Geophysical Exploration G405

Lecture-3 Seismic Methods

By
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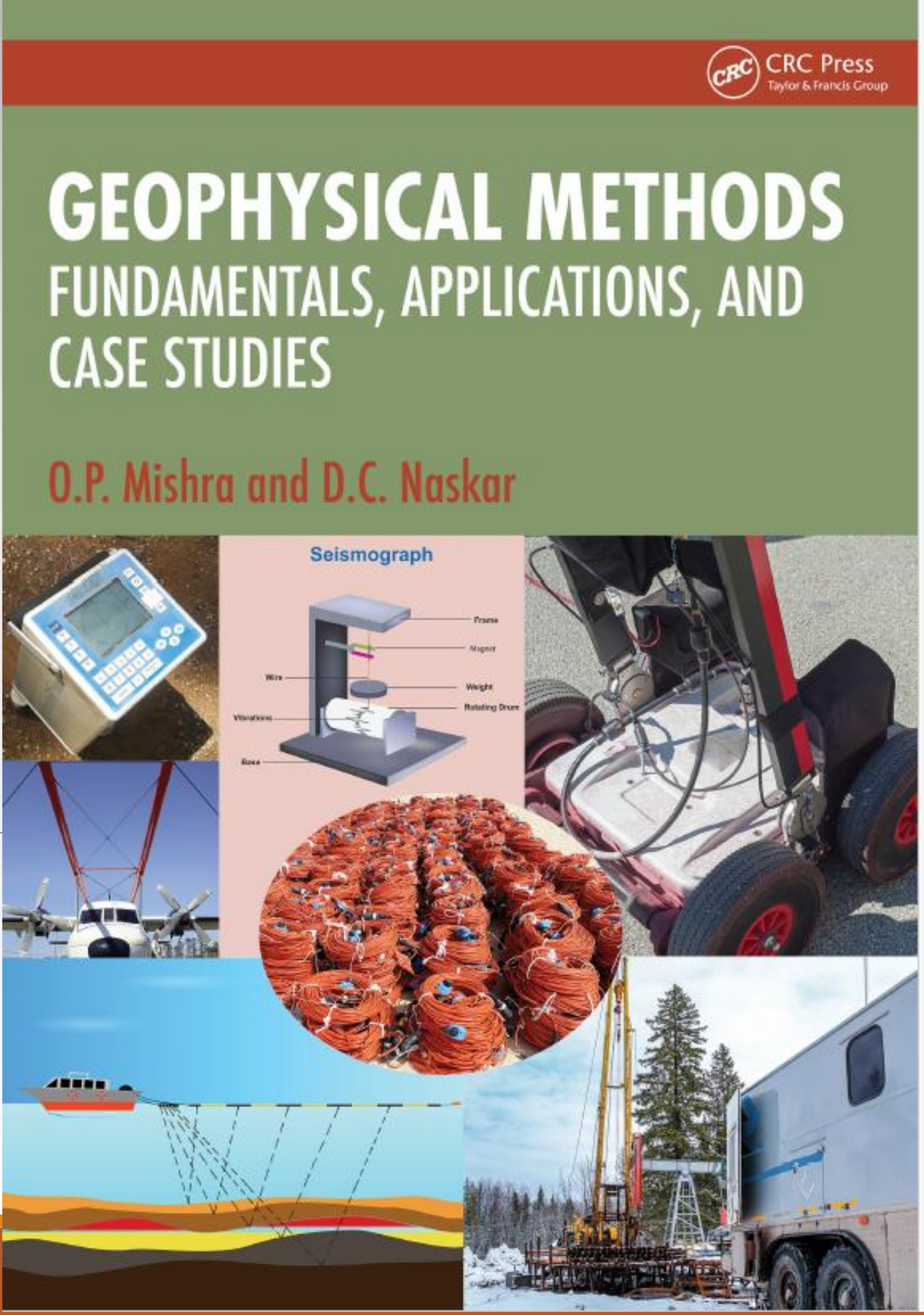


Seismic Method and Seismic Tomography

Introduction to Seismic Methods
Seismic methods involve generating controlled seismic waves (using artificial sources like explosions or vibrators) that propagate through the subsurface. These waves reflect or refract at geological boundaries and return to the surface, where their arrival times are recorded by sensors (geophones or hydrophones). The data are used to map subsurface structures, such as layered sedimentary, bedrock depth, and hydrocarbon reservoirs. The method is derived from earthquake seismology but operates on a smaller scale with controlled sources.

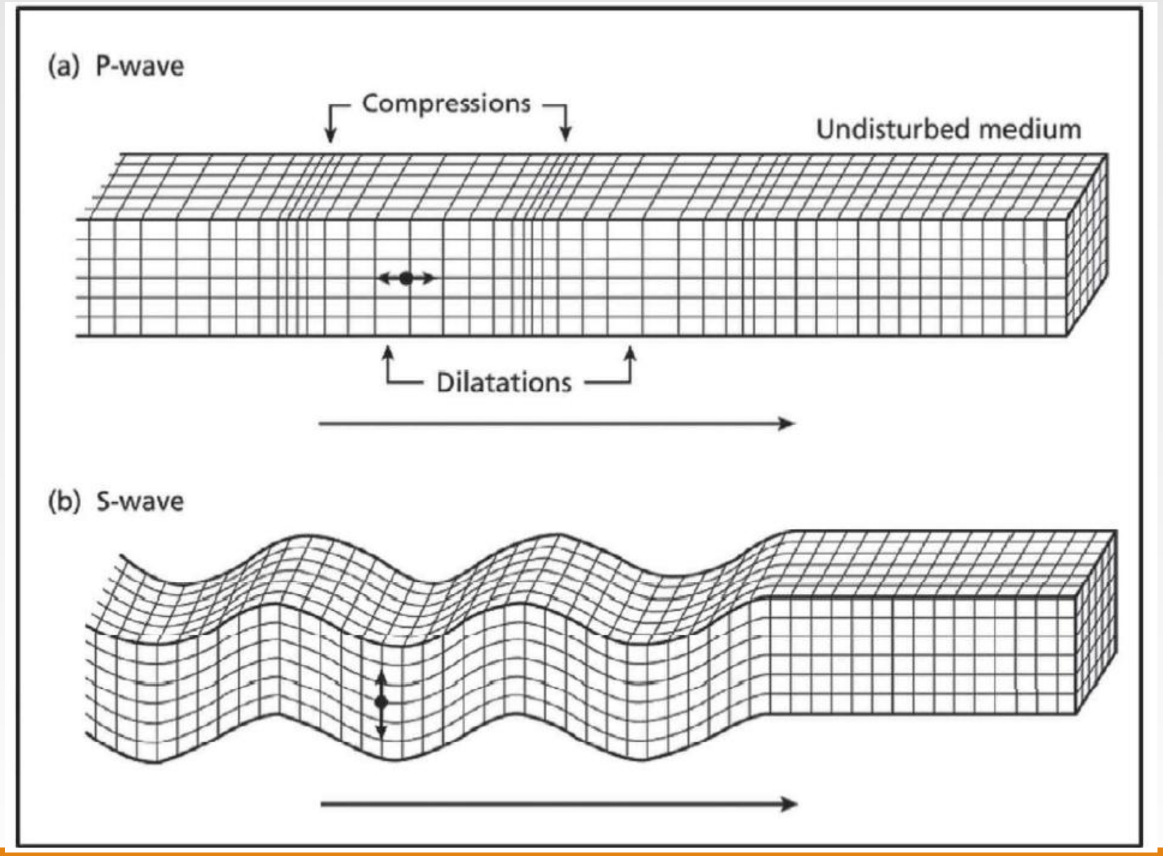
Seismic methods applications:
Oil and gas exploration, Mapping near-surface sediments, water tables, and bedrock.
Engineering and environmental studies (e.g., fault detection, aquifer characterization).

Historical use of seismic methods:
Reflection techniques have been used since the 1920s for petroleum exploration.
Refraction techniques are common in engineering.
Since the 1980s, advancements have improved resolution for shallow surveys (e.g., detecting layers up to 500 m deep).

Types of Seismic Waves:

Body Waves: Travel through the Earth's interior.

