Near-Surface Geophysics

Reflection and refraction seismics

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Seismics

Main Fields of Application

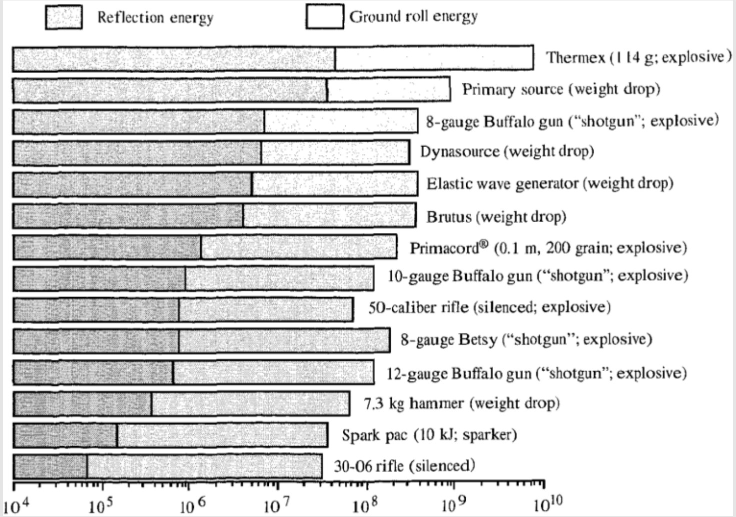
- Prospection and exploration of natural resources (oil, gas, ores, . . .).
- Exploration of the geological structure, e. g., for tunnel construction.
- Mapping of the interface between soil or unconsolidated rock and bedrock (ground investigation, slope instability, . . .).
- Mapping of aquifers.
- Mapping of residual waste sites.

Seismics

Sources of Seismic Waves

While seismology uses the waves radiated by natural earthquakes, seismic uses artificial sources, e. g.,

- Hammer stroke
- Weight dropping
- Explosives
- Seismic vibrators ("Vibroseis")
- Airguns (in marine seismics)



The different seismic sources differ concerning their energy and thus concerning their penetration depth.

Seismics

Hammer Stroke

Seismics

Explosives

Source: Teaching material R. Scholger

Seismics

Seismic Vibrators (Thumper trucks, AWDs, or “Vibroseis“)

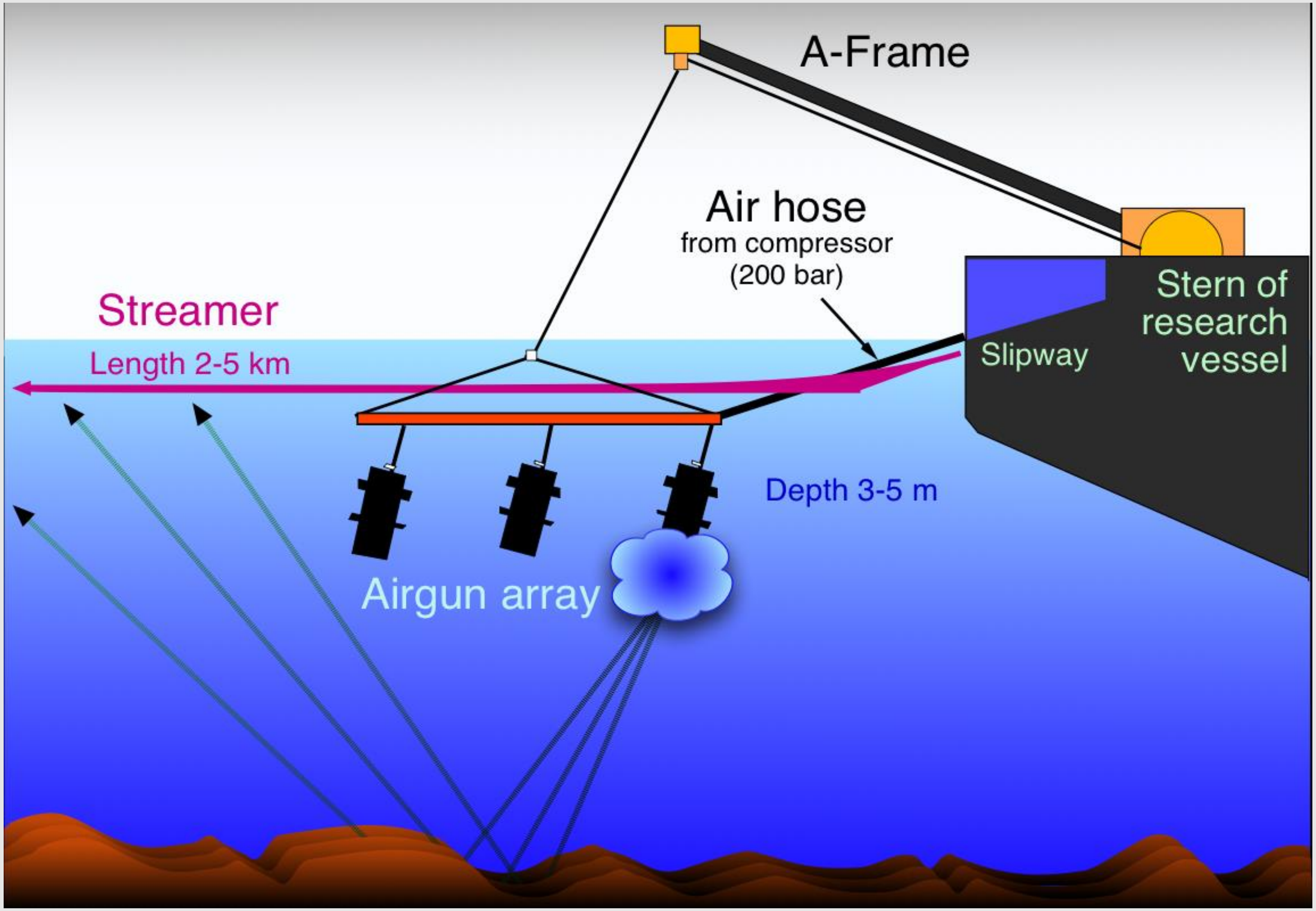
Source: Wikipedia

Seismics

Seismic Vibrators (Vibratory rammer/Earth temper)

Seismics

Airguns (in Marine Seismics)



Source: Wikipedia

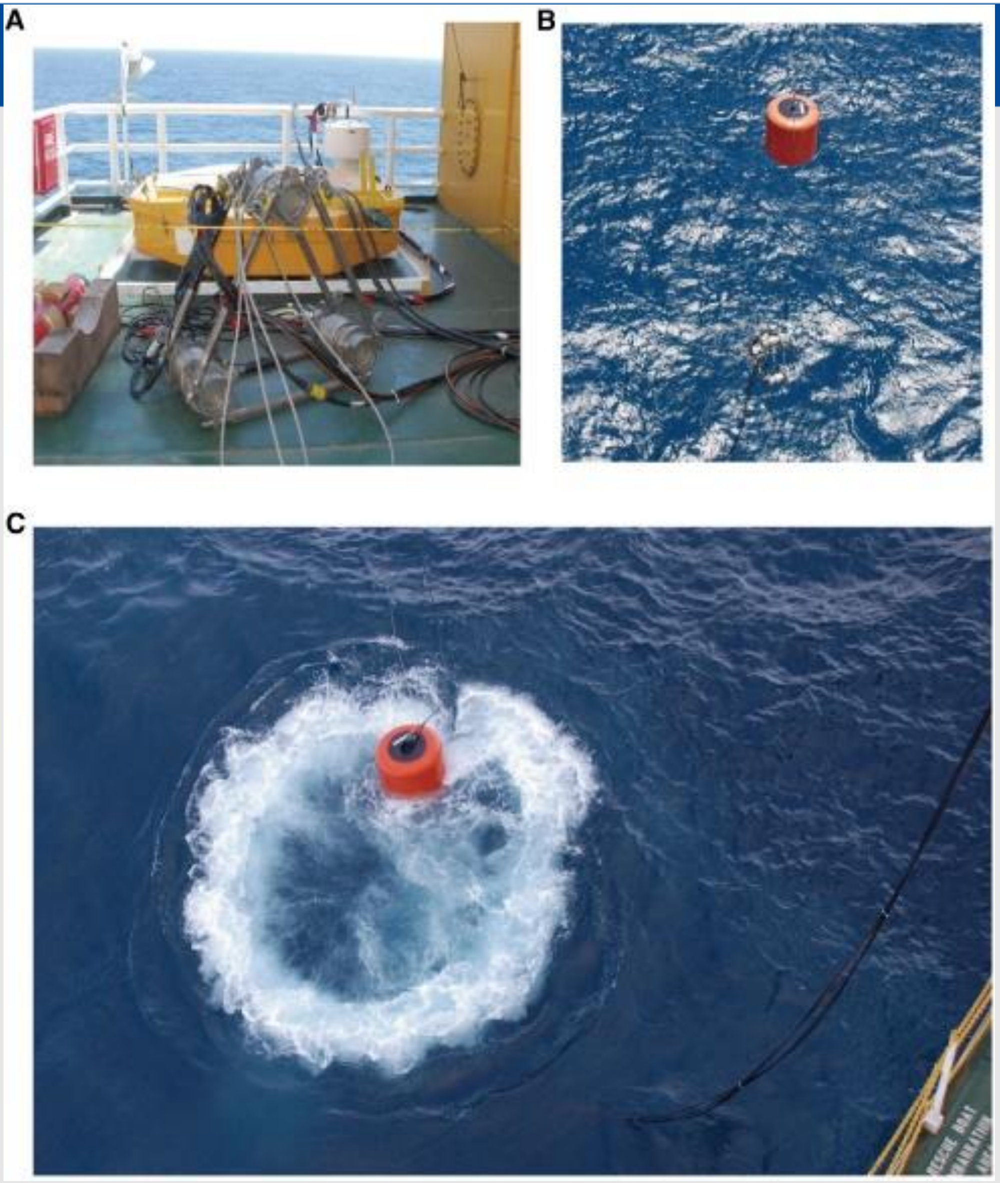
Seismics

Airguns (in Marine Seismics)

A - VSP air gun

B - Air gun array

(source: IODP 2018)



Seismic

Seismic Recording

Waves are recorded by either seismometers of geophones. Standard equipment:

Seismic source, e. g., hammer and plate.

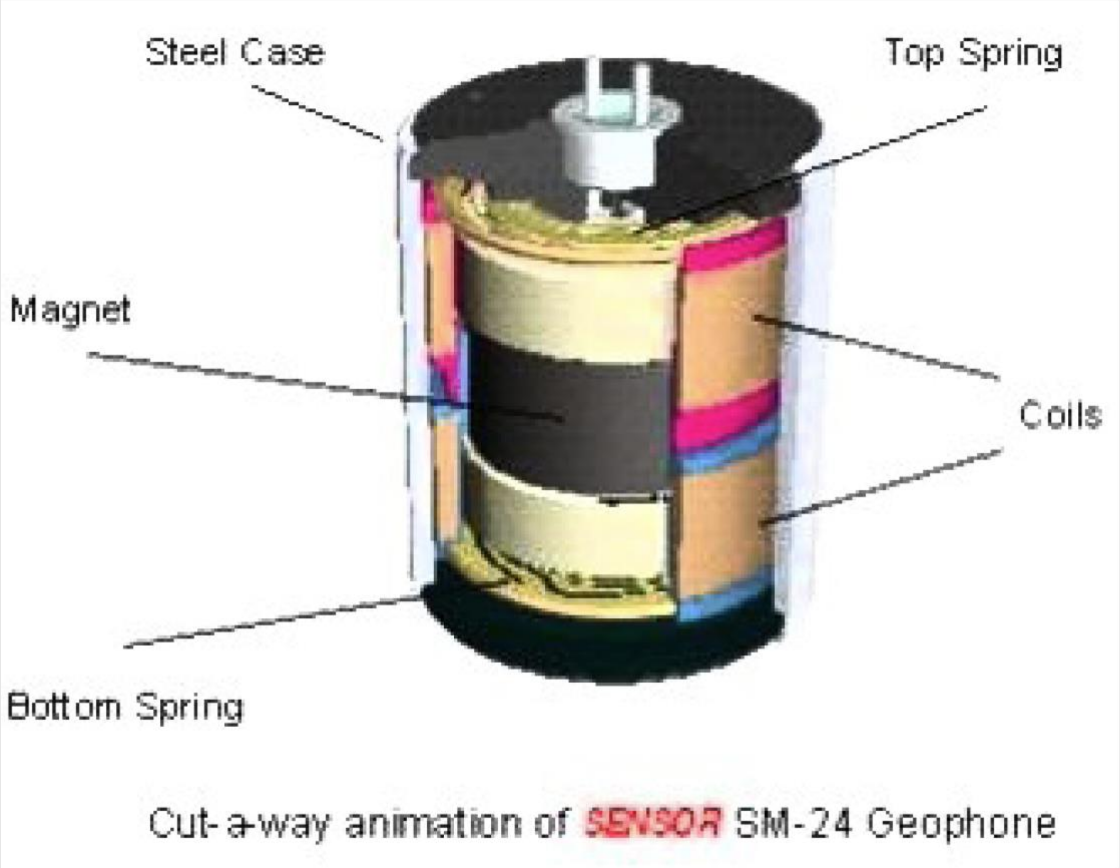
Geophones

- In principle a simplified seismometer for small amplitudes.
- Similar to a microphone.
- Consists of a permanent magnet and a coil; one directly connected to the casing, while the other can move. the induced voltage is proportional to the relative velocity.

