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 02: Shear Wave Splitting, Anisotropy in the Lithosphere and Asthenosphere

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CONCEPTS COVERED

- Recap
- Anisotropy in the lithosphere and the asthenosphere
  - Shear Wave Splitting
- Anisotropy in the mantle and the core
- Summary

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Recap

- Any material in which more than two elastic constants are need is called anisotropic.

- Minerals and rock comprises anisotropy either due to Lattice Preferred Orientation (LPO) or Shape-Preferred Orientation (SPO).

- Transverse isotropy is often characterized by three parameters
  $\xi = N/L = (S_1/S_2)^2$, $\phi = C/A = (P_2/P_1)^2$, $\eta = F/(A - 2L)$
  → If the material were isotropic, $\xi = \phi = \eta = 1$.
  → For layered structures, generally $\xi > 1$ and $\phi < 1$

- In general, the P-wave velocity varies with azimuth as:

$$P(\theta) = A_1 + A_2 \cos(2\theta) + A_3 \sin(2\theta) + A_4 \cos(4\theta) + A_5 \sin(4\theta)$$

- The magnitude of anisotropy is characterized by:

$$k = \frac{v_{\max} - v_{\min}}{v_{mean}}$$

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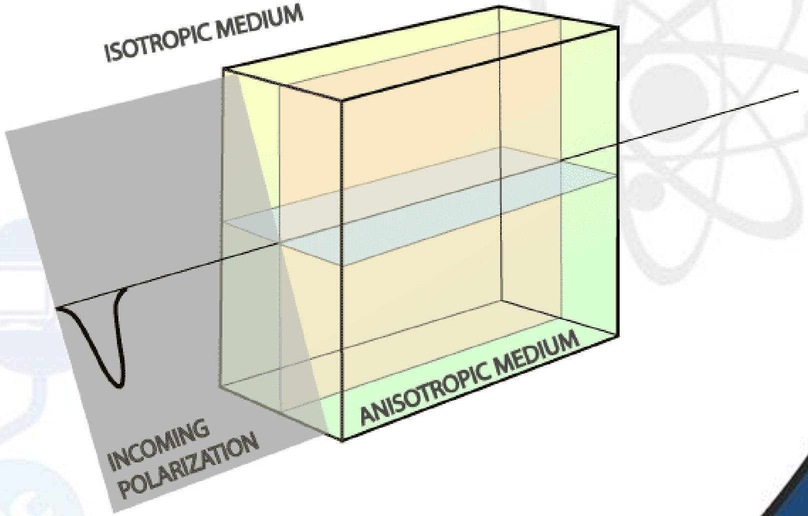
Anisotropy in the lithosphere and the asthenosphere

Shear Wave Splitting



- **Anisotropy within and beneath continental lithosphere is often studied with a technique called shear wave splitting.**

- **When SKS waves convert from P waves in the outer core to S waves in the lower mantle, they are entirely polarized in the radial (SV) direction, because all the initial SH energy was reflected when the downgoing S wave encountered the core–mantle boundary.**

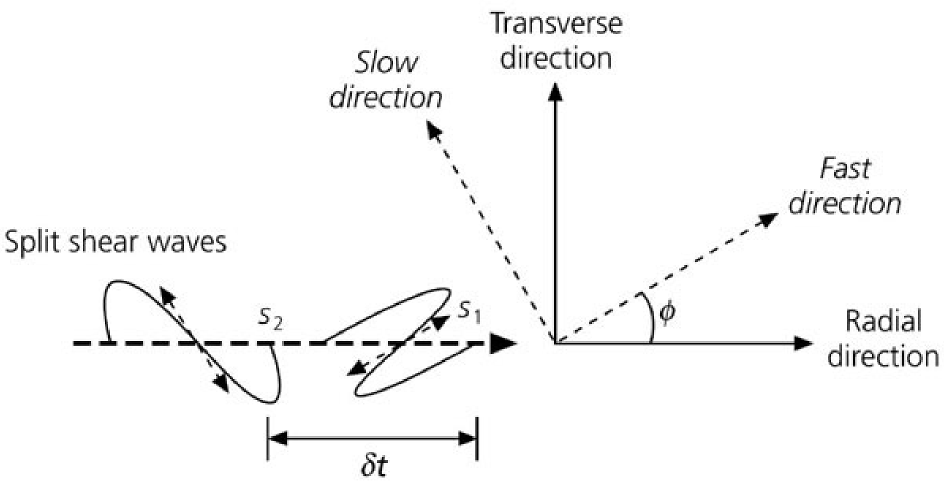
- **After encountering an anisotropic layer, the wave gets "split" onto the fast (qS_1) and slow (qS_2) axes.**

