direction at modern ridges
- Frozen anisotropy in ancient oceanic lithosphere correlated to paleo-spreading vectors (Smith *et al.*, 2004) from shearing of uppermost mantle during spreading
- In Asthenosphere, fast axis aligned with the direction of current plate motions across whole pacific

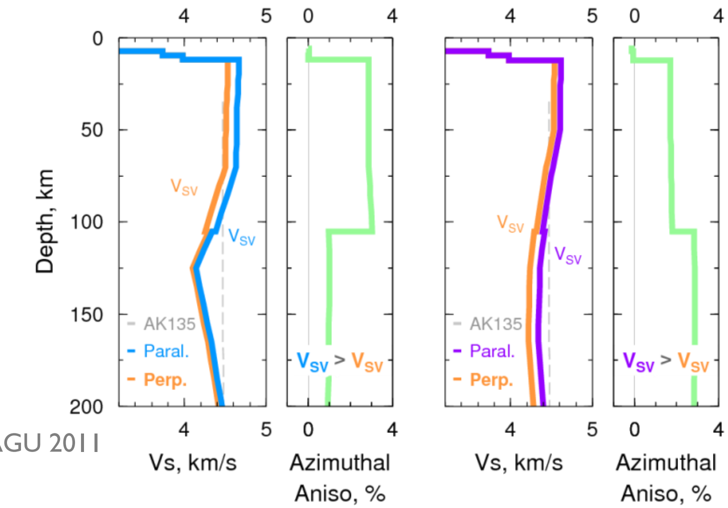


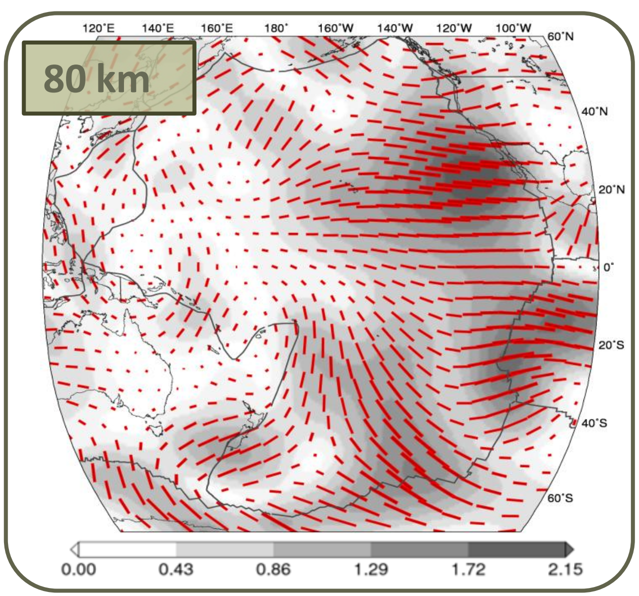
Smith *et al.*, 2004; Mueller *et al.*,. 1997

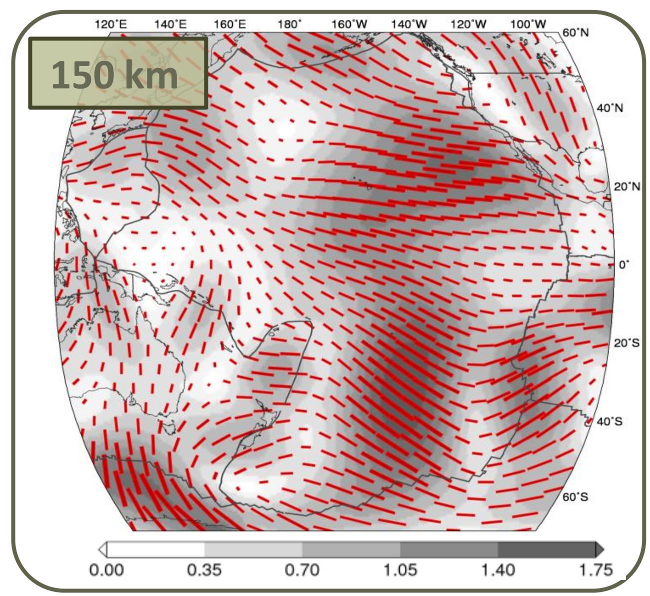
Benchmarking Magnitude of Azimuthal Anisotropy



