Seismic Scattering in the Deep Earth

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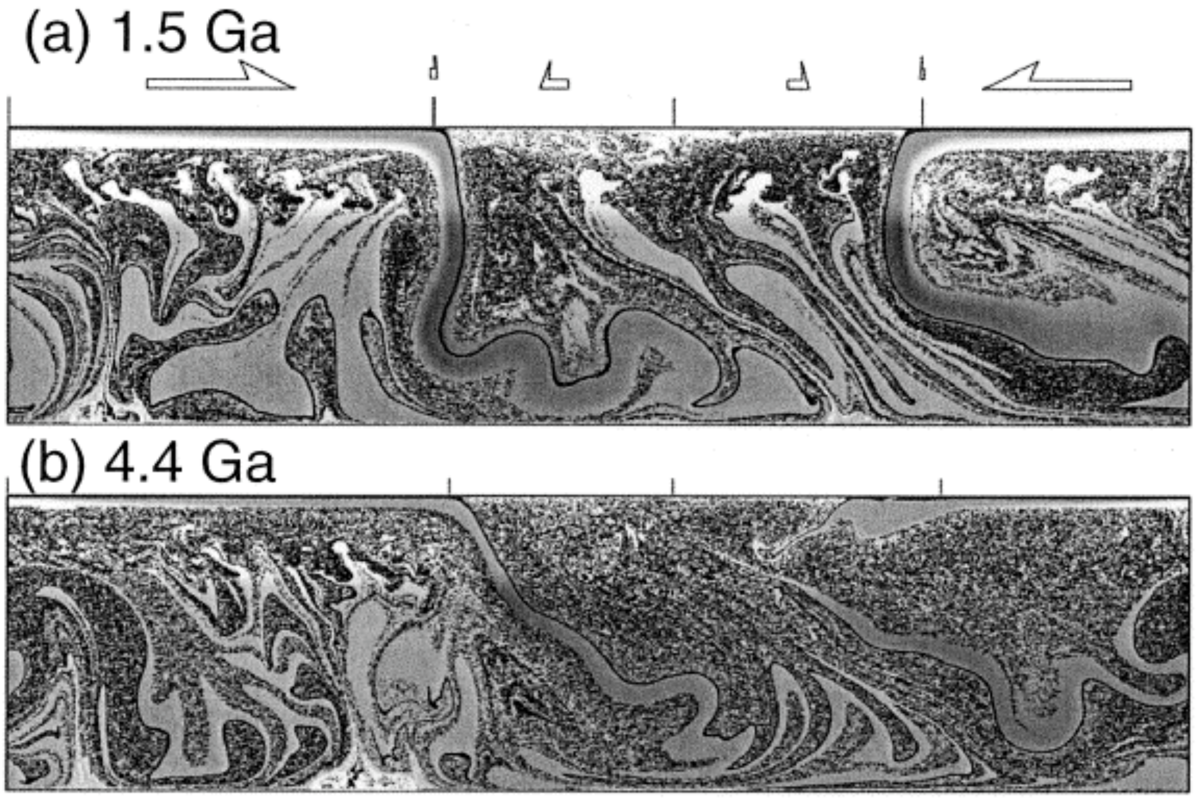
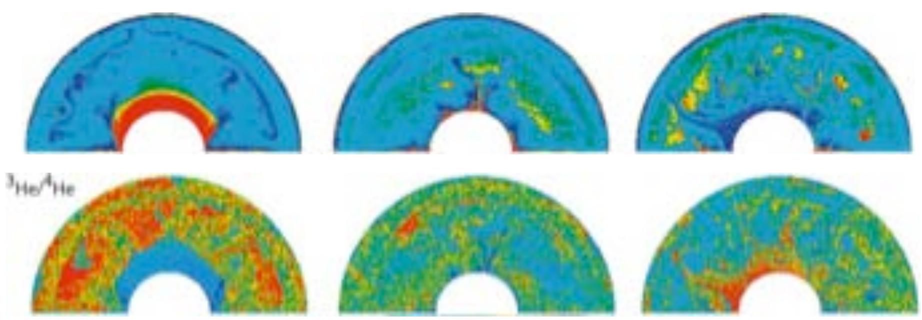
Mantle mixing calculations



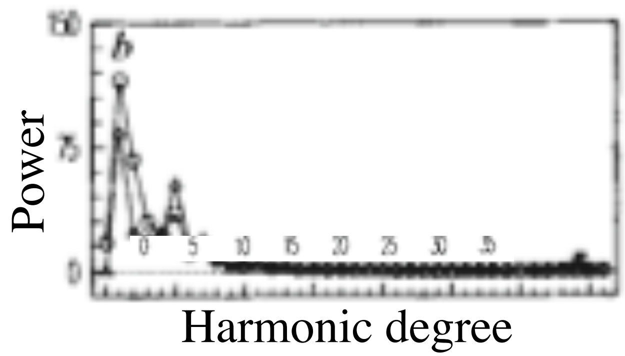
Heterogeneity is likely at all scales

Davies (2002)

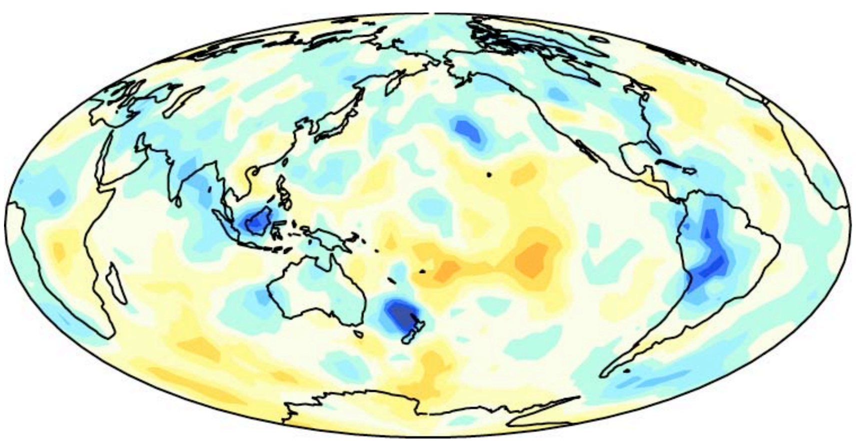


Xie & Tackley (2004)

Mantle tomography constraints



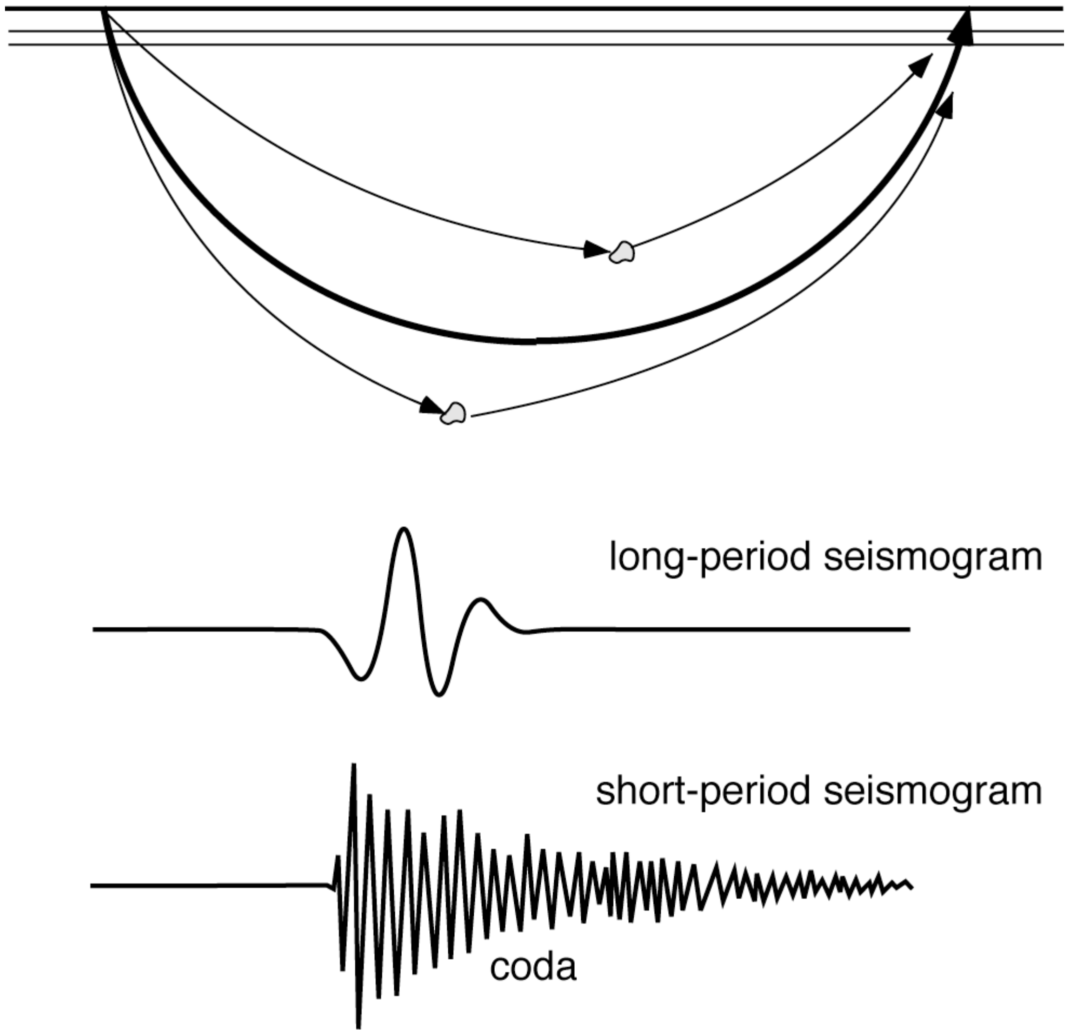
Global models dominated by long-wavelength structure (e.g., *Su & Dziewonski*, 1991)



1225 km depth slice (SIO 2004 model)

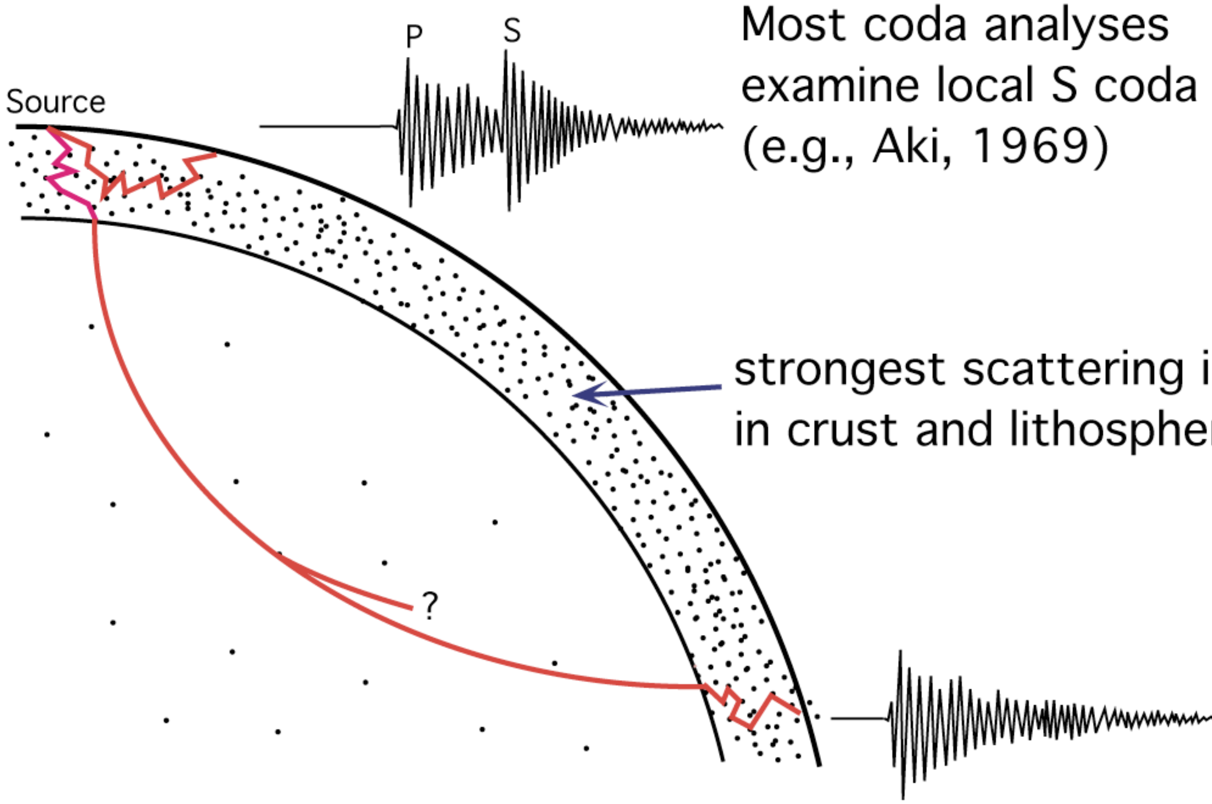
- But mid-mantle has whiter spectrum
- Resolution limited to 500 to 1000 km

Scattering to the rescue….



- High-frequency waves are scattered by small-scale structures
- Origin of coda in short-period seismograms
- Modeled with random heterogeneity

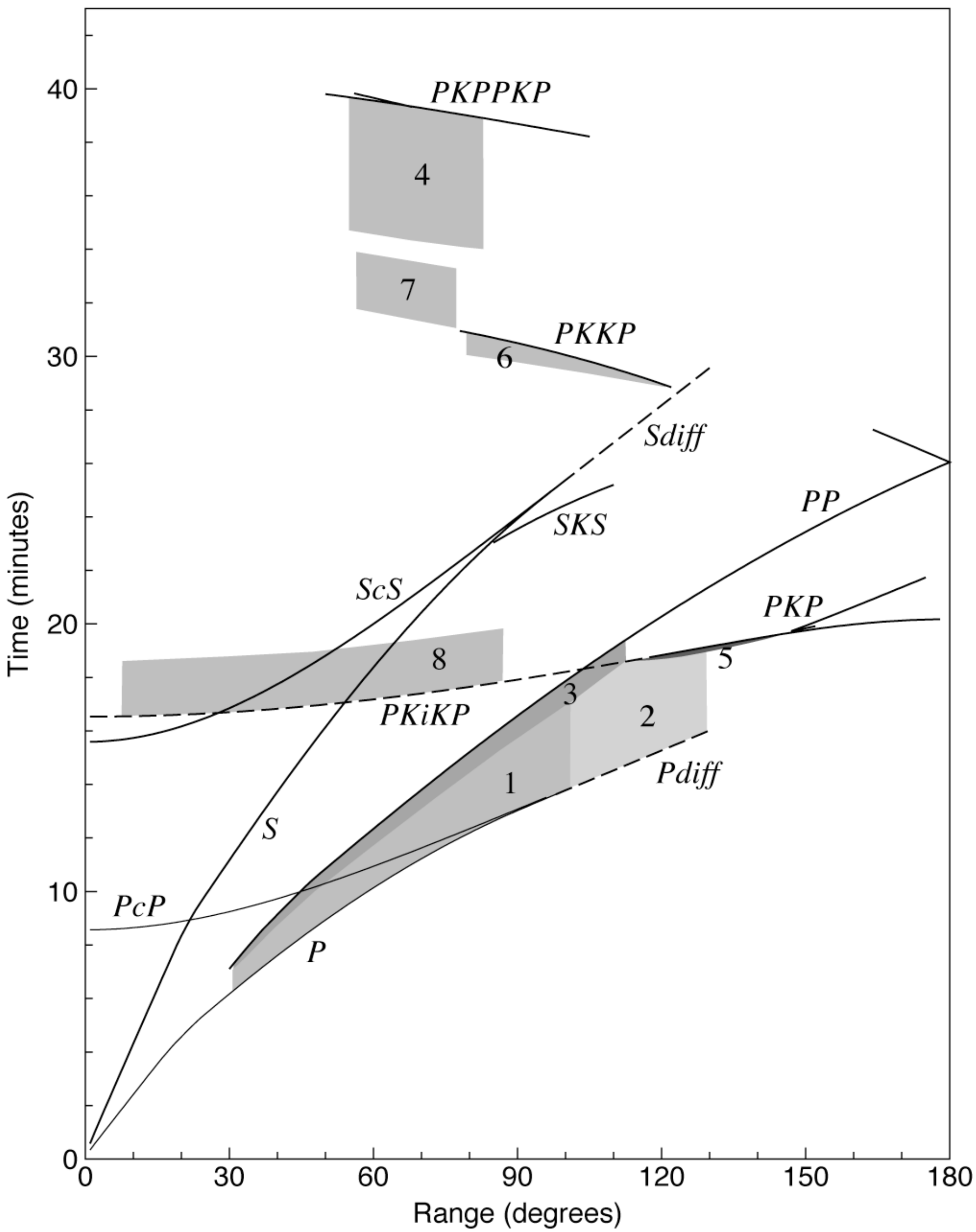
But strong near-surface scattering complicates study of deep mantle



Most coda analyses examine local S coda (e.g., Aki, 1969)

strongest scattering is in crust and lithosphere

Deep mantle scattering is hard to study because it is masked by much stronger scattering at shallow depths.