Shear Wave Splitting

- **Assuming transverse isotropy with a horizontal axis of symmetry, the two polarized waves travel at different speeds and arrive at different times.**

- **Thus, if the SKS signal on the radial component in an isotropic earth is s(t), its projection into the fast ($s_1(t)$) and slow ($s_2(t)$) polarizations is, respectively,**

Figure 3.6-6: Orientation of split shear waves.



$$s_1(t) = s(t)\cos\phi\,, \qquad s_2(t) = s(t-\delta t)\sin\phi$$

where ϕ is the polarization angle between the radial direction and the fast axis.

δt is the delay time between the fast and slow polarizations.

Typical values for dt from upper mantle splitting are 0.5-3.0 s.

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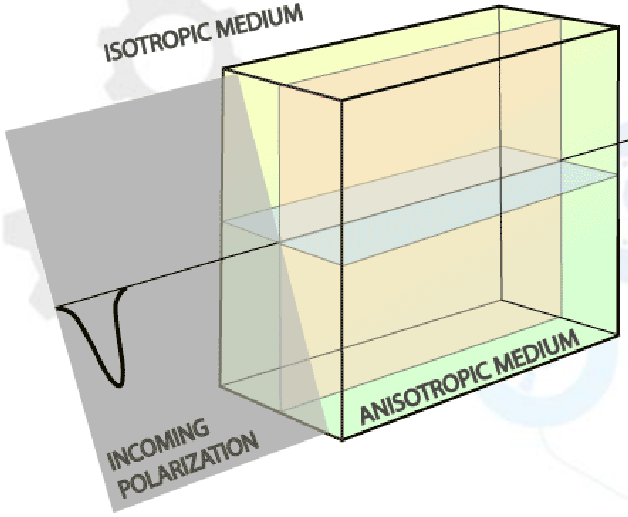
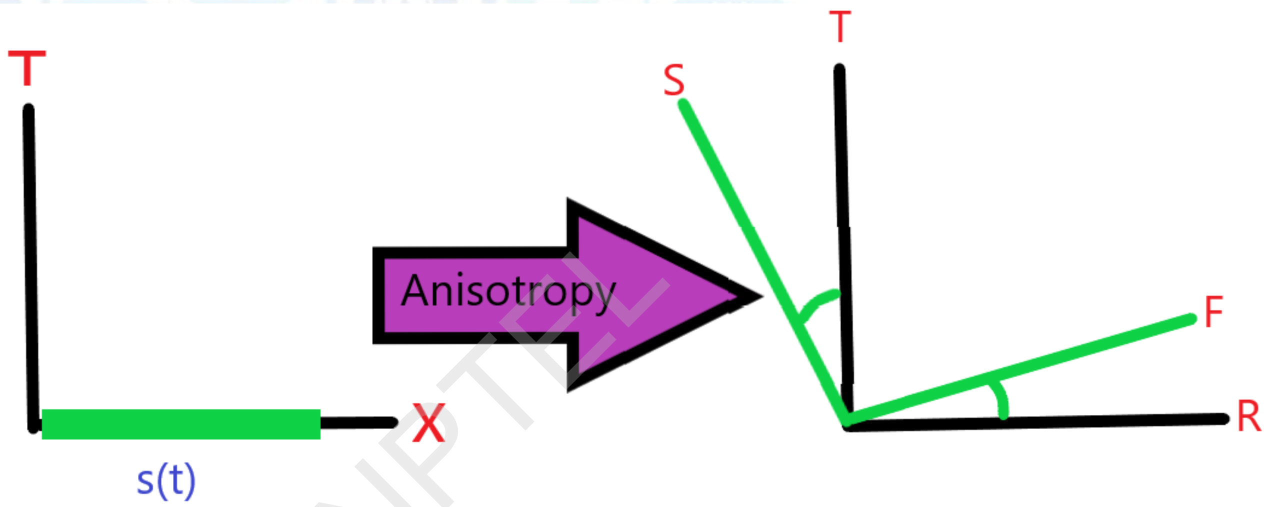
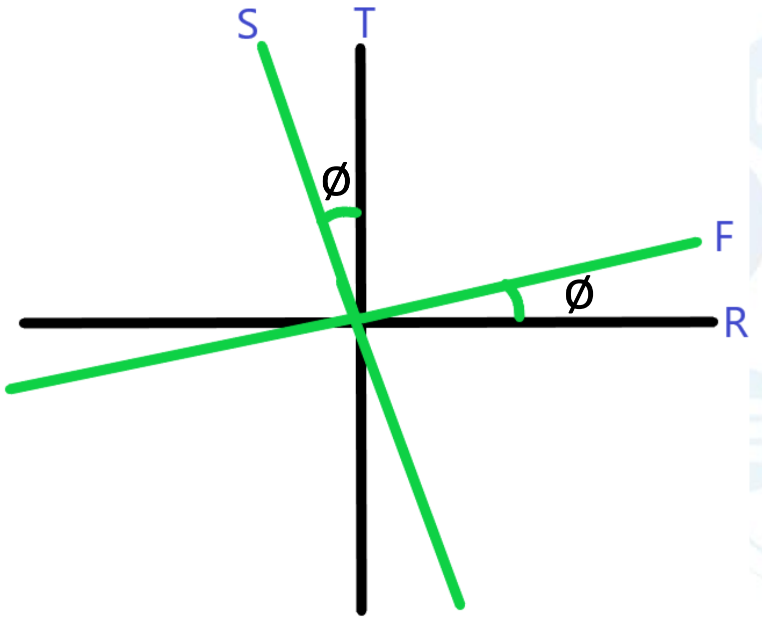