Seismograph unit records the signals from 6–48 geophones (channels) and the seismic source.

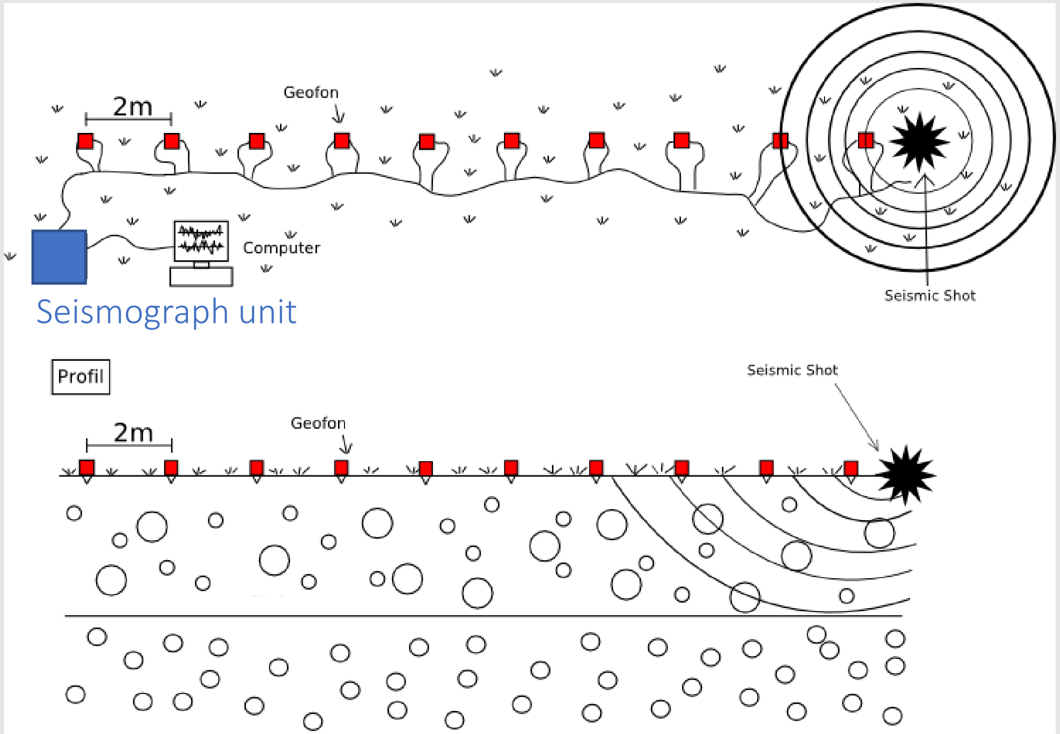
Seismic

A Simple Geophone



Seismics

Typical Setup of Hammer Stroke Seimics

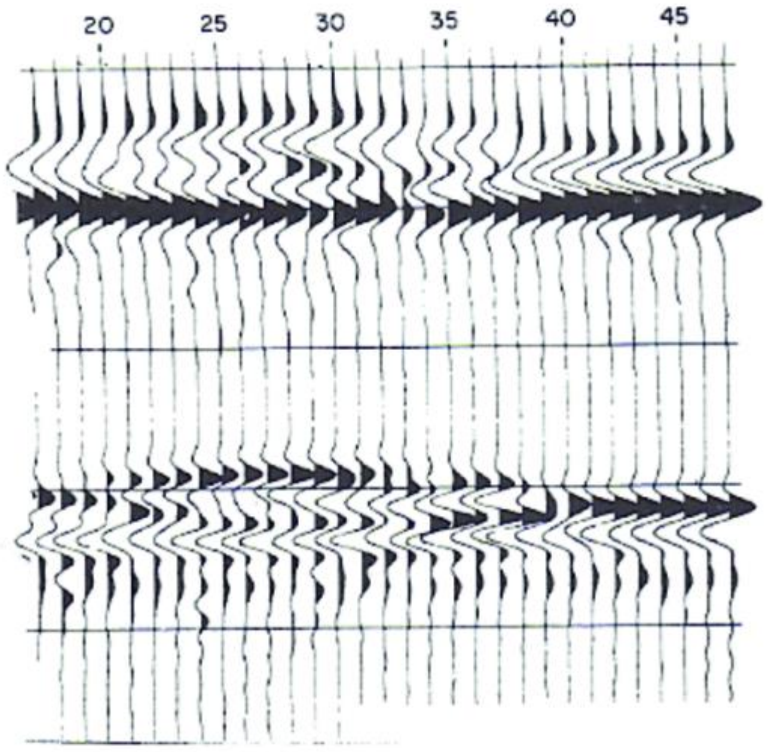


De-Multiplexed Order

	Channel		
Time	1	2	3
0.001	D001	E001	F001
0.002	D002	E002	F002
0.004	D003	E003	F003

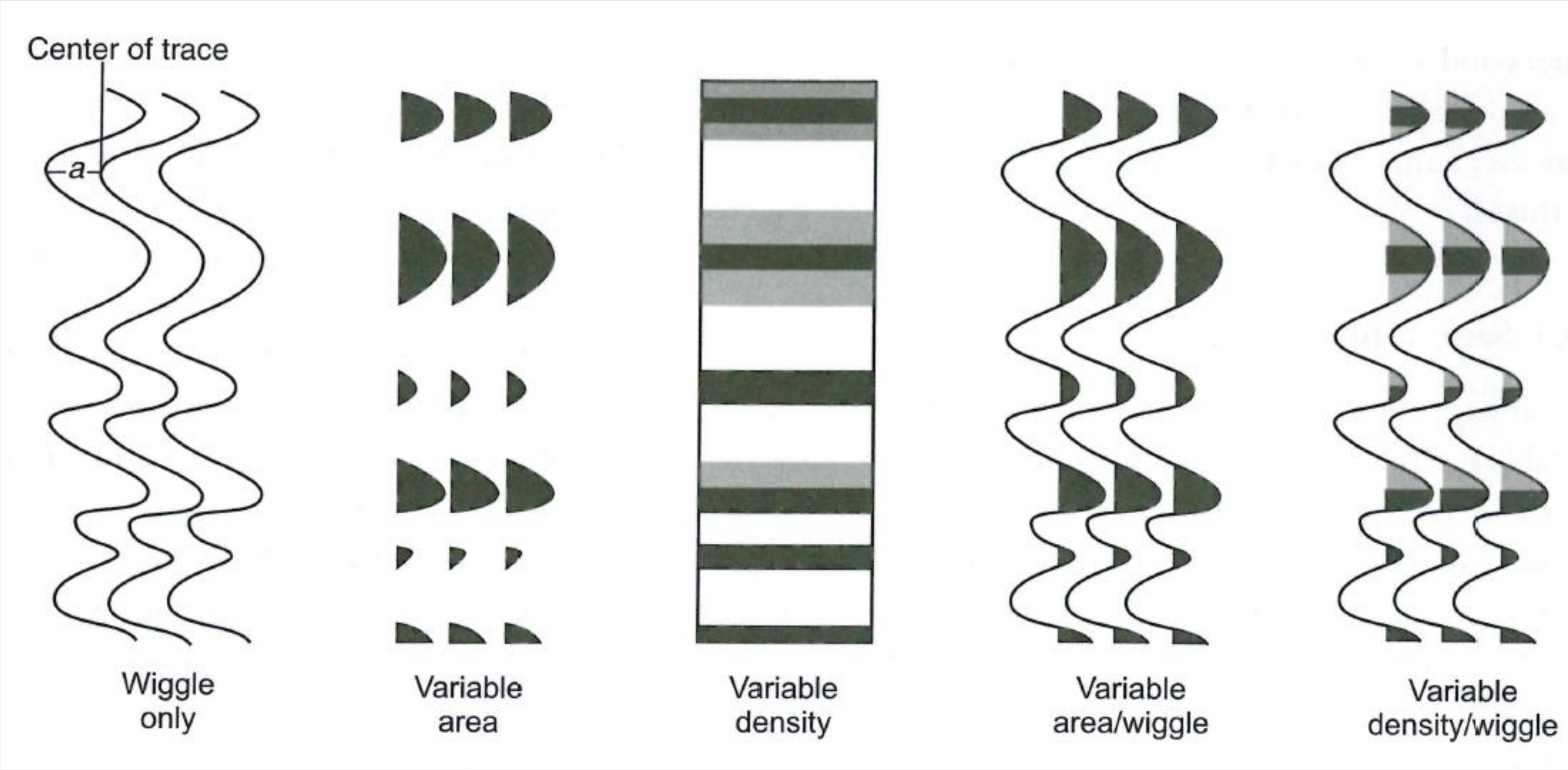
Seismics

Signal form



Seismics

Signal form

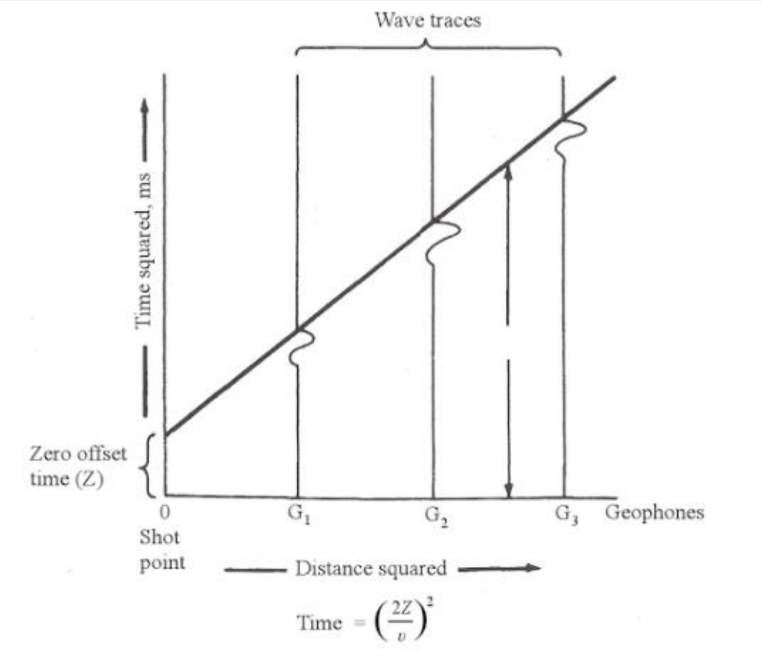


(source: Gluyas and Swarbrick, 2004)

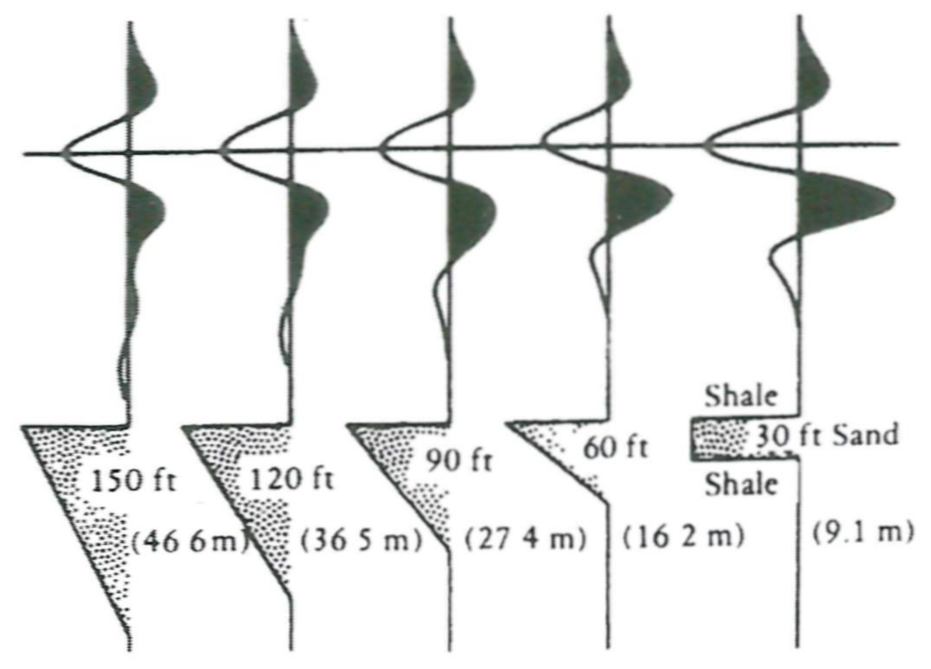
Seismics

Signal form

Travel-time:



Impedanz contrast:

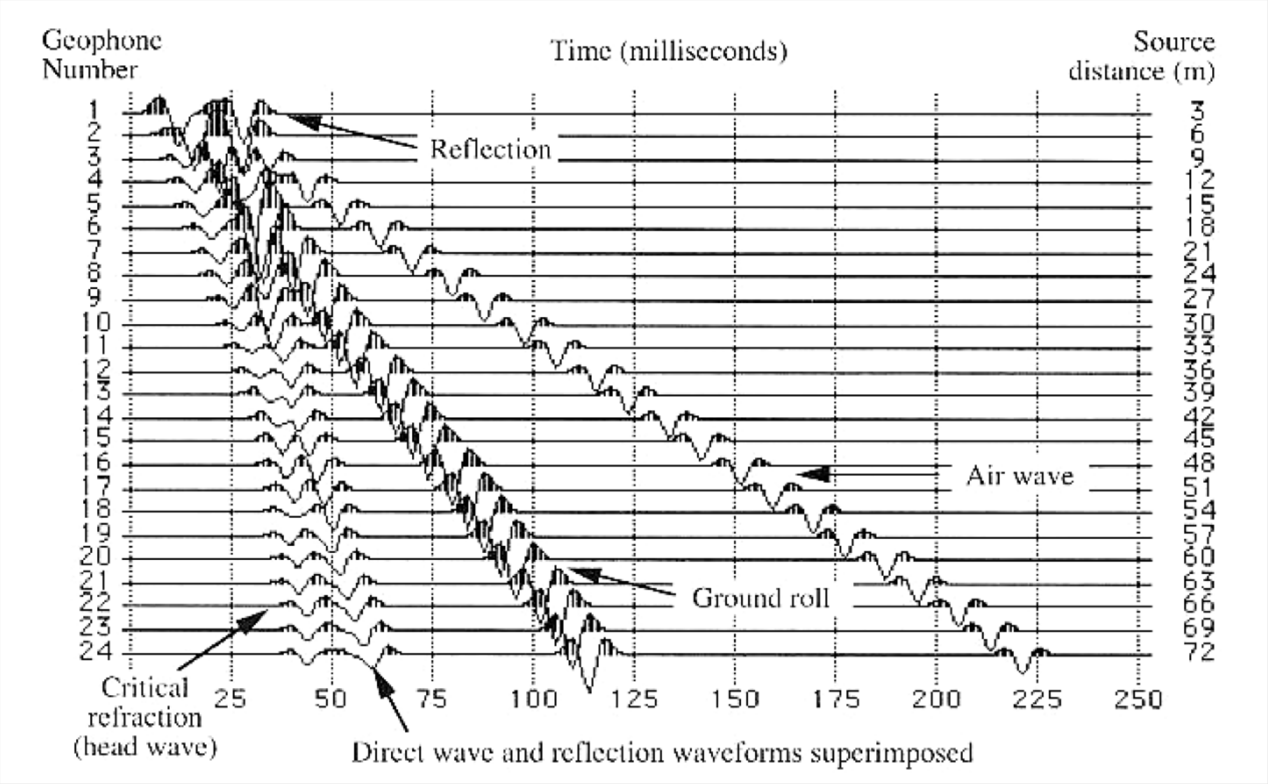


(source: Selley and Sonnenberg,1985)

Seismics

Seismic Picking

In most cases, only the first arrival times of the different waves at the geophones are analyzed.



Source: Burger et al., Introduction to Applied Geophysics

Seismics

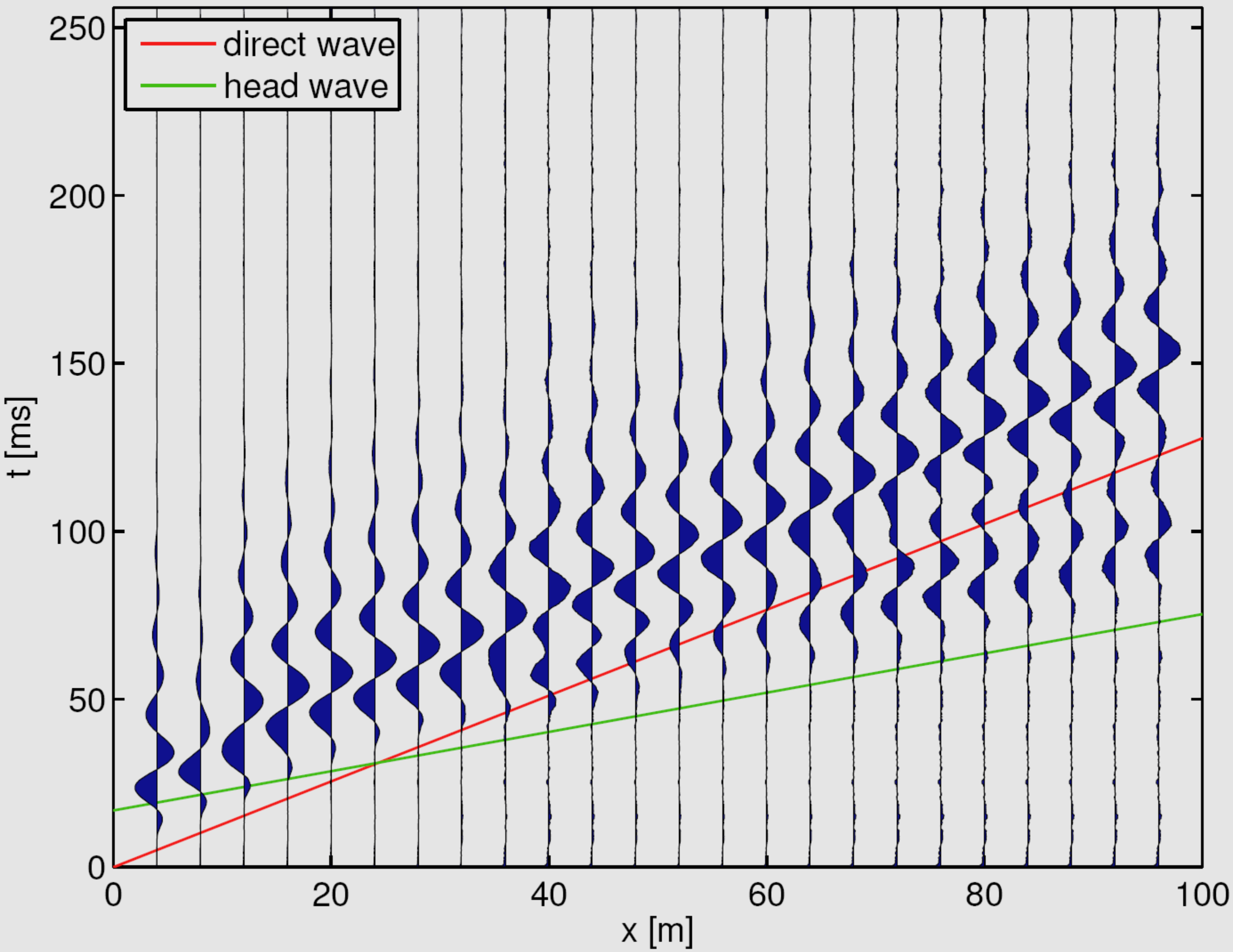
Seismic Picking

The first arrival times are mostly considered to be

- the time when the signal significantly rises above the noise,
- the time of the first maximum minus a quarter of the period, or
- the time of the zero after the first maximum minus a half of the period.

Picking is often supported by software.

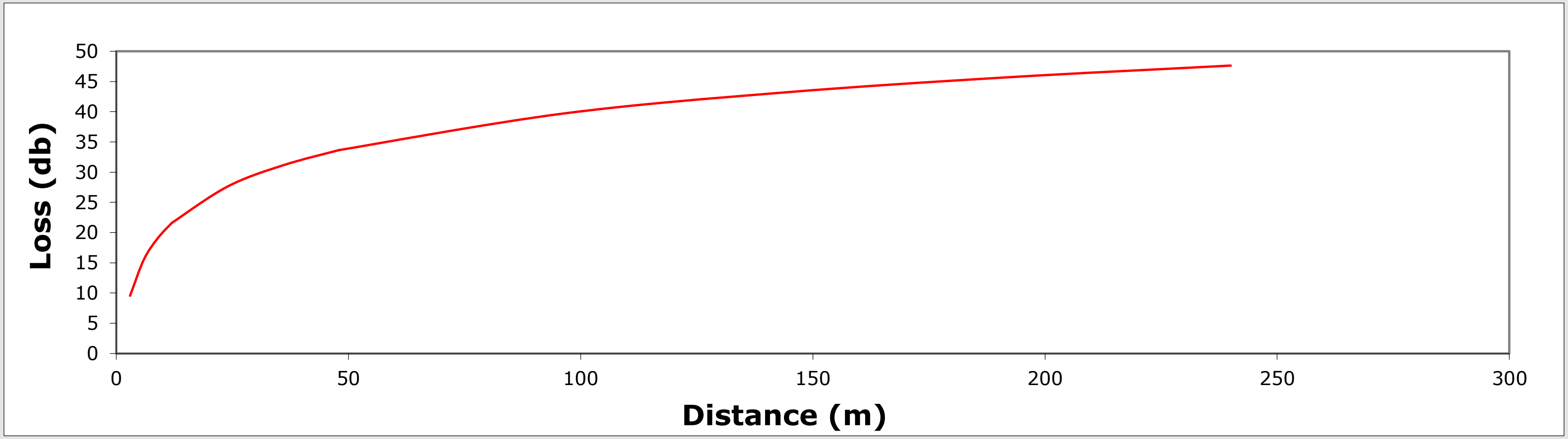
Seismic Picking



Seismics

Signal attenuation / absorption

Distance from shot (m)	3	6	9	12	12	24	36	48	48	96	144	192	240
Spherical spreading los (db)	9,5	15,6	19,1	21,6	21,6	27,6	31,1	33,6	33,6	39,6	43,2	45,7	47,6
Loss from previous point (db)		6,02	3,52	2,50		6,02	3,52	2,50		6,02	3,52	2,50	1,94



Seismics

Seismic Methods

Reflection seismics: Evaluation of the waves reflected at discontinuities.

