Seismic Scattering in the Deep Earth

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Mantle mixing calculations

(a) 1.5 Ga

Heterogeneity is likely at all scales

Davies (2002)

(b) 4.4 Ga

Xie & Tackley (2004)
Mantle tomography constraints

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

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

Power

Harmonic degree

1225 km depth slice (SIO 2004 model)
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. $P_{diff}$ coda
3. $PP$ precursors
4. $P'P'$ precursors
5. $PKP$ precursors
6. $PKKP$ precursors
7. $PKKP_x$
8. $PKiKP$ coda
Uniquely valuable PKP precursors

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

*PKP*$(DF)$ Precursors

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)
$P_{\text{diff}}$ coda provides more evidence for mid-mantle scattering

Earle & Shearer (2001)

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
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)
Yoshimoto (2000)
Margerin et al. (2000)

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

- 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:

One photon is reflected (on average)

20% reflection coef. (energy normalized)

Four photons go through (on average)
Spray rays randomly from source

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

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)
Deep Earth scattering observations

1. $P$ coda
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7. $PKKP_x$
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