$$s_1(t) = s(t)\cos\phi\,, \qquad s_2(t) = s(t-\delta t)\sin\phi$$



'K' wave coming after the outer core. All energy (i.e. SV energy) is in the radial direction.

As it enters anisotropy, s(t) gets distributed onto the fast and slow axes. The wave on the slow axis is delayed by δt.



→ **We generally prefer R-T coordinate system at a seismometer (radial (SV)-tangential (SH)).**

→ **So, to understand the waveform we see, we will want to rotate the F(t) and S(t) waveforms onto the radial and transverse channels.**

$$R(t) = F(t)\cos\phi - S(t)\sin\phi$$
$$= s(t)\cos^2\phi + s(t-\delta t)\sin^2\phi$$

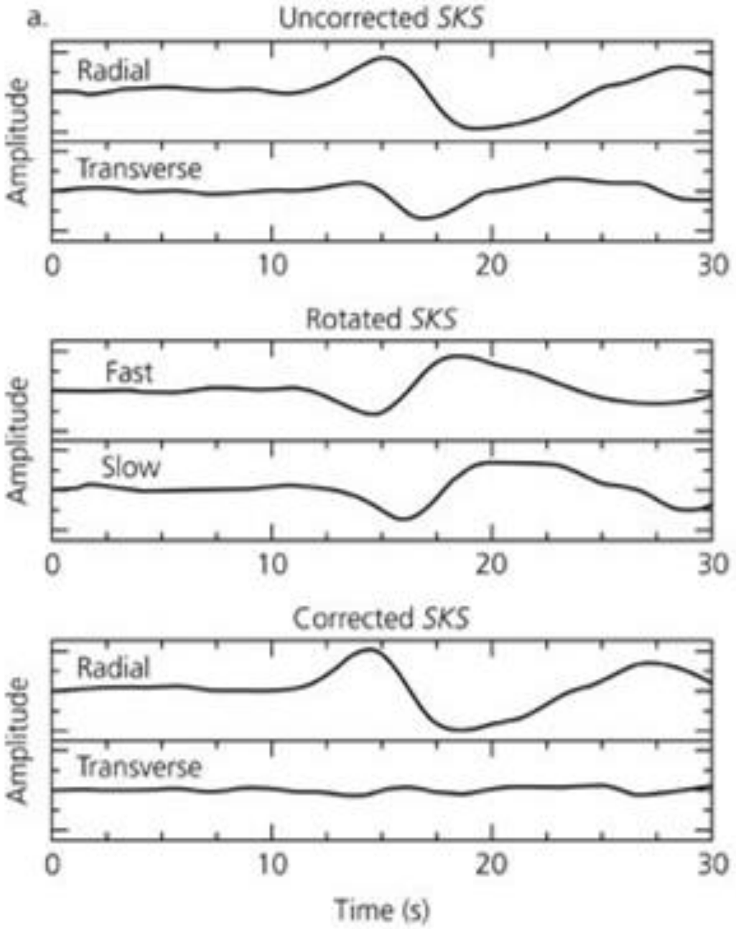
δt is the travel time difference between the fast and slow waves. If d is the distance the waves travel the anisotropic material, and v_f and v_s are the velocities of the qS1 (fast) and qS2 (slow), then

