NPTEL ONLINE CERTIFICATION COURSES

EARTHQUAKE SEISMOLOGY

Dr. Mohit Agrawal
Department of Applied Geophysics , IIT(ISM) Dhanbad

Module 07 : Anisotropic earth structure, Attenuation and Anelasticity.
Lecture 03: Wave Attenuation: Geometrical Spreading, Multipathing and Scattering

CONCEPTS COVERED

- **Wave Attenuation**
- **Geometrical Spreading**
- **Multipathing**
- **Scattering**
- **Summary**

Recap

- As shear waves travel across the mantle and crust, they can be split when traveling through anisotropic media that serve the basis of the Shear Wave Splitting to study the lithospheric anisotropy.

- We would normally not expect any SKS on the transverse component, but anisotropy yields a combination of both the fast and the slow polarizations on both the radial and the transverse components, given by:

$$R(t) = s(t)\cos^2\phi + s(t-\delta t)\sin^2\phi,$$
$$T(t) = [s(t) - s(t-\delta t)/2]\sin 2\phi$$

$$\delta t = \frac{d}{v_f} - \frac{d}{v_s}$$

v_f and v_s are the velocities of the qS1 (fast) and qS2 (slow),

- Source of anisotropy in the upper crust is the presence of fluid-filled cracks, horizontal sediment layers, intruded dykes, preferred orientation of olivine crystals yielded by spreading process.

Recap

- Seismic anisotropy within continents is thought to reflect crystal alignment created during a tectonic episode and then "frozen in."

- For plate collisions the fast axis is usually sub-perpendicular to the principal stress axis, or parallel to the resulting orogenic belts.

- Anisotropy in the Pacific ocean is derived by the parameter 'ξ' as a function of age and depth.

When $\xi > 1$, then

→ Love wave velocity is fast than Rayleigh wave and indicates horizontal mantle flow.

When $\xi < 1$, then

→ Love wave velocity is lesser than Rayleigh wave and indicates vertical mantle flow.

Wave Attenuation

- Apart from reflection and transmission, other processes that can reduce wave amplitudes:
  - geometric spreading
  - scattering
  - multipathing

    (scattering and multipathing:)
    - elastic processes.
    - energy conserved.
  - and anelasticity.
    - also known as intrinsic attenuation;
    - energy lost as heat by permanent deformation of the medium
    - without anelasticity, seismic waves will reverberate, accumulate and shatter the earth.

- seismograms from an April 14, 1995, earthquake in Texas recorded in Nevada (MNV, Δ = 15°) and Missouri (MM18, Δ = 14°).

- The MNV record has less high frequency energy because the tectonically active western USA is more attenuating than the stable mid-continent.

Figure 3.7-1: Regional effects of attenuation.