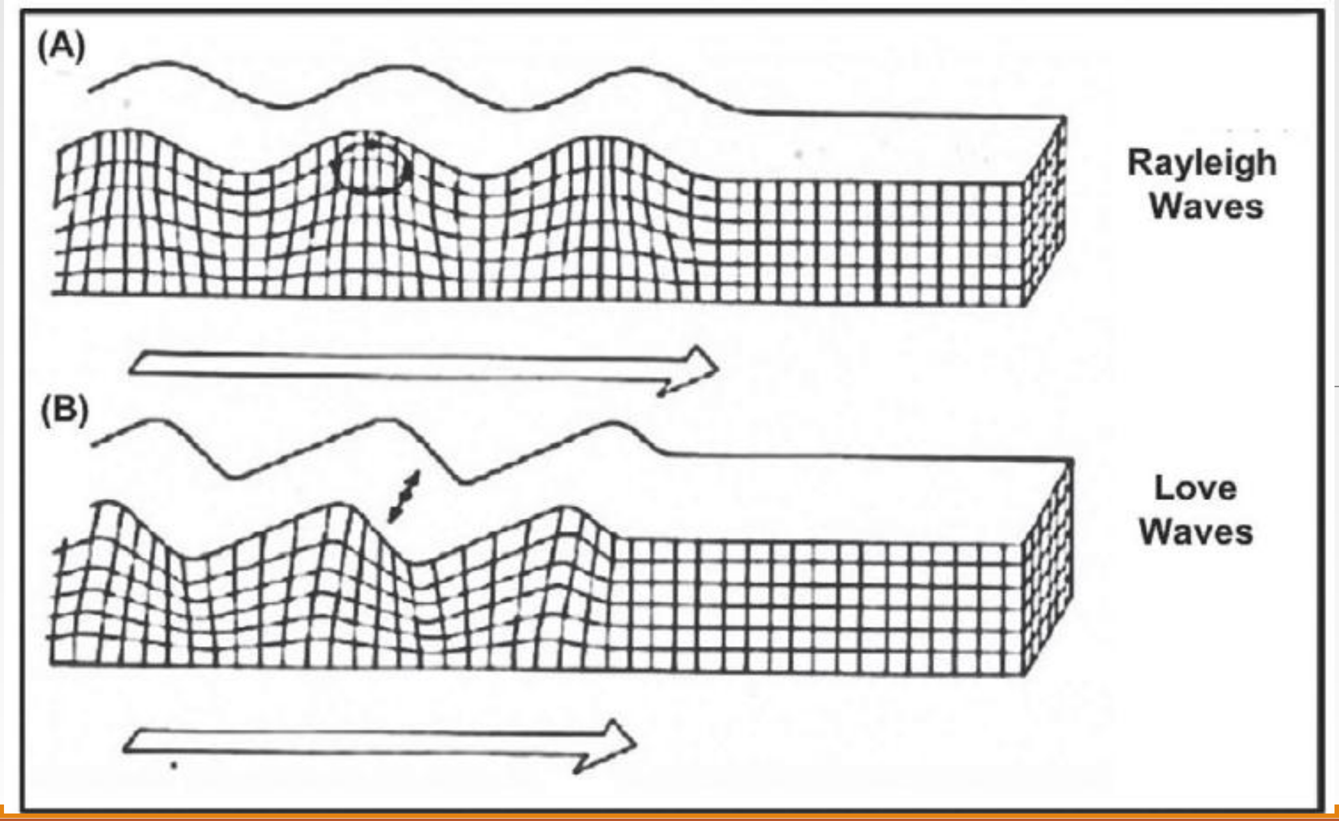
- **P-waves (Primary/Compressional)**: Fastest, with particle motion parallel to propagation. Can travel through solids and fluids.
- **S-waves (Secondary/Shear)**: Slower, with particle motion perpendicular to propagation. Only travel through solids.



Elastic deformations and ground particle motions associated with the passage of body waves:
(a) a P wave and
(b) an S wave.

Surface Waves: Travel along the Earth's surface with amplitude decreasing exponentially with depth.

- **Rayleigh waves**: Elliptical particle motion in a vertical plane.
- **Love waves**: Horizontal particle motion parallel to the surface, requiring a low-velocity layer over a higher-velocity layer.



Elastic deformations and ground particle motion associated with the passage of surface waves:
(a) a Raleigh wave
(b) a Love wave.

Seismic Wave Velocities

Wave velocities depend on the material's elasticity and density:

$V_P = \sqrt{(K + \frac{4}{3}\mu)/\rho}$ (P-wave velocity).

$V_S = \sqrt{\mu/\rho}$ (S-wave velocity).

Factors Affecting Velocity:

- **Geological age and depth**: Older, deeper rocks generally have higher velocities.
- **Porosity and fluid content**: Water-saturated rocks have higher P-wave velocities than dry rocks. The time-average equation estimates porosity:

$$\frac{1}{v} = \frac{\phi}{v_f} + \frac{1-\phi}{v_m}$$

where ϕ is porosity, v_f is fluid velocity, and v_m is matrix velocity.

Note:

- Unconsolidated sediments: V_P=200–2,500 m/s
- Consolidated rocks (e.g., granite, basalt): V_P=4,500–6,500 m/s

Seismic Velocities and Densities

Type of Rock or Medium	*P* Velocity V_P (m/s)	*S* Velocity V_S (m/s)	Density ρ (gm/cm^3)
Weathered rock	100–300	300–700	1.7–2.4
Dry sand	400–1,200	100–500	1.5–1.7
Wet sands	1,500–4,000	400–1,200	1.9–2.1
Clay	1,100–2,500	200–800	2.0–2.4
Marl/shale	2,000–3,000	750–1,500	2.1–2.6
Sandstone	3,000–4,500	1,200–2,800	2.1–2.4
Limestone	3,500–6,000	2,000–3,300	2.4–2.7
Chalk	2,300–2,600	1,100–1,300	1.8–2.3
Salt	4,500–5,500	2,500–3,100	2.1–2.3
Anhydride	4,000–5,500	2,200–3,100	2.9–3.0
Dolomite	3,500–6,500	1,900–3,600	2.5–2.9
Granite	4,500–6,000	2,500–3,300	2.5–2.7
Basalt	5,000–6,000	2,800–3,400	2.7–3.1
Coal	2,200–2,700	1,000–1,400	1.3–1.8
Water	1,450–1,500	—	1
Ice	3,400–3,800	1,700–1,900	0.9
Oil	1,200–1,250	—	0.6–0.9

Ray Paths in Layered Media

At interfaces between layers with different velocities, seismic energy partitions into reflected and transmitted waves.

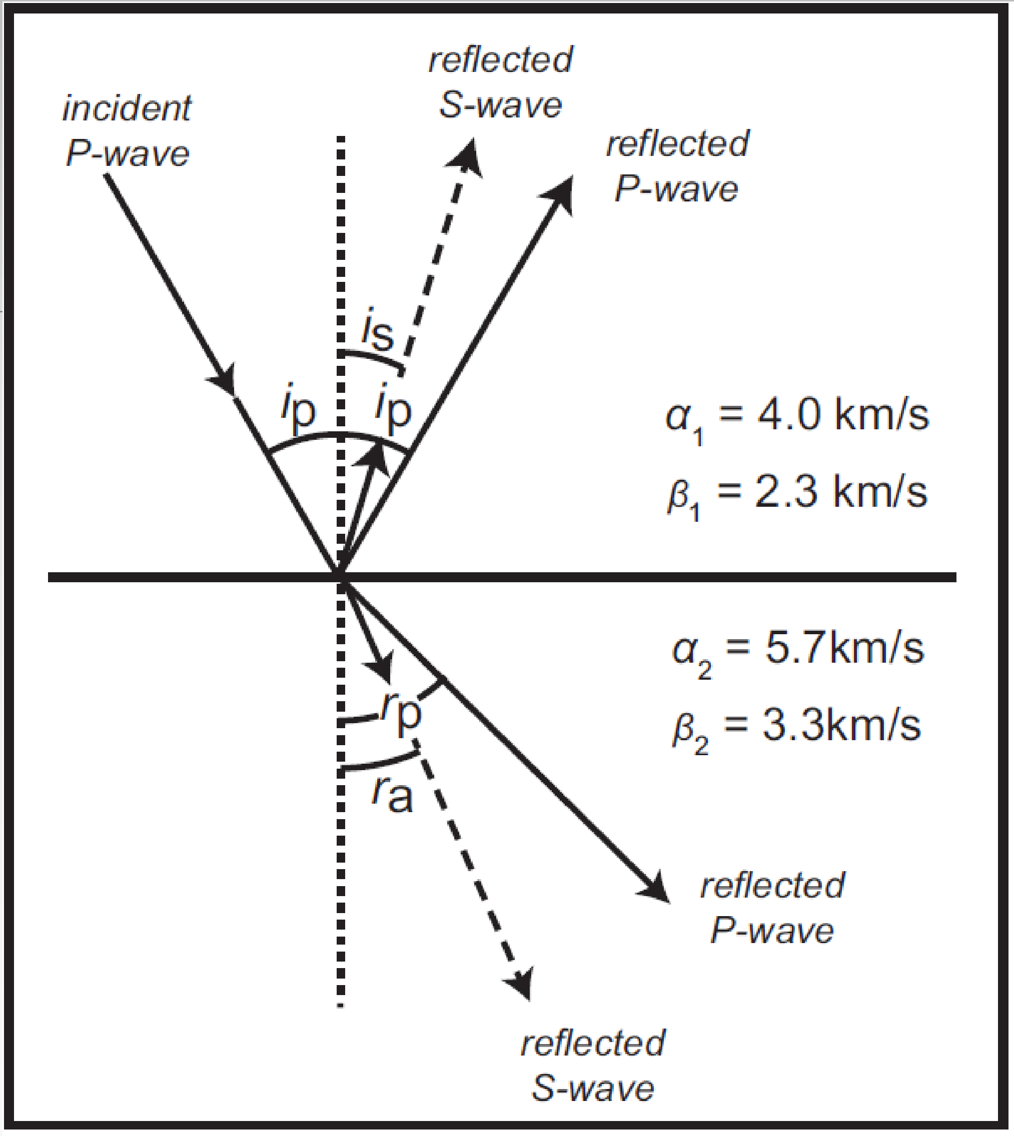
The **acoustic impedance** ($Z=\rho v$) determines reflection/transmission coefficients:

Reflection coefficient: $R = \frac{Z_2 - Z_1}{Z_2 + Z_1}$.

