SUSTech Southern University of Science and Technology

地球与空间科学系 DEPARTMENT OF EARTH AND SPACE SCIENCES

Regional and local crustal model building

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Nov 18, 2026

SIML SEISMIC IMAGING AND MONITORING LABORATORY

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Outline

- Global and regional crustal model building
- Case study 1: Oklahoma crustal model (continent+passive)
- Case study 2: Axial seamount imaging (ocean+active)
- Resolution, uncertainty and model evaluation

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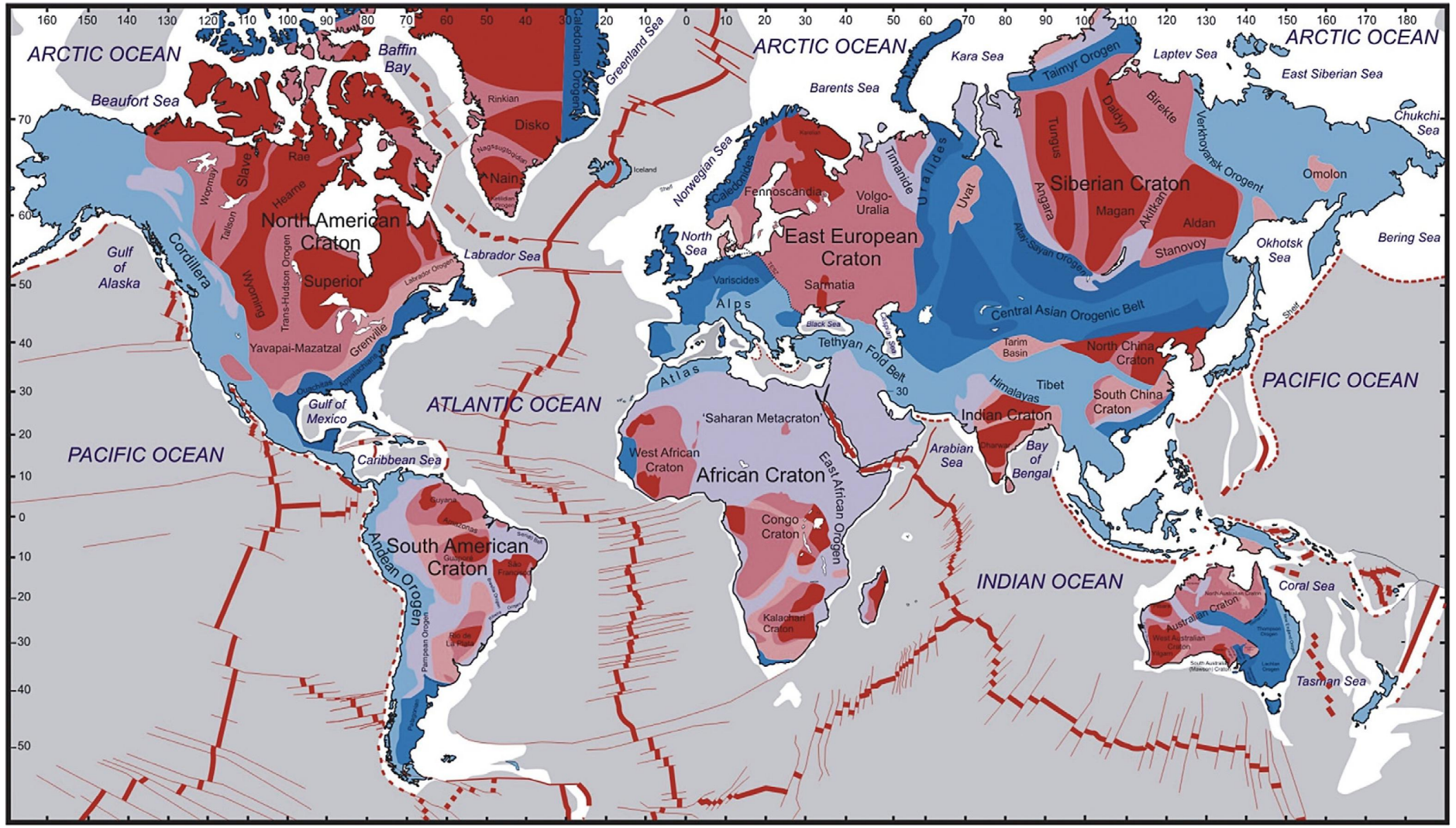
Complexity of Earth's crust



- Subduction zone
- Mid-oceanic ridges and transform faults
- Oceanic crust

Continental crust

- Shelf
- Mesozoic–cenozoic (250–0 Ma)
- Late Paleozoic-(400–250 Ma)
- Early Paleozoic (543–400 Ma)
- Neoproterozoic (1.0–0.54 Ga)
- Mesoproterozoic (1.6–1.0 Ga)
- Paleoproterozoic (2.5–1.6 Ga)
- Archaean (3.8–2.5 Ga)

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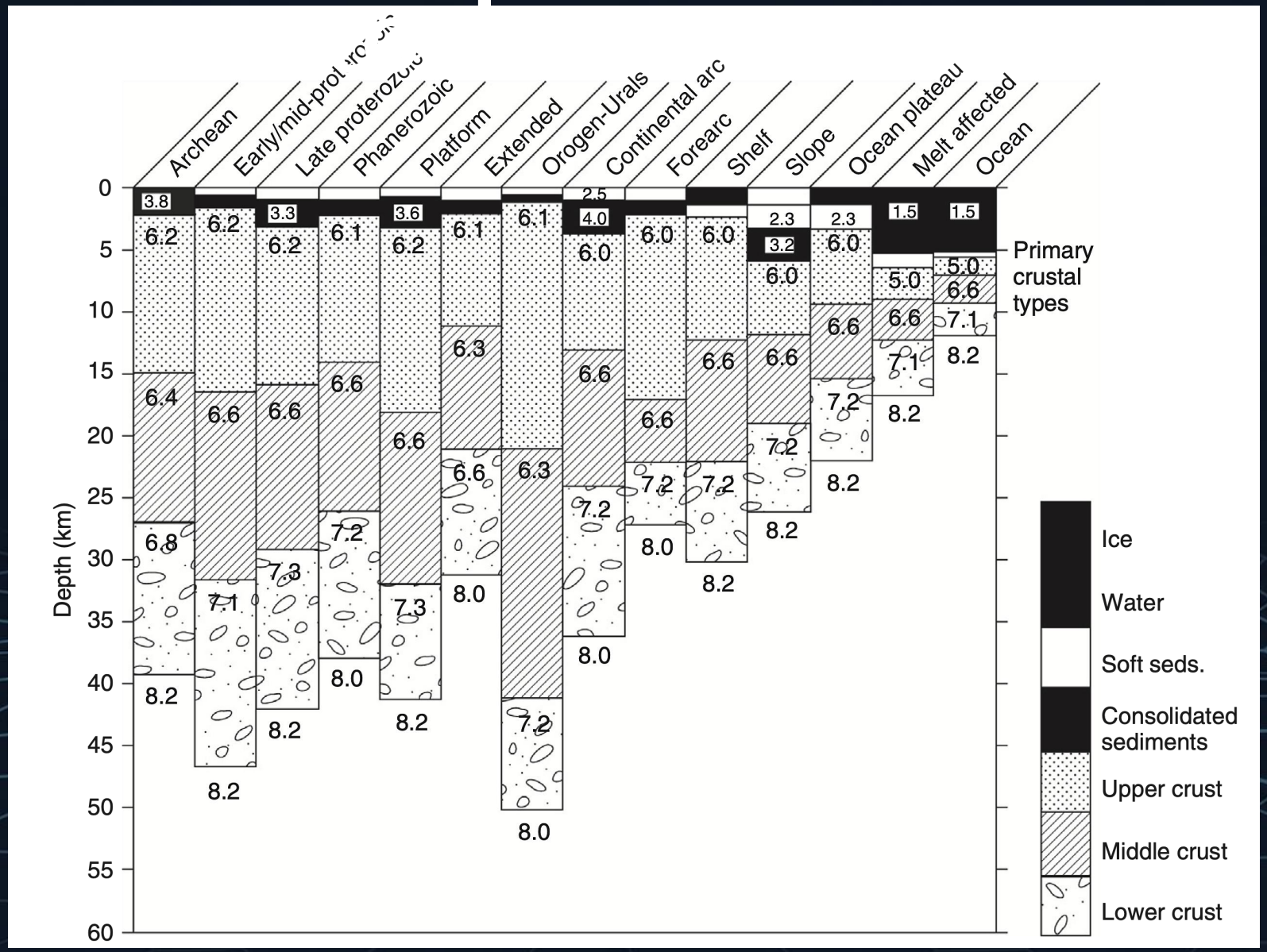
Velocity profiles for different



1D PREM model cannot account for this complexity

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History of global crustal models

Model	Year and citation	Grid spacing	How it was built and what changed
3SMAC	1996 Nataf & Ricard	2 ° × 2 °	Combined compilations of crustal layer thickness with thermal plate models, mineralogy, and laboratory measurements to predict seismic velocities, density, and attenuation.
CRUST5.1	1998 Mooney et al.	5 ° × 5 °	Compiled seismic refraction profiles and grouped them by tectonic setting. Assigned a representative seven–layer profile to each grid cell, including two sediment layers and three crystalline crustal layers.
CRUST2.0	2000 Bassin et al.	2 ° × 2 °	Refined CRUST5.1 with updated sediment, ice, and crustal thickness compilations. Retained the seven–layer structure and better represented coastlines, continental shelves, and mountain belts.
CRUST1.0	2013 Laske et al.	1 ° × 1 °	Used updated sediment and elevation data to build a distinct eight–layer profile for each cell, with three sediment layers. Crustal types assign properties to crystalline layers; layer thicknesses can vary within each type.
ECM1	2023 Mooney et al.	1 ° × 1 °	Uses about 19,200 active– and passive–source seismic measurements, updated sediment compilations, and field measurements to constrain continental S–wave velocities.

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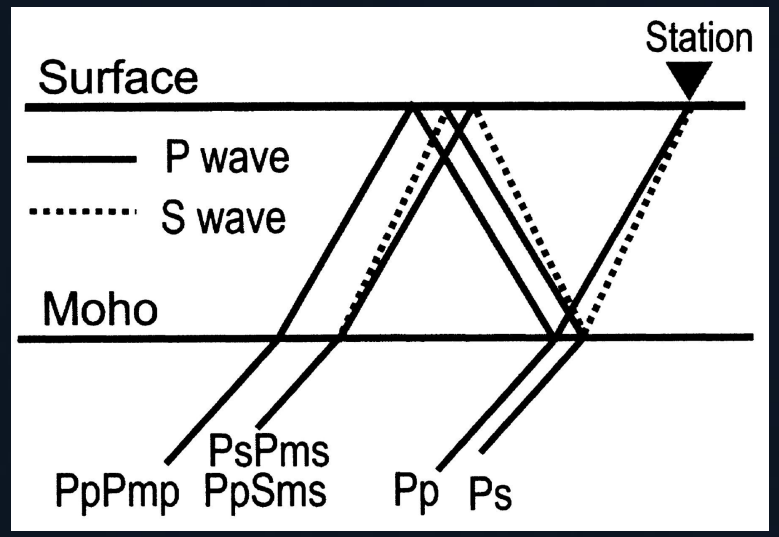
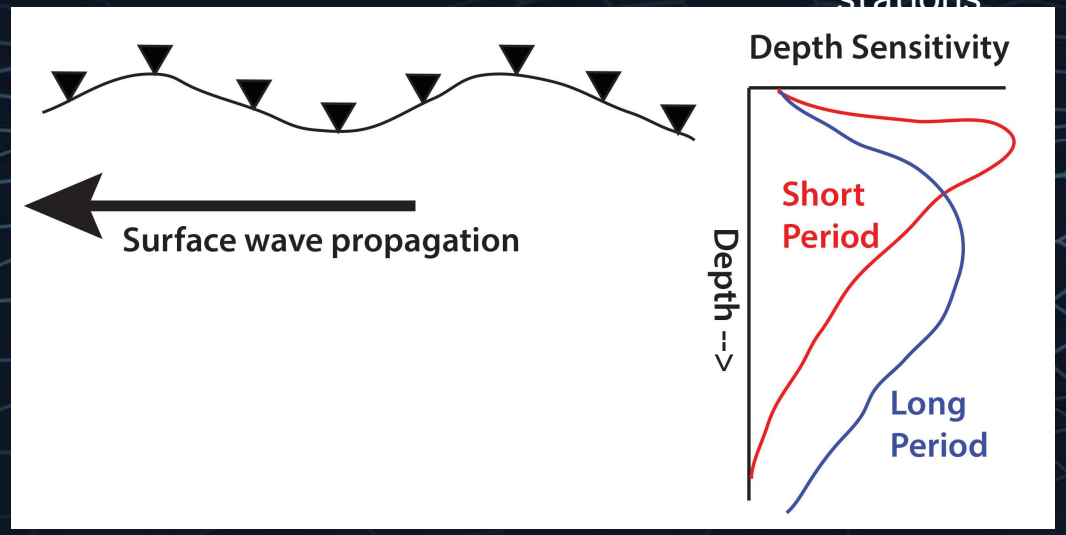
Common Seismic Imaging Methods

Receiver functions:



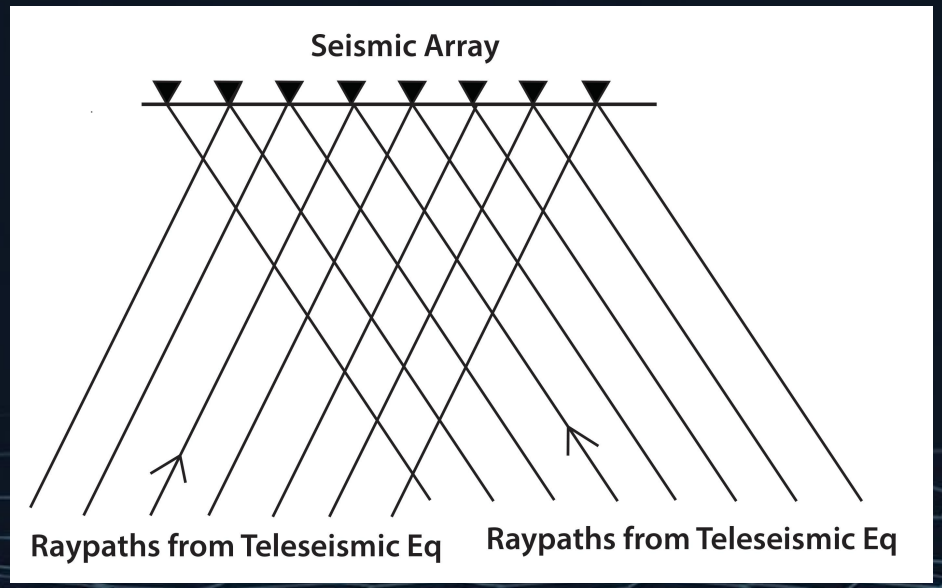
- Strengths: image discontinuities such as the Moho, sediment–basement interface, and 410 and 660 km boundaries
- Limitations: weak constraints on velocity and its gradients; mainly used to image shallow structure beneath stations

Surface-wave imaging:



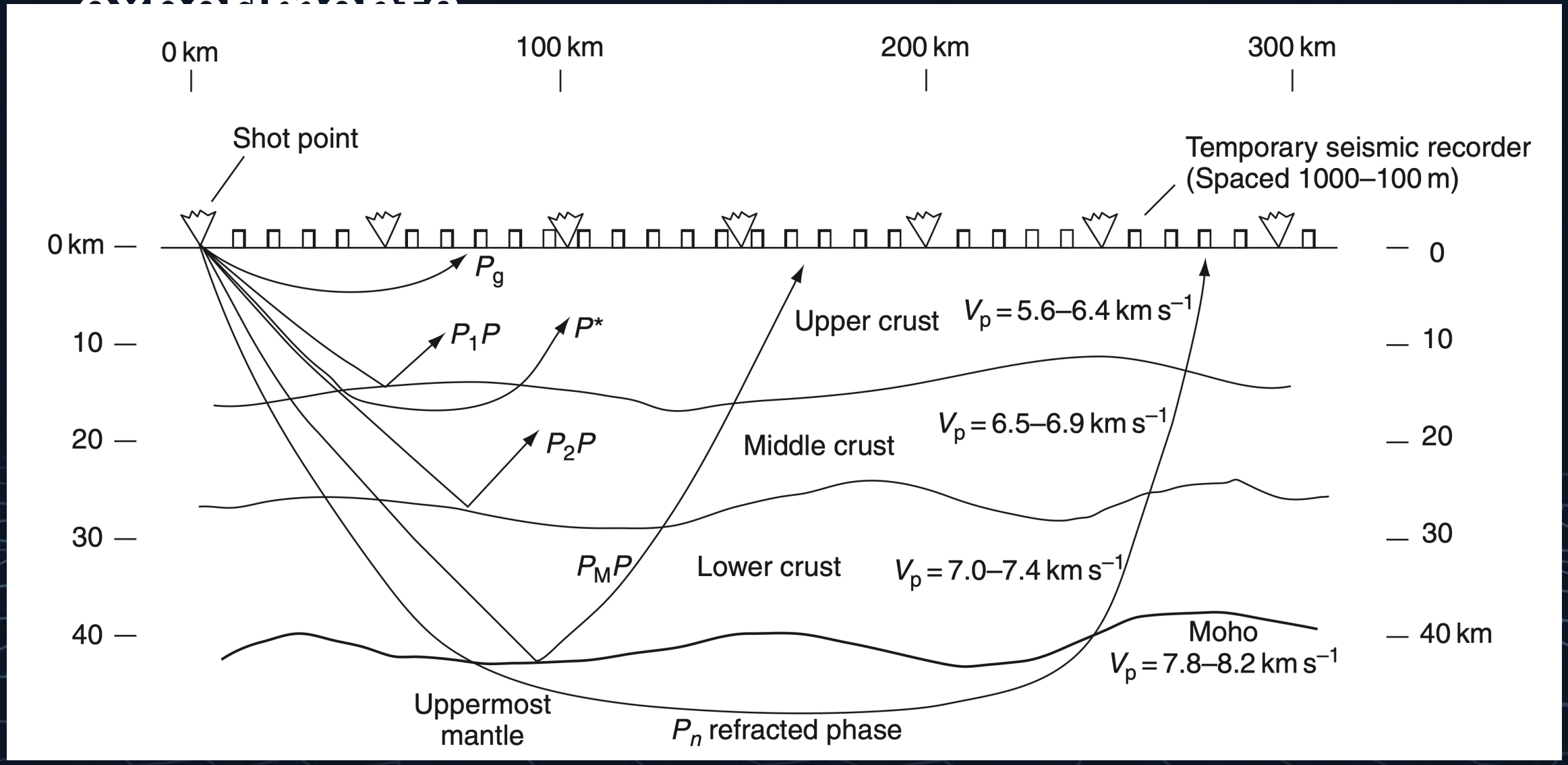
Body-wave imaging:

- Strengths: resolves lateral variations at depths of 100–1,000 km
- Limitations: requires dense station coverage and often has poor depth resolution



- Strengths: resolves depth variations and constrains absolute velocities
- Limitations: generally lower lateral resolution; typically limited to the upper 300 km

Active source refraction/reflection experiments



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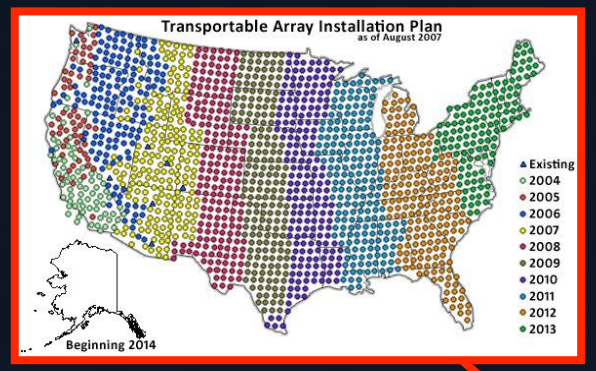
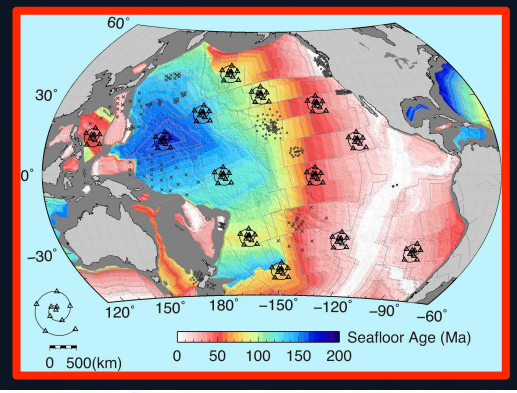
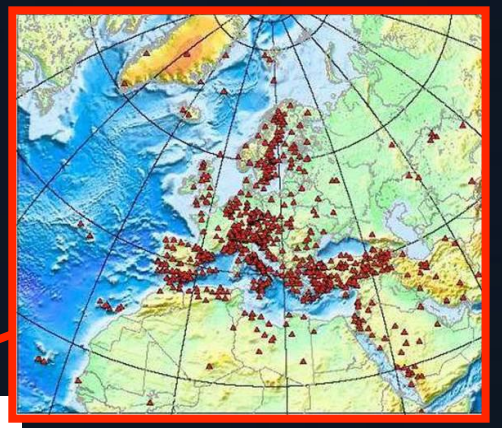
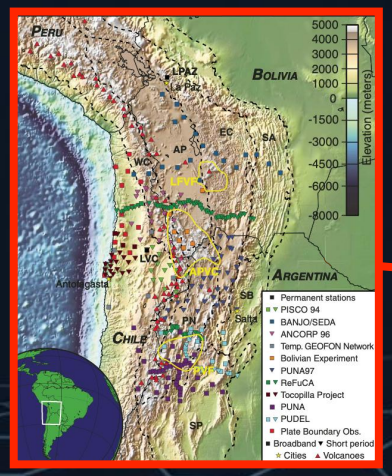
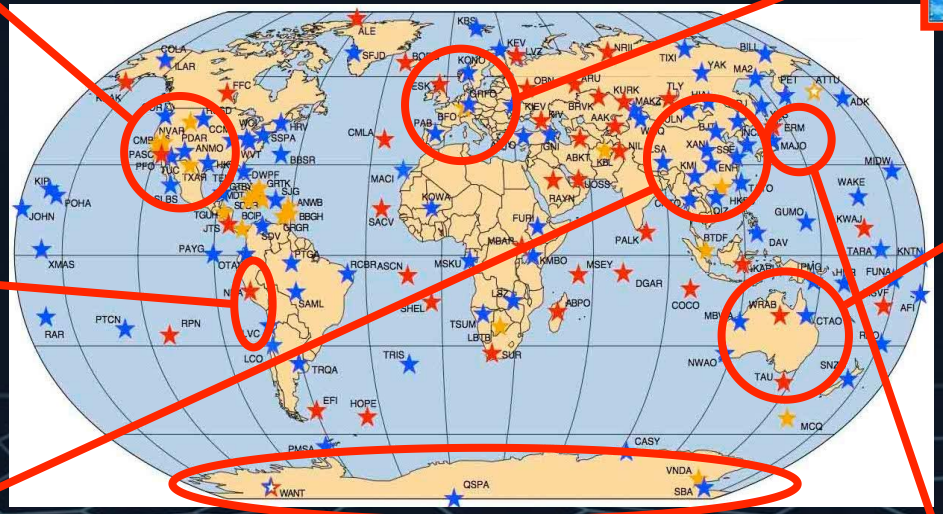
Global and regional seismic networks



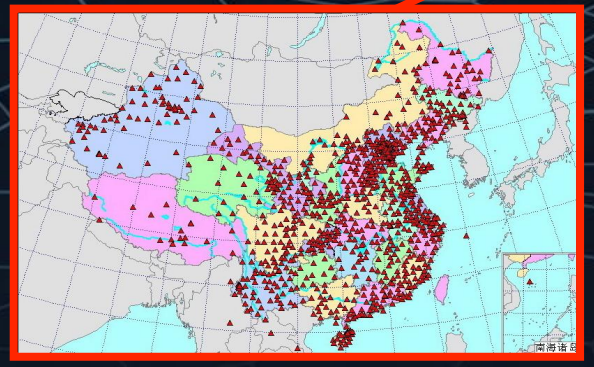


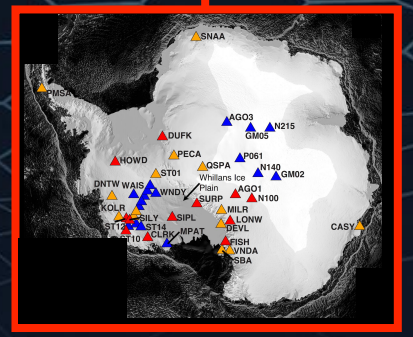


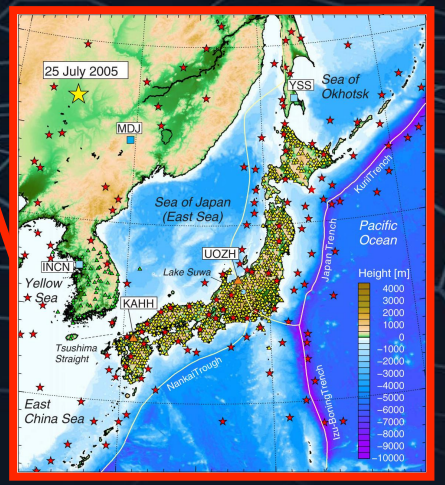












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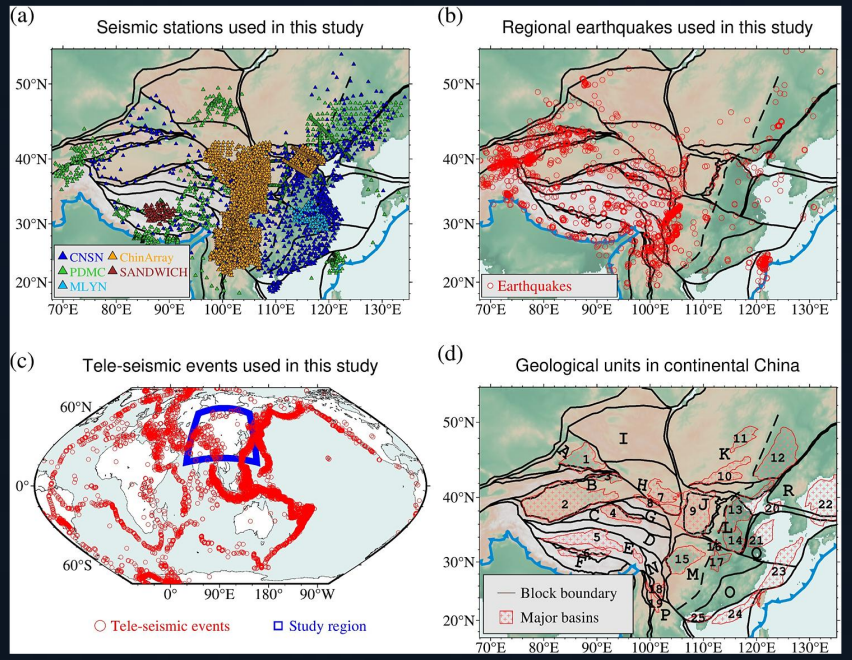
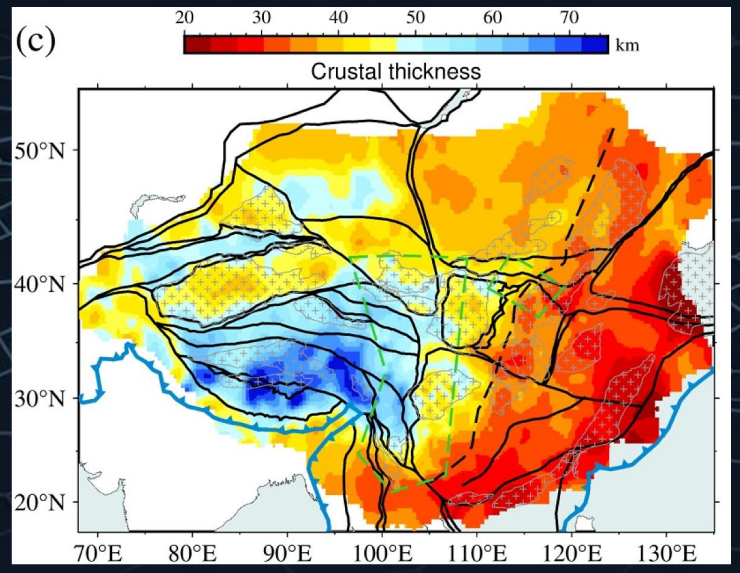
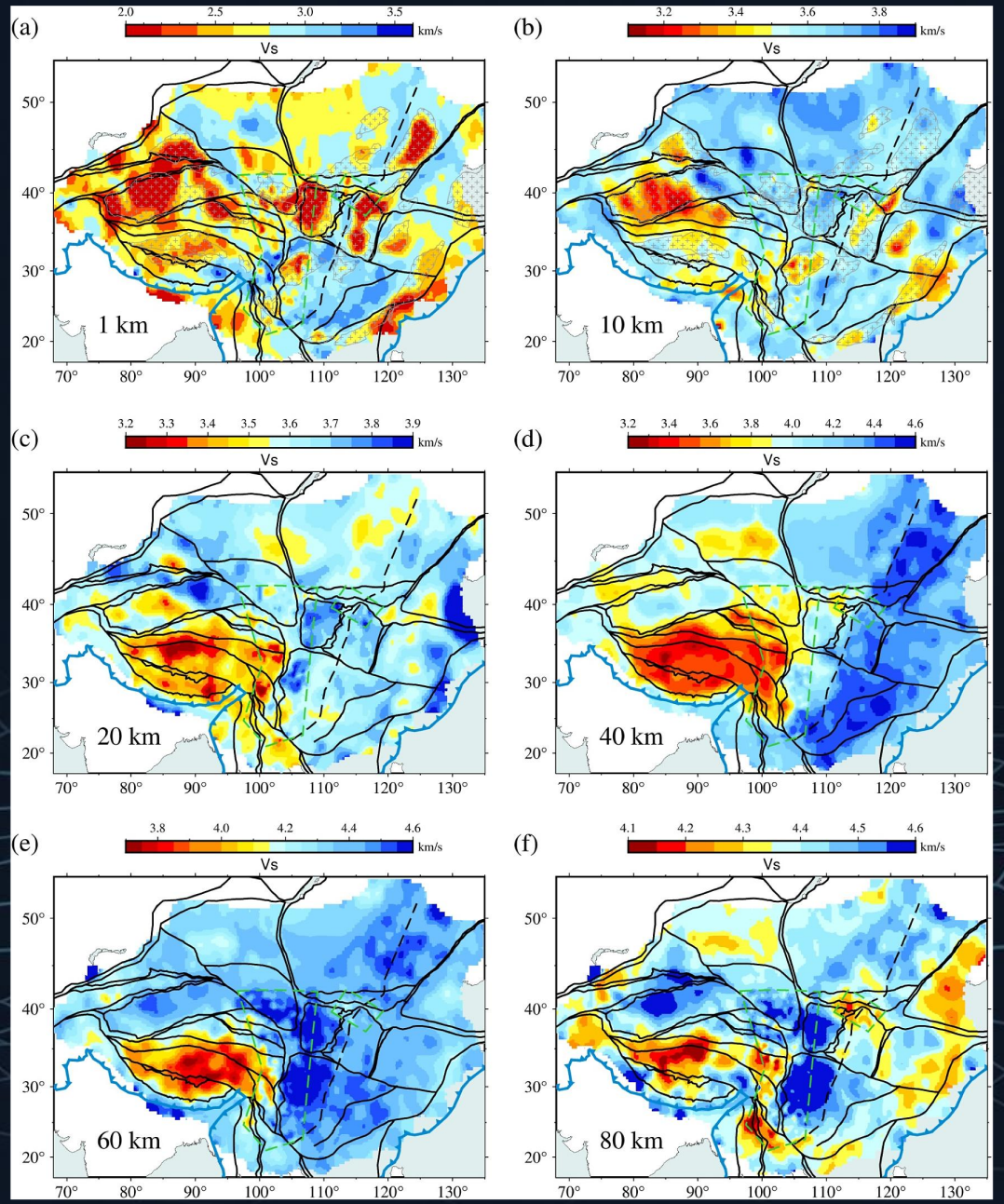
Crustal model for China







