Seismic Wave Types

ESS 314 Geophysics · University of Washington

Week 1, Lecture 4 · April 2, 2026

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By the end of this lecture…

- **[LO-4.1]** *Classify* P, S, Rayleigh, Love waves by particle motion, polarization, and medium
- **[LO-4.2]** *Explain* physically why S-waves cannot travel in fluids — beyond stating $\mu = 0$
- **[LO-4.3]** *Compare* V_P and V_S across Earth materials; identify the controlling properties
- **[LO-4.4]** *Apply* the S–P time method to estimate earthquake distance from one seismogram
- **[LO-4.5]** *Distinguish* Rayleigh from Love waves; explain why Love requires layering

One Earthquake, Three Arrivals

2011 Tōhoku M9.0 — recorded in Seattle 8,000 km away

The **P-wave** arrives first — fast, compressional, vertical motion

Then the **S-wave** — slower, shear, horizontal motion, larger amplitude

Then **surface waves** — slowest, largest, longest duration

Same source. Same Earth. Different wave physics.
(The same question has been asked — and answered — on the Moon and Mars.)

Why Multiple Wave Types?

The 3D elastic wave equation has two independent solutions:

$$\rho \frac{\partial^2 \mathbf{u}}{\partial t^2} = (\lambda + 2\mu)\, \nabla(\nabla \cdot \mathbf{u}) - \mu\, \nabla \times (\nabla \times \mathbf{u})$$

Helmholtz decomposition $\mathbf{u} = \nabla\phi + \nabla \times \boldsymbol{\psi}$ splits this into:

$$\frac{\partial^2 \phi}{\partial t^2} = V_P^2\, \nabla^2 \phi \qquad \frac{\partial^2 \boldsymbol{\psi}}{\partial t^2} = V_S^2\, \nabla^2 \boldsymbol{\psi}$$

> The wave equation *must* produce exactly two body-wave families — elastic deformation has exactly two independent modes: **volume change** (P) and **shape change** (S).

P-waves: Longitudinal Motion

P = Primary · Compressional · Longitudinal

Particle motion **parallel** to propagation — alternating compression (C) and rarefaction (R)

Exists in **solids and fluids** — fastest seismic arrival

$$V_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

> Think: a slinky pushed end-to-end. The compression pulse travels forward while individual coils oscillate back-and-forth *along* the slinky's axis.

P-wave Particle Motion

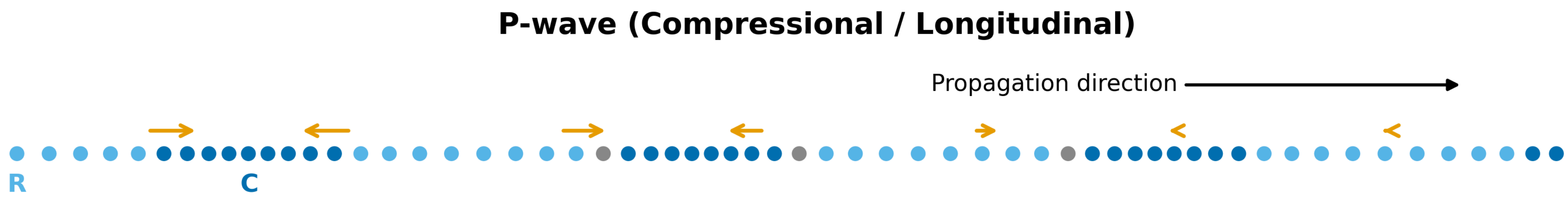


Figure 4.1. P-wave: longitudinal (compressional) particle motion — particles move parallel to the ray. Python-generated — assets/scripts/fig_pwave_swave_motion.py

S-waves: Transverse Motion

S = Secondary · Shear · Transverse

Particle motion **perpendicular** to propagation — exists in **solids only**

$$V_S = \sqrt{\frac{\mu}{\rho}} \qquad (V_S < V_P \text{ always})$$

Two independent polarizations:

Polarization	Plane of motion	Mode conversion at interface?
SV	Vertical plane of the ray	Yes → converts to P or Rayleigh
SH	Horizontal, ⊥ to ray plane	No → generates Love waves only