Transmission coefficient: $T = \frac{2Z_1}{Z_2 + Z_1}$.

- **Normal incidence**: Only P-waves are generated.
- **Oblique incidence**: Generates both P- and S-waves (reflected and refracted).
- **Critical refraction**: Occurs when the refracted ray travels parallel to the interface.

$$\sin i_c = V_1/V_2$$



The generation of reflected and refracted P and S waves from a P wave incident on a plane interface.

Seismic Data Acquisition Systems

1.Sources:

1. **Hammer/plate**: For shallow surveys (<20 m).
2. **Explosives**: High energy but environmentally restricted.
3. **Vibrators**: Sweep frequencies over time, used in reflection surveys.
4. **Airguns**: Marine surveys, releasing compressed air bubbles.

2.Sensors:

1. **Geophones**: Land surveys, measure ground motion.
2. **Hydrophones**: Marine surveys, measure pressure changes.

3.Recording:

1. **Seismographs**: Digitize and store ground motion data as seismograms.
2. **Dynamic range**: Critical for capturing weak signals (modern systems exceed 100 dB).

Seismic Reflection Method

Measures the **two-way travel time (TWTT)** of waves reflected from subsurface interfaces. Used for detailed imaging of layered structures.

$$\frac{\sin\theta_1}{V_1} = \frac{\sin\theta_2}{V_1}$$

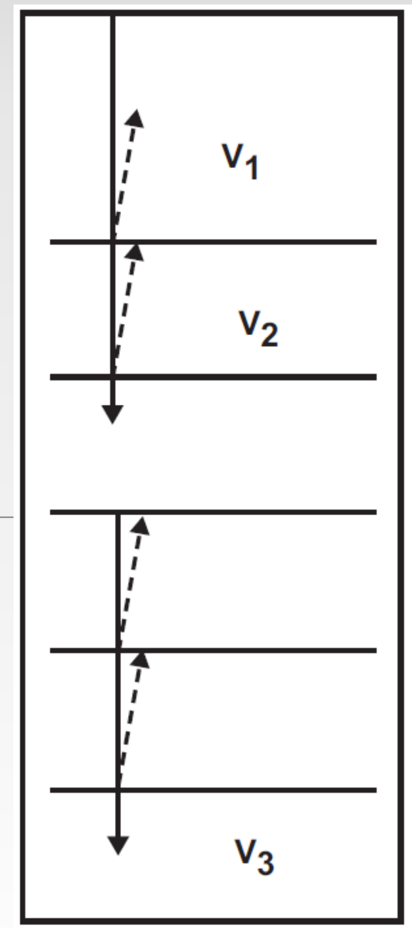
$$\boxed{\theta_1 = \theta_2}$$

For a horizontal reflector:

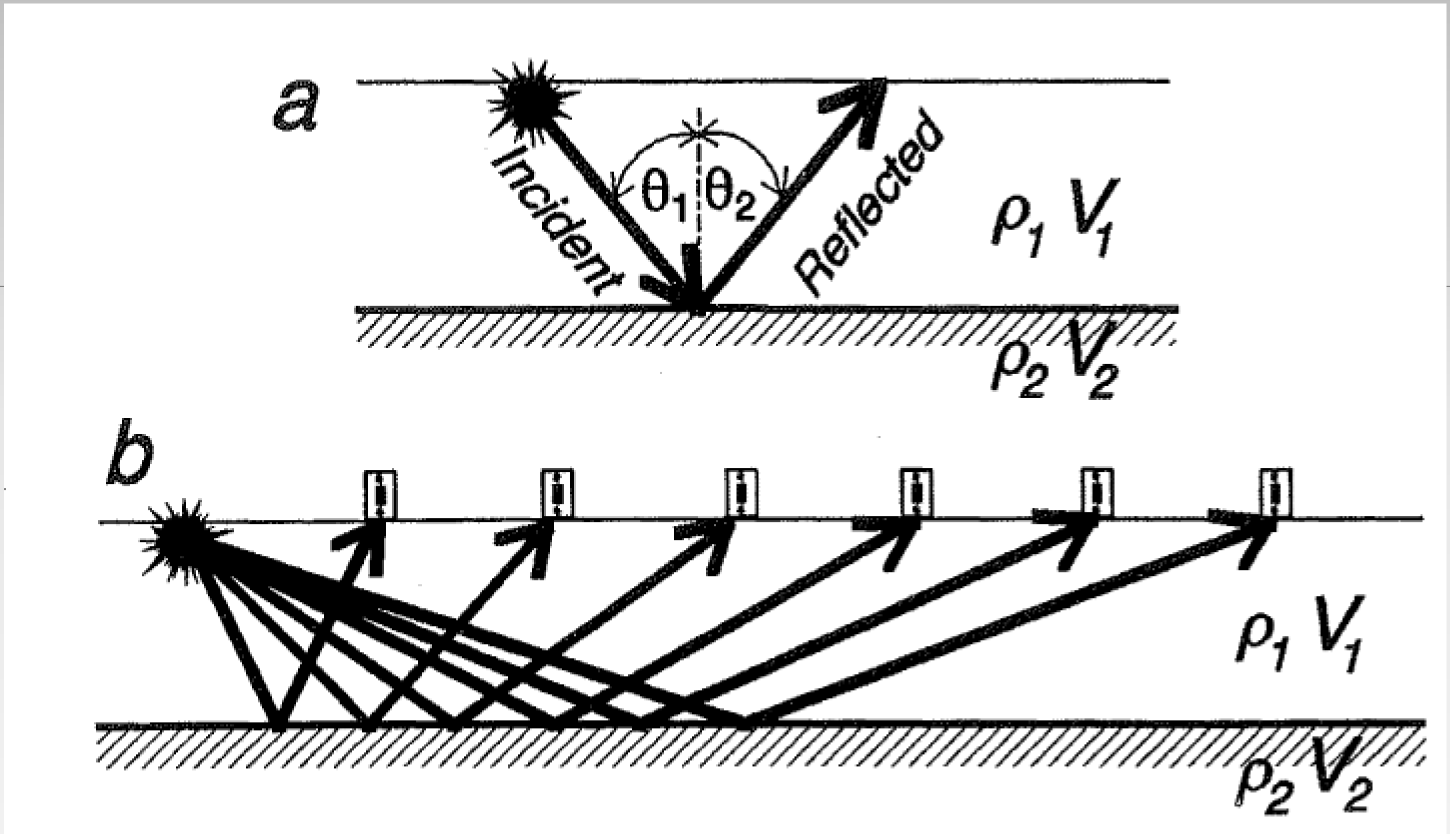
$$\boxed{t = \frac{2d}{V}\sqrt{1 + \frac{x^2}{4d^2}}}$$

Normal moveout (NMO):
Corrects for geophone offset:

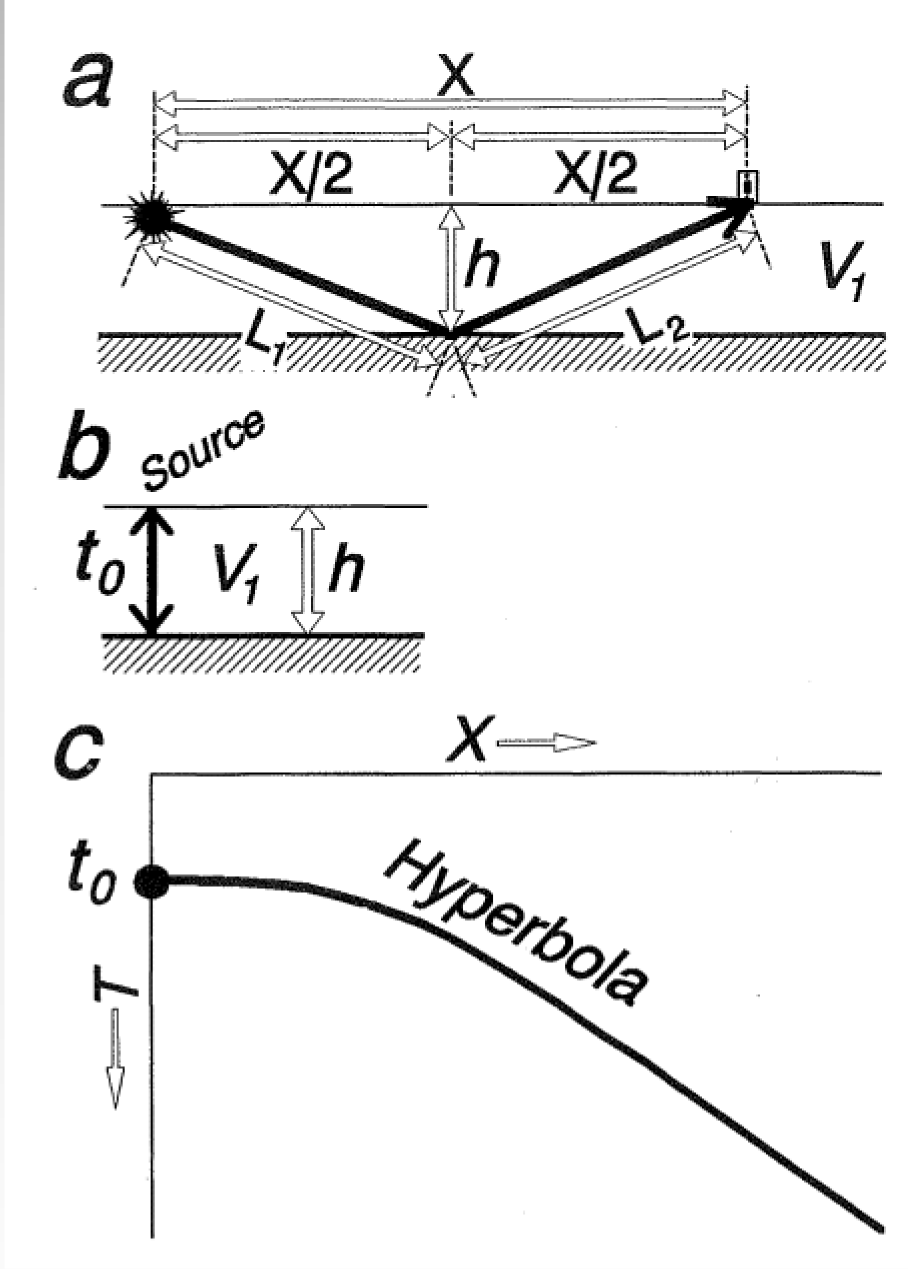
$$\boxed{\Delta t_n = \frac{x^2}{2V^2 t_0}}$$



Vertical reflected ray paths in a horizontally layered ground.



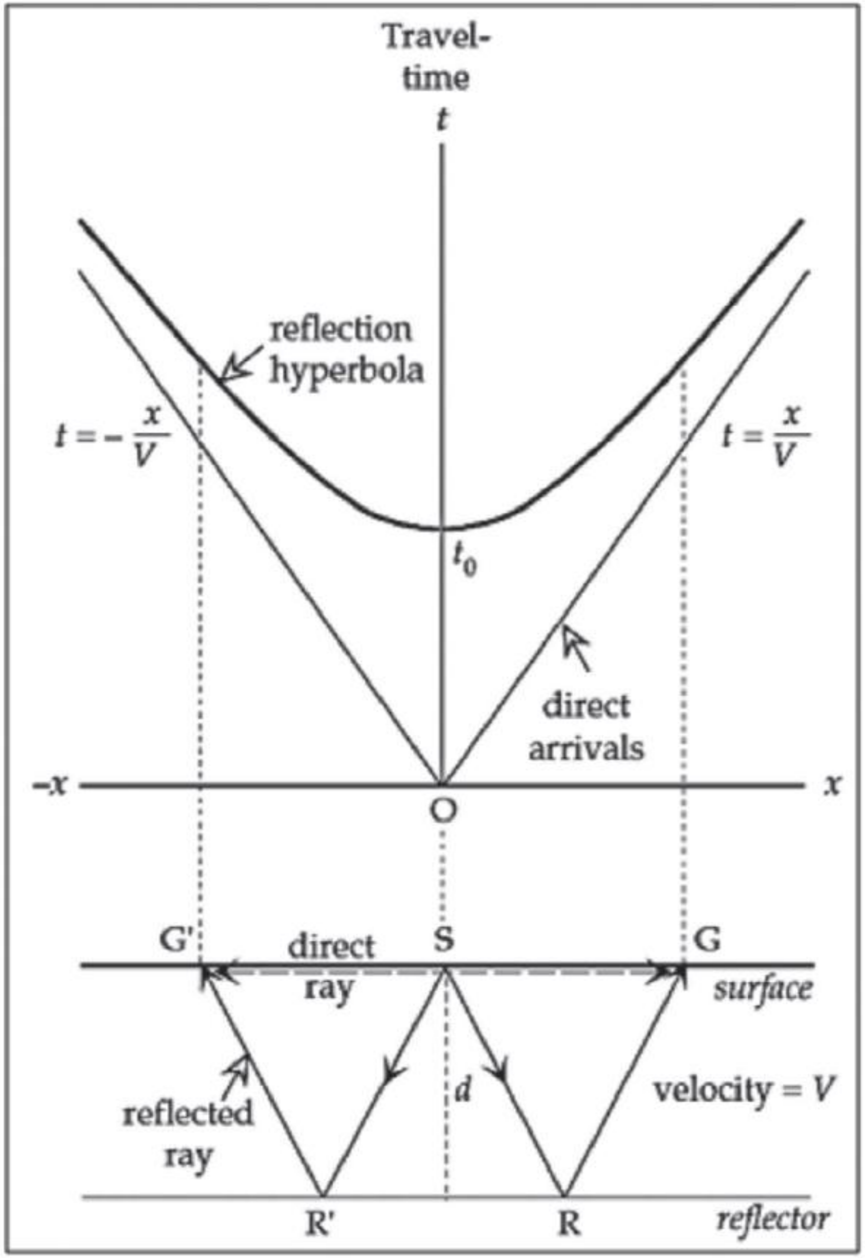
a) A compressional wave is reflected back at an angle (0_2) equal to the incident angle (0_1). p_1, V_1 and p_2, V_2 represent the densities and compressional wave velocities of the two layers. Reflection occurs when the acoustic impedance of the lower layer (p_2 X V_2) differs from that of the upper layer (p_1 X V_1). b) V-shaped ray-paths for a compressional wave from a source to six receivers, reflected from a horizontal interface.

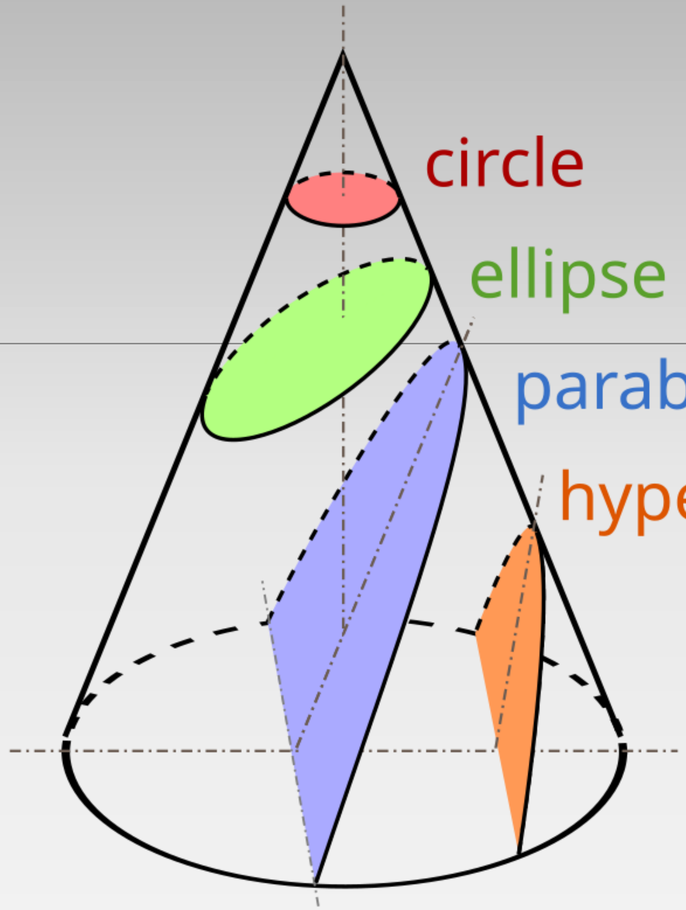


a) Geometry used to determine travel time of ray reflected from horizontal interface.

b) Geometry of ray directly down to horizontal interface at depth (h), reflected back to the source location. The travel time (t_0) is $2h/V_1$.

c) The reflected wave appears as a hyperbola on a travel-time graph, with the T-axis intercept at t_0.