$$\delta t = d/v_f - d/v_s$$

$$T(t) = F(t)\cos\phi + S(t)\sin\phi$$
$$= s(t)\cos\phi\sin\phi - s(t-\delta t)\cos\phi\sin\phi$$

Shear Wave Splitting

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:



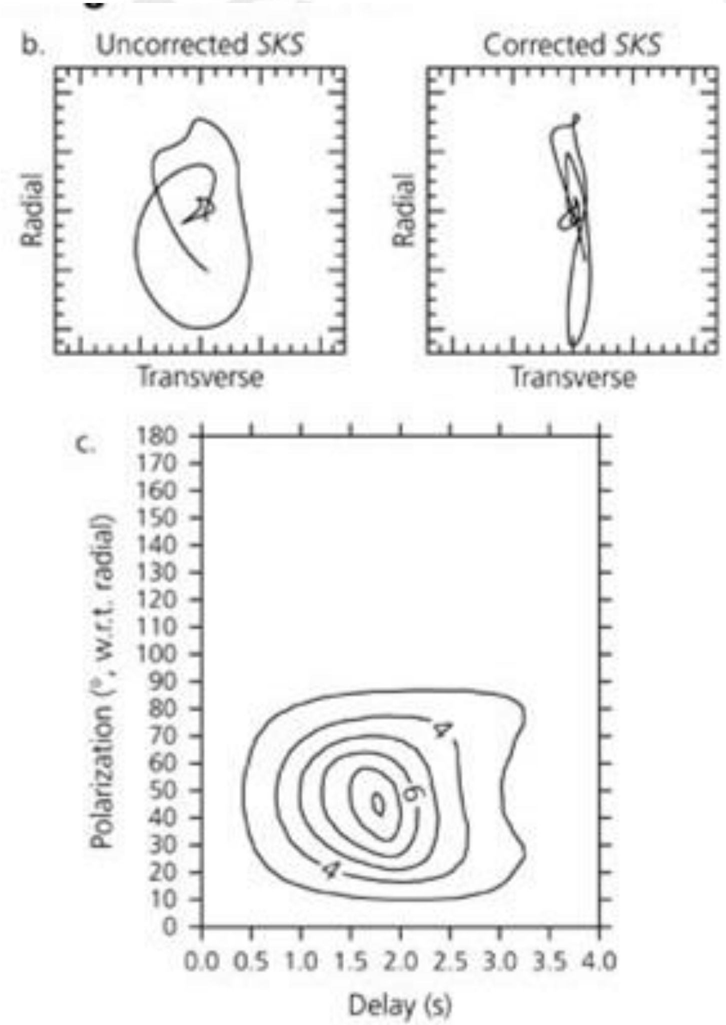
$$R(t) = s(t)\cos^2\phi + s(t-\delta t)\sin^2\phi,$$
$$T(t) = [s(t) - s(t-\delta t)/2]\sin 2\phi$$

Top: radial and transverse components before processing. Note the large SKS signal on the transverse component, which should not be there for an isotropic earth.

Middle: SKS waveforms after rotation into the fast and slow polarizations yields $s_1(t)$ and $s_2(t)$. It uses polarization angle. Both should look similar because s(t) is same.

Bottom: SKS waveform after the splitting has been removed so that all SKS is on the radial component.

Shear Wave Splitting



- **Before correction, particle motion occurs on both components, but after correction, the motion is limited to the radial component.**
- **The fact that this technique removes the transverse signal shows the appropriateness of the transversely isotropic model.**
- **We prepare a grid between ϕ and δt and minimize the transverse signal, as shown by the contour plot.**
- **"Typical values for the magnitude of shear wave splitting, δt, are in the 0–2 s range."**

Anisotropy in the lithosphere and the asthenosphere

Points to remember!