(Xiao et al, JGR, 2024

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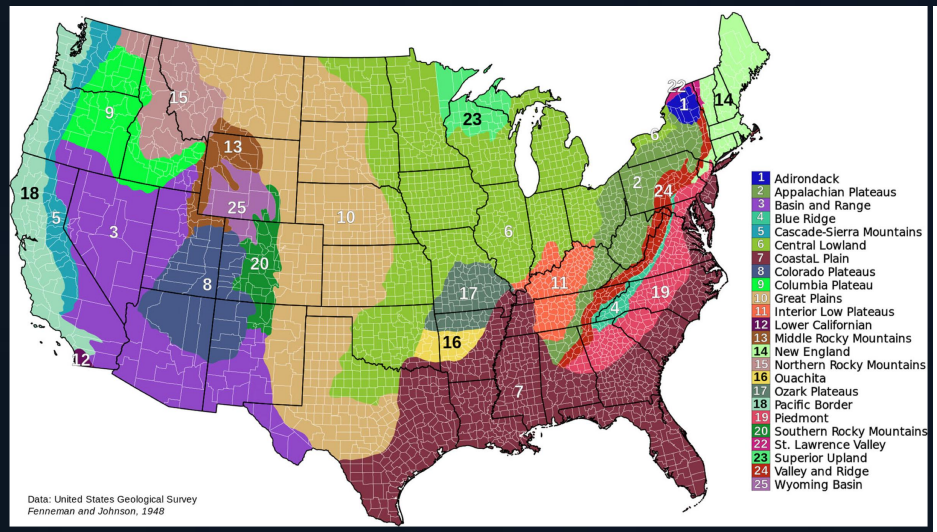
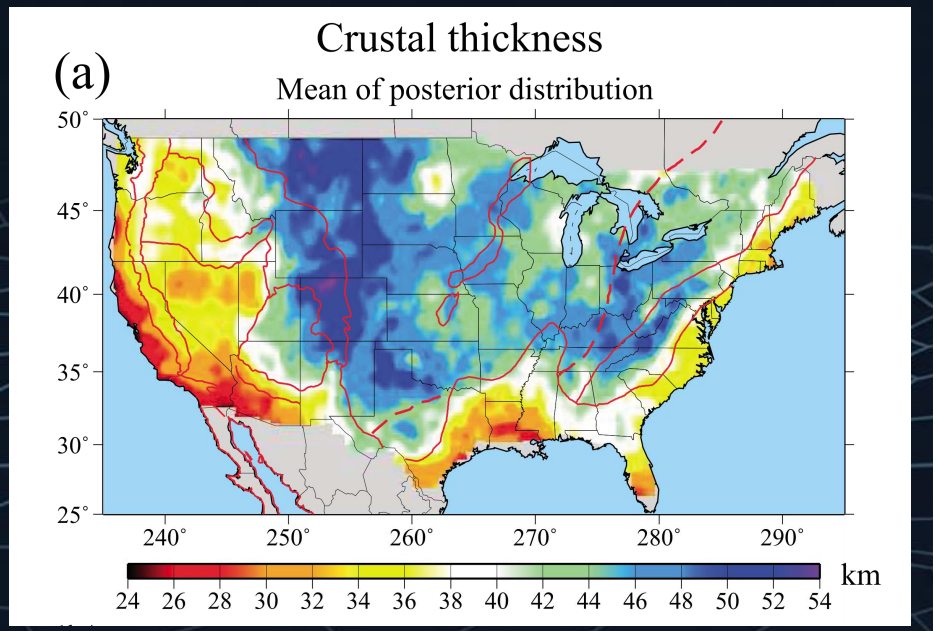
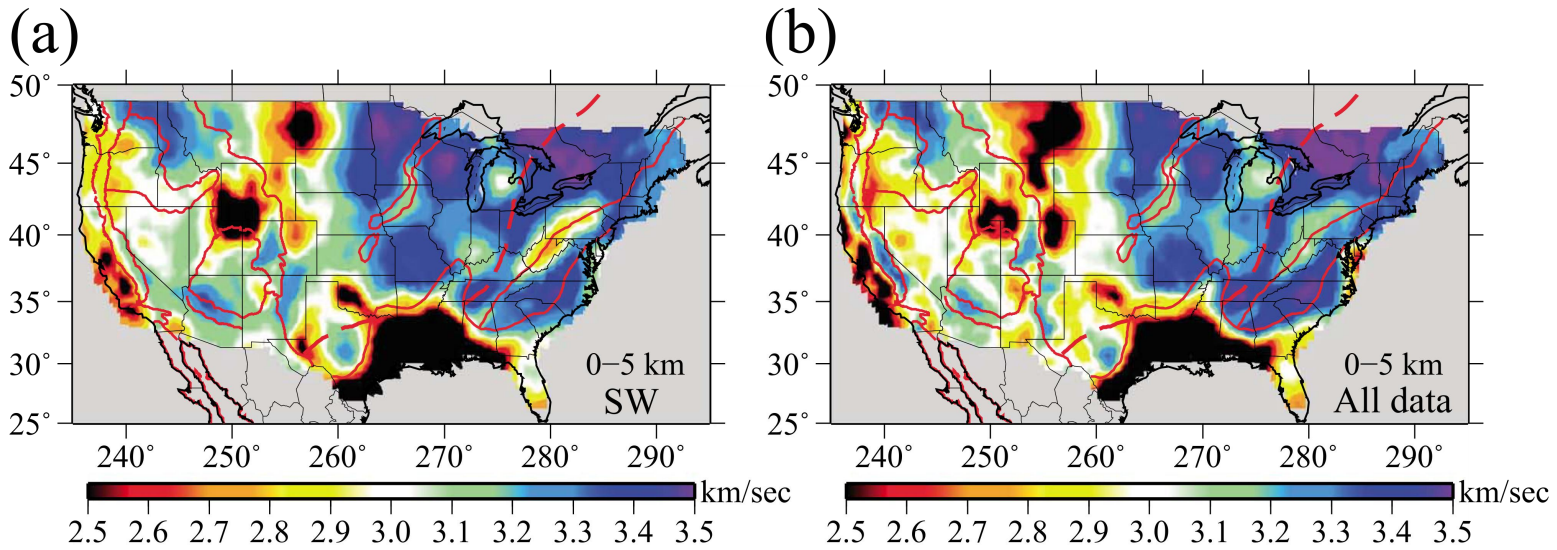
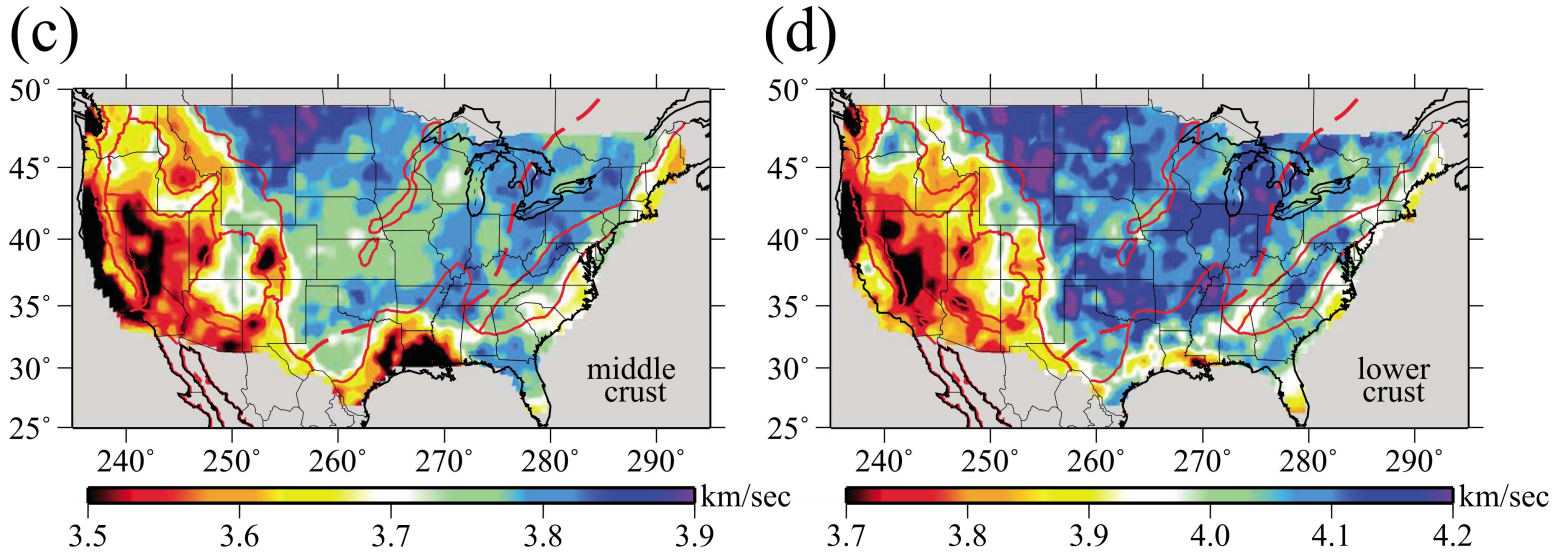
Crustal model for US









(Shen et al, JGR, 2016)

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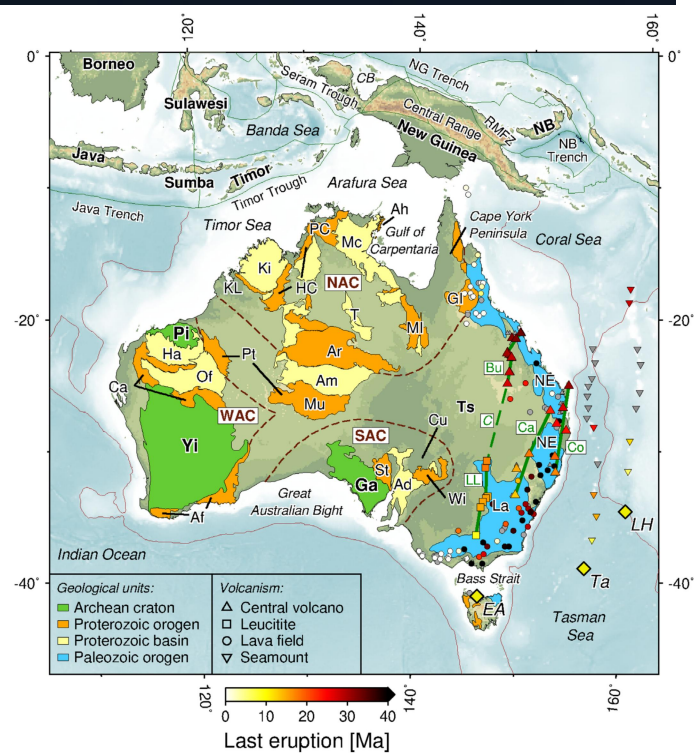
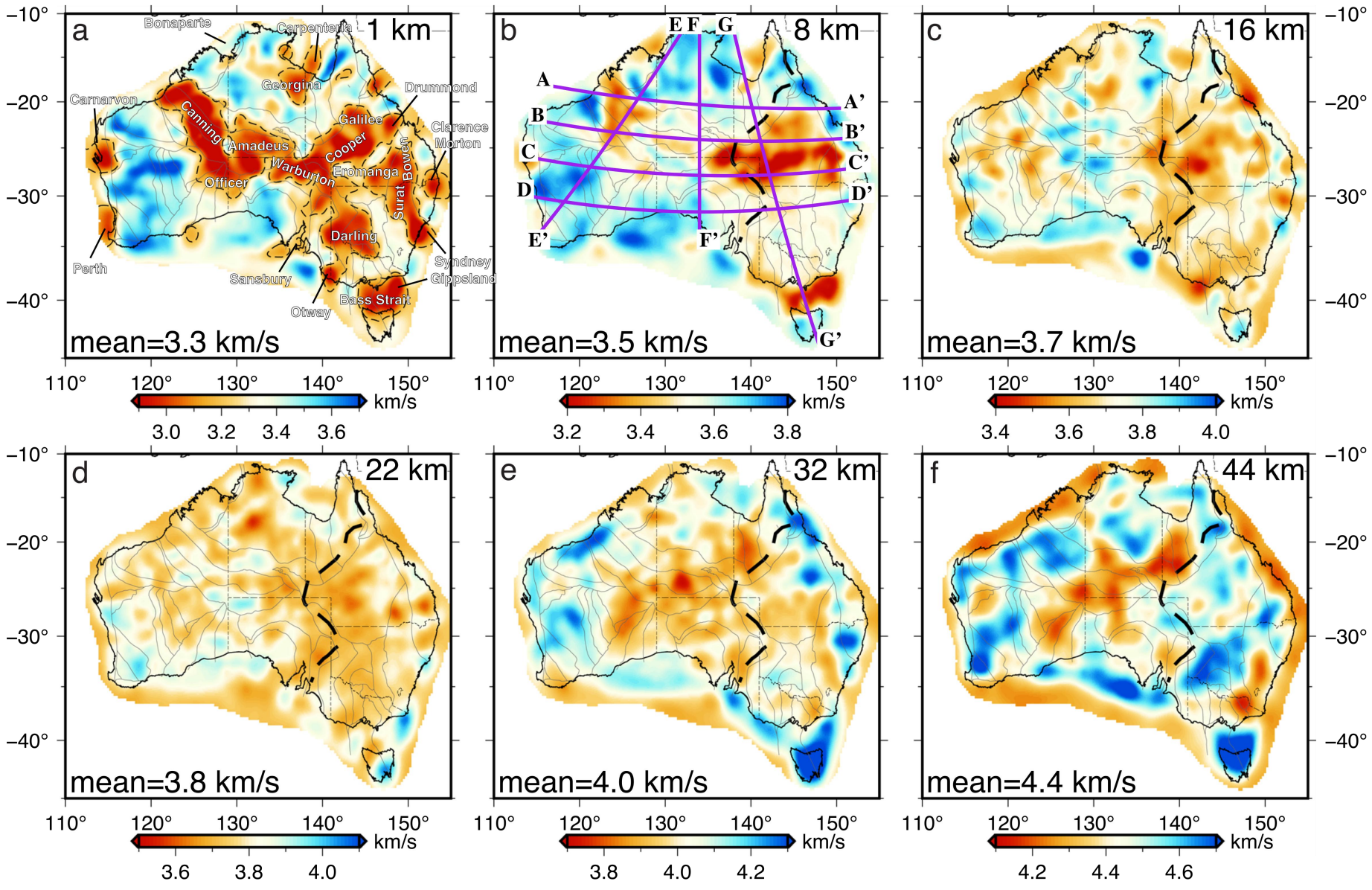
Crustal model for Australia



(Chen et al, NC, 2023)



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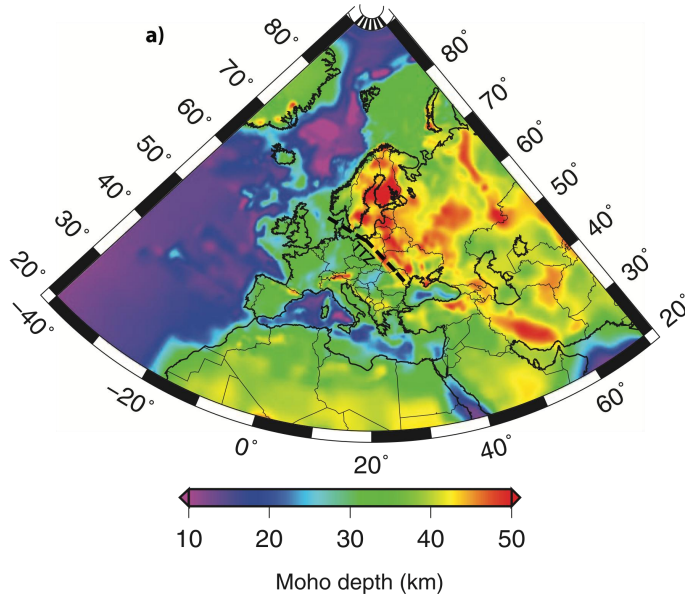
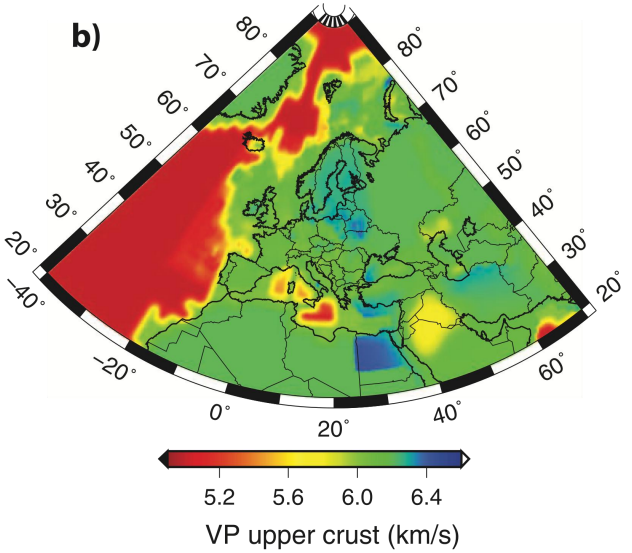
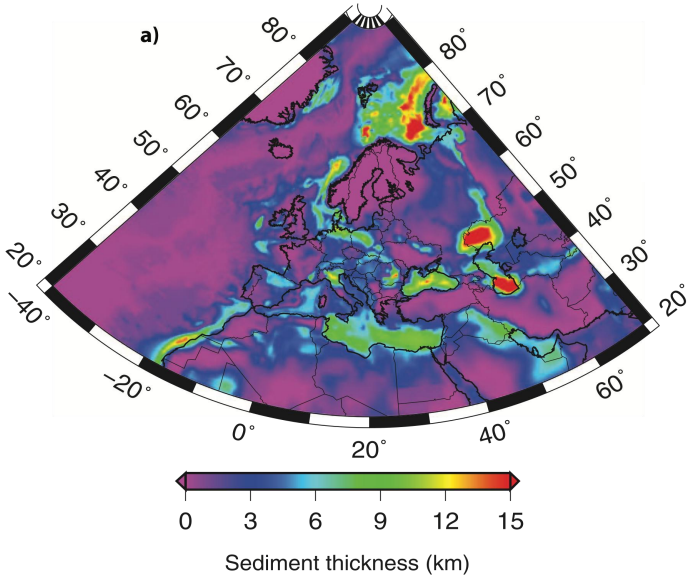
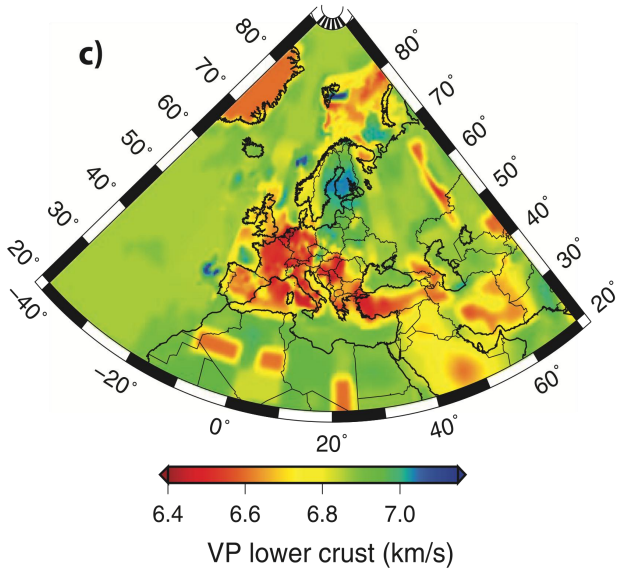
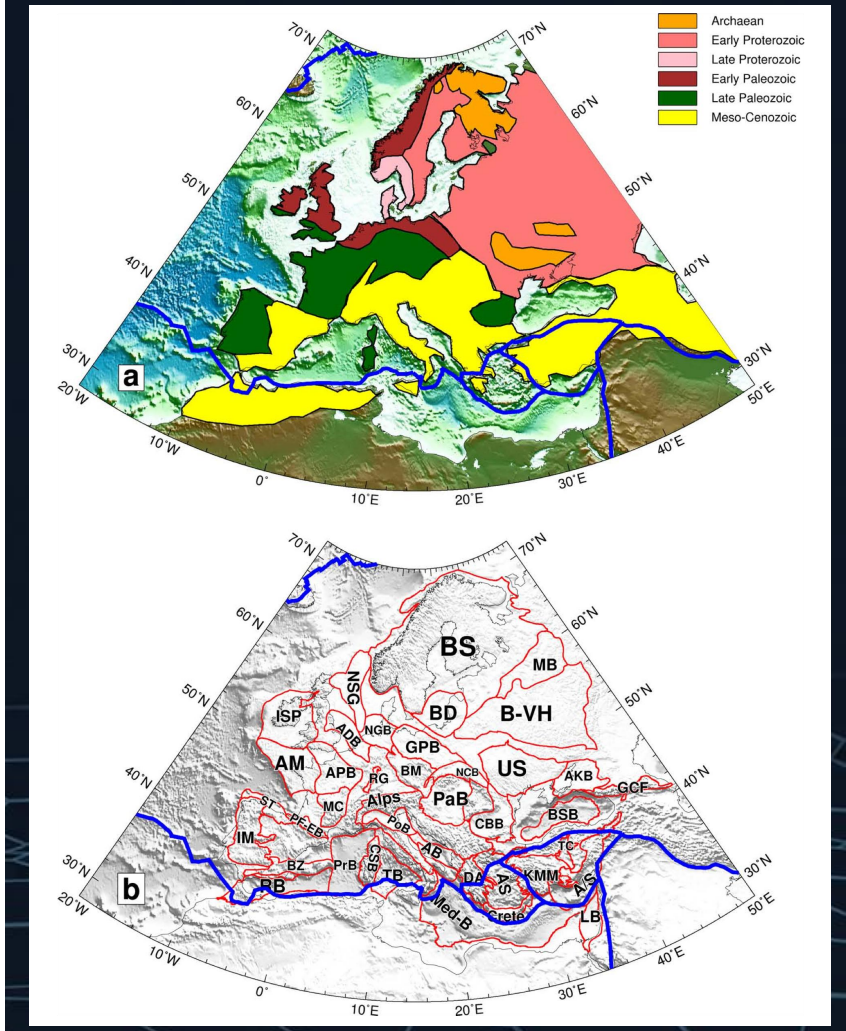
Crustal model for Europe