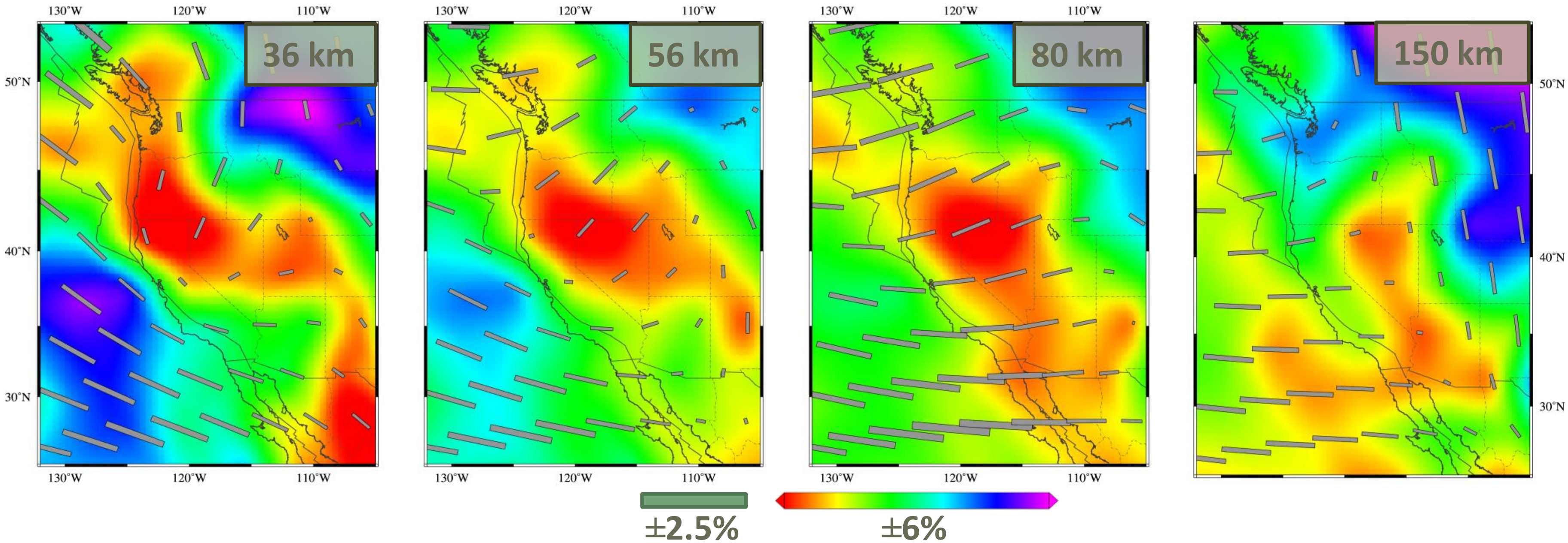
Lynch, Agius, Schaeffer, and Lebedev; AGU 2011