- **Horizontal sediment layers can create transverse isotropy of up to 15% with a vertical symmetry axis.**

- **Azimuthal anisotropy is thought to exist with a horizontal axis perpendicular to the dikes intruded in the upper crustal layer of vertical-sheeted basaltic dikes.**

- **A primary source of anisotropy in the upper crust is the presence of cracks, often fluid-filled. When these cracks occur in horizontal sediments that would by themselves have vertical-axis transverse isotropy, the combined result can be orthorhombic symmetry.**

- **The lower continental crust tends to have strong sub-horizontal layering, perhaps resulting from ductile deformation, which causes seismic anisotropy.**

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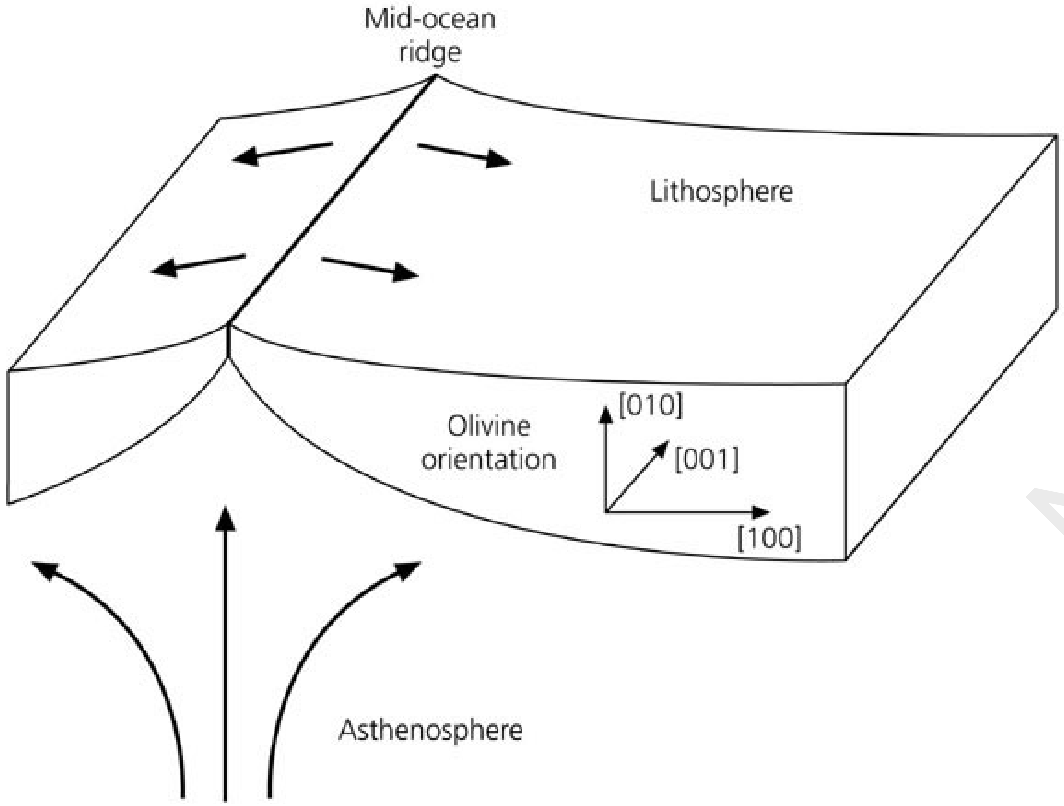
Anisotropy in the lithosphere and the asthenosphere

Figure 3.6-4: Example of anisotropy in the oceanic lithosphere.



- **Sub-crustal oceanic lithosphere shows strong azimuthal anisotropy.**

- **Spreading process yields a preferred orientation of olivine crystals in the oceanic lithosphere, with the fast axis of velocity in the spreading direction.**