Deep Earth scattering observations

1. *P* coda
2. *Pdiff* coda
3. *PP* precursors
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5. *PKP* precursors
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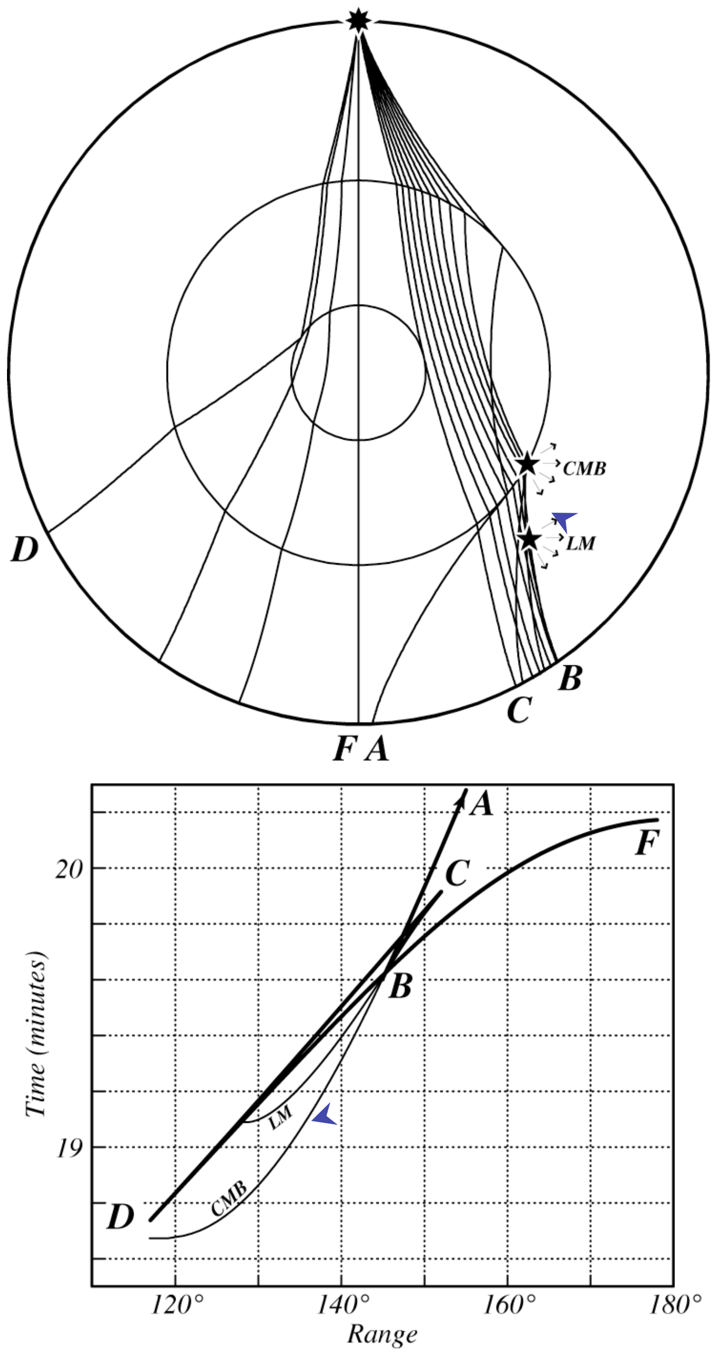
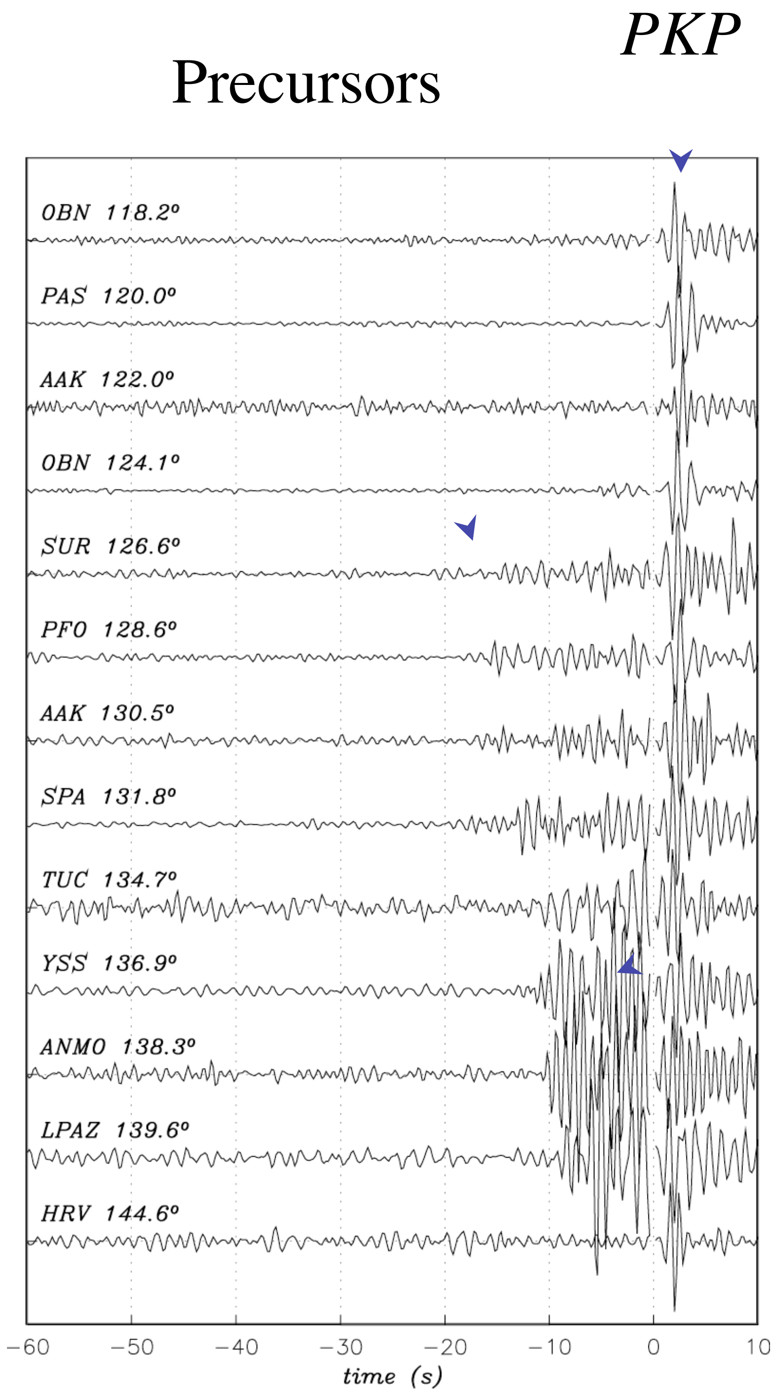
7. *PKKPx*
8. *PKiKP* coda



Uniquely valuable *PKP* precursors

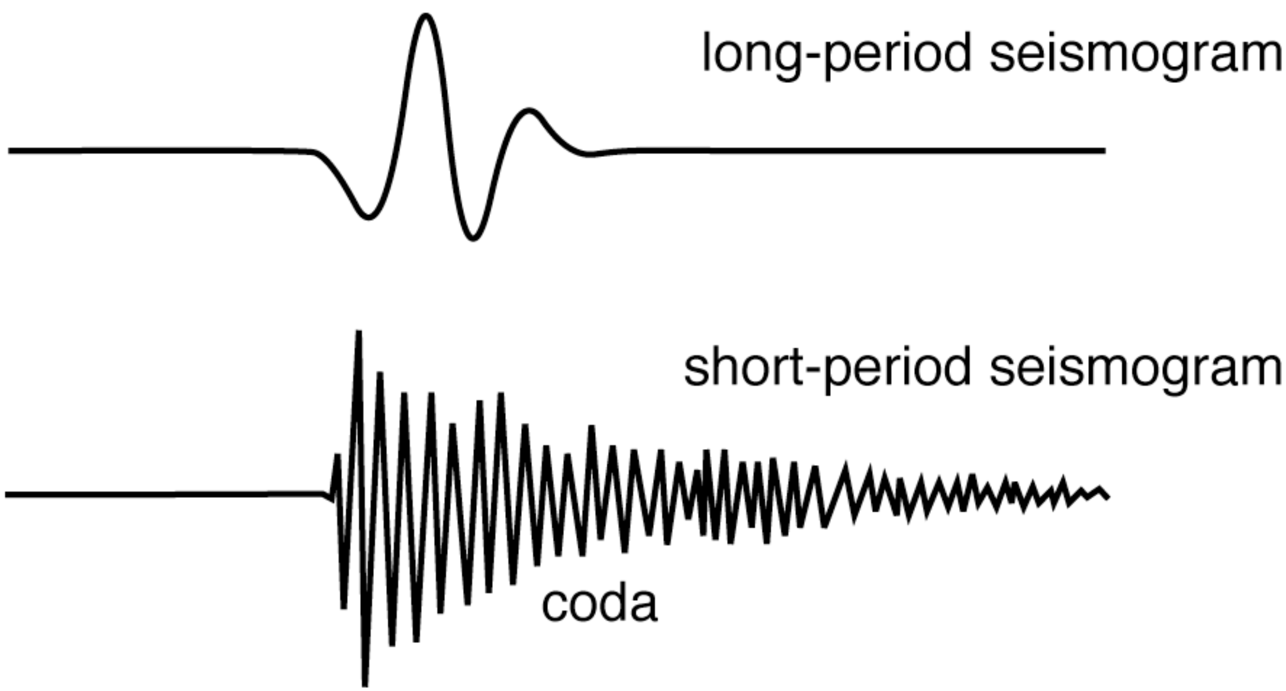
- Core *P* velocity drop bends rays so that scattered waves can arrive *before* direct phases