S-wave Particle Motion

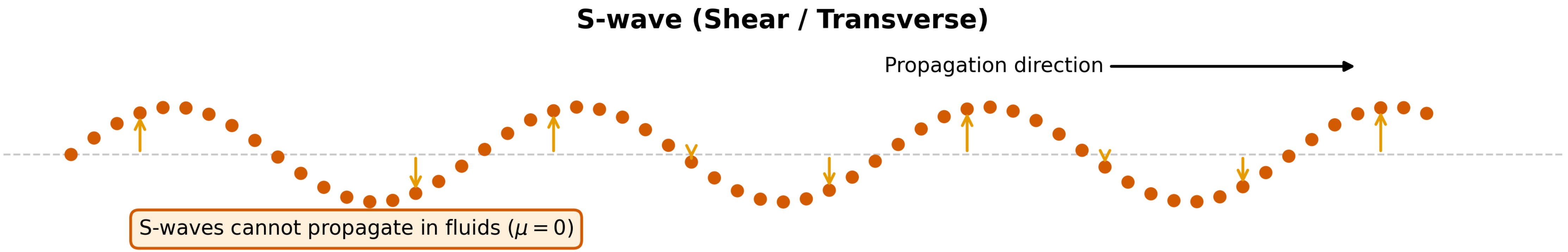


Figure 4.2. S-wave: transverse (shear) particle motion — particles move perpendicular to the ray. Python-generated — assets/scripts/fig_pwave_swave_motion.py

SV and SH Polarization Geometry

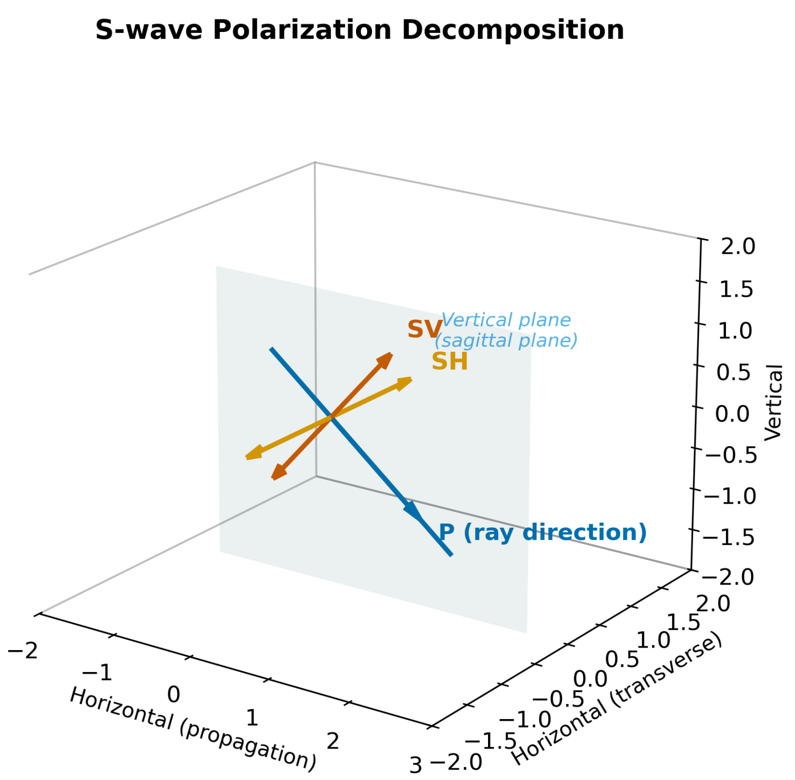


Figure 4.3. SV motion lies in the vertical plane of the ray; SH motion is horizontal and perpendicular to it. Python-generated — assets/scripts/fig_sv_sh_polarization.py

Why No S-waves in Fluids?

In a fluid: $\mu = 0 \Rightarrow V_S = 0$ — but the *formula* is not the *reason*.

The physical argument:

1. An S-wave requires the medium to **shear-distort and elastically spring back**
2. In a fluid, molecules **flow and rearrange** rather than storing shear elastic energy
3. No shear restoring force → no transverse oscillation propagates

> Consequences in this course:
>
> - S-wave **shadow zone** → liquid outer core (Lectures 17–18)
> - For those interested in ocean physics: ocean basins are **transparent to P-waves** (hydroacoustic *T*-phases) but **opaque to S**
> - High V_P/V_S in saturated sediments → direct fluid detection