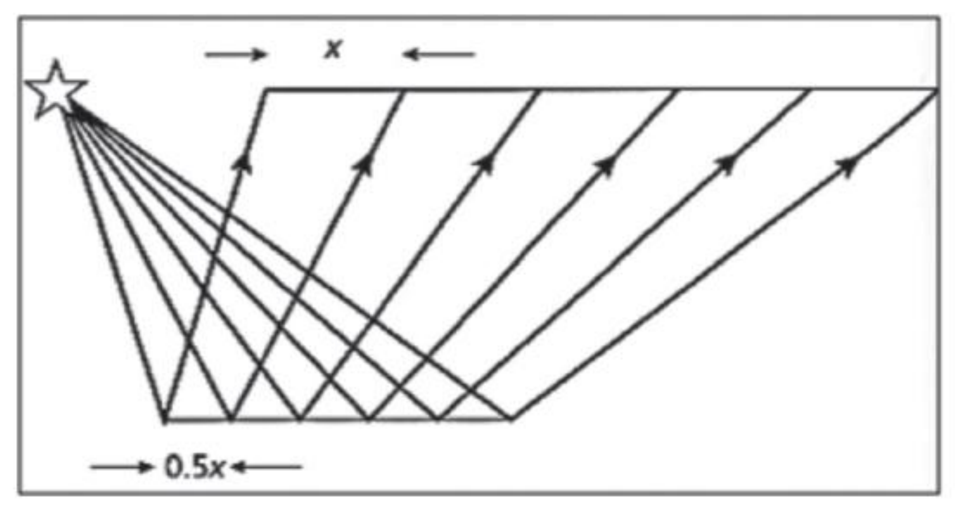


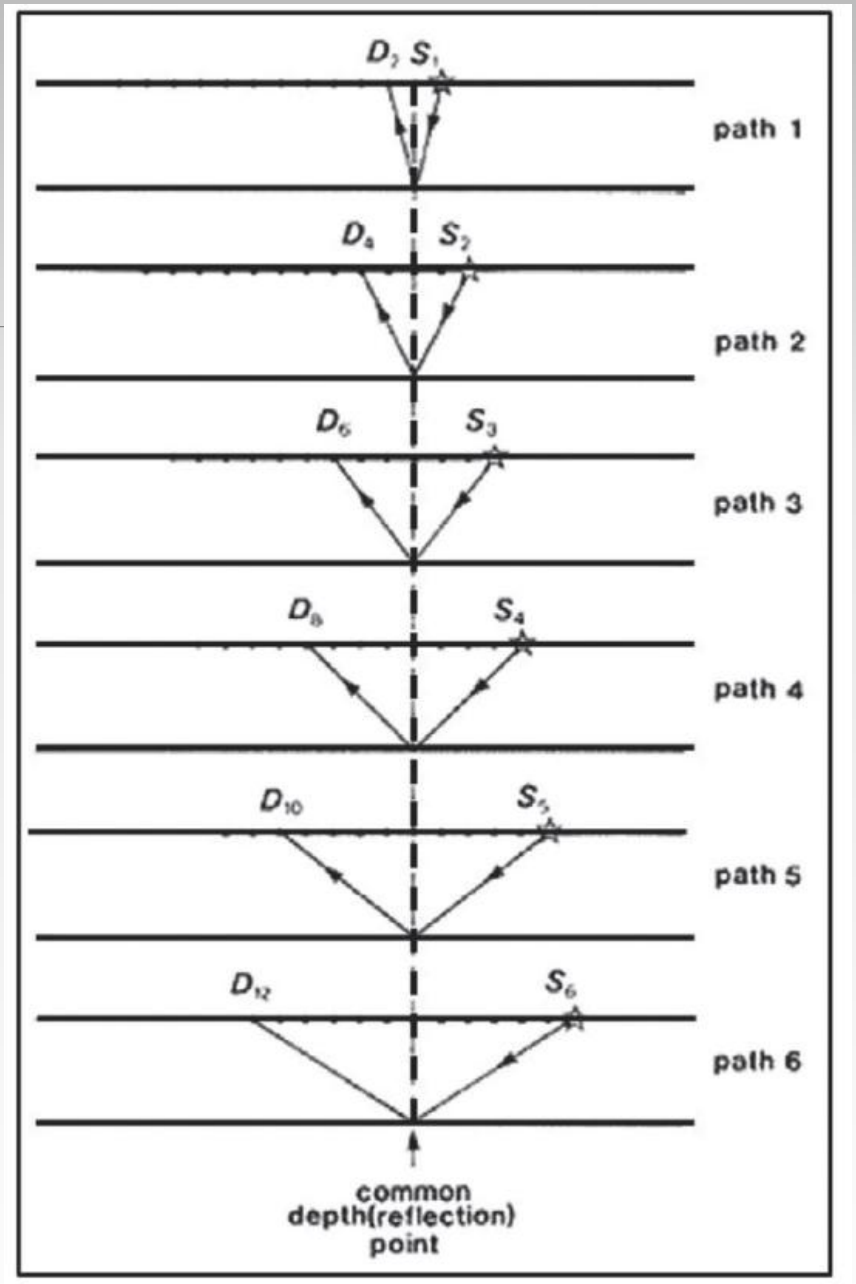
The ‘travel time vs distance’ curve for reflections from a horizontal boundary is a hyperbola.

The vertical reflection time t_0 is the intercept of the hyperbola with the travel time axis.

Survey Techniques:

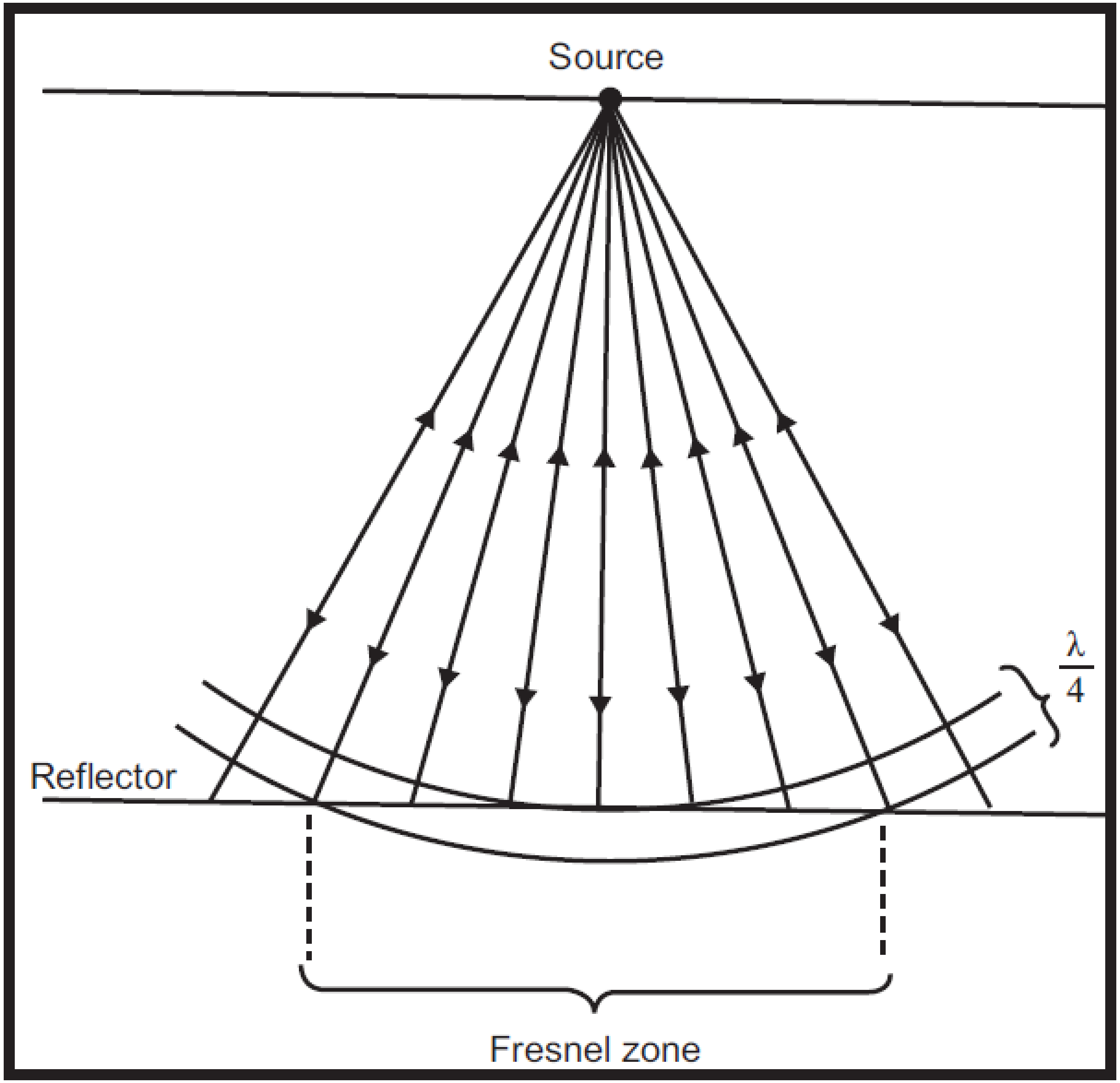
- **Common Midpoint (CMP)**: Enhances signal-to-noise ratio by stacking reflections from the same subsurface point.