PKP Precursor Examples

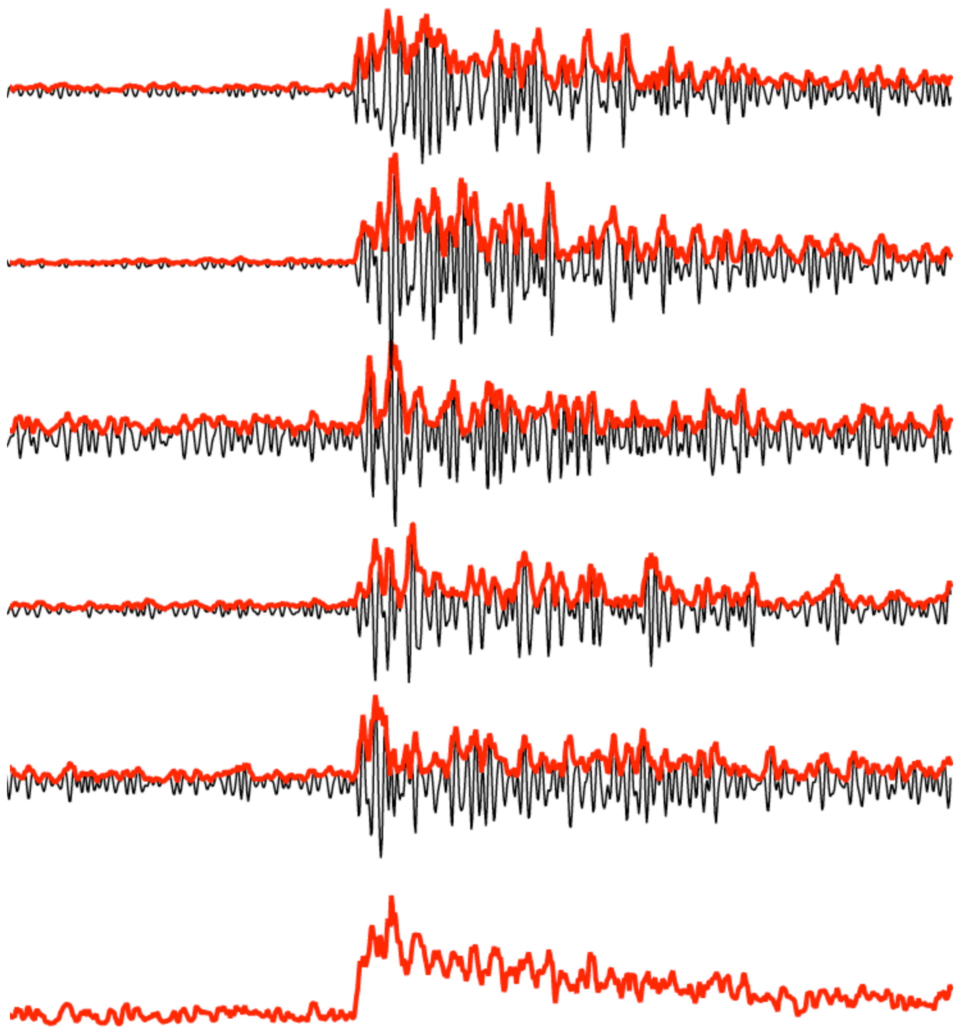


Higher amplitudes at longer range, where scattering angles are less

Stacking complications at short periods…



Stacking incoherent waves

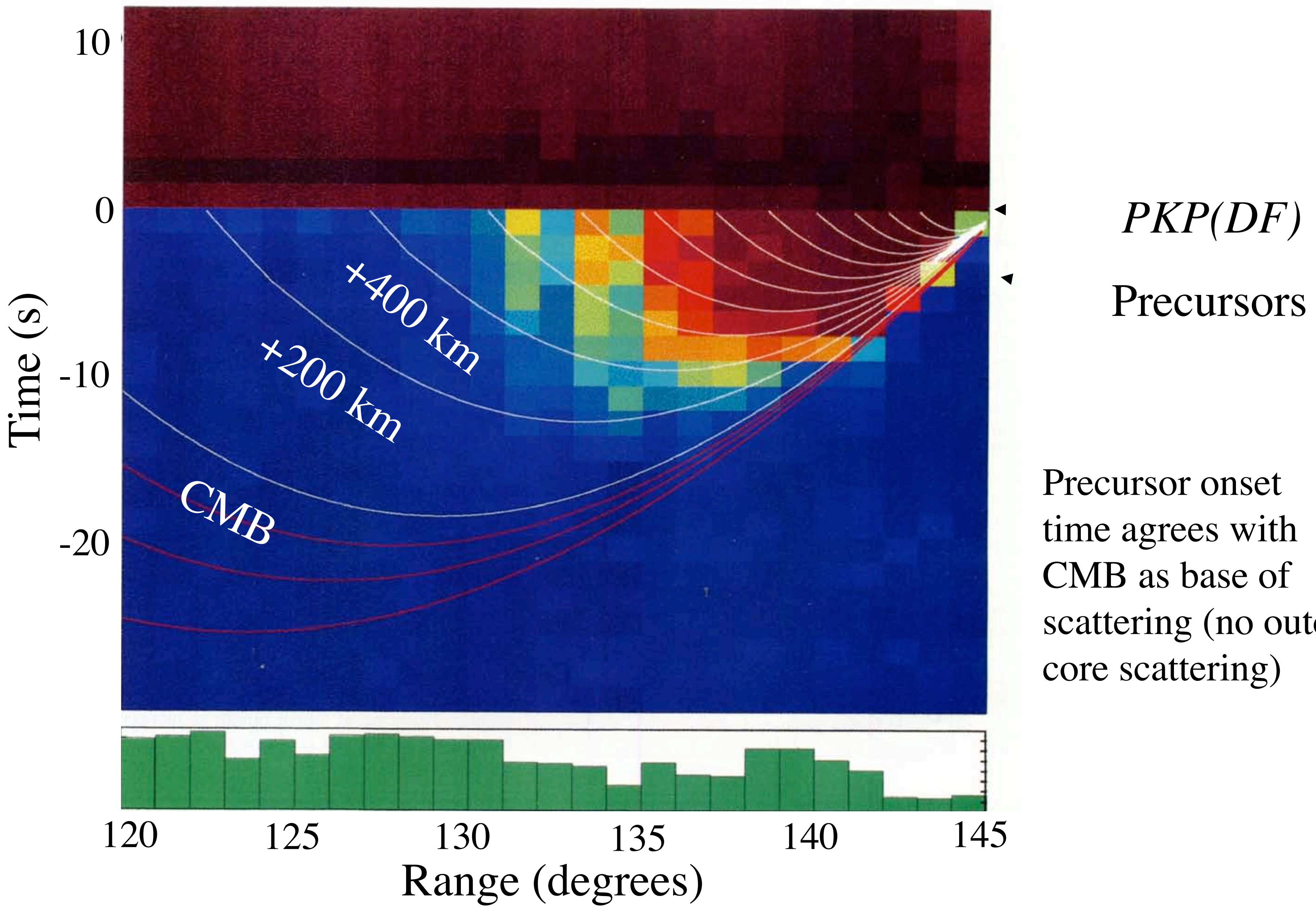


~1 Hz seismograms are incoherent

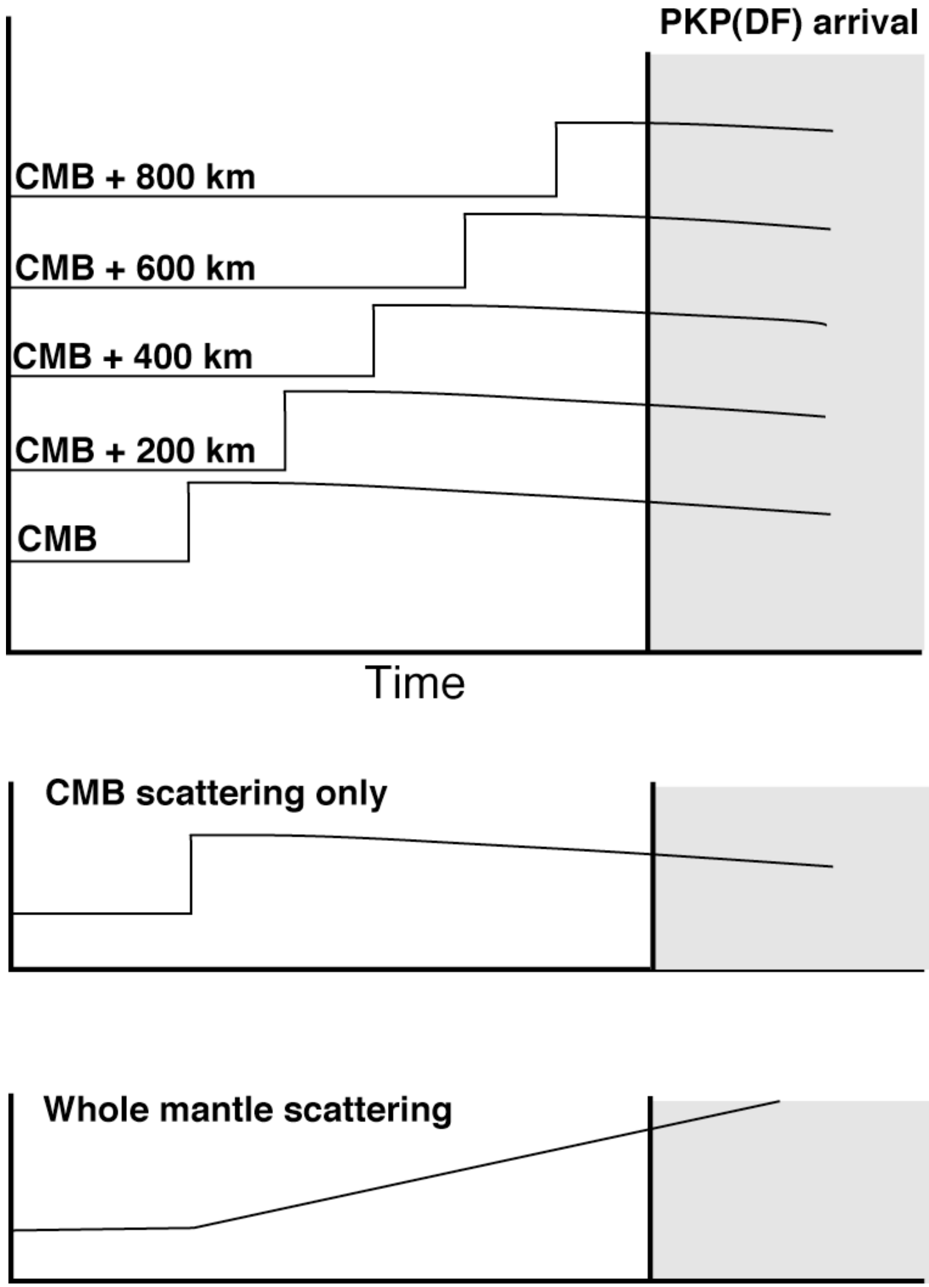
Compute envelope functions

Stack envelope functions, correcting for energy in pre-event noise

Average *PKP* Precursor Wavefield

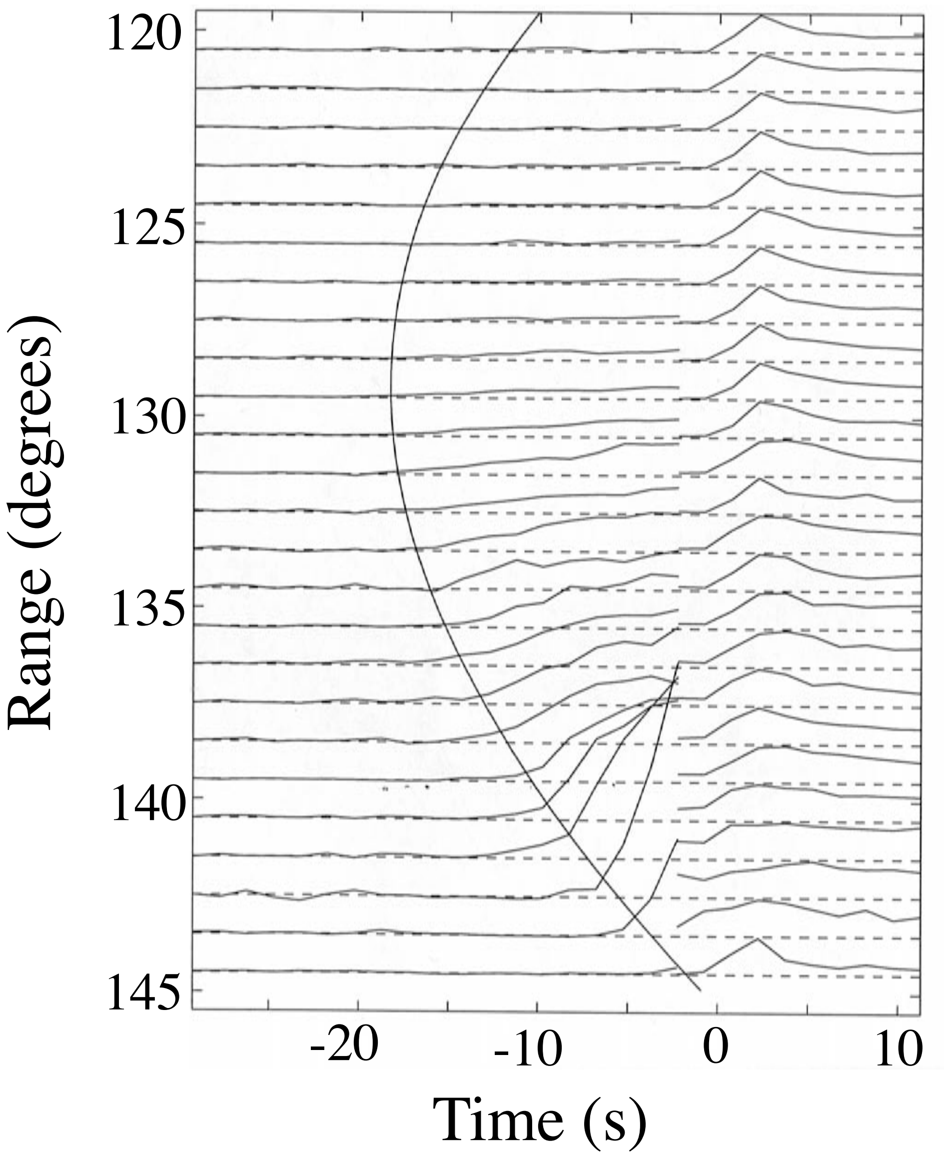


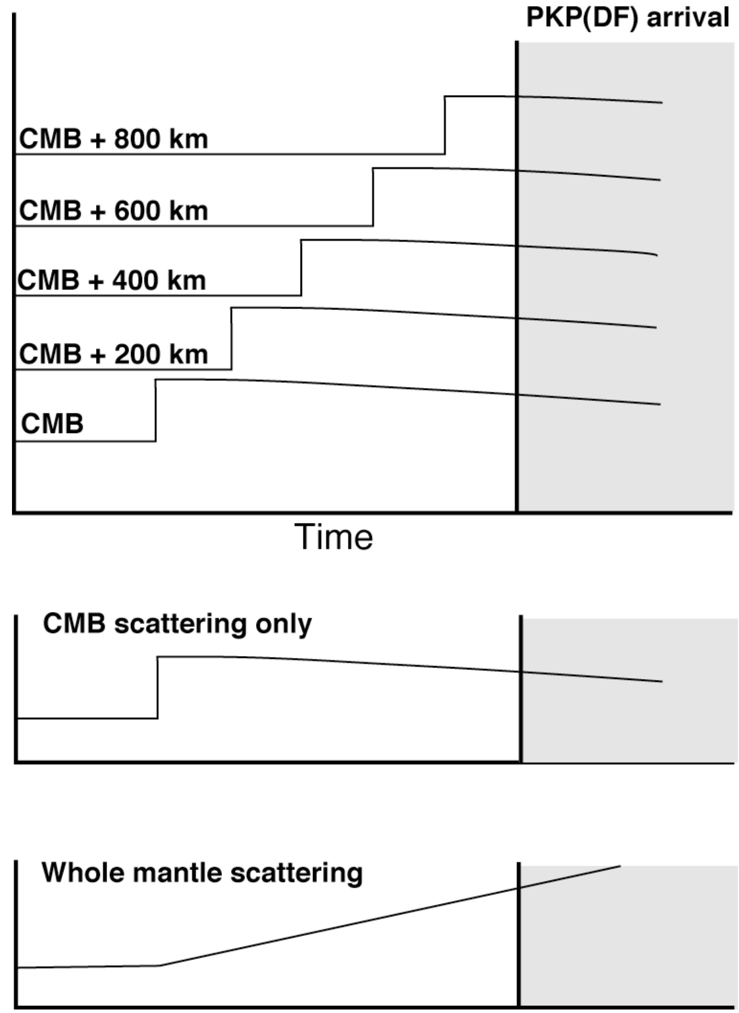
Precursor onset time agrees with CMB as base of scattering (no outer core scattering)



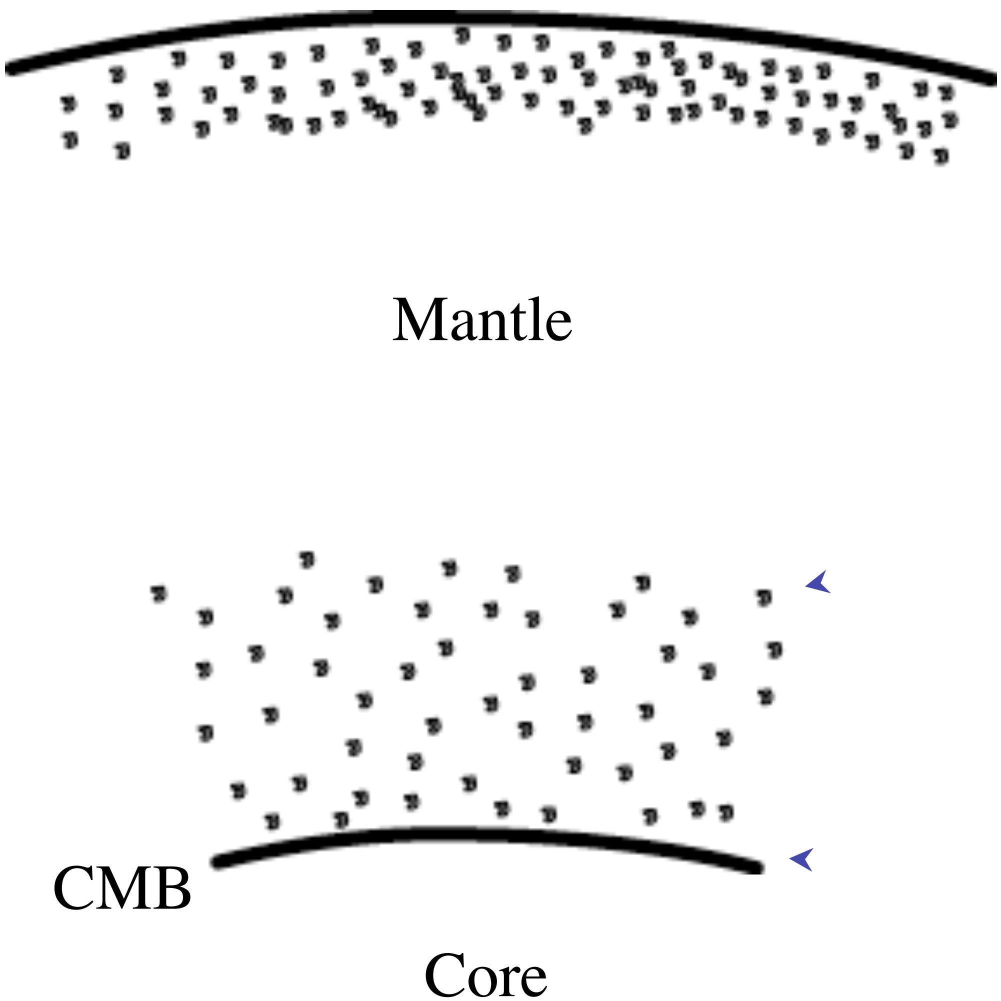
Predicted *PKP* precursor envelopes for scattering at different depths

