Engineering and Environmental Geophysics

Seismic prospecting

Outline

Methods for engineering geophysics

- seismic methods (refraction / reflection / surface wave)

- electrical methods (ERT)

- E-M methods (FDEM, RADAR)

- case histories

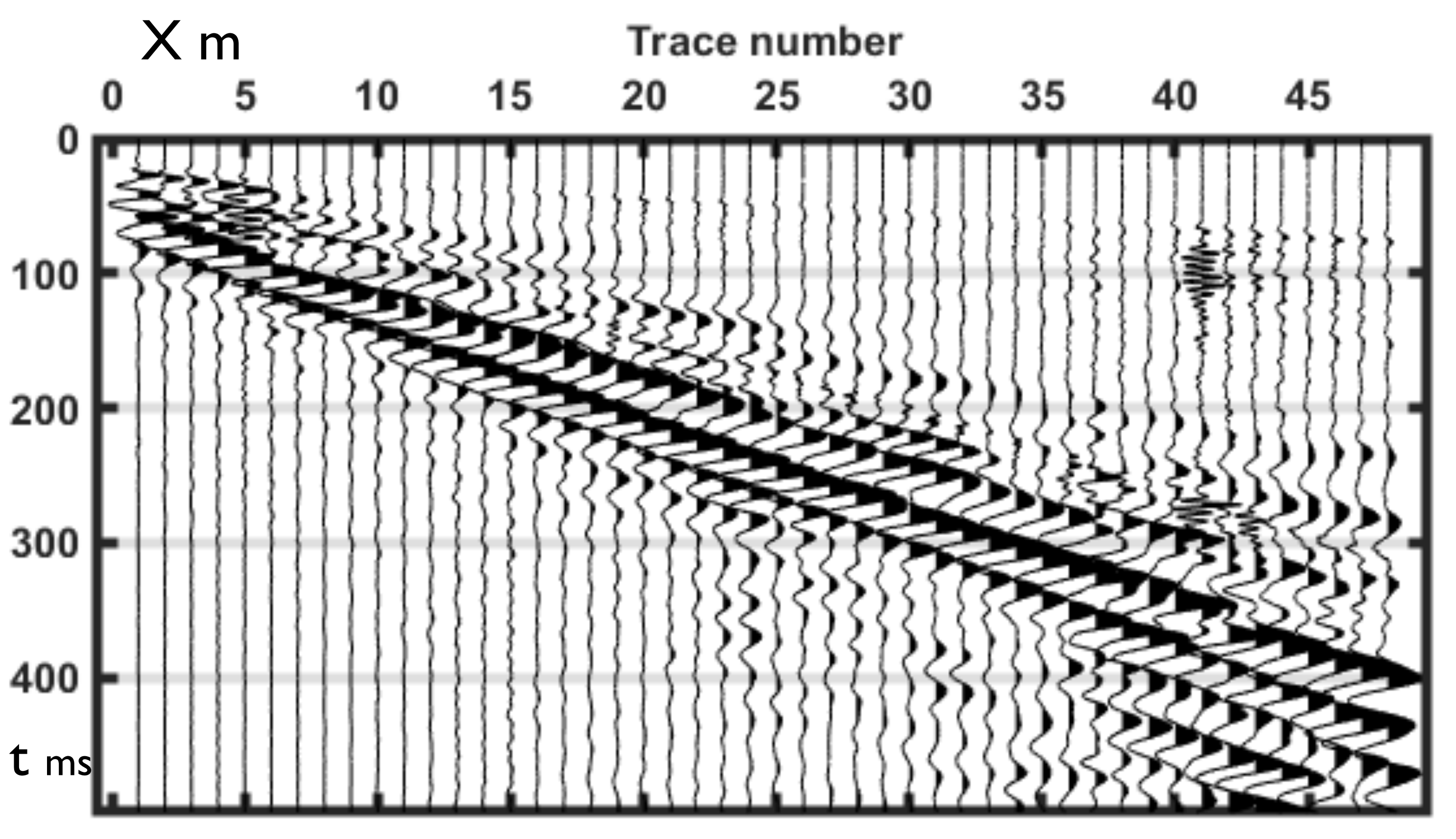
Method	Structure	Dynamic
Seismic	+ +	
Electro-Magnetic	+	++
DC resistivity methods ERT	++	++
Ground Penetration Radar	++	+
Distributed Temp. Sensing		++
Magnetics	+	
Gravimetry	+	+
Spectral Induced Polarization	+	
Self Potential		+
Borehole logs	+ +	+

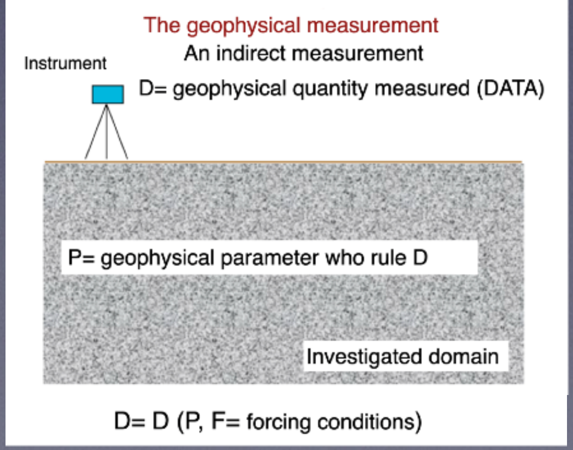
Physical Properties (P)

Seismic	Elastic moduli and density
Gravimetry	: Density
Magnetic meth.	Magnetic susceptibility
ERT meth.	Electrical resistivity
Electro-magnetic meth.	Electrical conductivity
Induced Polarization	Electrical complex conductivity
Spontaneous Potentials	Electrical conductivity
Ground penetrating Radar	Dielectric constant

Seismic Methods

Study the wave elastic propagation in the subsoil and furnish the mechanical parameters



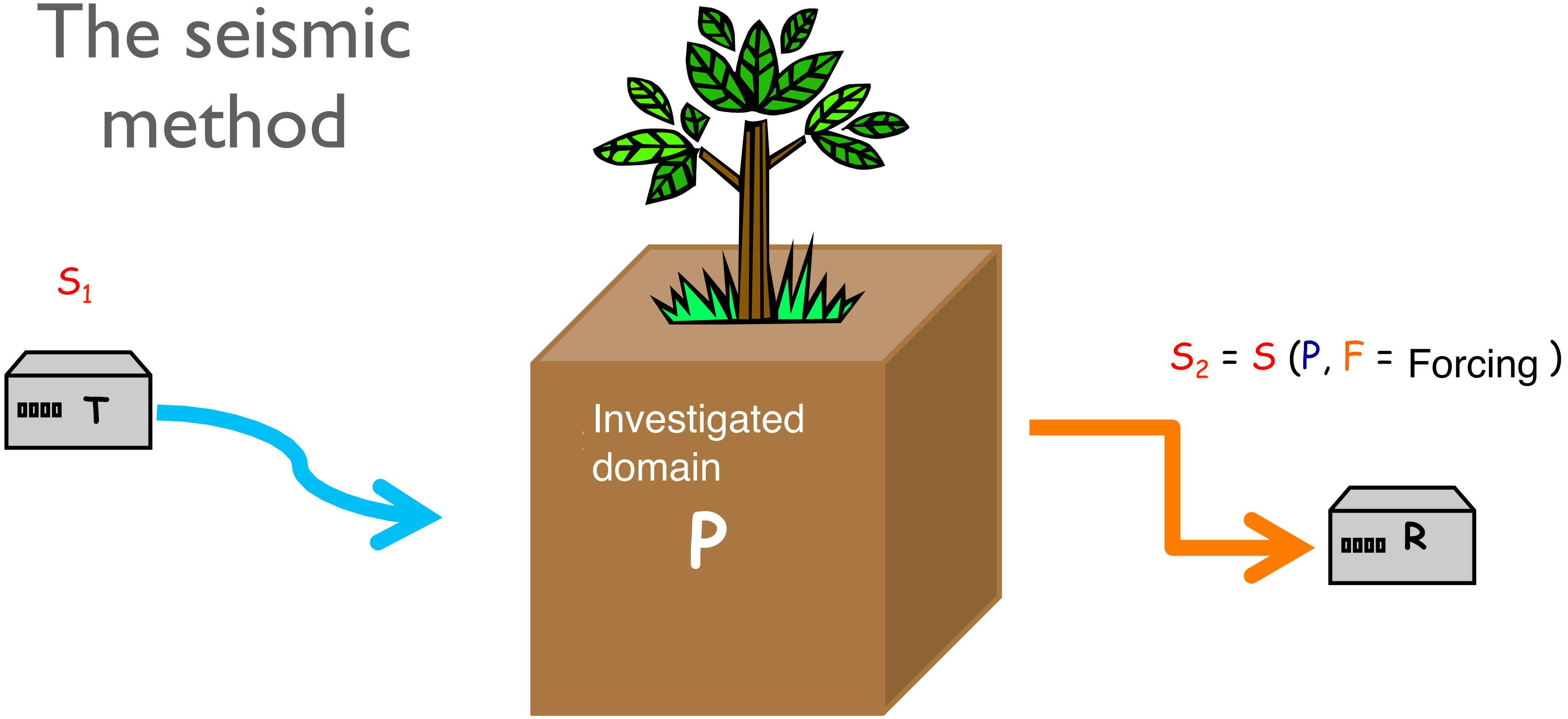


Physics parameter P

=

Elastic properties

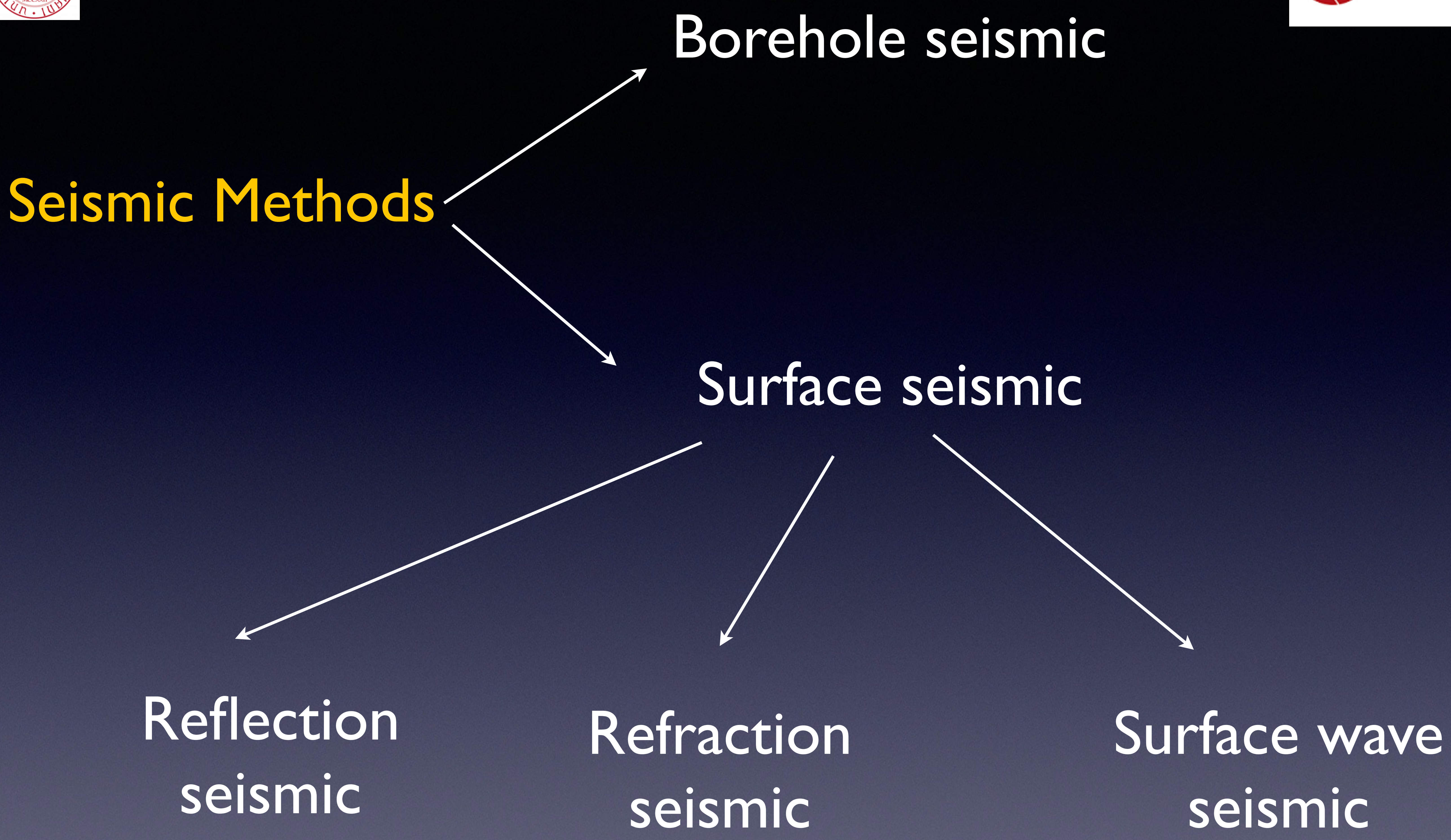
The seismic method



S_1 = Signal = Elastic wave source

S_2 = Signal = Induced vibration

P = Physical parameter Elastic moduli/ density



Seismic Methods

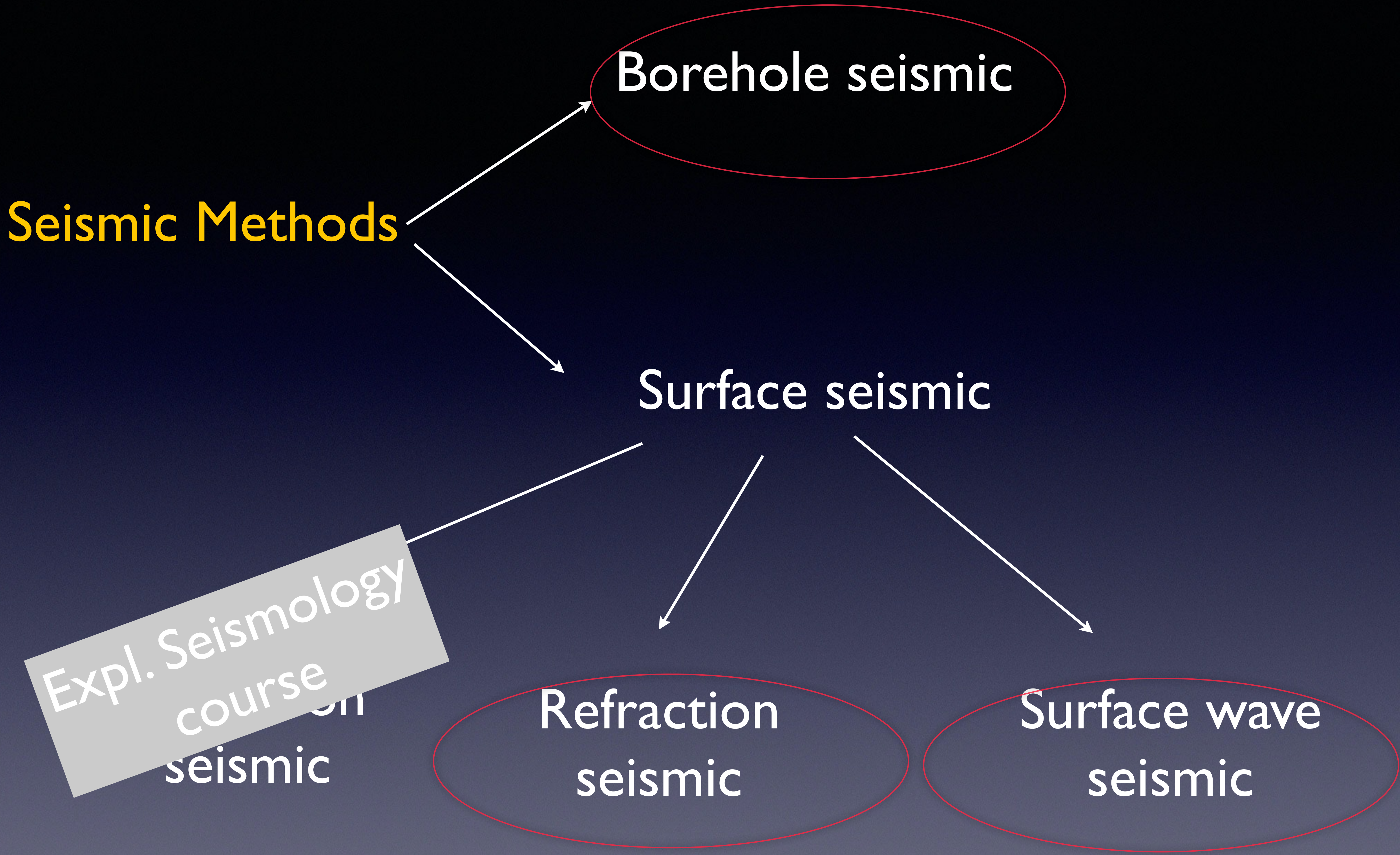
Borehole seismic

Surface seismic

Reflection seismic

Refraction seismic

Surface wave seismic



Seismic Methods

Borehole seismic

Surface seismic

Expl. Seismology course

on

seismic

Refraction seismic

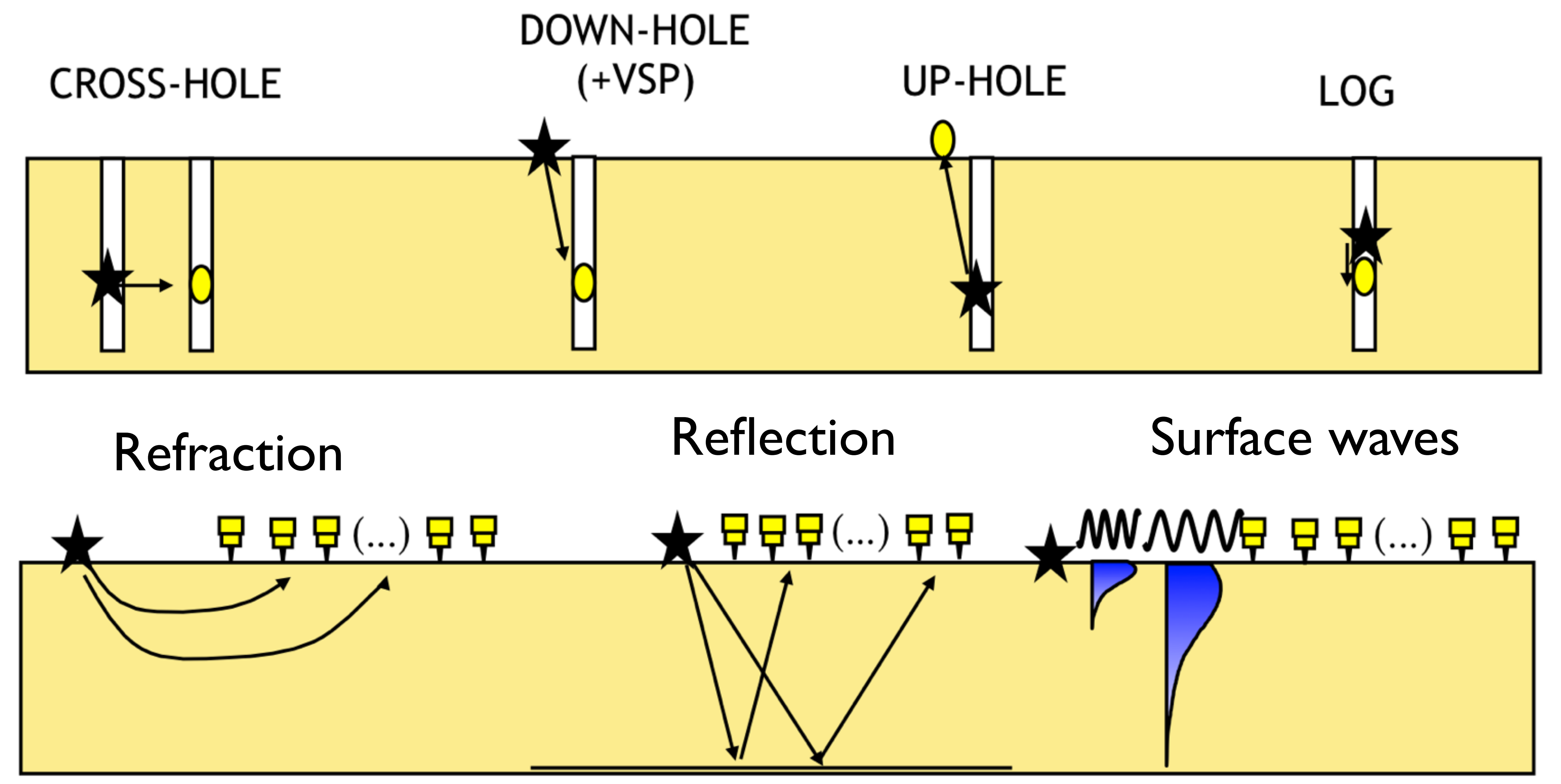
Surface wave seismic

Seismic Methods

- Methods
- Equipments
- surveys design
- processing

Seismic Methods

Borehole Seismic

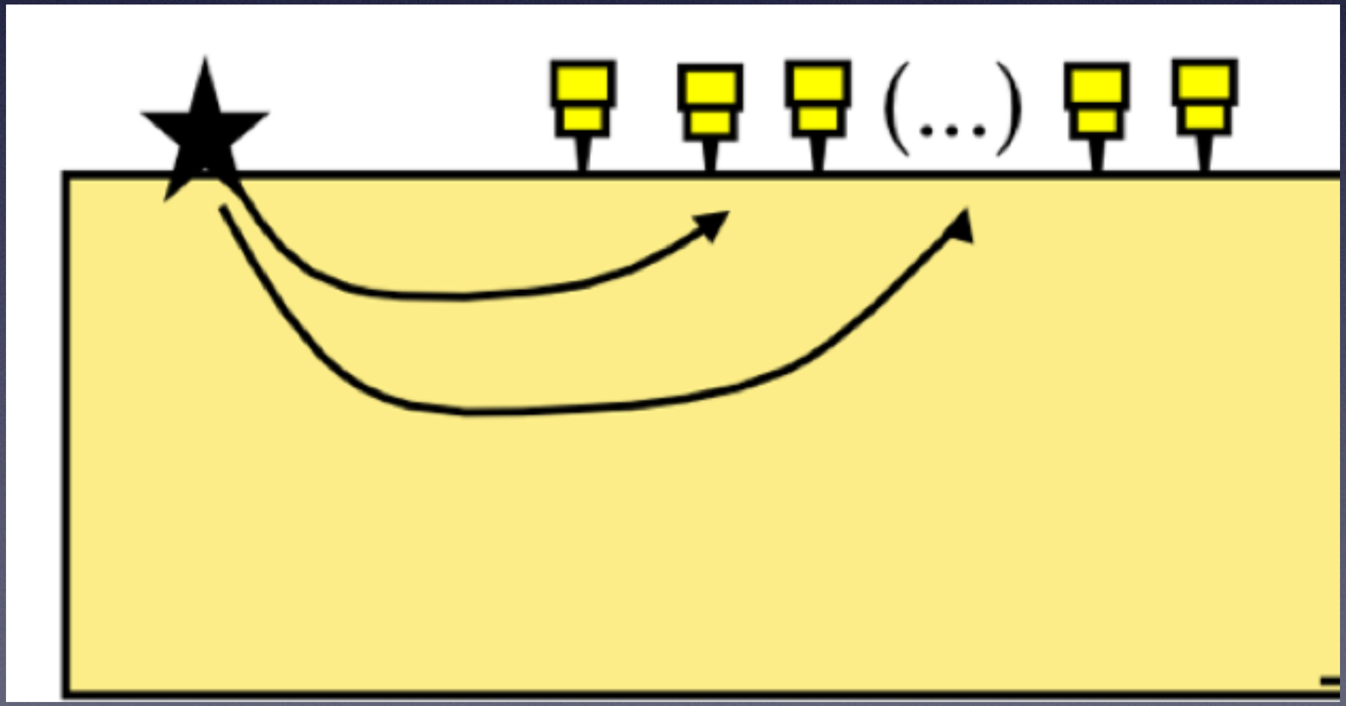


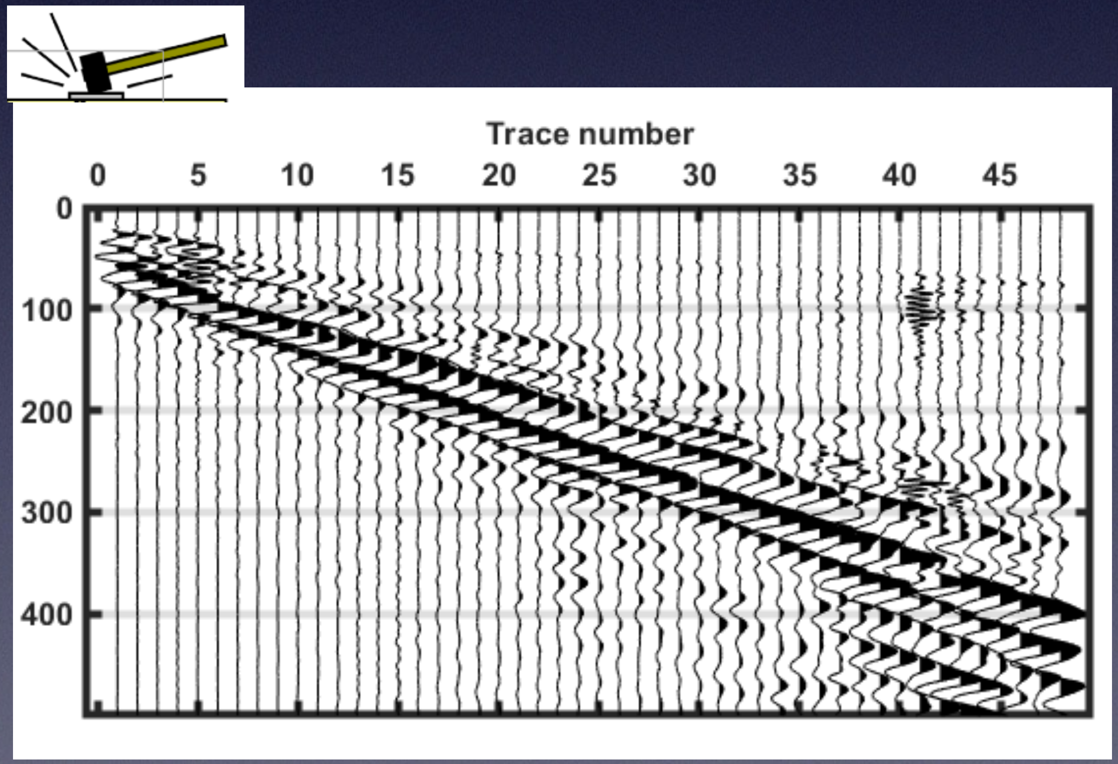
Surface seismic

Seismic method

Surface methods

Energy and receivers on surface

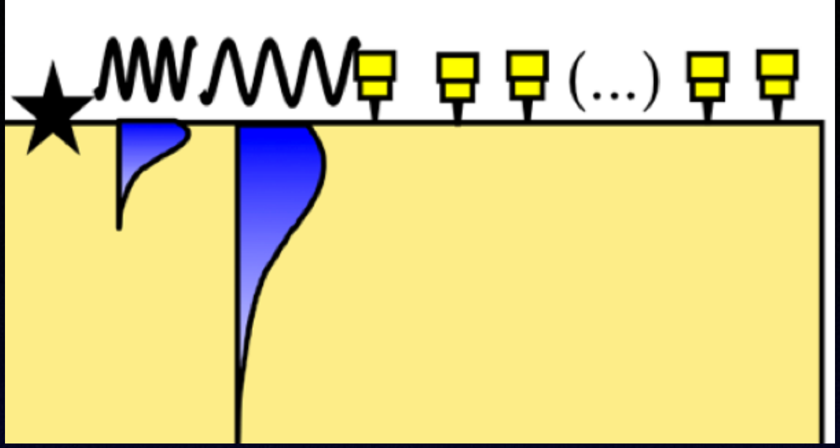




Seismic method

Surface methods

Surface wave methods



Study the DISPERSION of surface wave d

To retrieve (indirectly) Vs

$$V_{S,30} = \frac{30}{\sum_{i=1,n} H_i/V_{S_i}} \quad [m/s]$$

e.g. seismic soil classification parameter

Seismic method wave motion - Wave equation

u, v, w= displacement in x, y, z

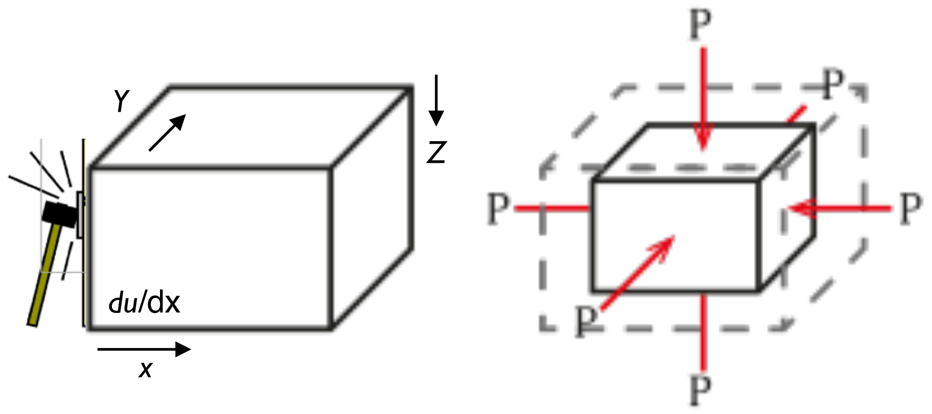
strain (ε) tensor

$$\varepsilon_{xx} = du/dx$$

$$\varepsilon_{yy} = dv/dy$$

$$\varepsilon_{zz} = dw/dz$$

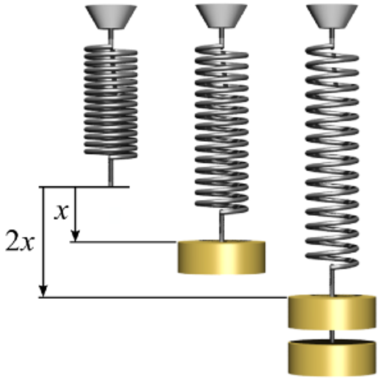
Stress-strain



...a relation between strain and stress...

Dilatation $\Delta=\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz}$

Hooke law (isotropic media)



Normal stress
(Example for x)

$$\sigma_x = \lambda\,\Delta + 2\,\mu\varepsilon_y$$

for x,y,z

Pure shear stress
(Example for y)

$$\sigma_y = \mu\varepsilon_y$$

for i ≠ j

lamè constant

λ	μ
compress.	*Shear*

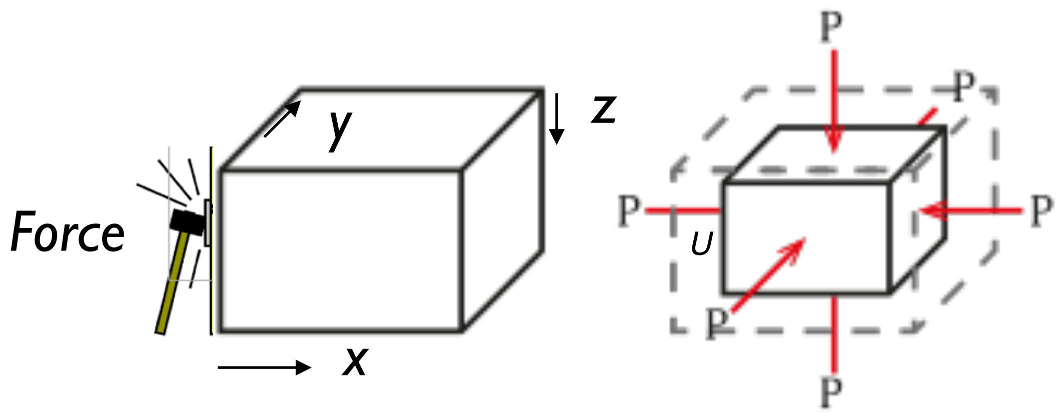
Seismic method wave motion - Wave equation

density

Mass of the cube $dm = \rho \, dxdydz$

Newton Law $F = m*a$

stress



$$\rho \frac{d^2 u}{d t^2} = \frac{d\sigma_{xx}}{d x} + \frac{d\sigma_{xy}}{d y} + \frac{d\sigma_{xz}}{d z}$$

Displacement u

Hooke law

dilatation

$$\rho \frac{d^2 u}{d t^2} = (\lambda + \mu) \frac{d\Delta}{d x} + \mu \Delta^2 u$$

Lame parameters

diff for x, y, z

Dilatation

laplacian

$$\rho \frac{d^2 \Delta}{d t^2} = (\lambda + 2\mu) \nabla^2 \Delta$$

Wave Equation !

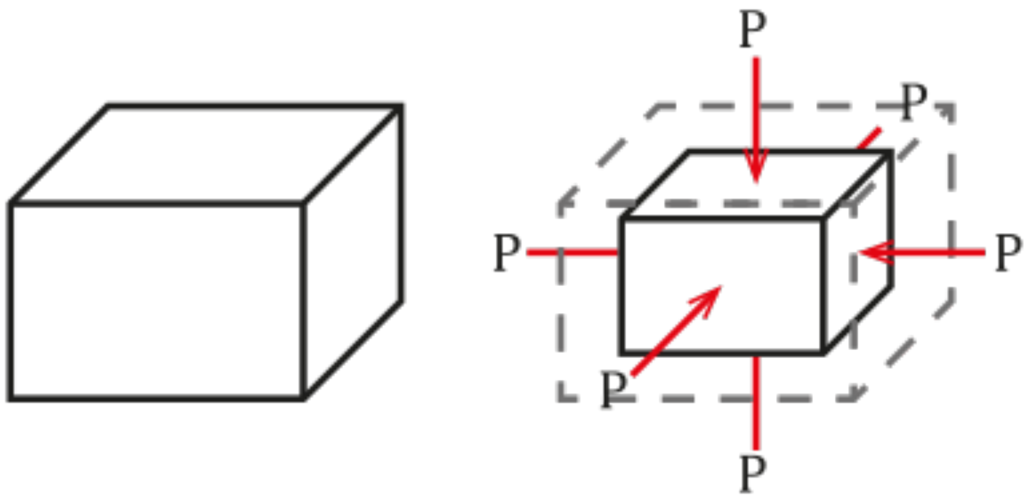
Lame parameters

Seismic method wave motion - Wave equation

In seismic are most used the compressibility modulus

Bulk modulus ***K*** *(rather than* λ*)*

The increment in pressure need to cause an increase of density



$$K = \lambda + (2/3\ G)$$

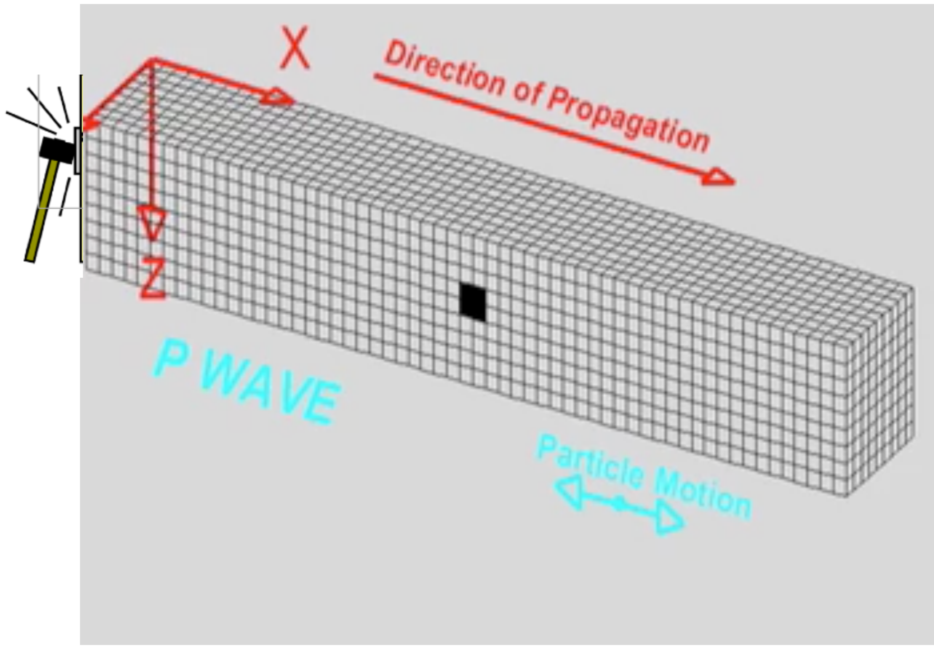
And shear modulus expressed as ***G*** *(rather than* μ*)*

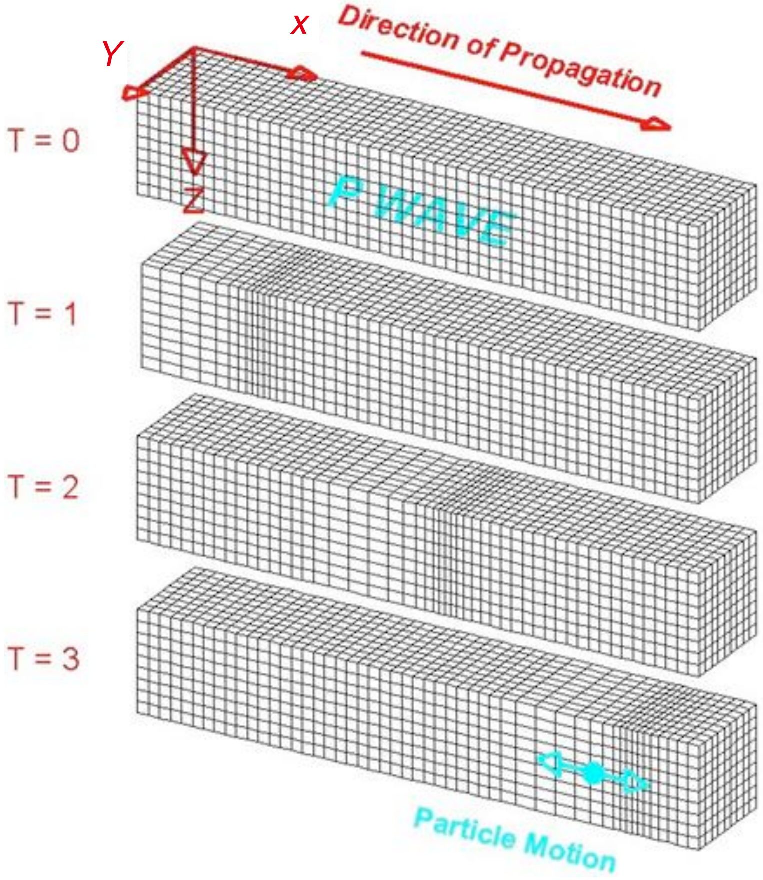
$$\mathbf{G} = \mu$$

Seismic method wave motion - Wave equation

volumetric deformation ε

Compressional wave
(P waves)

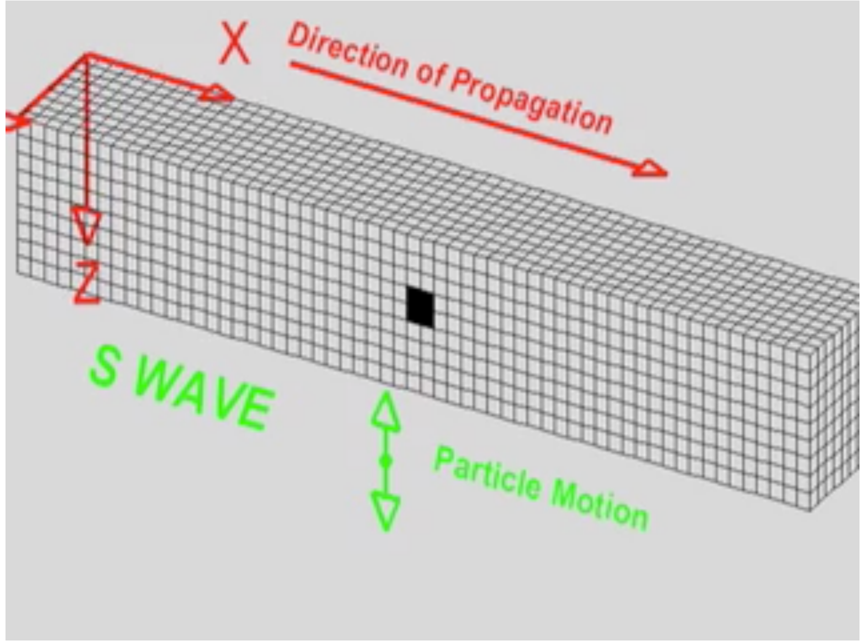


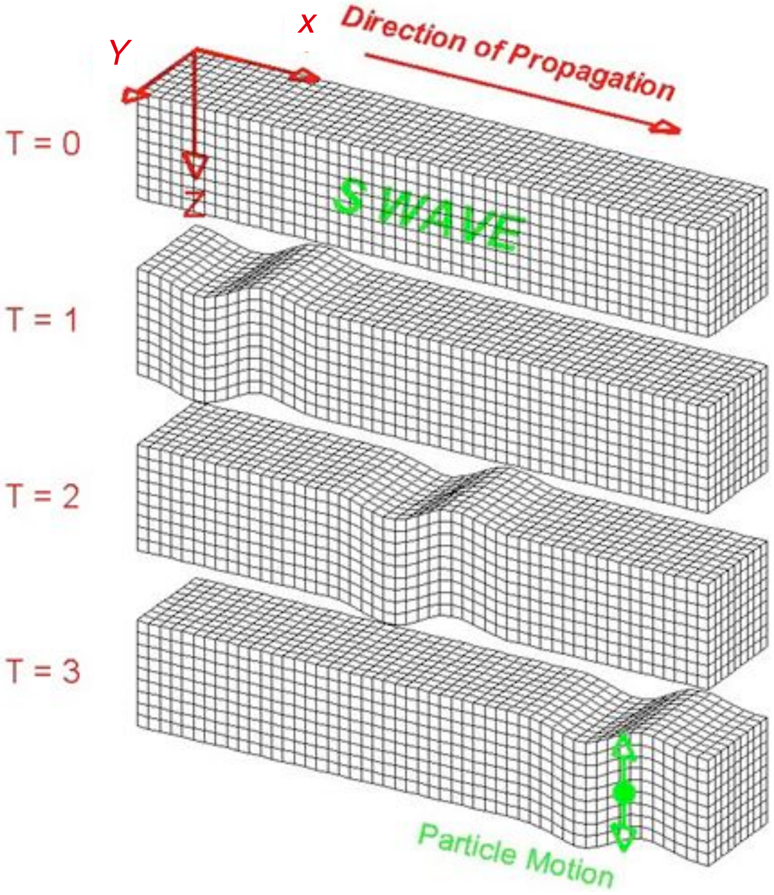


BODY WAVES

shear deformation Ω

Shear waves
(S wave)