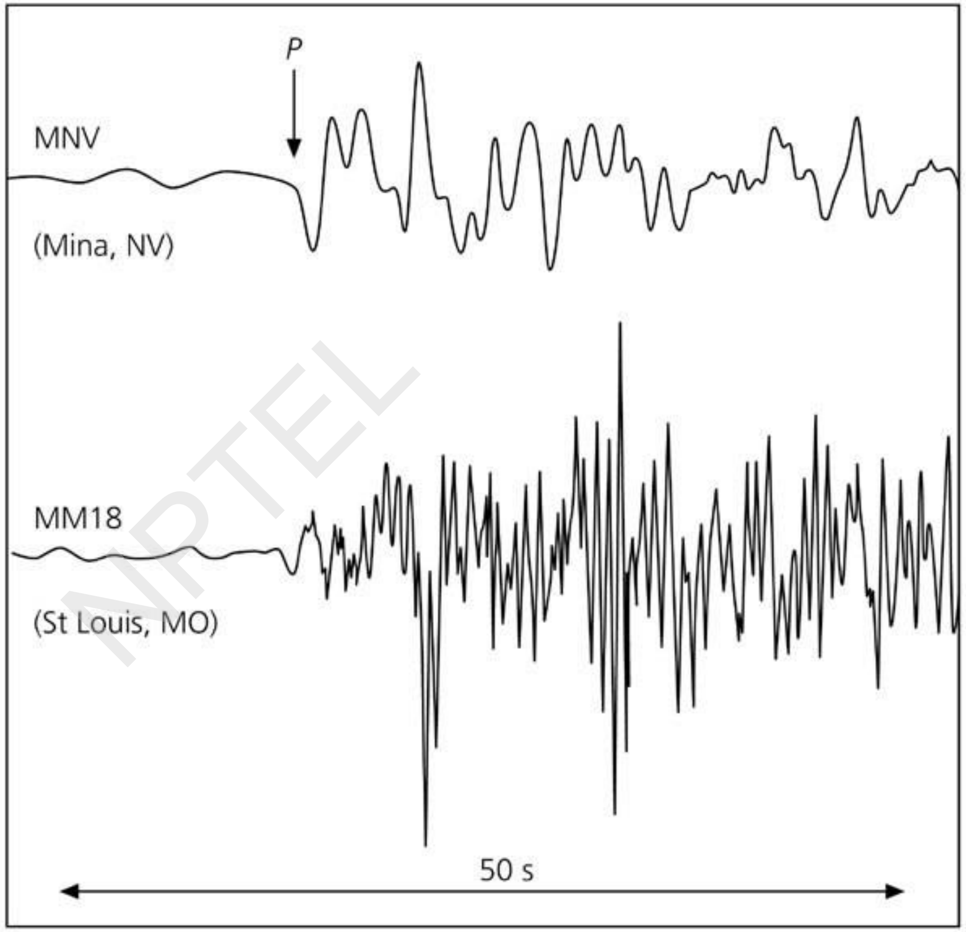
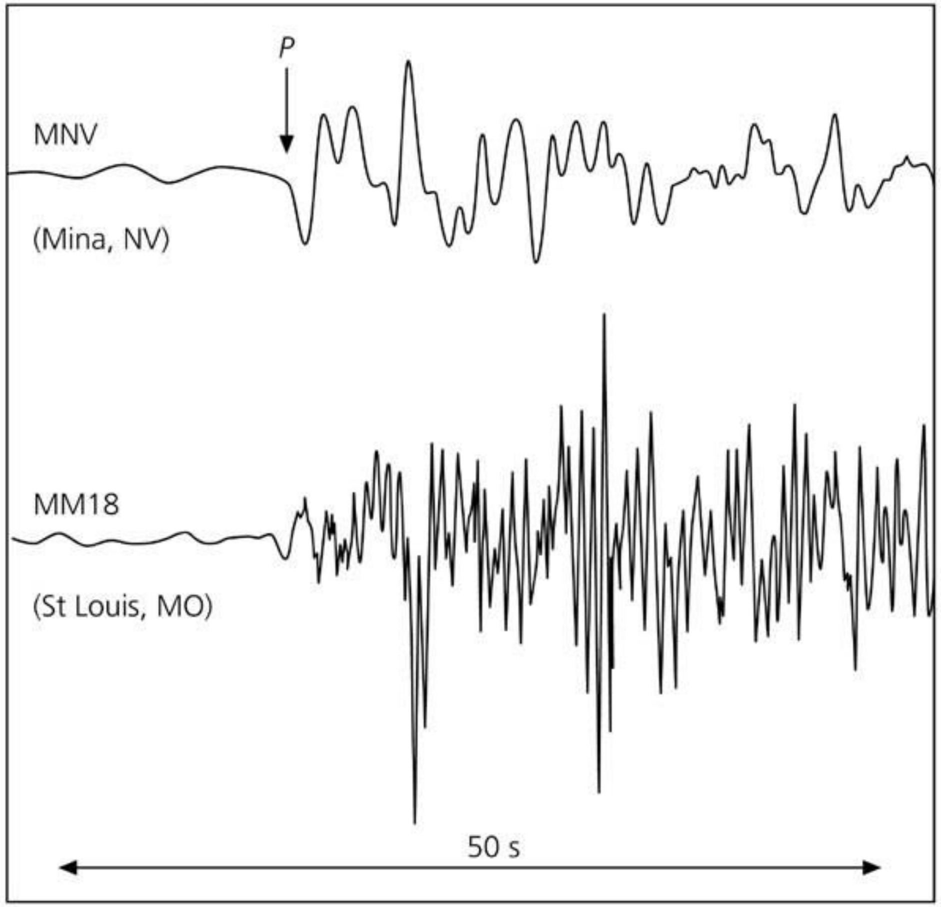


Figure 3.7-1: Regional effects of attenuation.