(Molinari and Morelli, GJI, 2011

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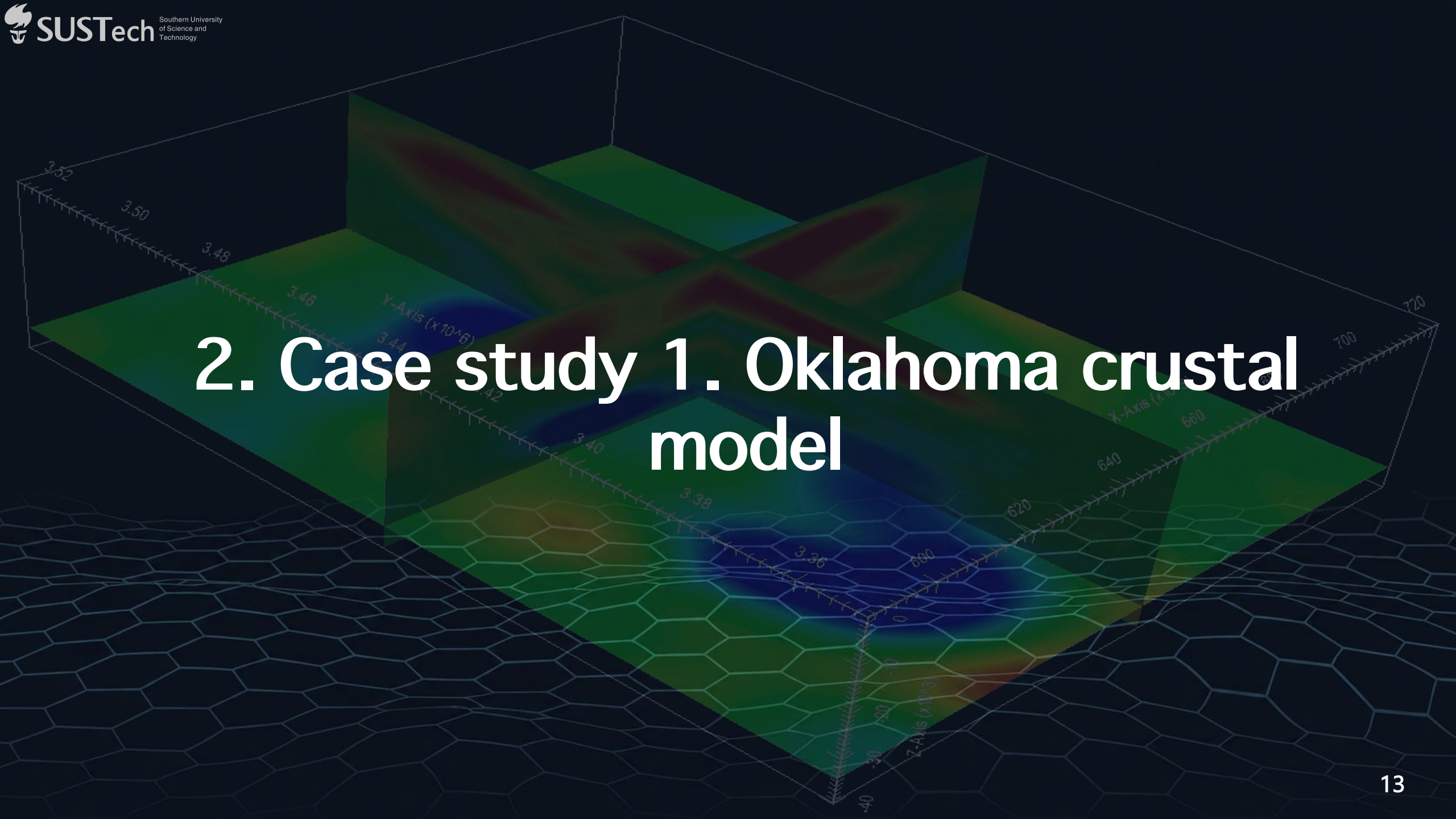

2. Case study 1. Oklahoma crustal model

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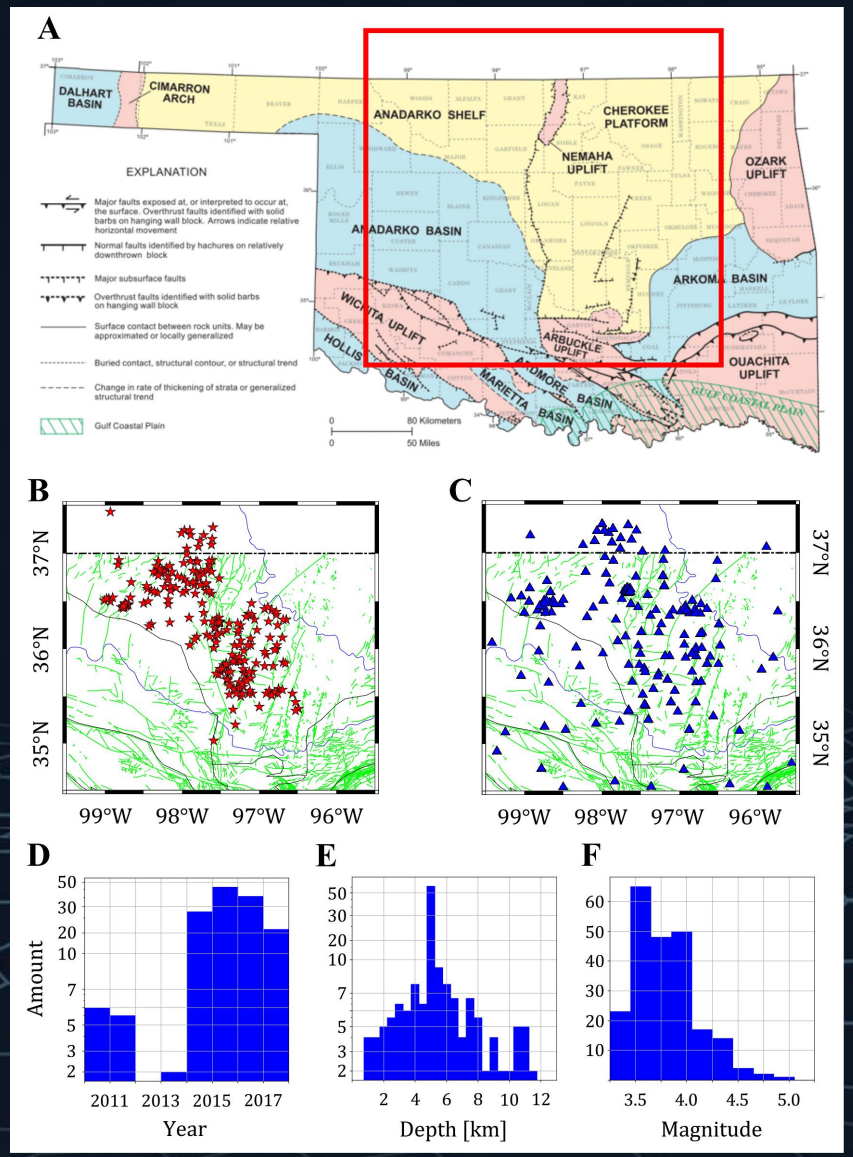
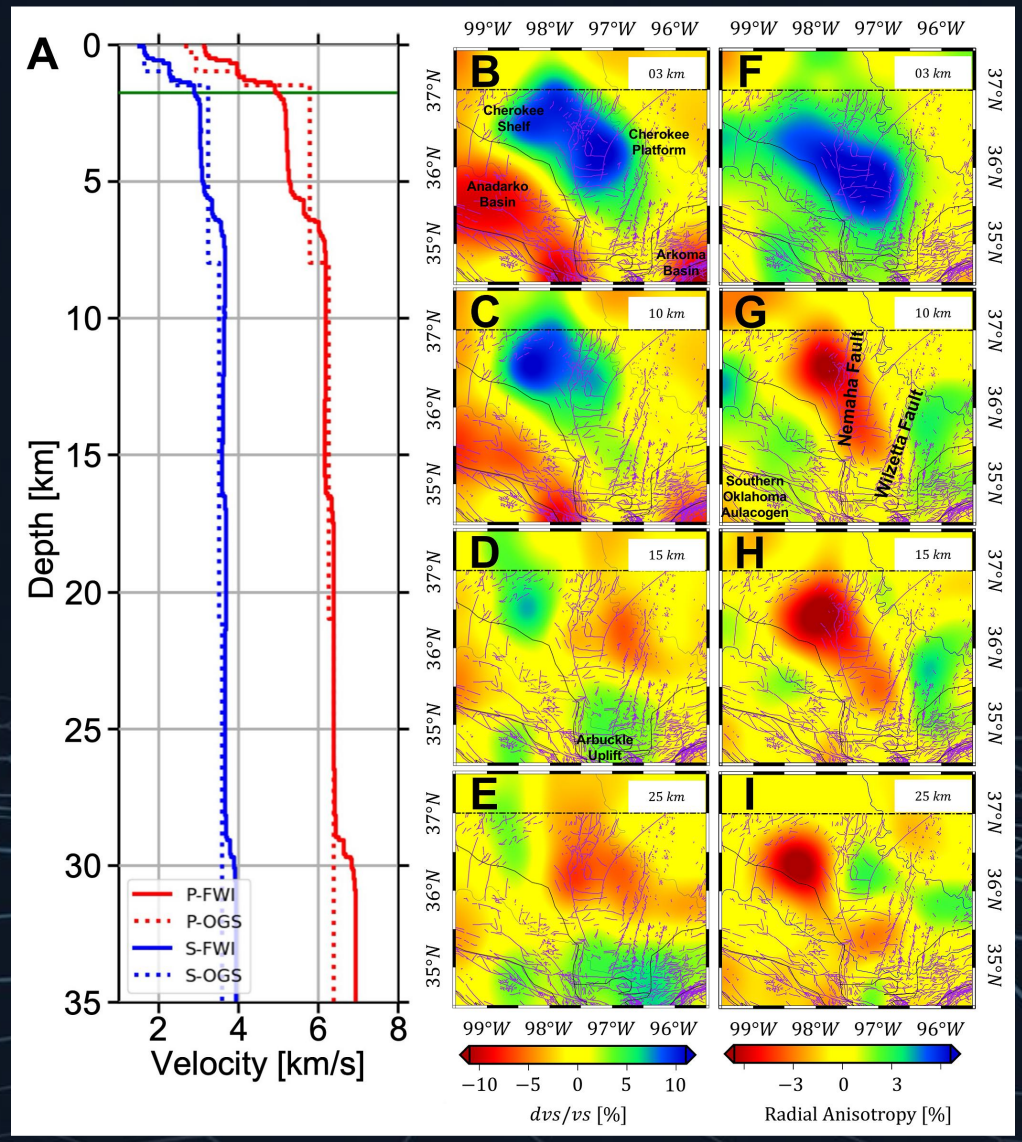
Oklahoma Data and Inversion Results





157 earthquakes and 176 seismic stations

(Zhang et al., JGR, 2023)

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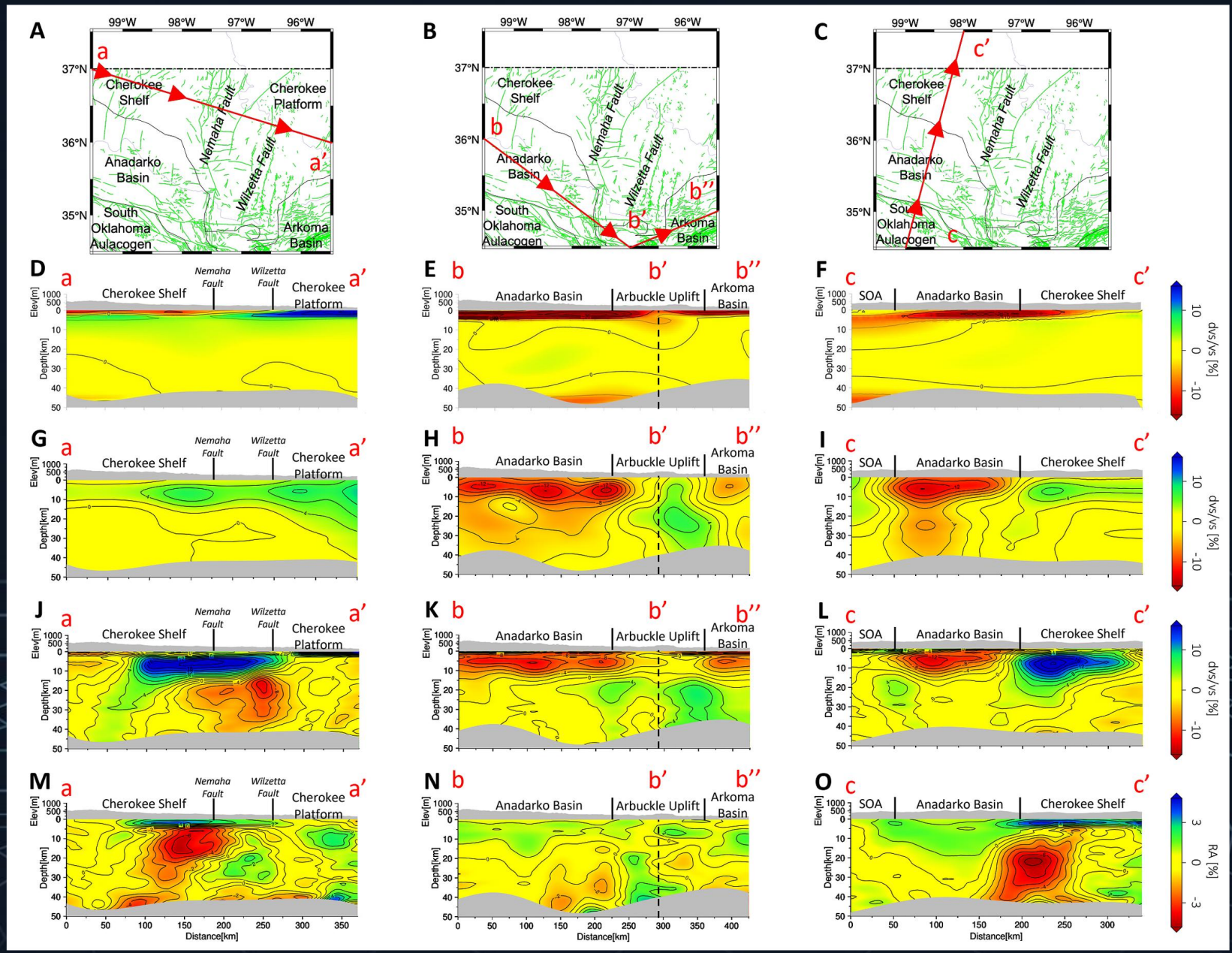
Comparison of Velocity Models

US2016
(Shen and Ritzwoller, JGR, 2016)

Starting model
(Zhu, GJI, 2018)
Ambient-noise FWI

New model
(Zhang et al., JGR, 2023)