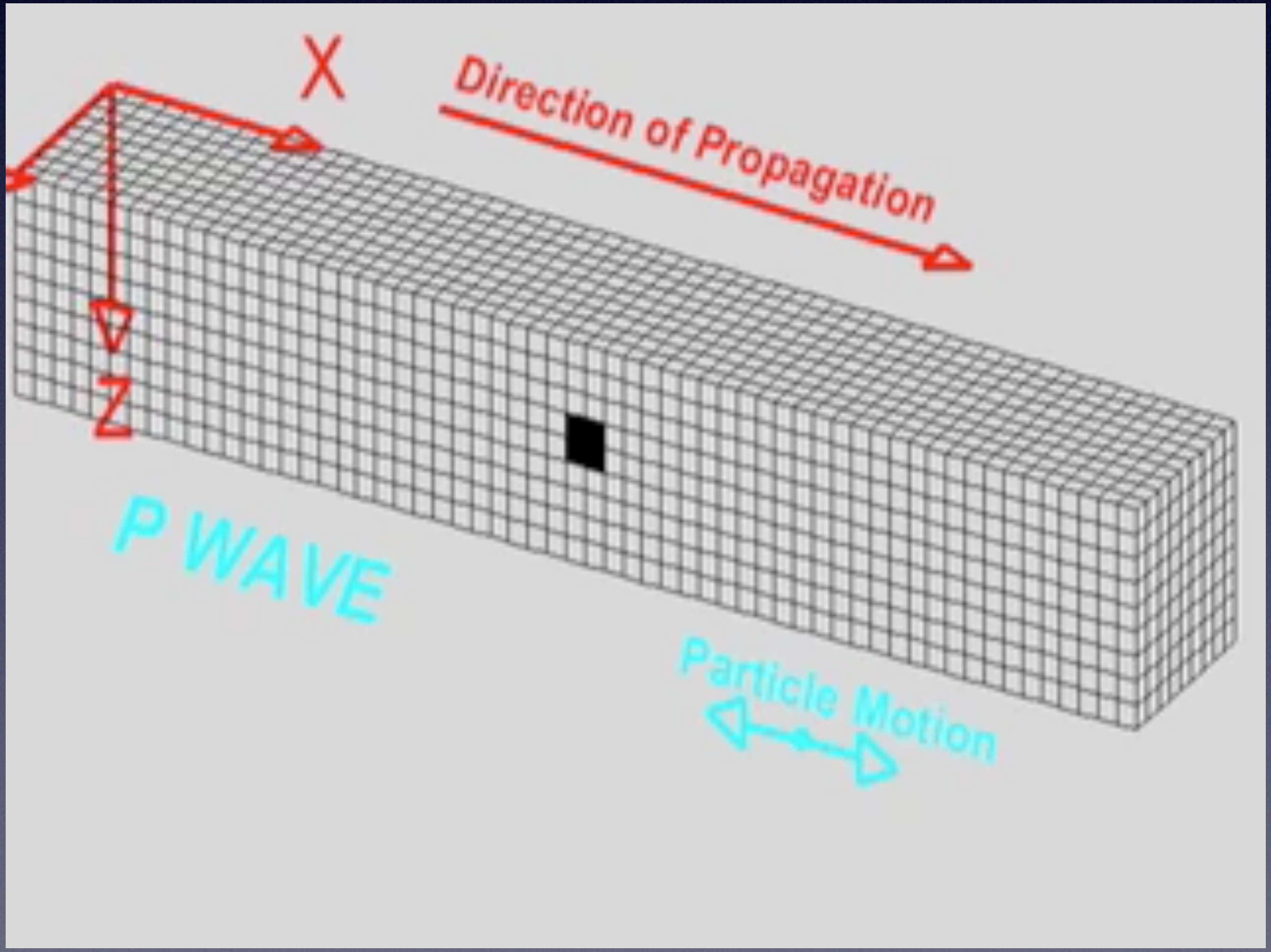


P ε

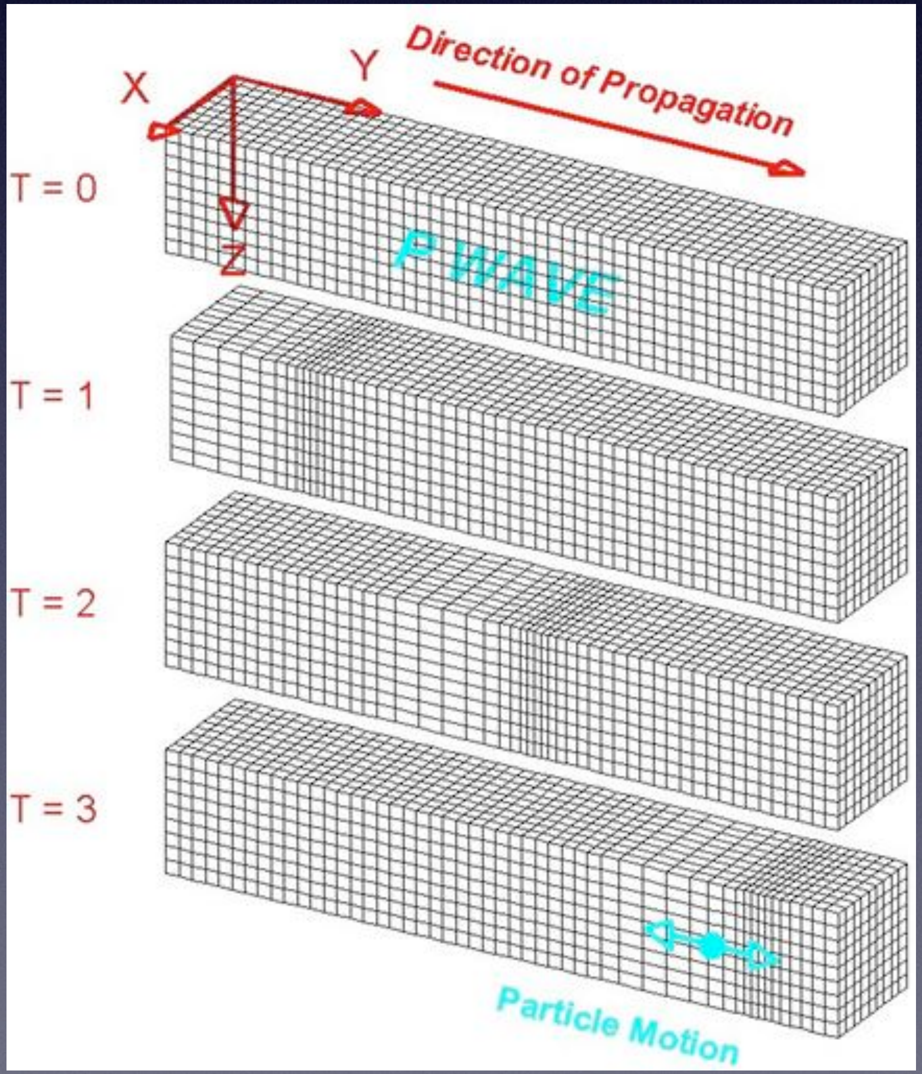
P-waves

Compressional wave

(onde P)



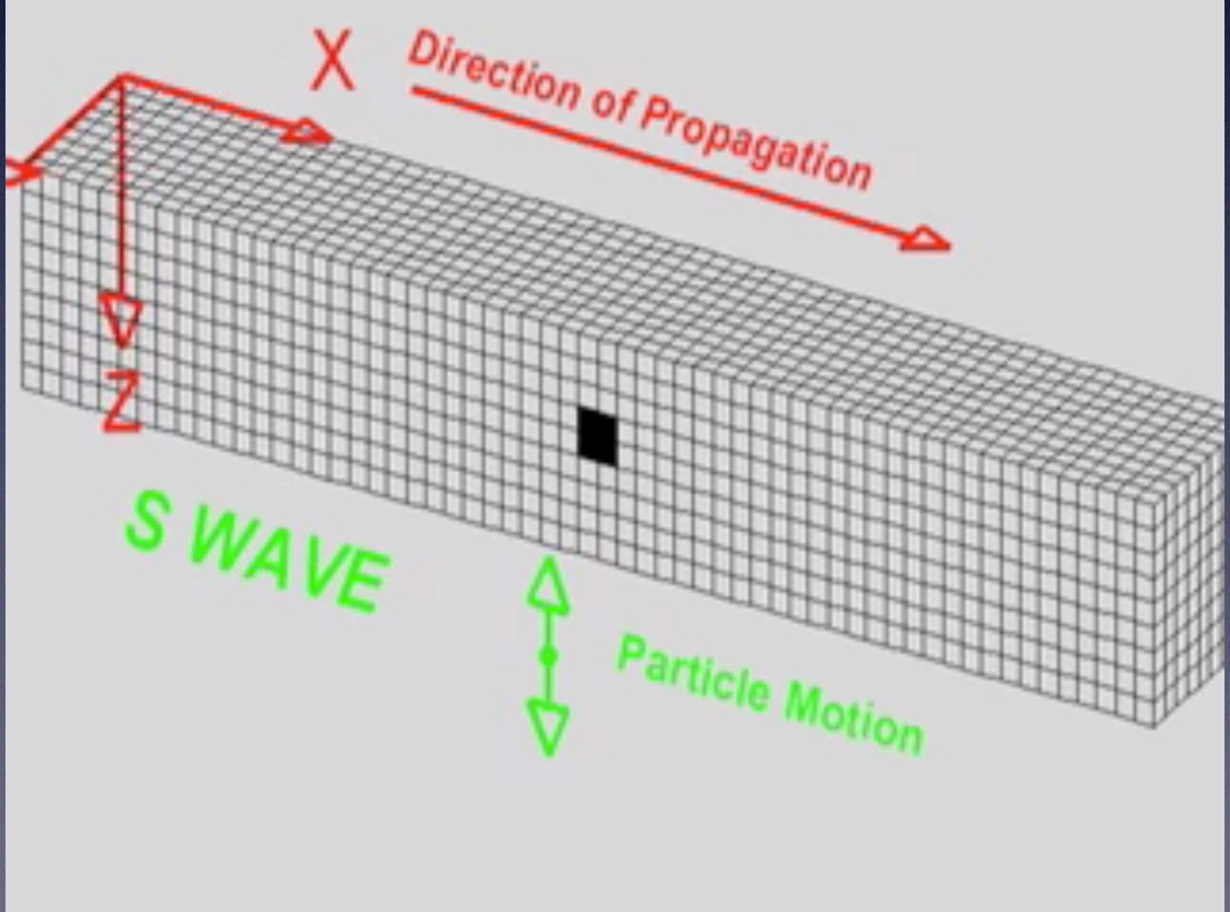
Volumetric deformation ε



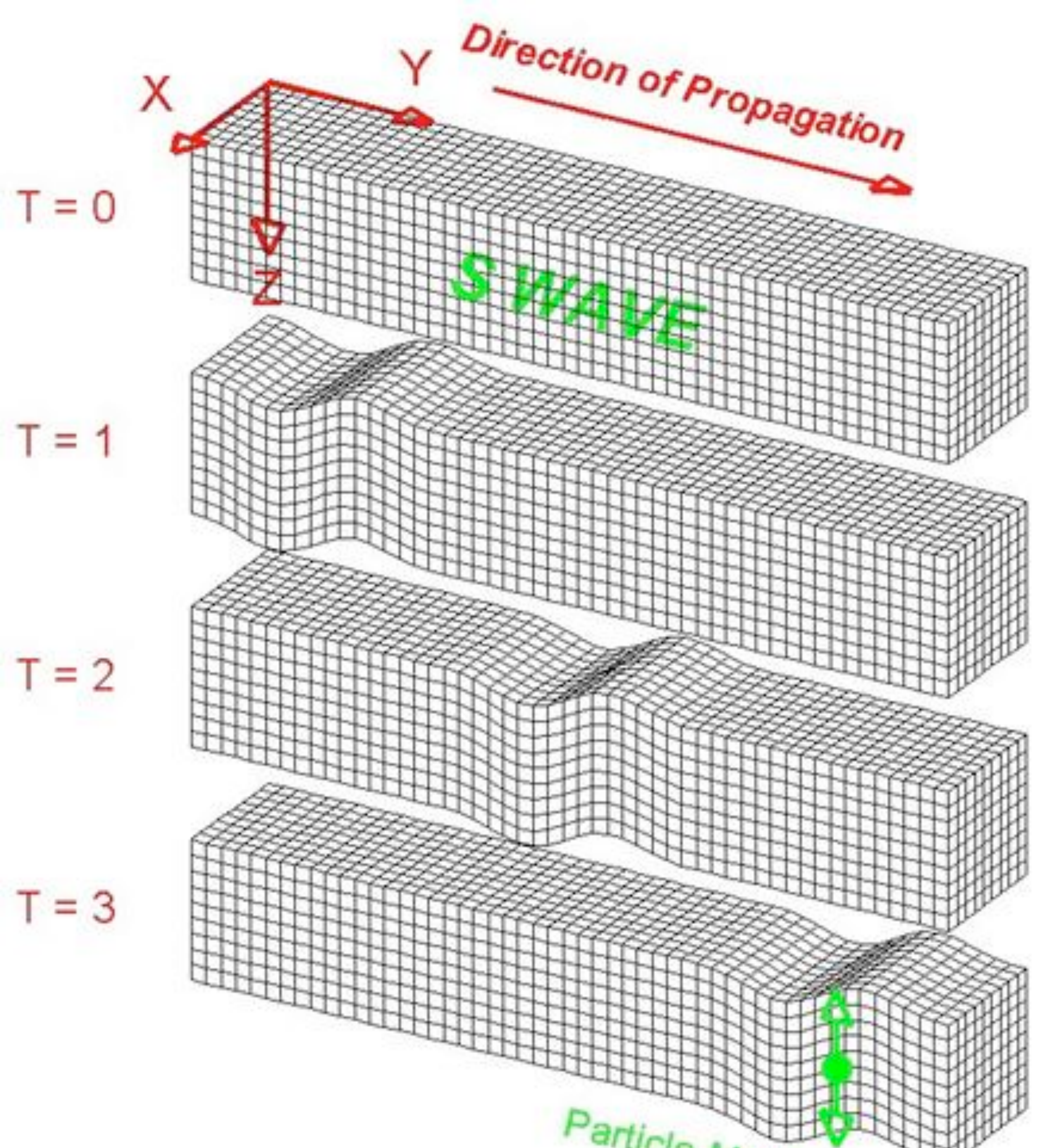
S

S-waves

Shear wave



Tangential deformation Ω



Wave propagation in homogenous, elastic , isotrope media

Body waves

Solution of differential wave equation

P wave

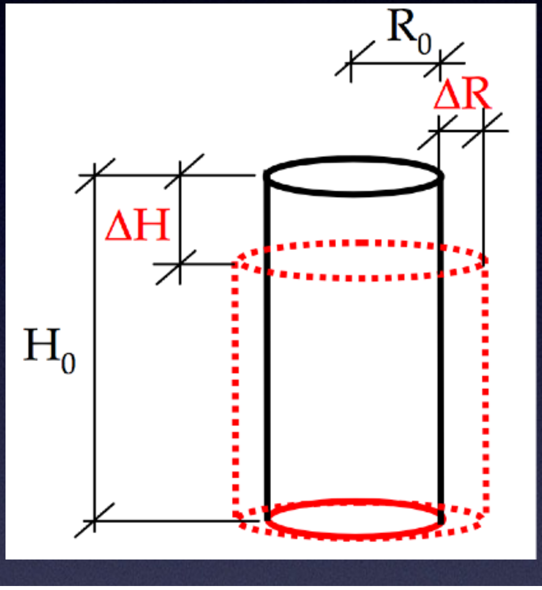
Volumetric deformation (strain)

$$\frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = \frac{\lambda + 2G}{\rho}\nabla^2 \bar{\varepsilon}$$

$$\varepsilon = \frac{\Delta V}{V_0}$$

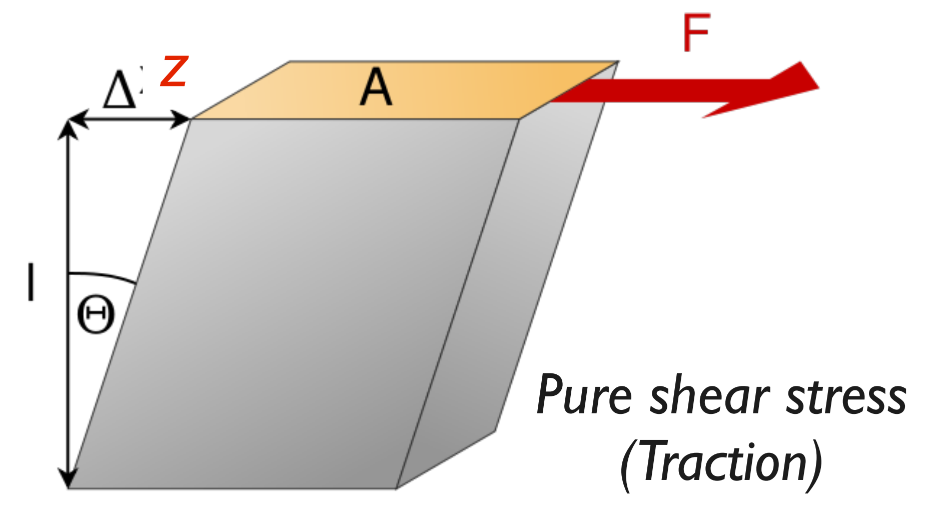
dVolume

Volume Iniziale



S wave

$$\frac{\partial^2 \Omega}{\partial t^2} = \frac{G}{\rho}\cdot\nabla^2 \Omega$$



Pure shear stress (Traction)

G = shear modulus
λ= compression modulus
ρ= density

Tangential deformation Ω

Wave propagation in homogenous, elastic , isotrope media

Solution of differential wave equation

$$\rho \frac{d^2\Delta}{d t^2} = (\lambda + 2G)\nabla^2\Delta$$

P wave

$$\frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = \frac{\lambda + 2G}{\rho}\nabla^2\bar{\varepsilon}$$

↑ Relationship

$$\frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = \text{[velocity of propagation]}\ \nabla^2\bar{\varepsilon}$$

S wave

$$\frac{\partial^2 \Omega_z}{\partial t^2} = \frac{G}{\rho}\cdot\nabla^2\Omega_z$$

↑ Relationship

$$\frac{\partial^2 \Omega_x}{\partial t^2} = \text{[velocity of propagation]}\ \nabla^2\Omega_x$$

Wave propagation in homogenous, elastic , isotrope media

Solution of differential wave equation

P wave

$$\frac{\partial^2 \bar{\varepsilon}}{\partial t^2} = \frac{\lambda + 2G}{\rho} \nabla^2 \bar{\varepsilon}$$

Vp^2

Velocity of
Propagation P wave

$$\boxed{V_P = \sqrt{\frac{\lambda + 2G}{\rho}}}$$

S wave

$$\frac{\partial^2 \Omega_z}{\partial t^2} = \frac{G}{\rho} \cdot \nabla^2 \Omega_z$$

Vs^2

Velocity of
Propagation S wave

$$\boxed{V_S = \sqrt{\frac{G}{\rho}}}$$

In liquids
G= 0
Vs=0

Body wave

P Wave

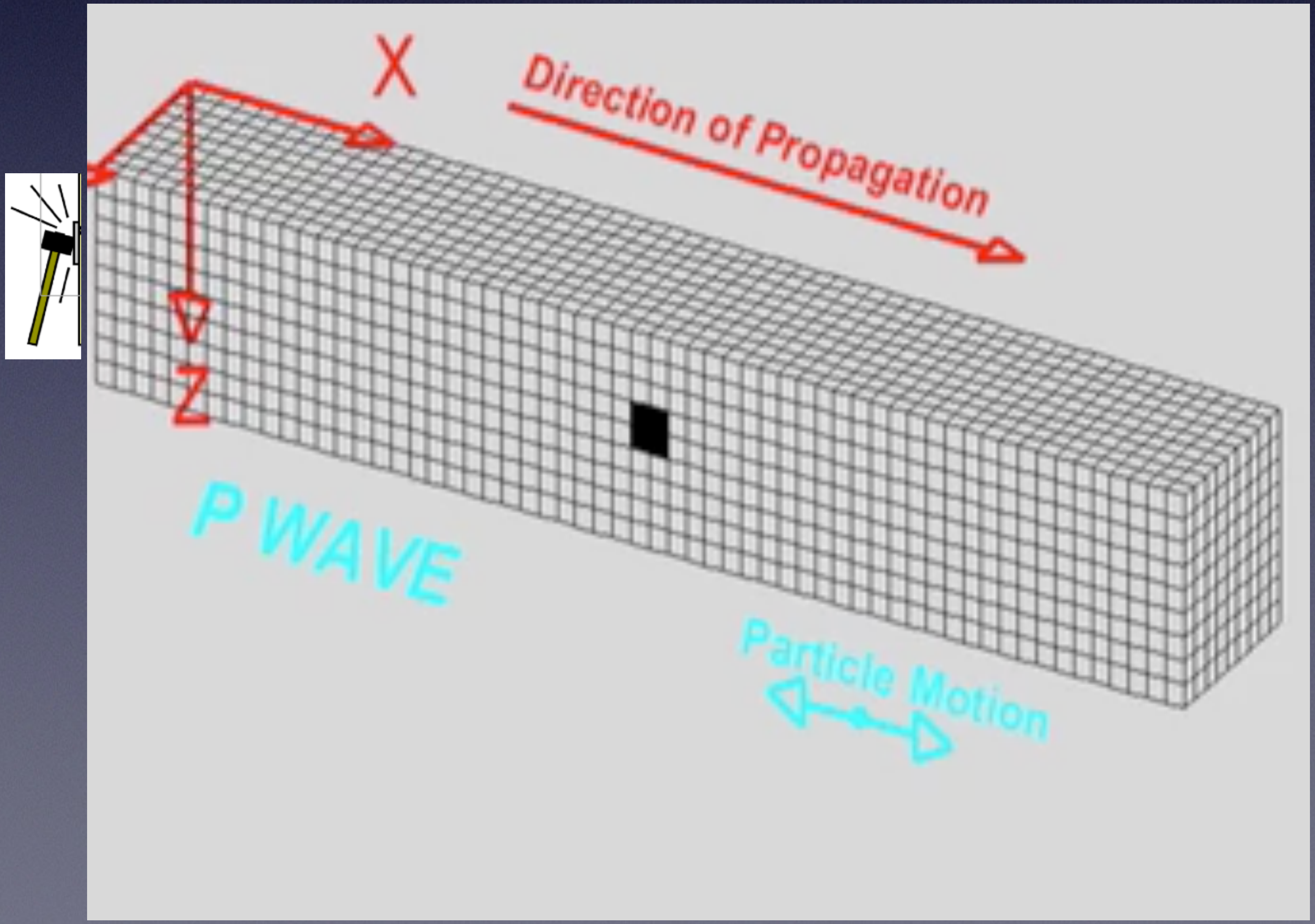
Compression and dilatation

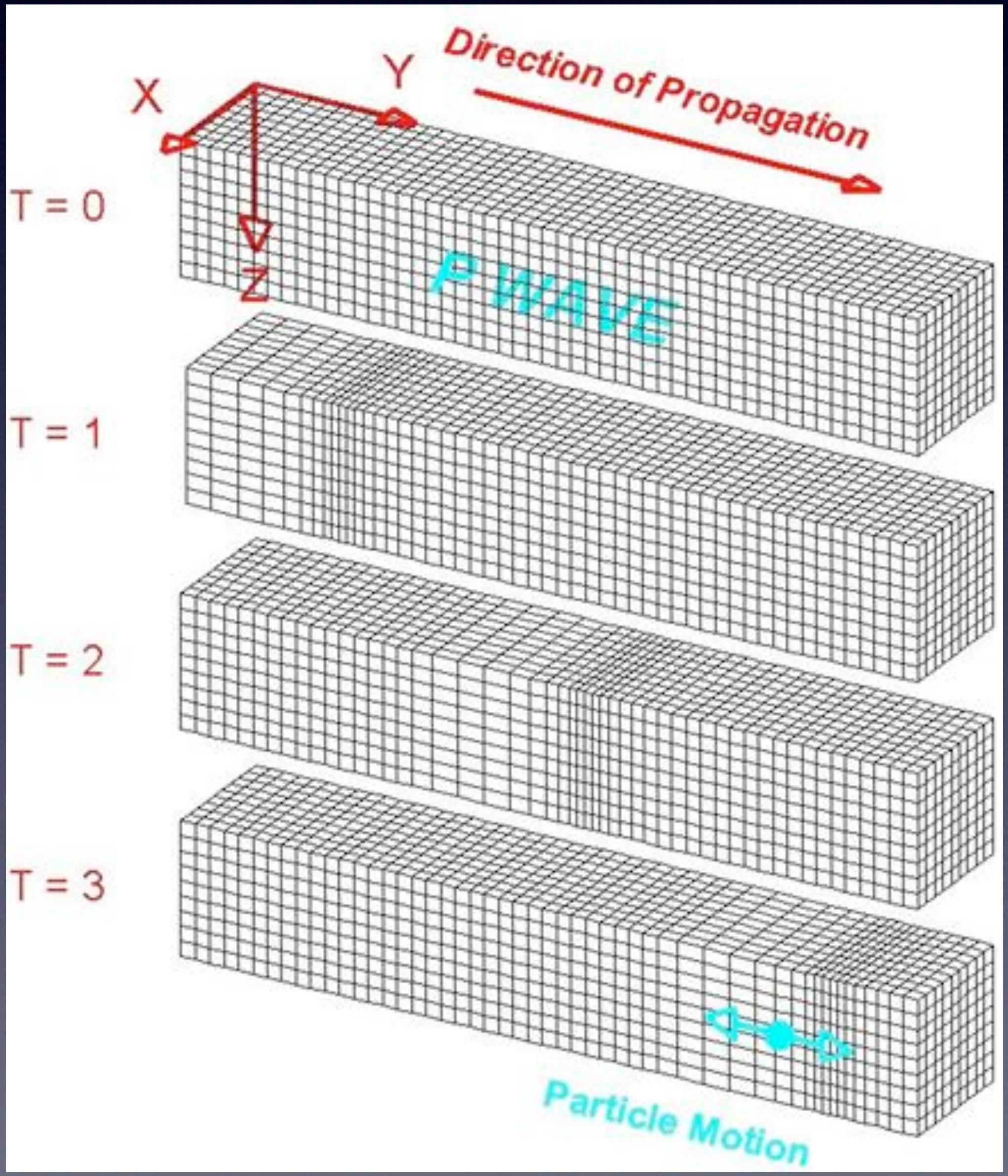
Compressiblity

$$V_P = \sqrt{\frac{\lambda + 2G}{\rho}}$$

Shear modulus

density





Body waves

S waves

Shear waves

$$\boxed{V_S = \sqrt{\frac{G}{\rho}}}$$

Shear modulus

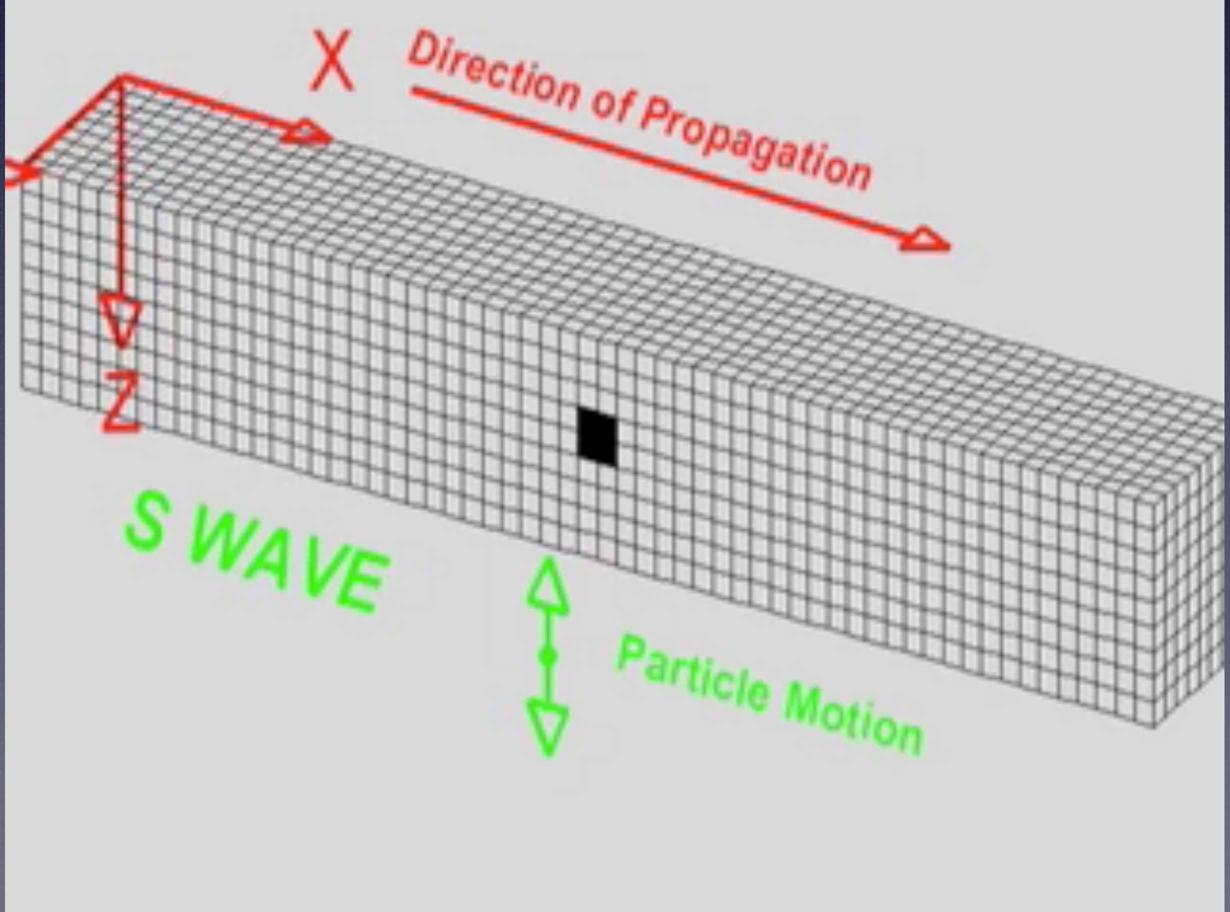
NB not dependent on compressibility !

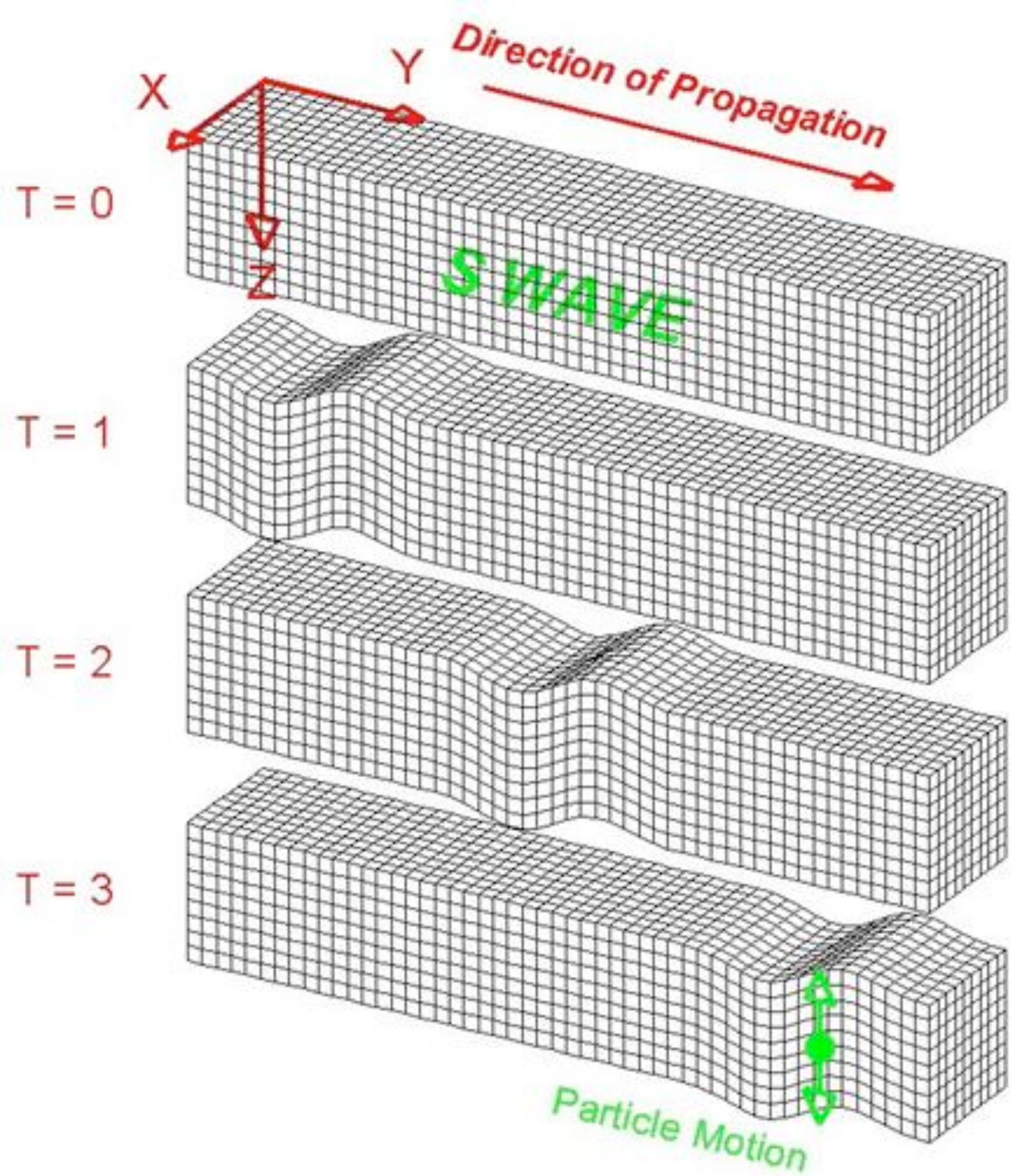
density

In fluids

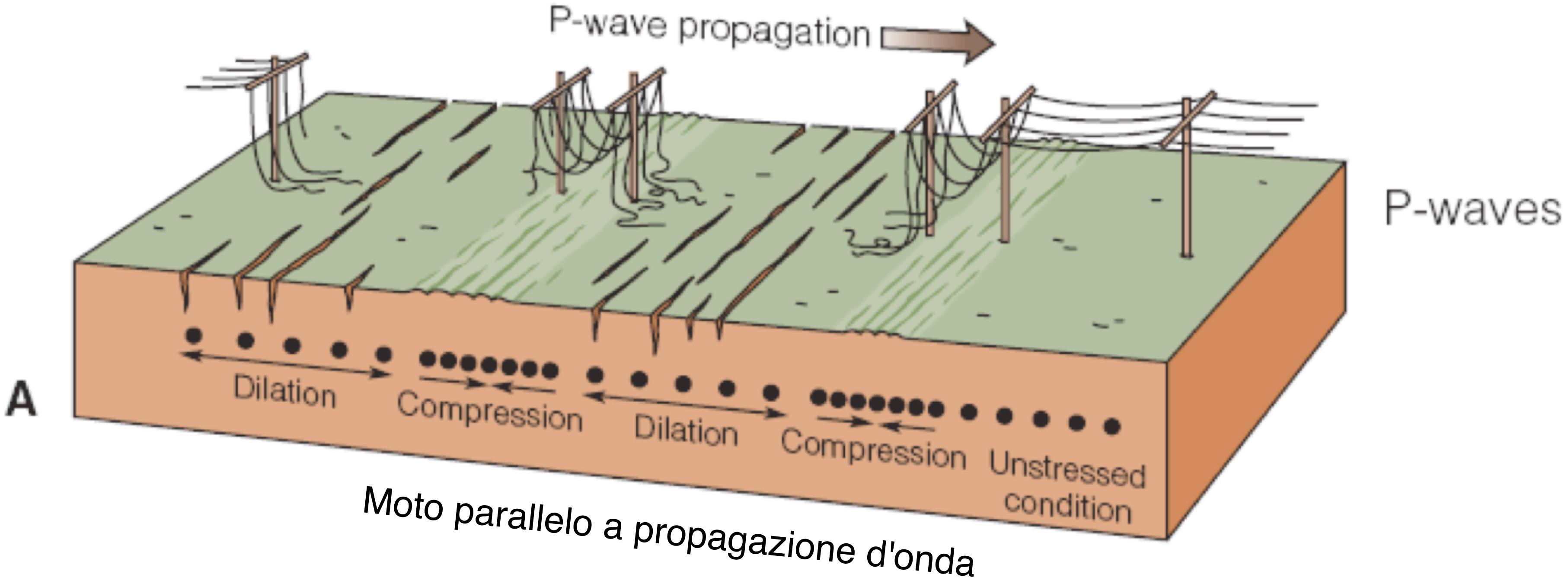
G= 0

Vs=0





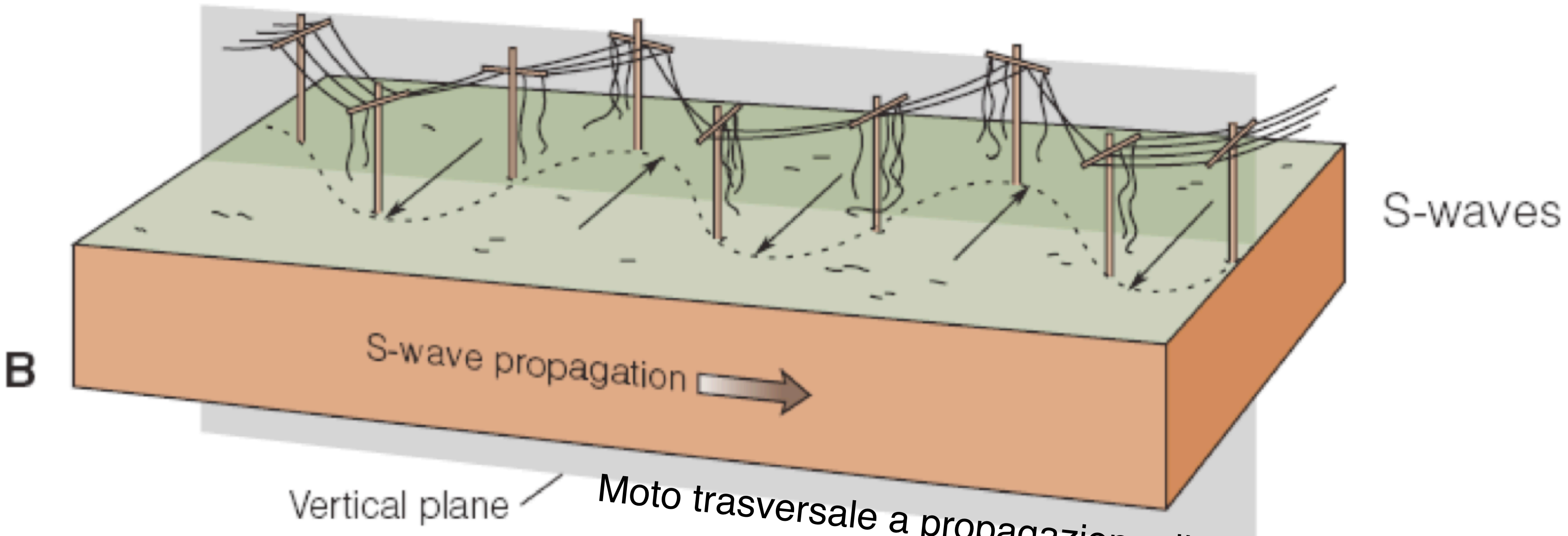
Seismic waves



Moto parallelo a propagazione d'onda

P

compressional

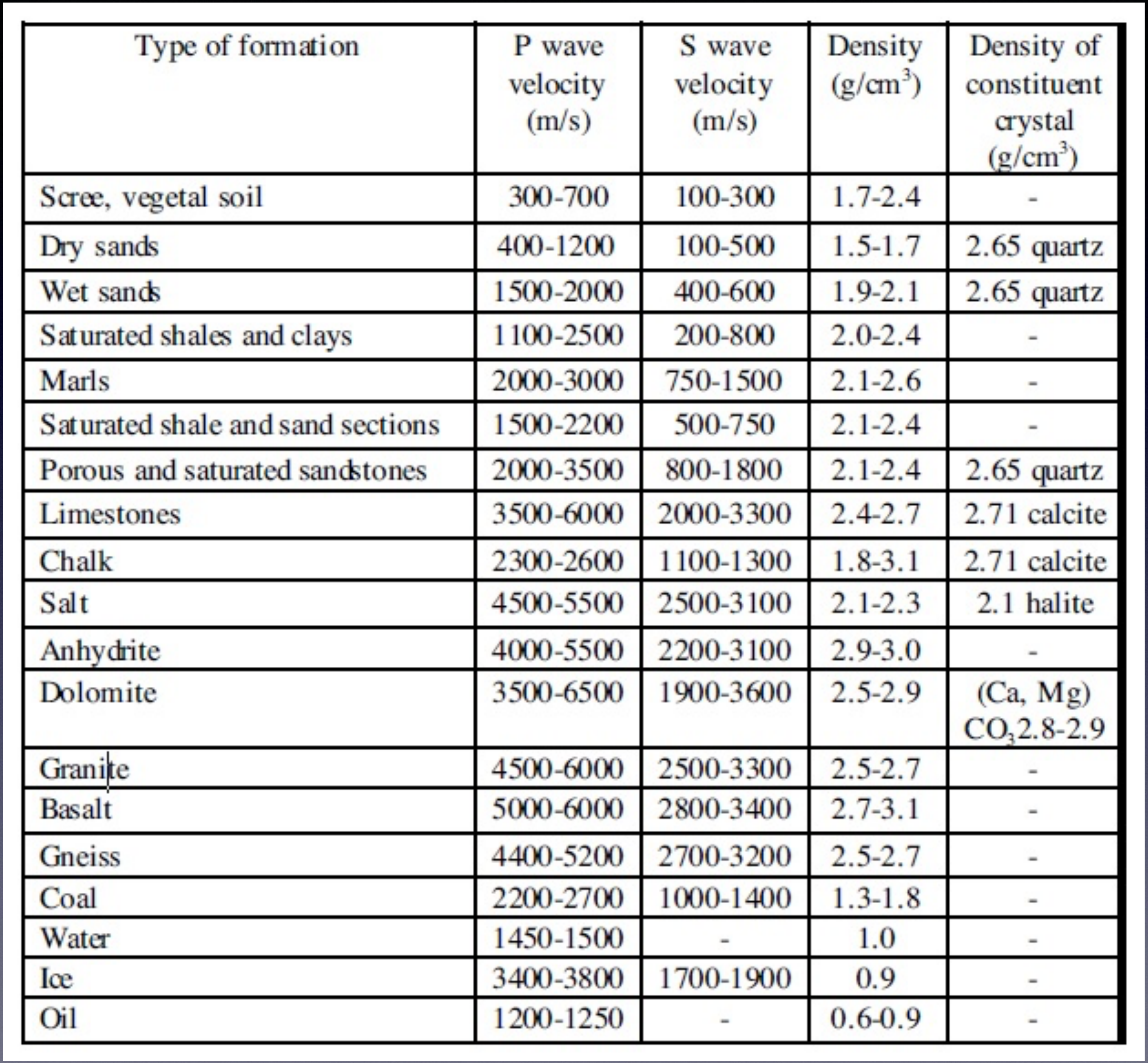


Moto trasversale a propagazione d'onda

S

Shear

P Velocity $\approx$ 1.9 S velocity



Type of formation	P wave velocity (m/s)	S wave velocity (m/s)	Density (g/cm^3)	Density of constituent crystal (g/cm^3)
Scree, vegetal soil	300-700	100-300	1.7-2.4	-
Dry sands	400-1200	100-500	1.5-1.7	2.65 quartz
Wet sands	1500-2000	400-600	1.9-2.1	2.65 quartz
Saturated shales and clays	1100-2500	200-800	2.0-2.4	-
Marls	2000-3000	750-1500	2.1-2.6	-
Saturated shale and sand sections	1500-2200	500-750	2.1-2.4	-
Porous and saturated sandstones	2000-3500	800-1800	2.1-2.4	2.65 quartz
Limestones	3500-6000	2000-3300	2.4-2.7	2.71 calcite
Chalk	2300-2600	1100-1300	1.8-3.1	2.71 calcite
Salt	4500-5500	2500-3100	2.1-2.3	2.1 halite
Anhydrite	4000-5500	2200-3100	2.9-3.0	-
Dolomite	3500-6500	1900-3600	2.5-2.9	(Ca, Mg) CO_3 2.8-2.9
Granite	4500-6000	2500-3300	2.5-2.7	-
Basalt	5000-6000	2800-3400	2.7-3.1	-
Gneiss	4400-5200	2700-3200	2.5-2.7	-
Coal	2200-2700	1000-1400	1.3-1.8	-
Water	1450-1500	-	1.0	-
Ice	3400-3800	1700-1900	0.9	-
Oil	1200-1250	-	0.6-0.9	-