Causes

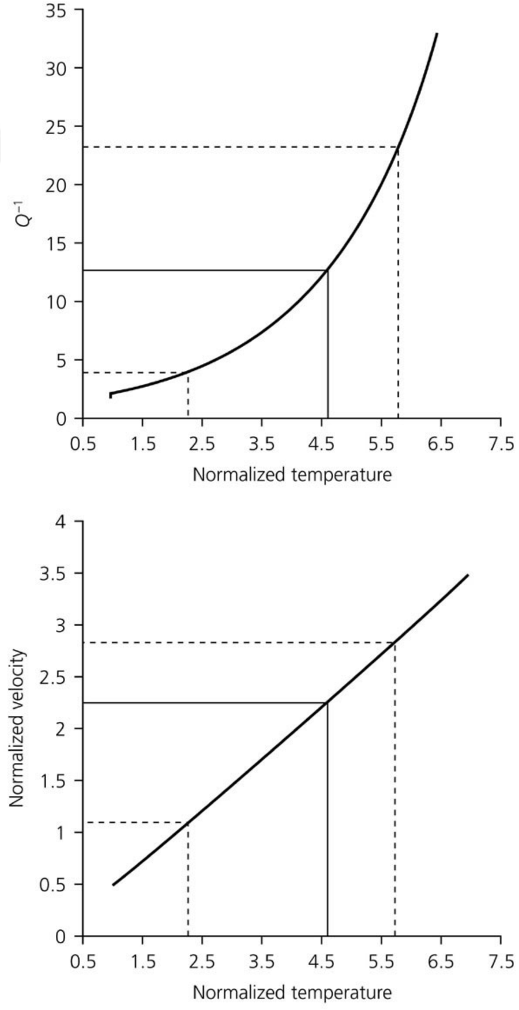
Macroscopic: internal friction

Microscopic:

- ❑ **Stress-induced migration of defects in minerals.**
- ❑ **Frictional sliding on crystal grain boundaries**
- ❑ **Vibration of dislocations**
- ❑ **Flow of hydrous fluids**
- ❑ **Magma through grain boundaries.**

Wave Attenuation

Figure 3.7-2: Cartoon of the effects of temperature on velocity and attenuation.



- **Attenuation facilitates to study temperature variations within the earth, such as mantle convection, plate tectonics, magmatism, etc.**

- **Elastic velocities are also sensitive to temperature, but are better for mapping cold (fast) anomalies like subducting slabs than hot (slow) material like that at mid-ocean ridges.**

- **Seismic velocities depend nearly linearly upon temperature.**

- **Whereas attenuation depends exponentially on temperature.**

Wave Attenuation

Geometric spreading

- **Variation of seismic wave amplitudes with distance is geometric spreading, in which the energy per unit wave front varies as a wave front expands or contracts.**

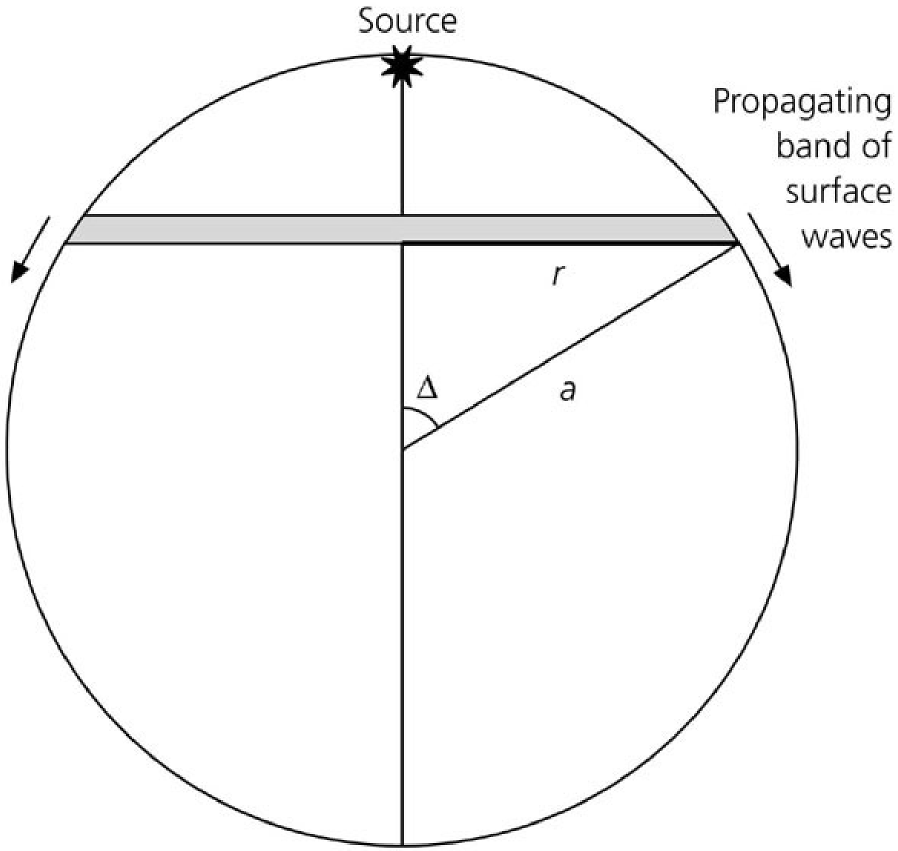
- **Geometric spreading differs for surface and body waves.**

- **On a homogeneous flat earth, the surface waves would spread out in a growing ring with circumference $2\pi r$, where r is the distance from the source.**

- **Conservation of energy requires that the energy per unit wave front decrease as 1/r, whereas the amplitudes decrease as $1/r^{1/2}$ (square root of energy).**

Geometric spreading : Surface Waves

Figure 3.7-4: Geometric spreading of surface waves.