Stacks suggest whole mantle scattering



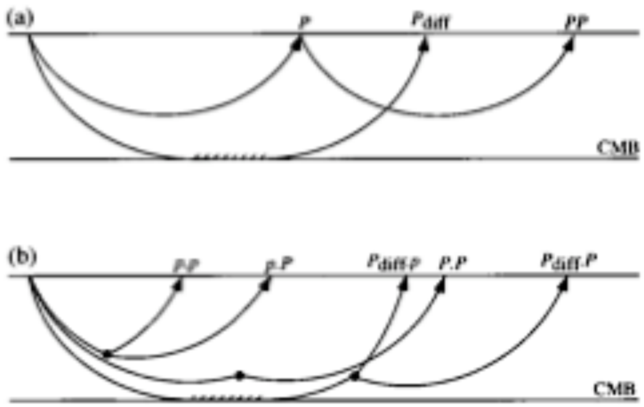


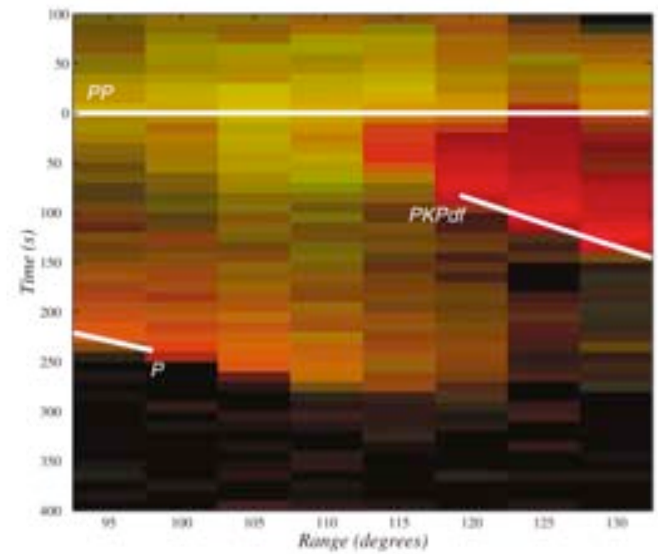
PKP Precursor Interpretation



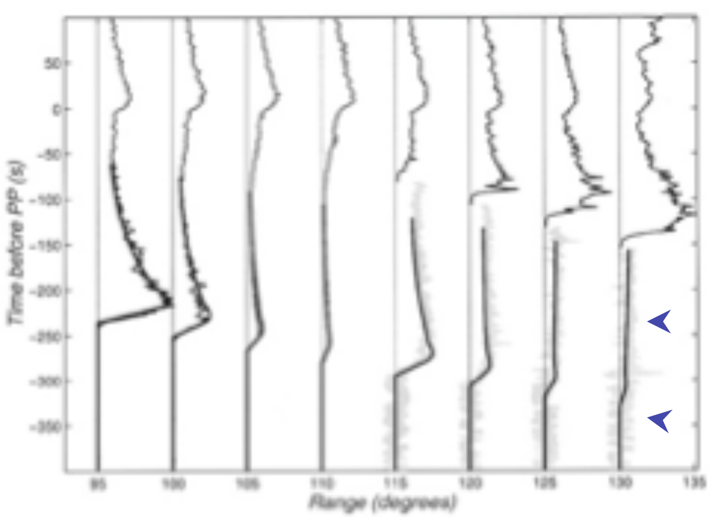
- ~0.5 to 1% RMS velocity perturbations at ~10 km scale length
- Recent analyses show scattering extends at least 1000 km above CMB (*Hedlin et al*., 1997; *Cormier*, 1999; *Margerin & Nolet*, 2003).
- Early studies put scattering near CMB (e.g., *Cleary & Haddon*, 1972)

P_{diff} coda provides more evidence for mid-mantle scattering





Earle & Shearer (2001)

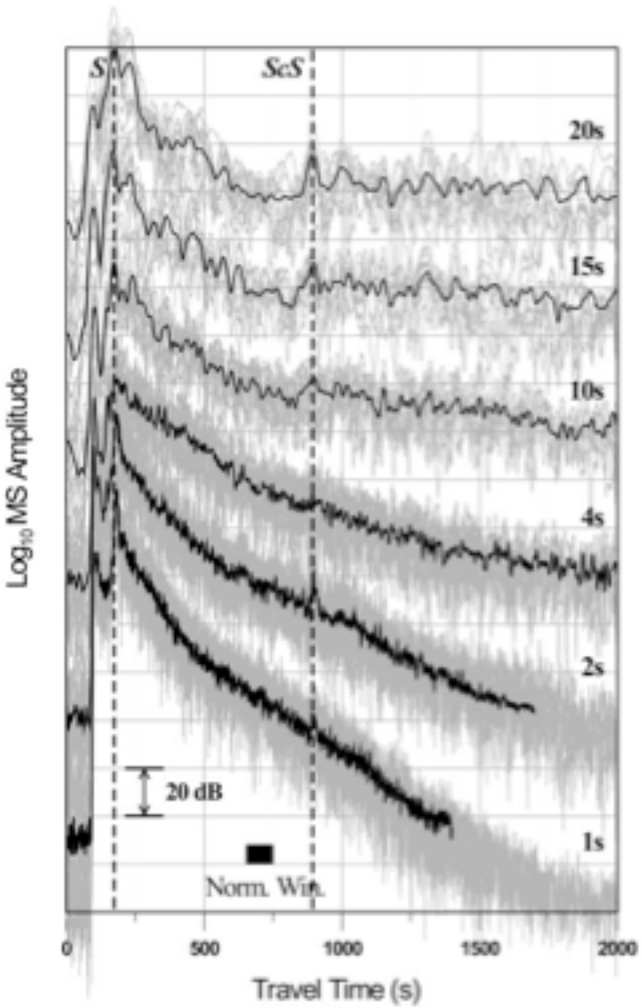


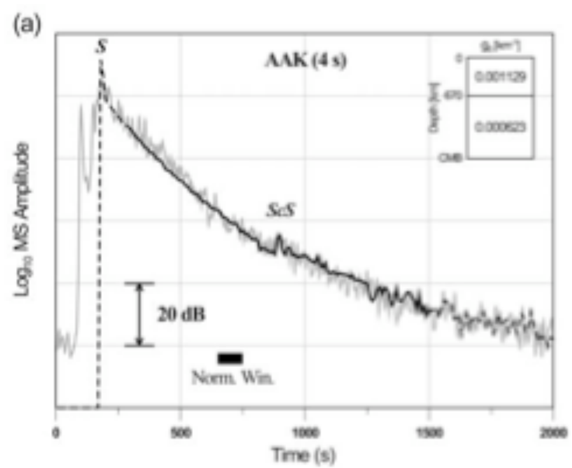
coda

P_{diff}

Good fit to data stack obtained with 1% RMS velocity heterogeneity throughout the mantle

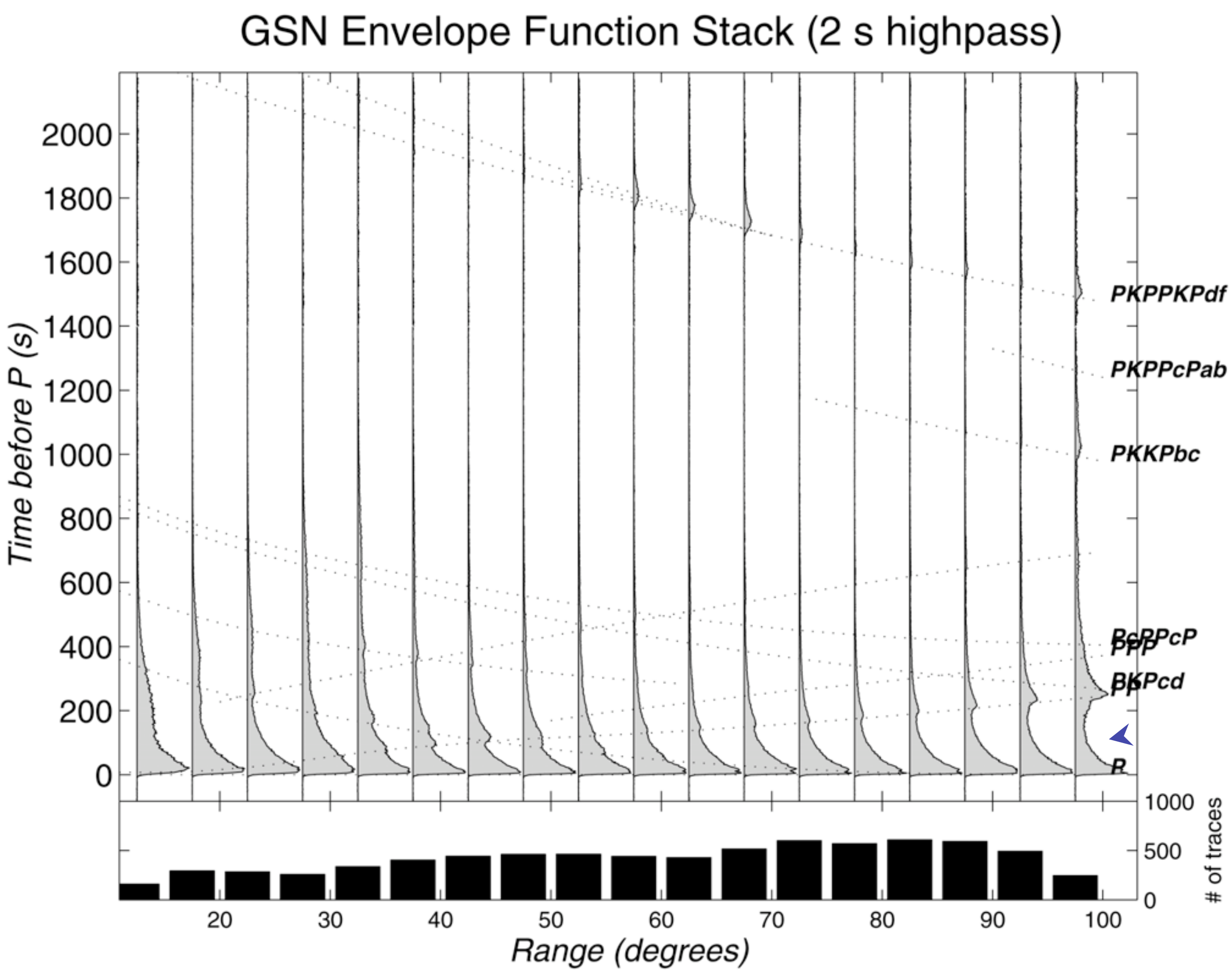
ScS coda analysis supports lower mantle scattering





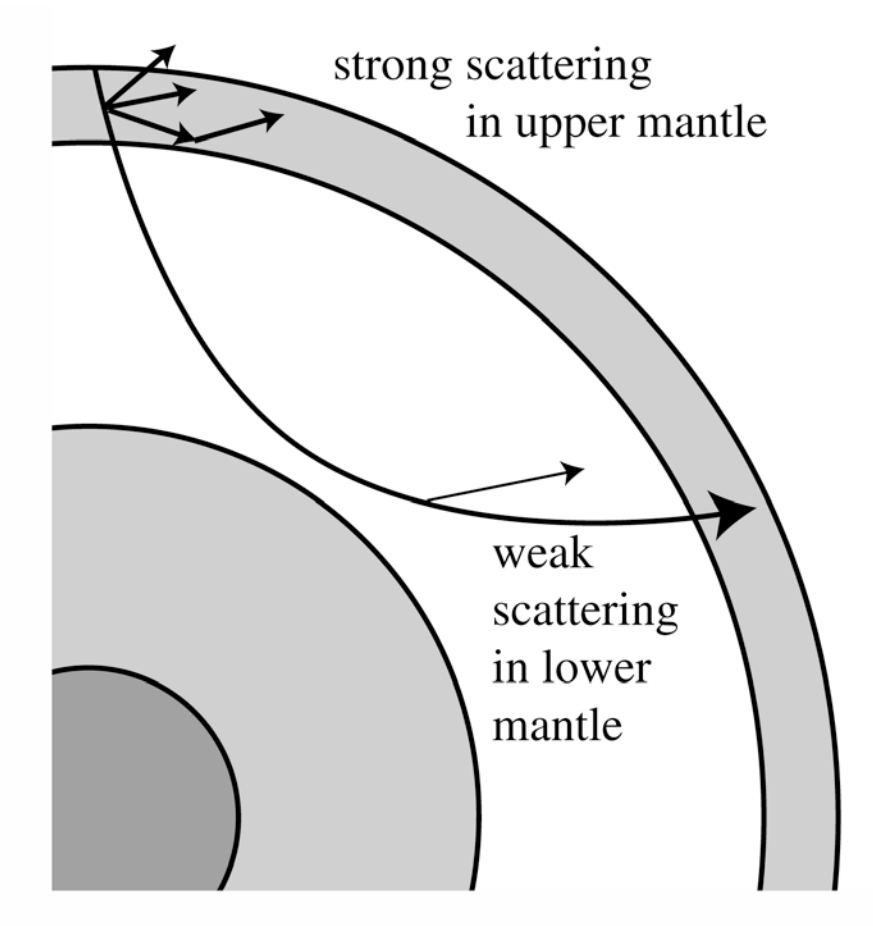
Lee et al. (2003) used radiative transfer modeling