Surface waves

For constructive interference at the boundary with air

2 types: Rayleigh waves
Love waves

Differently from body waves (3d) they propagate in 2d,
Attenuati is less f(distance r) :

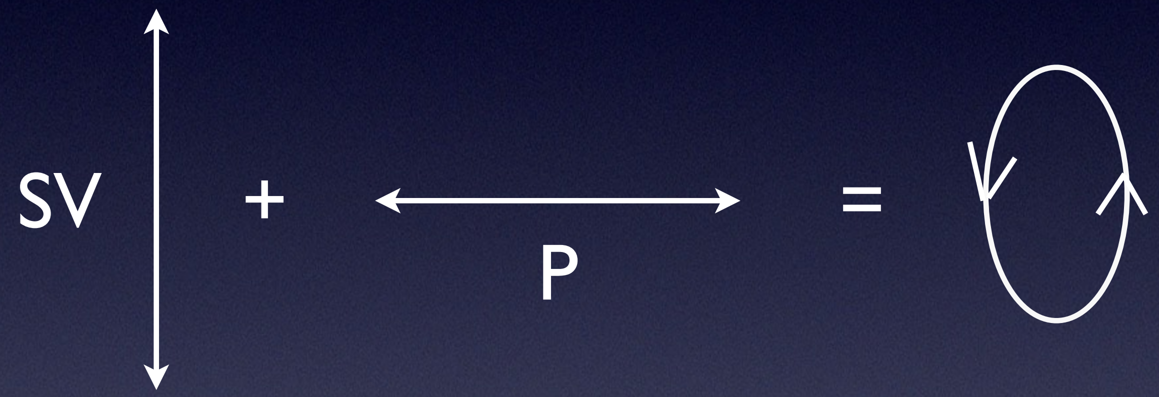
$\boxed{r^{-0.5}}$ Rather than $\boxed{r^{-1}}$

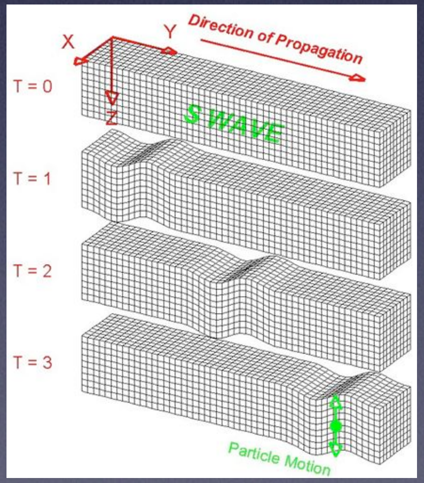
Surface waves body waves

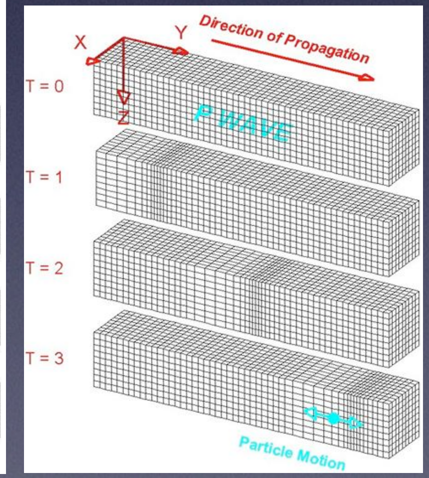
Rayleigh waves are mostly adopted

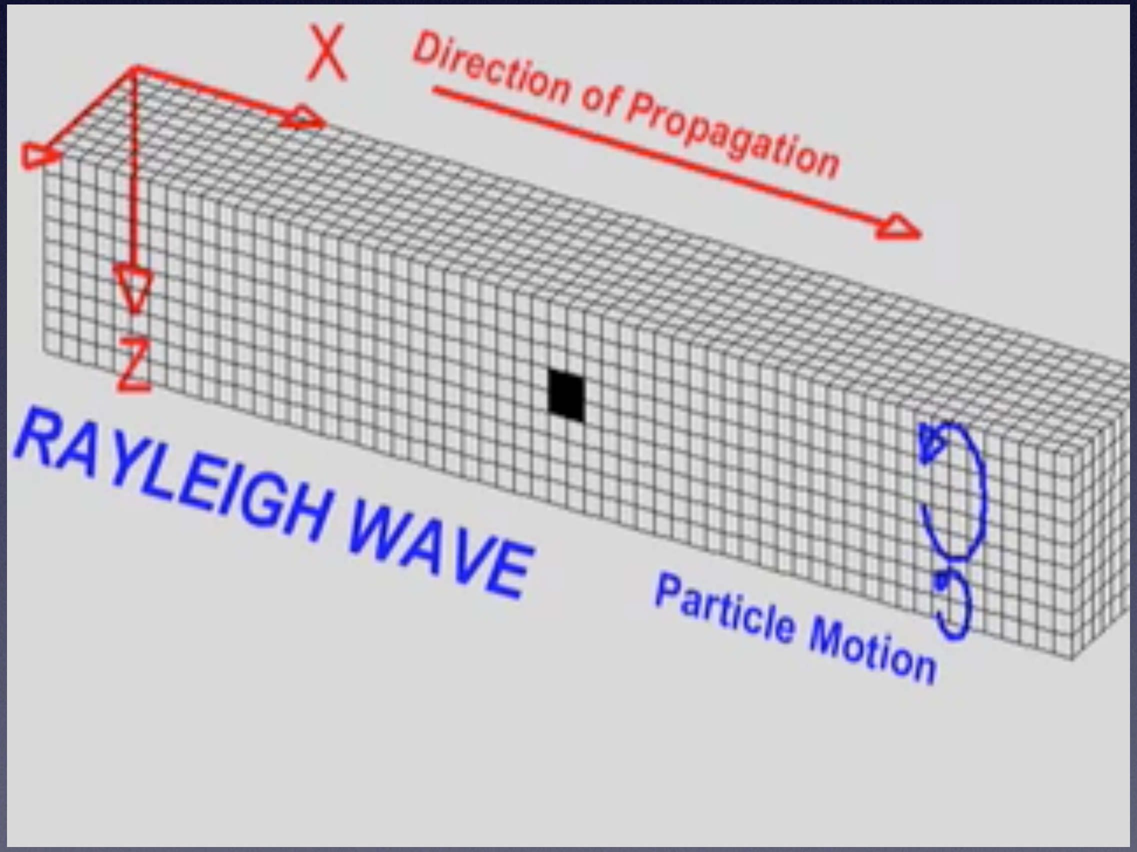
Generated from P and SV waves interference at surface

SV = S wave vertically polarised





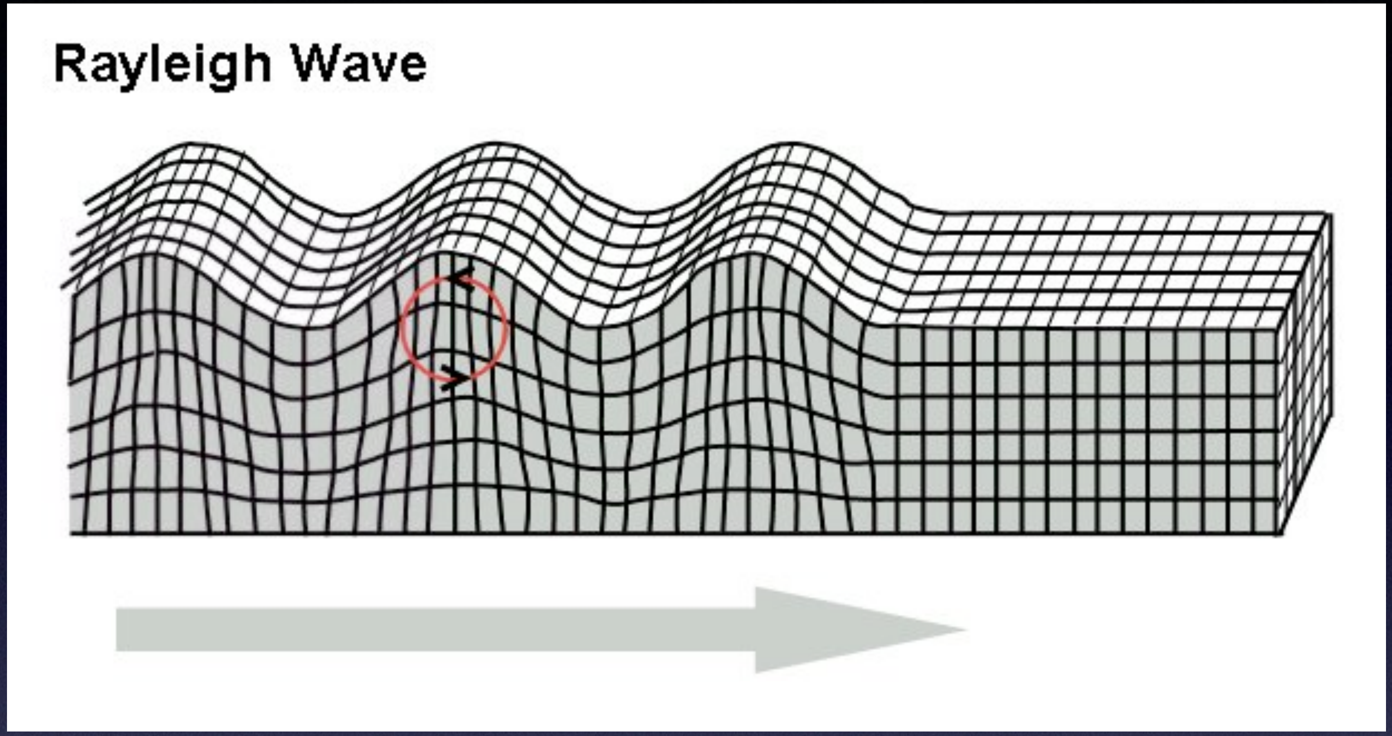




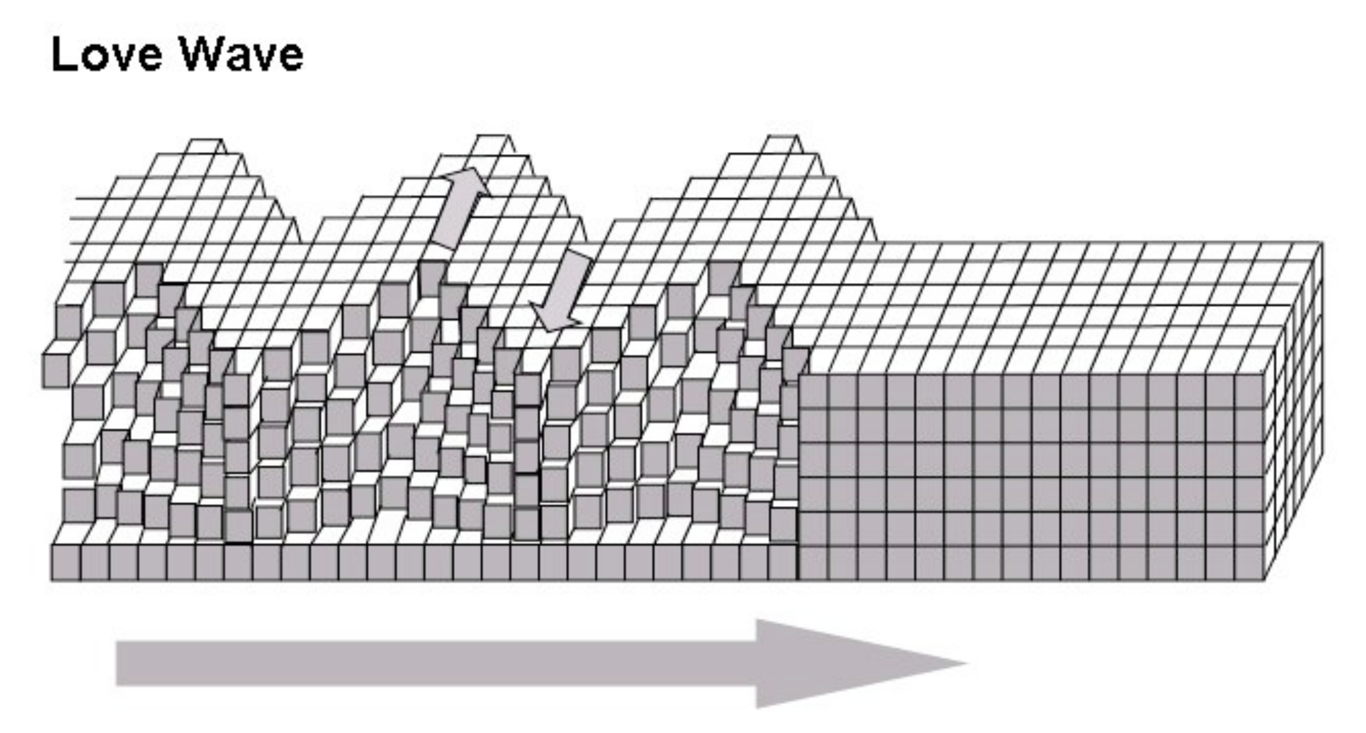
- Motus is elliptical

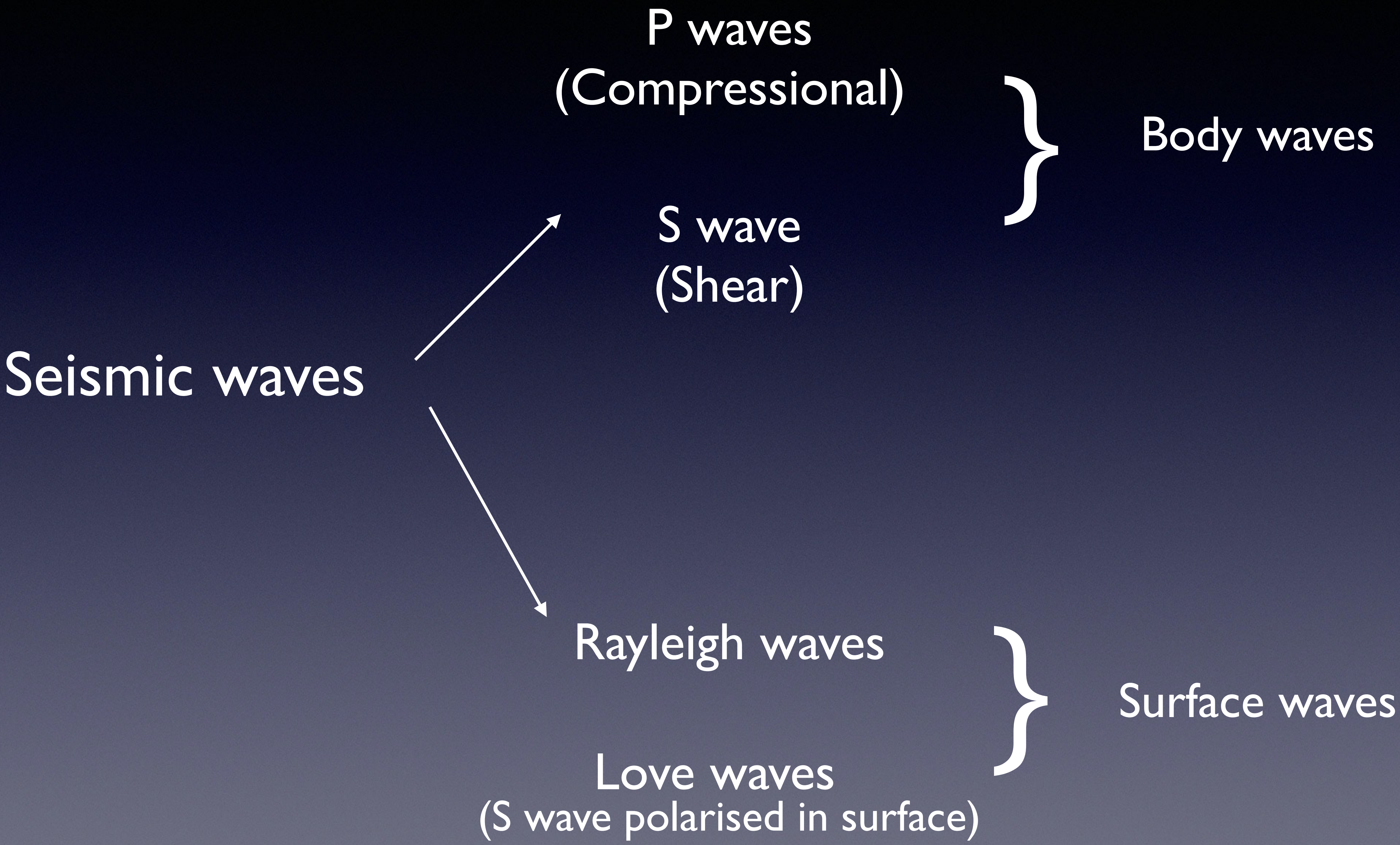
Surface waves

Rayleigh waves



Love waves





Seismic waves

P waves
(Compressional)

S wave
(Shear)

Body waves

Rayleigh waves

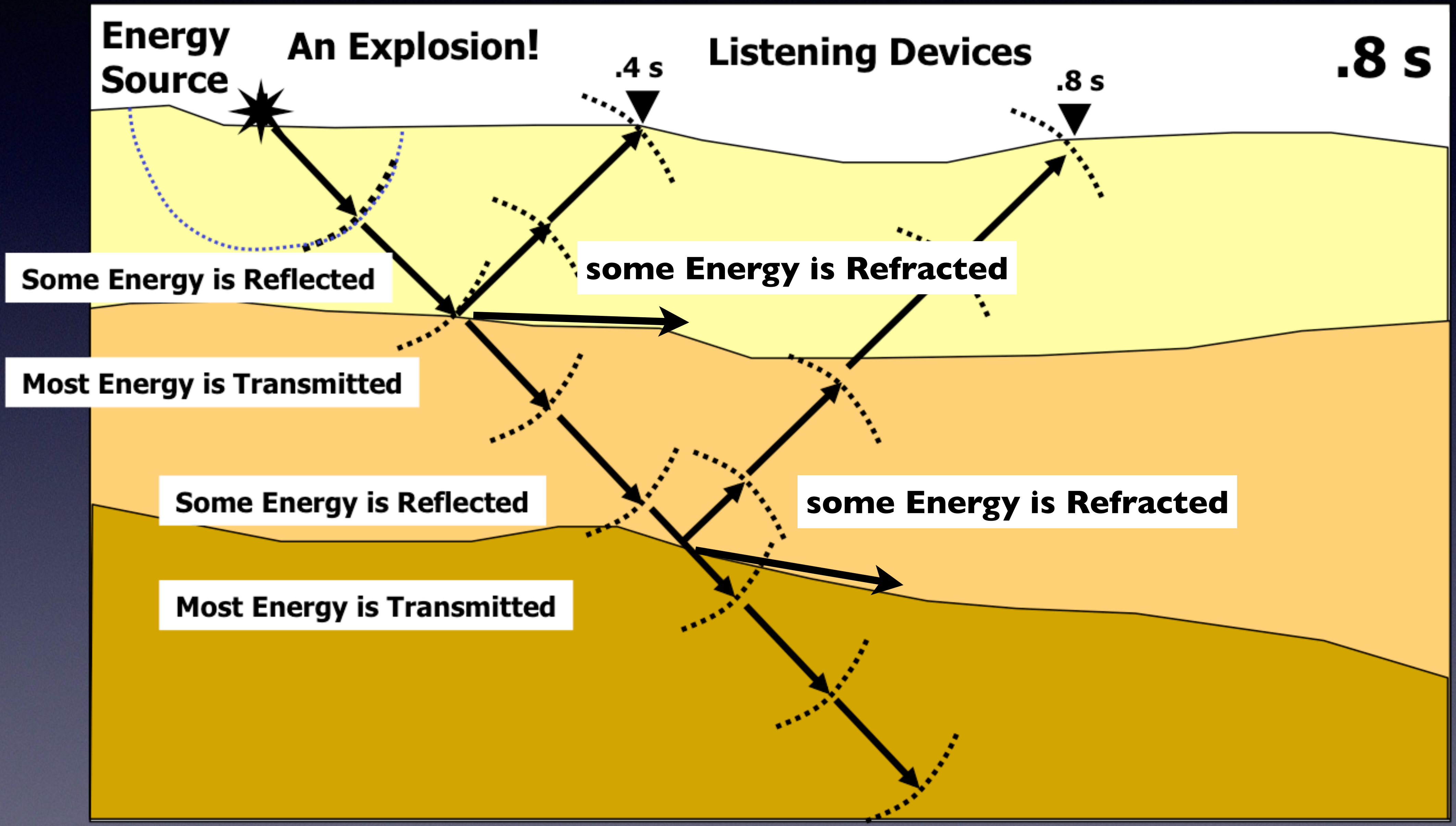
Love waves
(S wave polarised in surface)

Surface waves

Seismic method

Bach at surface

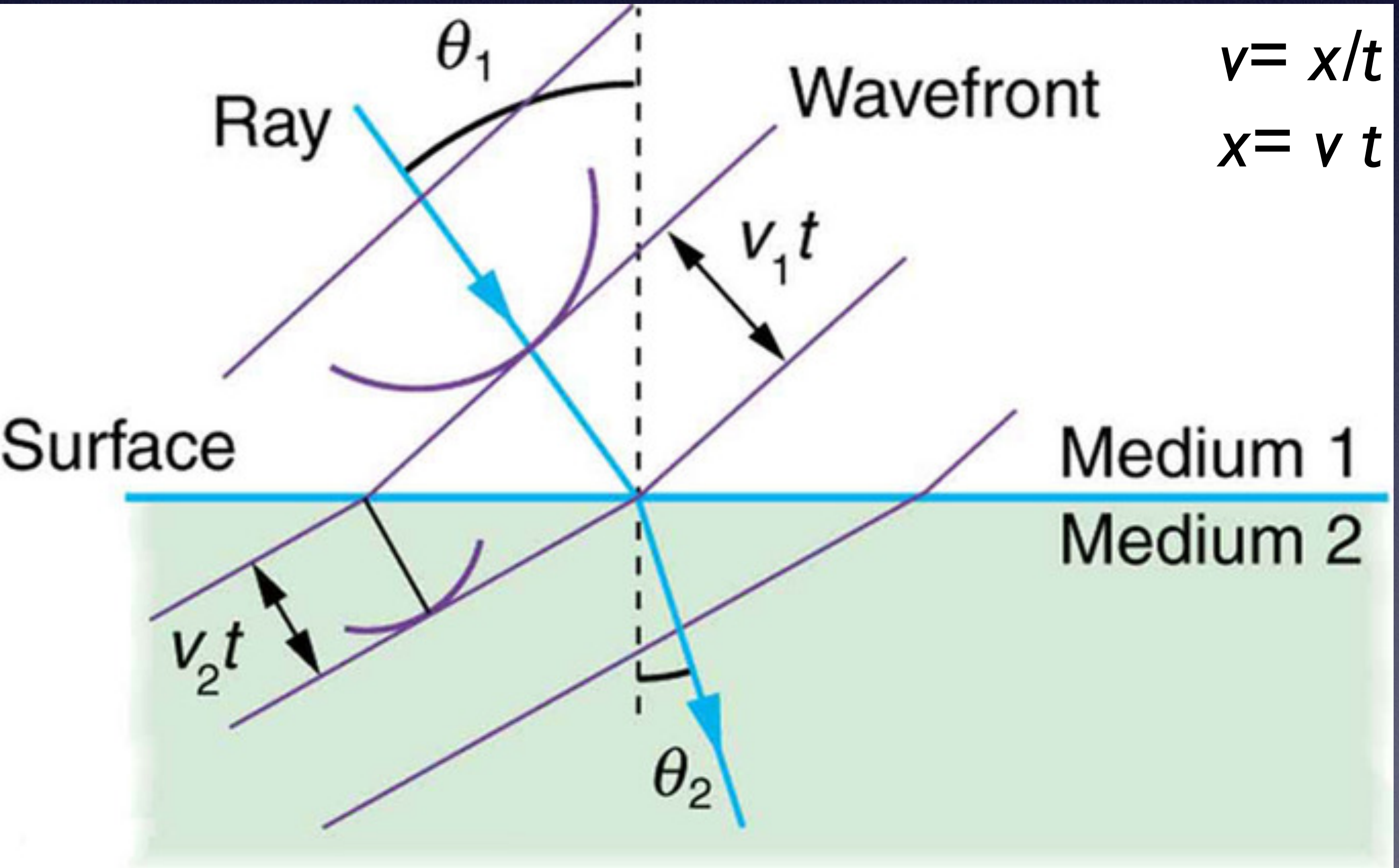
Seismic energy is transmitted/reflected/refracted



Huygens-Fresnel principle

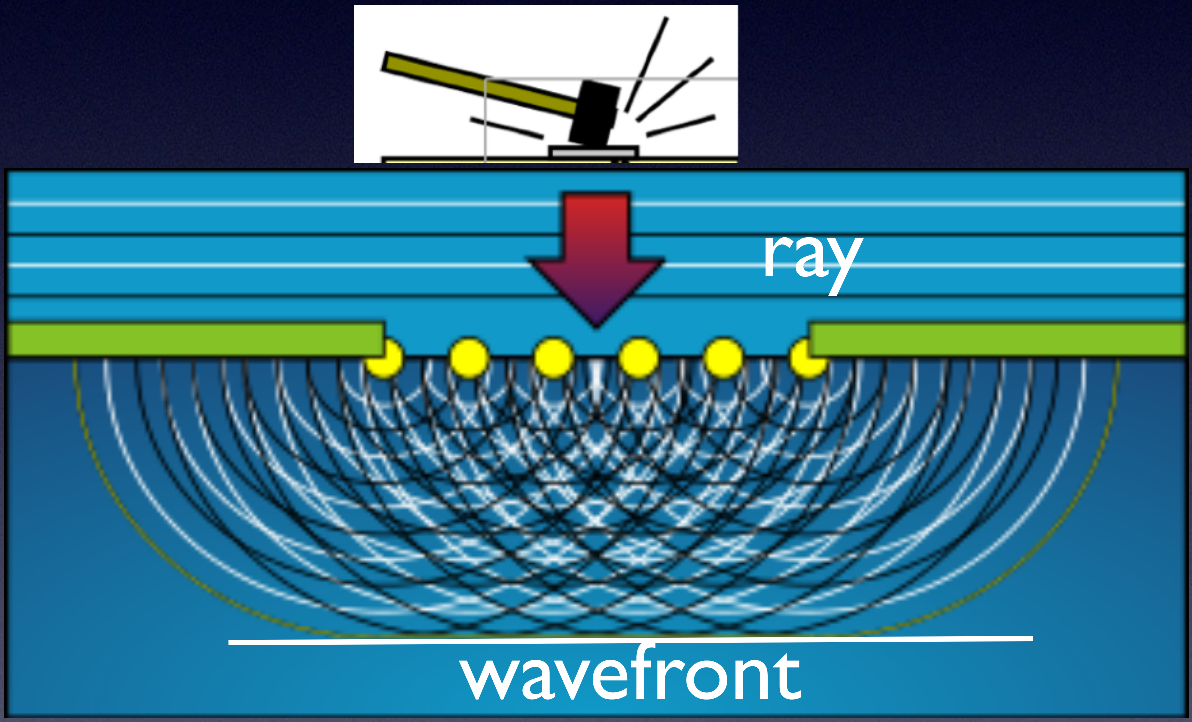
Given a source (S) generating a spheric wavefront, , each point of the primary wavefront act as a secondary source generating waves of the same characteristics of the primary one (wavelength, frequency, velocity d'onda),

except if the media changes…



v= x/t

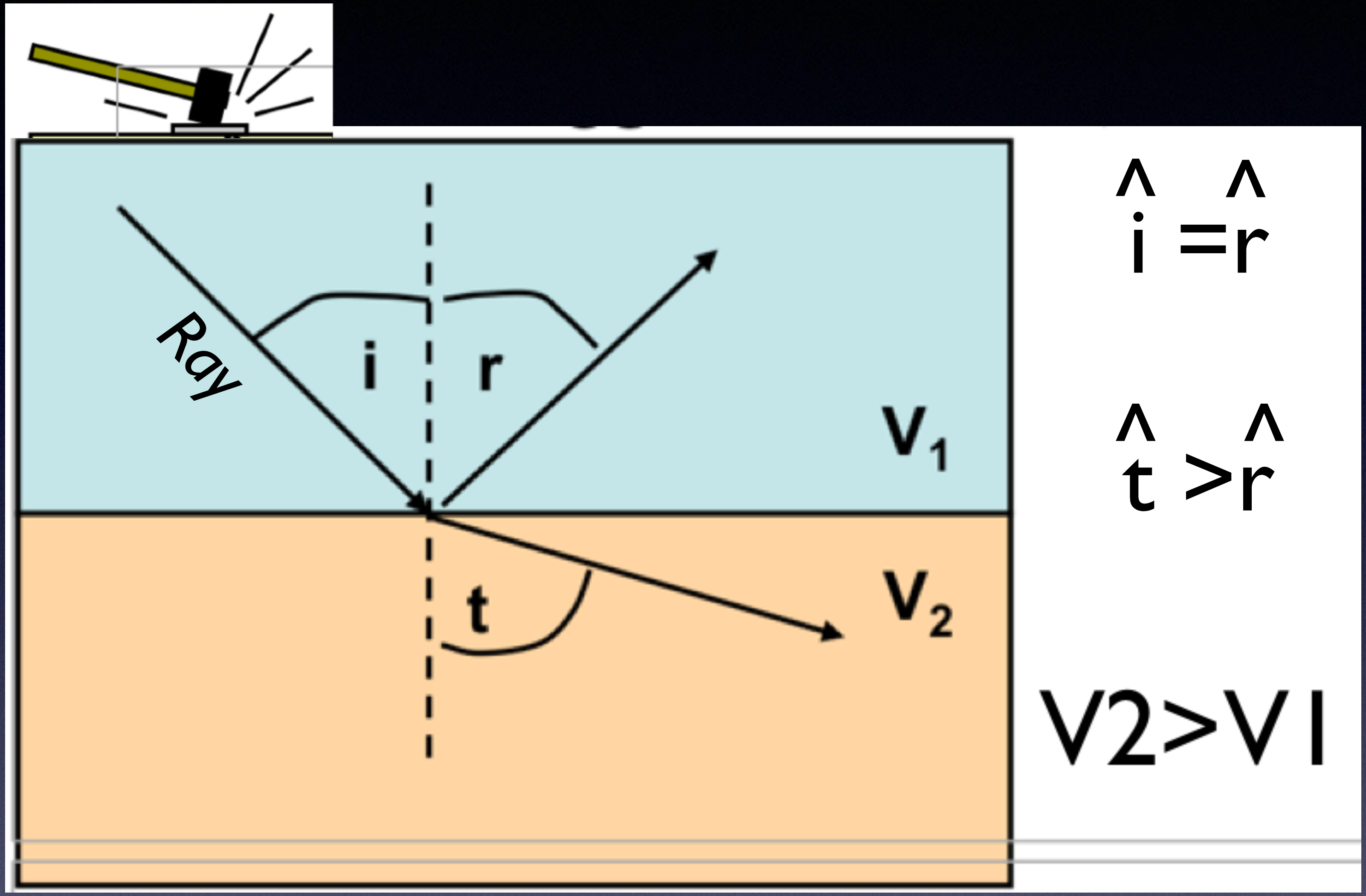
x= v t



ray

wavefront

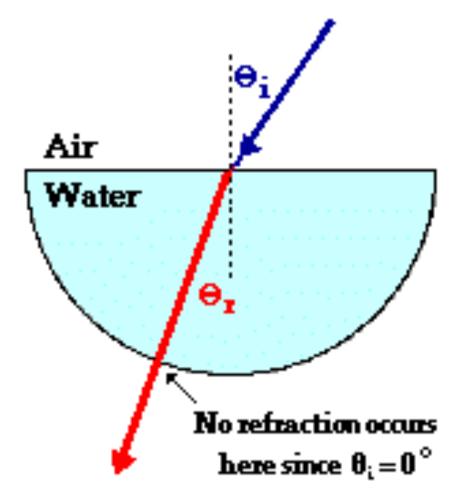
Snell Law



In presence of impedance contrast the ray is reflected with the same incidence angle

Acoustic Impedance Contrast $= \dfrac{\rho_2 V_2}{\rho_1 V_1} > 1$ → Reflection

…in water…

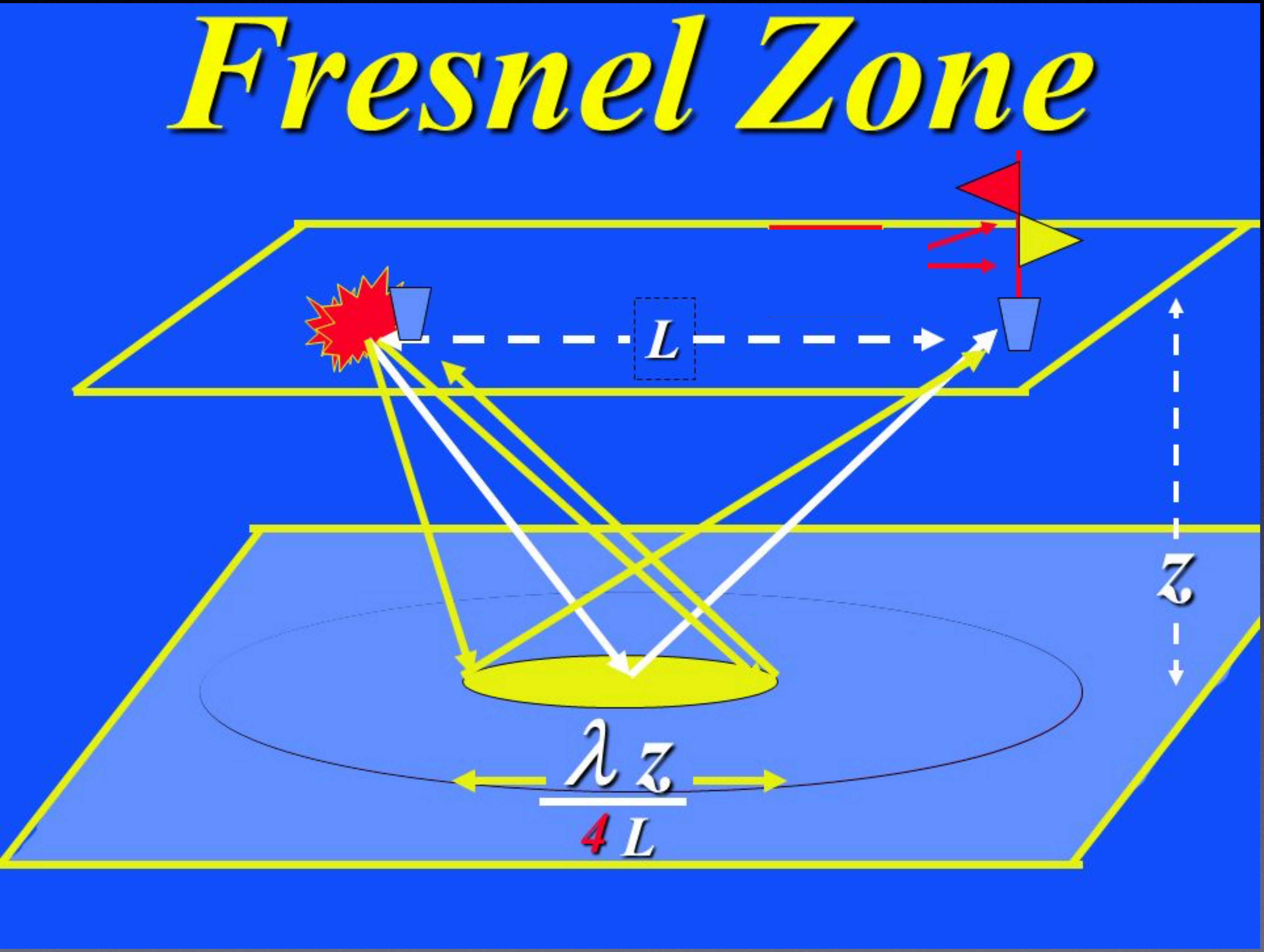


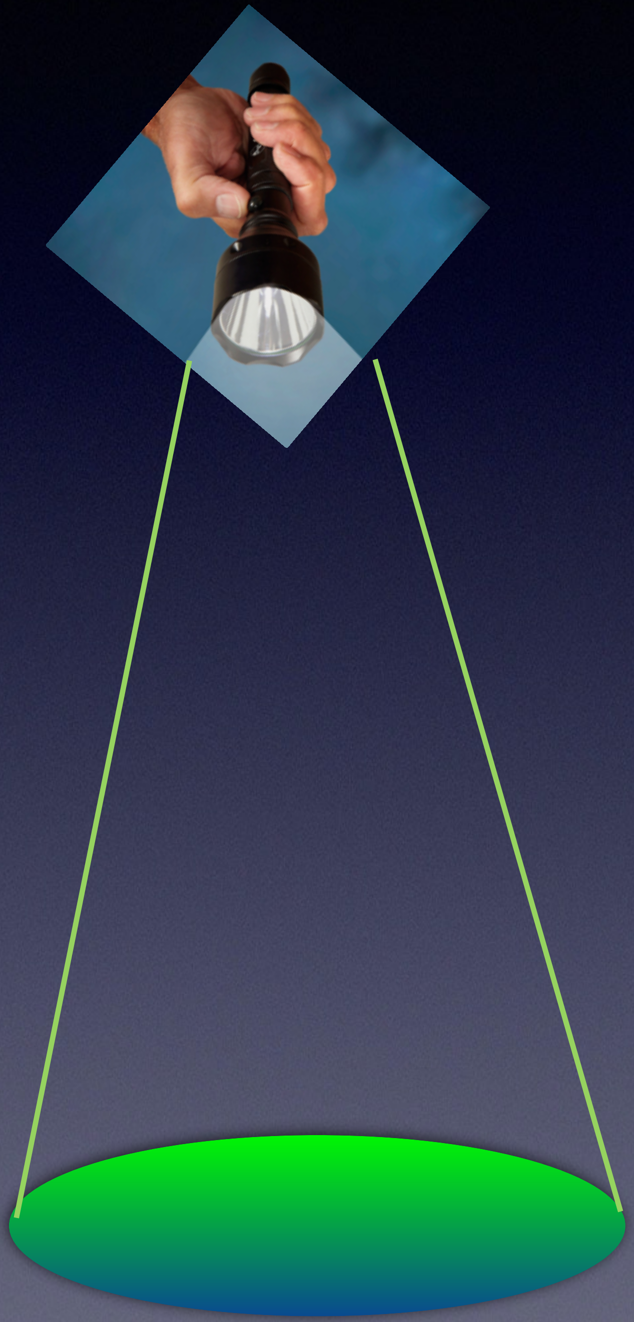
Seismic method

λ= wavelength
L= total lenght array
z= depth

RESOLUTION: the 'Fresnel zone'

$f\,(\lambda, L, z)$





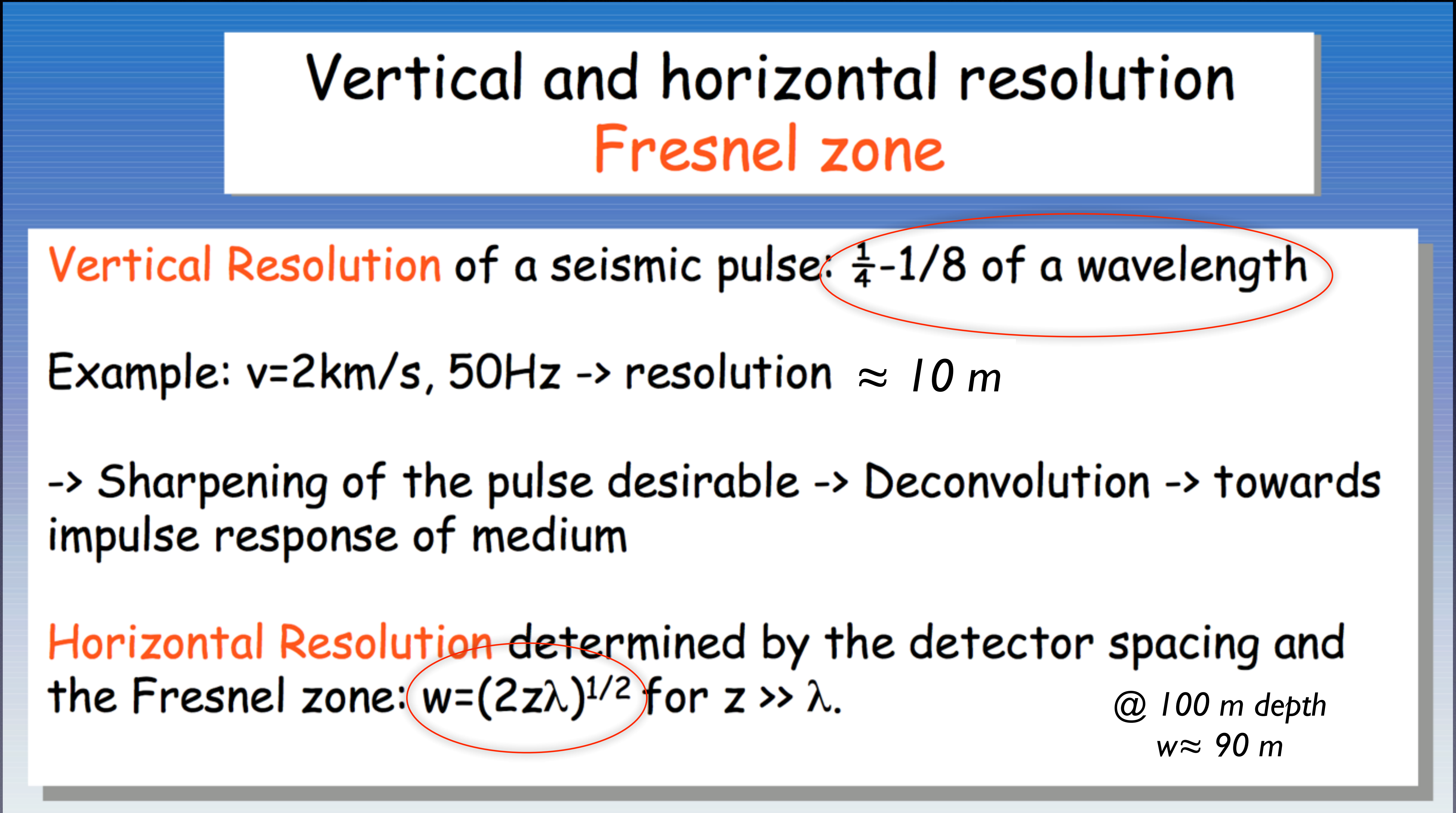
$\lambda = V / f$

Seismic methods

RESOLUTION: the 'Fresnel zone'

$f\,(\lambda, L, z)$

$\lambda = V / f$



Vertical and horizontal resolution
Fresnel zone

Vertical Resolution of a seismic pulse: $\frac{1}{4}$-1/8 of a wavelength

Example: v=2km/s, 50Hz -> resolution $\approx$ *10 m*

-> Sharpening of the pulse desirable -> Deconvolution -> towards impulse response of medium

Horizontal Resolution determined by the detector spacing and the Fresnel zone: $w=(2z\lambda)^{1/2}$ for $z \gg \lambda$.