Radial anisotropy



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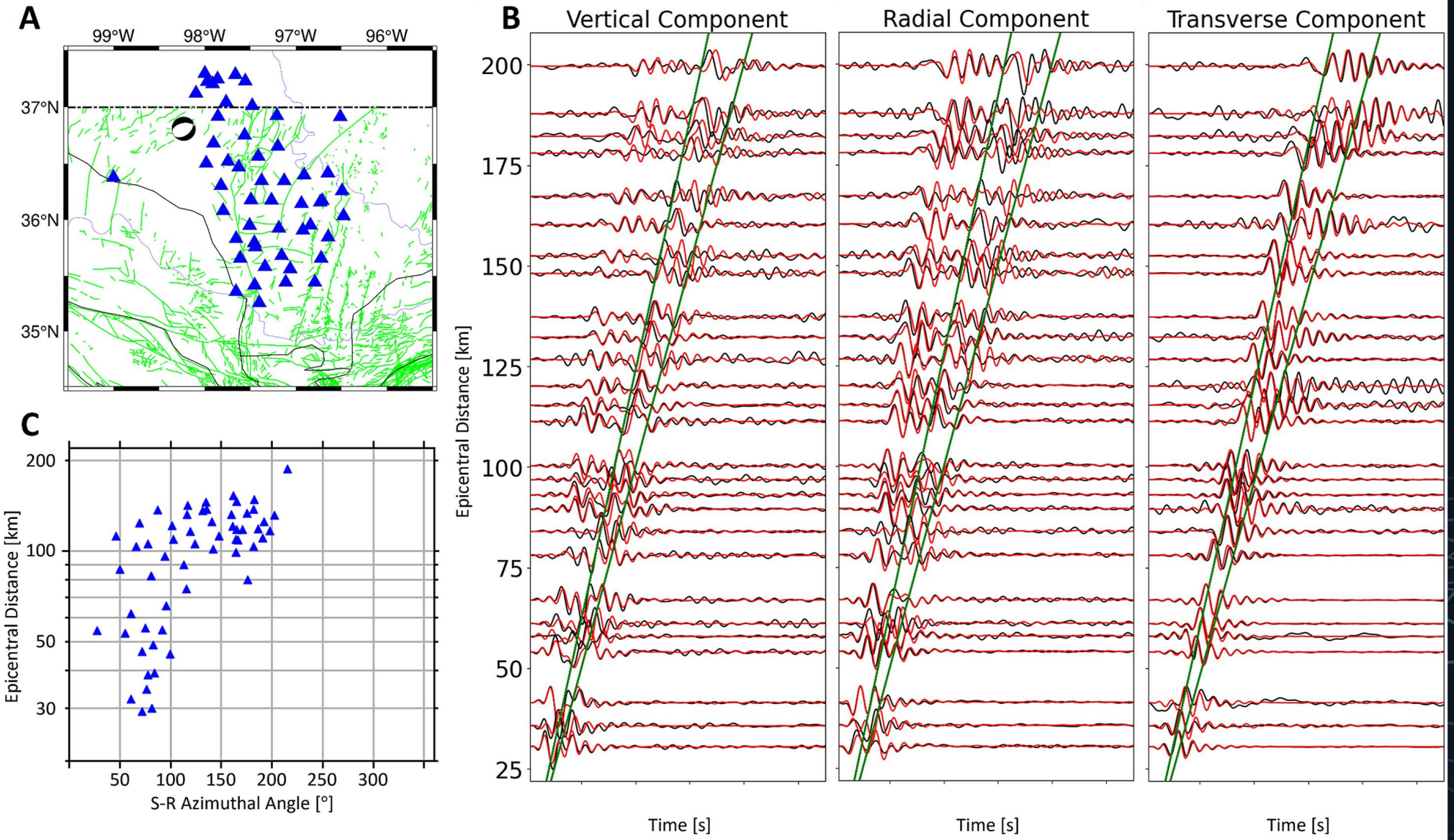
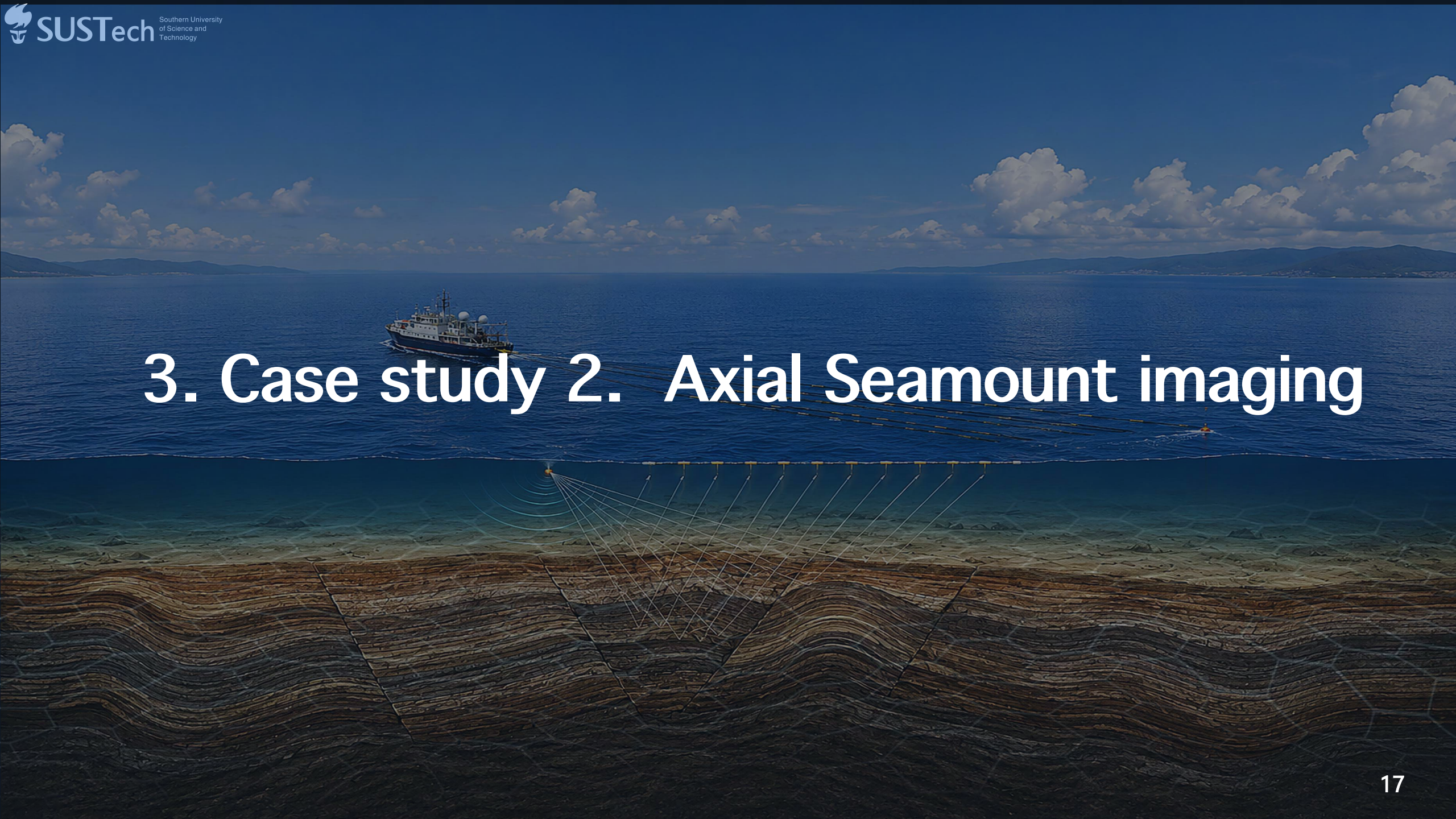
Comparison of Three-Component Seismograms



5–30 s bandpass

Red: synthetic

Black: observed



3. Case study 2. Axial Seamount imaging

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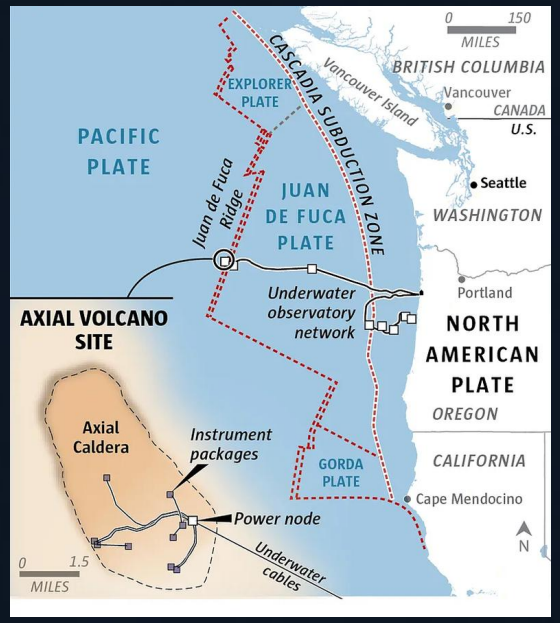
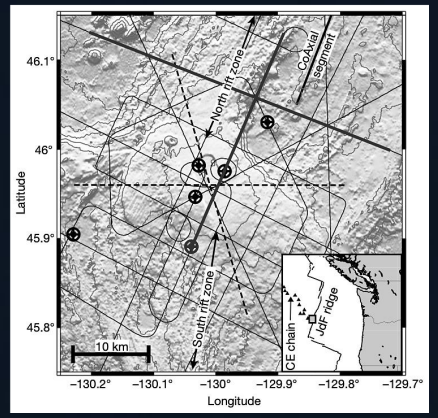
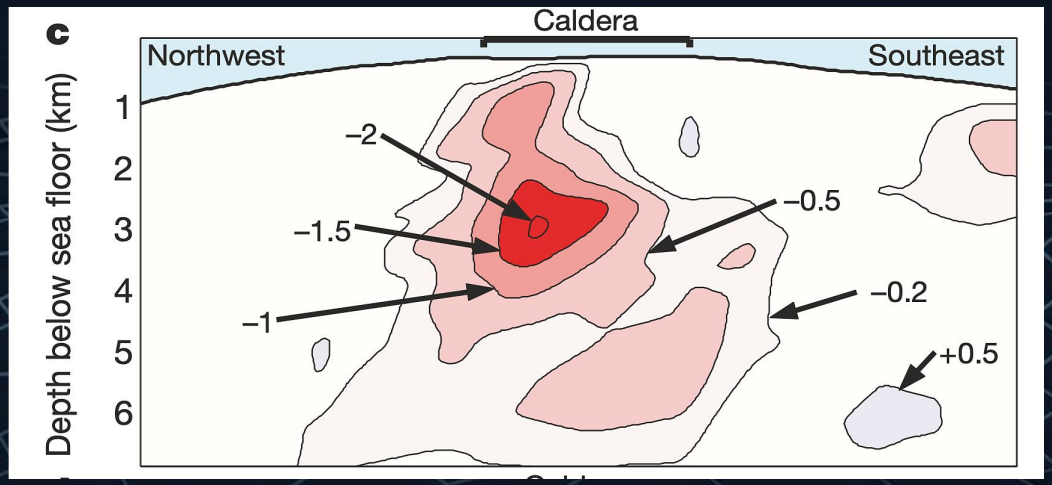
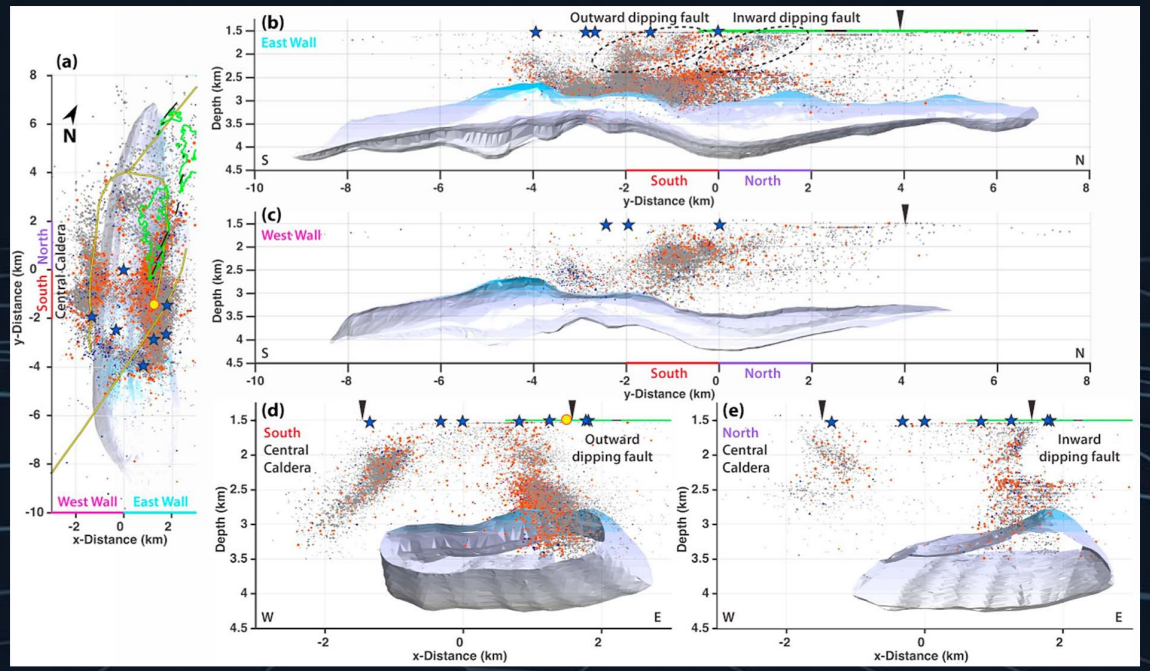
Axial Seamount





- Axial Seamount is an active submarine volcano located at the intersection between the Juan de Fuca ridge and Cobb hotspot
- One of the best monitored submarine volcanoes worldwide
- A key window into mid-ocean ridge accretion processes
- Active source traveltime tomography has revealed the approximate structure of its main magma reservoir structure





OBS Traveltime tomography (West et al, Nature, 2001)

MCS result (Arnulf et al, JGR, 2018)

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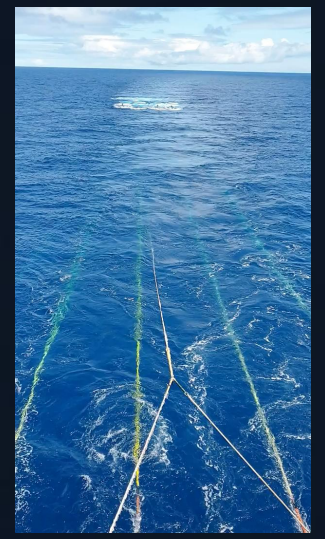
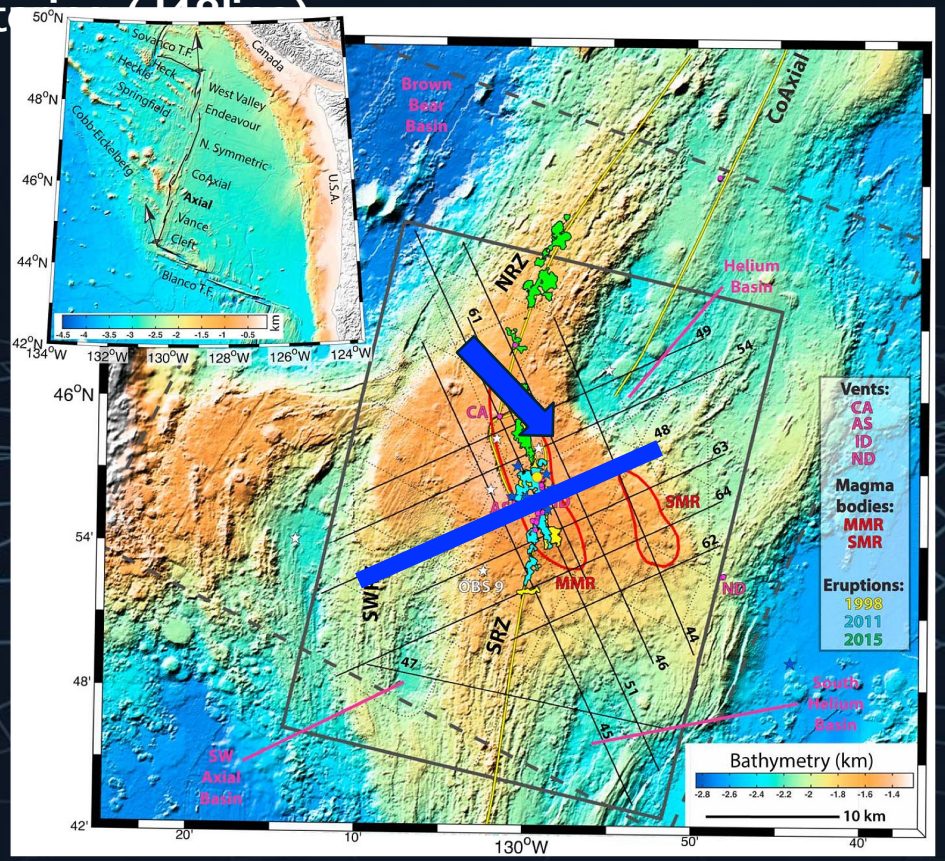
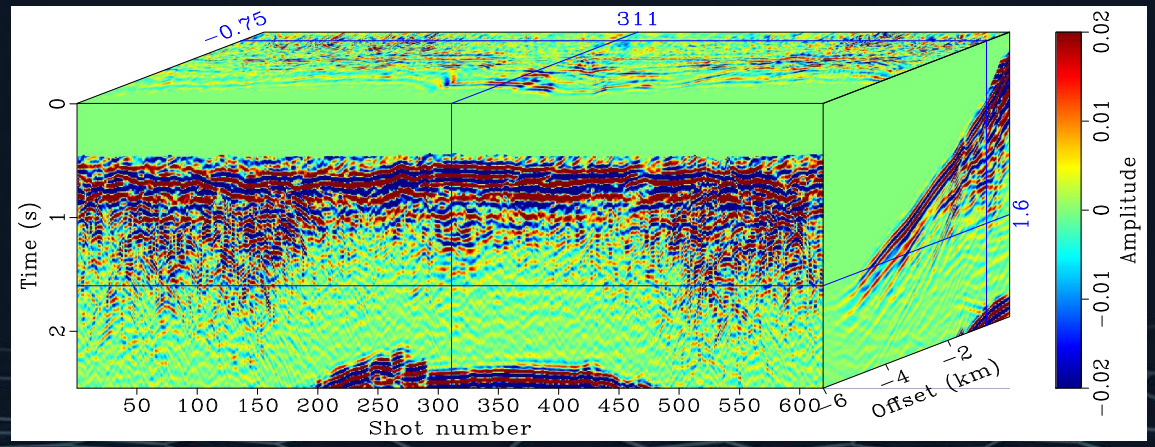
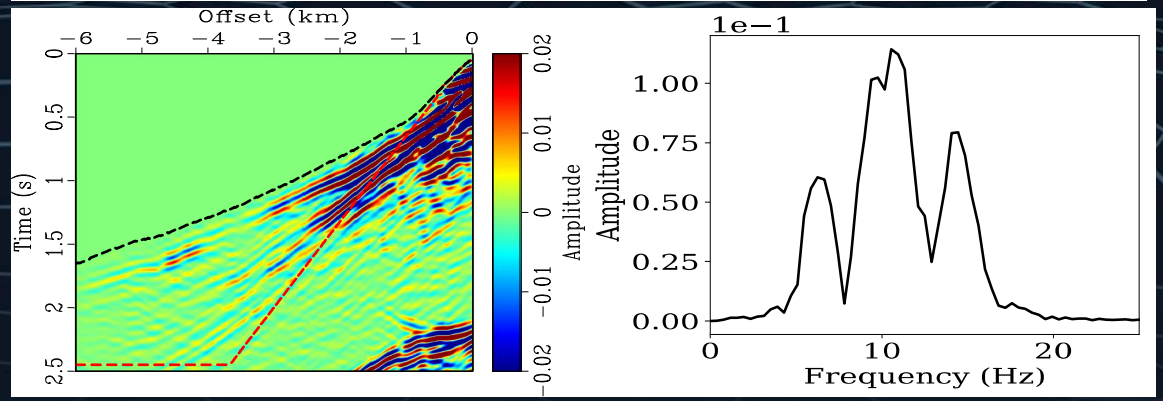
Active Source Data from Axial Seamount