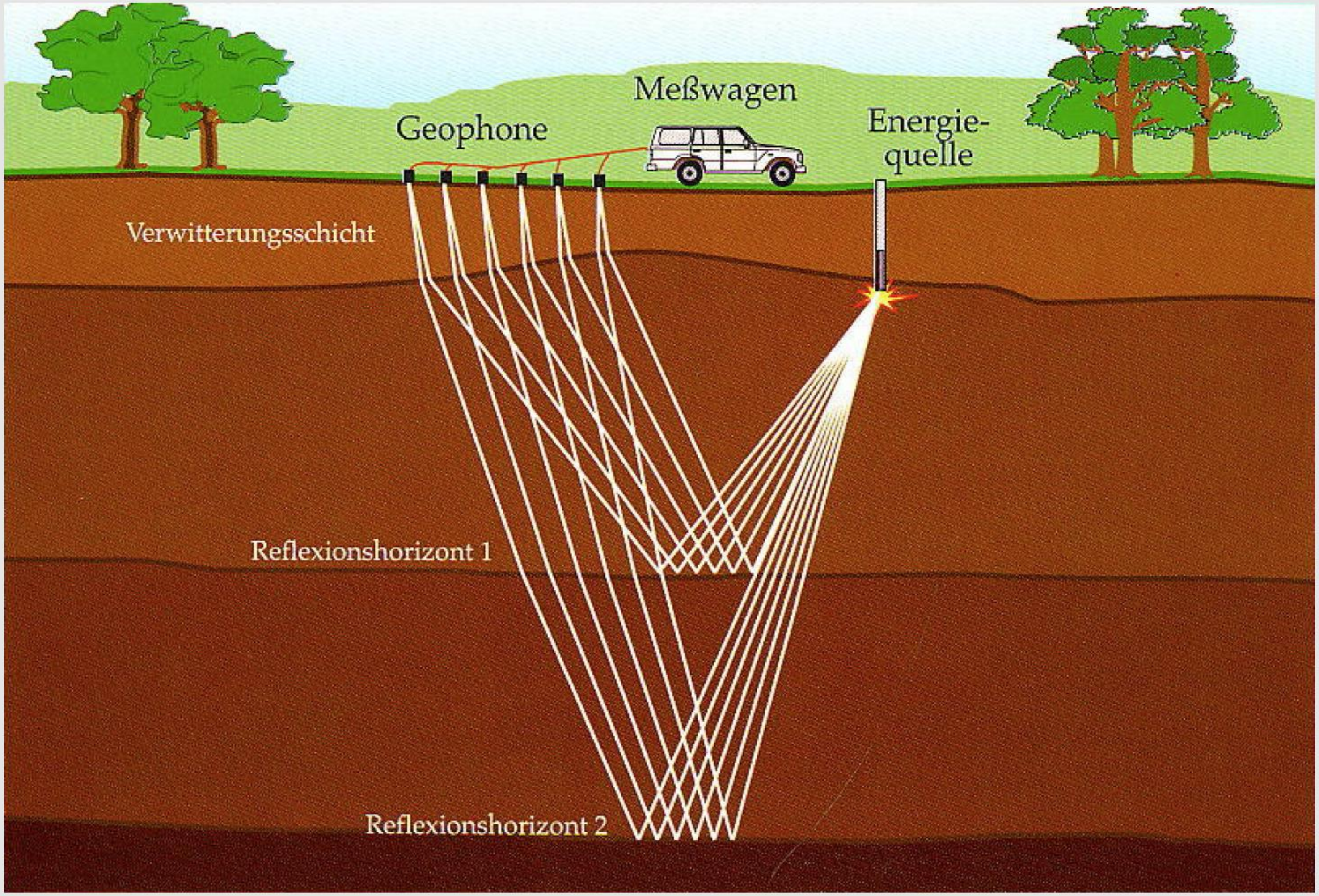
Refraction seismics: Evaluation of the head wave, i. e., the refracted wave at the limit to total internal refraction.

Seismic tomography: Inverting the signals of many sources and receivers. Mainly applied in large-scale seismology.

- Both reflection and refraction seismics address discontinuities where the seismic velocities change.
- Im most cases, only the first arrival times of the P-waves are evaluated.

Reflection Seismics

Basic Setup



Reflection Seismics

Reflection at the First, Horizontal Discontinuity

Travel time of the reflected wave to a geophone at distance x from the source (geophone offset):

$$t = \frac{\sqrt{4d_1^2 + x^2}}{v_1}$$

with

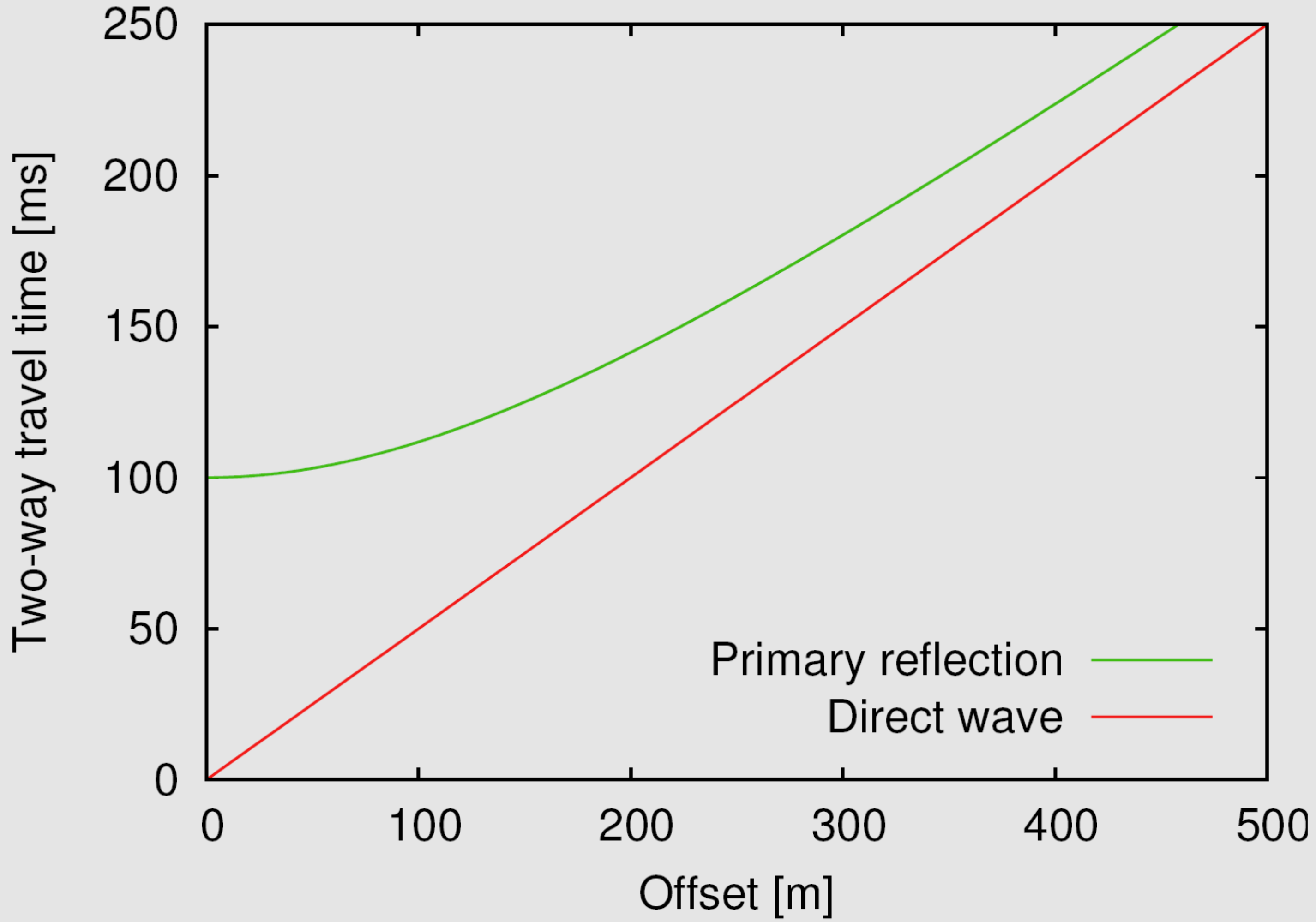
$$\begin{aligned} d_1 &= \text{thickness of the upper layer} \\ v_1 &= \text{P-wave velocity of the upper layer} \end{aligned}$$

This equation describes a hyperbola:

$$\frac{t^2}{(2d_1/v_1)^2} - \frac{x^2}{(2d_1)^2} = 1$$

Reflection Seismics

The Reflection Hyperbola



Reflection Seismics

Evaluating the Reflection Hyperbola

- v_1 can be determined from the travel time curve of the direct wave.
- d_1 can be determined from v_1 and the hyperbola.

Question

What are v_1 and d_1 in the example on the previous page?

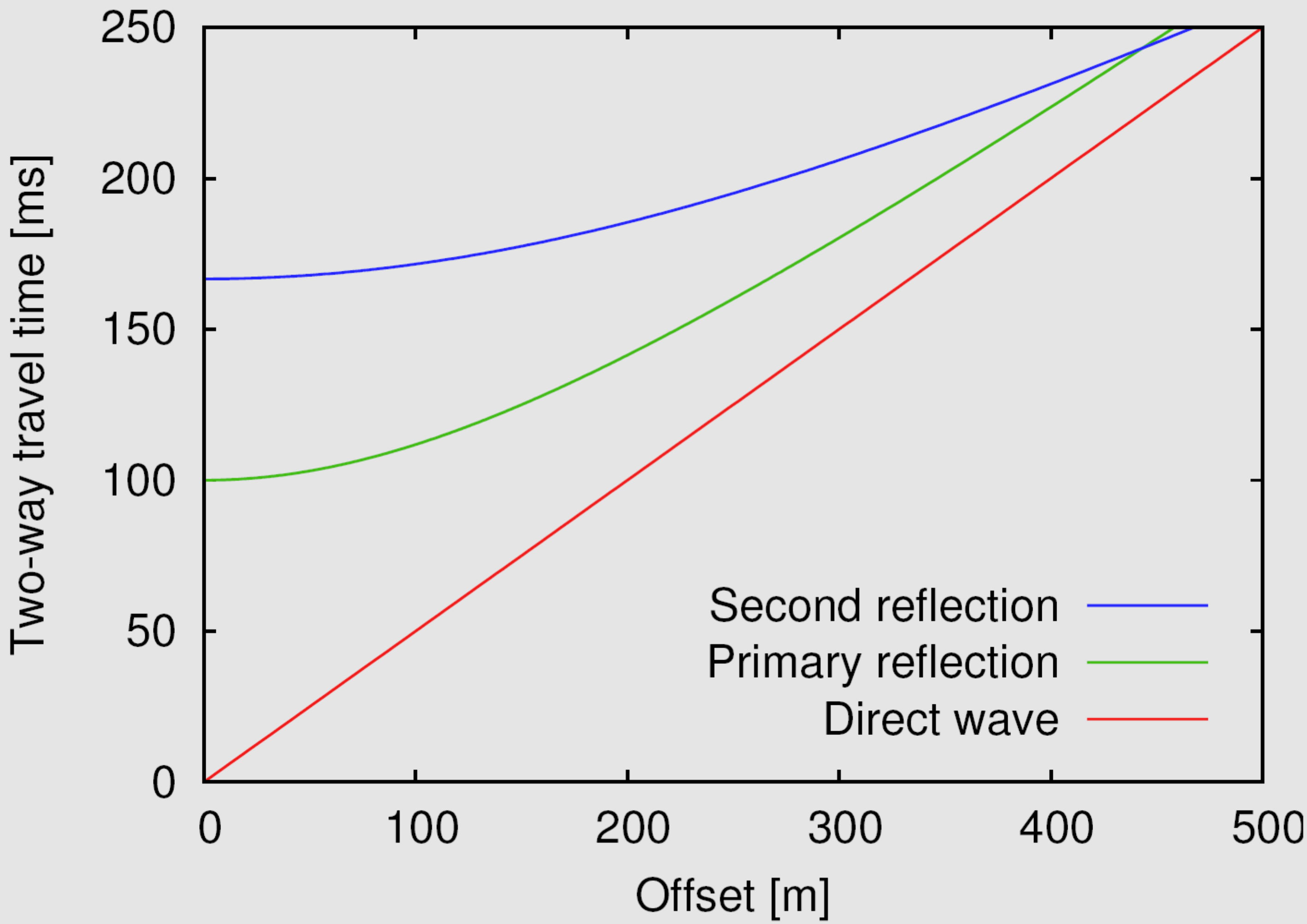
Evaluating the Reflection Hyperbola

v_1 can also be determined without the direct wave, either

- from the asymptotic slope of the hyperbola for $x \to \infty$ (requires large offsets), or
- from the curvature of the hyperbola.

Reflection Seismic

Multiple Reflections



Reflection Seismic

Multiple Reflections

- Even in horizontally layered media, secondary and later reflections are only approximately hyperbola.
- v_2, v_3, ... can in principle be derived from the hyperbolas, but this is more complicated than for the primary reflection.
- The uncertainty increases from layer to layer.

Question

What is the depth of the second discontinuity in the example on the previous page?

Reflection at Tilted or Curved Interfaces

Transfer of travel times to depths (depth migration) can be done, e. g., by constructing spherical wave fronts.