@ 100 m depth
w≈ 90 m

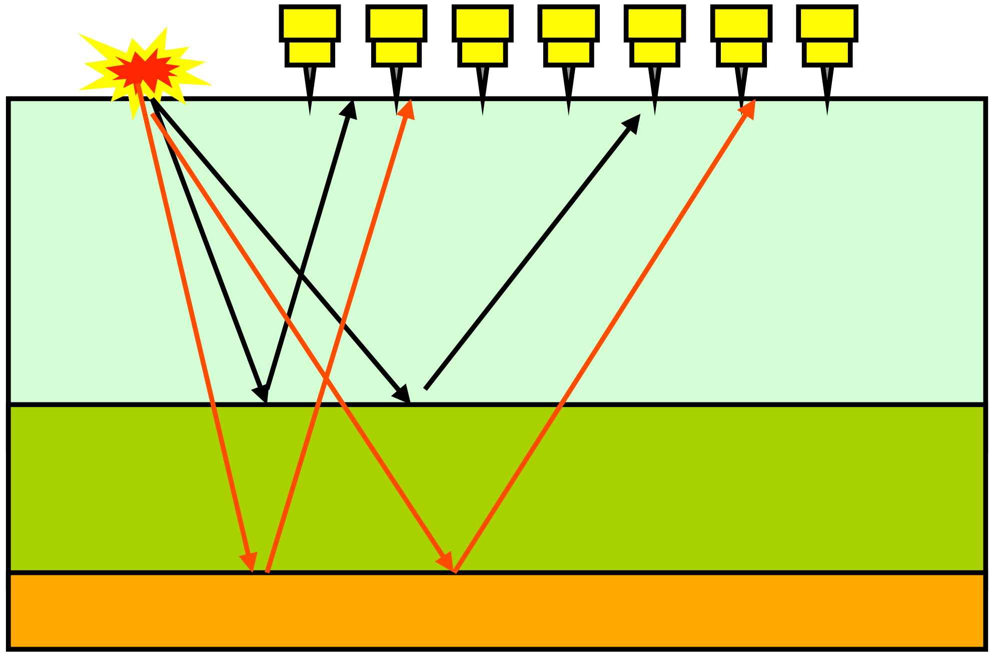
Seismic method

EXTRA MATERIAL

REFLECTION SEISMIC

Studi di Padova

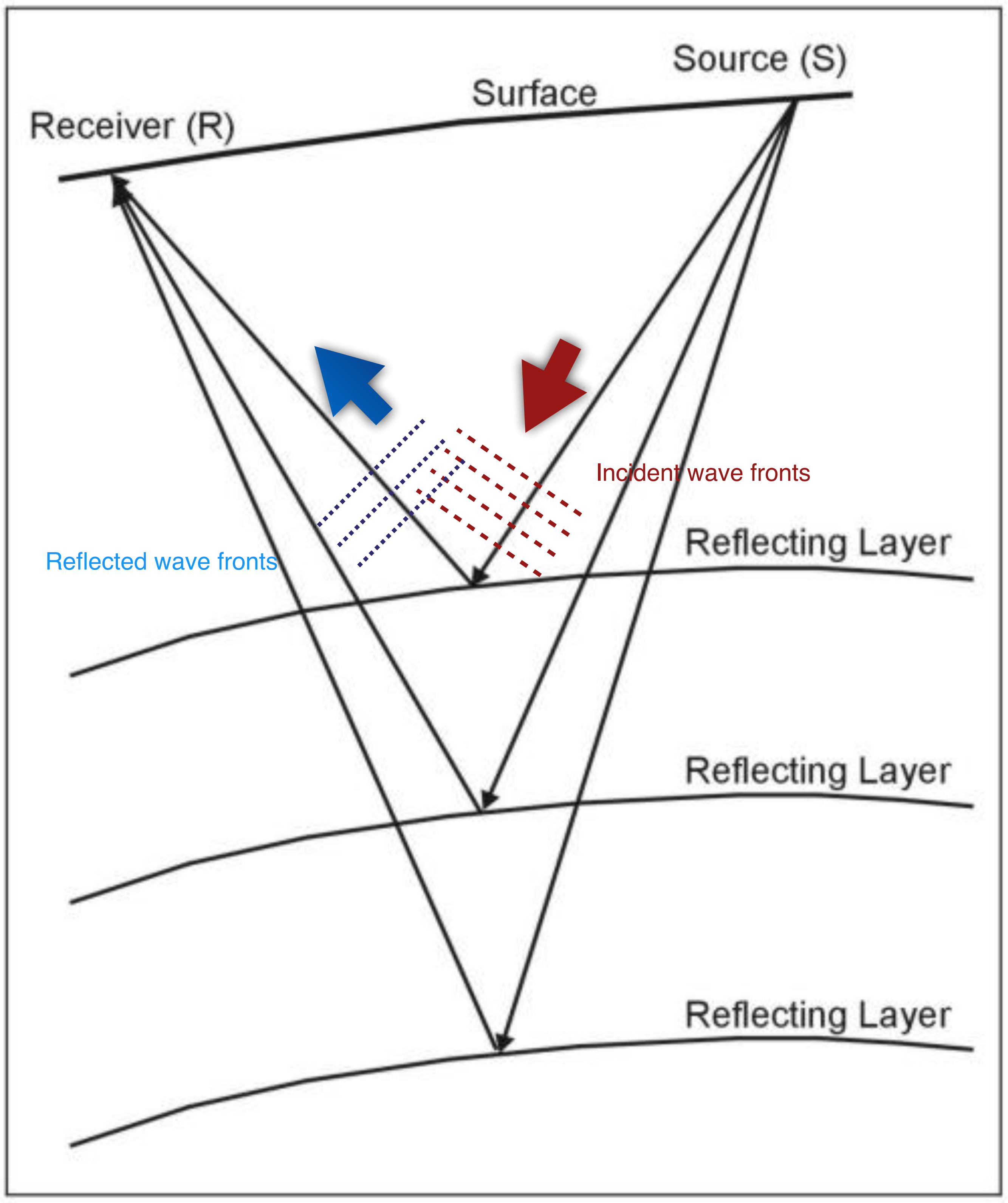
Reflections



Oil & Gas

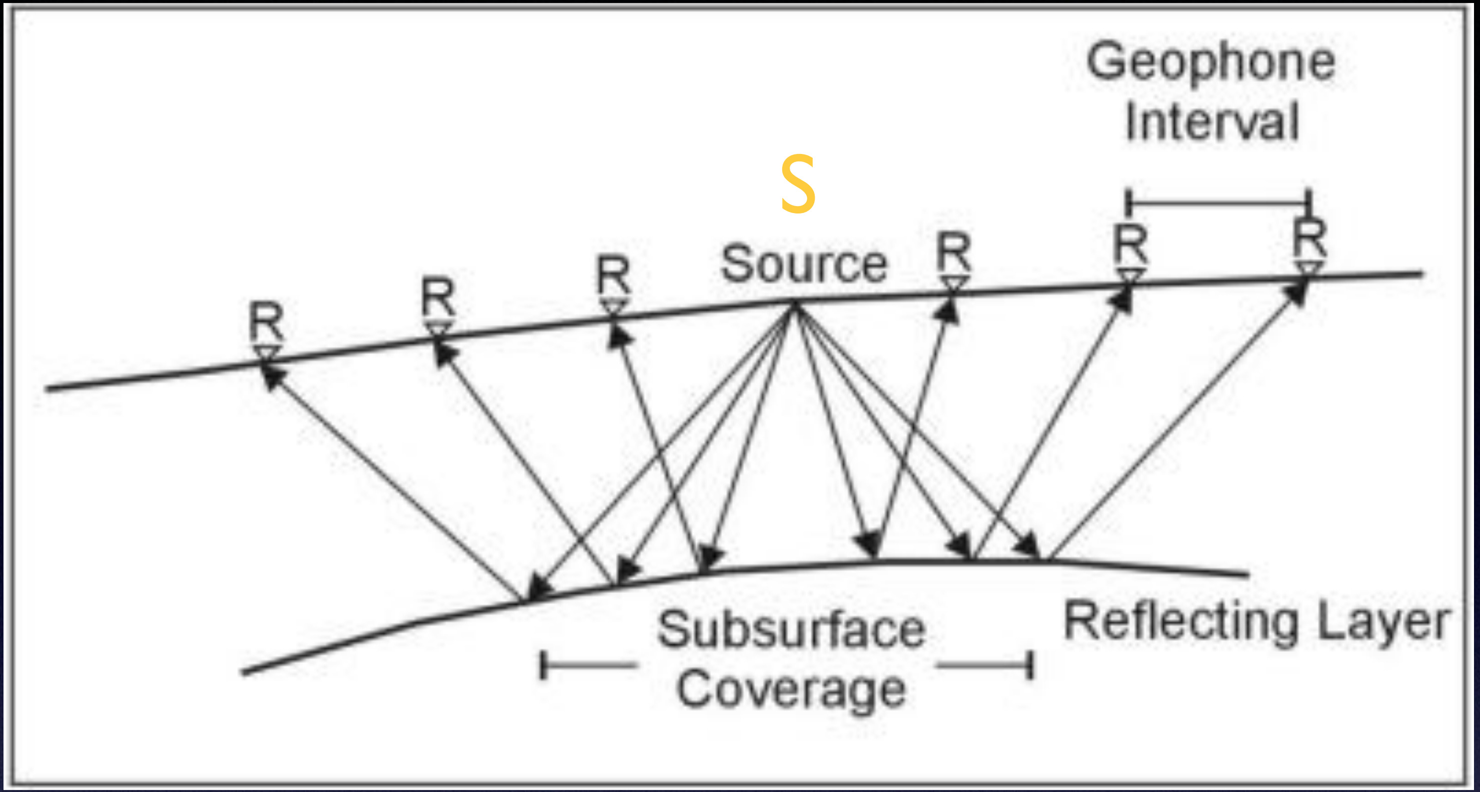
We generate waves that reflect on surface interface, having information on shape and depths if DEEP Structures

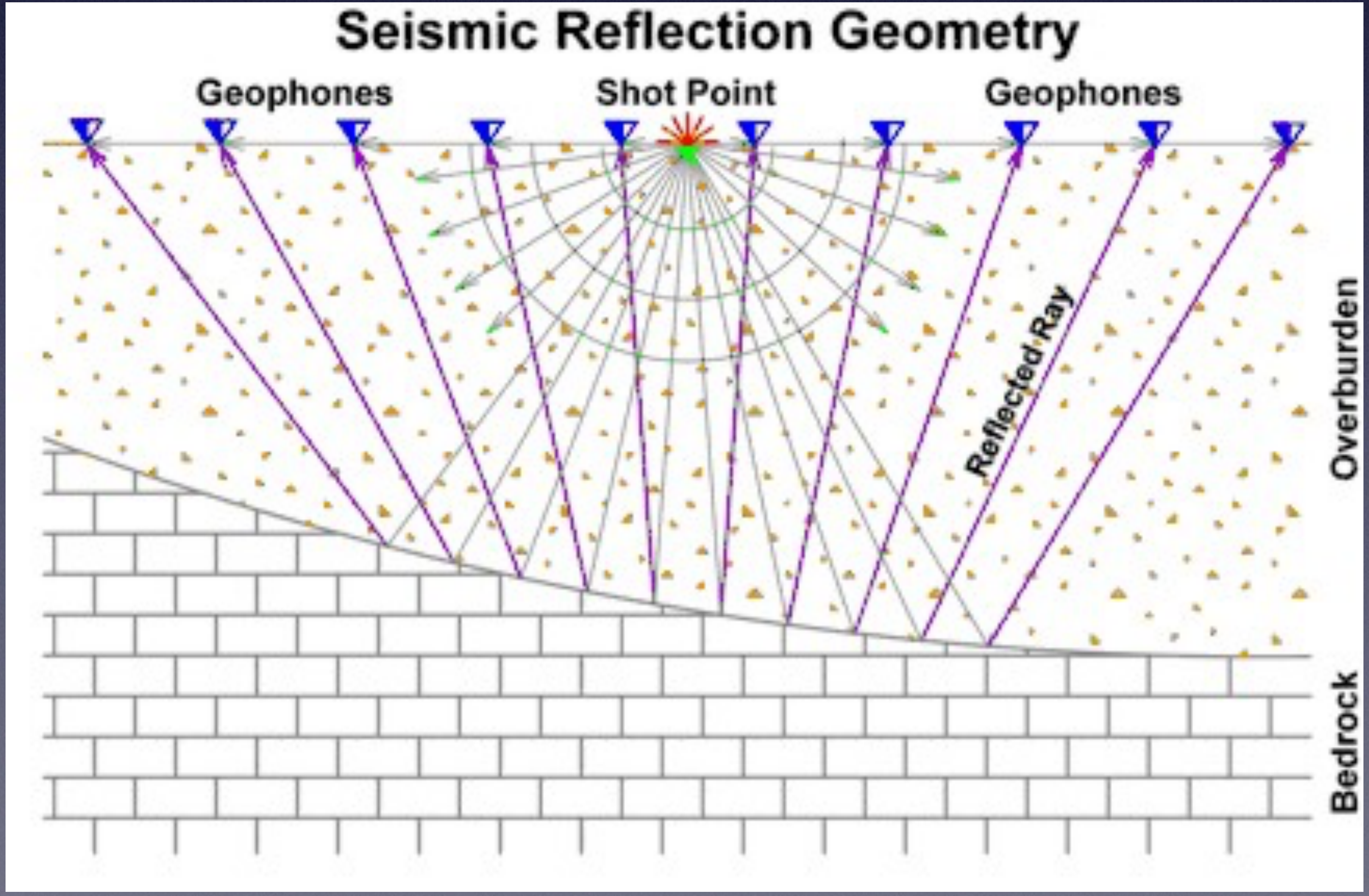
REFLECTION SEISMIC



Reflection from different Layering in the subsoil

Seismic method



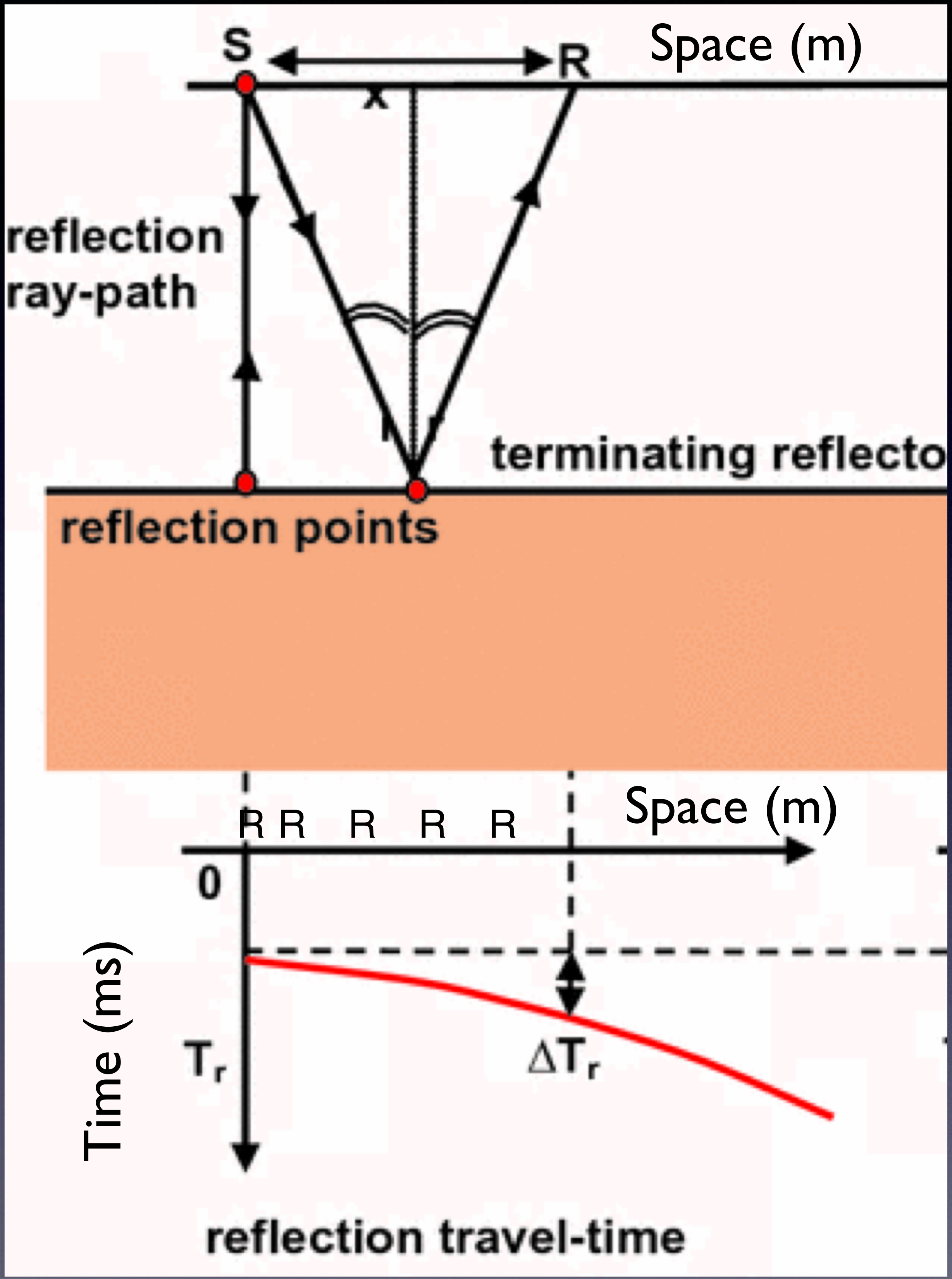


Recording signal emitted
by the source S
using the receiver R

R are the receivers

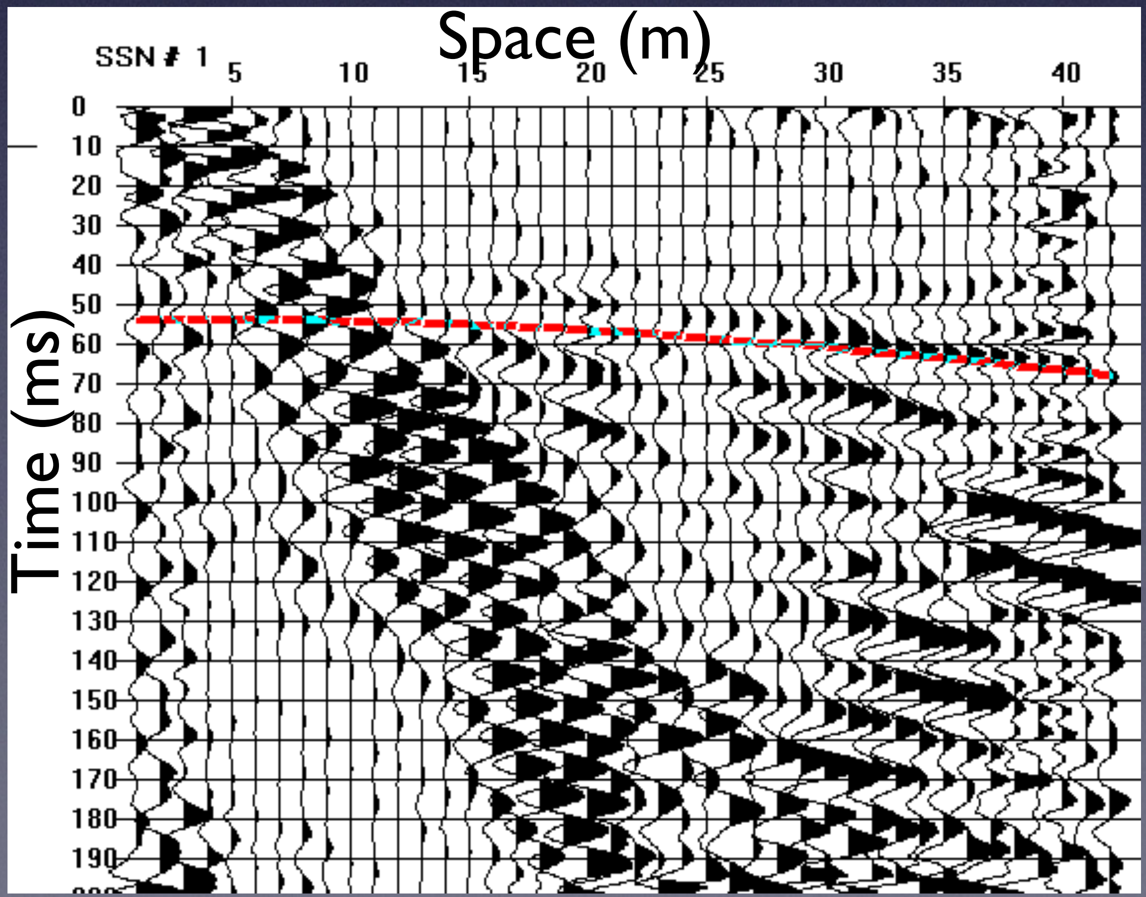
Geophones

EXTRA MATERIAL



Record signal in time

Seismogram space/time

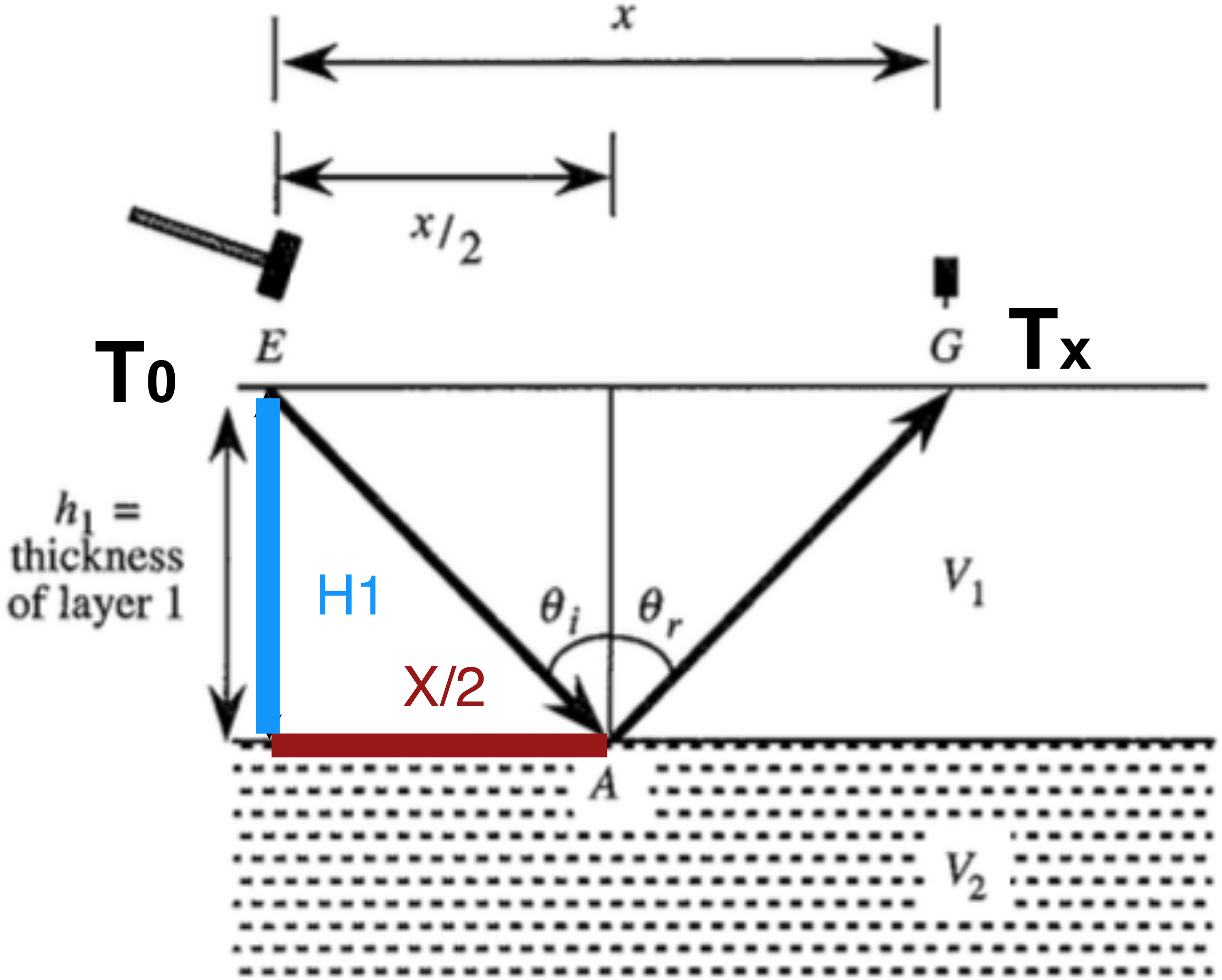


Two Way travel Time TWT

EXTRA MATERIAL

Seismic Reflection

$$\text{Time} = \frac{\text{space}}{\text{Velocity}}$$



$$\text{time} = \frac{EA + AG}{V_1}$$

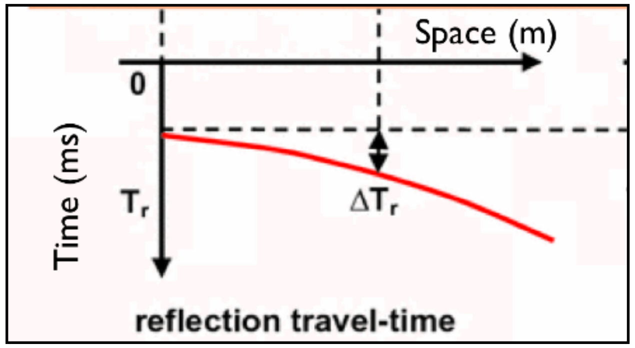
$$EA = AG = \left[\left(\frac{x}{2}\right)^2 + h_1^2\right]^{1/2}$$

$$\text{time} = \frac{\left(x^2 + 4h_1^2\right)^{1/2}}{V_1}$$

$$T_0 = 2h/V_1$$

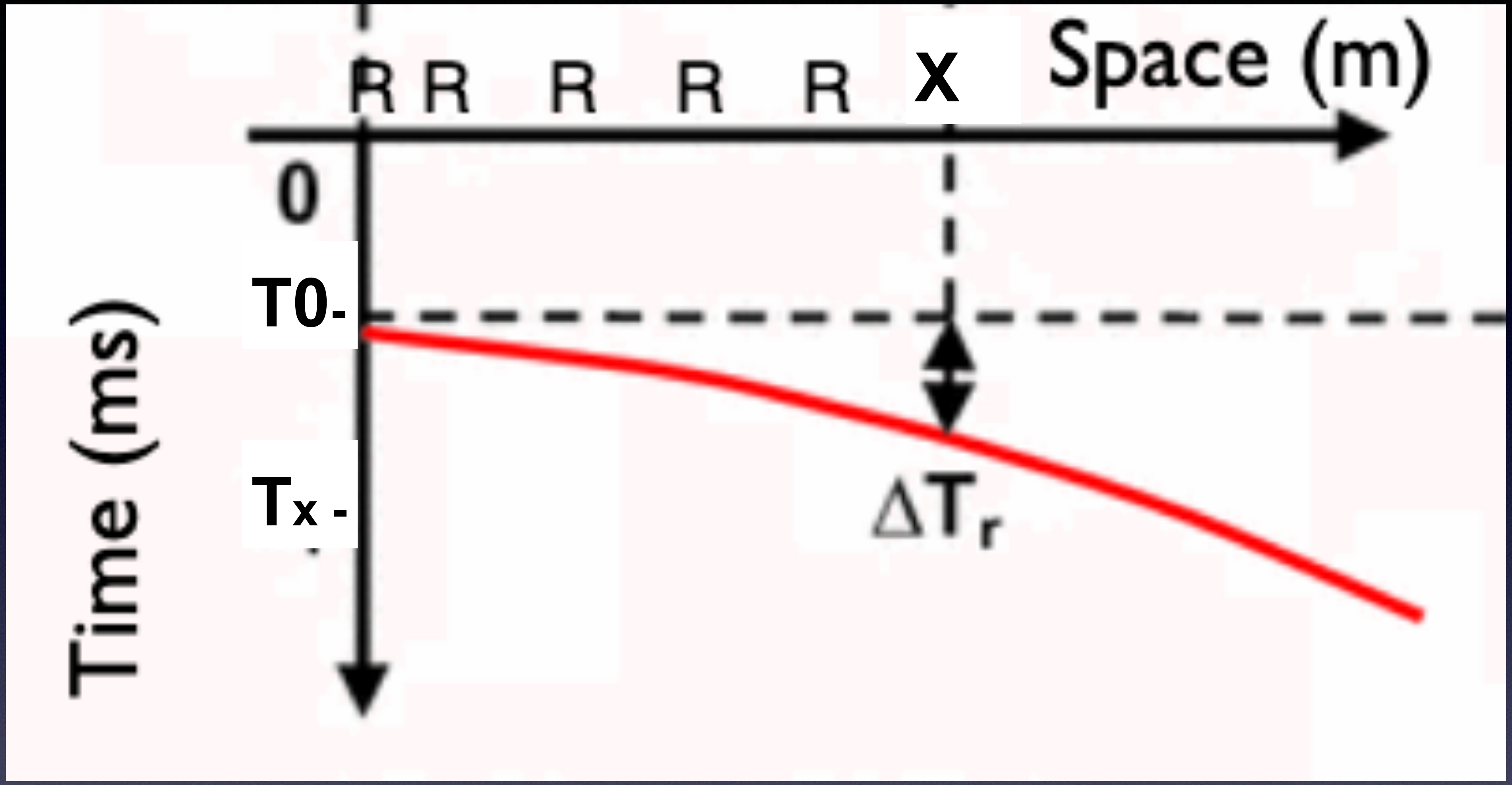
Hyperbola

spazio -tempo



$$T^2_x = T^2_0 + X^2 / V_1^2$$

EXTRA MATERIAL



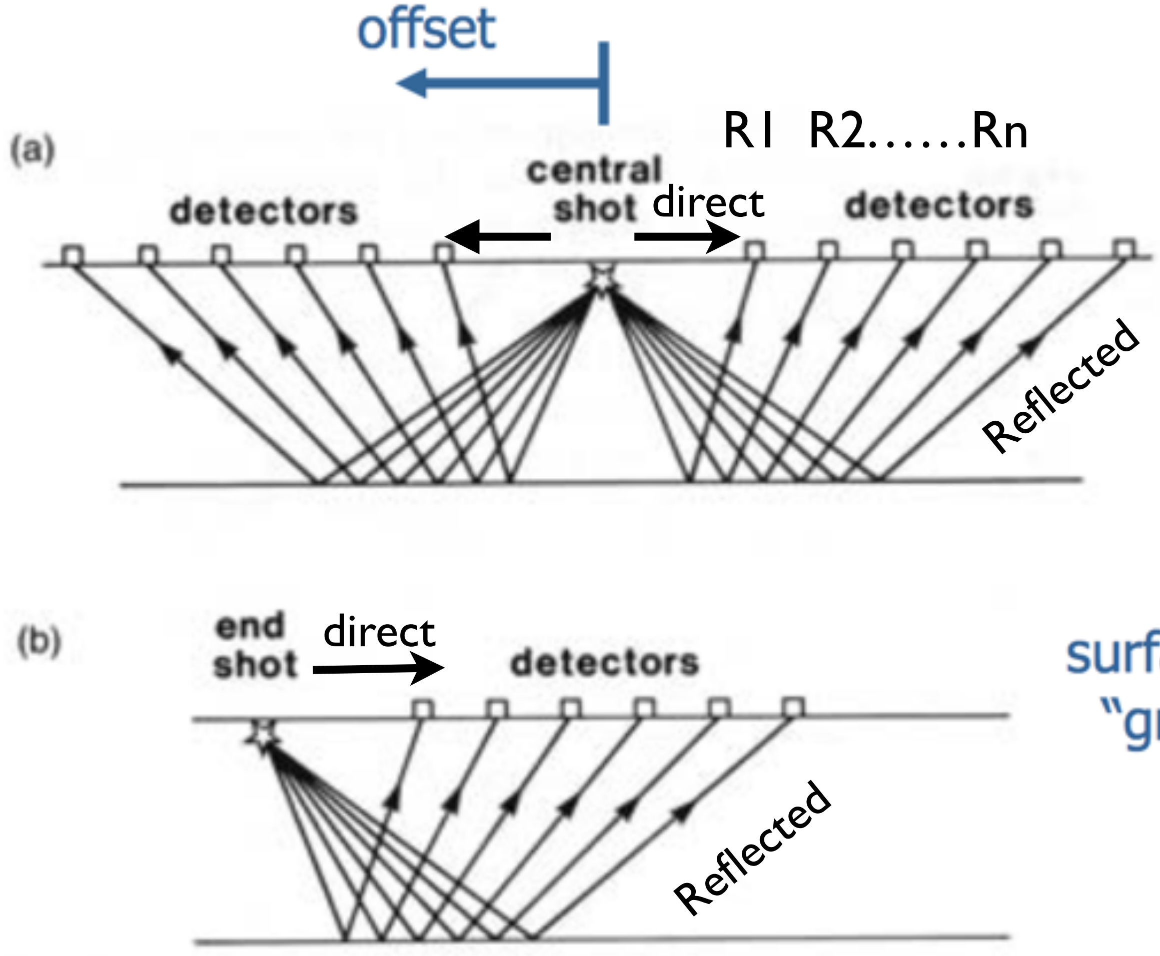
2 equations 2 unknowns

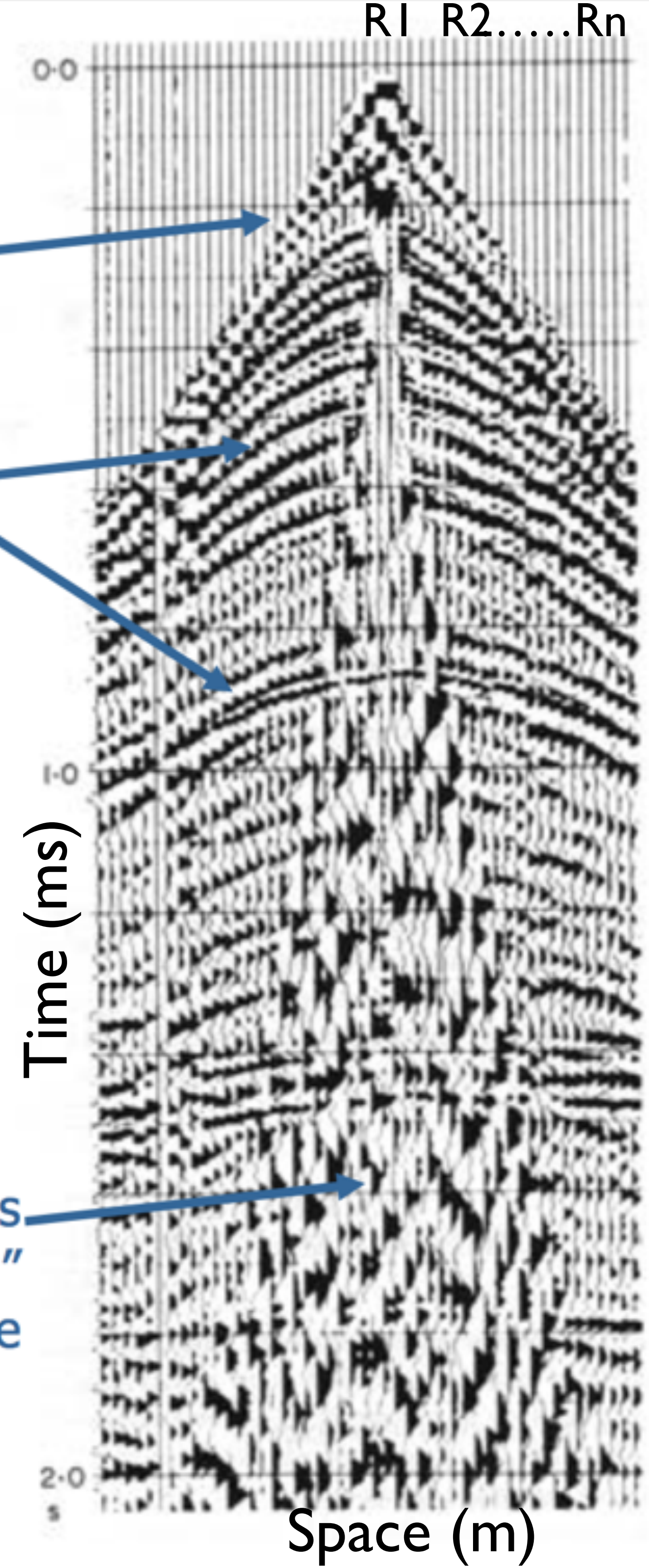
- Upper layer velocity V1
- Thickness of upper layer h

$$\begin{cases} T_0 = 2h/V_1 \\ T^2_x = T^2_0 + X^2 / V_1^2 \end{cases}$$

Seismic method

Shot gathers



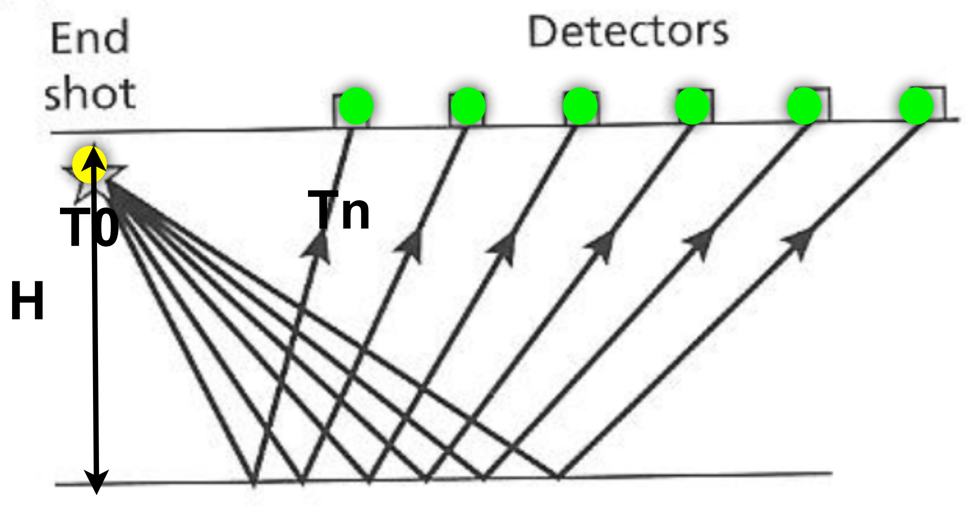


Seismic methods

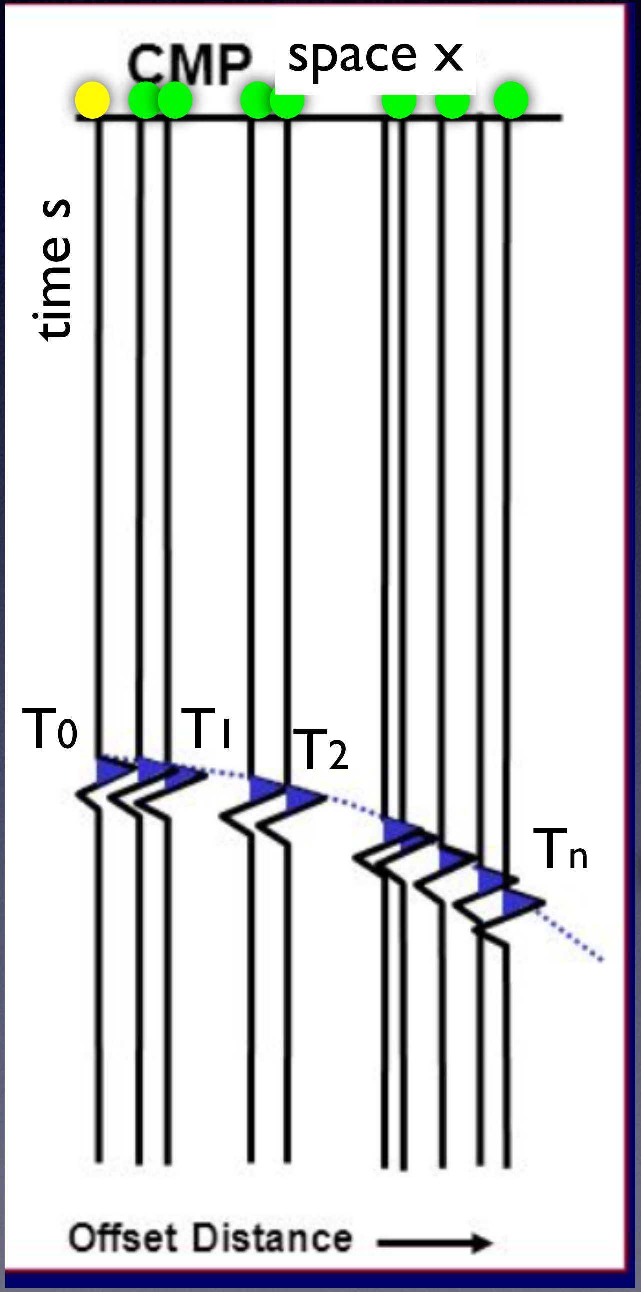
Reflections on Seismograms
are REFLECTION HYPERBOLA

space x

Seismic acquisition

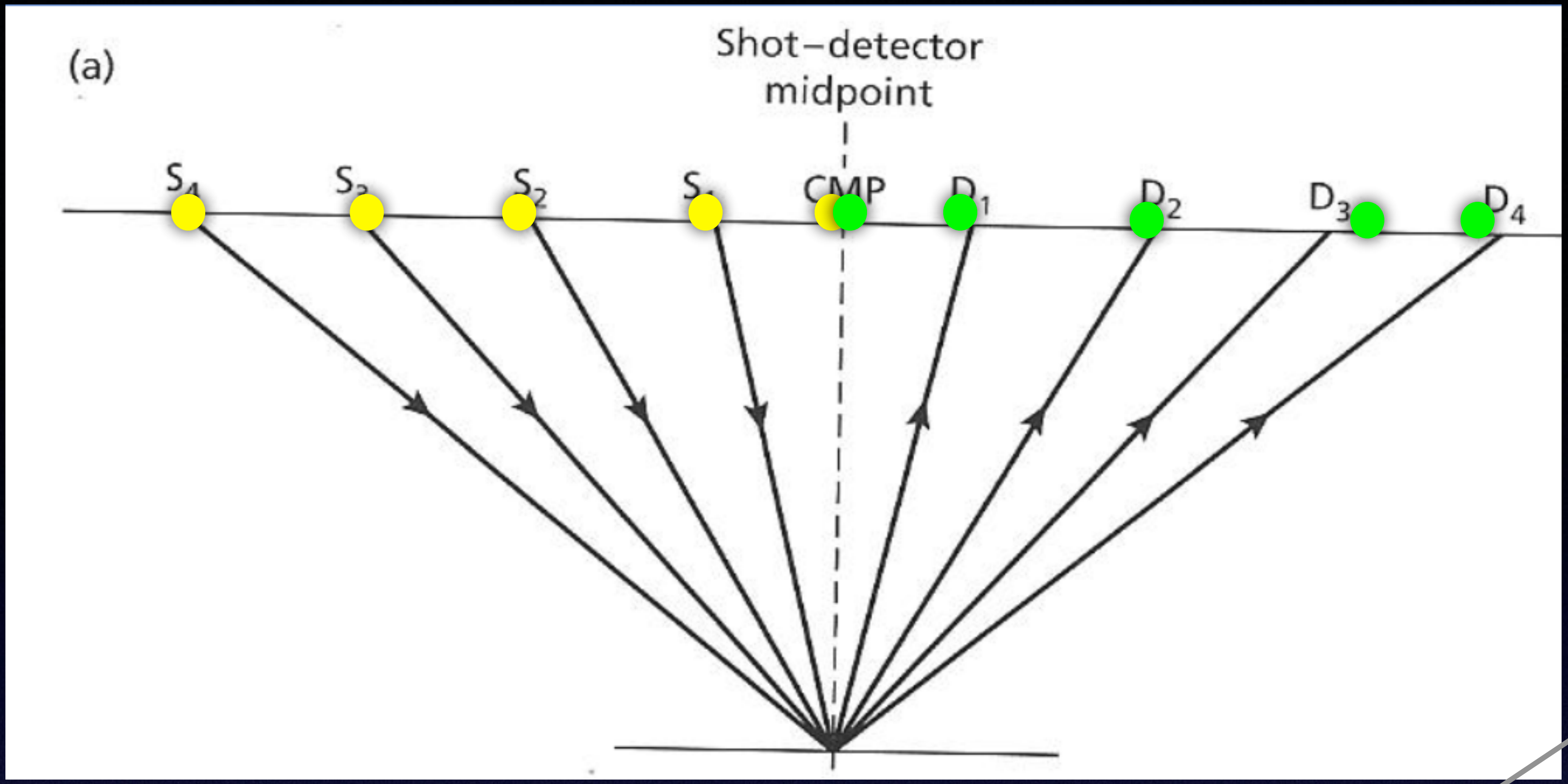


Seismogram (space-time)