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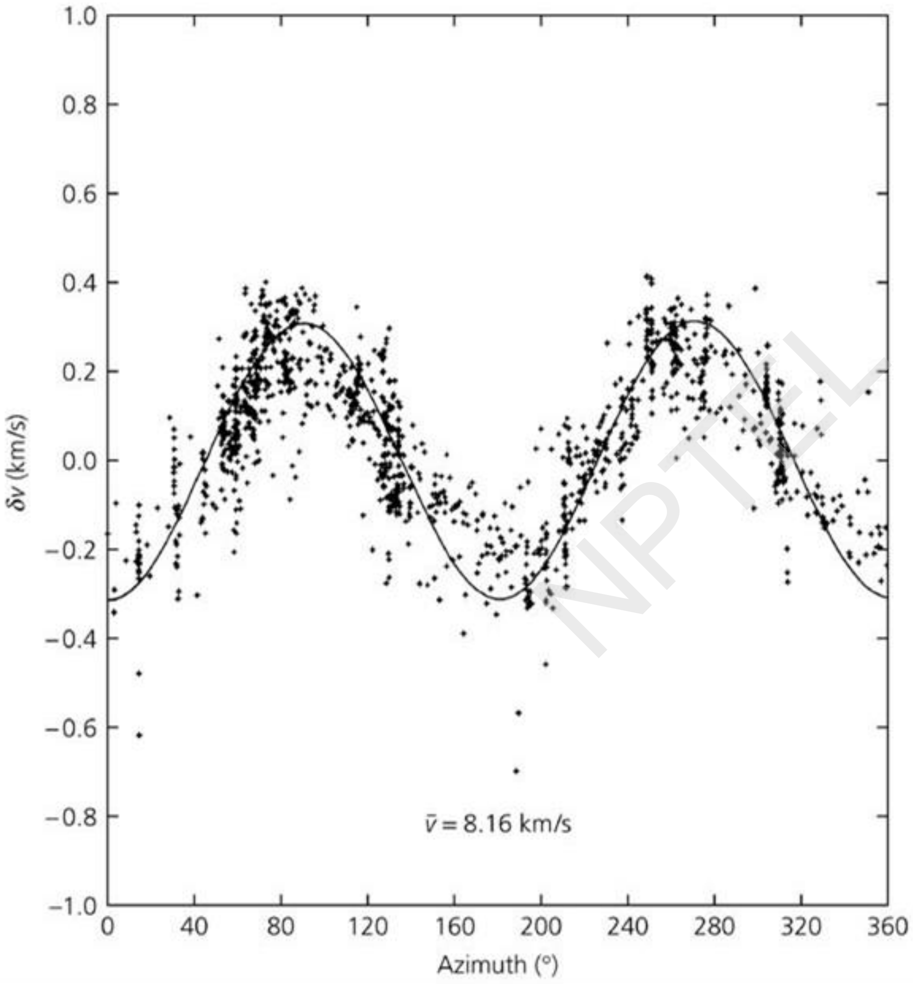
Anisotropy in the lithosphere and the asthenosphere



- **Variations of P_n wave velocities near Hawaii.**
- **The maxima at 90^0 and 270^0 show that the fast direction of the azimuthal anisotropy is in the direction of spreading when the plate formed.**

Anisotropy in the lithosphere and the asthenosphere

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

- The anisotropy is a result of the last episode of tectonism, which resets any previous anisotropy.

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

- There may also be deeper anisotropy due to oriented olivine in the flowing asthenosphere. However, it is sometimes difficult to distinguish this effect from lithospheric anisotropy.