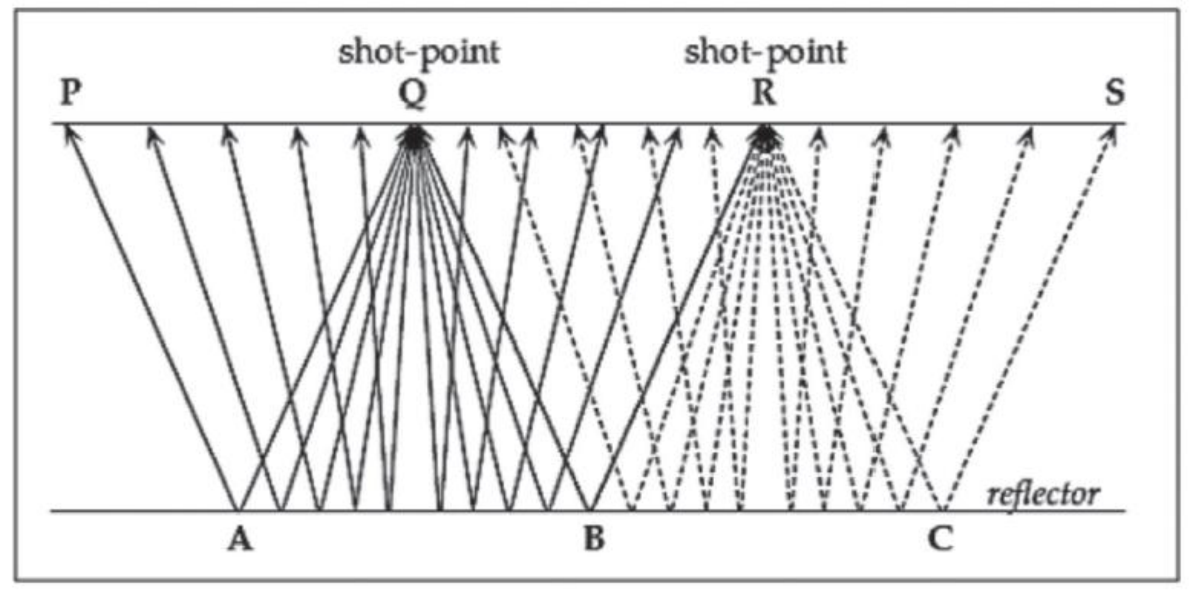




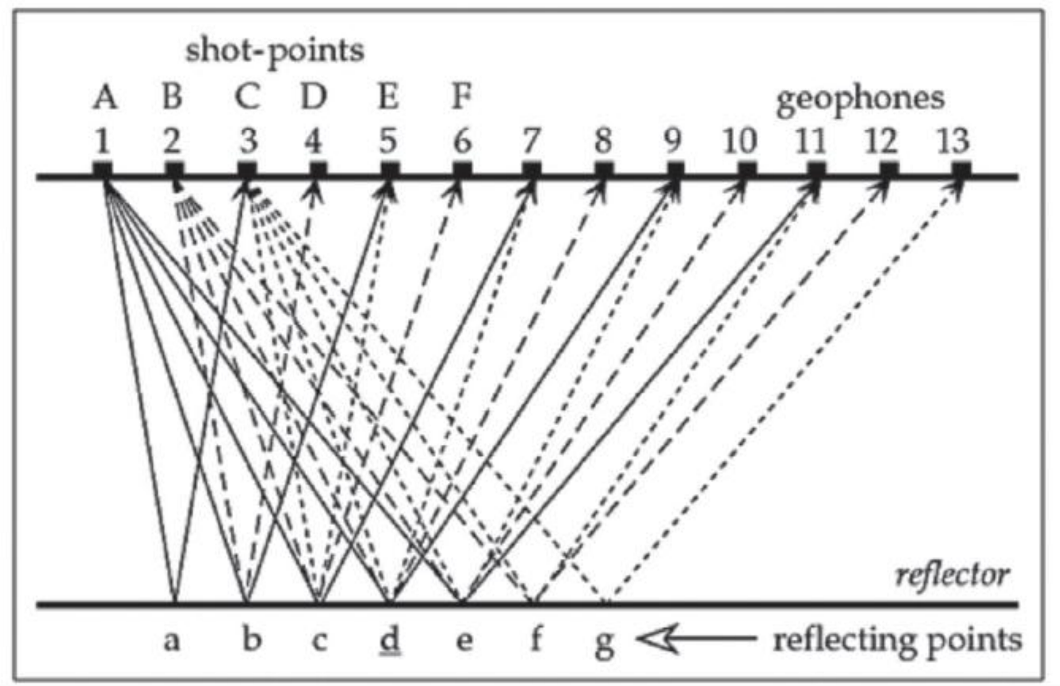
- **Vertical resolution**: ~1/4 to 1/8 of the wavelength **(e.g., 10 m for =2km/s, *f*=50Hz).**

- **Horizontal resolution**: Depends on Fresnel zone width **($w \approx 2z\lambda$).**





The split–spread method of obtaining continuous subsurface coverage of a seismic reflector.



Common midpoint method of seismic reflection shooting, showing rays from successive shot points at *A*, *B*, and *C* and the repeated sampling of the same point on the reflector (e.g. *d*) by rays from each shot point.

Seismic Refraction Method

Used to map interfaces where velocity increases with depth. Relies on **head waves** traveling along layer boundaries.

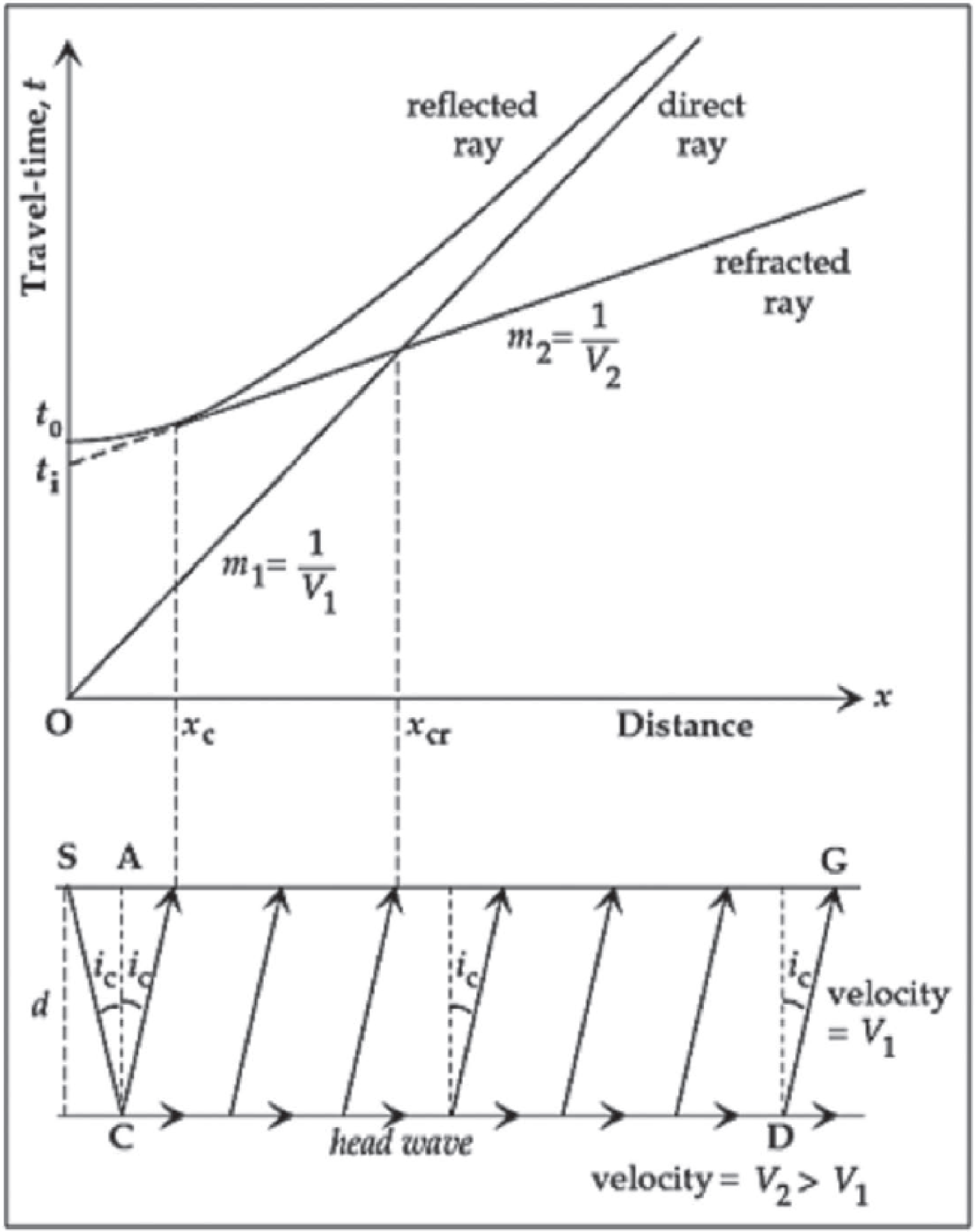
For a horizontal interface:

$$t = \frac{x}{V_2} + \frac{2d \cos i_c}{V_1}$$

Crossover distance: Where direct and refracted arrivals intersect:

$$x_{cr} = 2d\sqrt{\frac{V_2^2 - V_1^2}{V_1 V_2}}$$

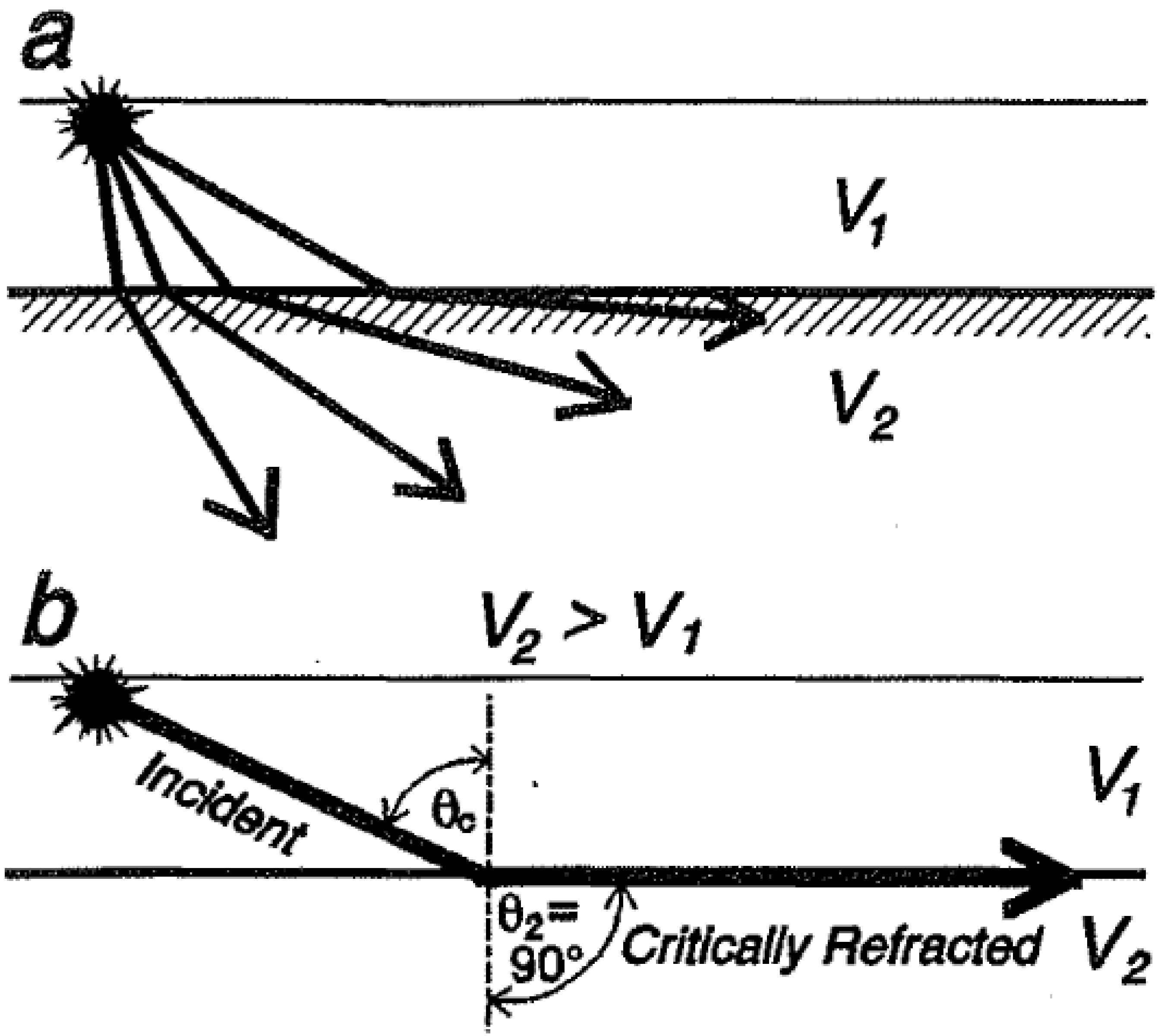
Dip Correction: Requires shooting profiles in opposite directions to estimate true velocities and dip angles.



Travel time vs distance curves for the direct ray and the reflected and refracted rays at a horizontal interface between two layers with seismic velocities $\mathbf{V}_1$ and $\mathbf{V}_2$.

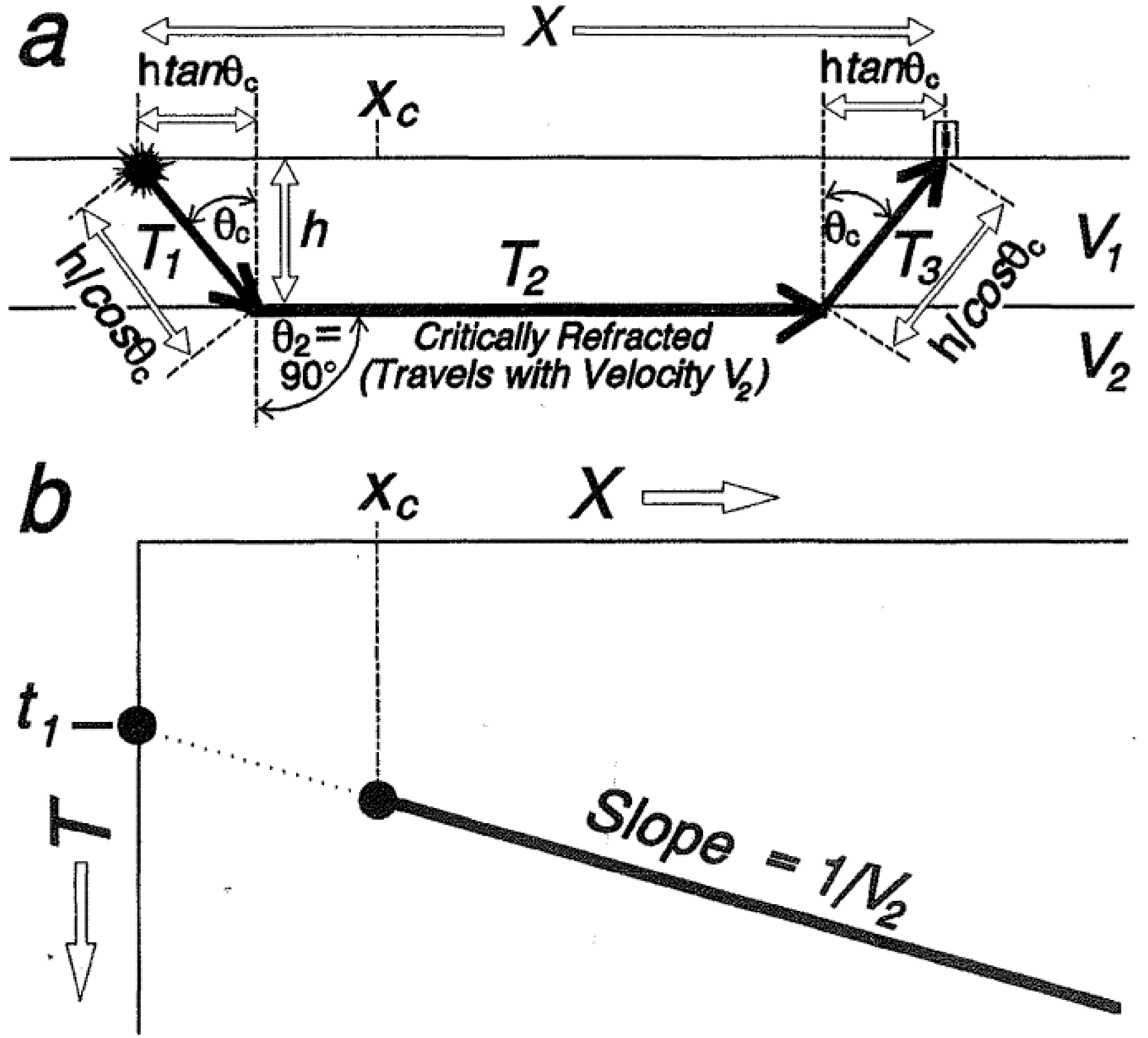
- The angle of refraction increases as the angle of incidence increases.