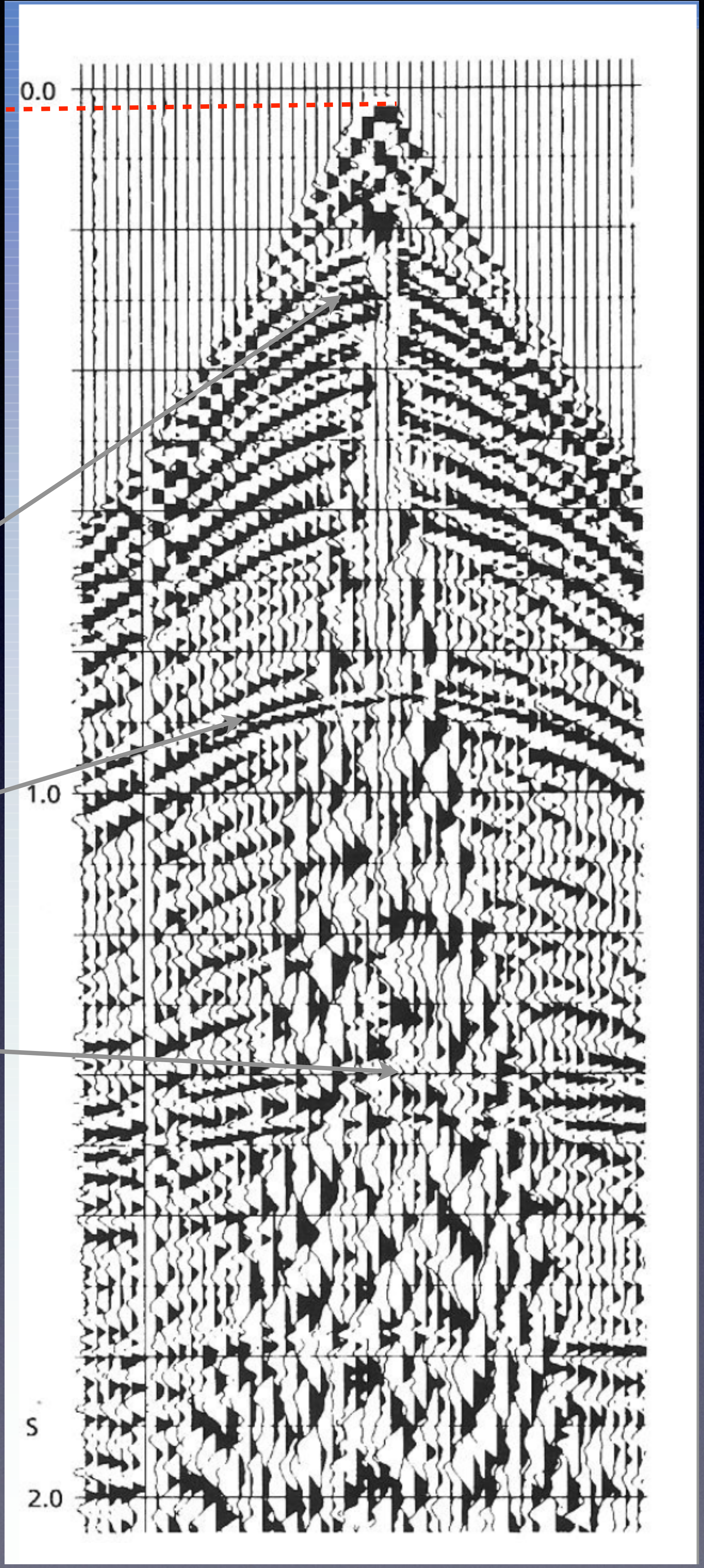


$$T^2 x = T^2_0 + X^2 / V1^2$$

$$T_0 = 2H/V1$$



Reflection Hyperbola



To

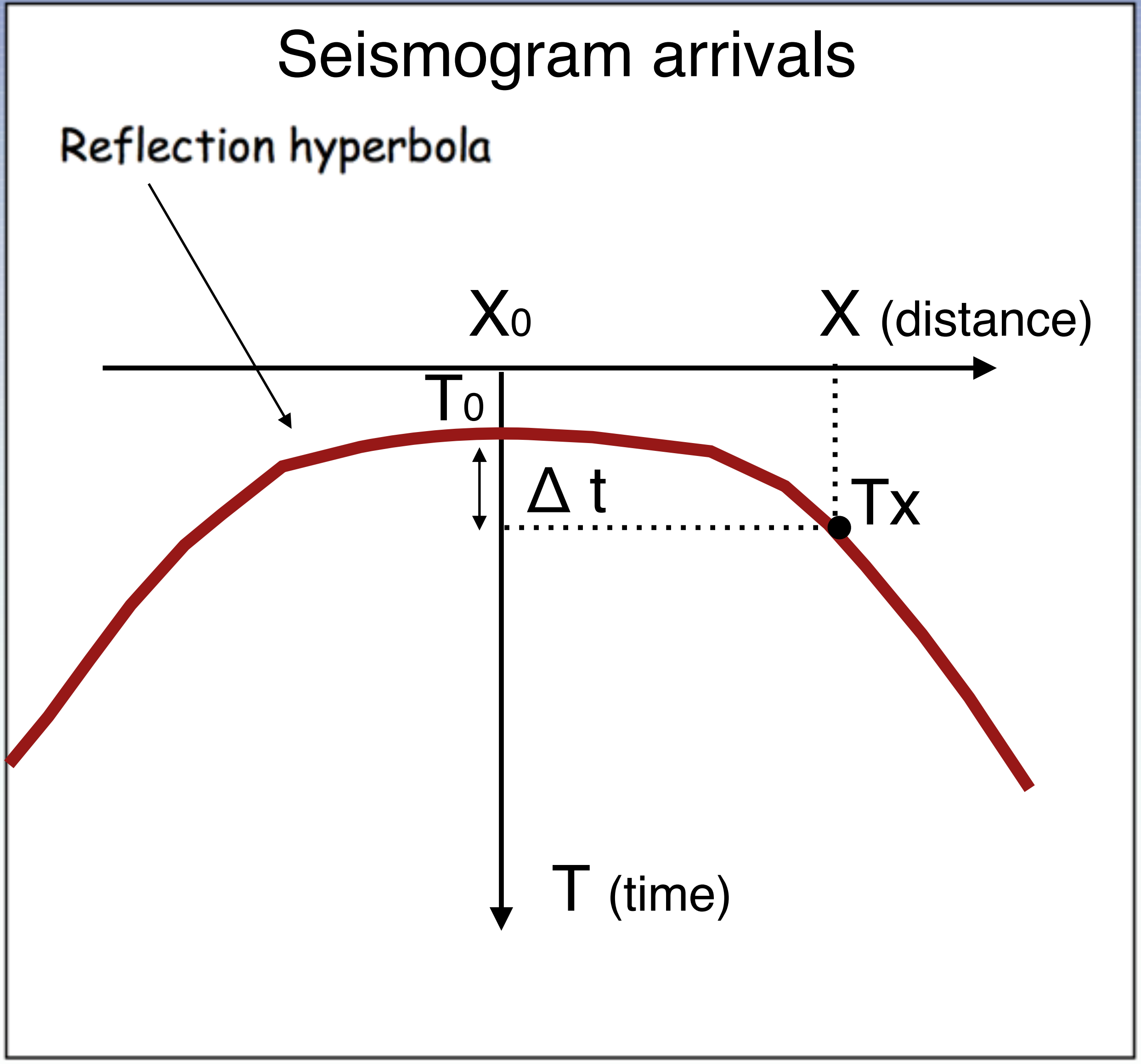
TWT (two way travel time) s

space (m)

EXTRA MATERIAL

$$T^2_x = T^2_0 + X^2 / V_1^2 \qquad T_0 = 2h/V1$$

The arrival times t(x) of reflections from an interface at depth *h* as a function of offset x are given as



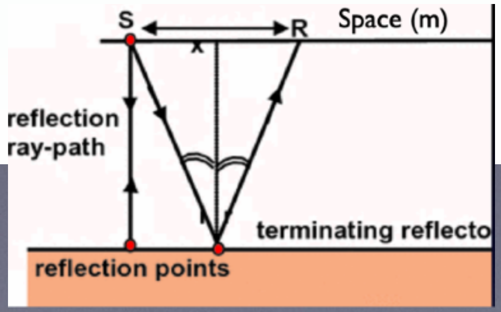
Seismogram arrivals

$$t(x) = \frac{1}{v}\sqrt{x^2 + 4h^2}$$

$$t^2 = \frac{4h^2}{v^2} + \frac{x^2}{v^2} = t_0^2 + \frac{x^2}{v^2}$$

$$\Delta T = t_x - t_0 \approx \frac{x^2}{2V^2 t_0}$$

Normal moveout (NMO)



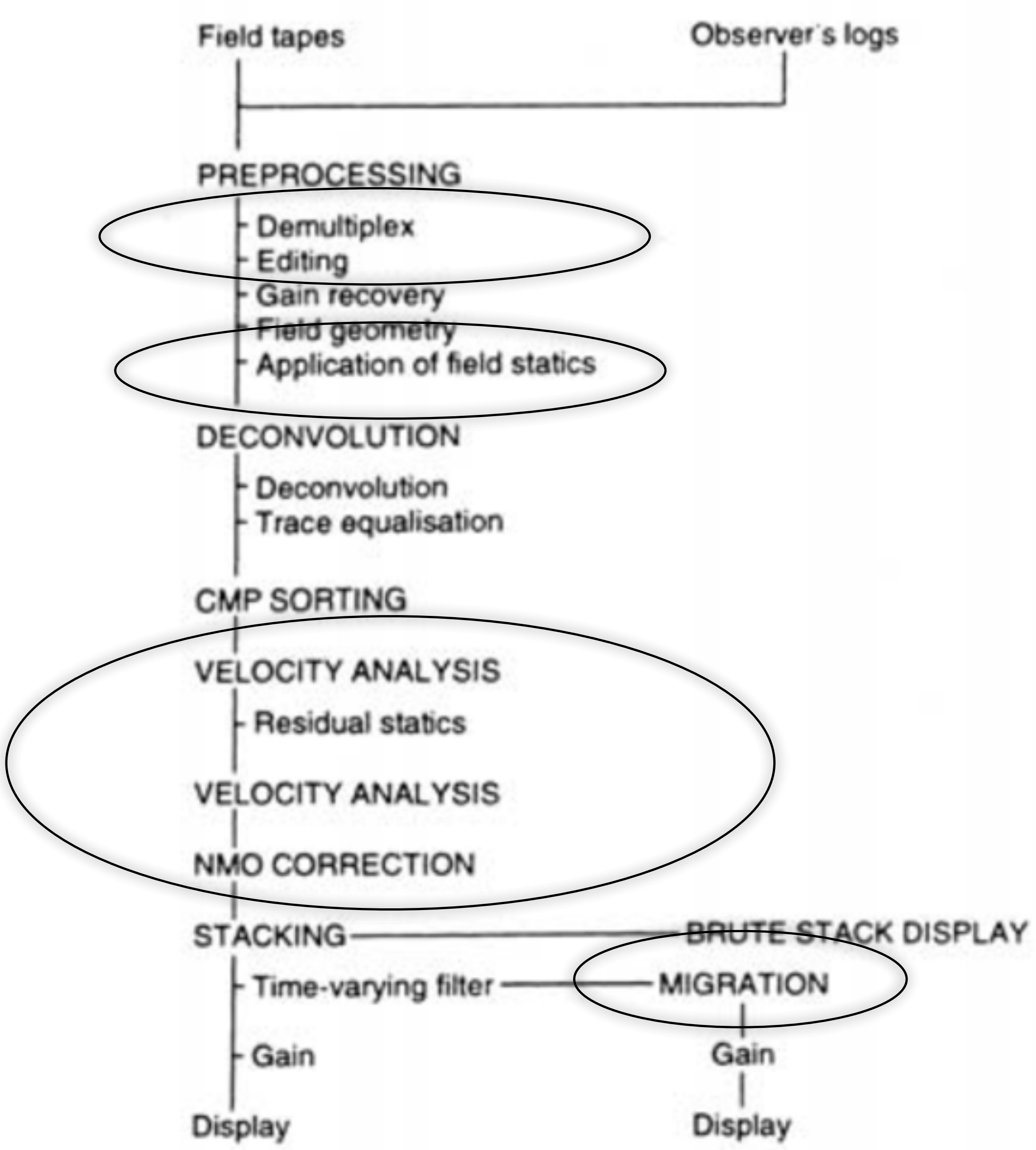
Easiest way to find V1

EXTRA MATERIAL *Metodi Sismici*

sismica a riflessione - Processing complesso

Seismic reflection processing

Flow overview



Field tapes
Observer's logs
PREPROCESSING
Demultiplex
Editing
Gain recovery
Field geometry
Application of field statics
DECONVOLUTION
Deconvolution
Trace equalisation
CMP SORTING
VELOCITY ANALYSIS
Residual statics
VELOCITY ANALYSIS
NMO CORRECTION
STACKING
BRUTE STACK DISPLAY
Time-varying filter
MIGRATION
Gain
Gain
Display
Display

-Statics correction
-Muting
-Velocity analysis (NMO)
-migration

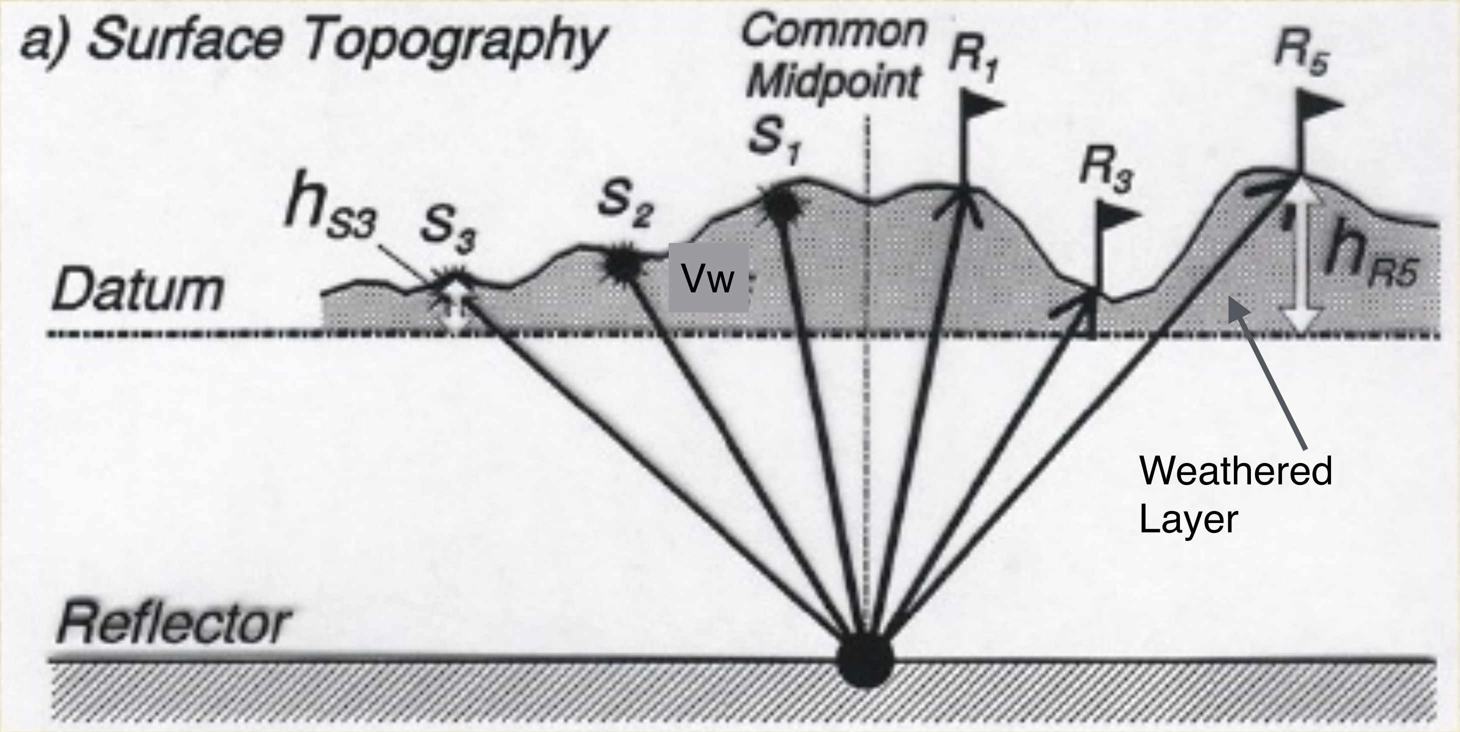
These are the main steps in processing

The order in which they are applied is variable

EXTRA MATERIAL

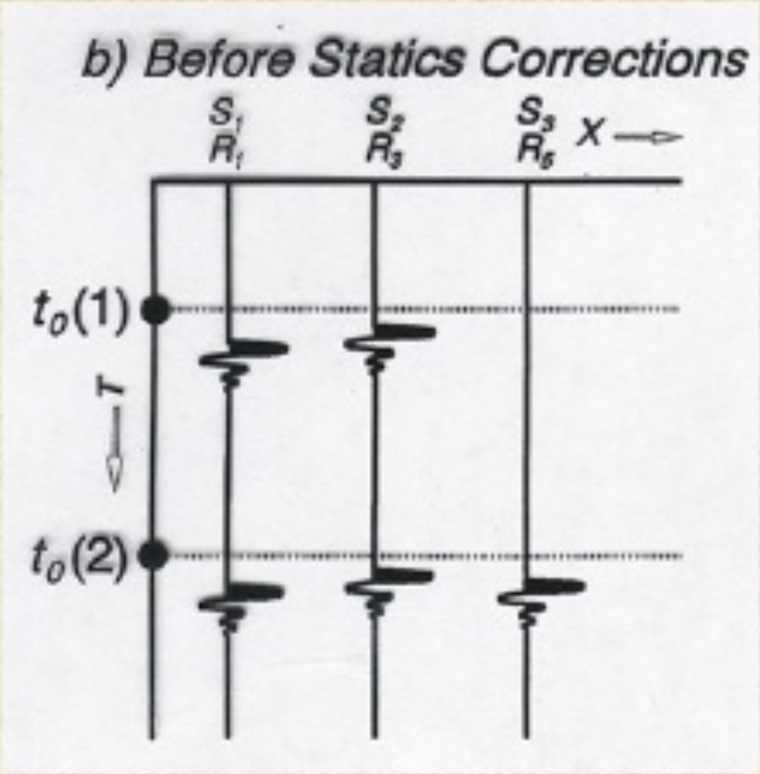
Static Corrections

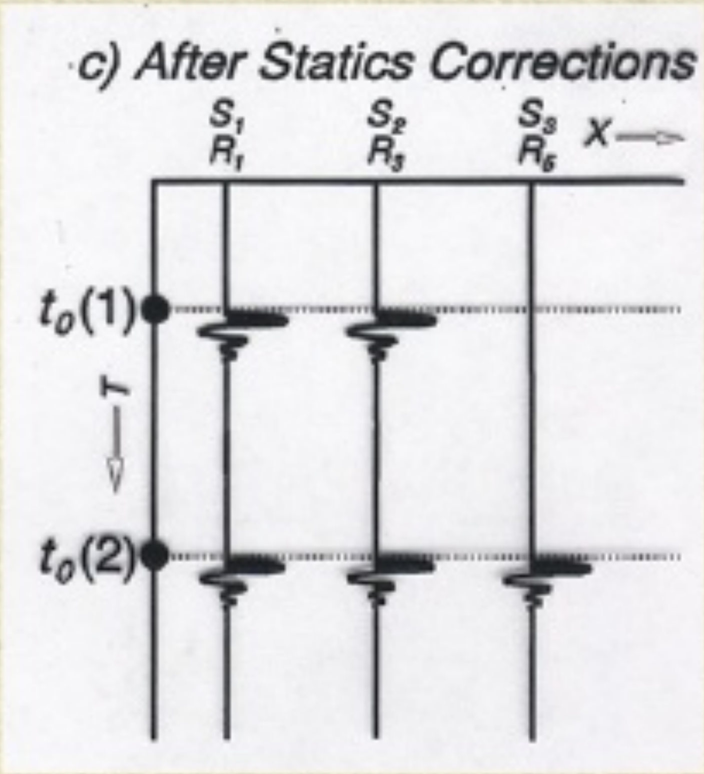
(Topographic Correction)



Time corr = hr / Vw

Vw	Assumed velocity of the material above
hr	Thickness of the weathered layer





EXTRA MATERIAL

Metodi Sismici

Es. Correzione delle statiche

Static corrections

Correct for surface topography and the weathered surface layer

Surface topography

Time correction to each trace:

$$t_g = \left(E_g - E_d\right)/V$$

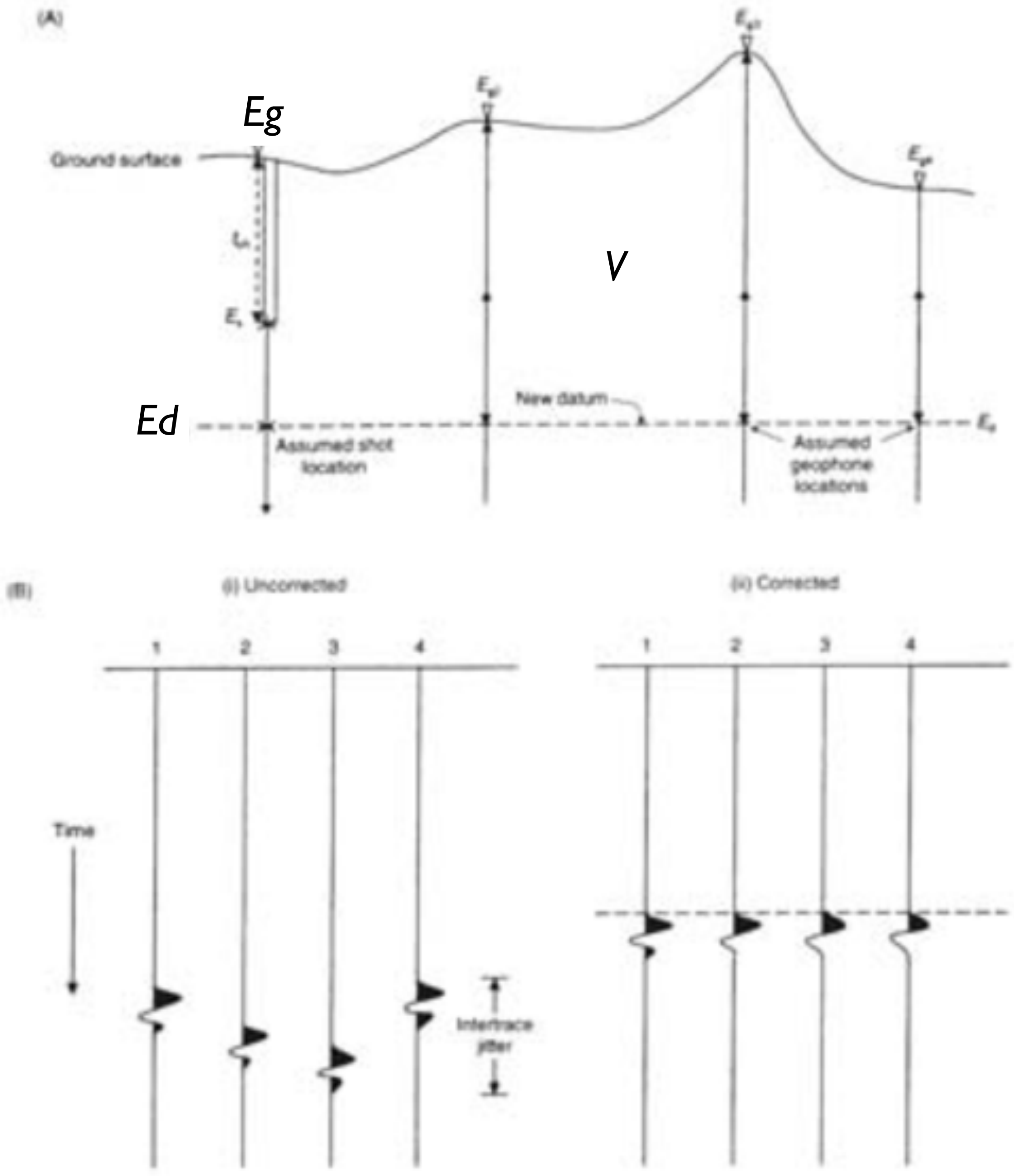
Source depth

$$t_s = \left(E_s - E_d\right)/V$$

total correction

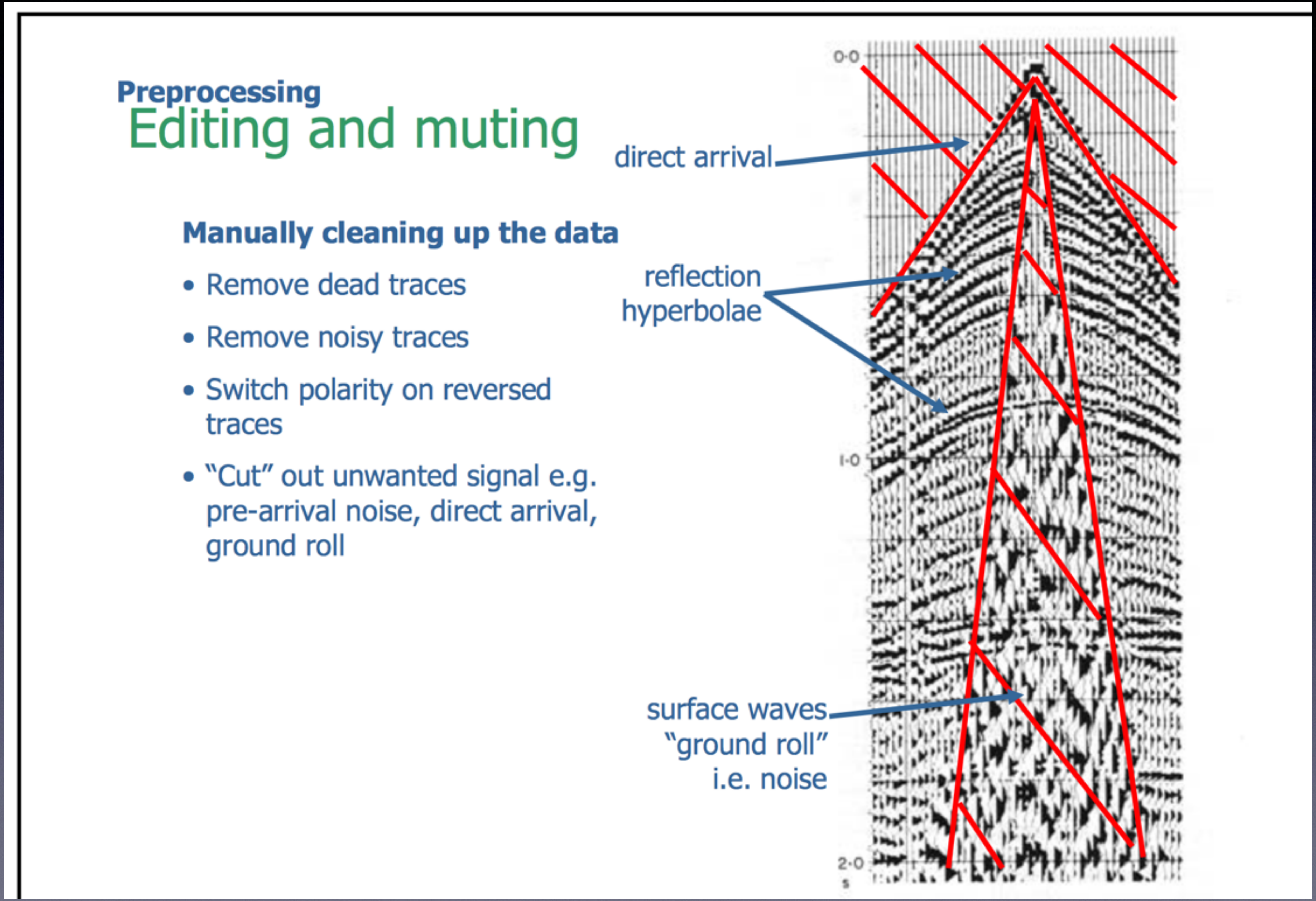
$$t_e = t_s + t_g$$

Shift each trace by this amount to line up deeper reflectors



Editing and Muting = clean the raw data

EXTRA MATERIAL



Preprocessing

Editing and muting

Manually cleaning up the data

- Remove dead traces
- Remove noisy traces
- Switch polarity on reversed traces
- “Cut” out unwanted signal e.g. pre-arrival noise, direct arrival, ground roll

direct arrival

reflection hyperbolae

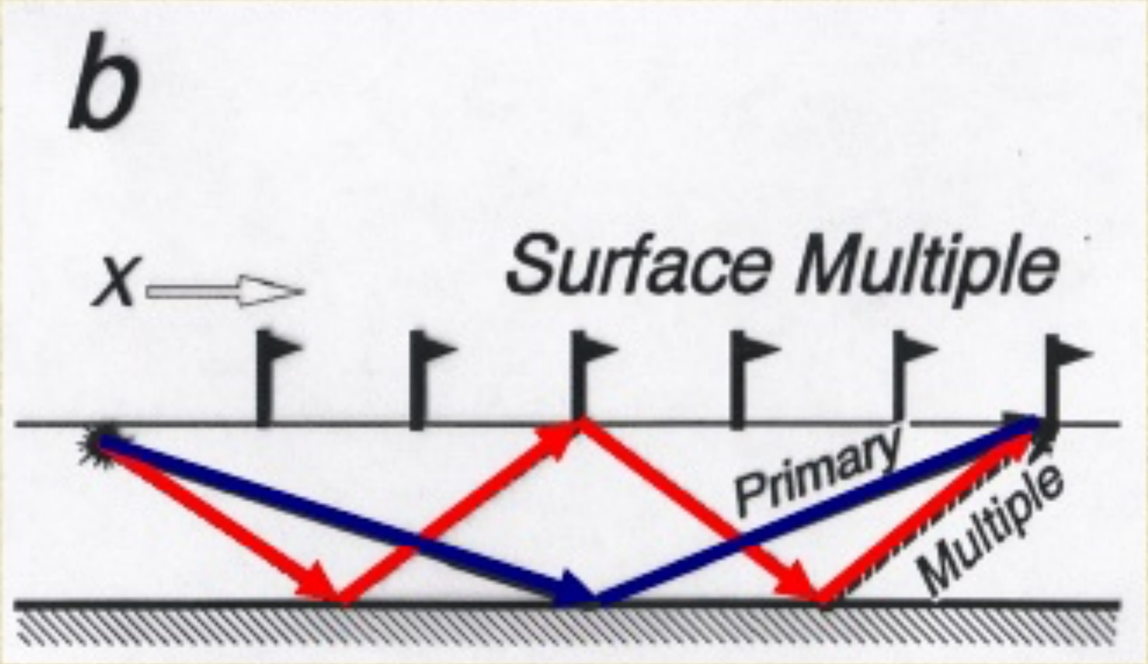
surface waves “ground roll” i.e. noise

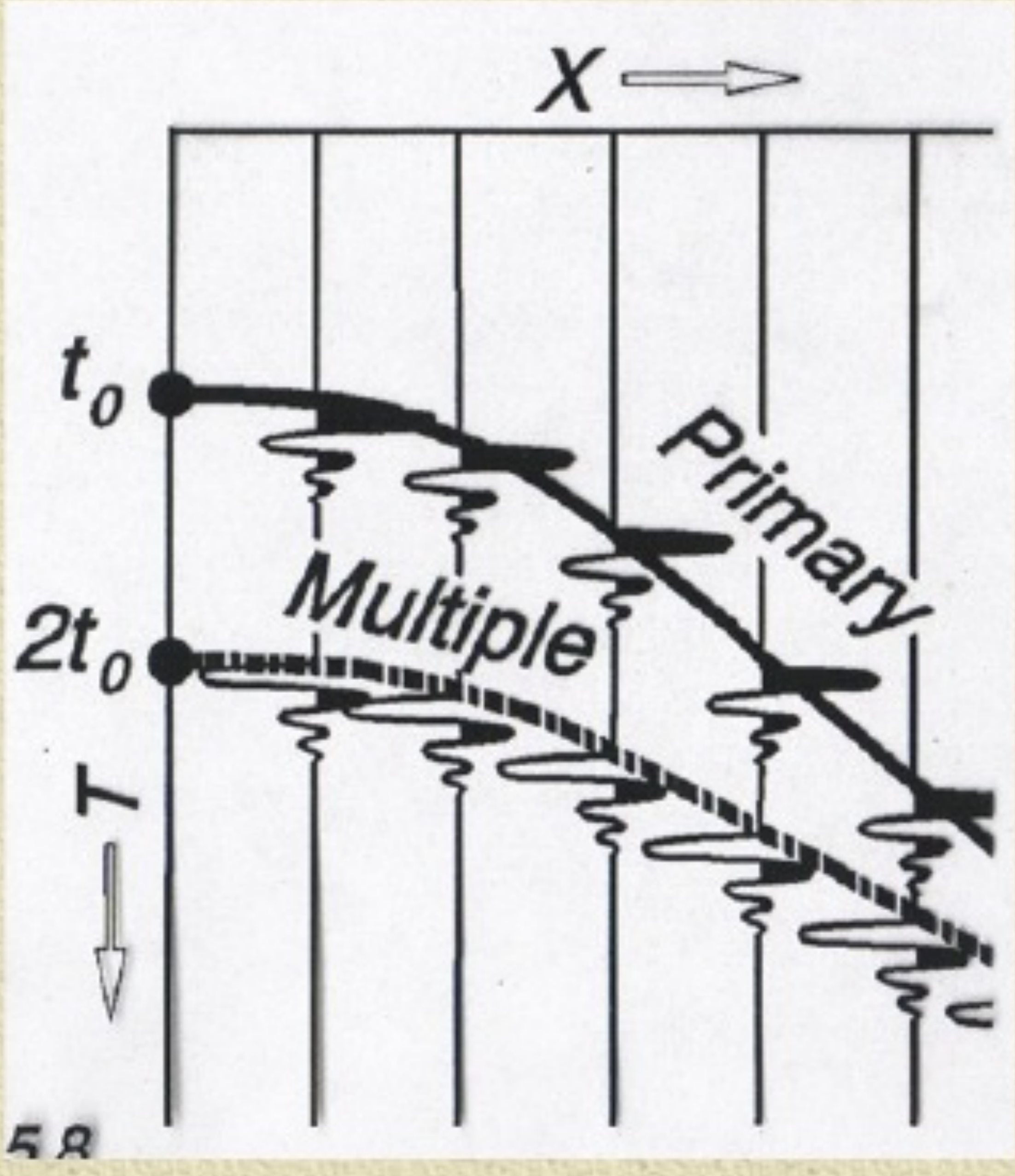
Editing and muting

EXTRA MATERIAL

Multiples

Muting

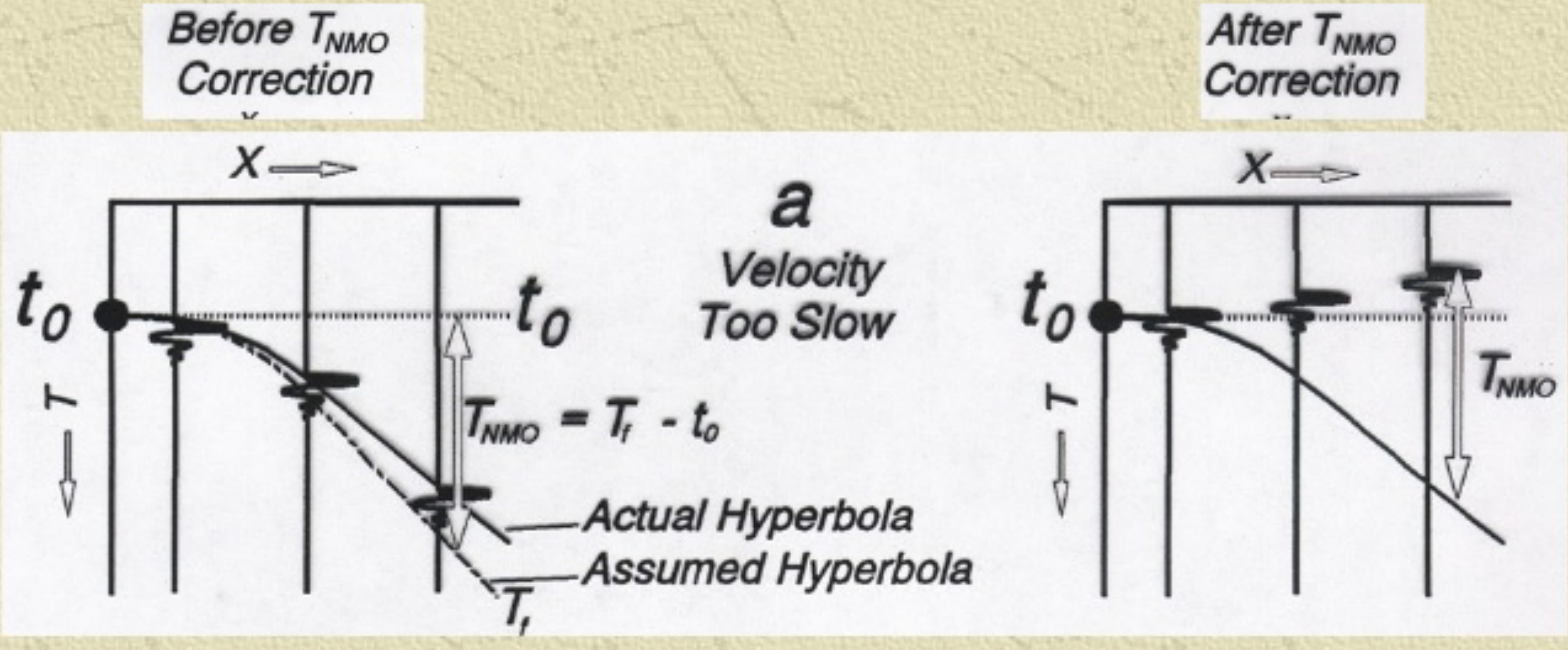




Reflected energy back up again following a reflection back down at the surface.