- Multichannel seismic data were acquired in 2002 (EW0207 cruise)
- Air gun sources were towed at 7.5 m depth with 37.5 m shot spacing
- The receiver system used 480 hydrophone channels with 12.5 m spacing, streamer length 6 km
- Processing included denoising, amplitude correction, true-amplitude relocation, and band-pass filt[illegible]







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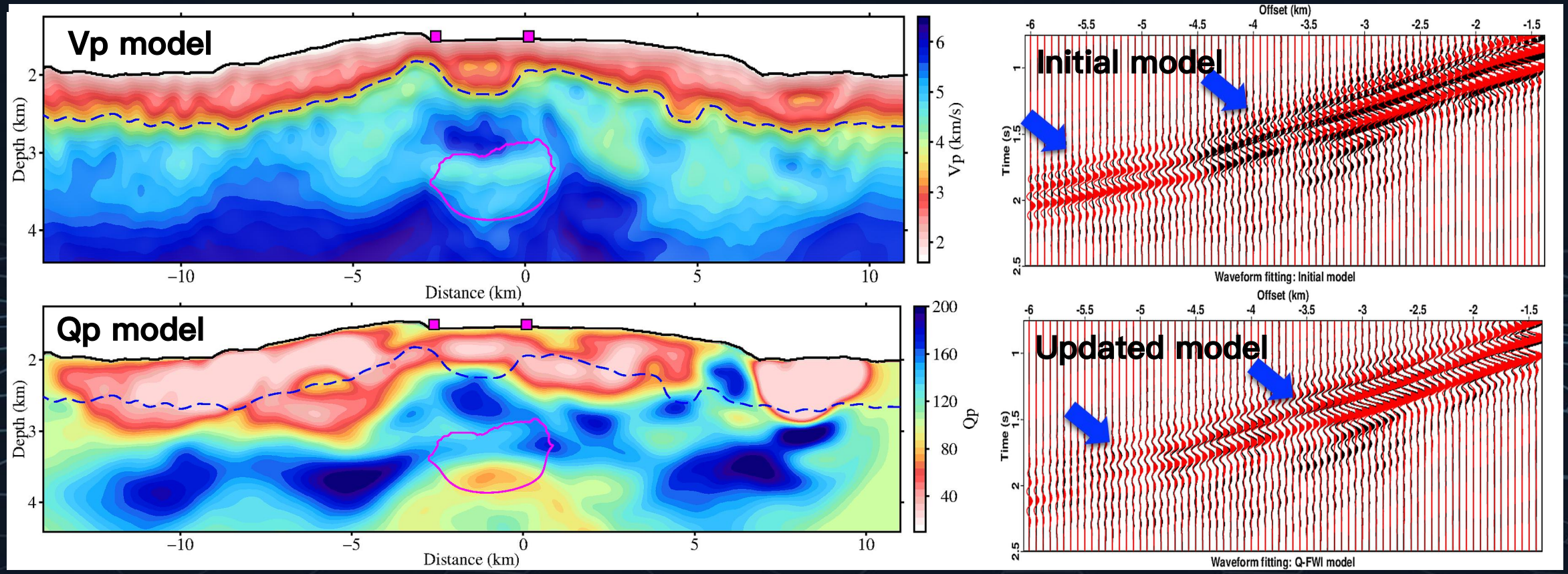
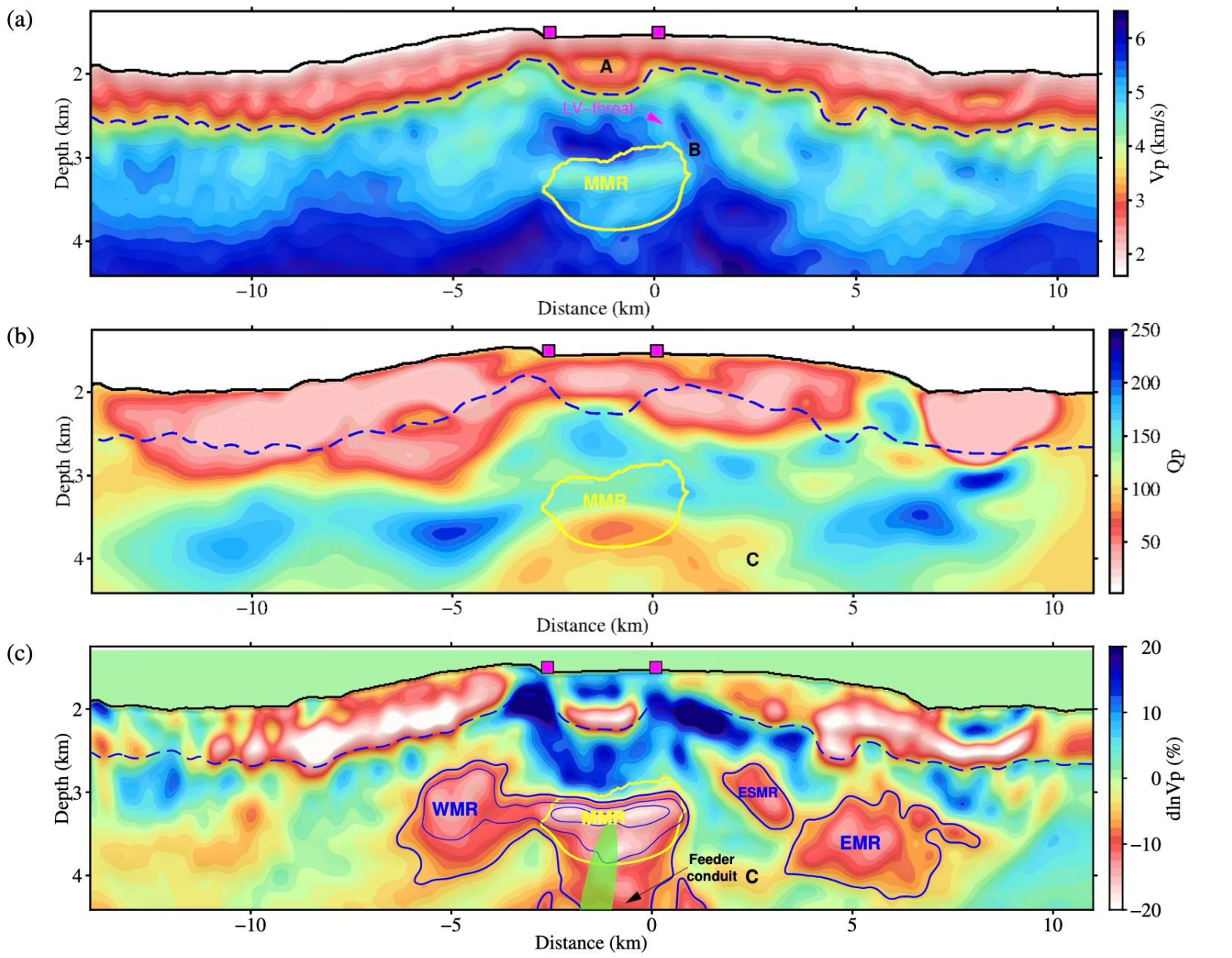
Velocity and Attenuation Inversion Results

- FWI can produce high resolution P wave velocity and quality factor models
- It achieves good data fitting, especially at far offsets
- Multiscale inversion, frequency band 3-9 Hz

Black: data; red: synthetic



2D Vp and Q models for the Axial seamount



$$T(\mathbf{x}) = T_0(\mathbf{x}) + \delta \ln V_p(\mathbf{x}) \Big/ \frac{\partial \ln V_p(\mathbf{x})}{\partial T}$$

$$\frac{\partial \ln V_p(\mathbf{x})}{\partial T} = \frac{\partial \ln V_p}{\partial T}\bigg|_{anhar} - \frac{F(\kappa)}{\pi Q_p(\mathbf{x})} \frac{H^*}{RT^2(\mathbf{x})}$$

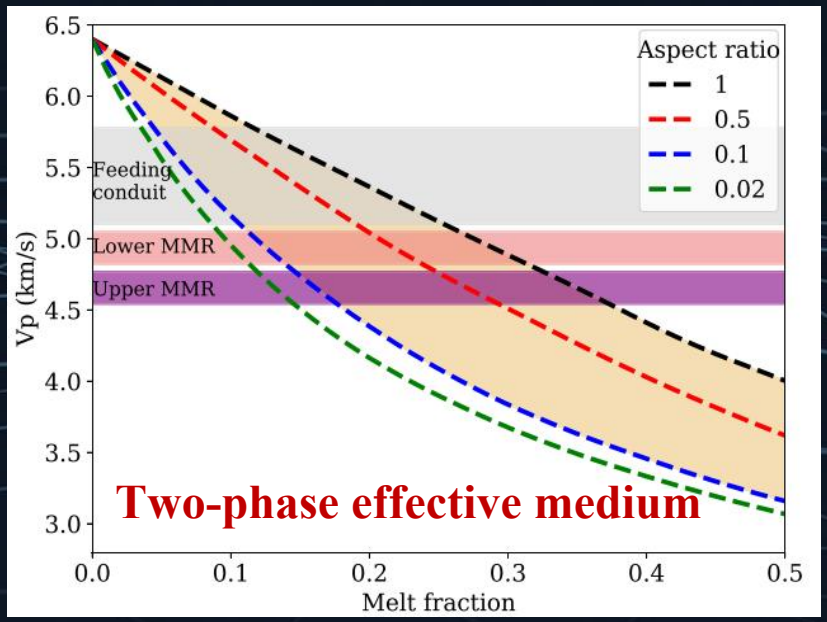
T_0: Reference off-axis temperature

Qp : FWI Qp model

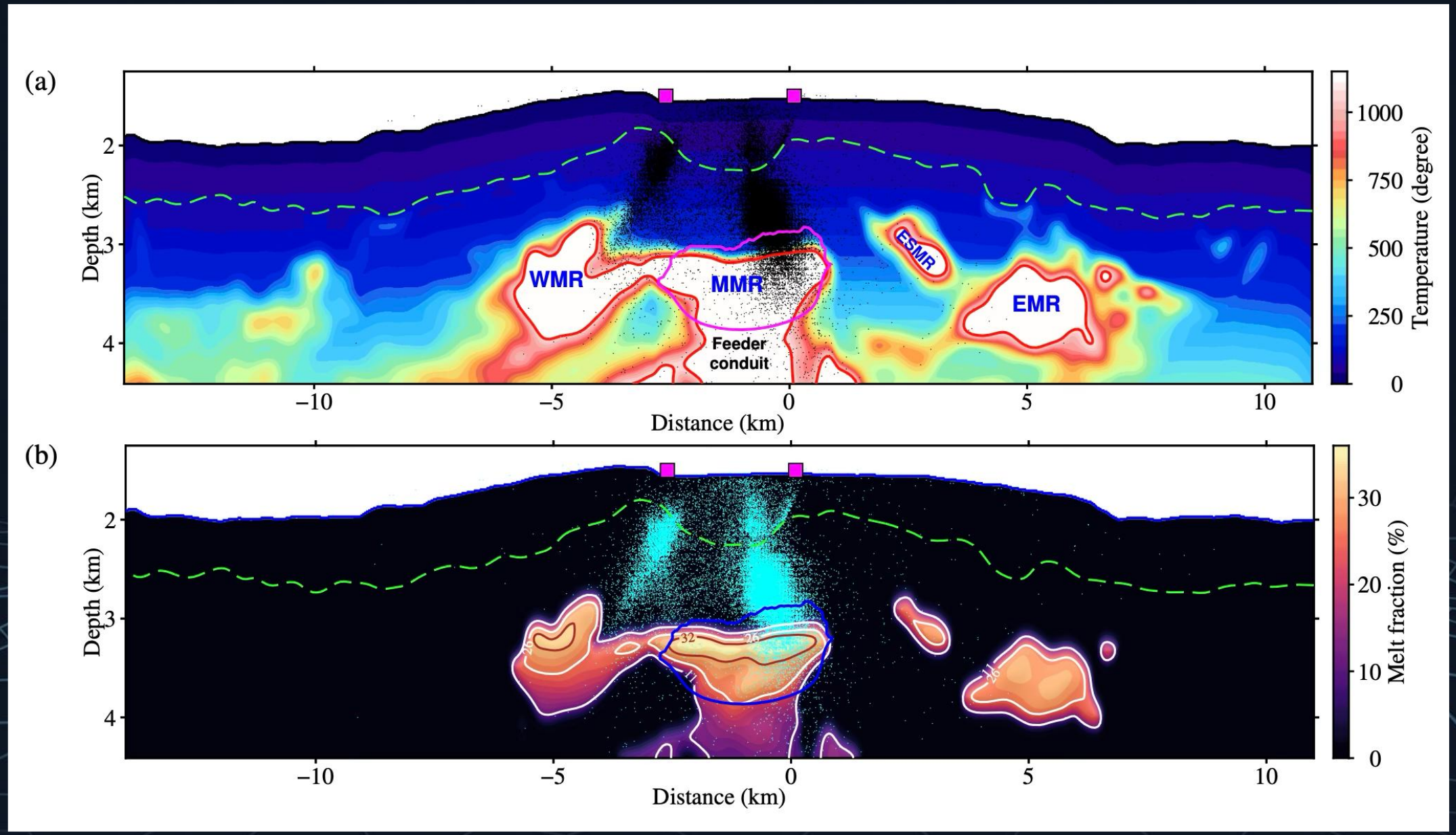
R : the universal gas constant

H*: the activation enthalpy

κ: the power law exponent



Distribution of temperature and partial melting



(Yang et al, NC, 2024)



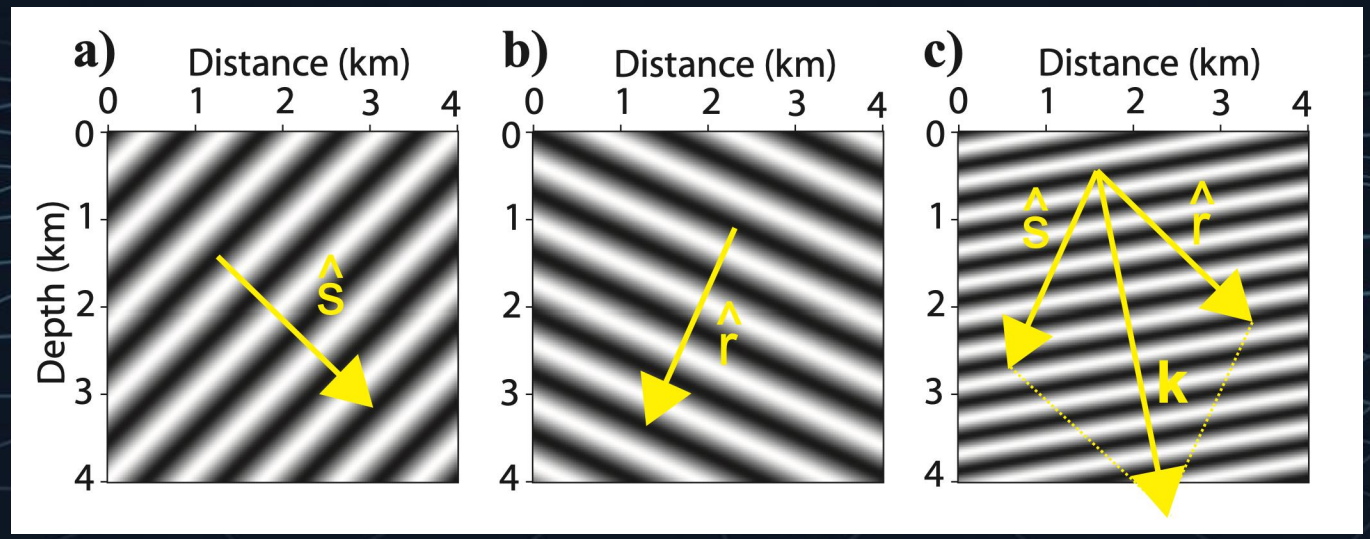
4. Resolution, uncertainty and model evaluation