Largest scattered signal in high-frequency wavefield is *P* coda



coda

Whole Earth Scattering: A Challenging Modeling Problem

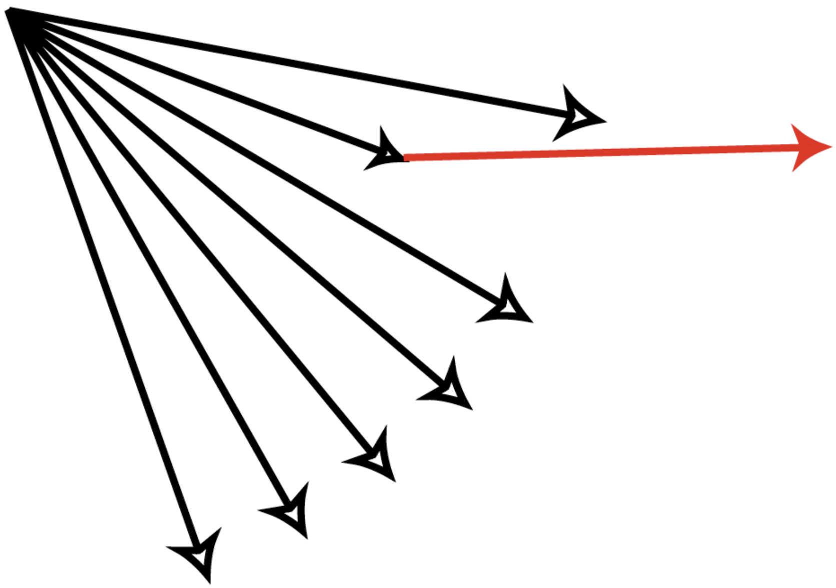


Synthetics should include:

- Strong scattering (multiple)
- Weak scattering (single, Born)
- P and S waves
- Random perturbation models
- Reflection/transmission coef.
- Geometrical spreading
- Intrinsic attenuation
- Energy conservation

Monte Carlo seismic "photon" method

Spray particles
from source



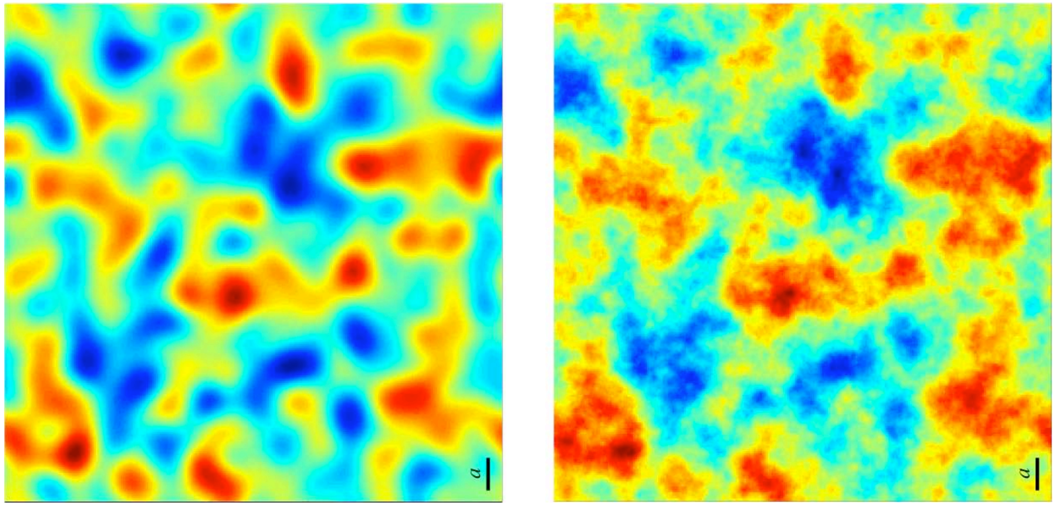
Randomly scatter using probabilities computed from random media theories.

Gusev and Abubakirov (1987)
Hoshiba (1991, 1994, 1997)
Yoshimoto (2000)
Margerin et al. (2000)

(Long used in physics, related to radiative transfer theory)

Scattering in random media

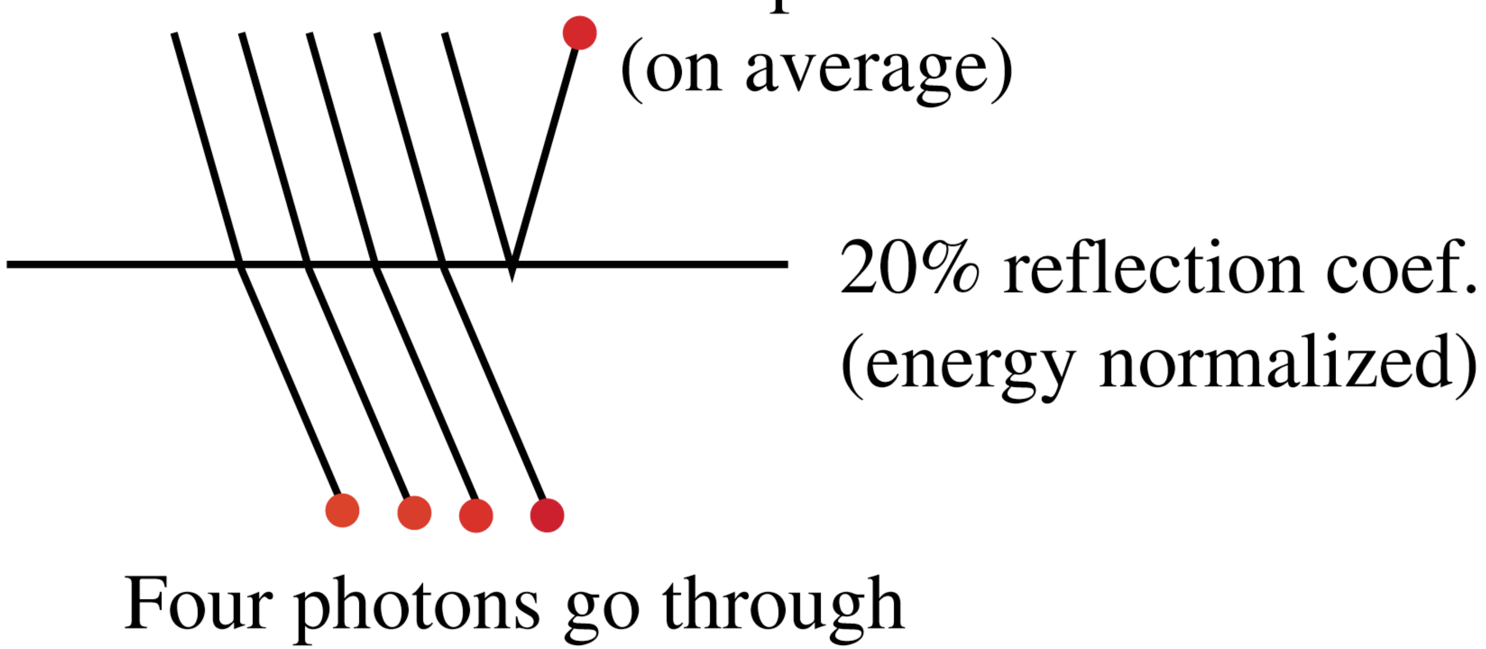
Gaussian ACF Exponential ACF

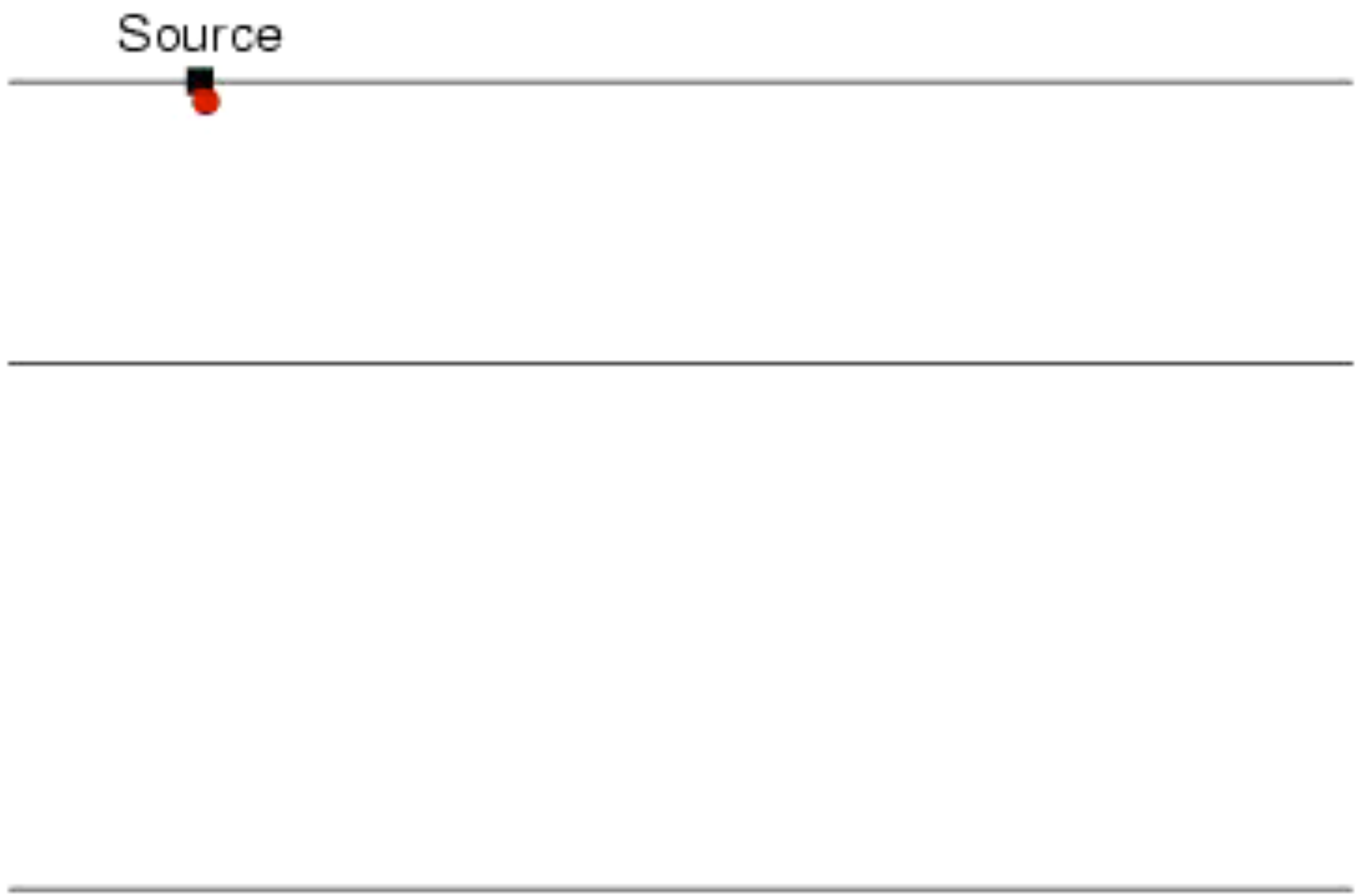


- These models have just two parameters: correlation distance and RMS velocity perturbation
- Born theory gives scattering power per volume and power at different scattering angles
- Easy to convert to particle probability, mean free path

Energy partitioning at interfaces and scattering regions is handled as probability for change in photon path.

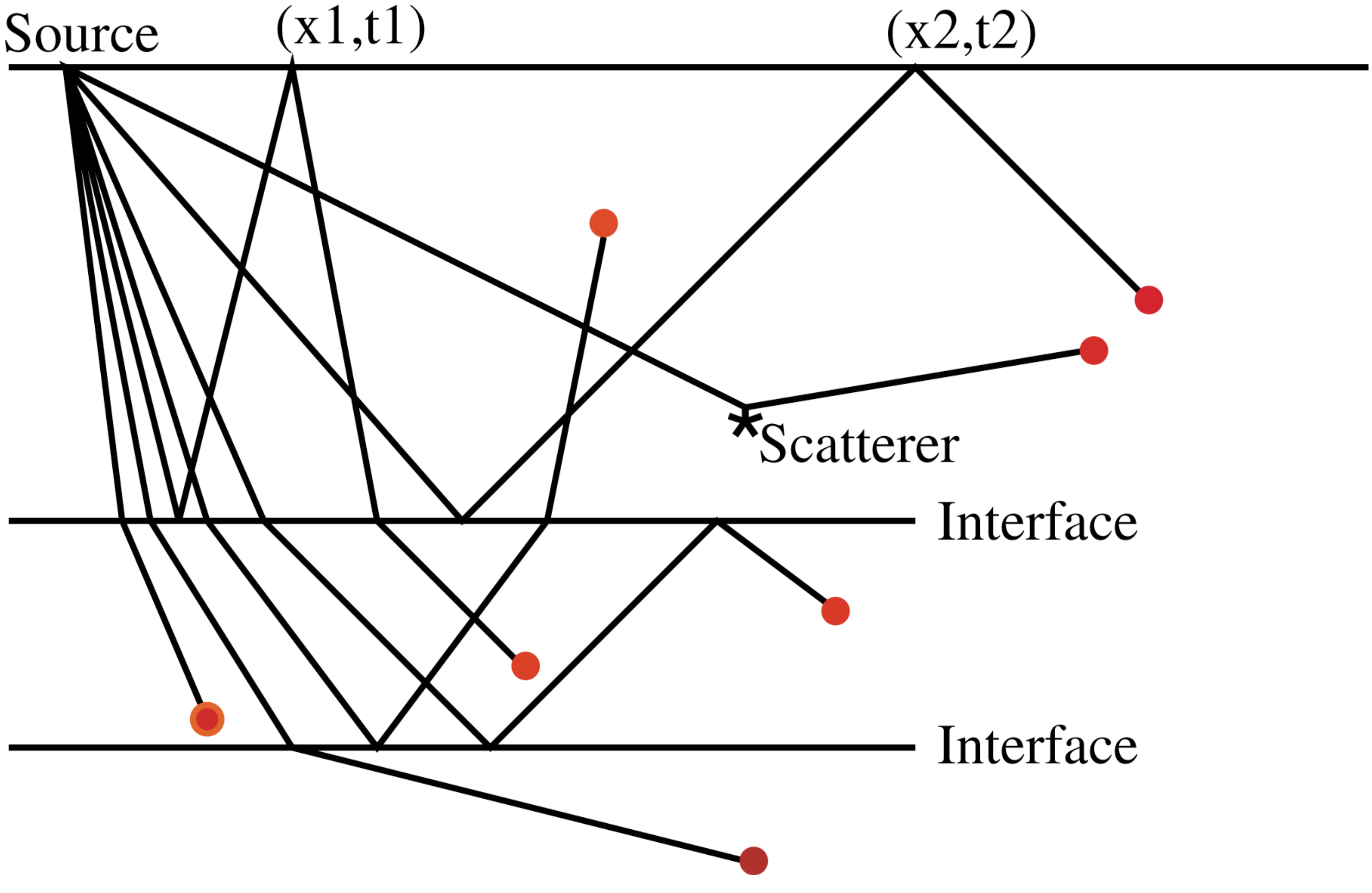
Example:

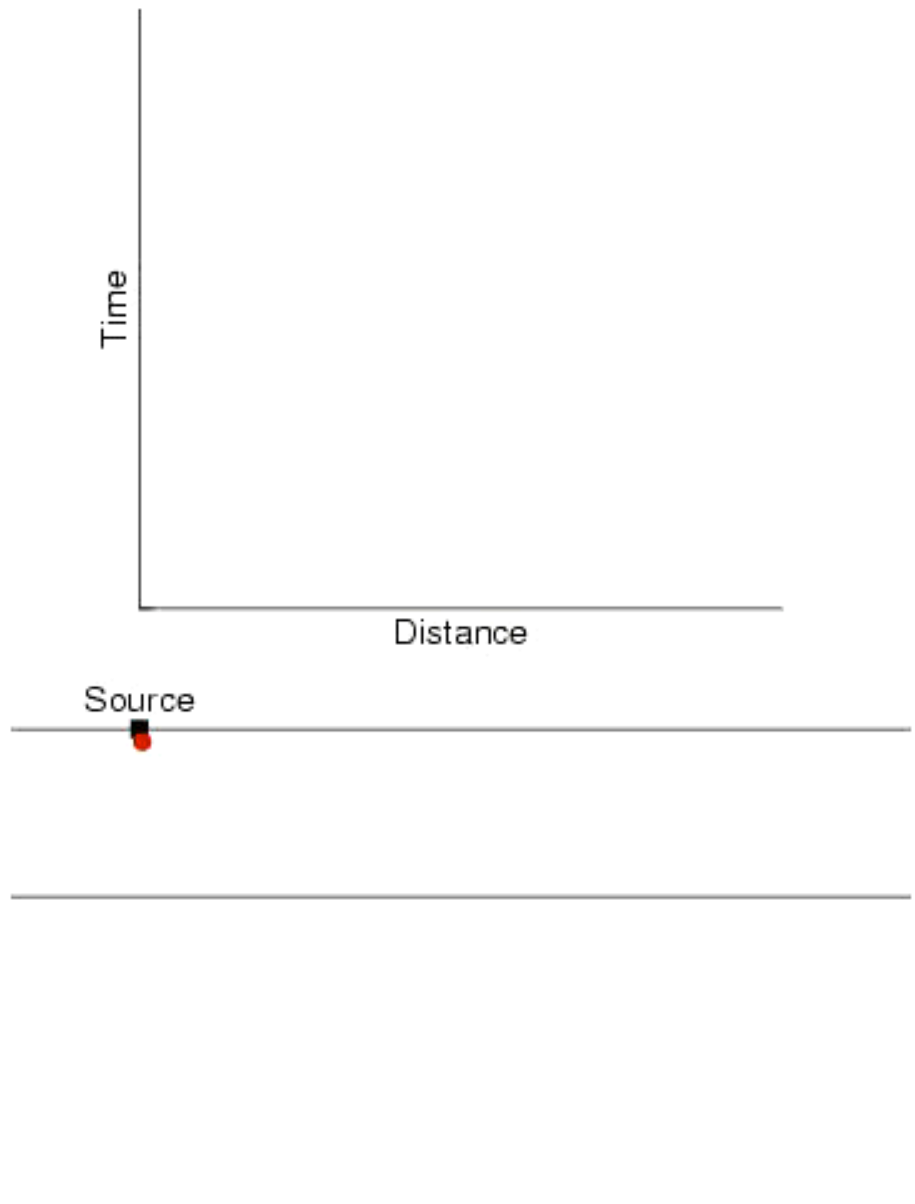



Source

Spray rays randomly from source

When particle hits surface, add energy to appropriate (x,t) bin in wavefield



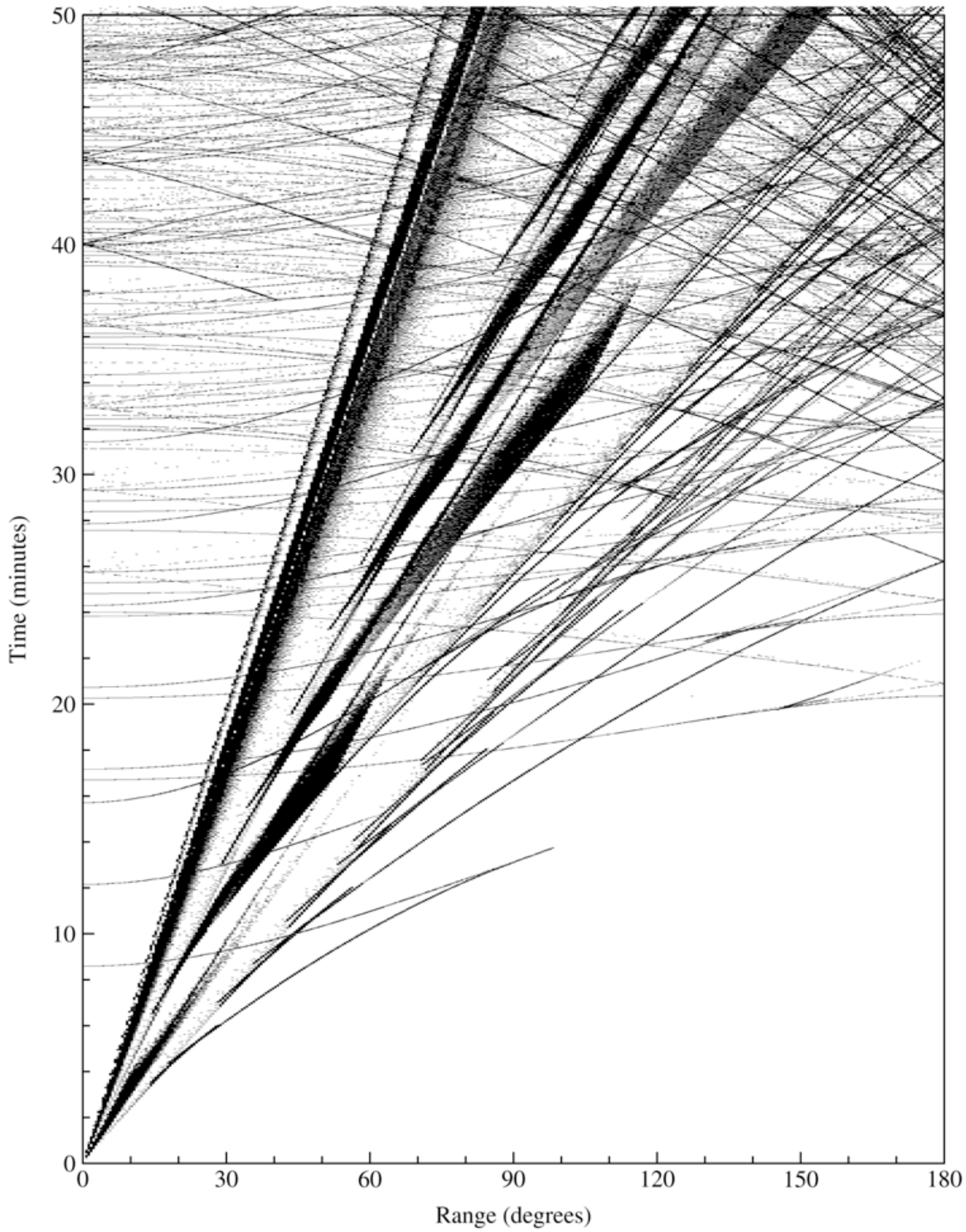

Time
Distance
Source

Advantages of Method

- Energy conservation is maintained
- No need to specify all possible ray paths
- Computes *complete* wavefield
- Includes both intrinsic and scattering Q
- Includes multiple scattering
- Handles both volume and interface scattering

Limitations

- Ray theory doesn't get diffracted waves
- Polarity/phase information is lost

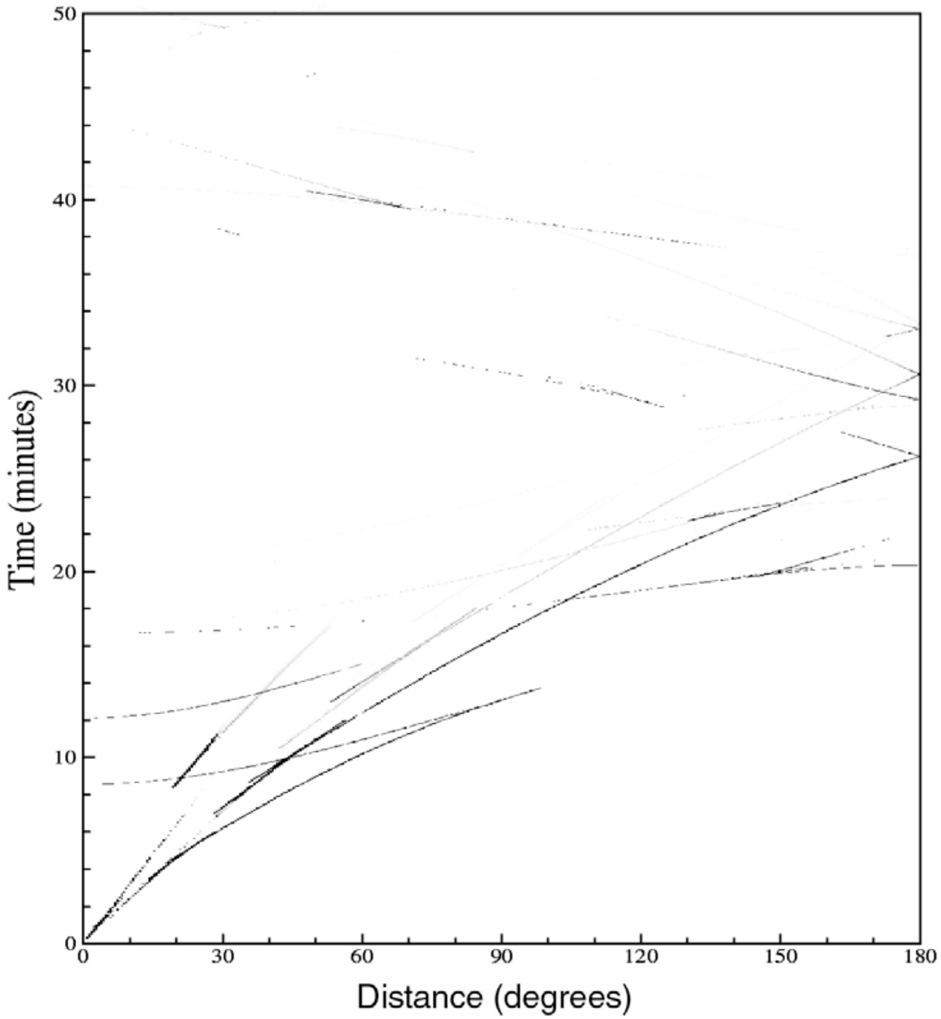


IASP91 travel time curves

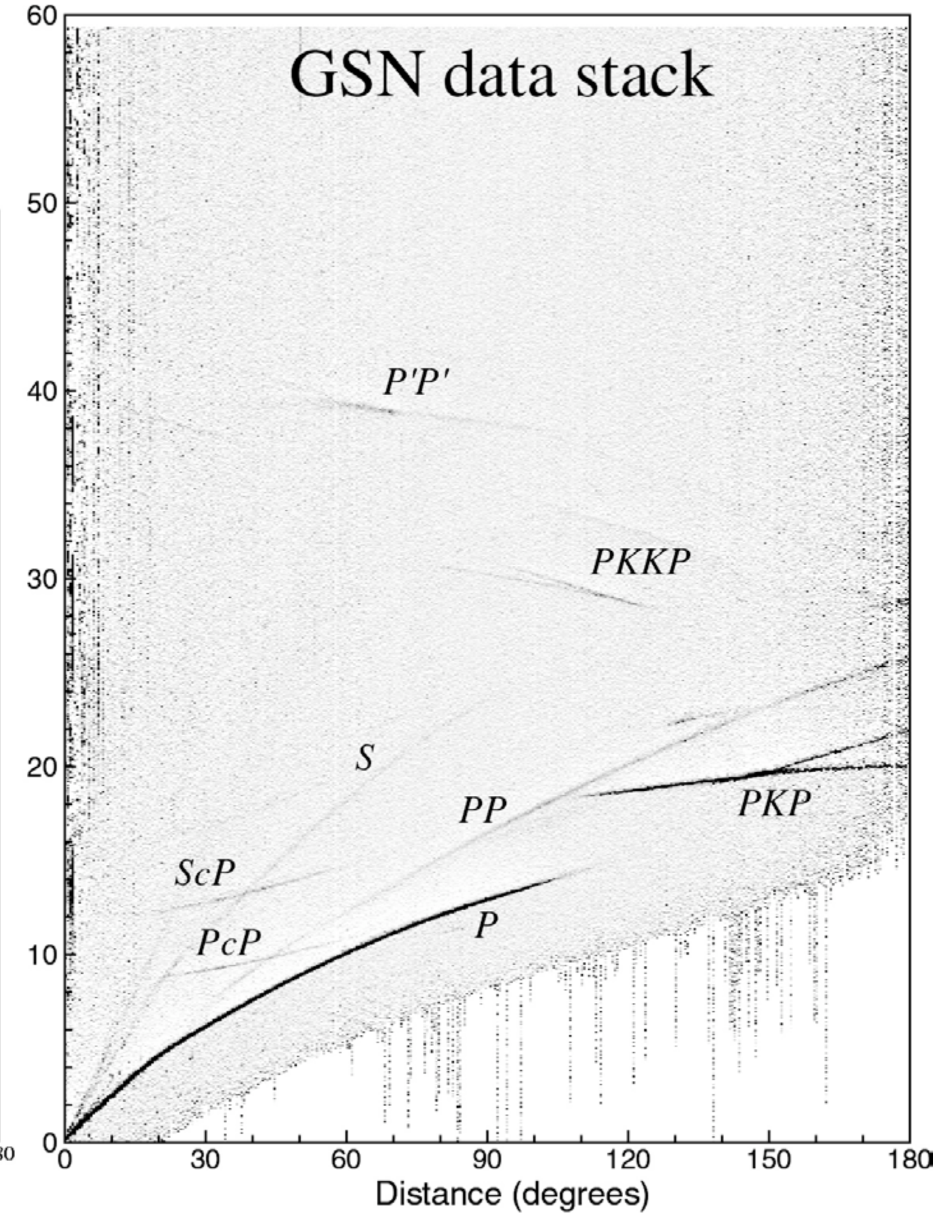
- Assume equal partitioning between reflected & converted waves at surface, CMB and ICB
- No attenuation
- Automatically generates all possible travel time curves for P and S
- Actual amplitudes for most are too small to see in data

Photon results

(1-D Earth model with realistic attenuation)