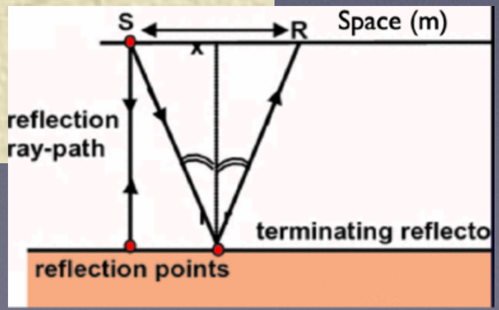
EXTRA MATERIAL

Velocity Analysis



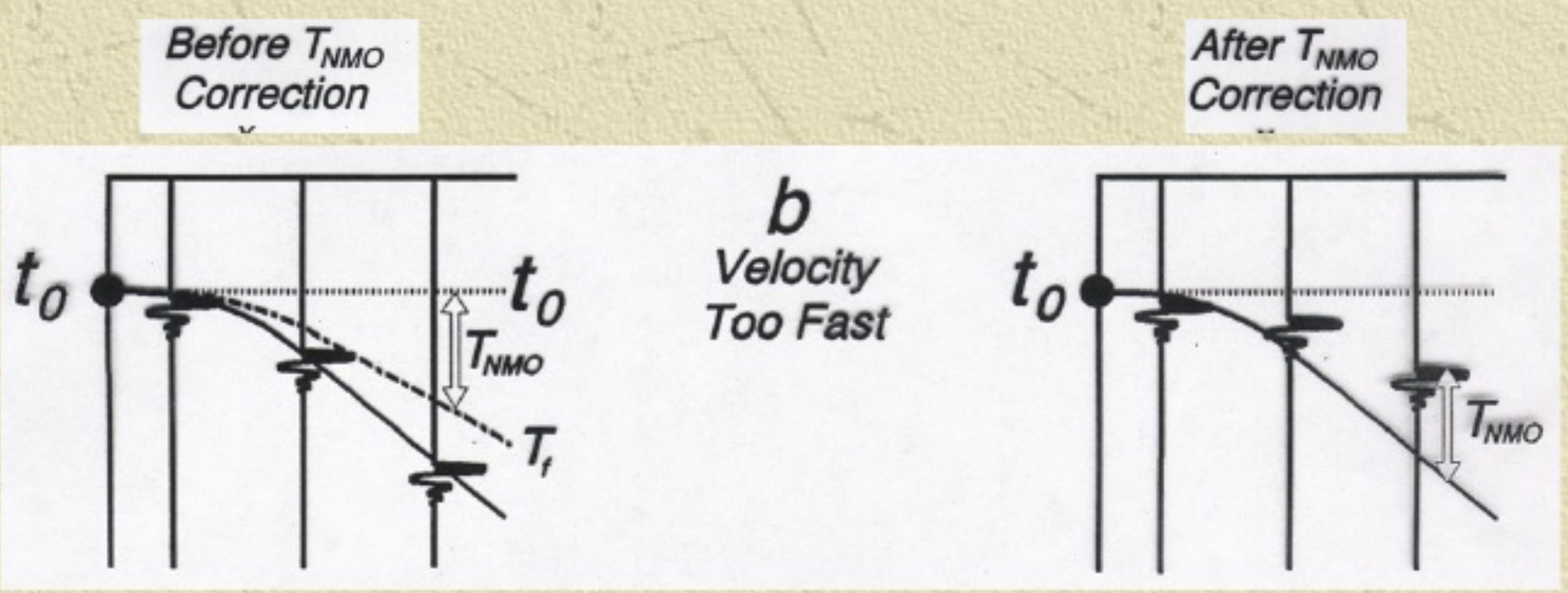
Overcorrected by too slow velocity

Normal MOVE OUT CORRECTION



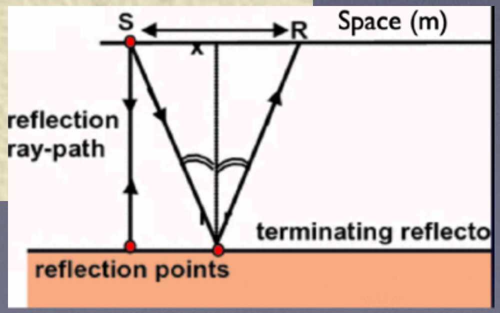
EXTRA MATERIAL

Velocity Analysis



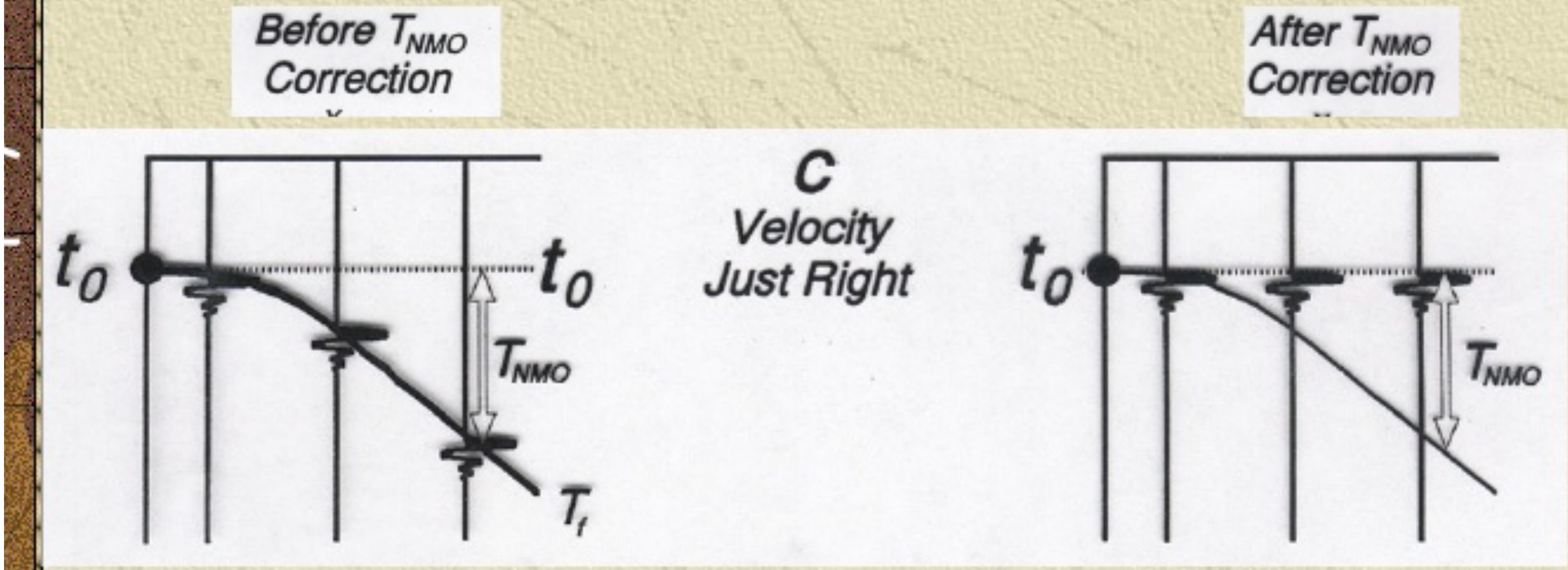
Under corrected by too fast velocity

Normal MOVE OUT CORRECTION

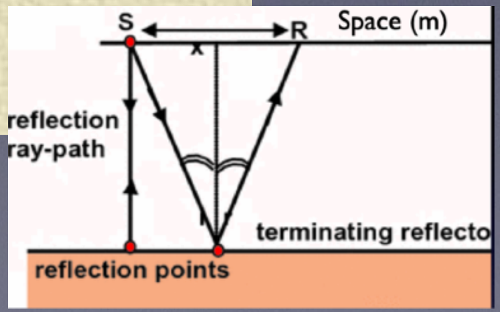


EXTRA MATERIAL

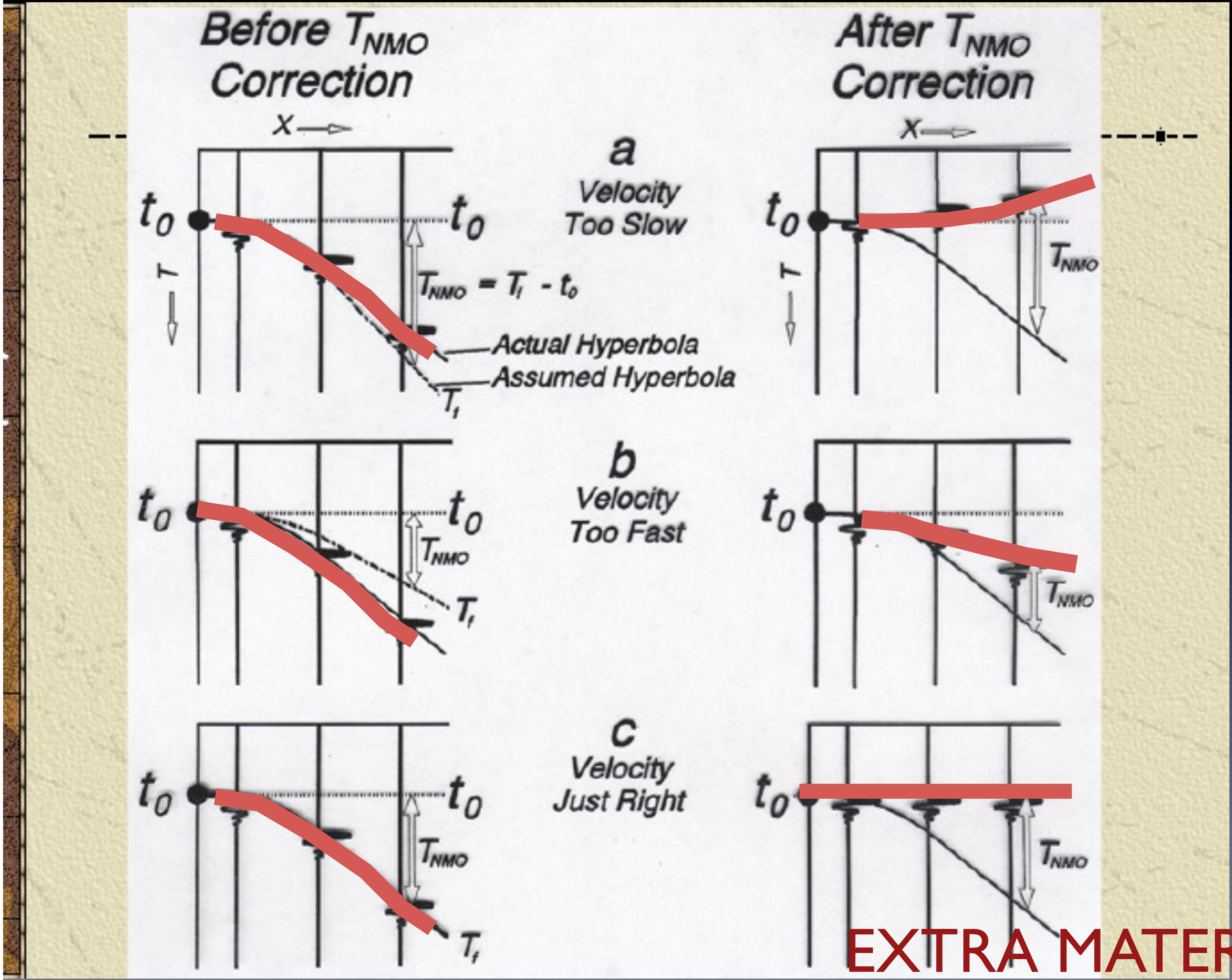
Velocity Analysis



NMO - Normal Moveout Correction
Now Corrected

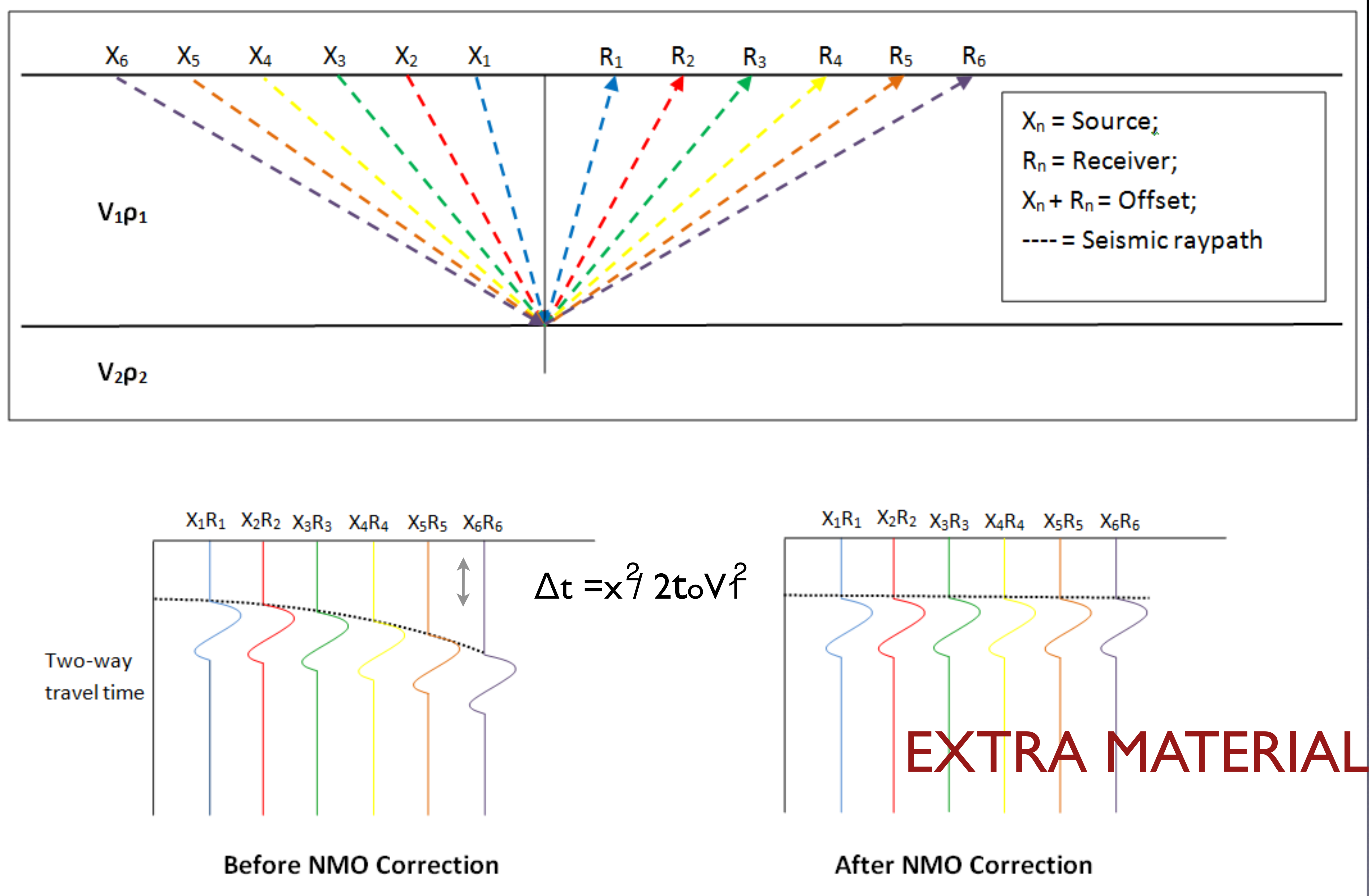


Normal MOVE OUT CORRECTION



EXTRA MATERIAL

Es. Normal Move Out Correction

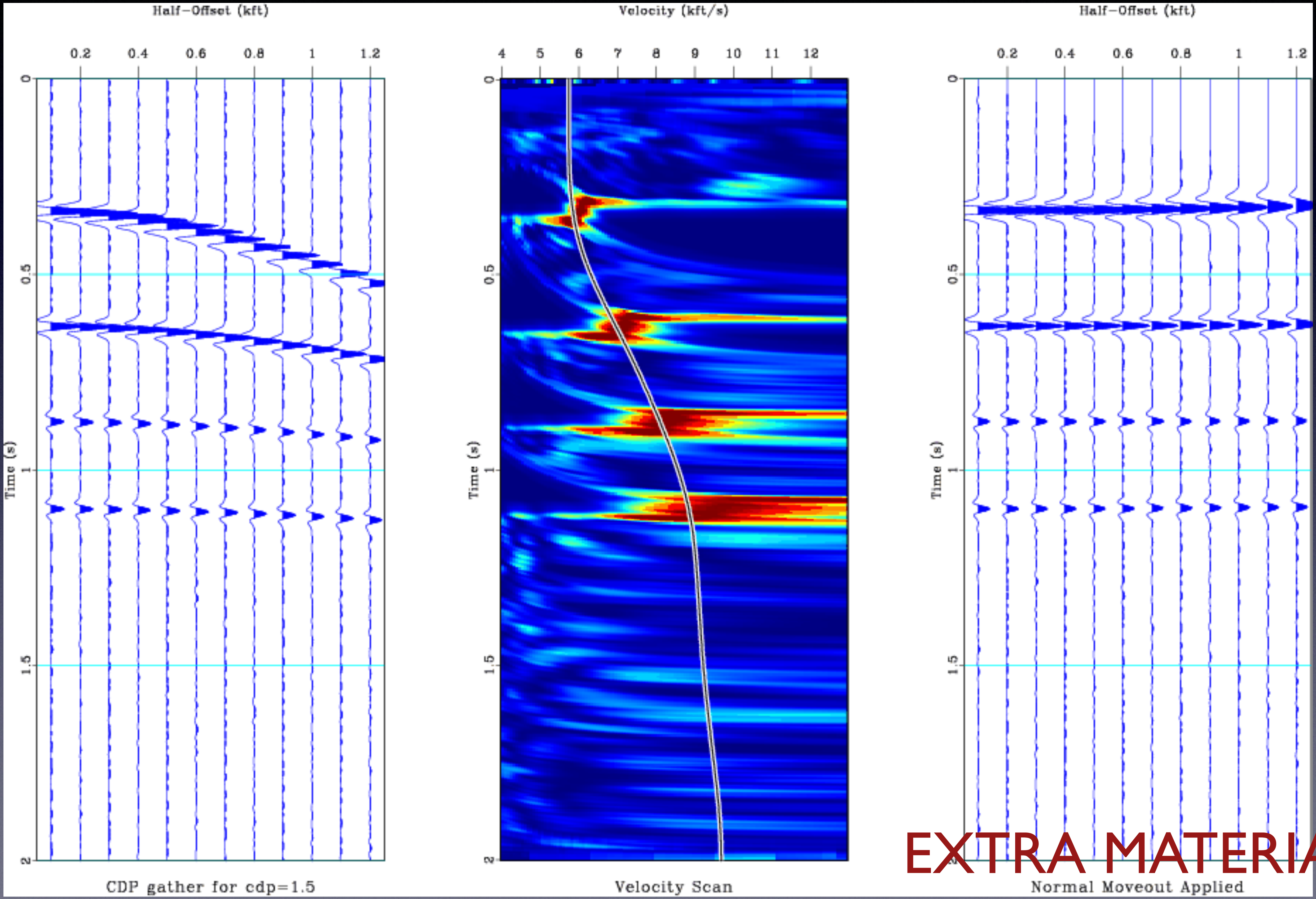


$$\Delta t = x^2 / 2t_0V_1^2$$

EXTRA MATERIAL

Es. Normal Move Out -Velocity analysis

Multi-layers system

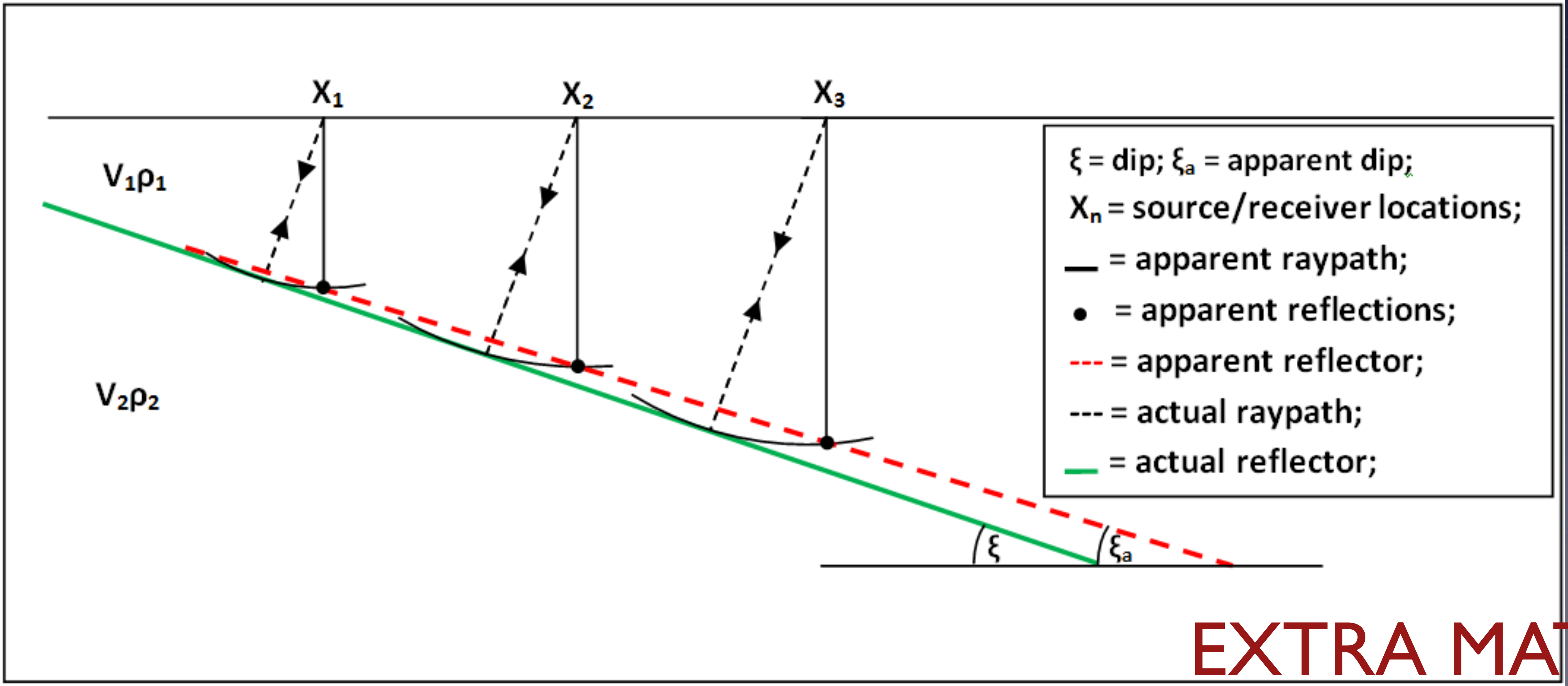


EXTRA MATERIAL

Migration

FROM TIME DOMAIN to SPACE DOMAIN

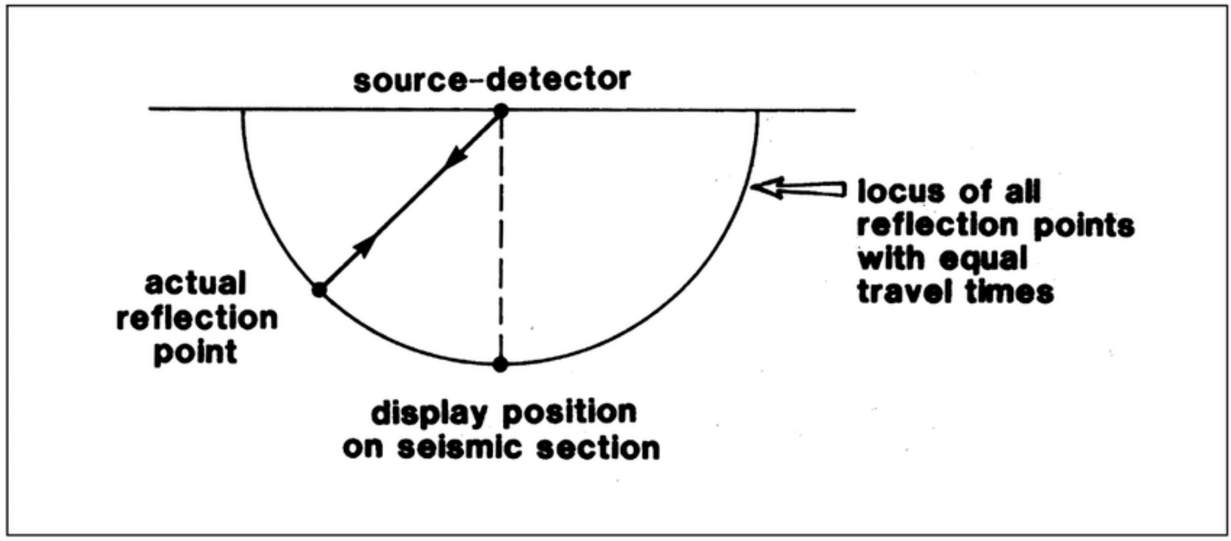
Seismic migration is the process by which seismic events are geometrically re-located in either space or time to the location the event occurred in the subsurface rather than the location that it was recorded at the surface, thereby creating a more accurate image of the subsurface.

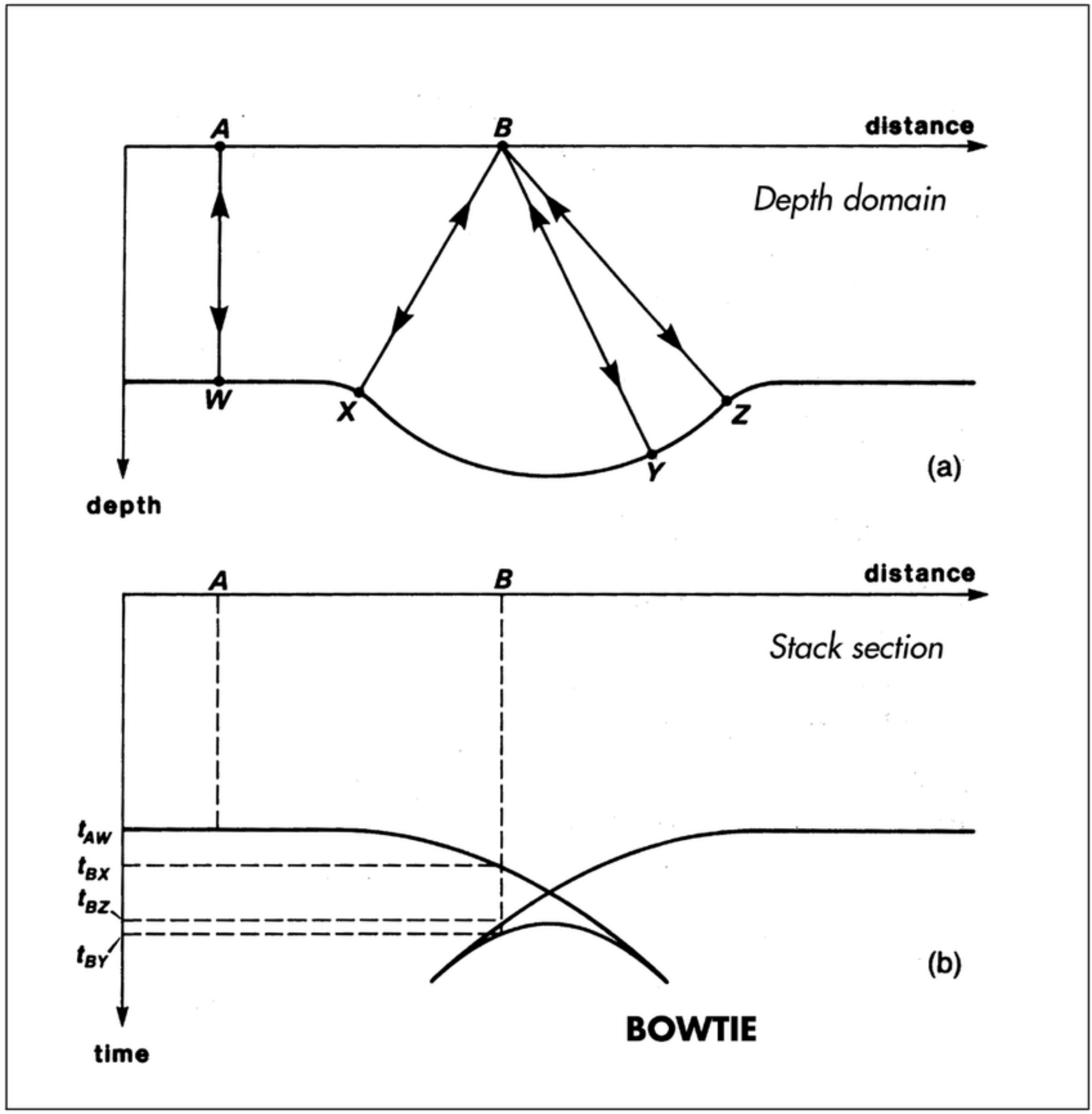


Spheric wavefront

EXTRA MATERIAL

Migration





FROM TIME DOMAIN
to

SPACE DOMAIN

es.

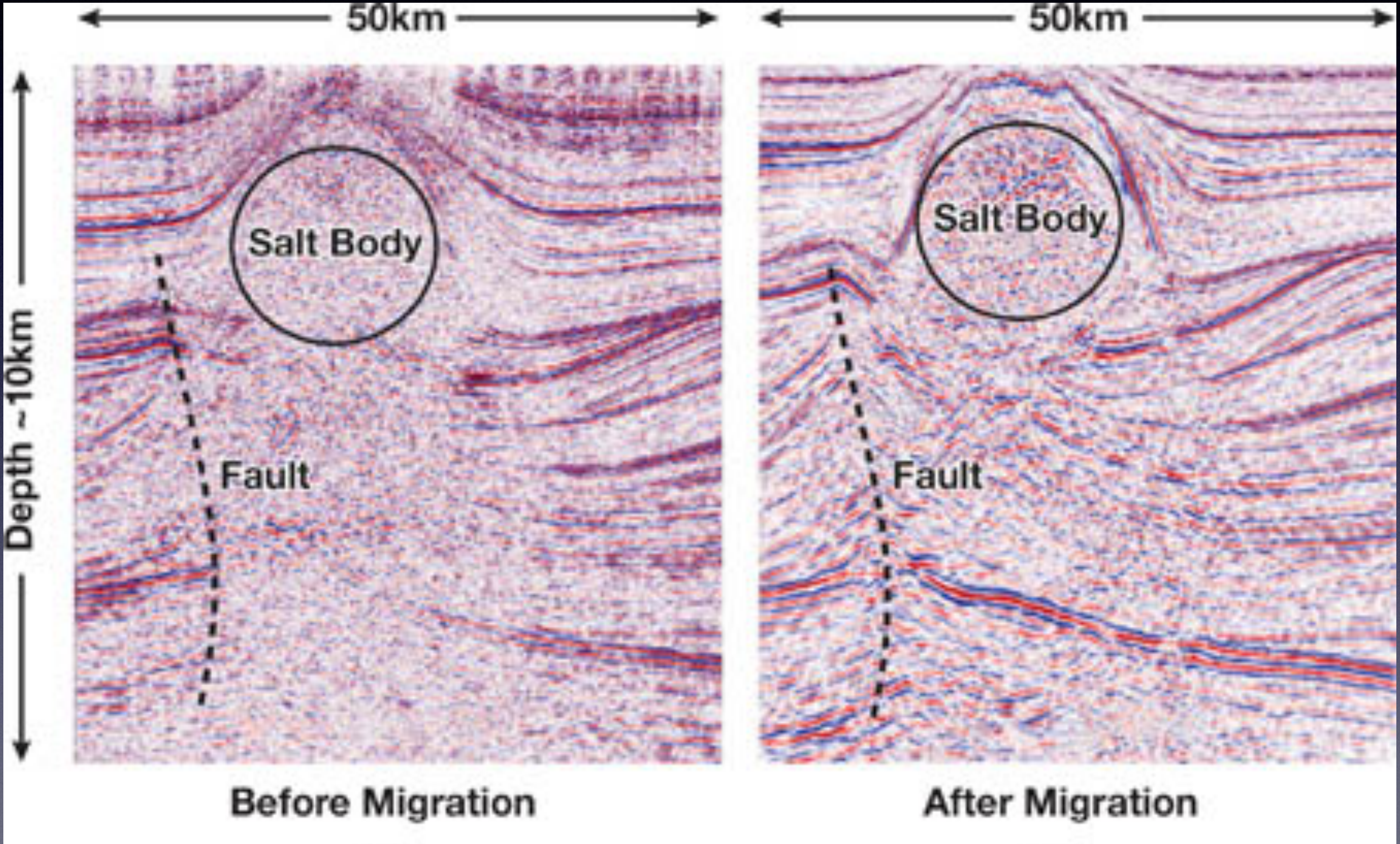
Kirchhoff migration

EXTRA MATERIAL

~30% of the world's CPU time is spent on seismic reflection processing (from stanford.pangea)

Metodi Sismici

Migrazione: Passare da DOMINIO TEMPO a DOMINIO PROFONDITA'
(note le velocità)

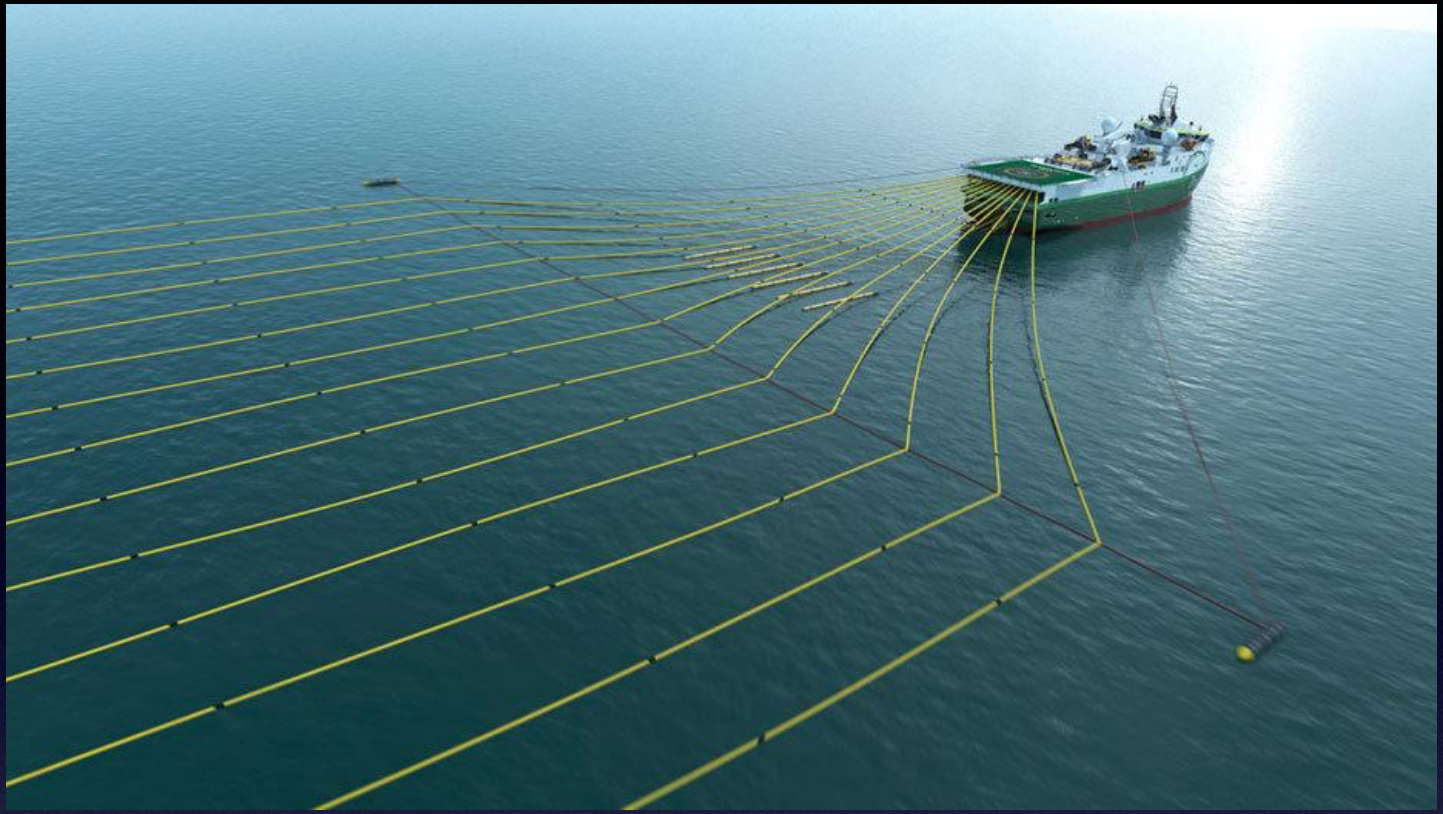


(a)

(b)