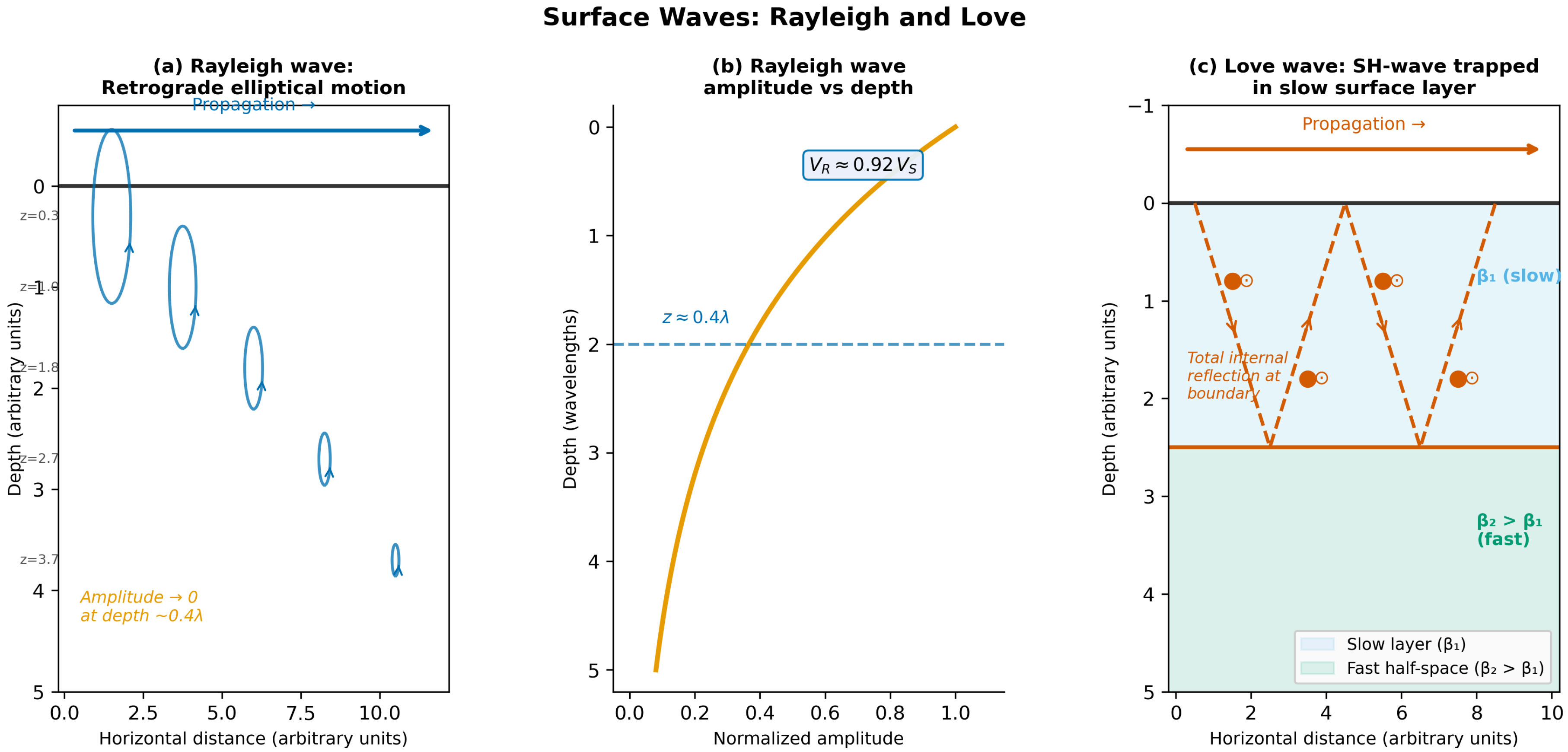
Surface Waves: Trapped at the Free Surface

Free surface boundary (zero traction) allows **guided waves** that decay as e^{-kz} and are **dispersive**:

Type	Particle motion	Speed	Requires
Rayleigh	Retrograde ellipse (P + SV)	$\approx 0.92\,V_S$	Any elastic half-space
Love	Horizontal SH only	$V_{S1} < V_L < V_{S2}$	Velocity layering

Both are **slower** than body waves and carry the **largest amplitudes** at teleseismic distances.

Rayleigh and Love Waves



Panel (a)/(b): Rayleigh wave particle motion is retrograde elliptical, decaying exponentially below ~0.4λ depth. Panel (c): Love wave requires a slow layer overlying a faster half-space (total internal reflection of SH waves).

Figure 4.4. Rayleigh: retrograde elliptical decay with depth (left, center). Love: SH trapped in slow surface layer by total internal reflection (right). Python-generated — assets/scripts/fig_surface_waves.py

Why Love Waves Need Layering

Rayleigh waves exist in **any** elastic half-space — they are a natural free-surface solution.

Love waves require a **slow layer over a faster half-space** $(V_{S2} > V_{S1})$:

1. SH waves hit the base at subcritical angles → **total internal reflection**
2. Repeated reflections between the free surface and the interface **constructively interfere**
3. Result: a trapped guided wave with purely horizontal SH particle motion

> A homogeneous half-space has Rayleigh but *not* Love waves — observing Love waves requires a layered Earth.
>
> For those interested in planetary science: NASA's InSight used surface wave dispersion from marsquakes to map the Martian crustal layering.