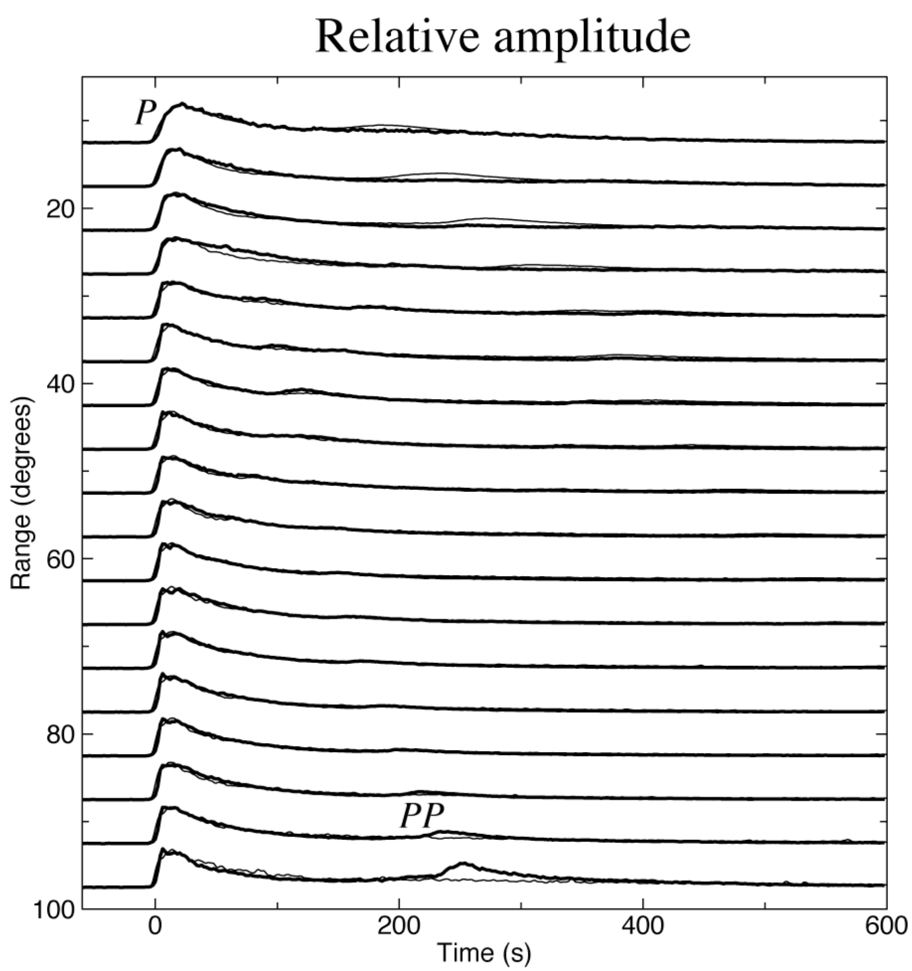


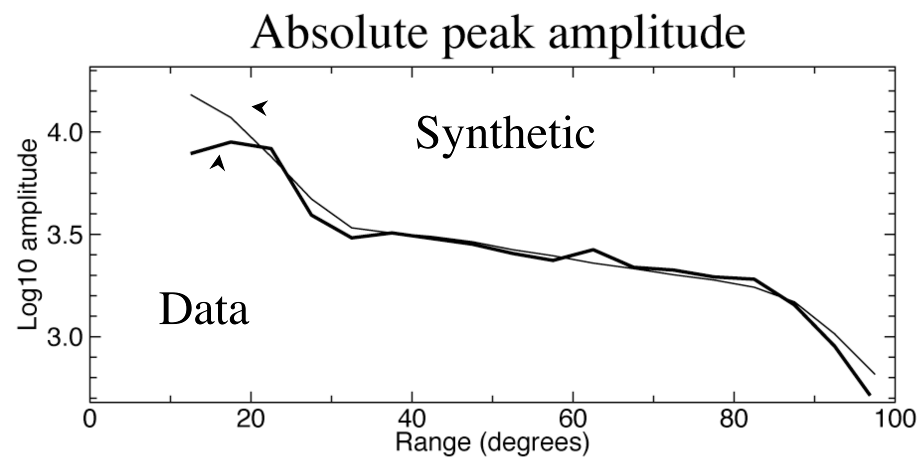
GSN data stack



from *Shearer & Earle* (2004)

Synthetic fit to *P* coda requires some lower mantle scattering



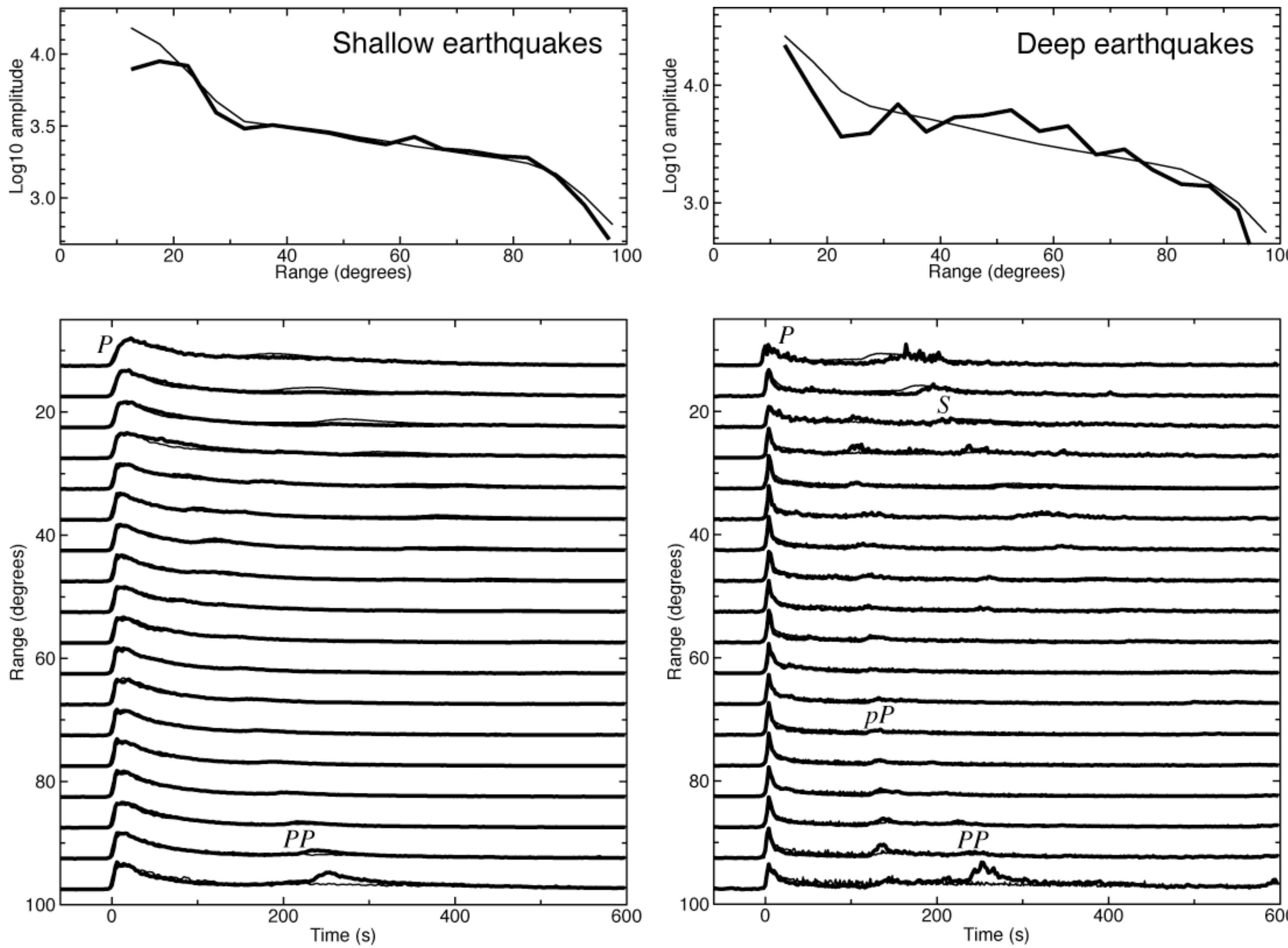


Surface source, 3-layer scattering model

- 4% velocity variation above 200 km
- 3% variation from 200 to 600 km
- 0.5% heterogeneity below 600 km
- Higher *Q* than *Warren & Shearer* (2001)
- 4-km scale length in upper mantle
  8-km scale length in lower mantle

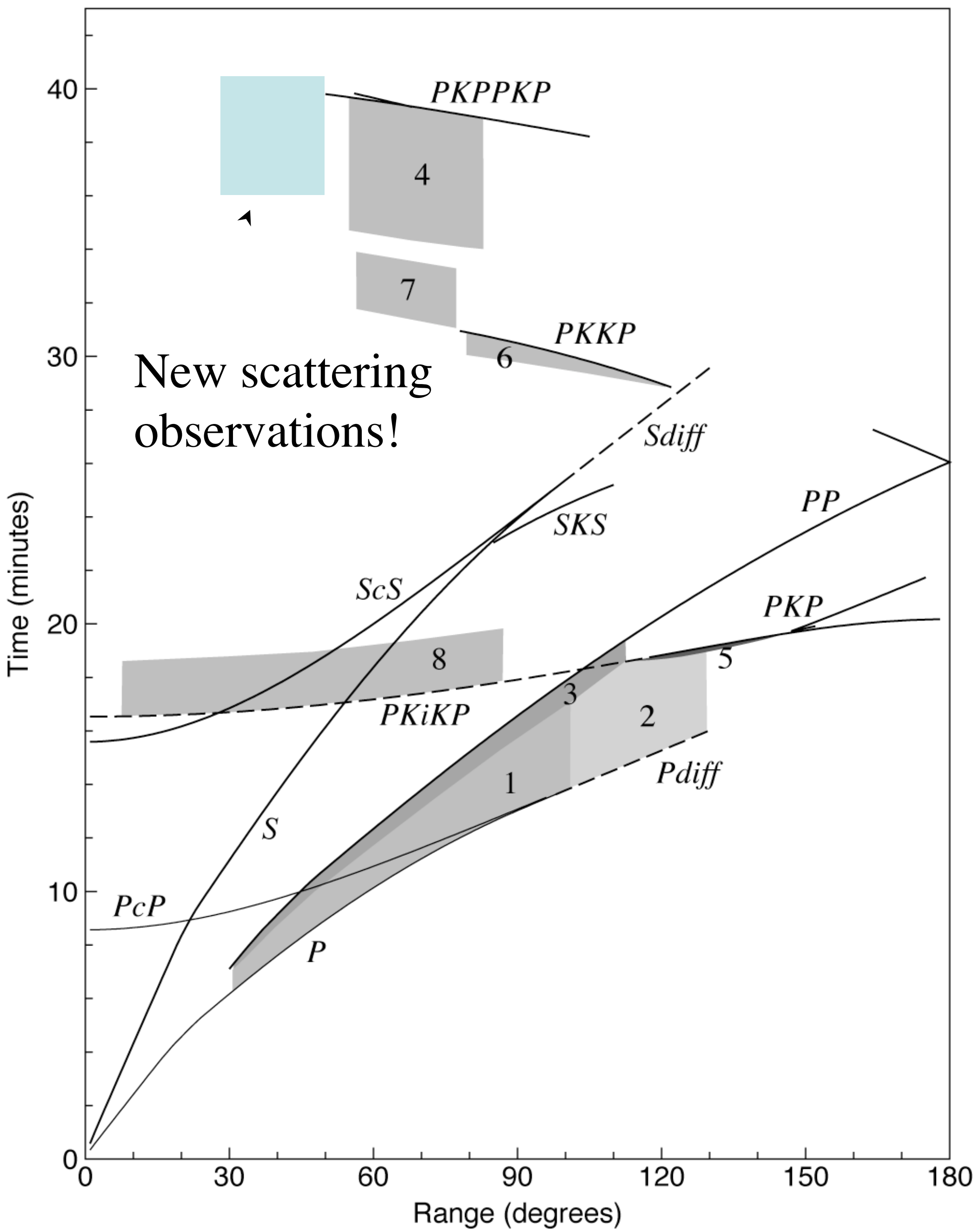
from *Shearer & Earle* (2004)

Same model fits both shallow and deep earthquake results



New results from LASA array: *P'P'* scattering at short distances

from *Earle & Shearer* (2007)



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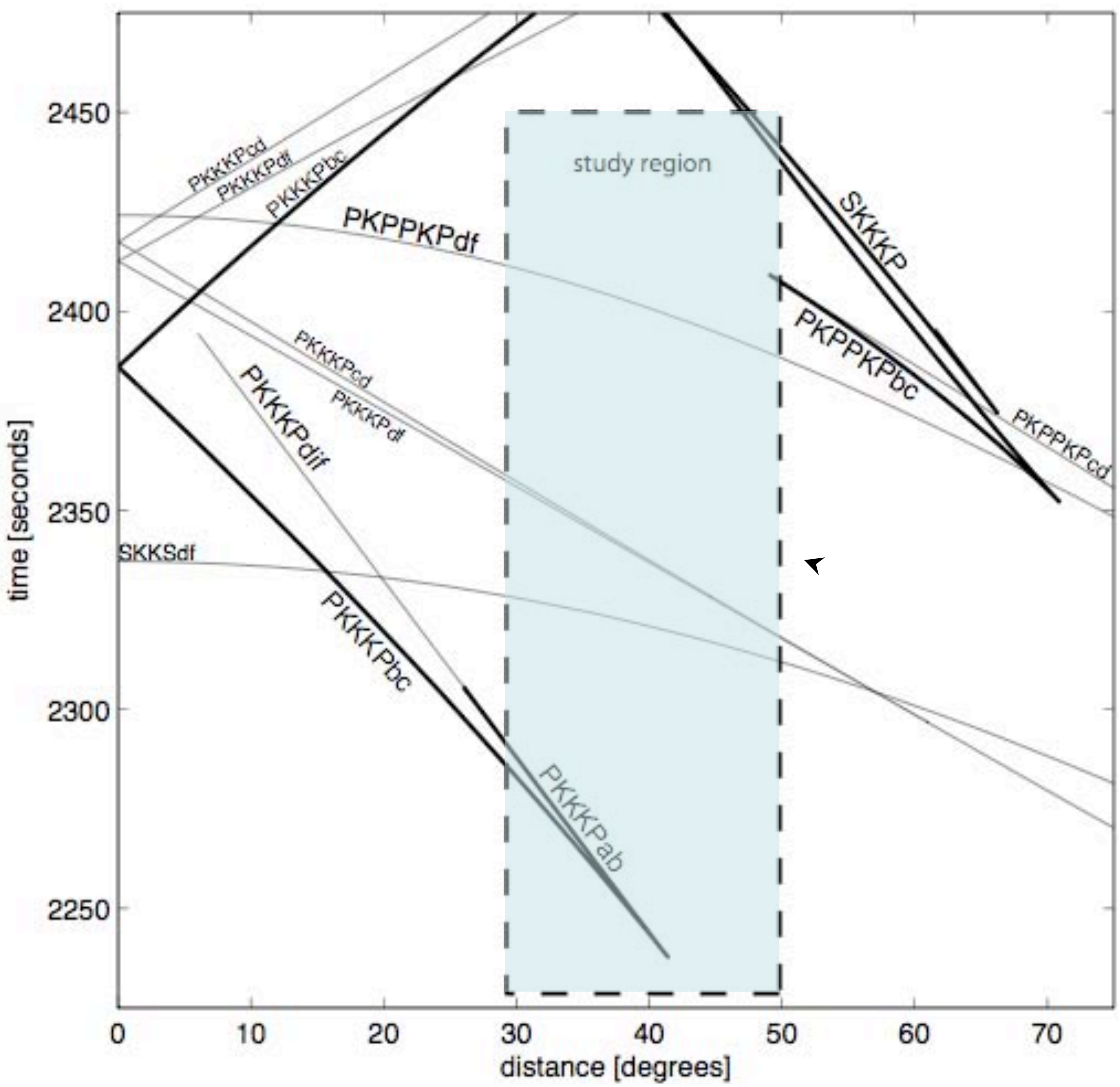
8. *PKiKP* coda