- If $V_2 > V_1$, the angle of refraction can reach 90°. Critical refraction then occurs, with energy following the top part of the higher velocity layer. For such a case the angle of incidence is called the critical angle (Oc)-

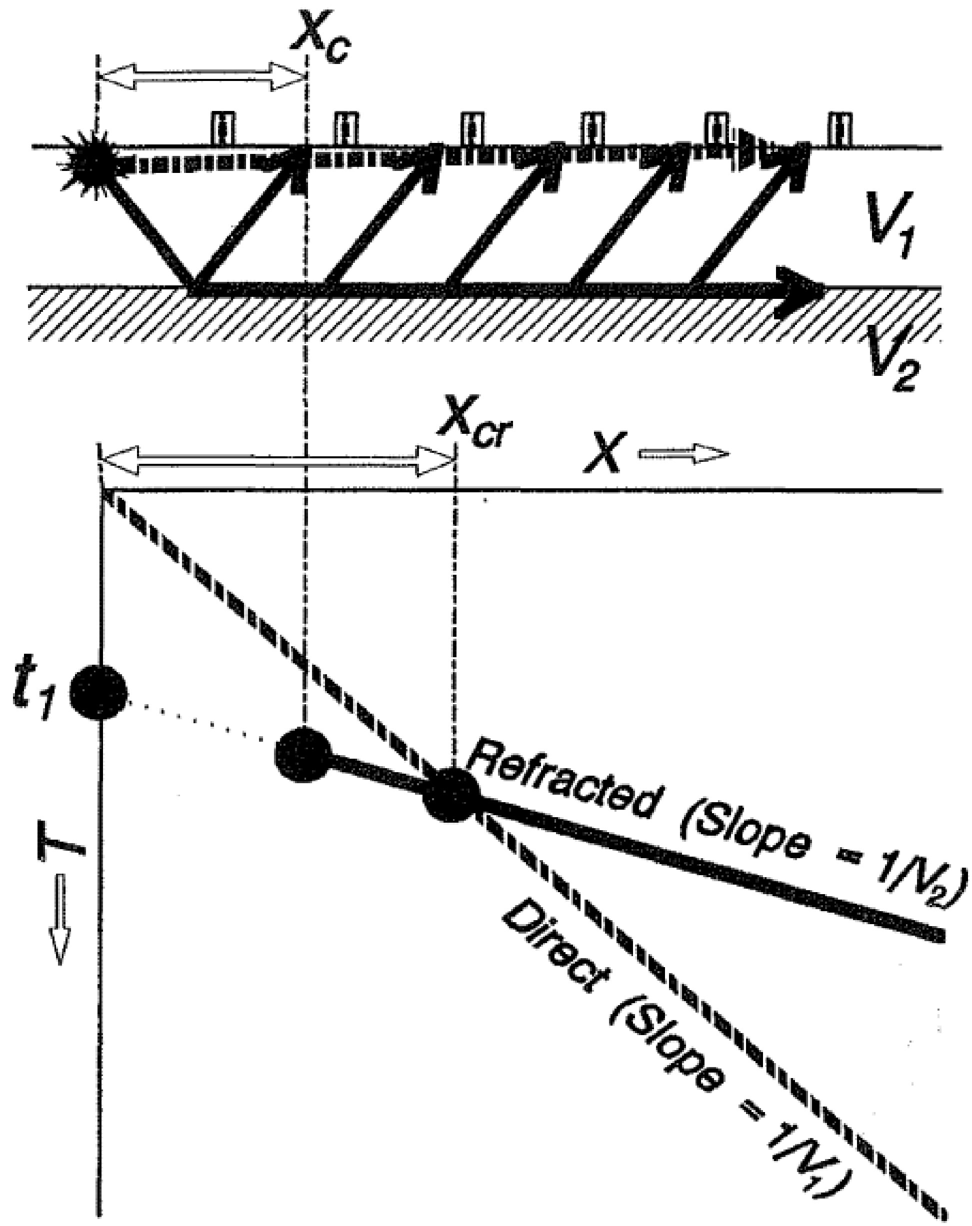


- Geometry showing the three segments (T1, T2, T3) comprising the total time path for a critically refracted ray that returns to the surface.

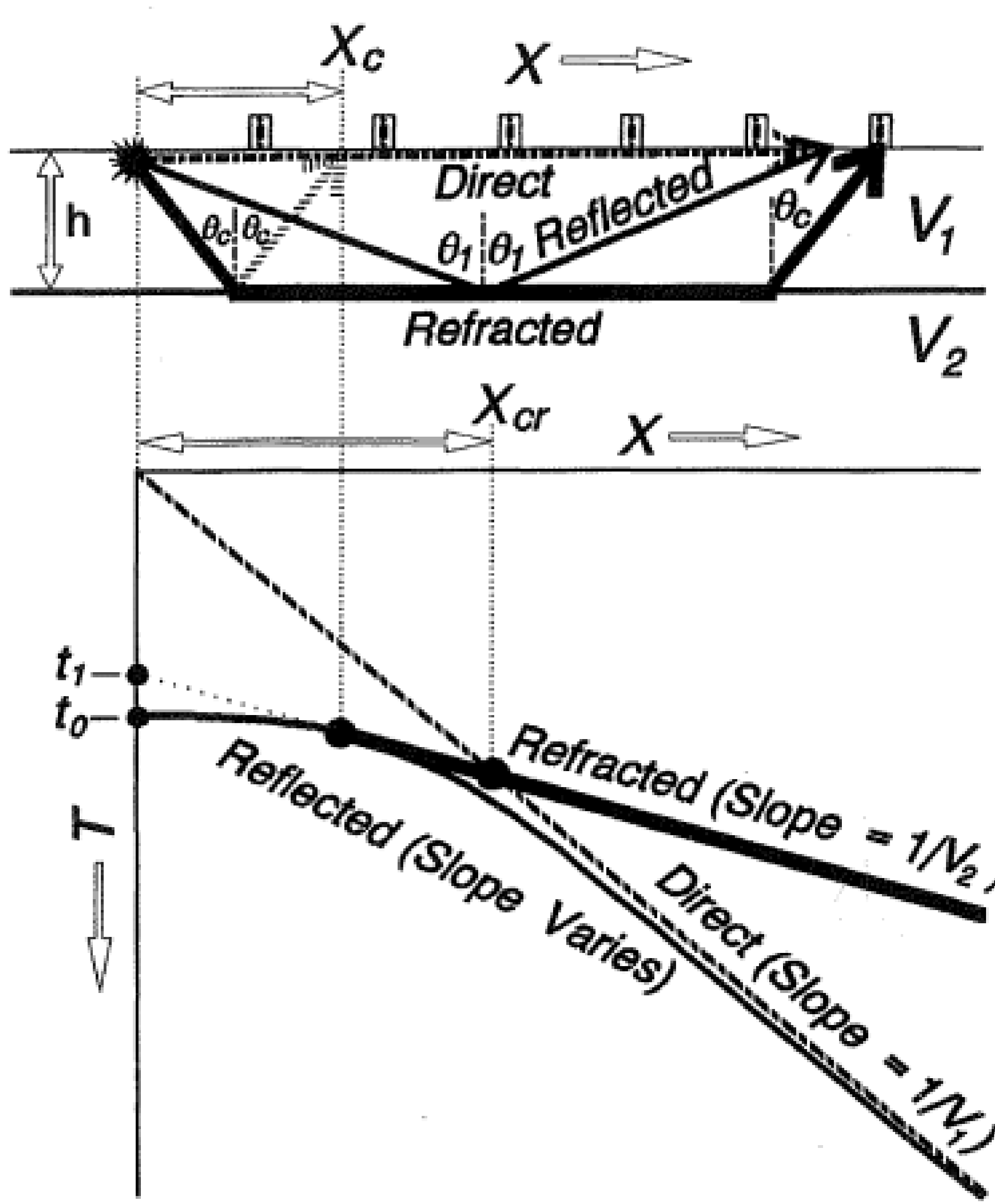
- Travel-time curve for critically refracted wave. The wave arrives at the surface only at and beyond the critical distance (Xe)-The intercept time (t1) is the projection of the curve to the T-axis.



Selected raypaths and
travel-time graph for the direct
(dashed) and critically refracted (solid)
arrivals. x. = critical distance; **x., =**
crossover distance.



Selected raypaths and travel-time graph of direct, critically refracted, and reflected waves for a horizontal interface separating a higher velocity (V_2) layer from a lower velocity (V_1) surficial layer. Xe is the critical distance (closest distance from the source where the critically refracted wave is observed) and Xcr the crossover distance (beyond that distance the critically refracted wave arrives before the direct wave).



Seismic Tomography

Creates 2D/3D images of subsurface velocity variations by solving inverse problems using travel time data.

Types:

- ❖ **Local tomography**: High-resolution imaging of crust/lithosphere (e.g., reflection/refraction surveys).
- ❖ **Global tomography**: Uses earthquake data to image mantle/core (resolution ~100s of km).

Applications:

- ✓ Mapping mantle plumes (e.g., Yellowstone, Hawaii).
- ✓ Imaging subducting slabs (e.g., Farallon plate under North America).
- ✓ Resolving anisotropy and compositional variations.

Limitations:

- ✓ Non-unique solutions require statistical validation.
- ✓ Limited by seismic network coverage (e.g., oceanic gaps).
- ✓ Resolution depends on wavelength (long wavelengths limit detail).

Seismic methods are indispensable for subsurface exploration, offering insights into geological structures, resource exploration, and hazard mitigation. Advances in acquisition, processing (e.g., full waveform inversion), and tomography continue to enhance resolution and applicability across scales.