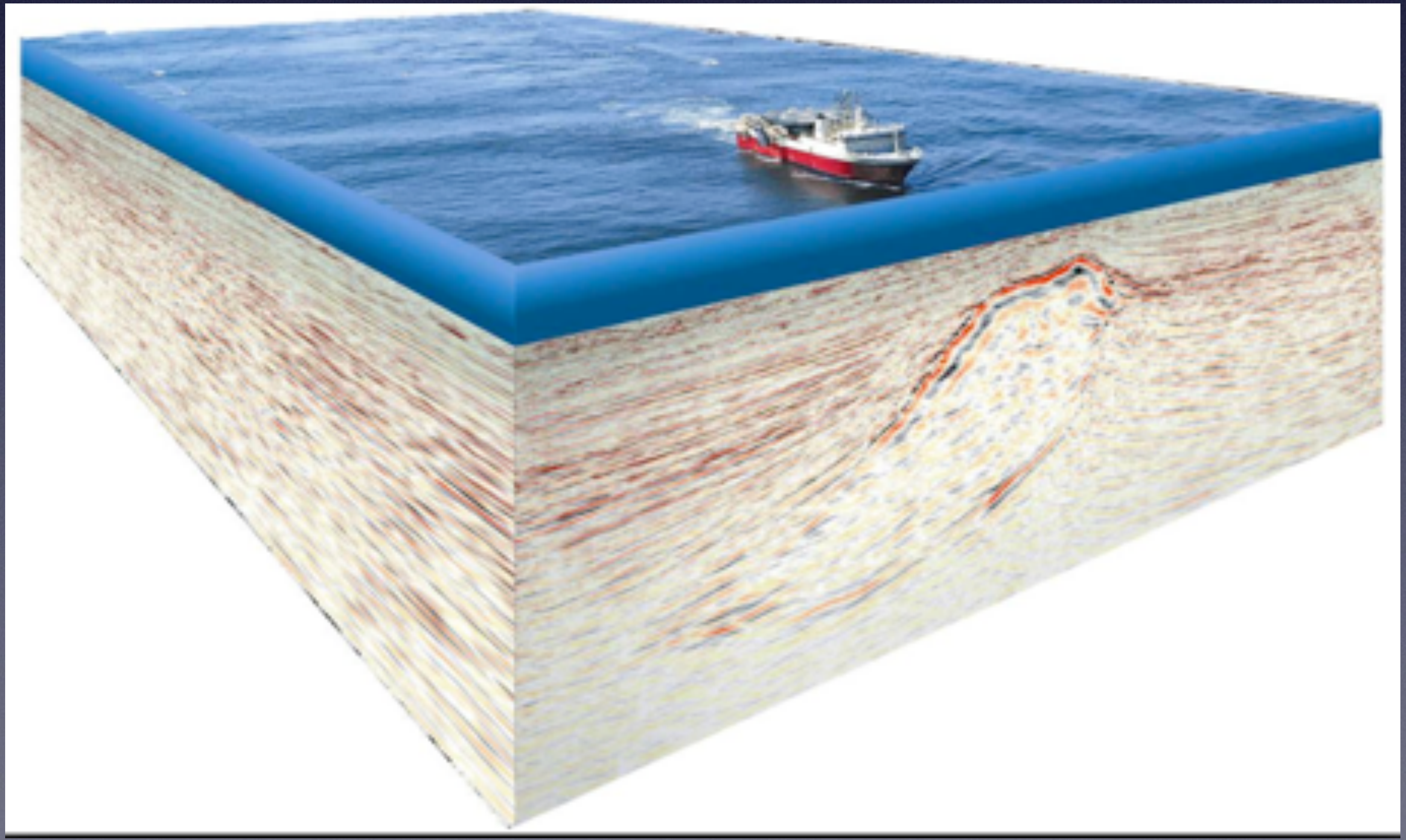
EXTRA MATERIAL

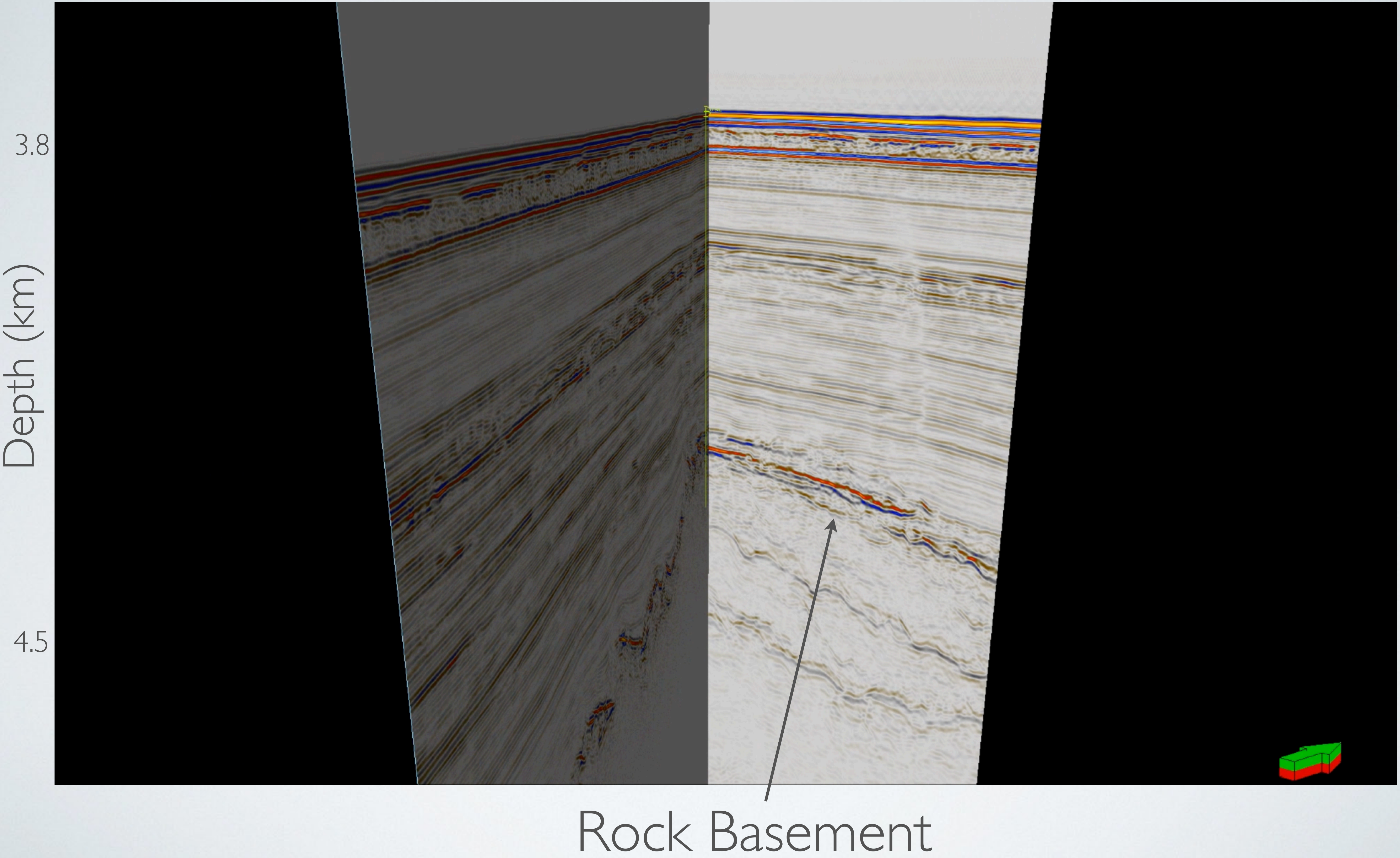
Seismic methods



Reflection seismic

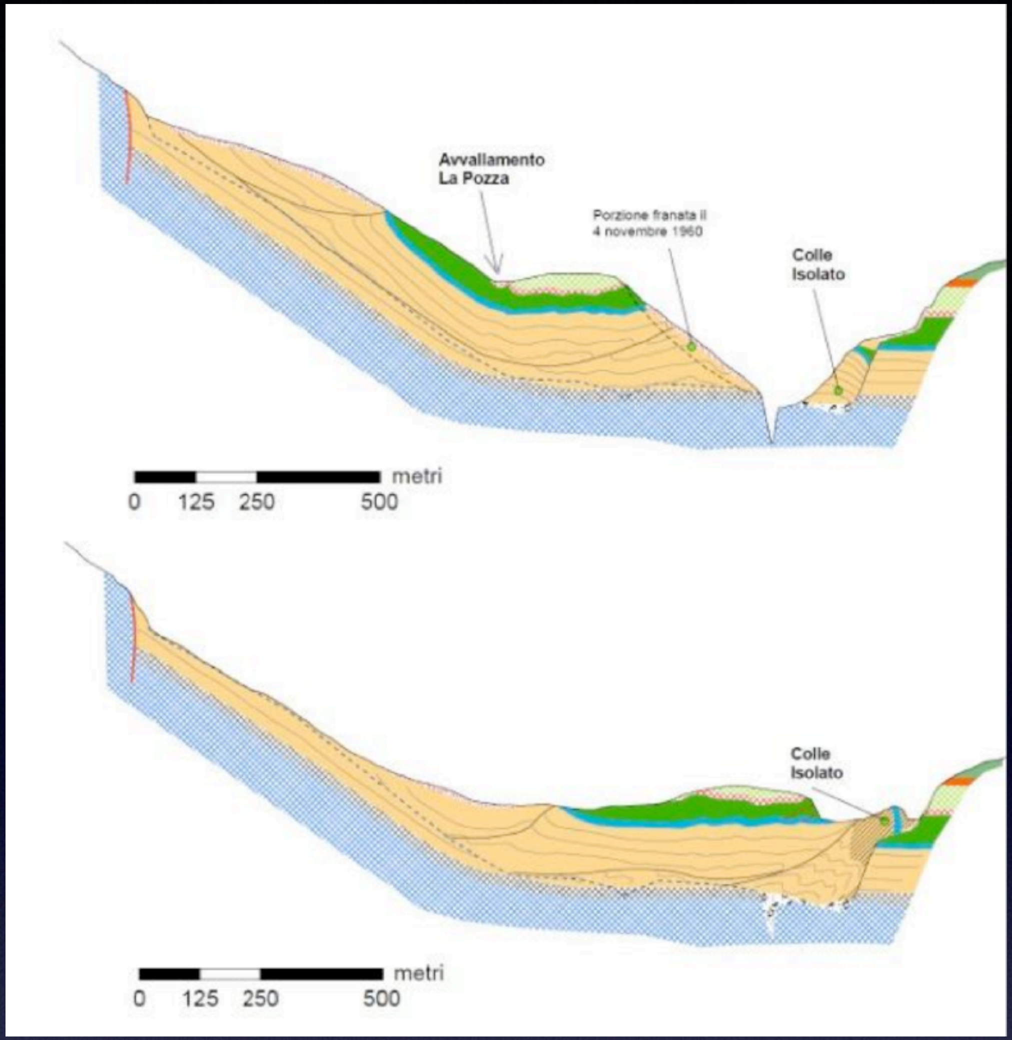
seismic imaging

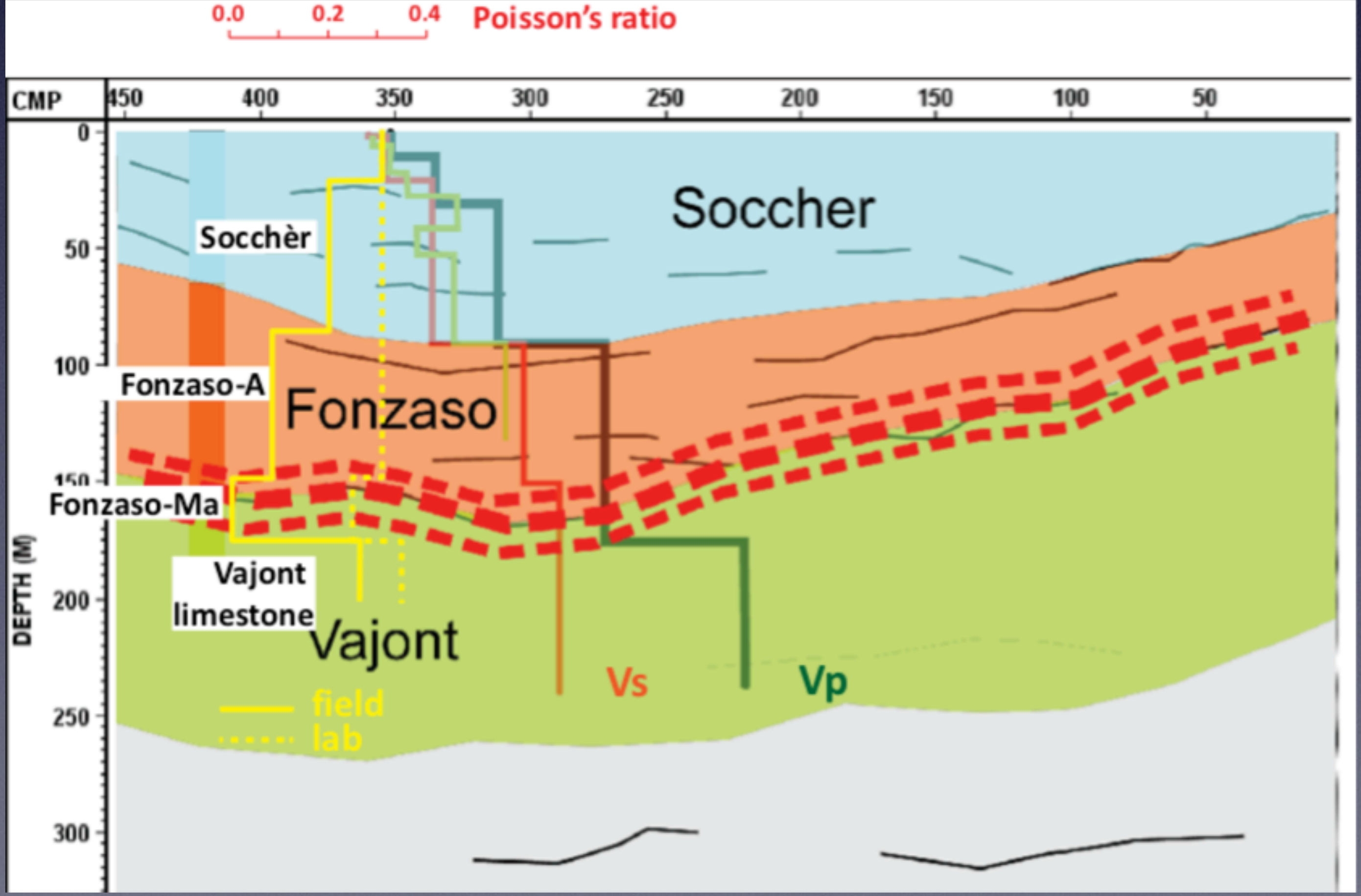


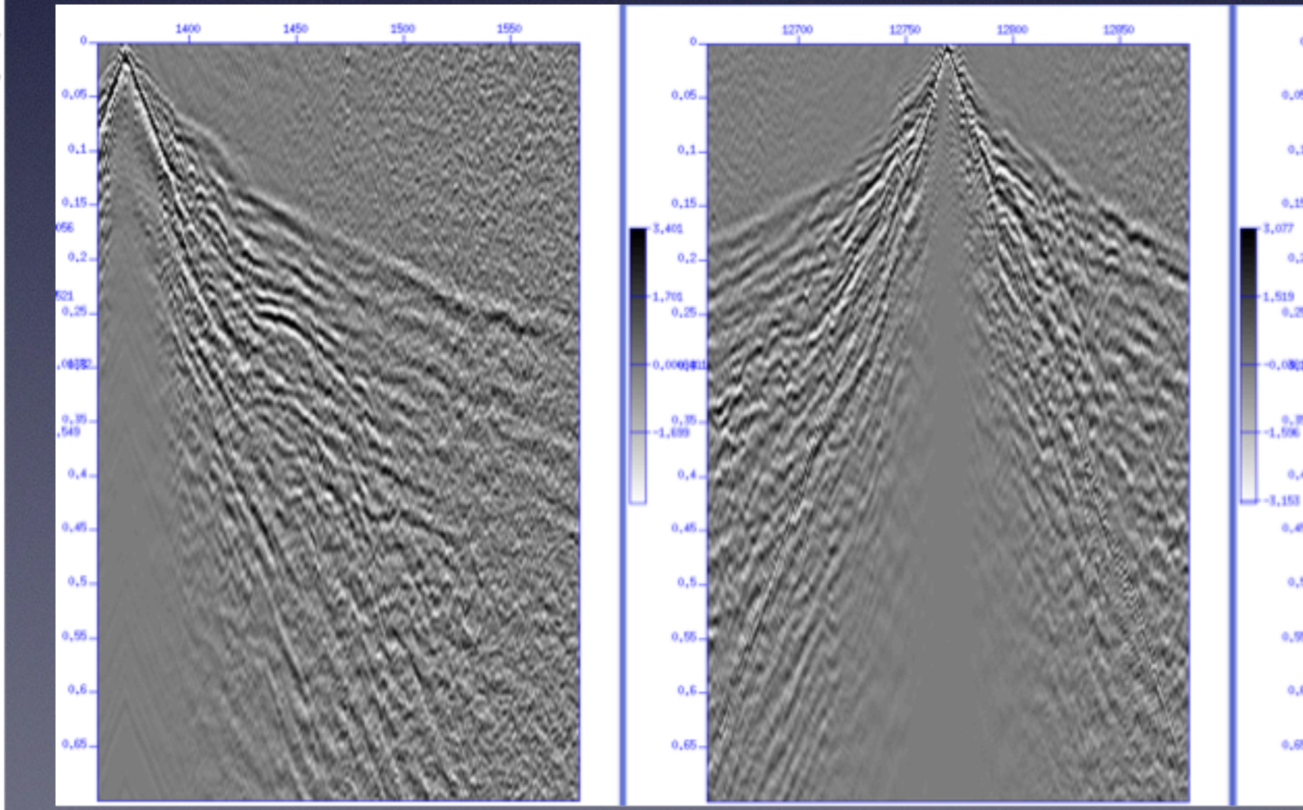

3.8
4.5
Depth (km)
Rock Basement

Example of engineering application

Vajont landslide seismic reflection







Seismic Methods

Reflection seismic

Huge depth exploration ($h \approx L$)

L = length of array
H = Depth investigation

Good resolution ($f(\lambda, S, dx, etc.)$)

Structural information of the subsoil

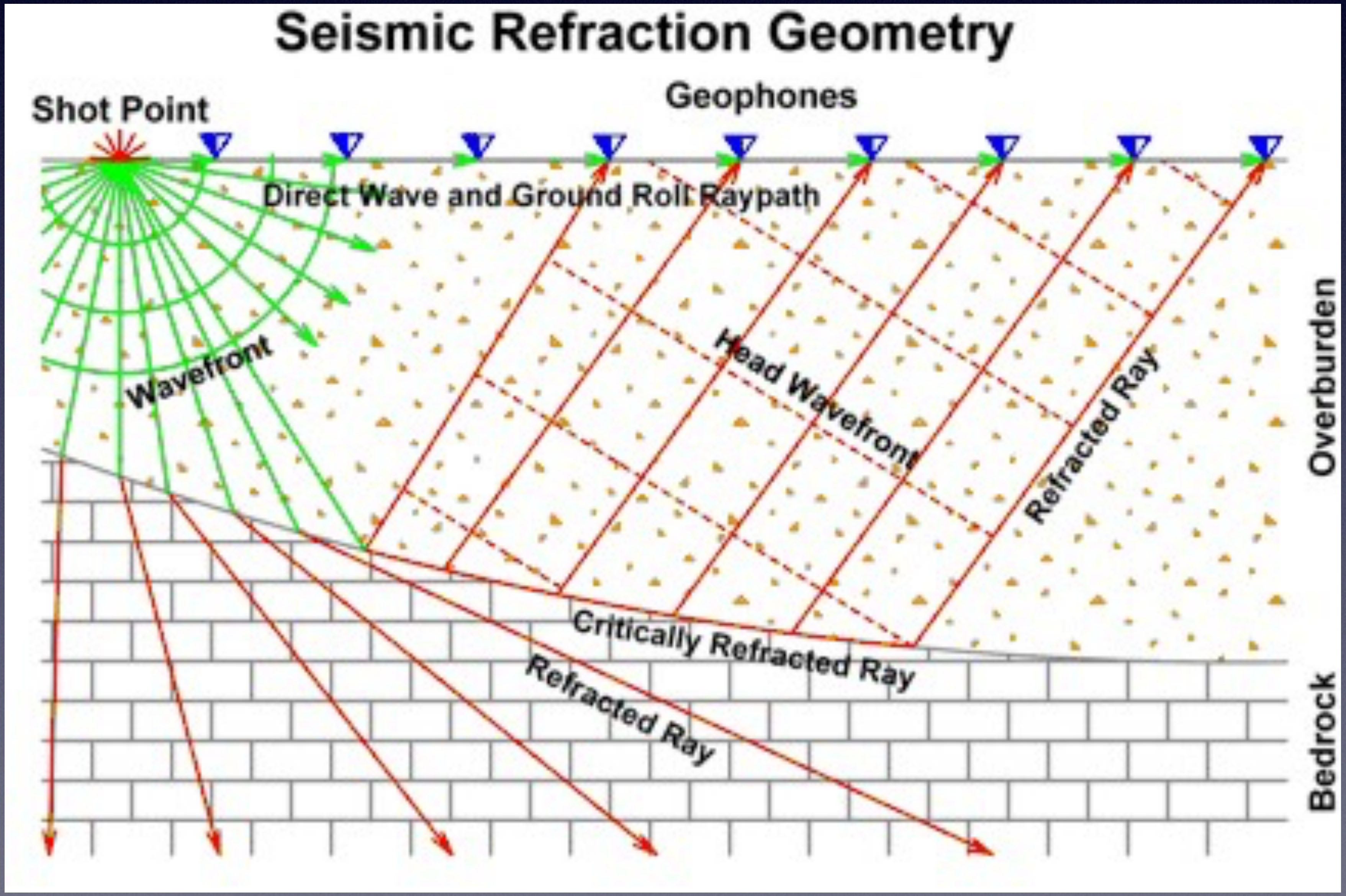
In P or in S waves

Expansive, complex processing

For the engineering purpose, most diffused is the:

REFRACTION seismic

Studying refracted waves to characterise velocity and depth of buried layers

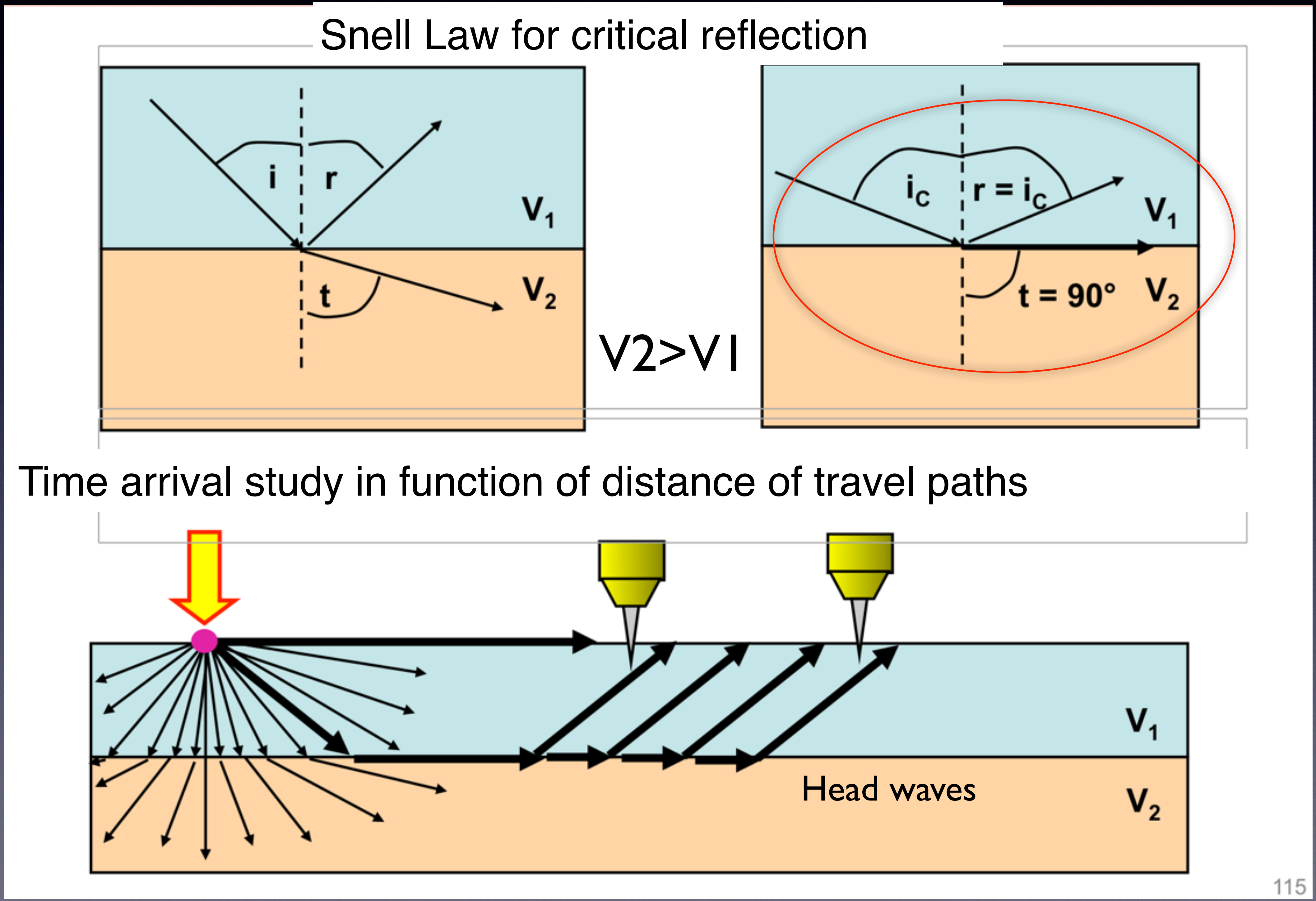


Critically refracted waves

Head-waves

Seismic methods

REFREACTION



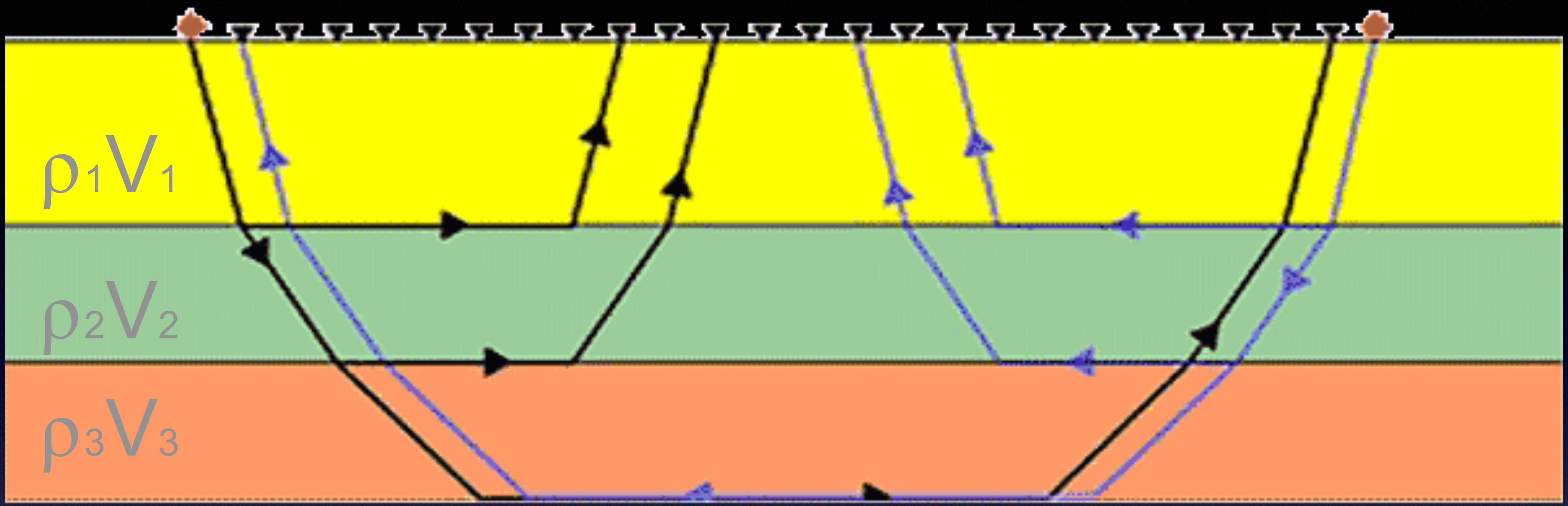
Snell Law for critical reflection

V2>V1

Time arrival study in function of distance of travel paths

115

Refraction Seismic mehtods



Impedance Contrast $= \frac{\rho_2 V_2}{\rho_1 V_1} > 1$ → REFRACTION

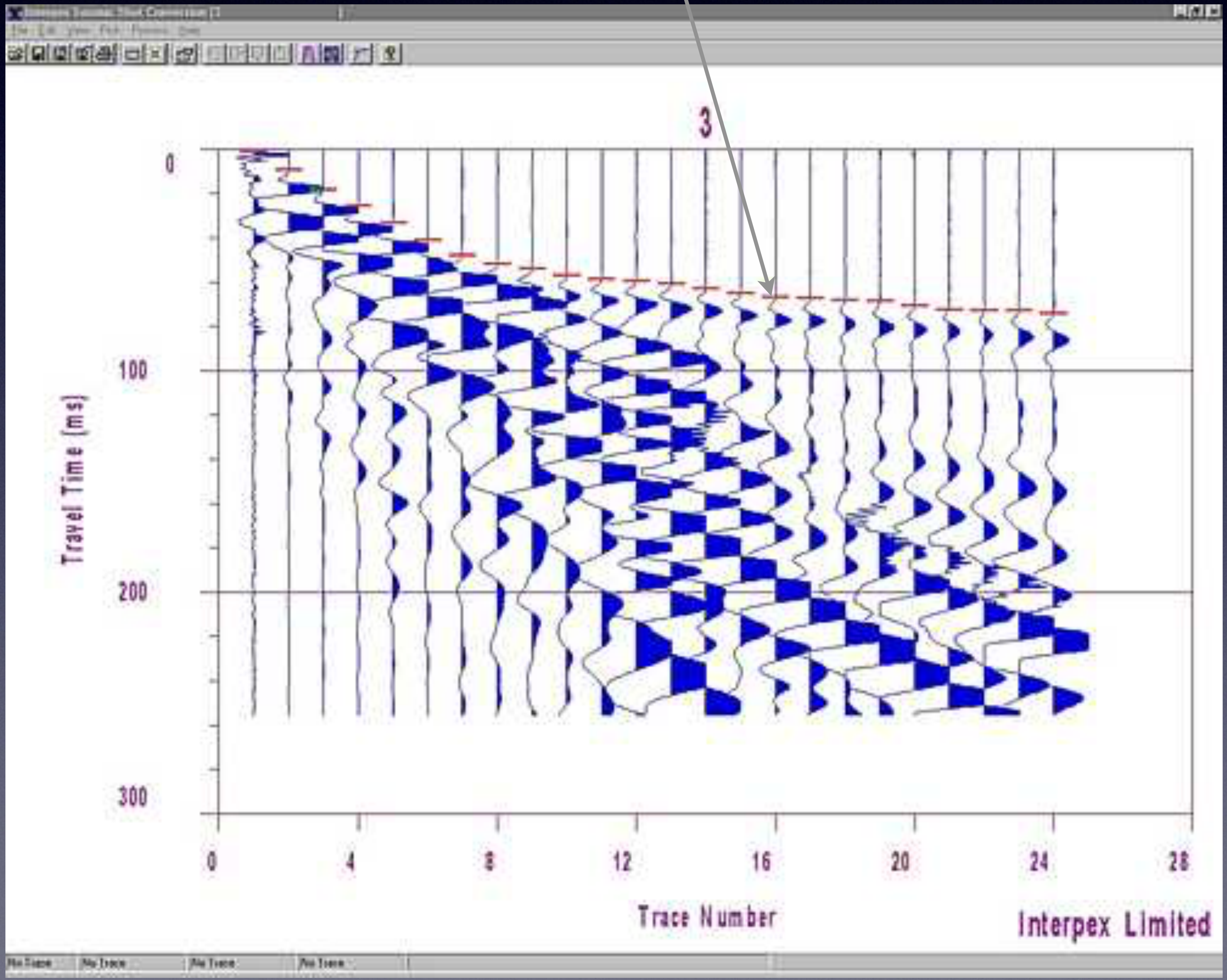
If V2 < V1 NO REFRACTION !

→ Blind to inversion velocity in depth

Refraction seismic

Measuring the time arrival of the generated seismic waves….

first break Picking



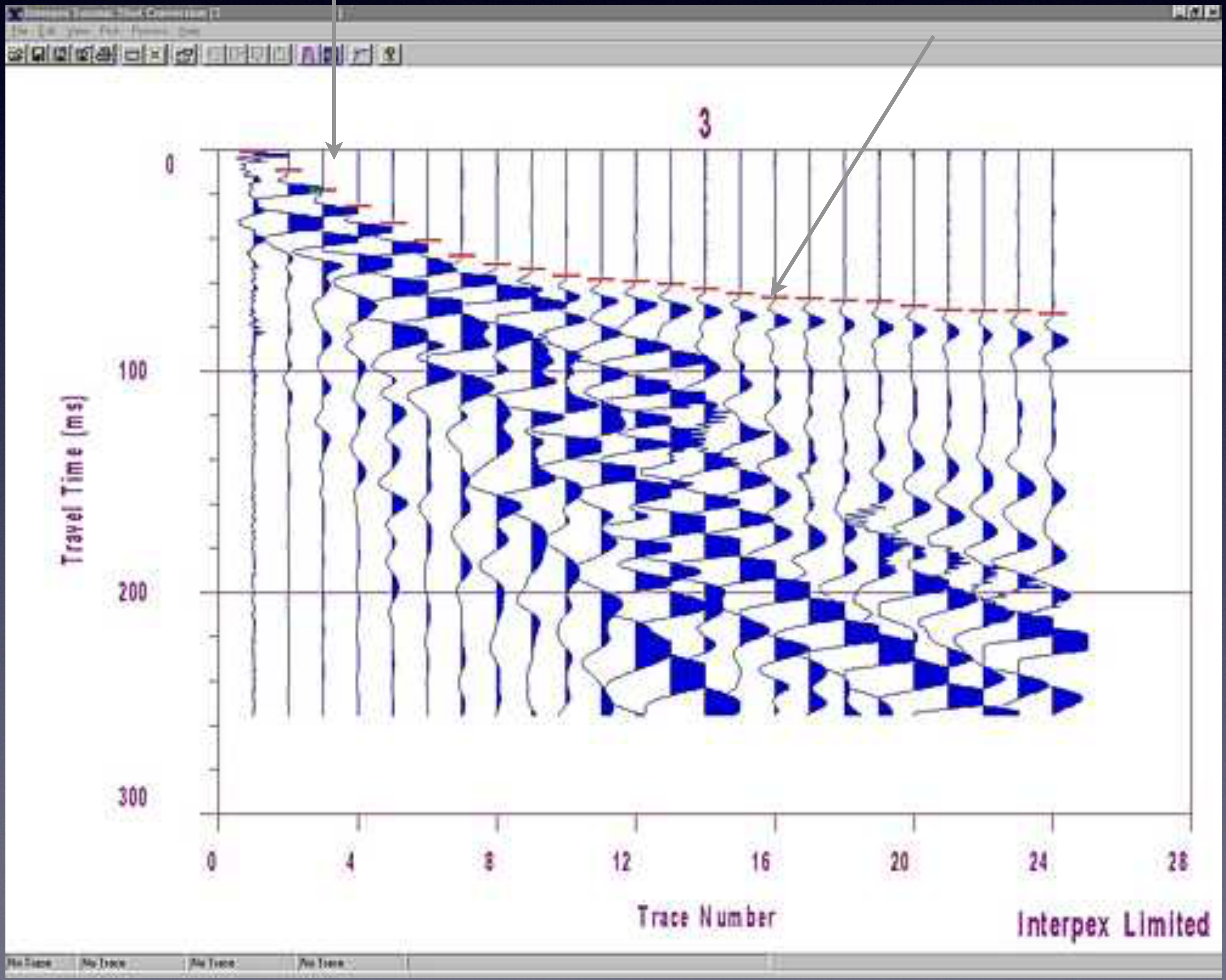
Refraction seismic

Measuring the time arrival of the generated seismic waves….

first break Picking

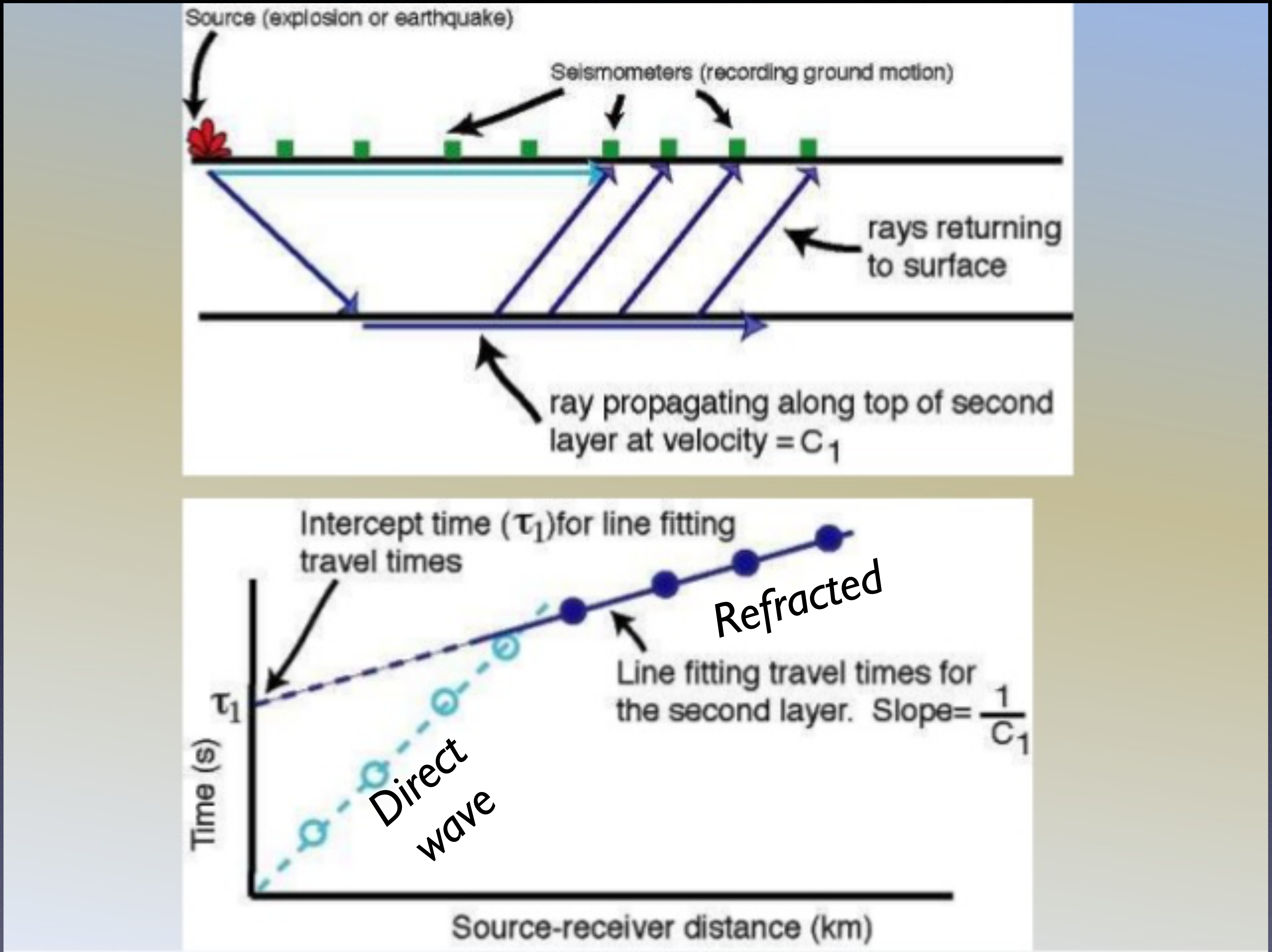
Direct wave (slow)

Refracted wave (fast)



2 straight lines are identified (In the case of 2 layers)

REFRACTION



Measuring time arrival

Direct and refracted Waves

Slope of the dromocrhone = $\frac{1}{V}$

Straight line ➡ ax+by+c=0

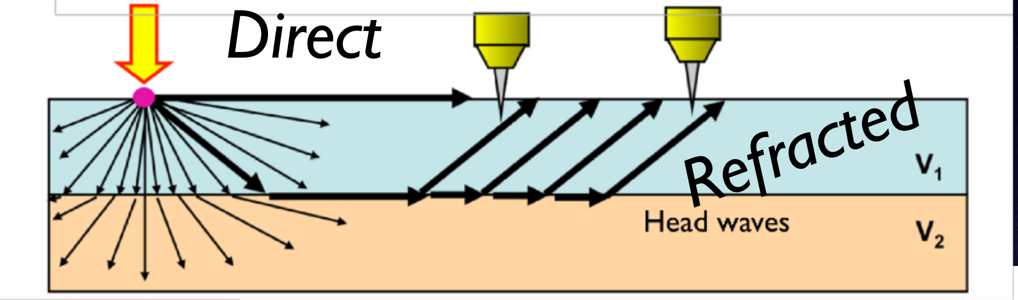
y= mx +q

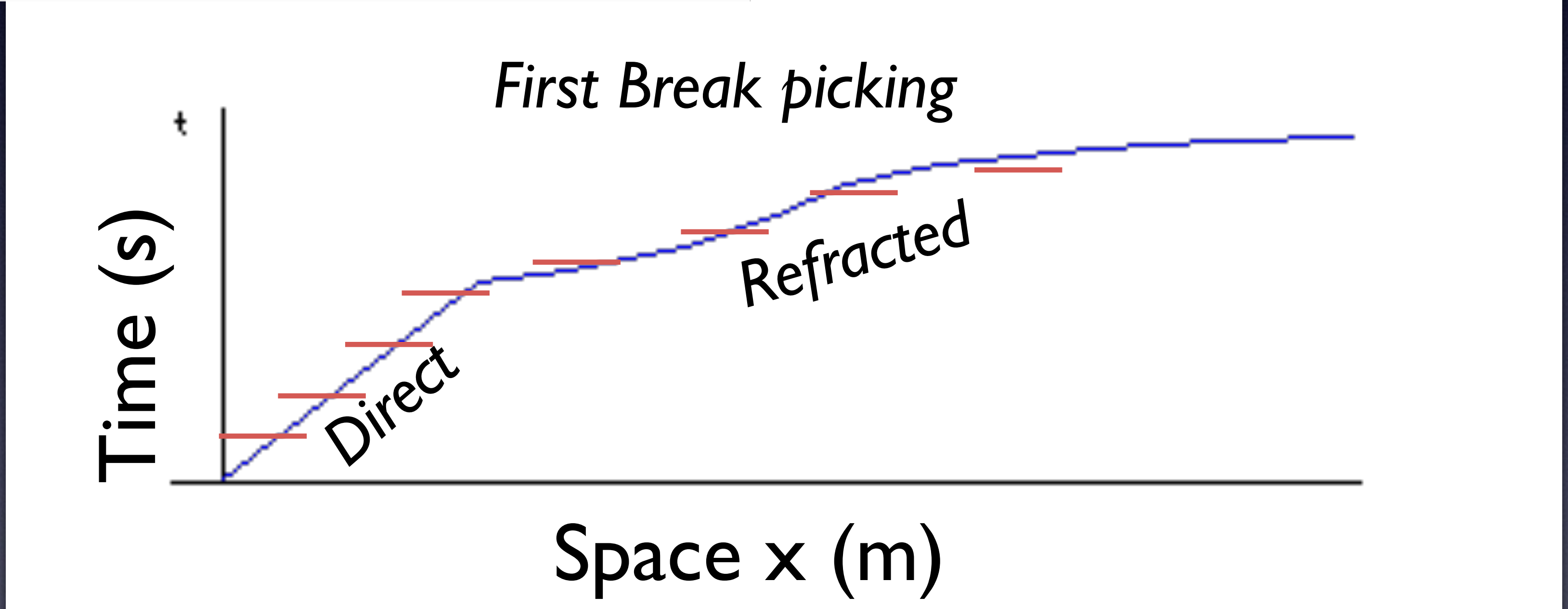
m = *angular coef. (Slope)* = $-\frac{a}{b}$

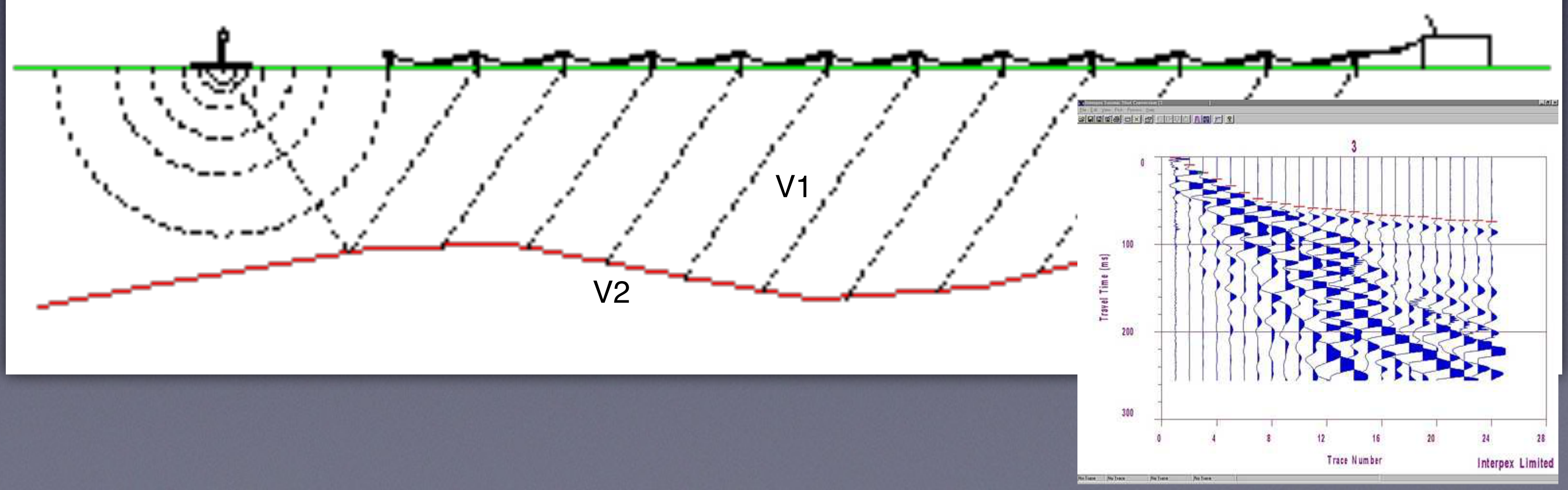
Refraction Seismic

Time arrivals first break Picking

In a space-time diagram (dromochrone)