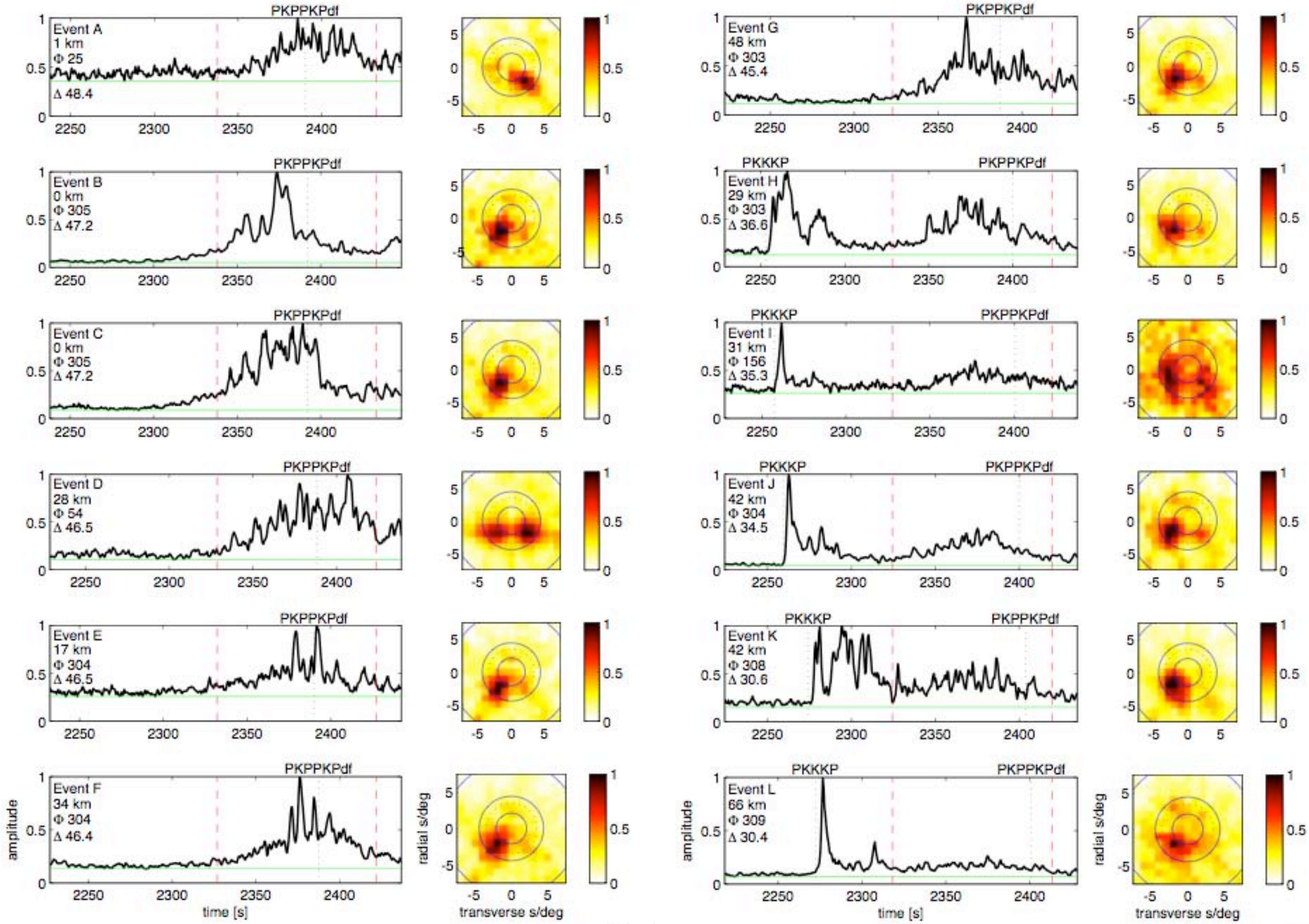
observed

not observed



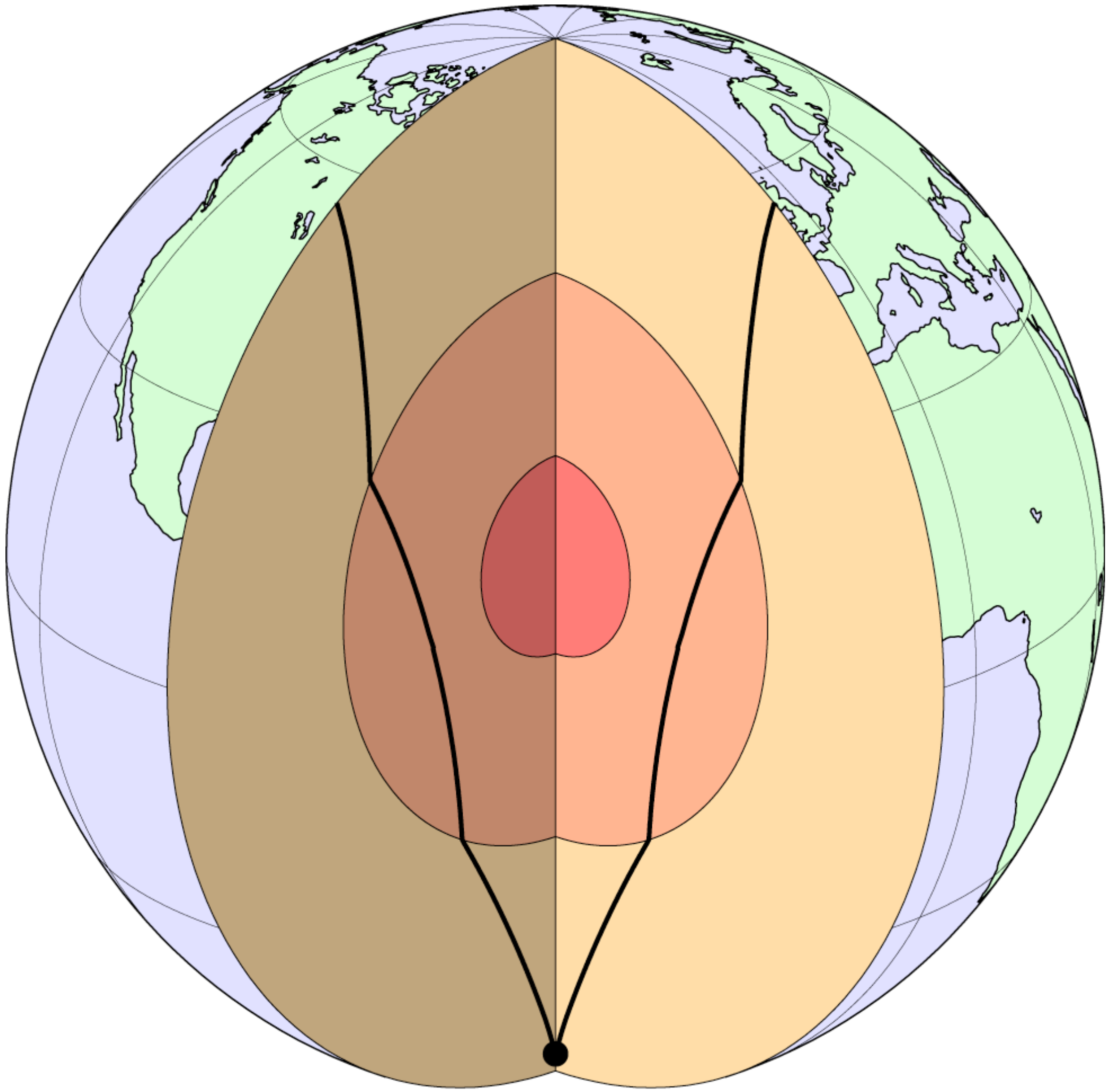
"Quiet" part of wavefield at short periods

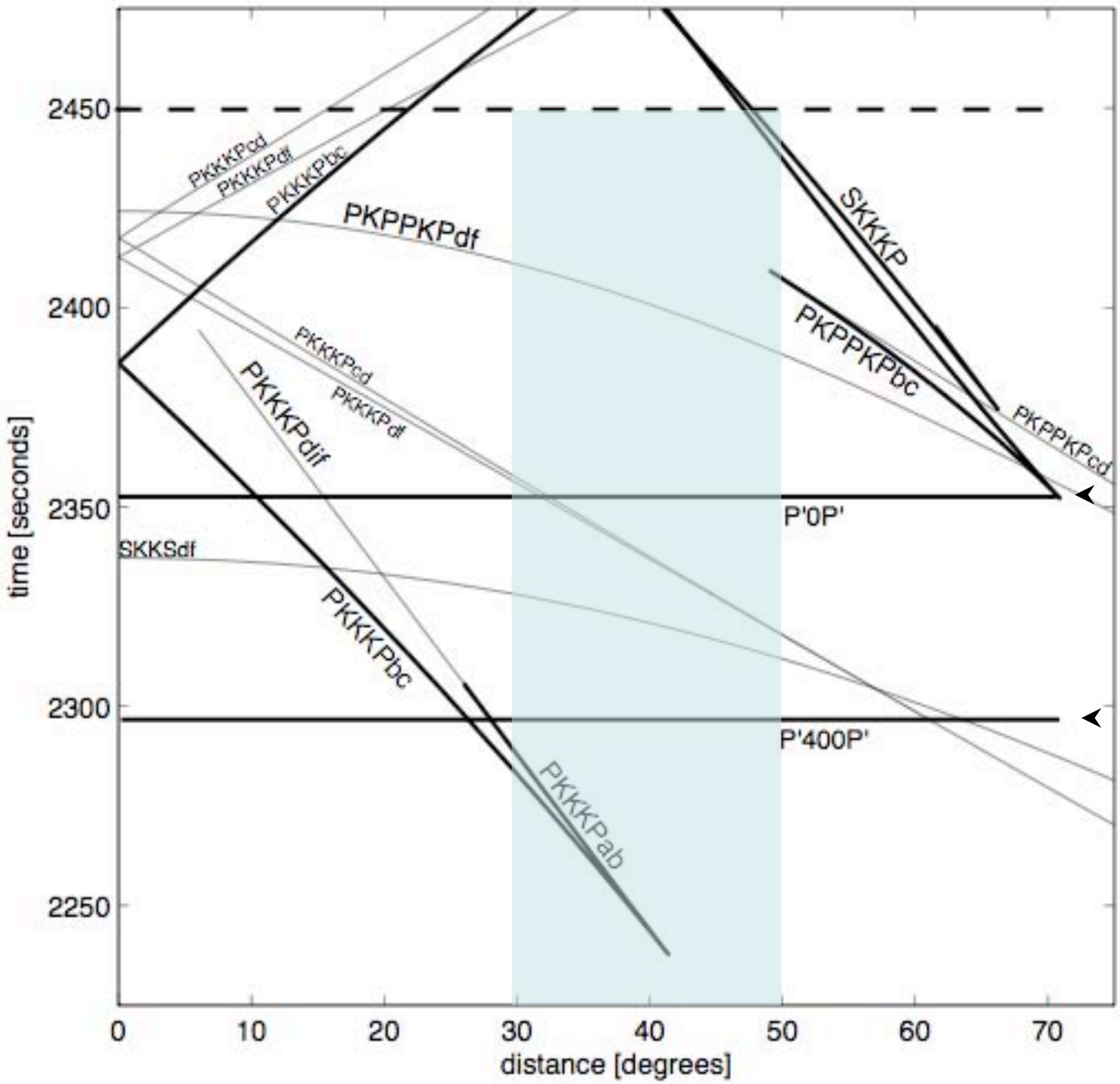
from *Earle & Shearer* (2007)



from *Earle & Shearer* (2007)

Ray geometry for *P'-d-P'* scattering

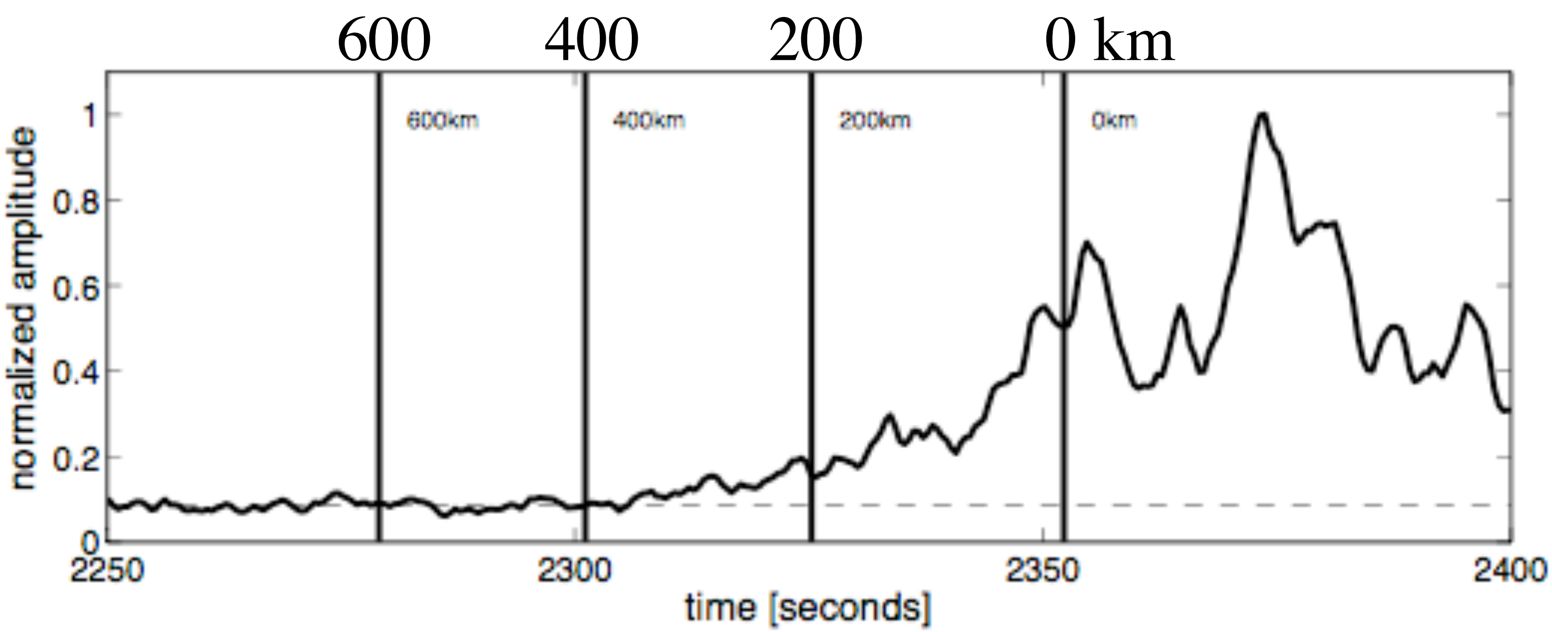




Onset time for *P'P'* scattering from surface

Onset time for *P'P'* scattering from 400 km

Modeling *P'dP'* scattering at short distances may provide best insight yet into depth dependence of high-frequency scattering in the mantle



Conclusions

- Many different seismic studies indicate small-scale (~10 km) random heterogeneity in deep mantle
- RMS amplitude is still an issue (*Margerin & Nolet* get much smaller number than *Hedlin et al.*)
- Needed: Analysis at different frequency bands to constrain power spectrum of heterogeneity over 1 to 500 km band
- Implications for geochemistry and convection modeling should be explored
- Monte Carlo code should be useful for modeling *lots* of additional scattered phases, including newly discovered *P'dP'* scattering