Seismic Wave Speeds Across Earth Materials

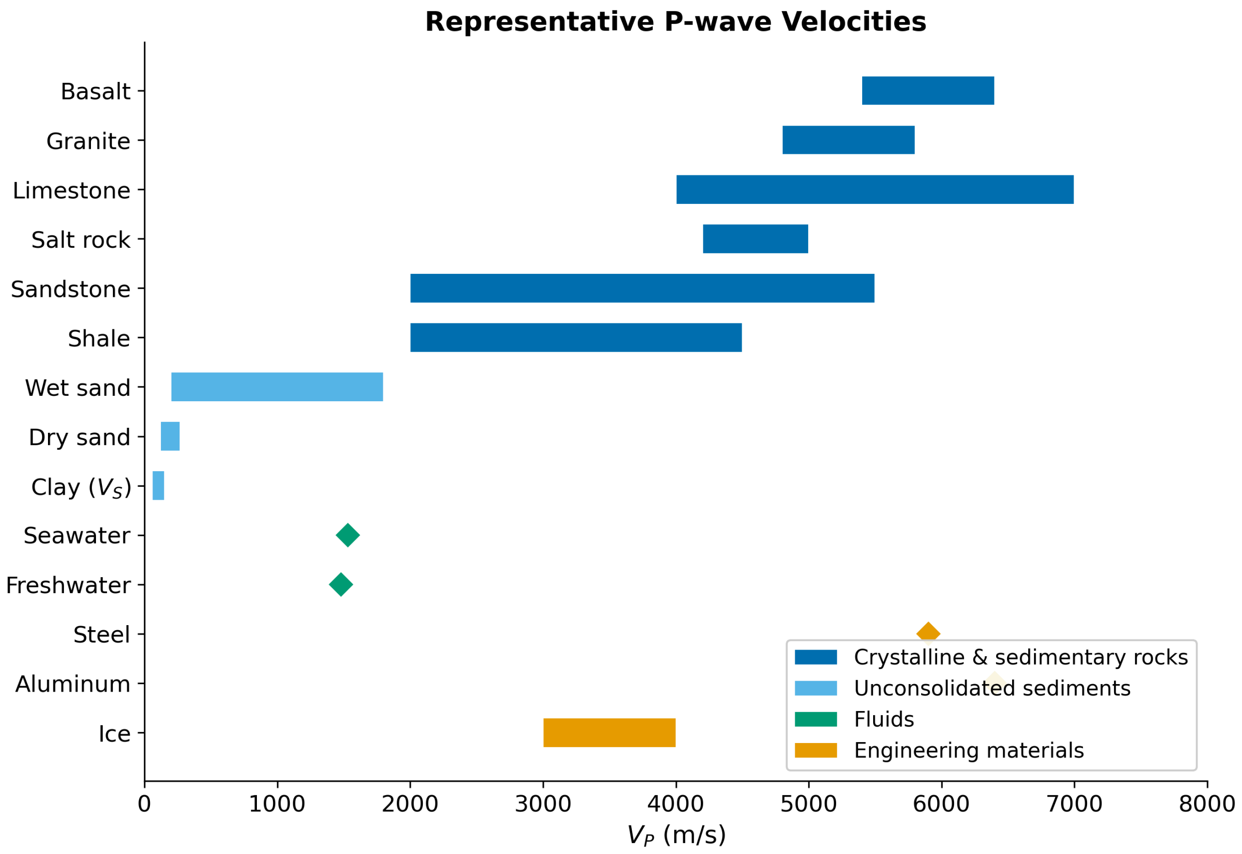


Figure 4.5. V_P spans ~100× from dry clay (60 m/s) to steel (~6000 m/s). Soft sediments can be 50× slower than basement rock. Python-generated — assets/scripts/fig_seismic_velocities.py

The V_P/V_S Ratio as a Fluid Indicator

$$\frac{V_P}{V_S} = \sqrt{\frac{\lambda + 2\mu}{\mu}} = \sqrt{\frac{2(1-\nu)}{1-2\nu}}$$

Material state	ν	V_P/V_S
Typical crustal rock	0.25	$\sqrt{3} \approx 1.73$
Dry, cracked rock	0.10–0.20	1.45–1.60
Water-saturated sediment	0.45–0.49	3.0–10.0
Perfect fluid	0.50	∞

High V_P/V_S → fluid saturation, magma, high pore pressure
Low V_P/V_S → gas sand, dry fractured rock
Seattle example: Duwamish Valley $V_P/V_S = 7.95$ (water-saturated alluvium) — why Pioneer Square shakes harder than Capitol Hill.