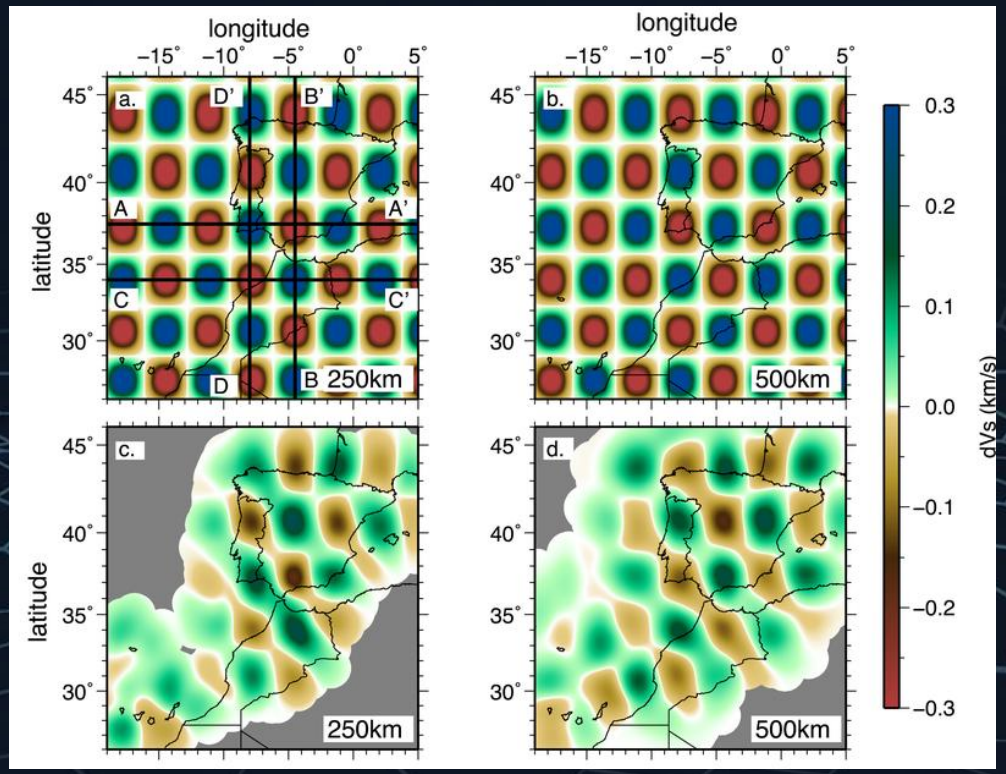
Resolution for seismic inversion

- Source-receiver coverage and sampling (active versus passive, 25 m versus 70 km)
- Data type and frequency band (all about wavelength)
- Data quality
- Inversion theory (travel time, waveform, migration, tomography)
- Checkerboard tests

$$\mathbf{k} = \frac{2f}{c_0}\cos\left(\frac{\theta}{2}\right)\mathbf{n},$$

Half wavelength limit





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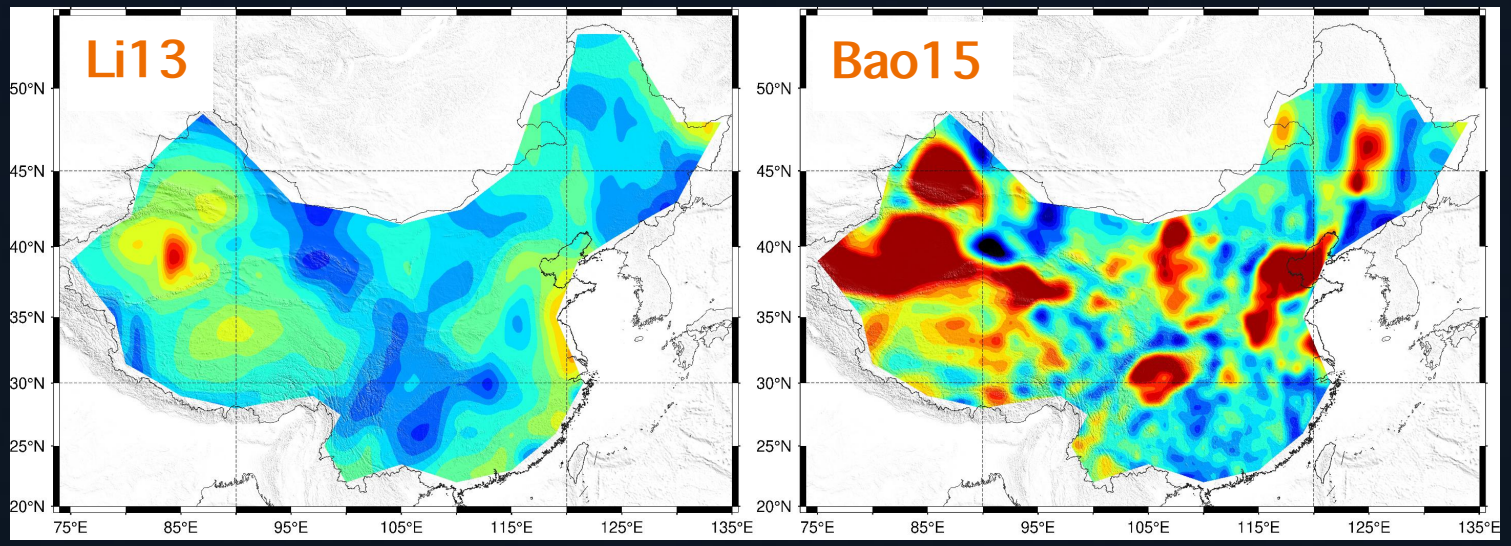
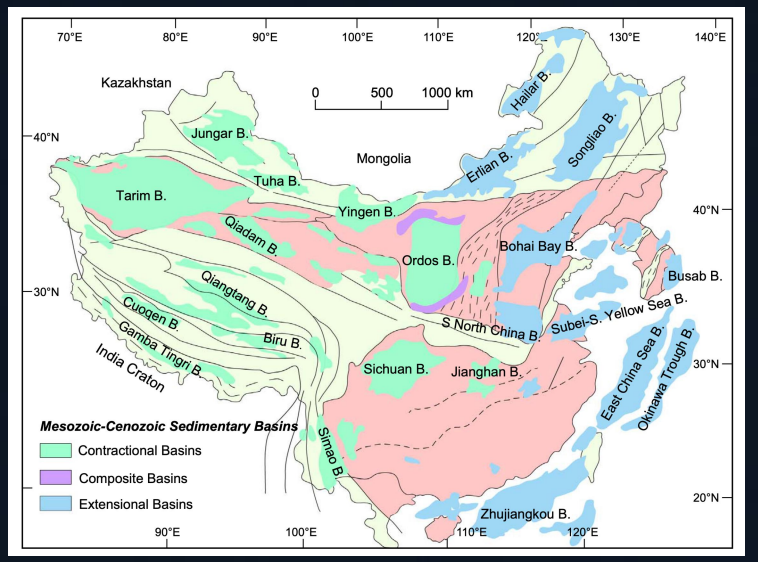
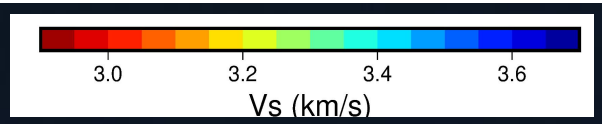
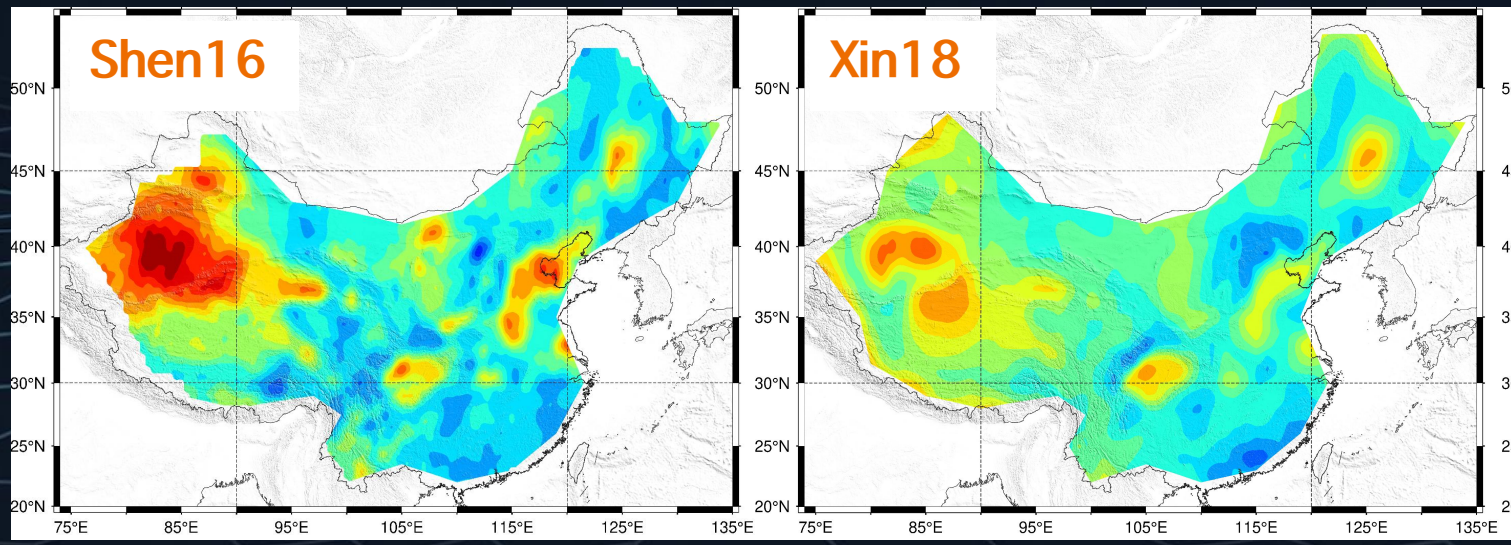
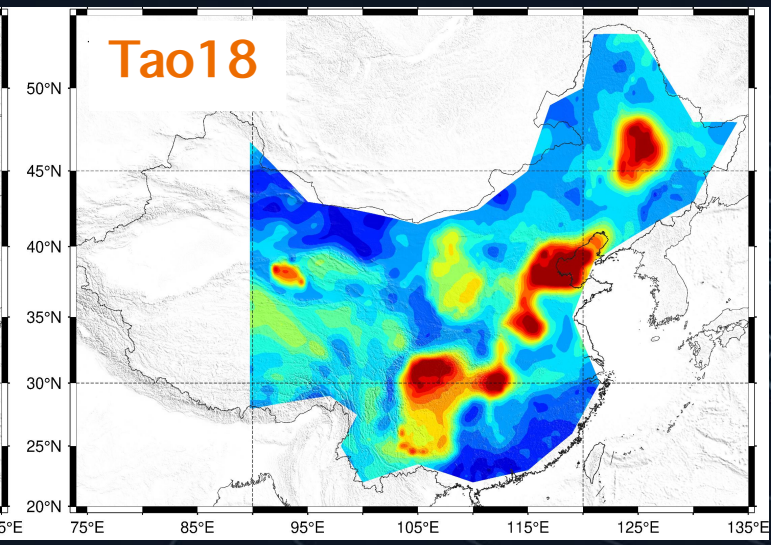
Different crustal models for China











Absolute velocity at 5 km, same color palette

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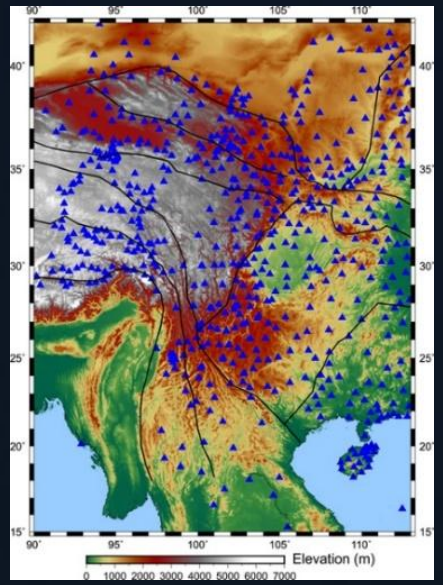
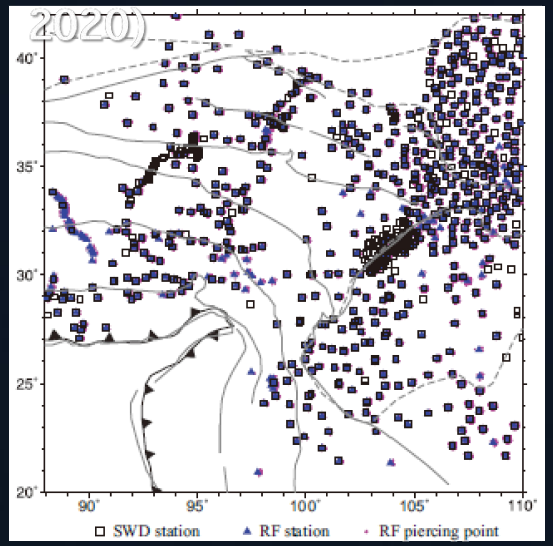
Evaluation of models for Sichuan–Yunnan province

Bao20 (Bao XW et al., 2020)



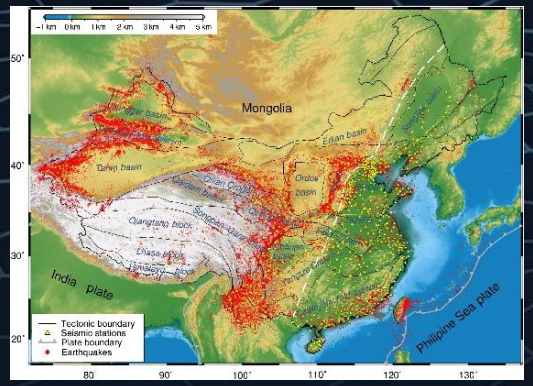
1–85 km Rayleigh-wave phase-velocity maps derived from the inversion of ambient noise cross-correlation functions

Feng20 (Feng M et al., 2020)



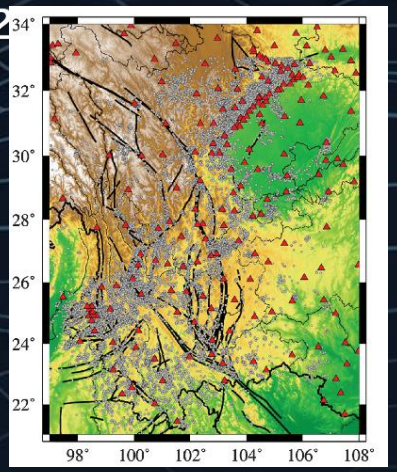
0–350 km depth Joint inversion of P-wave receiver functions and Rayleigh-wave dispersion maps with a priori constraints on Moho depth

Han21 (USTClitho2.0, Han SC et al., 2021)

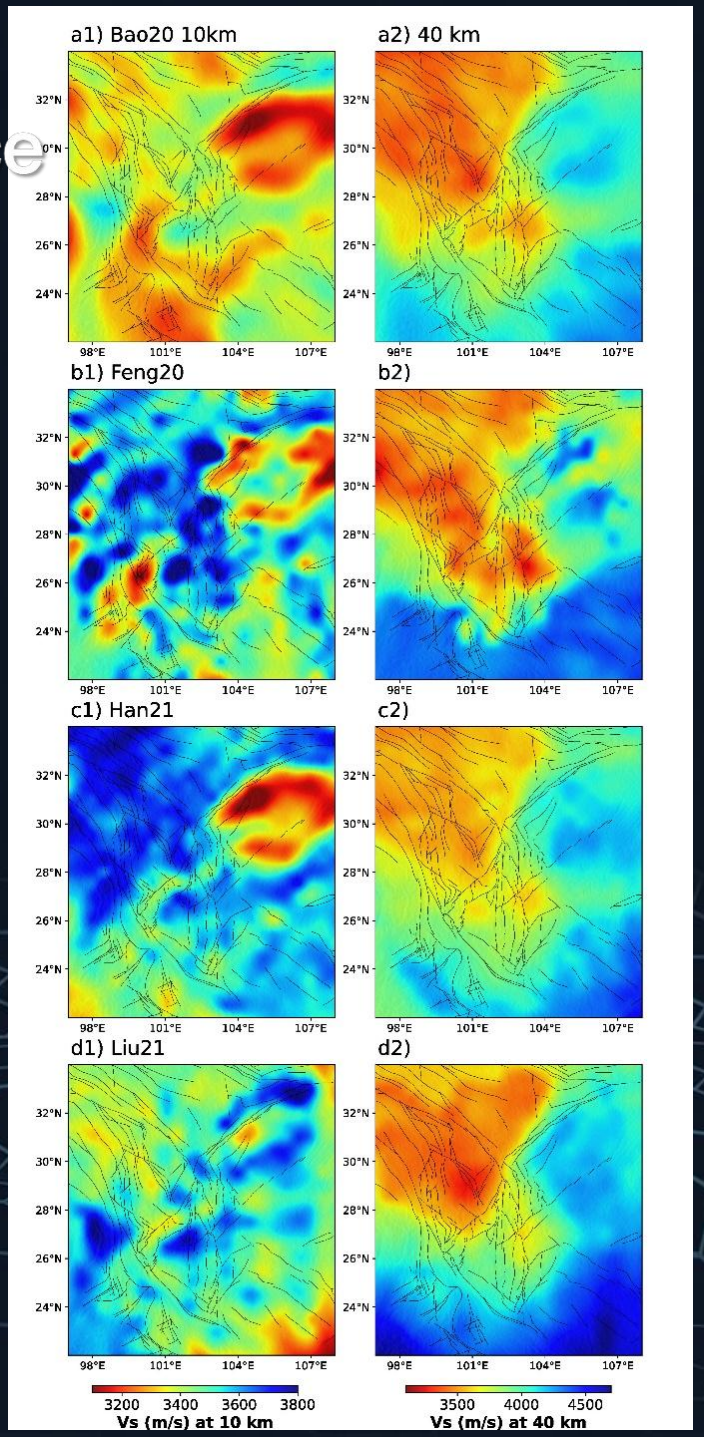


0–180 km depth Joint inversion of body-wave arrival times and Rayleigh-wave dispersion curves