- **Energy on the surface waves propagates in the form of rings,**

$$1/r = 1/(a \sin \Delta),$$

where Δ is the angular distance from the source

- **Thus the amplitudes decrease as $(a \sin \Delta)^{-1/2}$, with minimum at Δ = 90°, and maxima at 0° and 180°.**

Geometric spreading : Body Waves

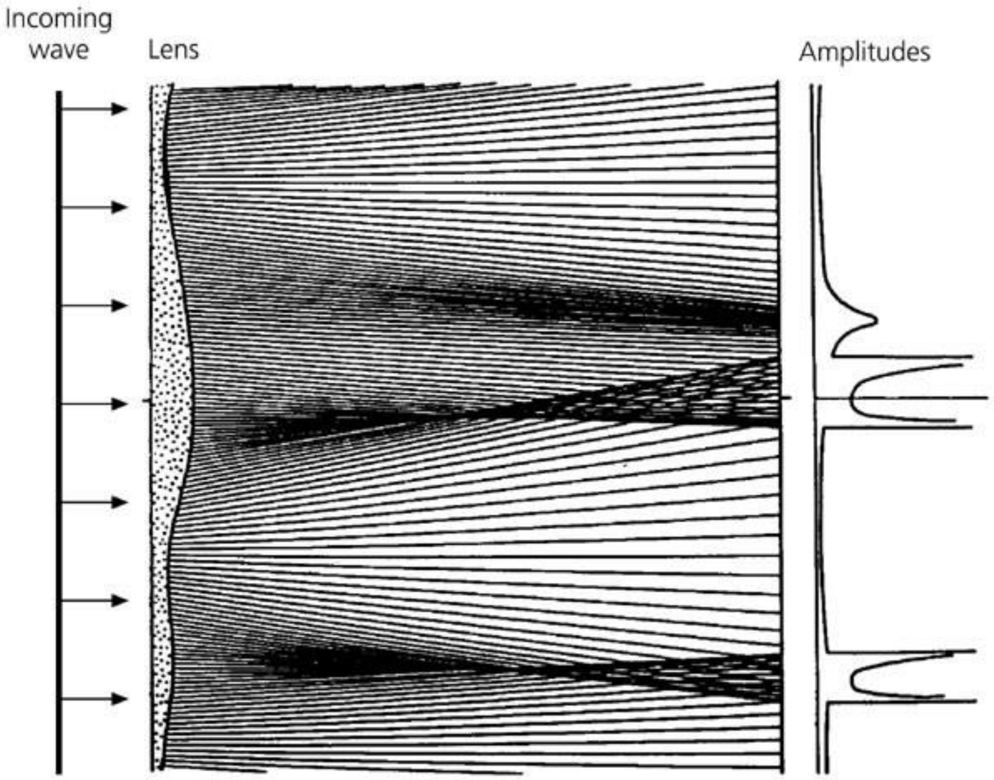
- **Energy is conserved on the expanding spherical wavefront whose area is $4\pi r^2$, where r is the radius of the wavefront moving away from a deep earthquake.**

- **Thus the energy per unit wave front decays as $1/r^2$, and the amplitude decreases as $1/r$.**

- **In reality, because body waves travel through an inhomogeneous earth, their amplitude depends on the focusing and defocusing of rays by the velocity structure.**

Multipathing

Figure 3.7-5: Example of velocity heterogeneities affecting wave amplitudes.