The S–P Time Method

P and S travel the same distance d at speeds $V_P > V_S$:

$$\Delta t_{SP} = t_S - t_P = d\left(\frac{1}{V_S} - \frac{1}{V_P}\right) \qquad \Rightarrow \qquad d = \frac{\Delta t_{SP}}{\frac{1}{V_S} - \frac{1}{V_P}}$$

One seismometer + one clock = earthquake distance

Used in real time by **PNSN** and **ShakeAlert**

Worked Example: S–P Distance Estimate

$t_P = 42.0$ s, $t_S = 74.8$ s, $V_P = 6.2$ km/s, $V_P/V_S = \sqrt{3}$

$$V_S = \frac{6.2}{\sqrt{3}} \approx 3.58\ \mathrm{km/s} \qquad \Delta t_{SP} = 74.8 - 42.0 = 32.8\ \mathrm{s}$$

$$d = \frac{32.8}{\frac{1}{3.58} - \frac{1}{6.2}} = \frac{32.8}{0.279 - 0.161} = \frac{32.8}{0.118} \approx \mathbf{278}\ \mathrm{km}$$

Seattle → Portland ≈ 280 km — consistent with a Cascades or Willamette Valley source.

What Each Seismometer Component Records

Component	Most sensitive to
Vertical (Z)	P-wave (compressional, vertical motion); Rayleigh wave (vertical ellipse component)
Horizontal N–S, E–W	S-wave (transverse); Love wave (horizontal SH); Rayleigh wave (horizontal ellipse component)

A Love wave has *no vertical component* — a vertical-only seismometer misses it entirely.
This is why three-component instruments are essential for full wave-type identification.

ShakeAlert: P-waves Save Lives

The USGS ShakeAlert system detects **fast-arriving P-waves** to issue alerts before **more damaging S-waves** arrive.

For a **Cascadia M9**:

- P-wave reaches coast: ~15 s after rupture
- Strong S-wave shaking reaches Seattle: 60–90 s later

That **60–90 s warning window** = time to stop trains, pause surgeries, move away from windows.

The physics: $V_P > V_S$ — always.

V_{S30} and Building Codes

V_{S30} = time-averaged shear velocity in the top 30 m of soil

Site Class	V_{S30} (m/s)	Description
A	> 1500	Hard rock
B	760–1500	Rock
C	360–760	Dense soil / soft rock
D	180–360	Stiff soil
E	**< 180**	**Soft soil**

Design earthquake force for Class E is **3–5× larger** than Class B.

In Seattle: Capitol Hill (glacial till, ~500 m/s) vs. Pioneer Square (artificial fill, ~180 m/s).

AI Literacy: Phase Pickers and Wave Physics (LO-7)

Deep learning models (PhaseNet, EQTransformer) pick P and S arrivals because of the physics from this lecture.

In-class prompt — try this now:

> *"A seismometer's vertical channel shows a sharp onset at 32 s; horizontal channels show a larger onset at 57 s. What wave types are these, and what can I estimate from the 25-second difference?"*

Evaluate the AI response:

- Does it identify vertical = P, horizontal = S? ✅
- Does it apply the S–P formula correctly? ✅
- Does it explain the *physical reason* for vertical vs. horizontal particle motion? ← key test
- Does it give overconfident velocities without acknowledging regional variability? ← flag this

Concept Check

1. A seismometer records only P-wave arrivals — no S-wave. List **three distinct physical reasons** this could happen. (Think about source, path, and instrument.)
2. A seismogram shows $\Delta t_{SP} = 20$ s and the station is 120 km from the earthquake. What does this imply about V_P/V_S? Is this consistent with typical crustal rock?
3. Why does an SH wave not convert to a P-wave when it reflects from a horizontal interface, while an SV wave can? Answer using particle motion geometry.

Summary

Wave	Motion	Speed	Exists in
P	Longitudinal (∥ ray)	$\sqrt{(\lambda + 2\mu)/\rho}$	Solids + fluids
S	Transverse (⊥ ray)	$\sqrt{\mu/\rho}$	Solids only
Rayleigh	Retrograde ellipse (P+SV)	$\approx 0.92\, V_S$	Any half-space
Love	Horizontal SH	$V_{S1} < V_L < V_{S2}$	Layered only

$V_P > V_S > V_R$ always. S-waves require $\mu \neq 0$ (shear restoring force).

Next class: Lab 1 — Introduction to Python — computing V_P, V_S for different rock types

Lecture 6 (Apr 6): Wavefronts, Rays, and Snell's Law