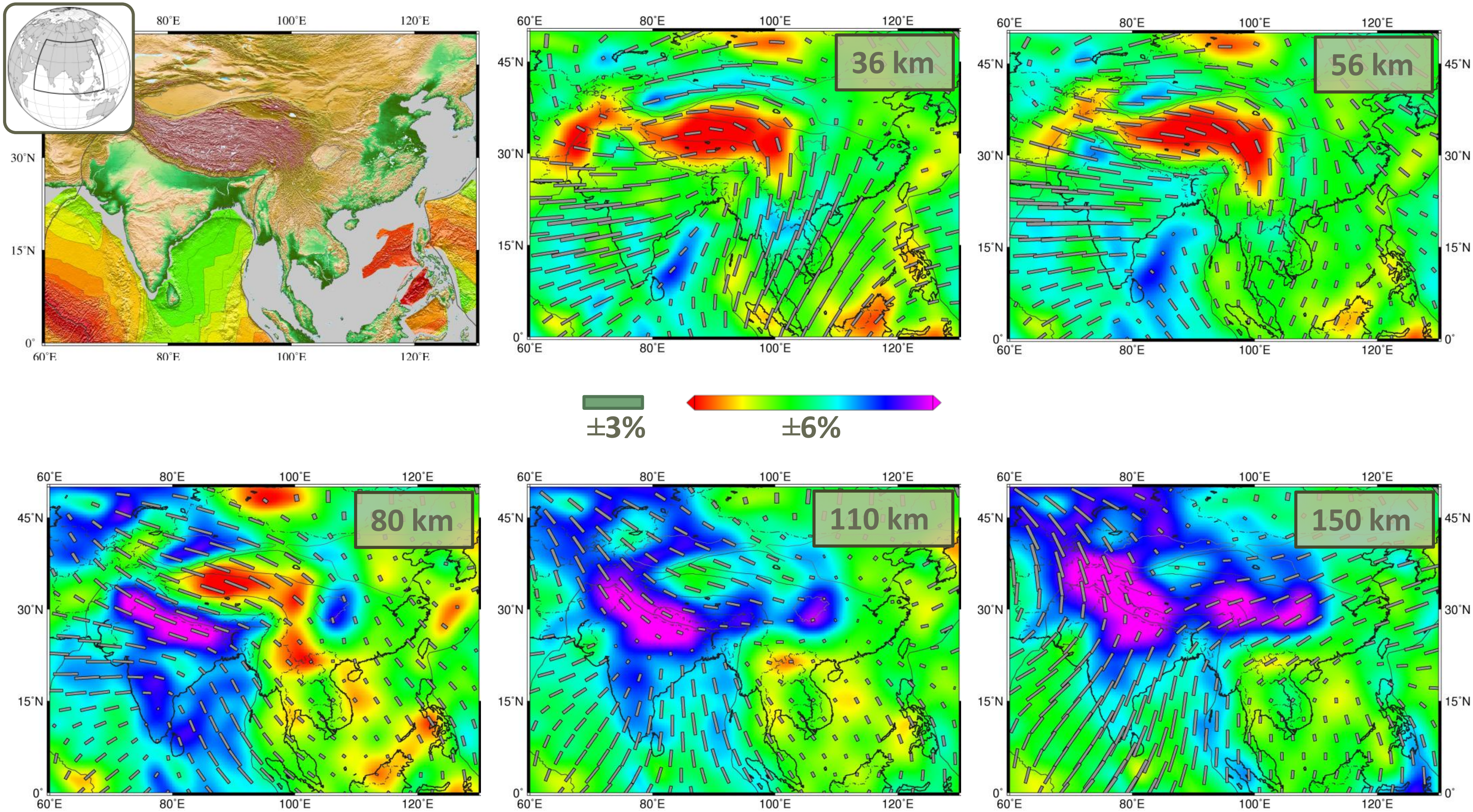


Anisotropy beneath Western North America

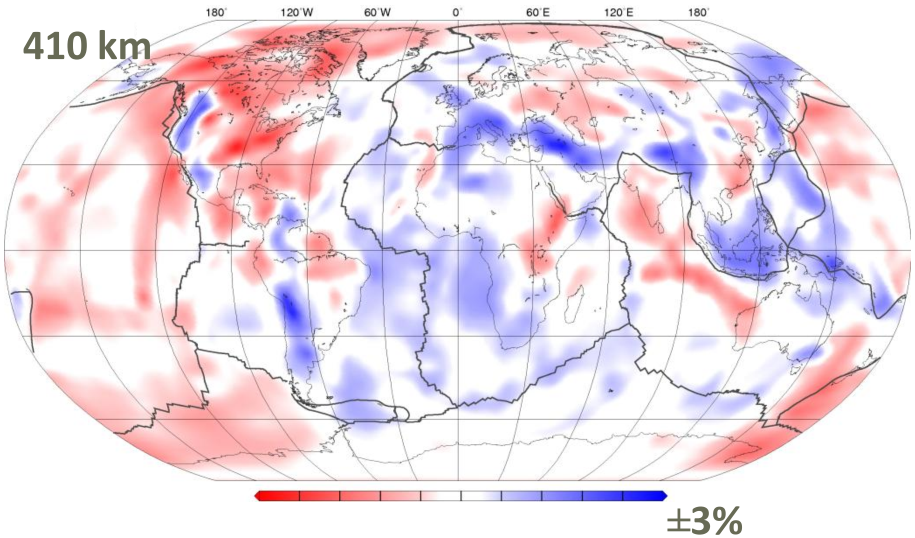


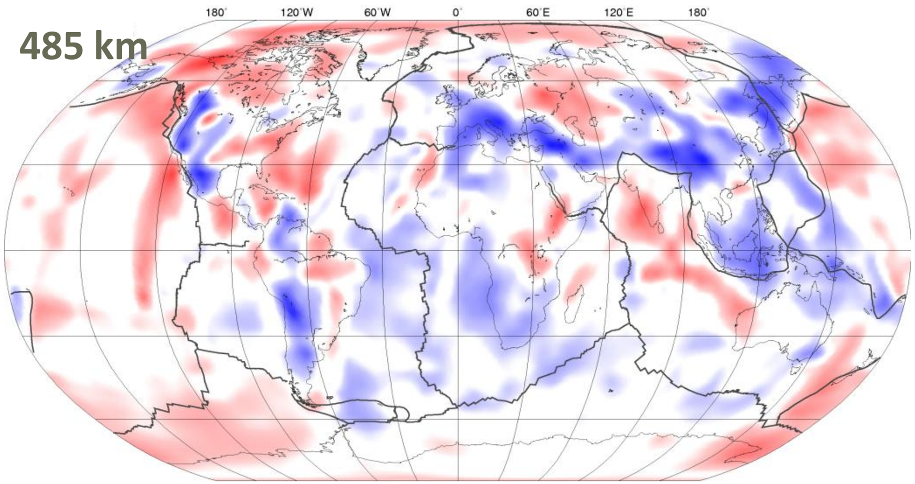
- Continental Anisotropy more complex
- Challenge for global tomography
- Complex patterns of anisotropy related to past and ongoing tectonics in western North America

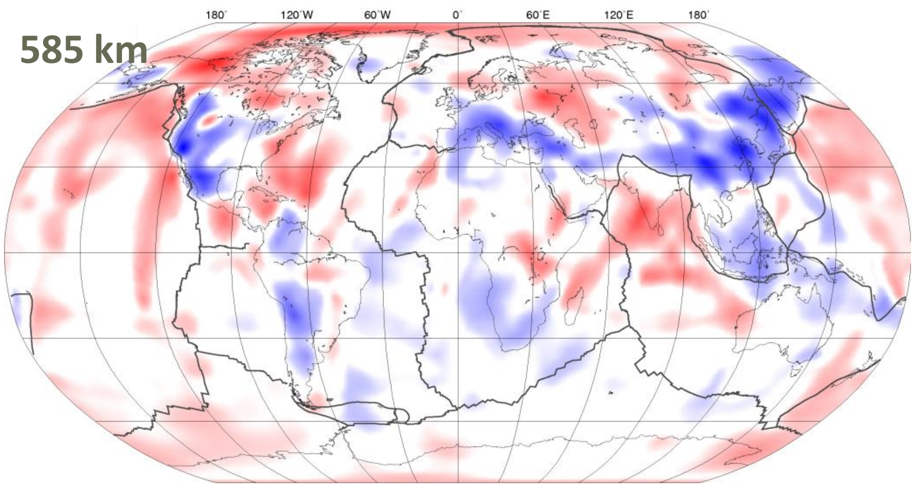
Anisotropic Structure beneath Tibet



Transition Zone Structure







- Most major subduction zones are marked by high velocity slabs within the transition zone
- Evidence for subducted Tethyan lithosphere within the transition zone (Hafkenscheid *et al.*, 2006 (JGR))

Conclusions

- Spectacular growth in the amount of broadband data: opportunity for a new generation of tomographic models
- Our new dataset: multimode-waveform fits for 1 million broadband seismograms
  - 750 000 vertical component (Rayleigh) and 250 000 horizontal (Love)
  - Provides statistical insight to validity of the approximations
  - Upper mantle heterogeneity as visualized empirically by fundamental and higher mode dispersion
- Our new model: constrained by waveforms of 550 000 vertical component seismograms
- Higher resolution of upper mantle structure and anisotropy globally compared to models of only a few years ago
  - Clear images of the lithosphere-asthenosphere system beneath continents and oceans
  - Detailed snapshots of subduction in western North America, and along the Tethys convergence zone
  - Accurate retrieval of the orientation and amplitude of anisotropy where they vary smoothly (Pacific Ocean)
  - Improved resolution of anisotropy in well sampled continental regions, e.g., Western North America, India-Asia collision zone