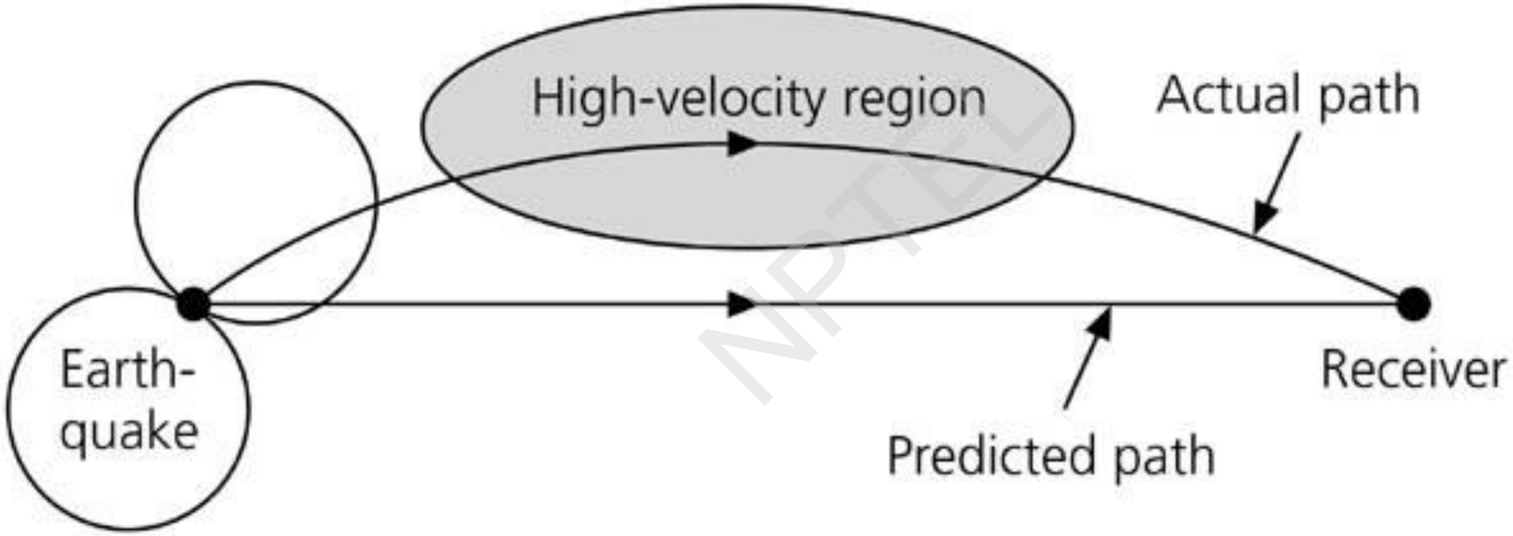
- **Seismic waves are also focused and defocused by lateral variations in velocity.**

- **Seismic waves refract towards low-velocity anomalies and away from high velocity anomalies.**

- **Regions of wide ray spacing have low amplitudes, and dense spacing yields large amplitudes. Concentrated lines, or caustics, cause very high amplitudes.**

- **Rays will preferentially pass through high velocity regions (Fermat's Principle).**

Figure 3.7-6: Cartoon of velocity heterogeneity causing multipathing.



- When multipathing occurs, the seismic waves arriving at a receiver can be viewed as having taken some ray paths in addition to the direct path.

- Fermat’s principle applies exactly only to waves of infinite frequency.

- For waves of finite frequency, we can view the seismic waveform as a coherent sum of energy that travels all possible paths that arrive within a half-period of the infinite-frequency wave, which took the shortest time.

- These paths form a volume called the first Fresnel zone around the infinite-frequency path. These are also called as banana-doughnut kernels.