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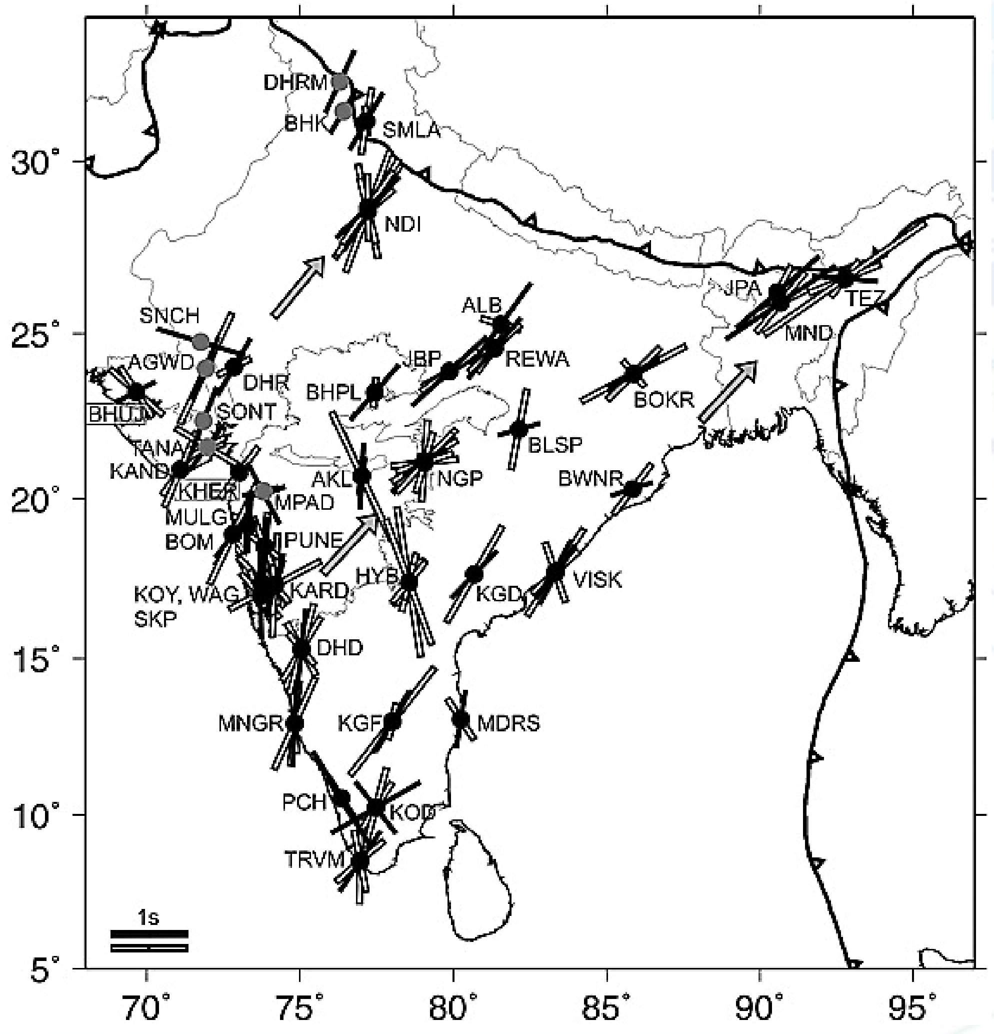
Anisotropy in the lithosphere and the asthenosphere



- ➔ **Most of the fast axis azimuths tend to be aligned in the NE direction, close to the absolute plate motion direction of the Indian plate, followed by a N-S trend.**
- ➔ **It is parallel to the direction of both absolute plate motion (and thus presumably asthenospheric flow).**

(From Saikia et al., 2010)

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Anisotropy in the lithosphere and the asthenosphere