Reflection Seismic

Intensity of the Reflected Waves

The intensity of the reflected waves depends on the contrast in the acoustic impedance

$$Z = \rho v.$$

Reflection coefficient R = amplitude ratio of reflected and incident wave

- In general, R increases with the contrast in Z.
- For normal incidence, P- and S-waves do not merge, and

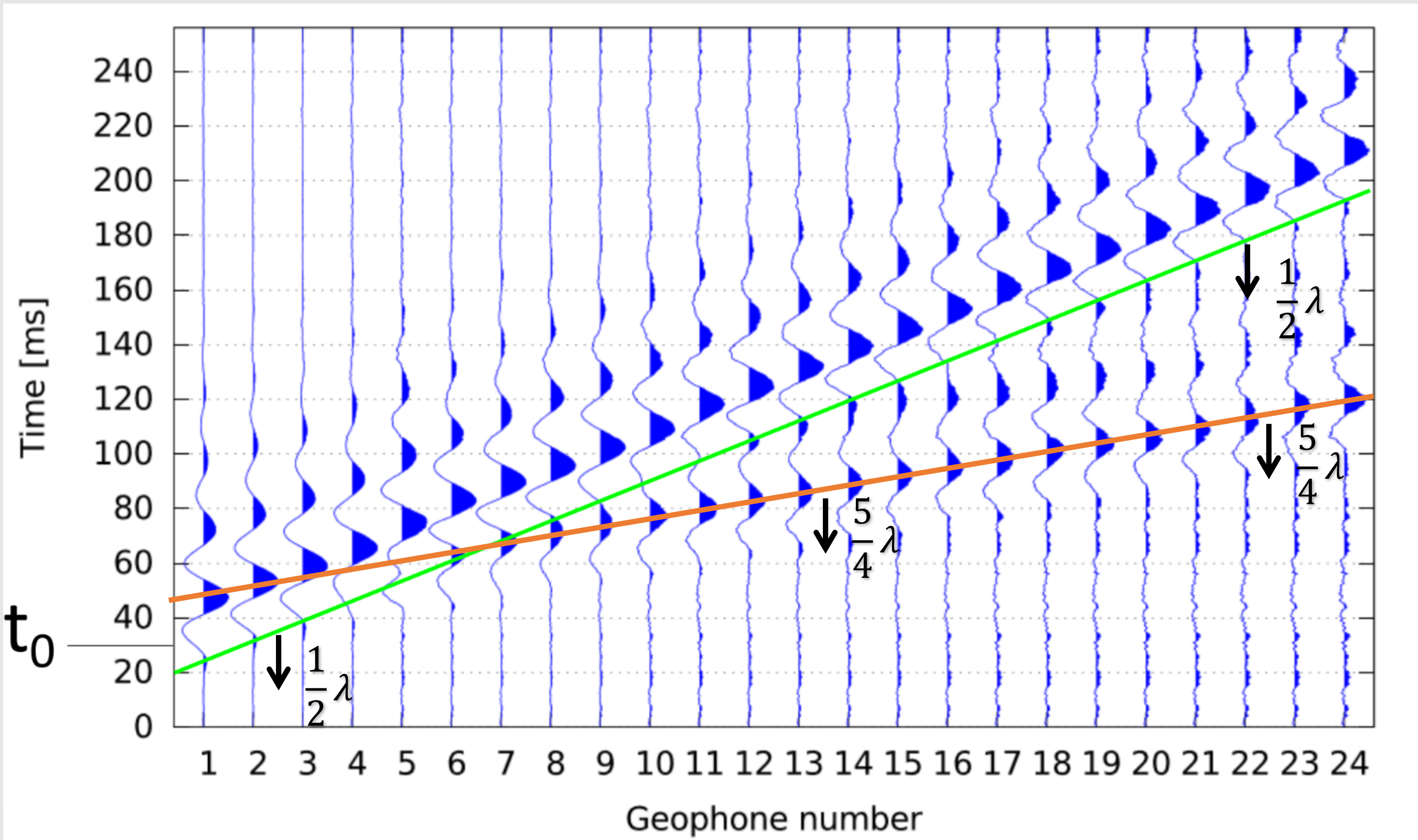
$$R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1}.$$

- Multiple reflexion costs much energy.

$$\Downarrow$$

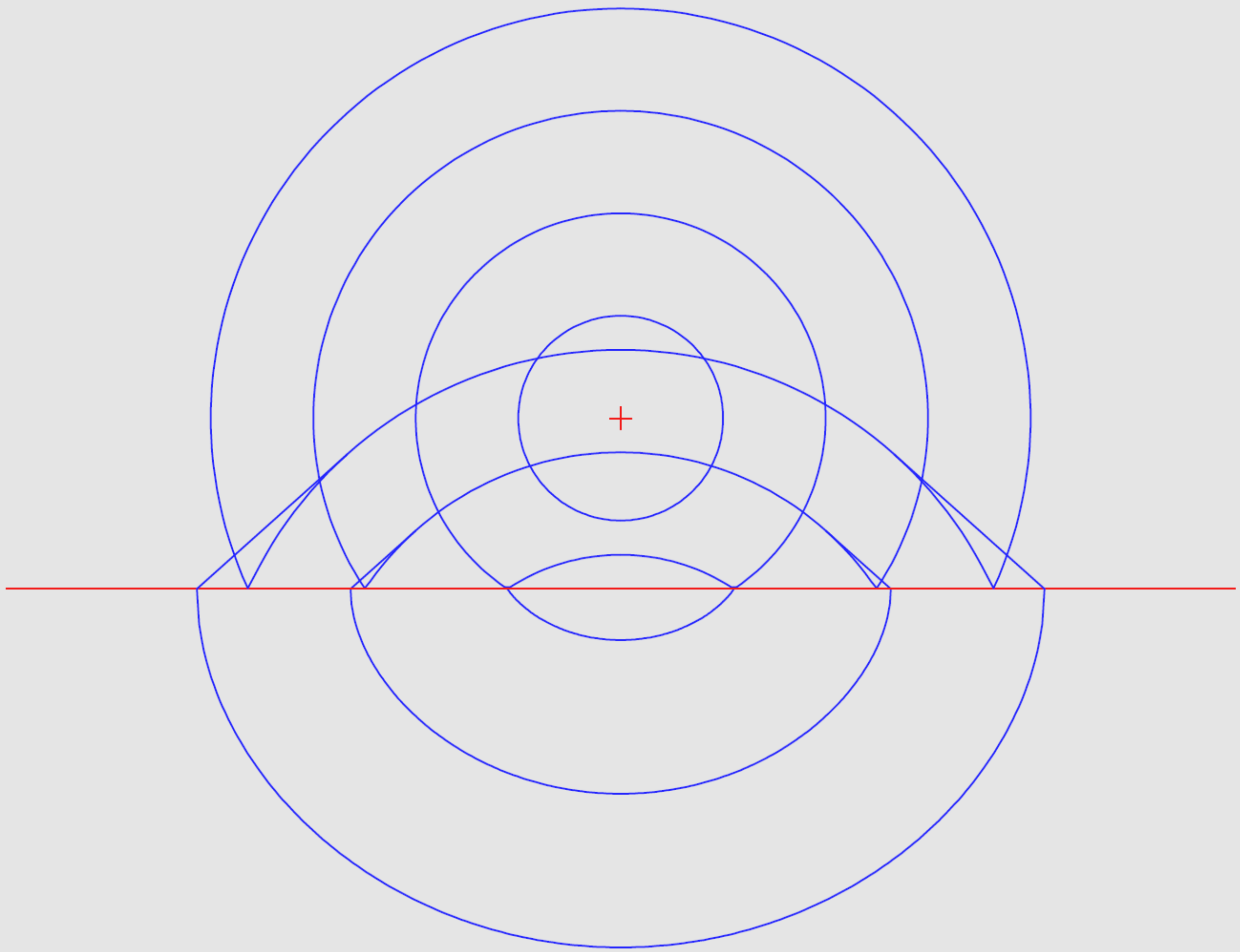
Multiple-layer reflection seismics requires strong seismic sources.

Sheet 3



Time [ms]
0
20
40
60
80
100
120
140
160
180
200
220
240
t_0
Geophone number
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
$\frac{1}{2}\lambda$
$\frac{5}{4}\lambda$
$\frac{1}{2}\lambda$
$\frac{5}{4}\lambda$

Reflection and Refraction of a Spherical Wave at a Planar Interface



Refraction Seismics

Refraction at the Critical Angle

If the angle of incidence on a planar interface from a medium with v_1 to a medium with $v_2 > v_1$ achieves the critical value α_c with

$$\sin \alpha_c = \frac{v_1}{v_2}$$

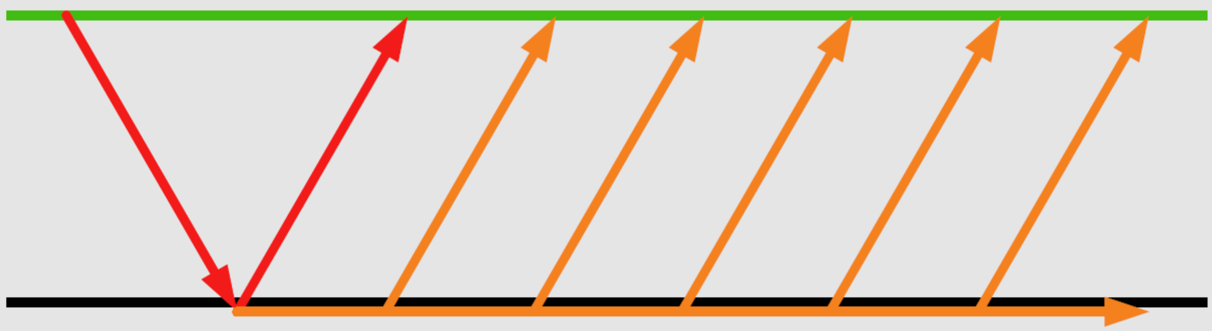
the refracted waves propagates along the interface with the velocity v_2.

Refraction Seismics

The Seismic Head Wave

Wave refracted at the critical angle = head wave = Mintrop wave (according to L. Mintrop, 1880–1956).

- Continuously radiates back into the first medium at the angle α_c.



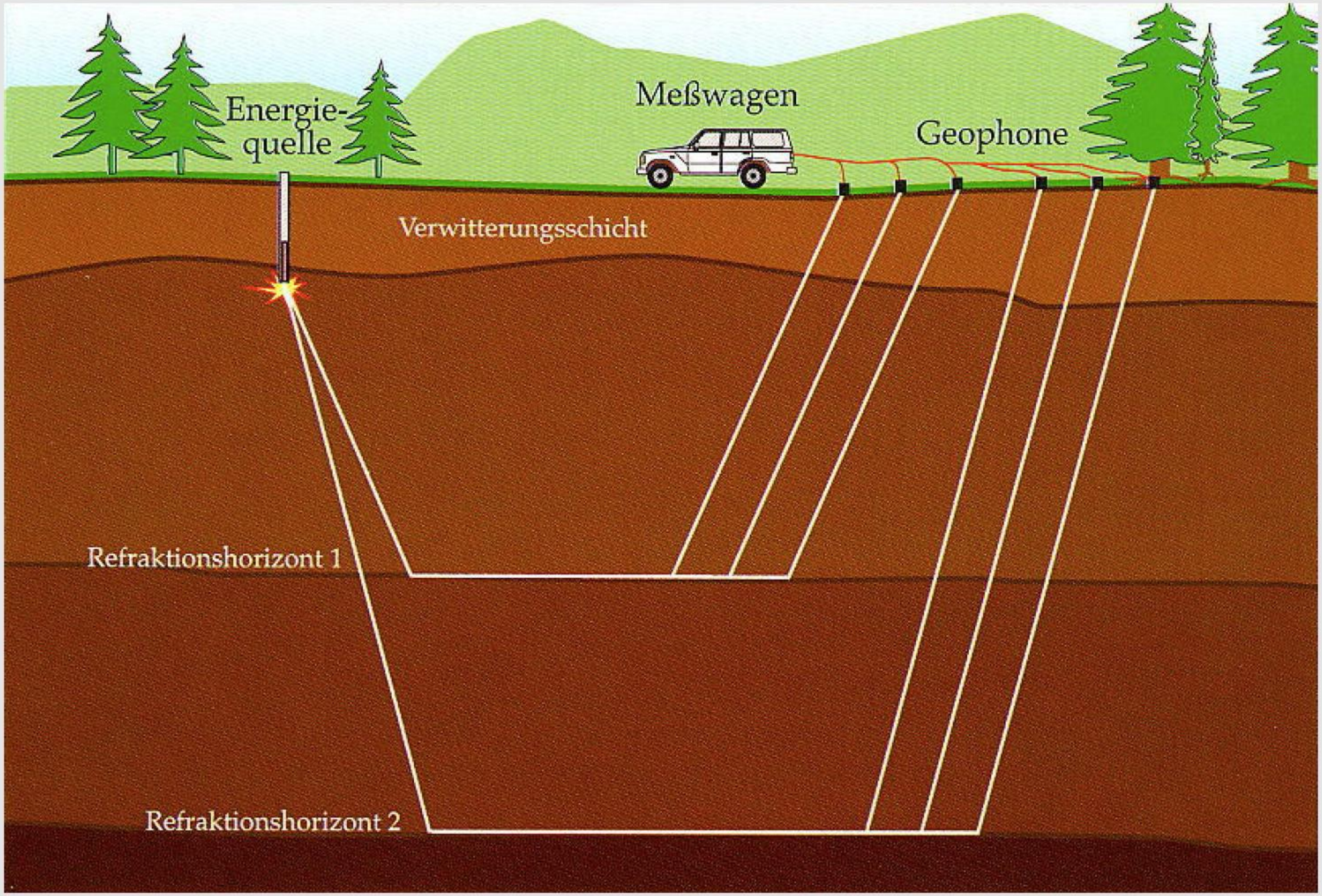
- Propagates along the surface with $v_2 > v_1$.