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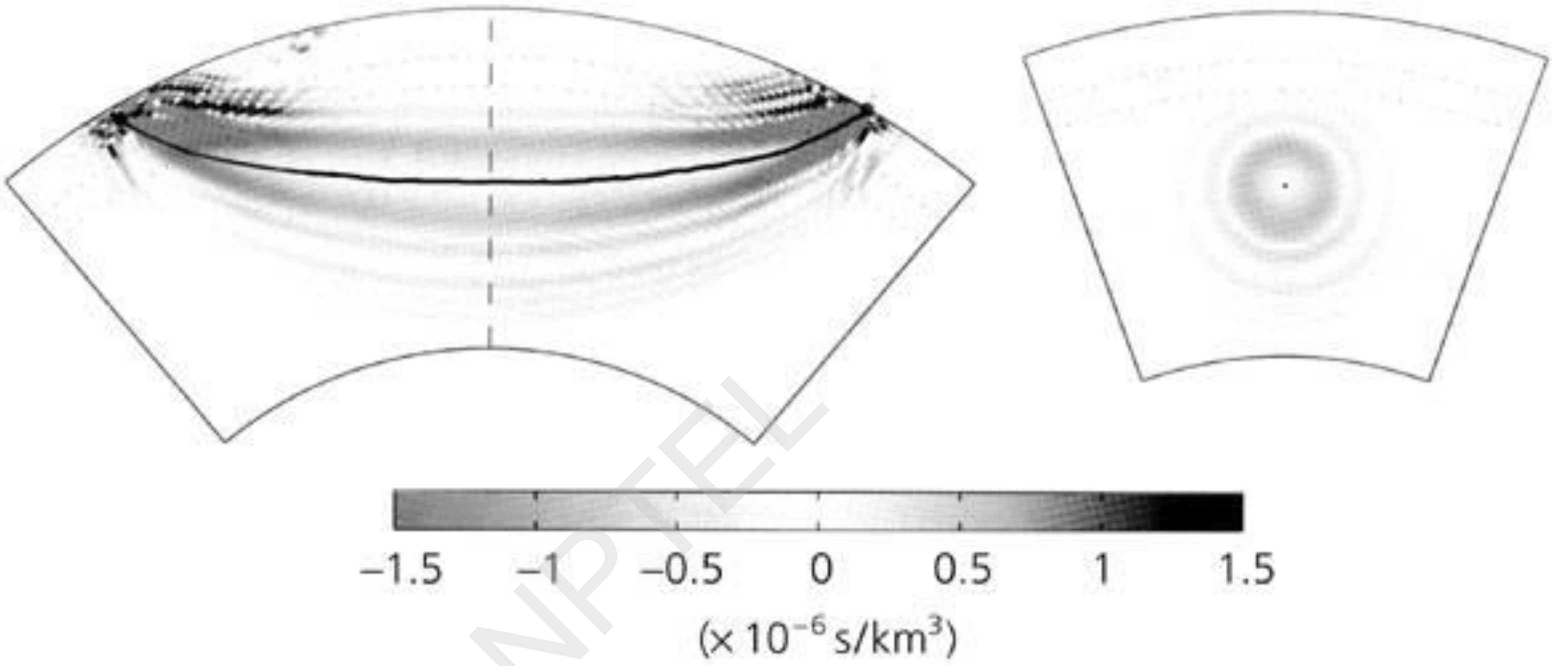
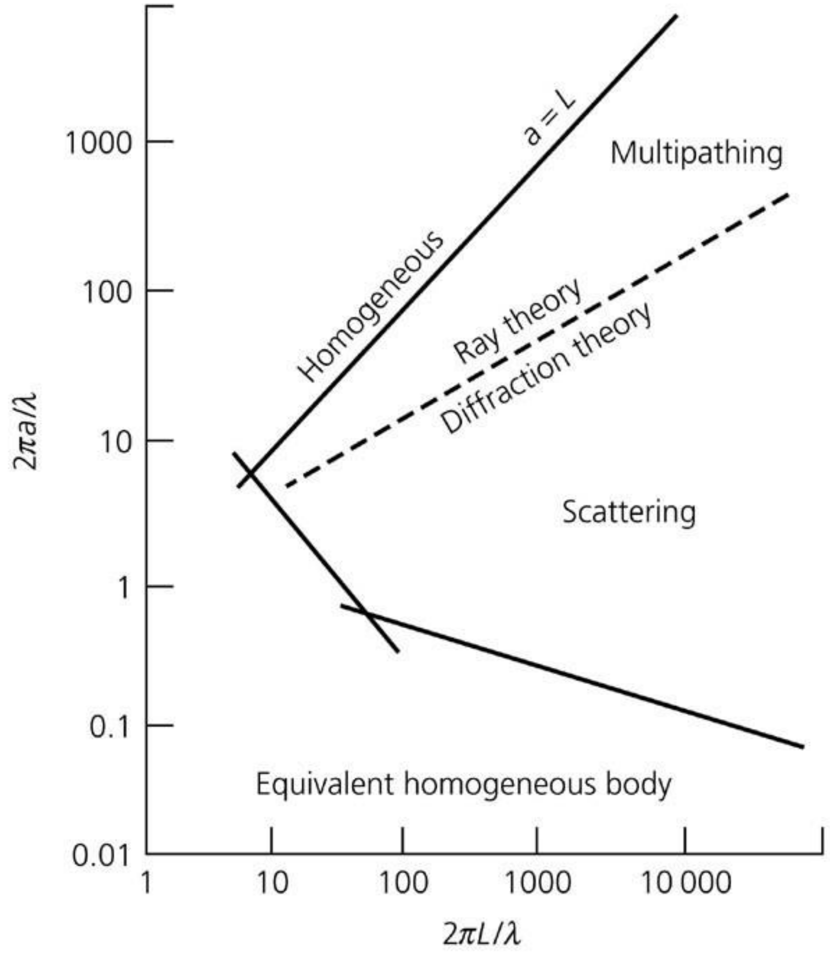
Figure 3.7-7: Fresnel zone for *S* and *sS* waves.



- ➔ Seismic waves sample a banana-shaped region about the ray in a laterally homogeneous earth.
- ➔ The curved ray path represents the effects of vertical velocity variations on the infinite frequency ray, and the surrounding "banana" represents the effects of finite-frequency waves.

Scattering

Figure 3.7-8: Different approaches to wave propagation in a heterogeneous medium.