Liu21 (CVM1.0, Liu Y et al., 202



0–70 km depth Body-wave arrival times and Rayleigh-wave dispersion



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Reasons for model differences

- Data type and coverage (body wave travel times, surface wave dispersion, waveforms, uneven distributions of sources and receivers)
- Data selection and weighting (frequency ranges, quality filters, weights)
- Wave propagation theory (ray theory, finite-frequency kernels, full waveform modeling and inversion)
- Model parameterization (grid spacing, depth layers, basis functions, anisotropy, attenuation)
- Regularization (smoothing, non-uniqueness, boundaries)
- Reference model (crustal correction, absolute velocity or relative perturbation, discontinuities in the 1D reference model)
- No universal, calibrated inversion machine (no mass spec)

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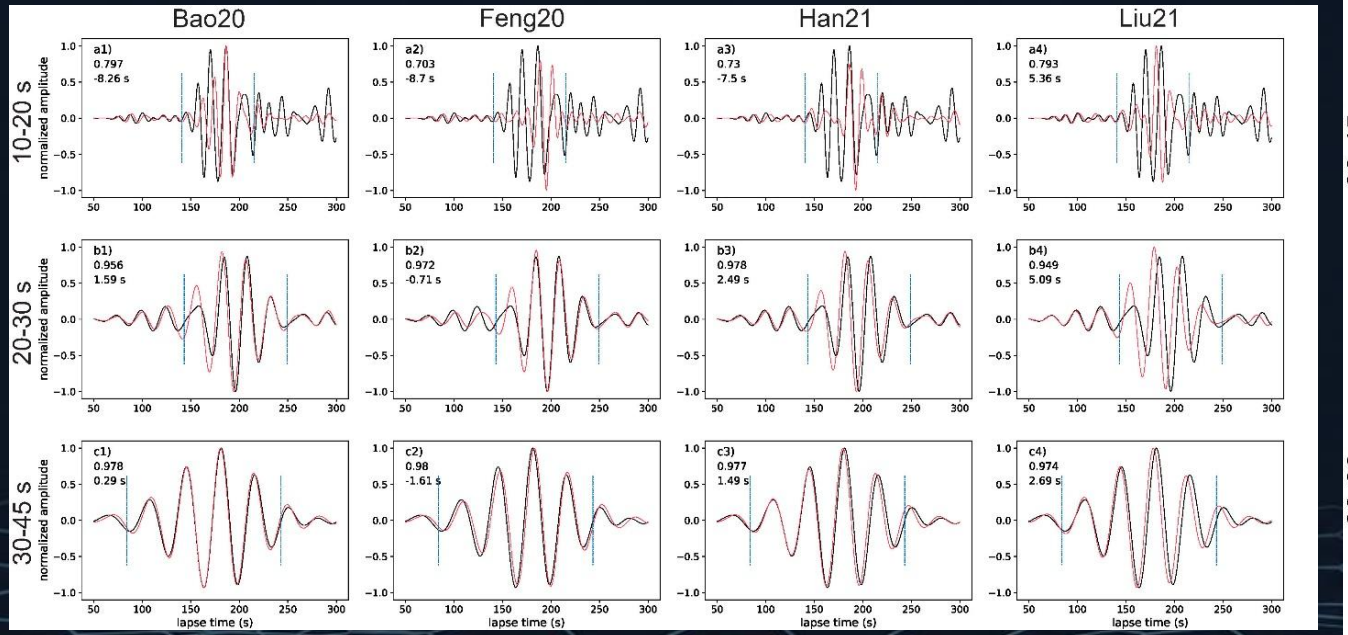
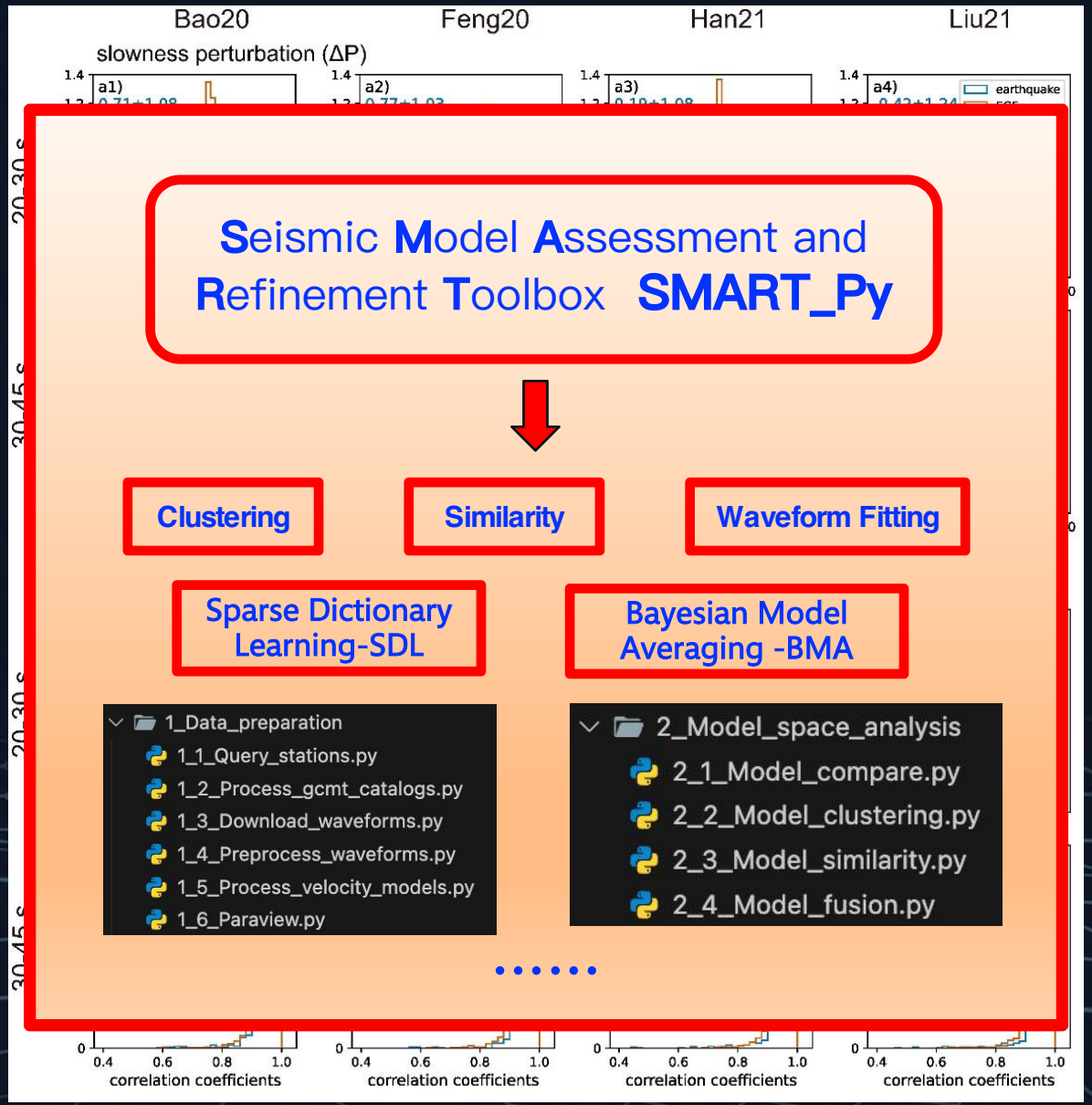
One potential solution: Model evaluation

Data (black) versus Predication (red)





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Moving beyond: Bayesian inversion?

A posteriori pdf | *A priori* pdf | Likelihood function

$$\rho(\mathbf{m}/\mathbf{d}) \propto \rho(\mathbf{m})\rho(\mathbf{d}/\mathbf{m}),$$

pdf: probability density function

- Metropolis–Hastings MCMC (MH–MCMC)
- Reversible–jump MCMC (RJ–MCMC)
- Simulated annealing
- Genetic algorithm
- Particle swarm optimization
- Neighborhood algorithm
- For 1D forward problems with fast solvers

Gaussian assumption:

$$\rho(\mathbf{m}) \propto \exp[-(\mathbf{m}-\mathbf{m_0})^{\mathrm{T}}\mathbf{C}_{\mathbf{prior}}^{-1}(\mathbf{m}-\mathbf{m_0})],$$

$$\rho(\mathbf{d}/\mathbf{m}) \propto \exp[-(\mathbf{d}-\mathbf{F}(\mathbf{m}))^{\mathrm{T}}\mathbf{C}_{\mathbf{d}}^{-1}(\mathbf{d}-\mathbf{F}(\mathbf{m}))].$$



Albert Tarantola (1949-2009)

"Hejun, don't shown me THE model,
show me a movie of models which can equally fit the d

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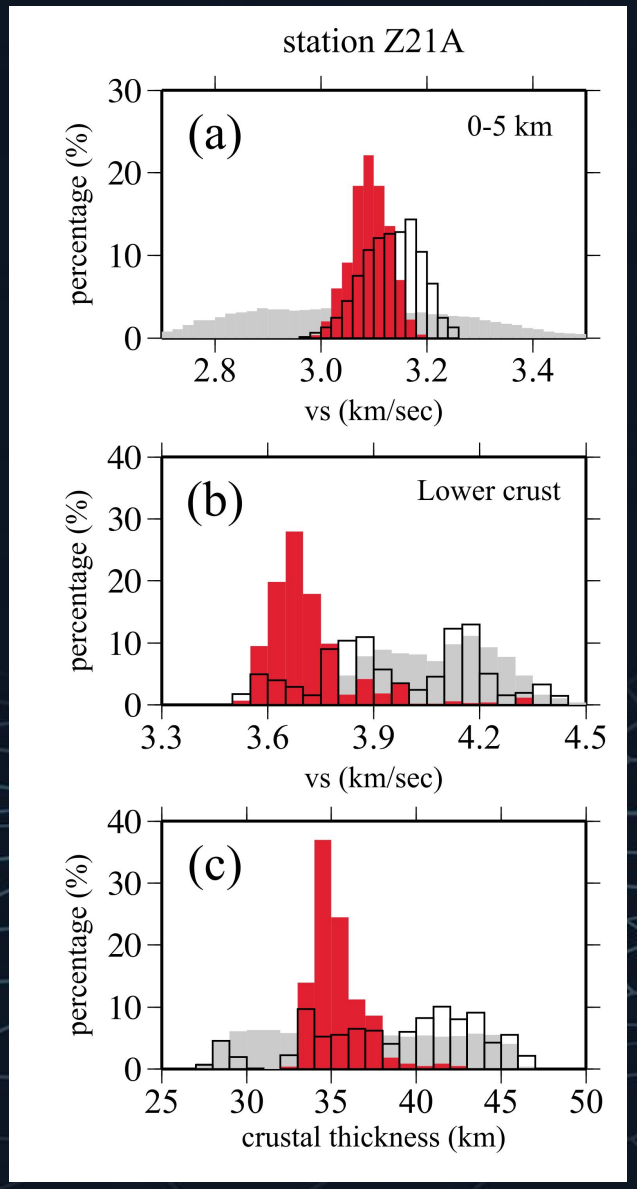
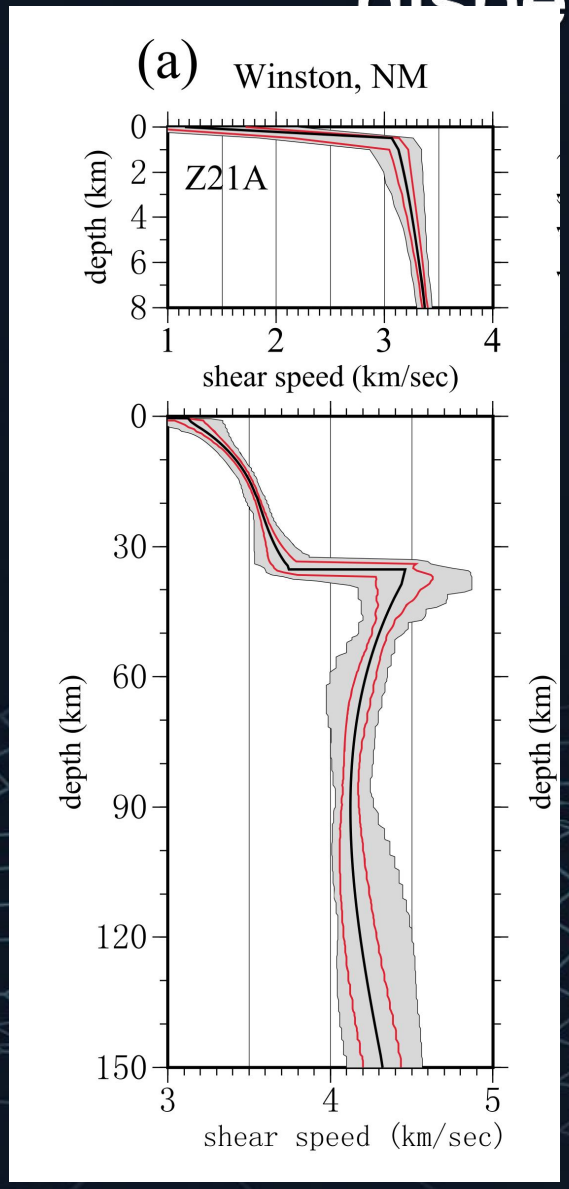
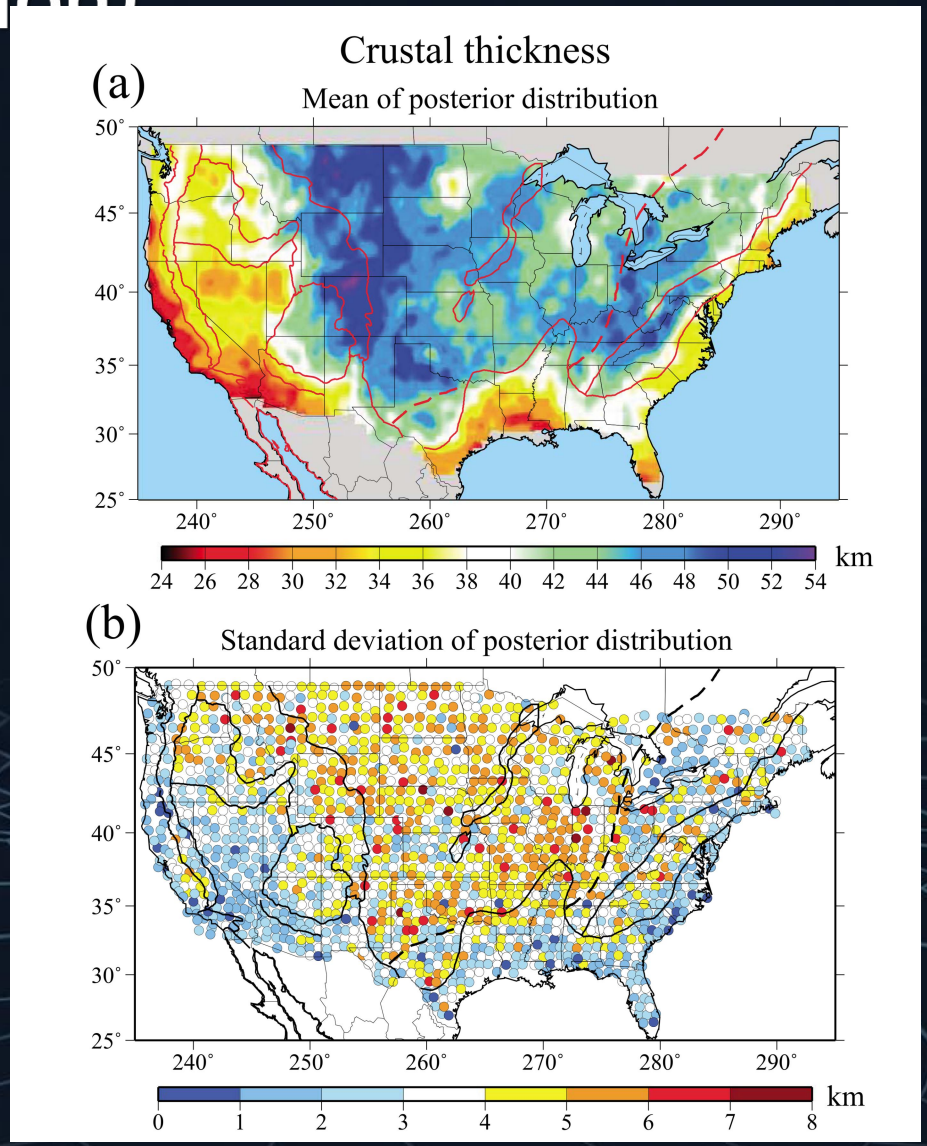
Uncertainty in joint inversion (Receiver function+surface wave dispersion)







(Shen et al, JGR, 2016)

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Conclusions

- **Global and regional crustal models have advanced substantially**, with finer grids, broader data coverage, and better constraints on crustal structure
- **Crustal thickness and seismic velocities vary widely across tectonic settings**, including cratons, orogenic belts, sedimentary basins, and ocean basins
- **Models from different groups can disagree on the depth, geometry, and strength of crustal features**, reflecting differences in data coverage, resolution, and inversion choices
- **Move beyond a single best-fit model.** Use Bayesian inversion to quantify uncertainty and explore AI-assisted approaches to make that analysis more

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Thanks!

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