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

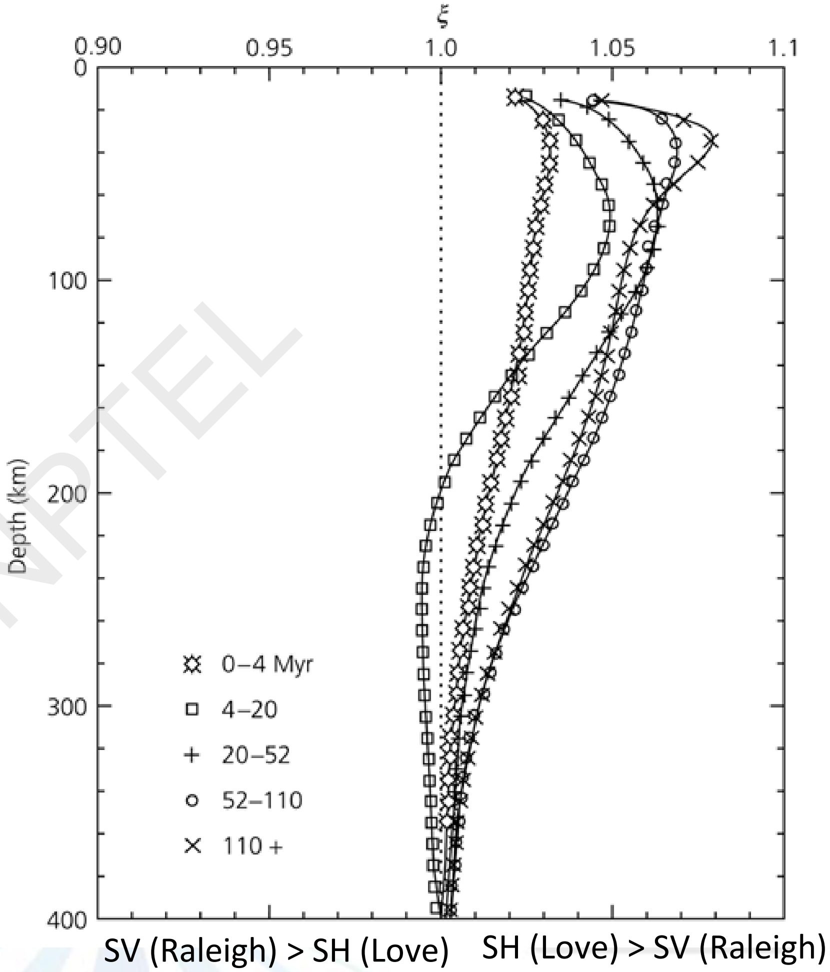
When ξ > 1, then

- **Love wave velocity is fast than Rayleigh wave.**
- **It indicates horizontal mantle flow.**

When ξ < 1, then

- **Love wave velocity is lesser than Rayleigh wave.**
- **It indicates vertical mantle flow.**

Figure 3.6-9: Anisotropy in the Pacific Ocean as a function of age and depth.



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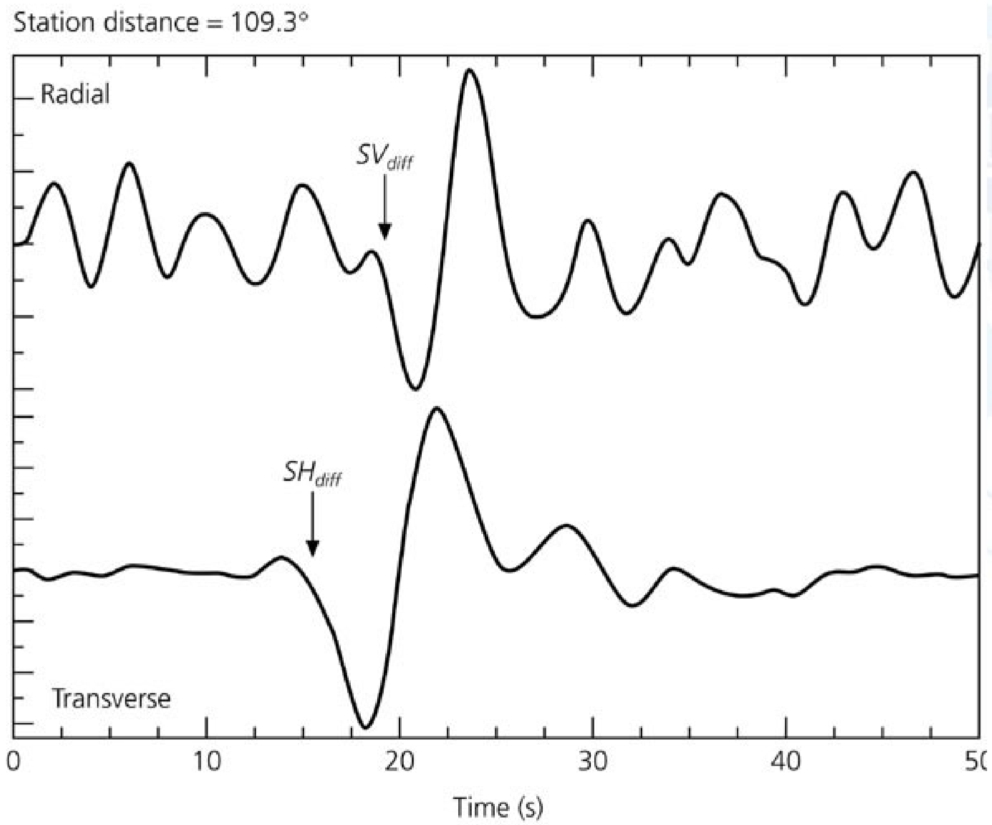
Anisotropy in the mantle and the core

Figure 3.6-10: Splitting of a diffracted *S* wave.



- **Evidence for anisotropy at the base of the mantle, shown by diffracted arrivals for a South American earthquake recorded at a Canadian station.**

- **Arrows show estimates of the onset times. Diffracted SH arrives before SV, suggesting transverse isotropy.**

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Summary

- 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:

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

$$\delta t = d/v_f - d/v_s$$

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.

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Summary

- **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.

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

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THANK YOU !

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