$$\Downarrow$$

Head wave finally outruns the direct wave (v_1)

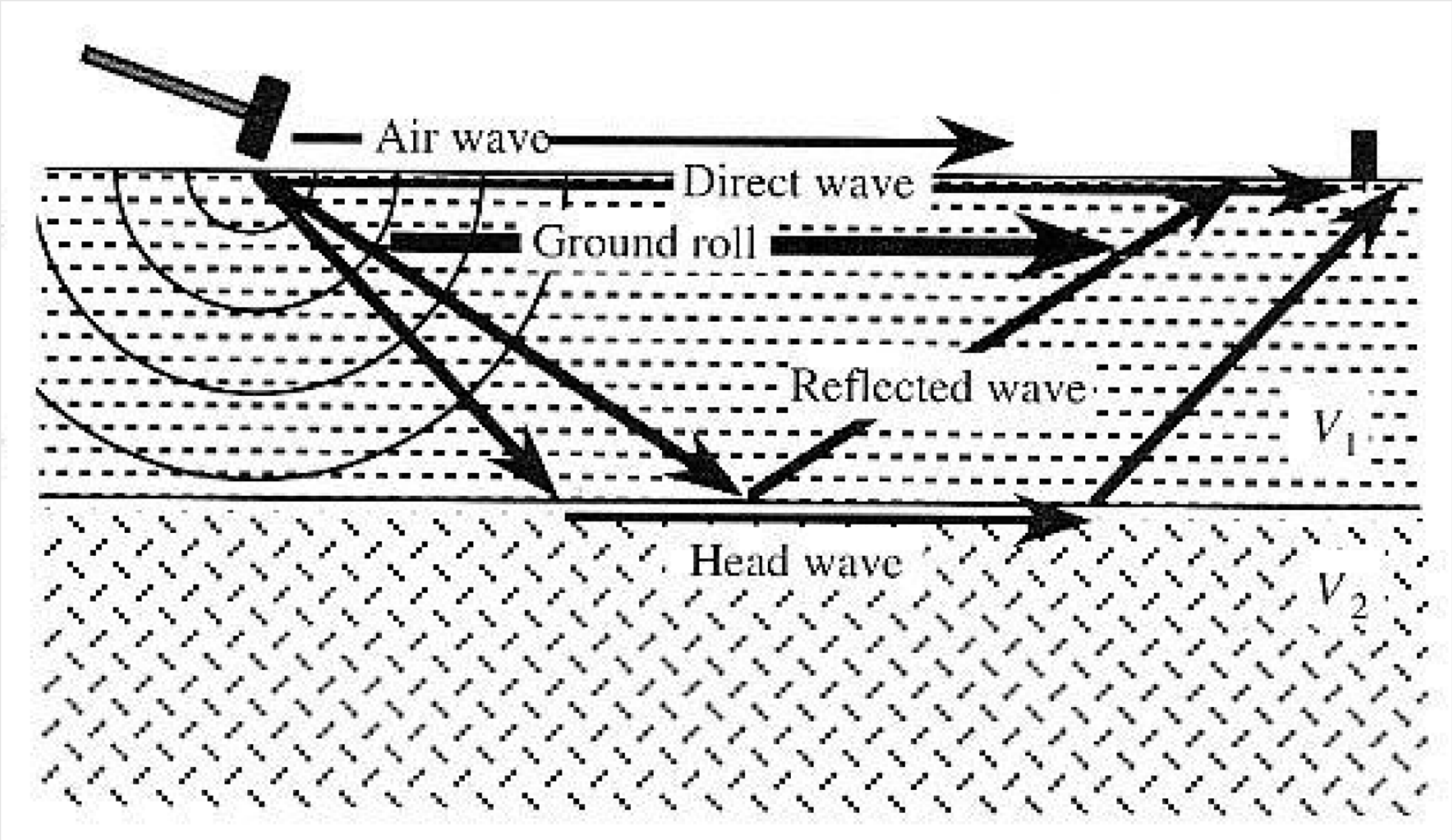
Refraction Seismics

Basic Setup



Refraction Seismics

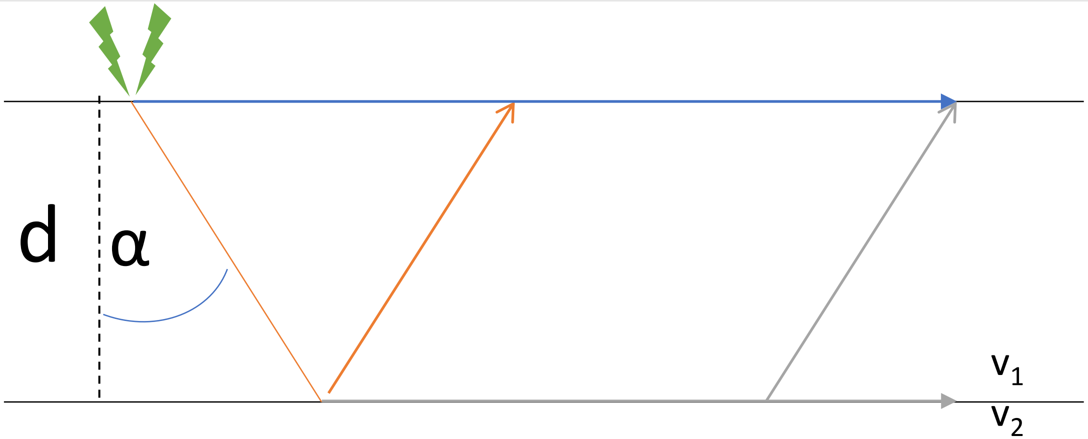
Types of Waves



Source: Burger et al., Introduction to Applied Geophysics

Reflraction Seismics

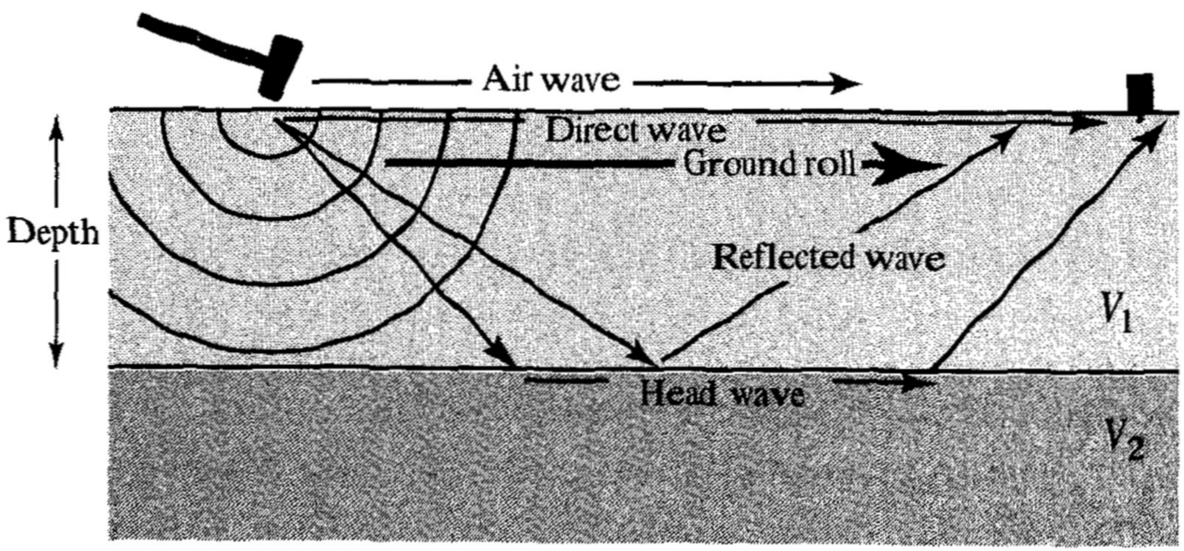
Typical hammer stroke setup



Refracted wave

Reflected wave

Direct wave



$V_1 = 1500$ m/s

$V_2 = 4000$ m/s

Refraction Seismics

Travel Time of the Head Wave at a Horizontal Interface

The wave reflected at the critical angle α_c needs the time

$$t = \frac{2d}{v_1 \cos\alpha_c}$$

(d = layer's thickness) and arrives at the surface again at

$$x = 2d \tan\alpha_c.$$

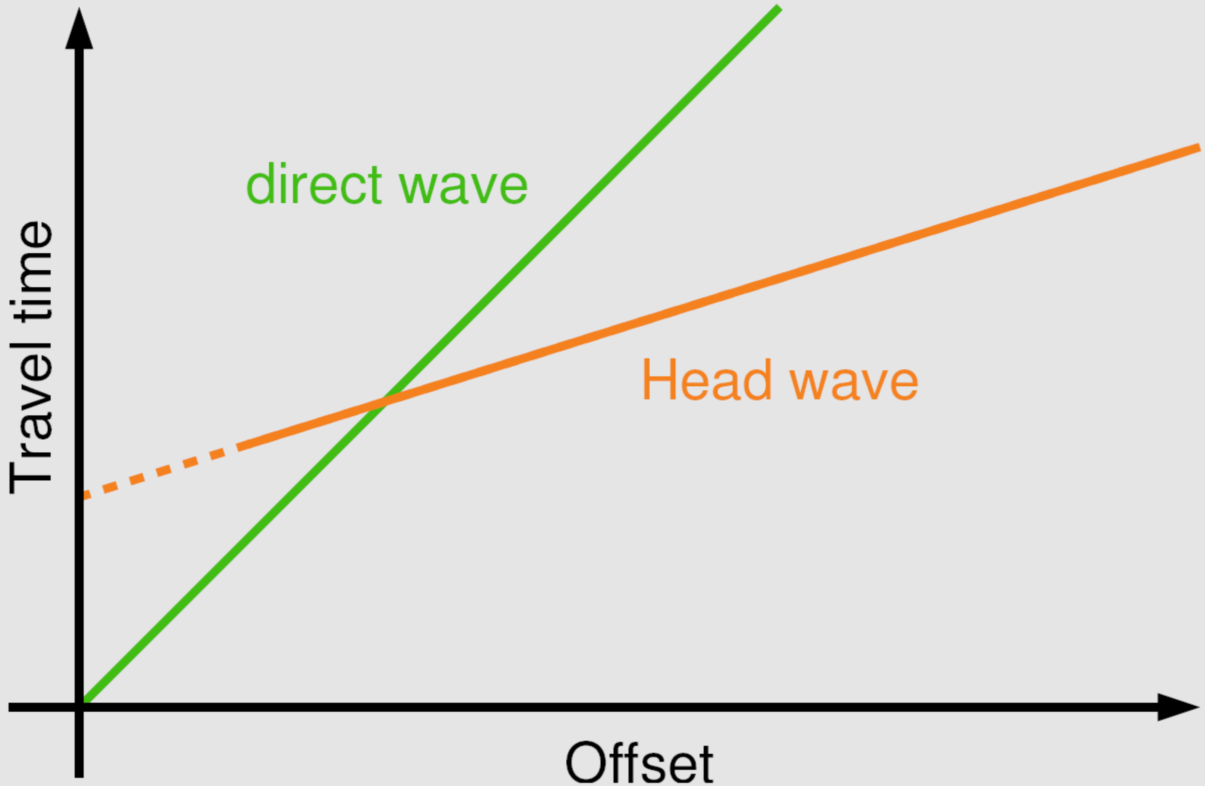
$$\Downarrow$$

The head wave reaches a receiver with offset x after

$$t = \frac{2d}{v_1 \cos\alpha_c} + \frac{x - 2d \tan\alpha_c}{v_2} = \frac{2\,d \cos\alpha_c}{v_1} + \frac{x}{v_2}$$