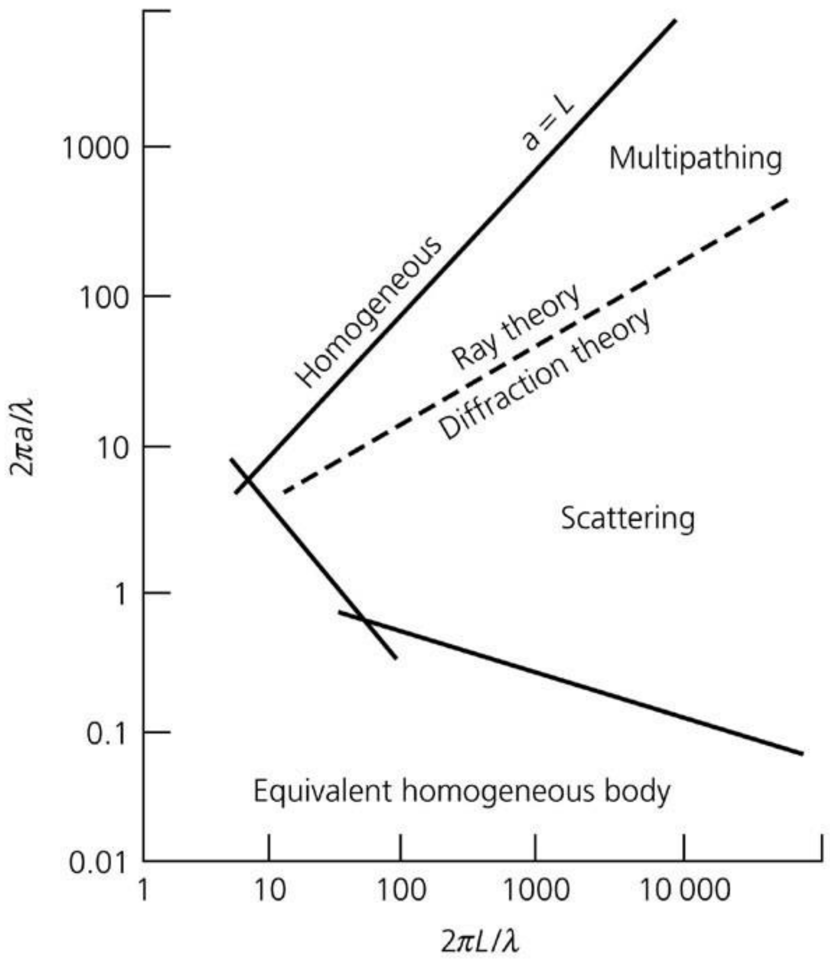
Scattering occurs a slightly smaller scale than multipathing

Both effects are complicated, and there is a tiny distinction between them.

Scattering occurs when there is a velocity heterogeneities on the order of λ. In this case, ray theory does not do well.

"When the heterogeneity is large compared to the wavelength, we regard the wave as following a distinct ray path that is distorted by multipathing."

Figure 3.7-8: Different approaches to wave propagation in a heterogeneous medium.



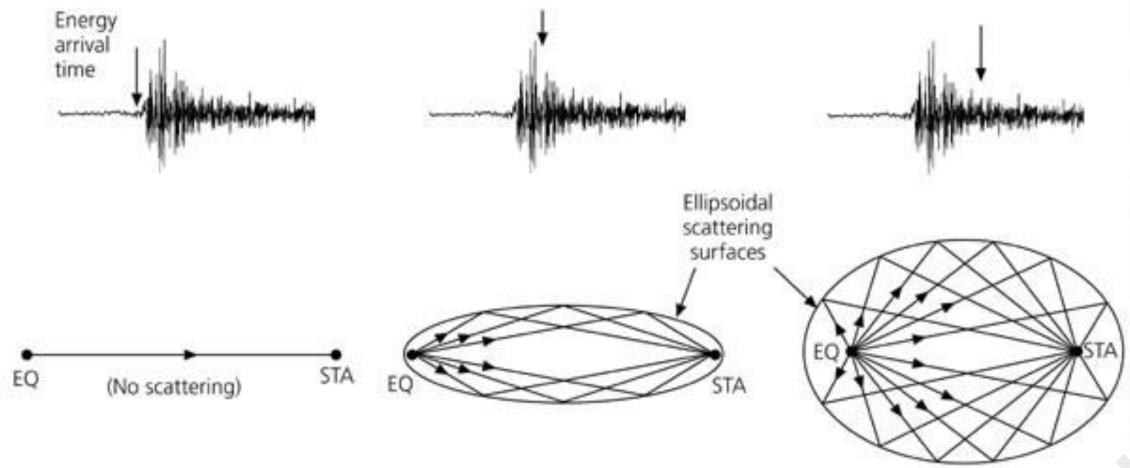
- **When the velocity heterogeneities are closer in size to the wavelength, we think of scattered energy rather than distinct ray paths.**
- **When the heterogeneities are much smaller than the wavelength, they simply change the medium's overall properties. Then scattering dominates.**

- **Diffraction can be viewed as behavior intermediate between scattering and multipathing.**

- **Scattering is especially important in the continental crust, which has many small layers and reflectors resulting from billions of years of continental evolution.**

Wave Attenuation: Scattering

Figure 3.7-9: Development of a *P*-wave coda.



Left : The unscattered wave travels the shortest distance and gives the initial arrival

Center: Scattered energy arrives after the first arrival. An infinite number of possible locations for scatterers yield arrivals at this same time. In a homogeneous medium the locus of these points forms an ellipsoidal surface.

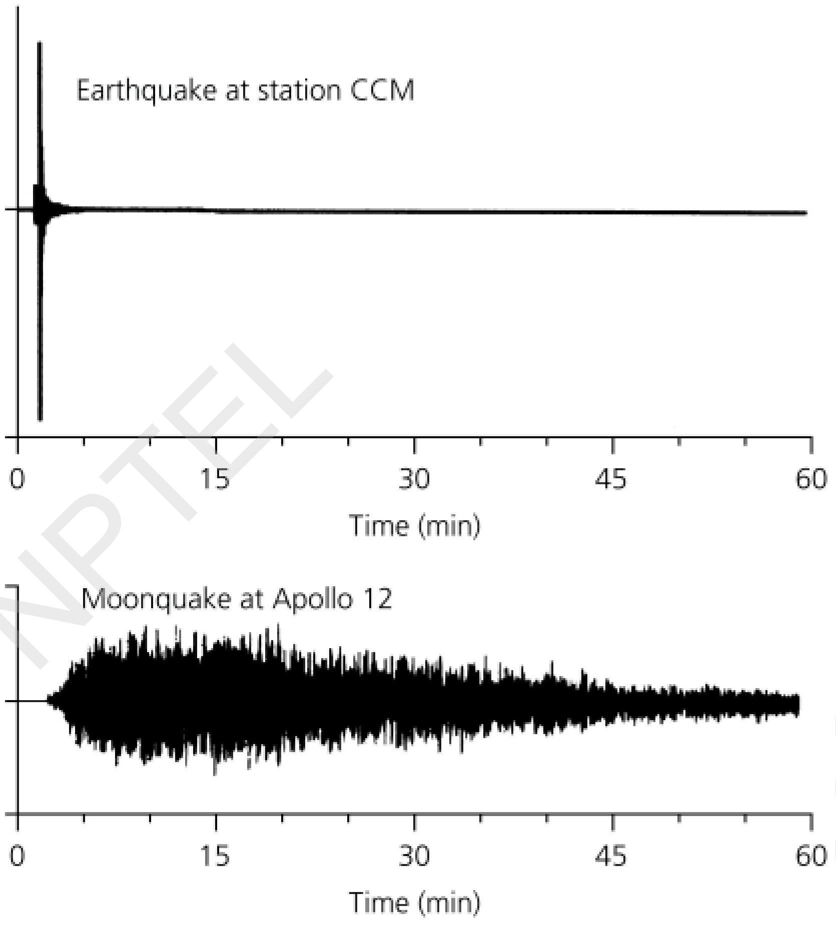
Right: Energy arriving later in the coda can be modeled as arising from a larger ellipsoidal surface of possible scatterers.

Comparison of seismograms for Earth and Moon.

- **High attenuation on Earth and Intense scattering on Moon.**

- **Since intrinsic attenuation is less on Moon, so it takes long time to damp out for the seismic energy.**

Figure 3.7-10: Comparison of seismograms on the earth and moon.



Summary

- Geometric spreading, scattering and multipathing reduces the amplitudes but propagating wavefield is conserved.

- Seismic velocities depend nearly linearly upon temperature, whereas attenuation depends exponentially on temperature. Thus combining velocity and attenuation studies can provide valuable information.

- Because the earth is a sphere, the ring wraps around the globe making the energy per unit wavefront of the surface waves vary as:

  $1/r = 1/(a \sin \Delta)$, where Δ is the angular distance from the source

- Amplitudes decrease as $(a \sin \Delta)^{-1/2}$, with minimum at $\Delta = 90°$, and maxima at 0° and 180°.

- For Body waves, energy per unit wave front decays as $1/r^2$, and the amplitude decreases as $1/r$.

Summary

- Seismic waves refract towards low-velocity anomalies and away from high velocity anomalies.

- When multipathing occurs, the seismic waves arriving at a receiver can be viewed as having taken some ray paths in addition to the direct path, and so have sampled a larger region of the earth.

- When the heterogeneity is large compared to the wavelength, we regard the wave as following a distinct ray path that is distorted by multipathing.

- Scattering is especially important in the continental crust, which has many small layers and reflectors resulting from billions of years of continental evolution.

- The main arrival has a polarity related to the direction of propagation but the scattered energy arrives from various directions shows little or no preferred particle motion.

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- Seismology course, Professor Derek Schutt, Colorado State Univ., USA.

THANK YOU !