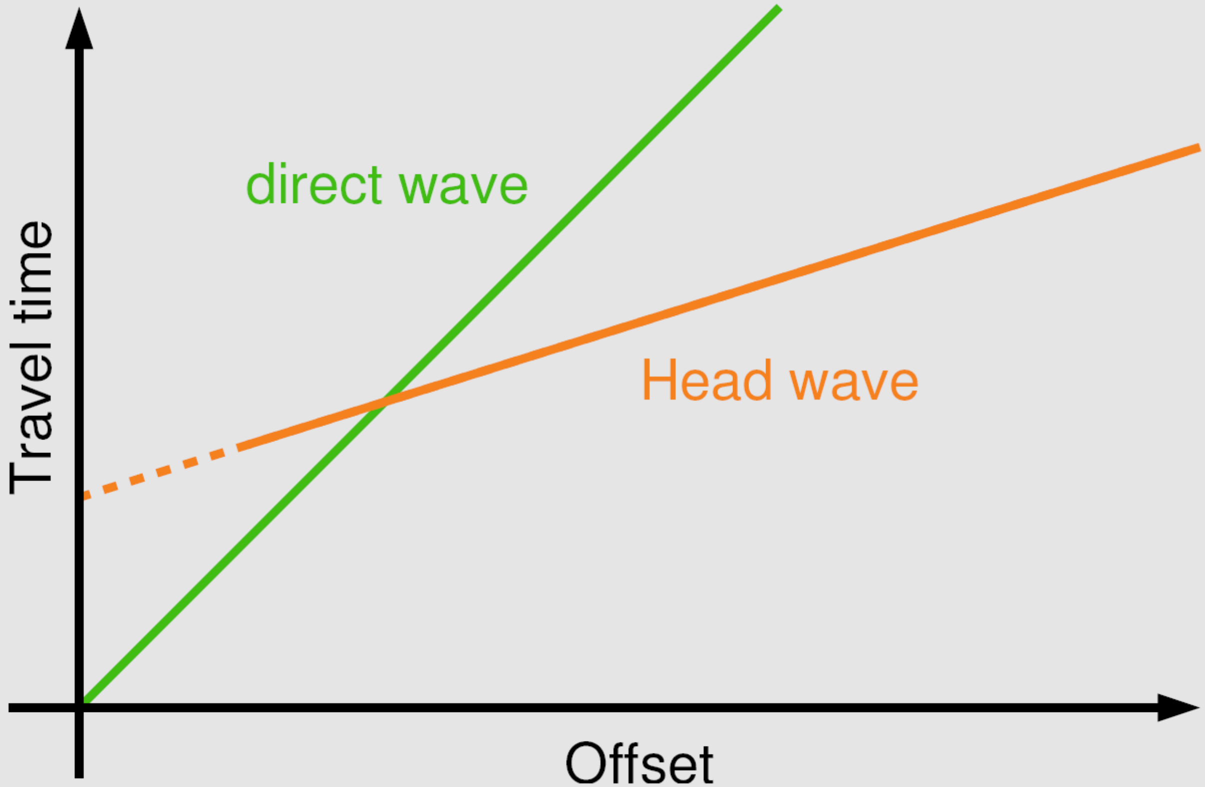
Refraction Seismics

Travel-Time Diagram for a Horizontal Interface



Refraction Seismics

Travel-Time Diagram for a Horizontal Interface

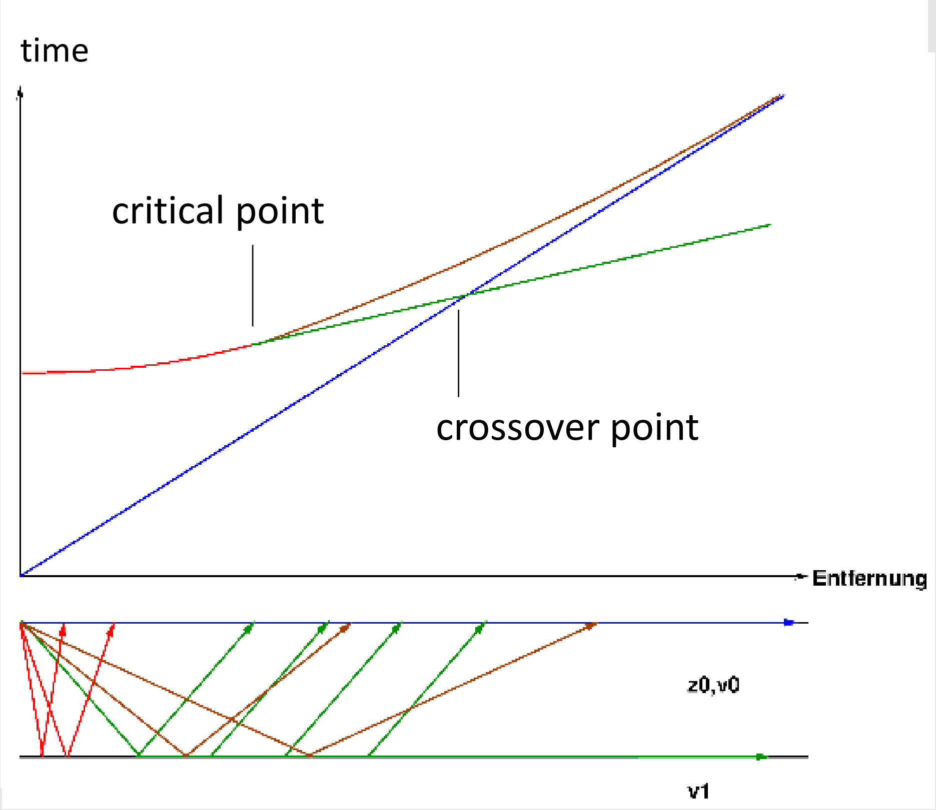


Question

What would the travel time curve for the reflected wave look like?

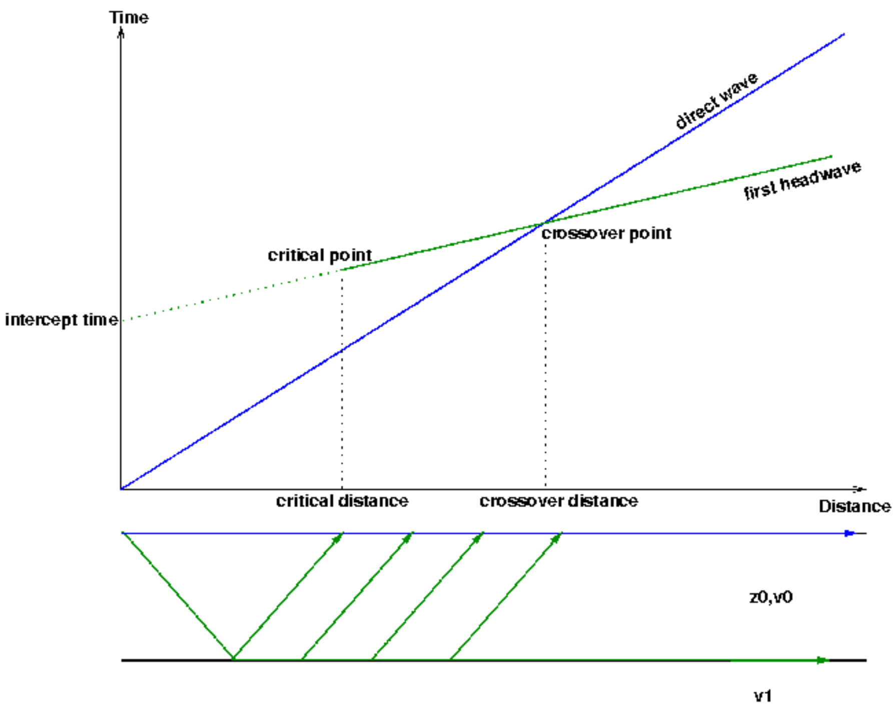
Travel time curves

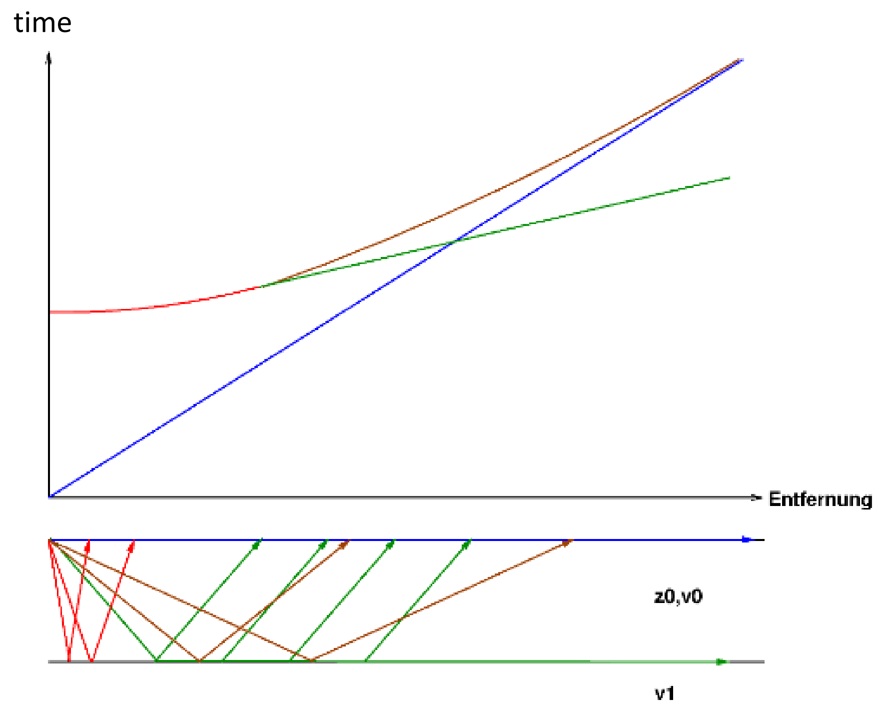
- blue: direct wave
  - *Slope reflects invert of velocity* $1/v_0$
- green: Head wave
- red: reflected wave, under critical
- brown: reflected wave, over critical



Travel time curves

- Propagating seismic waves (bottom) and related travel time diagram (top) of the direct (blue) and the first refracted phase (green)





Refraction Seismics

Travel Time Diagram

- Mostly, the waves radiated at one source (shot point) are recorded with several geophones located on a straight line..
- Direct and refracted waves are straight lines in the diagram, while reflected waves are (approximately) hyperbola.
- Often only the earliest arriving wave is picked.

Refraction Seismics

Quantitative Analysis in Case of a Horizontal Interface

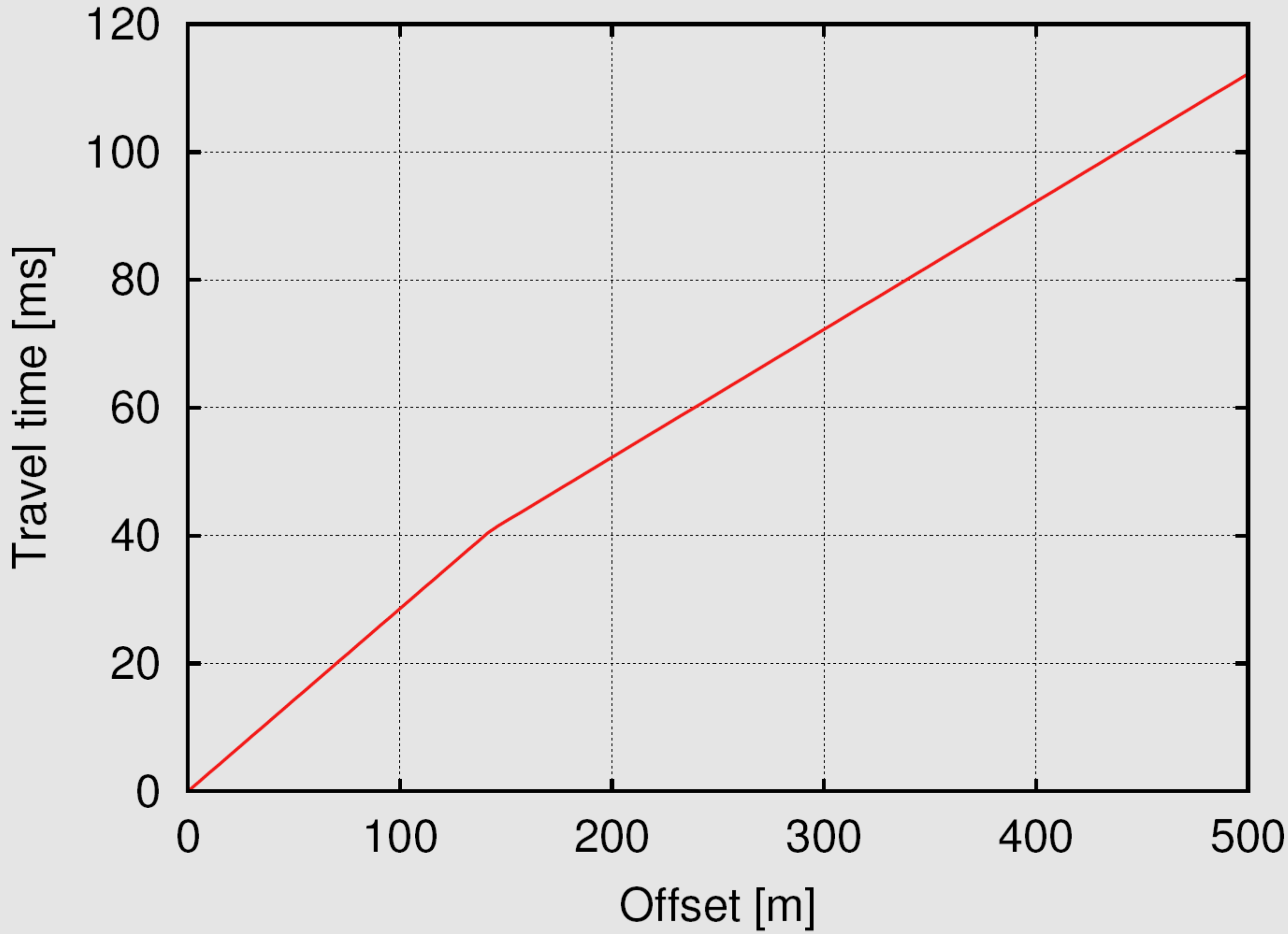
1. Slope of the travel time curve of the direct wave $S_d = \frac{1}{v_1}$
2. Slope of the travel time curve of the refracted wave $S_r = \frac{1}{v_2}$
3. Intercept time = extrapolated time where the travel time curve of the refracted wave crosses the time axis

$$t_0 = \frac{2\,d\,\cos\alpha_c}{v_1} = 2\,d\sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}$$

so that

$$d = \frac{t_0\,v_1}{2\cos\alpha_c} = \frac{t_0}{2\sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}}$$

Example



Travel time [ms]
0
20
40
60
80
100
120
0
100
200
300
400
500
Offset [m]

Refraction Seismics

What is a Useful Offset?

The travel time curves of the direct wave and the head wave intersect at

$$\frac{x}{v_1} = \frac{2\,d\,\cos\alpha_c}{v_1} + \frac{x}{v_2}$$

$$\Downarrow$$

$$x = \frac{2\,d\,\cos\alpha_c\,v_2}{v_2 - v_1} = 2\,d\sqrt{\frac{v_2 + v_1}{v_2 - v_1}}$$

The total offset (shot point to last geophone) should be a least two times x to recognize the travel time curves of both waves.

Refraction Seismics

What is a Useful Offset?

The travel time curves of the direct wave and the head wave intersect at

$$\frac{x}{v_1} = \frac{2\,d\,\cos\alpha_c}{v_1} + \frac{x}{v_2}$$

$$\Downarrow$$

$$x = \frac{2\,d\,\cos\alpha_c\,v_2}{v_2 - v_1} = 2\,d\,\sqrt{\frac{v_2 + v_1}{v_2 - v_1}}$$

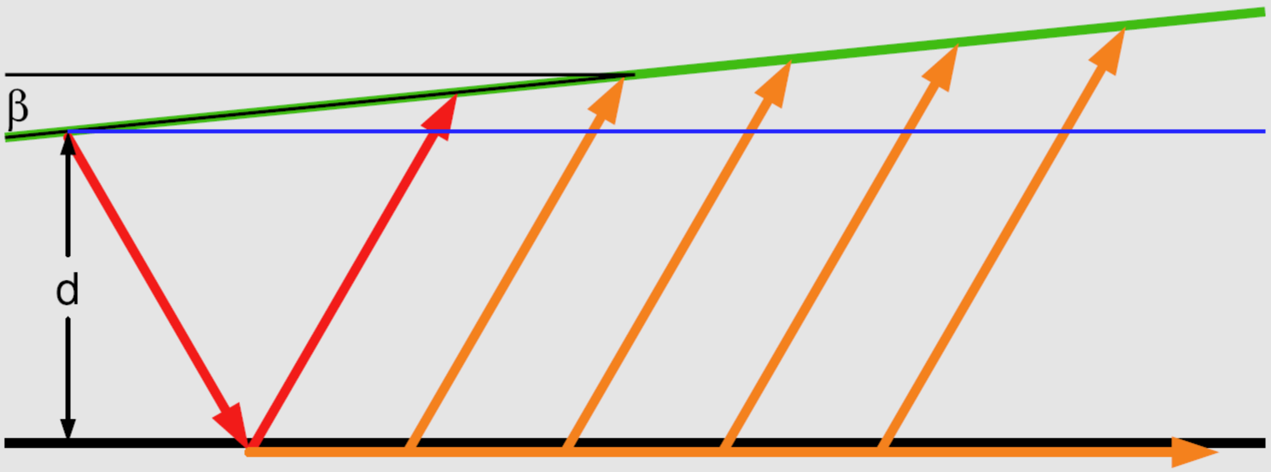
The total offset (shot point to last geophone) should be a least two times x to recognize the travel time curves of both waves.

Question

What would be a reasonable offset for locating the ground water level in an aquifer of sand an gravel in about 12 m depth?

Refraction Seismics

Travel Time Curve for a Sloping Interface



Intersection of the arriving rays with the blue line:

$$x_b = x \cos\beta - x \sin\beta \tan\alpha_c$$

Additional travel time from the blue line to the surface:

$$t - t_b = \frac{x \sin\beta}{v_1 \cos\alpha_c}$$

Refraction Seismics

Travel Time Curve for a Sloping Interface

Head wave arrives at x_b on the blue line at

$$t_b = \frac{2\,d\,\cos\alpha_c}{v_1} + \frac{x_b}{v_2}$$

so that the total travel time is

$$\begin{aligned} t &= \frac{2\,d\,\cos\alpha_c}{v_1} + \frac{x\,\cos\beta - x\,\sin\beta\,\tan\alpha_c}{v_2} + \frac{x\,\sin\beta}{v_1\,\cos\alpha_c} \\ &= \frac{2\,d\,\cos\alpha_c}{v_1} + \left(\frac{\cos\beta}{v_2} + \frac{\sin\beta\,\cos\alpha_c}{v_1}\right)x \end{aligned}$$

Refraction Seismics

Travel Time Curve for a Sloping Interface

Slope of the travel time curve:

$$S_r = \frac{\cos\beta}{v_2} + \frac{\sin\beta\,\cos\alpha_c}{v_1} = \frac{\sin(\alpha_c + \beta)}{v_1}$$

$$\Downarrow$$

If the interface dips in shot direction (downdip), the head wave is apparently slower than for a horizontal interface and vice versa.

Intercept time

$$t_0 = \frac{2\,d\,\cos\alpha_c}{v_1}$$

is the same as for a horizontal interface if the depth is taken perpendicularly to the interface (not to the surface).

Refraction Seismics

Shot and Reverse Shot

For a sloping interface the travel time curve is not sufficient to determine v_2, d, and β.

Measure a second travel time curve opposite to the original one (reverse shot).

Refraction Seismics

Shot and Reverse Shot

Steps of analysis:

1. Slope of the travel time curve of the direct wave $S_d = \frac{1}{v_1}$ (same as for a horizontal interface).
2. Use either
   (a) mean value of the absolute slopes of the travel time curves of both head waves:

$$\overline{S}_r = \frac{\cos\beta}{v_2} \approx \frac{1}{v_2}$$

   if β is not too large or
   (b) absolute slopes of the travel time curves of both head waves:

$$S_r = \frac{\sin(\alpha_c \pm \beta)}{v_1}.$$

Refraction Seismics

Shot and Reverse Shot

3. Depth of the interface is similar to the horizontal case:

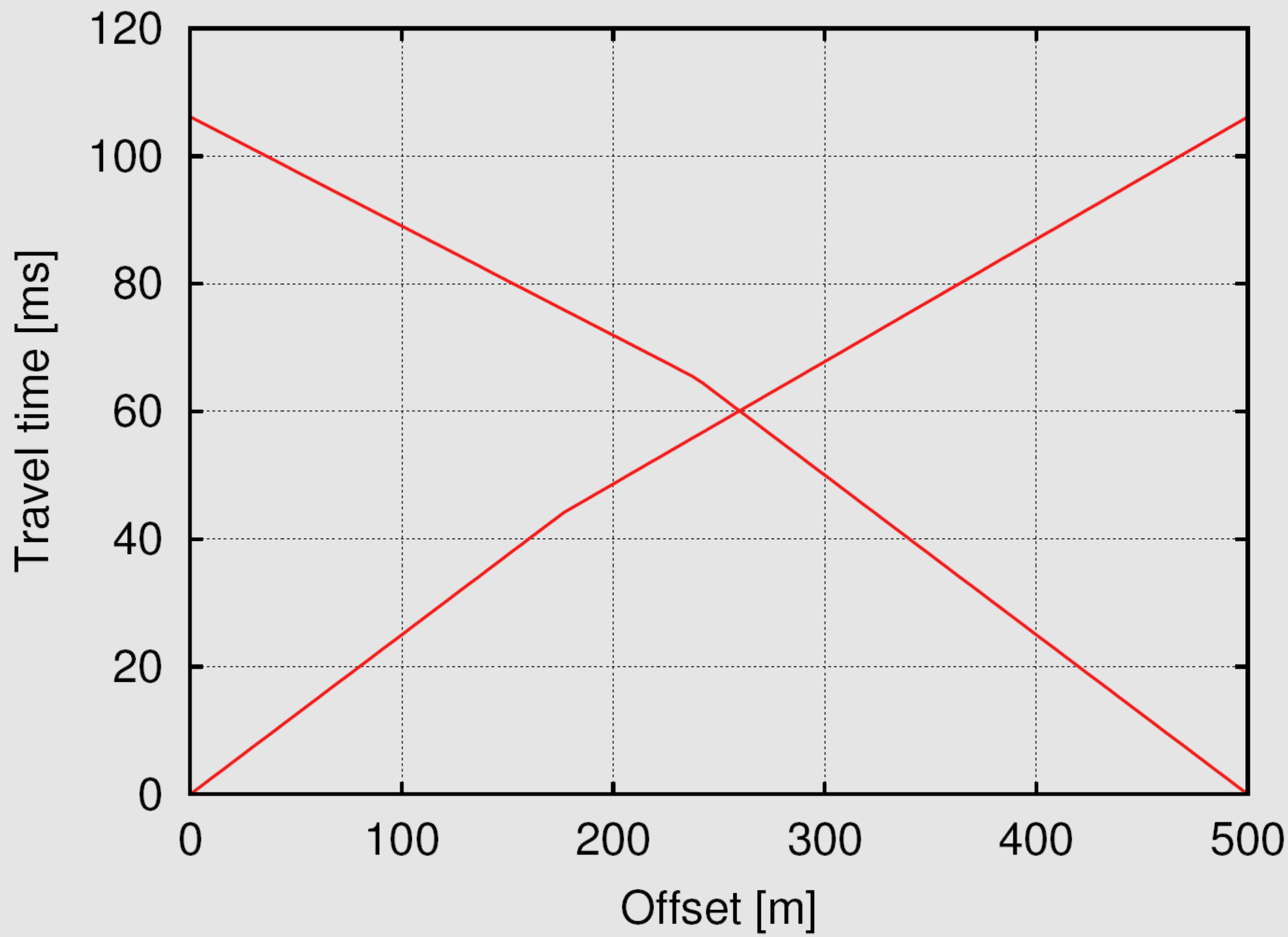
$$d = \frac{t_0 \, v_1}{2 \cos \alpha_c} = \frac{t_0}{2 \sqrt{\frac{1}{v_1^2} - \frac{1}{v_2^2}}}$$

where the intercept times of shot and reverse shot yield the depth below the respective shot point (normal to the interface).

If β is not small, the (vertical) depths can be obtained by $\frac{d}{\cos \beta}$.

Refraction Seismics

Example



Refraction Seismics

Multiple Refraction

- Several head waves.
- Evaluation becomes more complicated, but without principal problems.
- Important limitation: Only interfaces where the velocity increases towards to lower layer can be detected (also applies to the case of two layers).