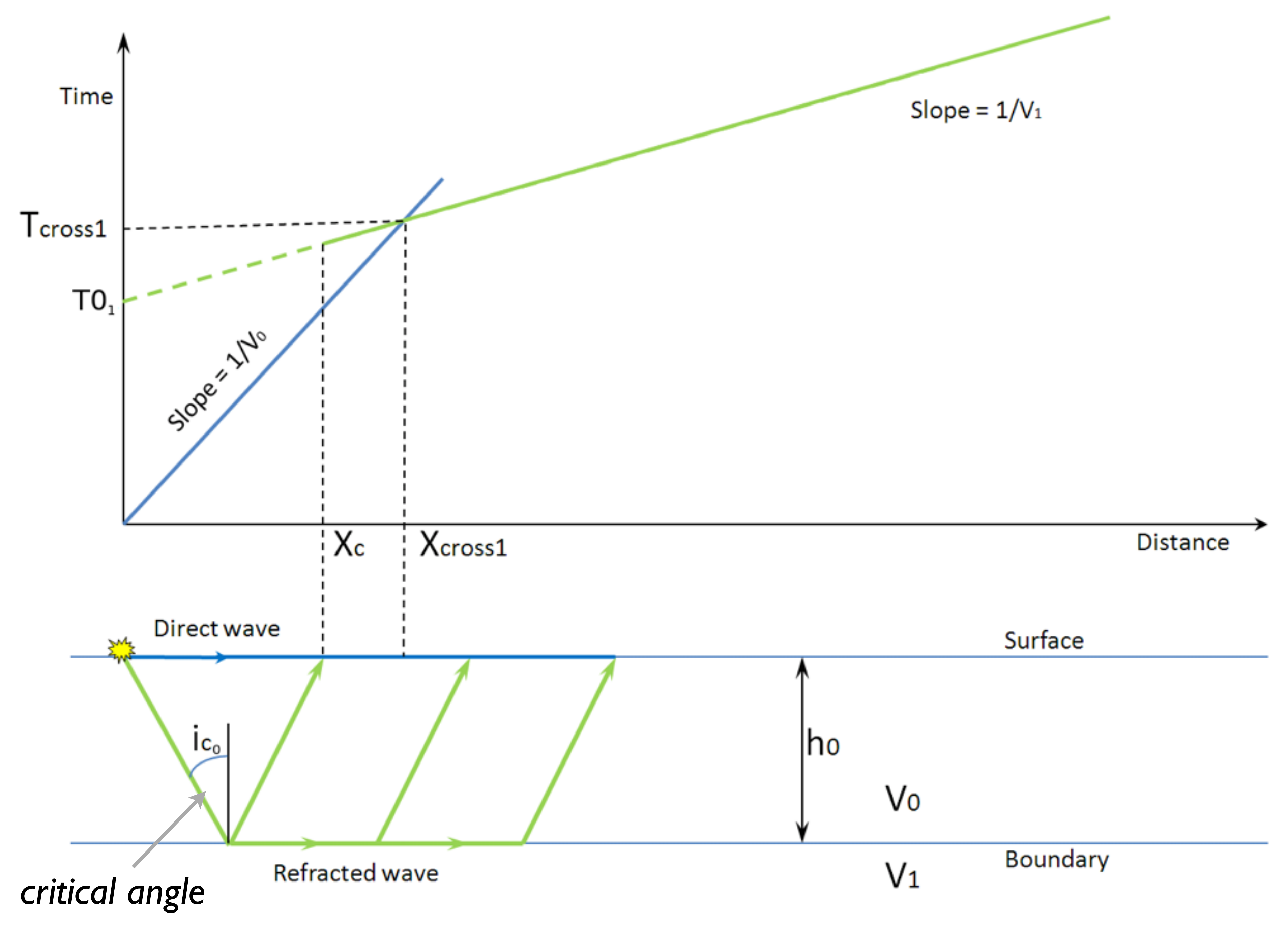






Dromochrone =
Travel-Time curves

REFRACTION SEISMIC

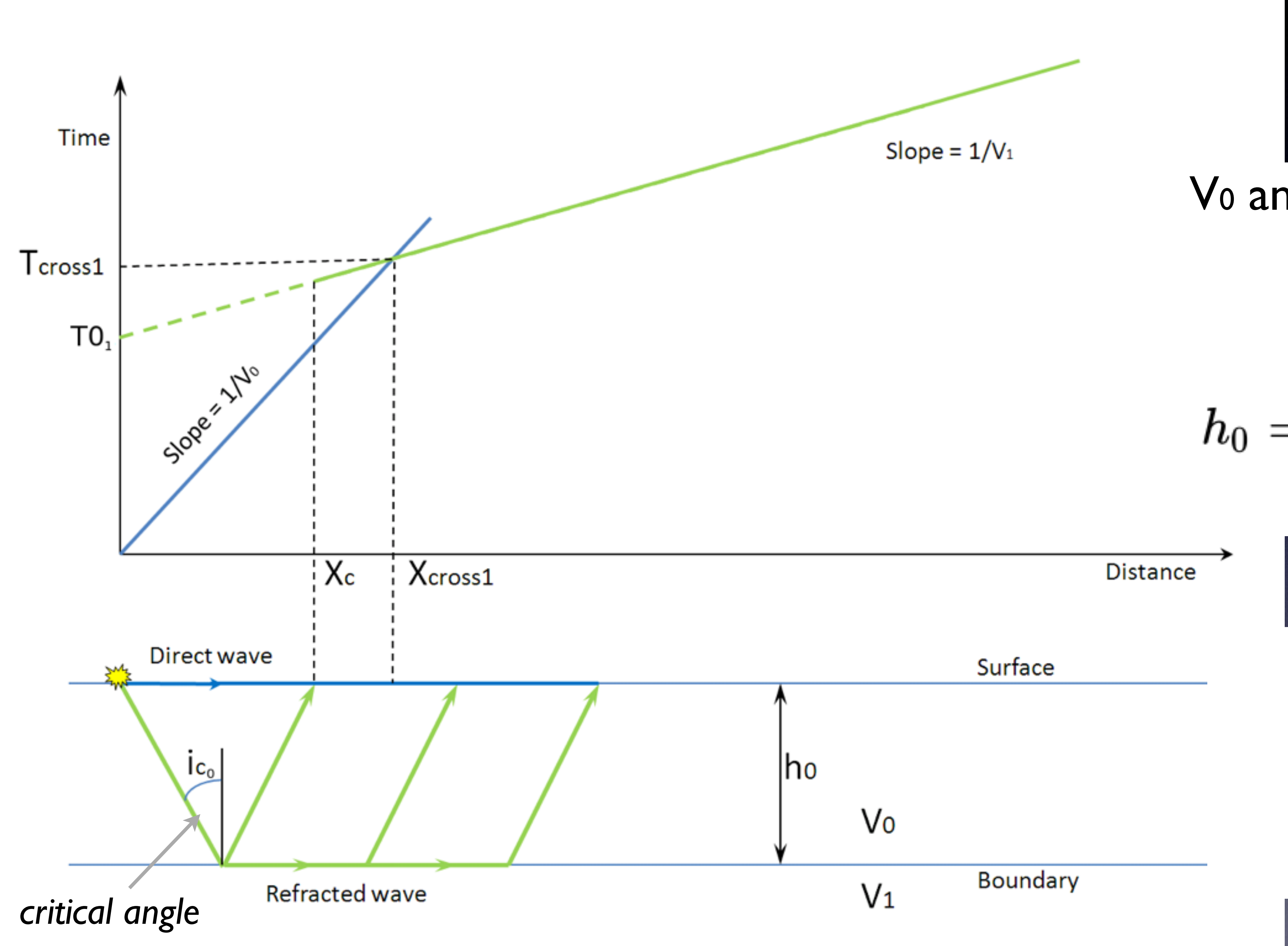


1) Slope of the dromochrone

2) Xcross Crossover point distance

3) T_0 Intercept time

REFRACTION SEISMIC



V_0 and V_1 from the slope

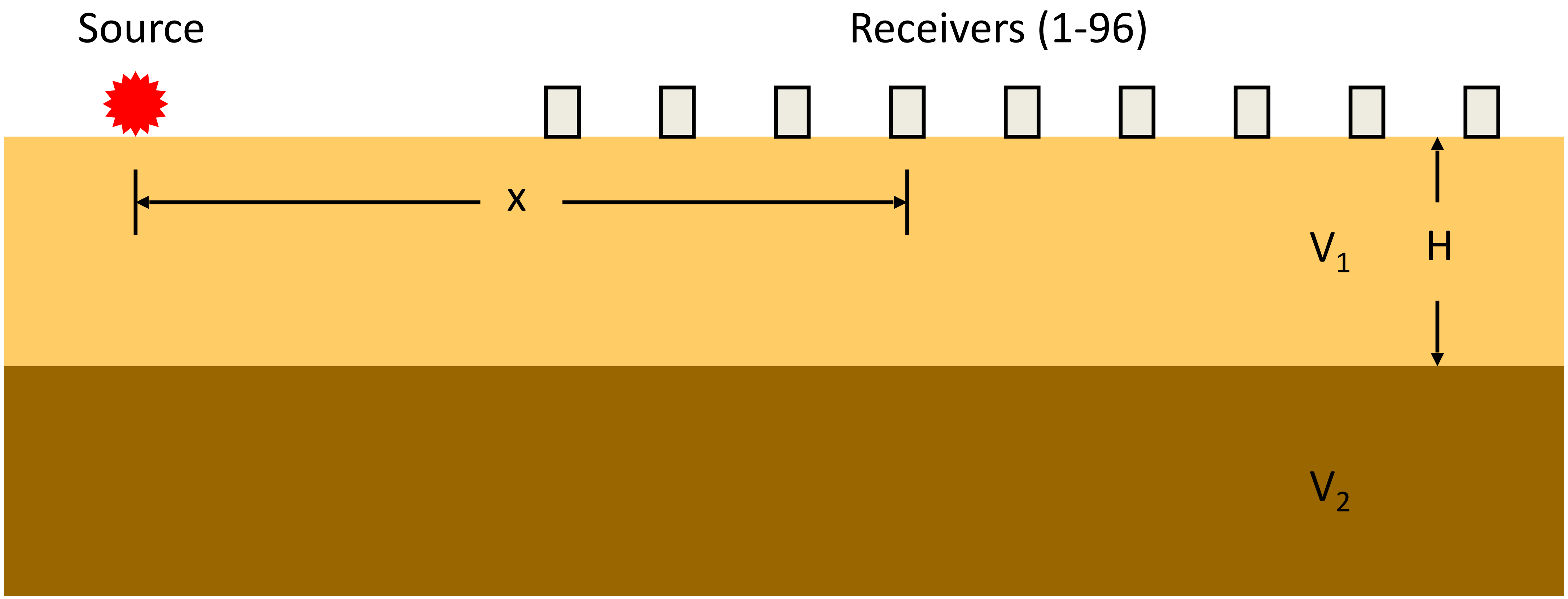
$$h_0 = \frac{X_{cross_1}}{2}\sqrt{\frac{V_1 - V_0}{V_1 + V_0}}$$

$$h_0 = \frac{1}{2} T_0 \frac{v_1 v_2}{\sqrt{v_2^2 - v_1^2}}$$

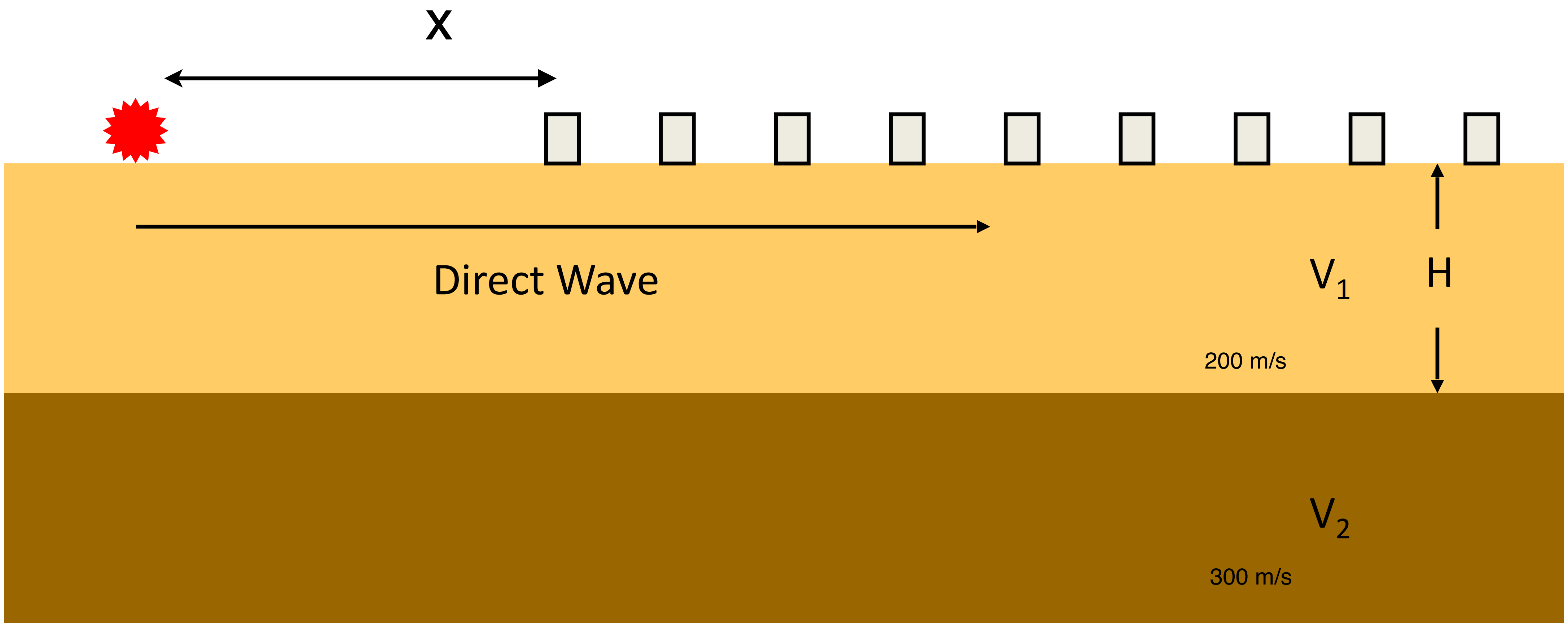
T0 intercept time

Velocity and thickness of the layers !

Acquisition



Seismic Refraction

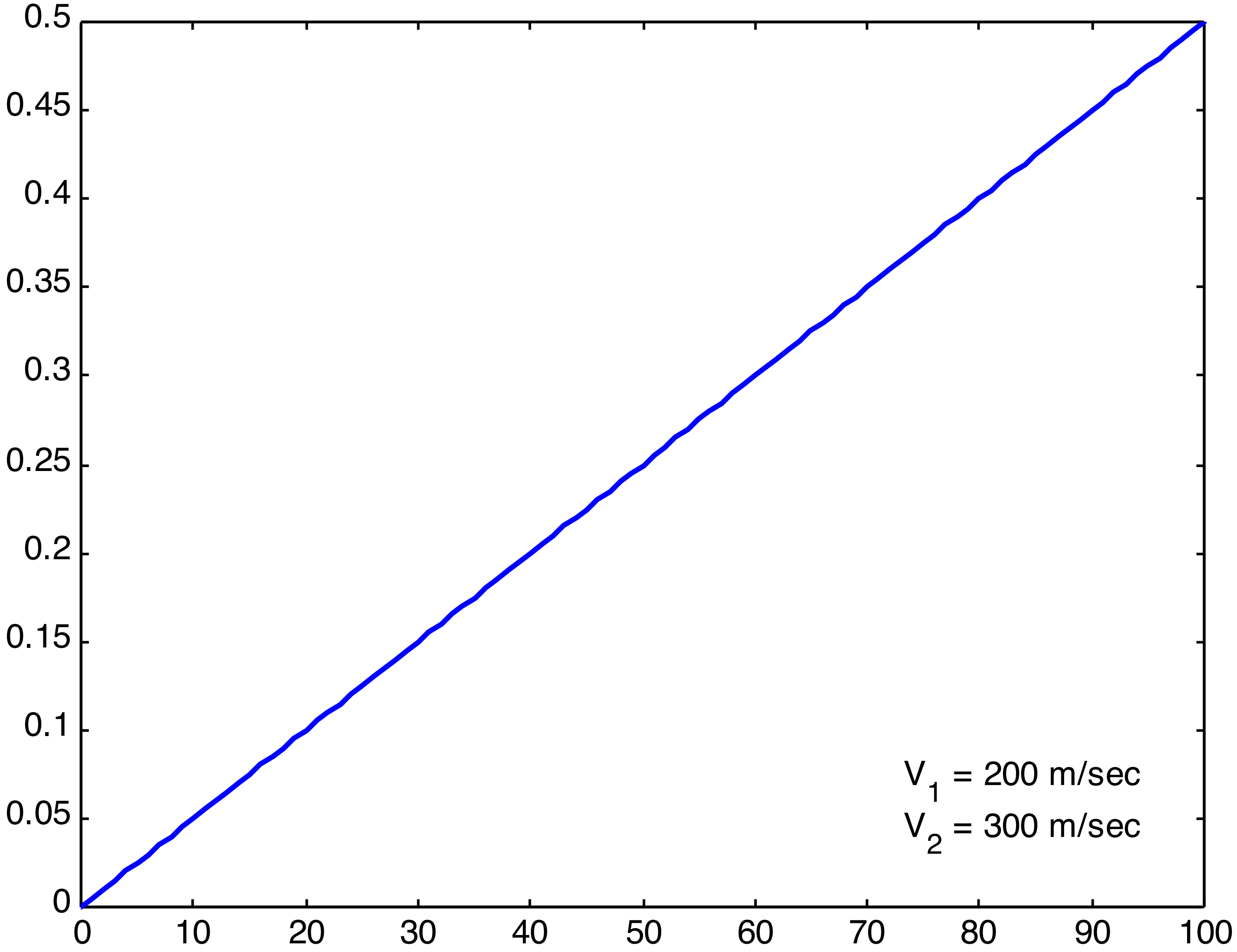


$$t_{direct} = \frac{x}{V_1}$$

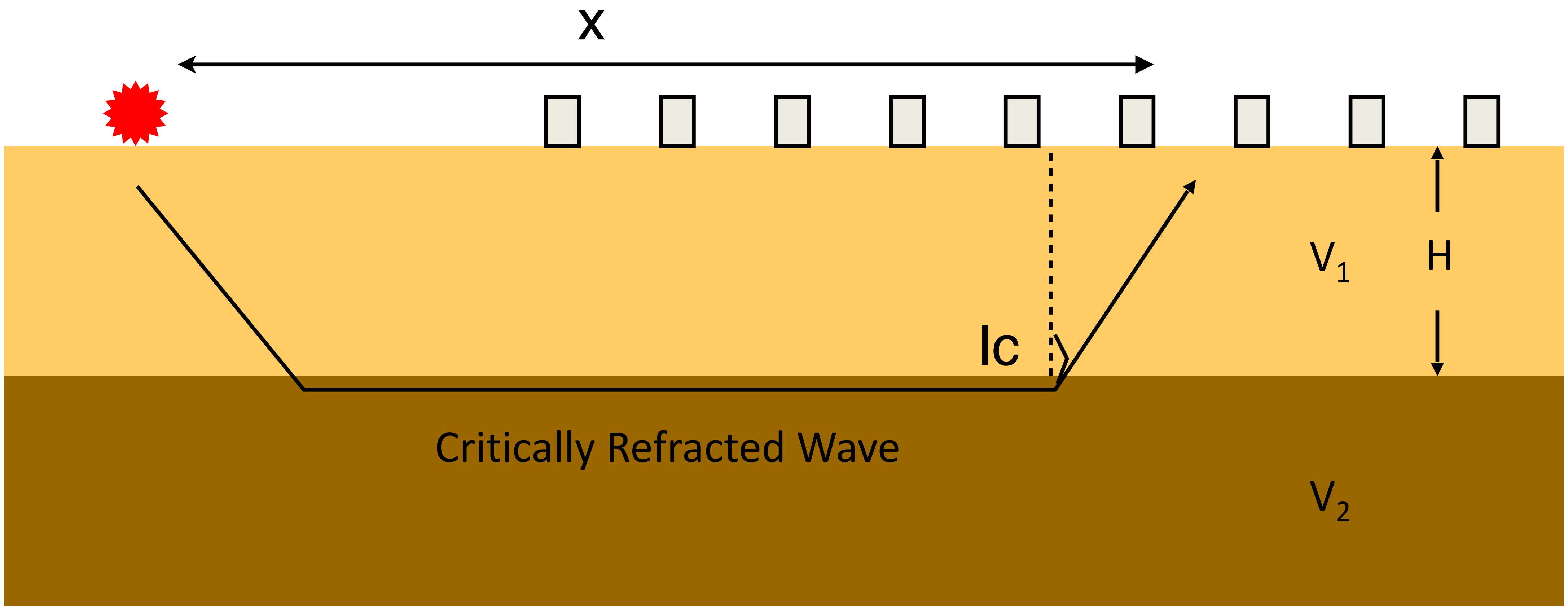
DIPARTIMENTO DI GEOSCIENZE

Seismic Refraction

$$t_{direct} = \frac{x}{V_1}$$



Seismic Refraction



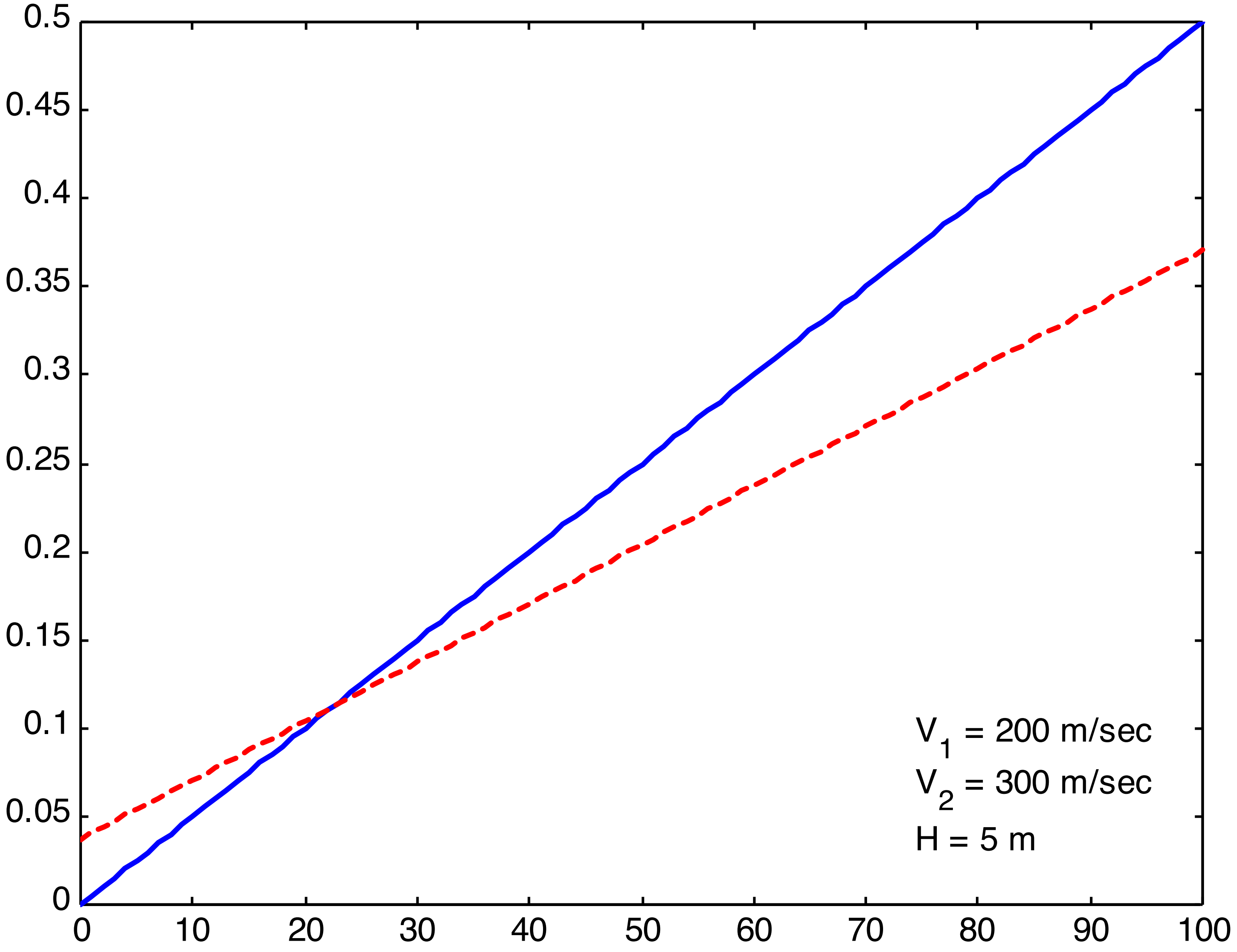
$$t_{refract} = \frac{2H}{V_1 \cos i_c} + \frac{x - 2H \tan i_c}{V_2}$$

$$= \frac{x}{V_2} + 2H\sqrt{\frac{1}{V_1^2} - \frac{1}{V_2^2}}$$

Seismic Refraction

$$t_{refract} = \frac{2H}{V_1 \cos i_c} + \frac{x - 2H \tan i_c}{V_2}$$

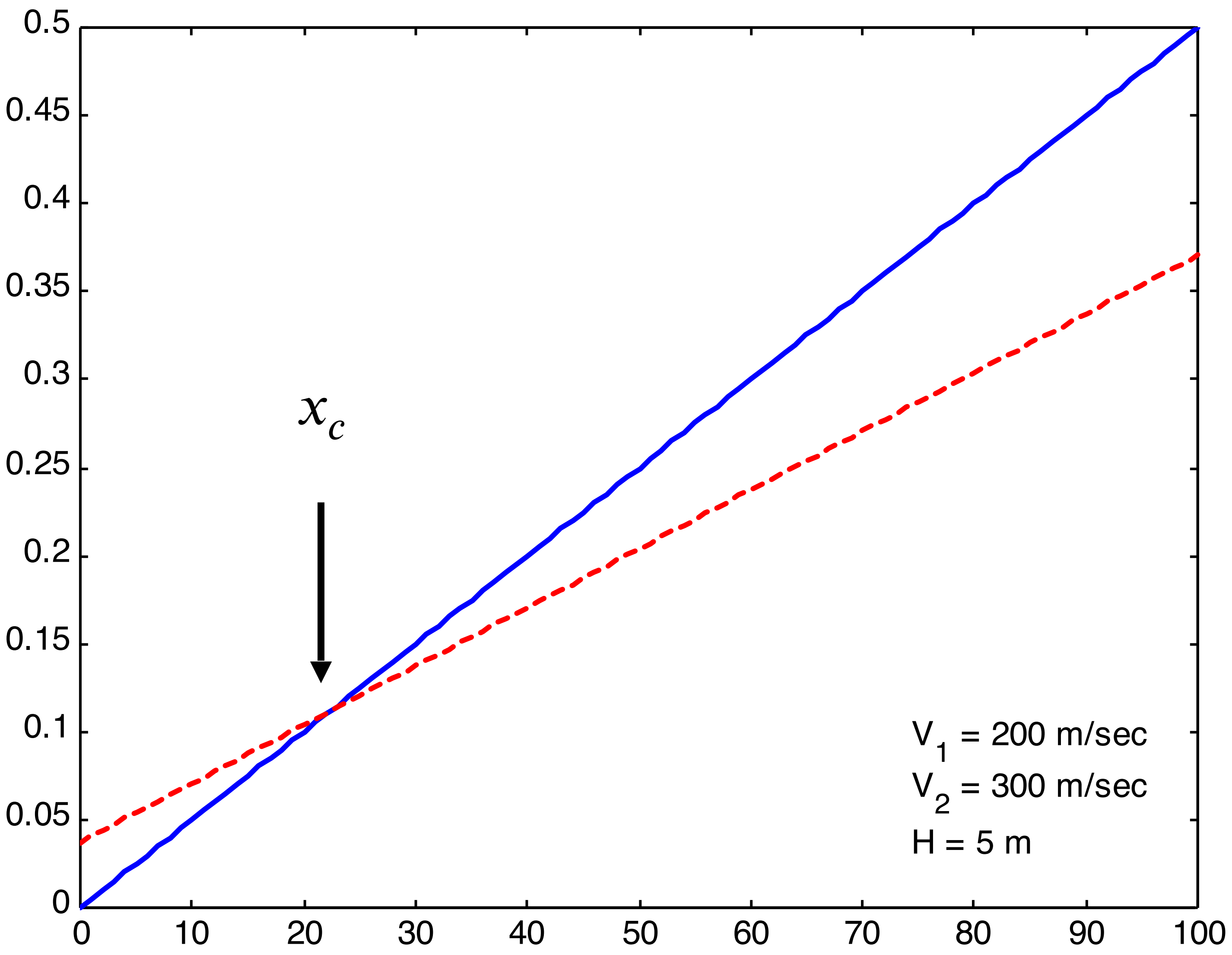
$$= \frac{x}{V_2} + 2H\sqrt{\frac{1}{V_1^2} - \frac{1}{V_2^2}}$$



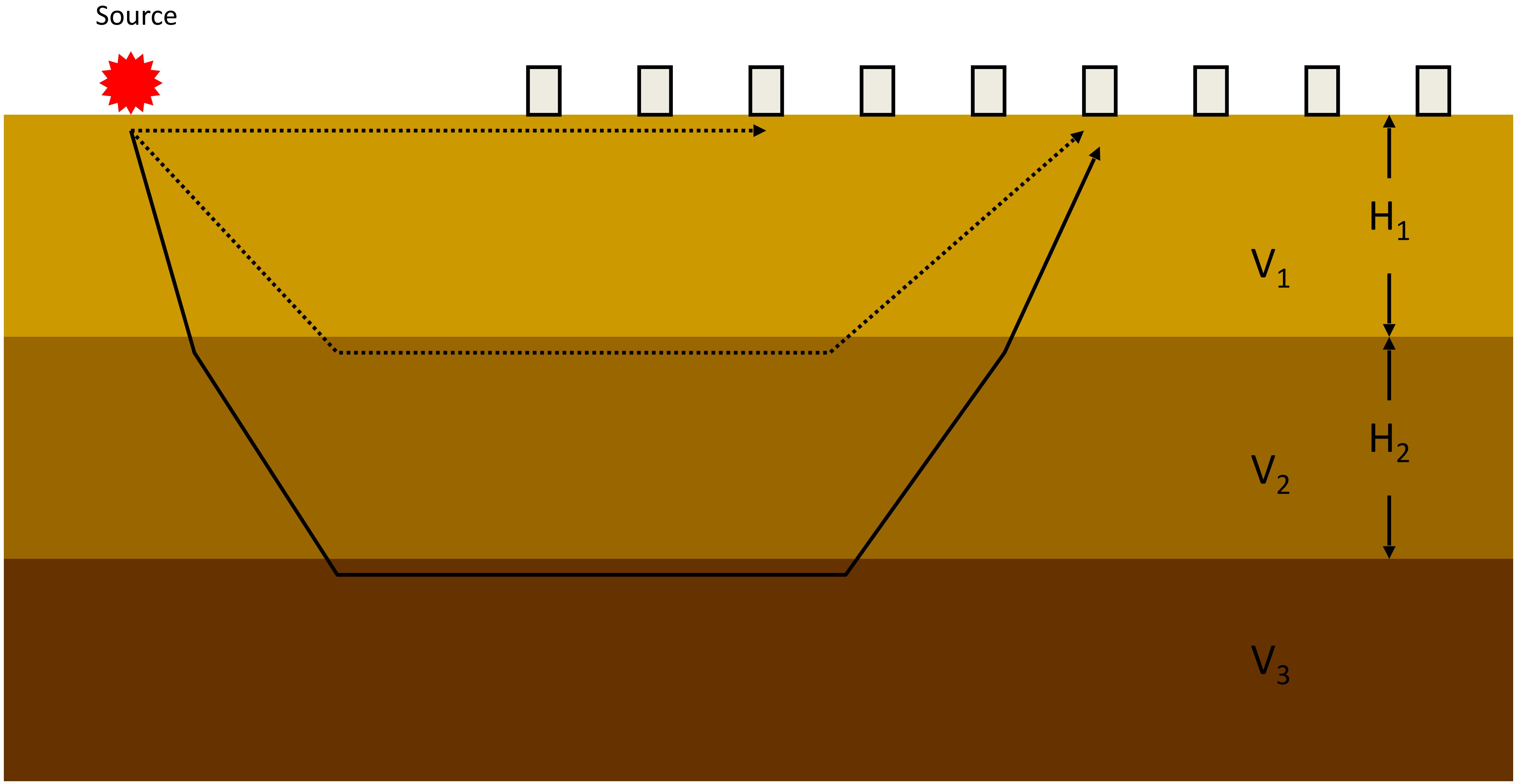
Seismic Refraction

$$x_c = 2H\sqrt{\frac{V_2 + V_1}{V_2 - V_1}}$$

$$H = \frac{x_c}{2}\sqrt{\frac{V_2 - V_1}{V_2 + V_1}}$$

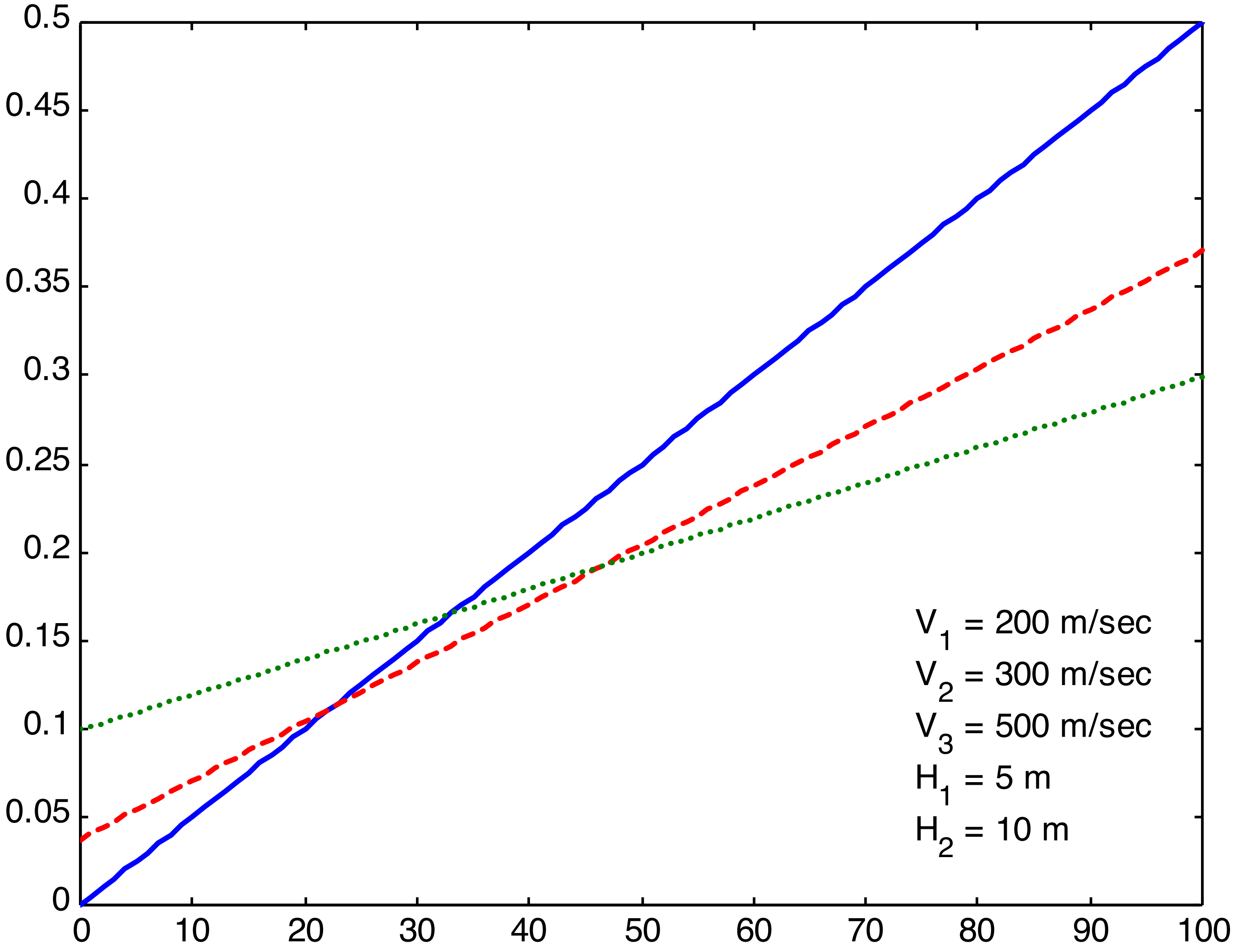


Seismic Refraction



DIPARTIMENTO
DI GEOSCIENZE

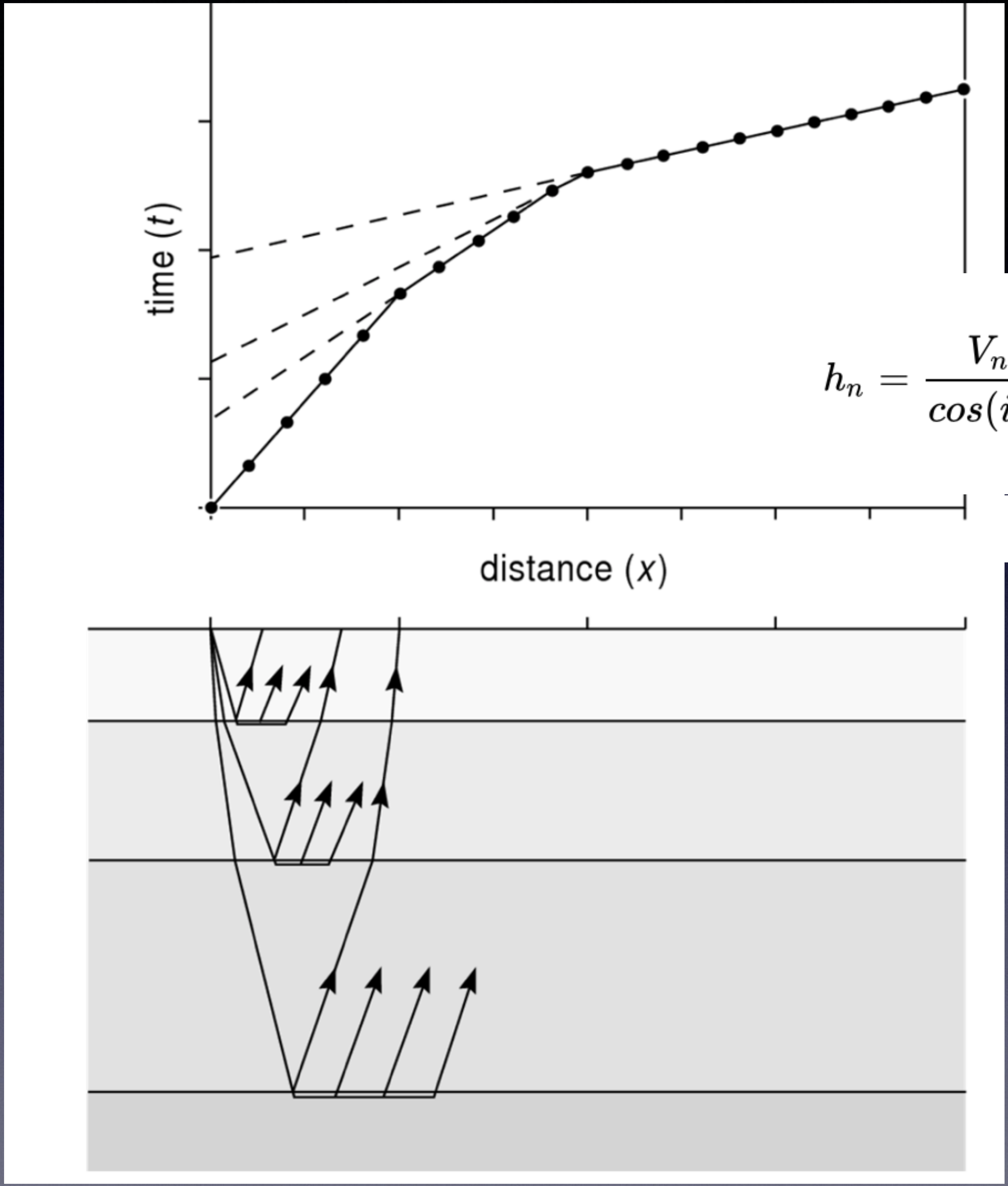
Seismic Refraction



DIPARTIMENTO
DI GEOSCIENZE

REFRACTION SEISMIC

Multiple Layers



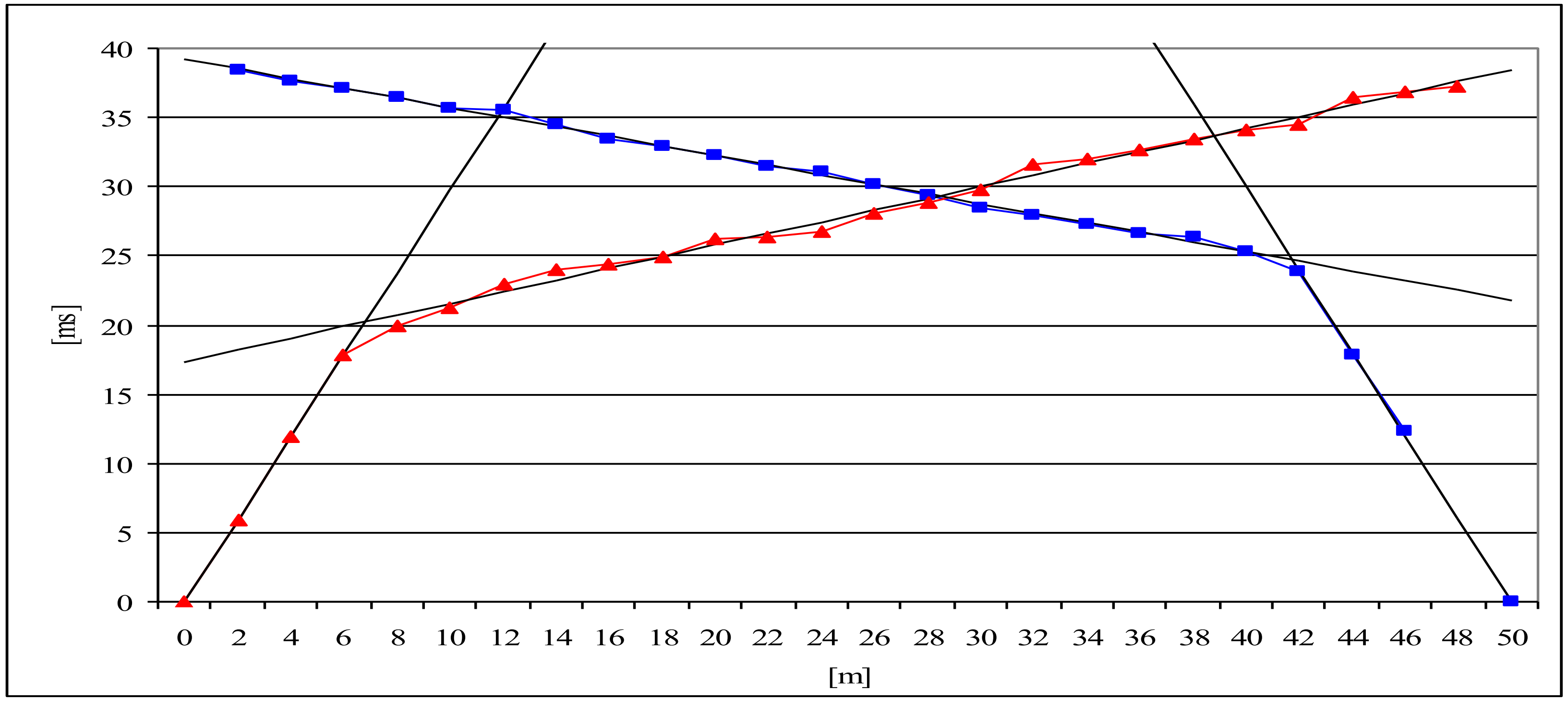
$$h_n = \frac{V_n}{cos(i_n)} \left(\frac{T0_{n+1}}{2} - \sum_{j=0}^{n-1} h_j \sqrt{\frac{1}{V_j^2} - \frac{1}{V_{j+1}^2}} \right)$$

T0n = n intercept time

Non planar
Deepening refractor

2D section

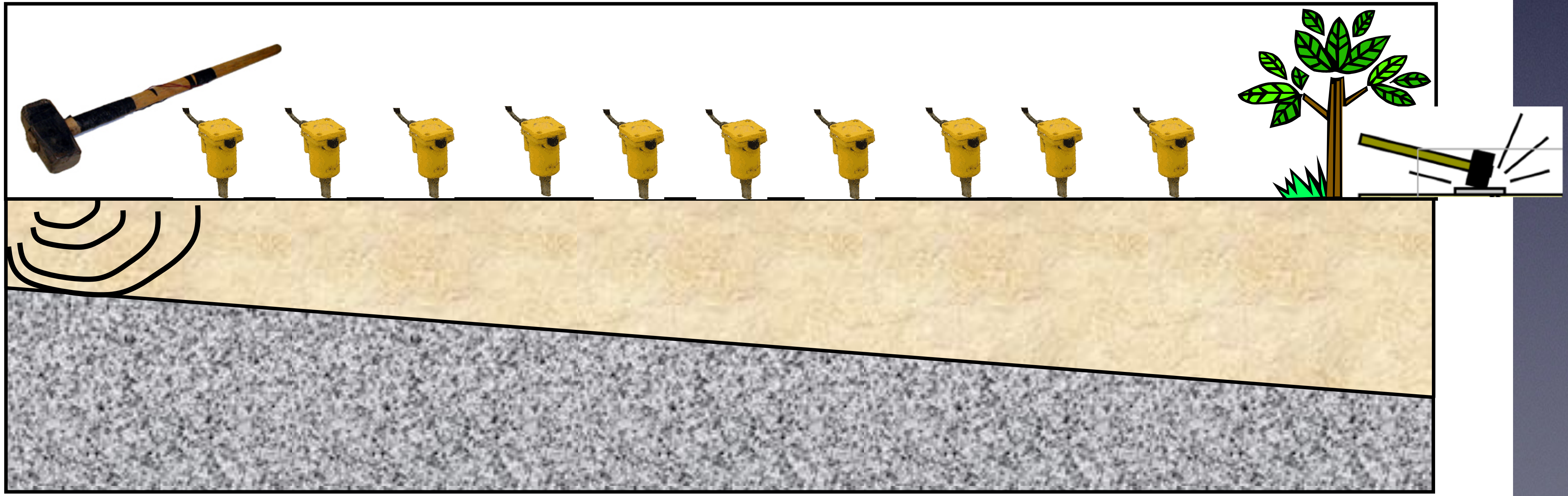
Subsoil 2D geometry



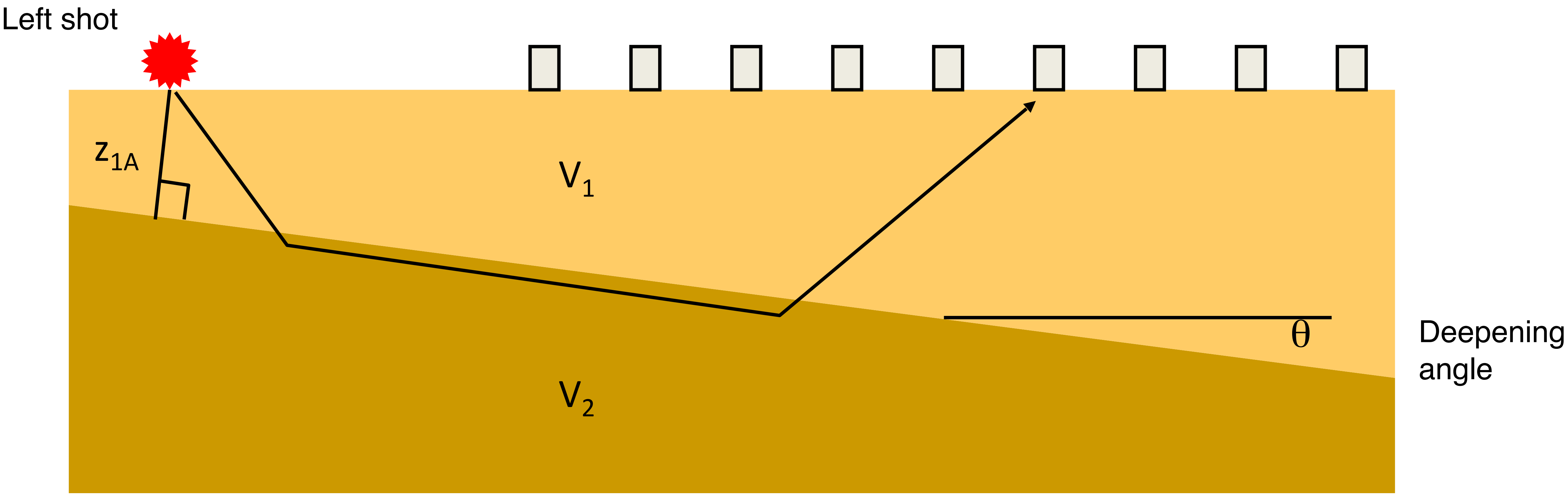
≠ Xcross

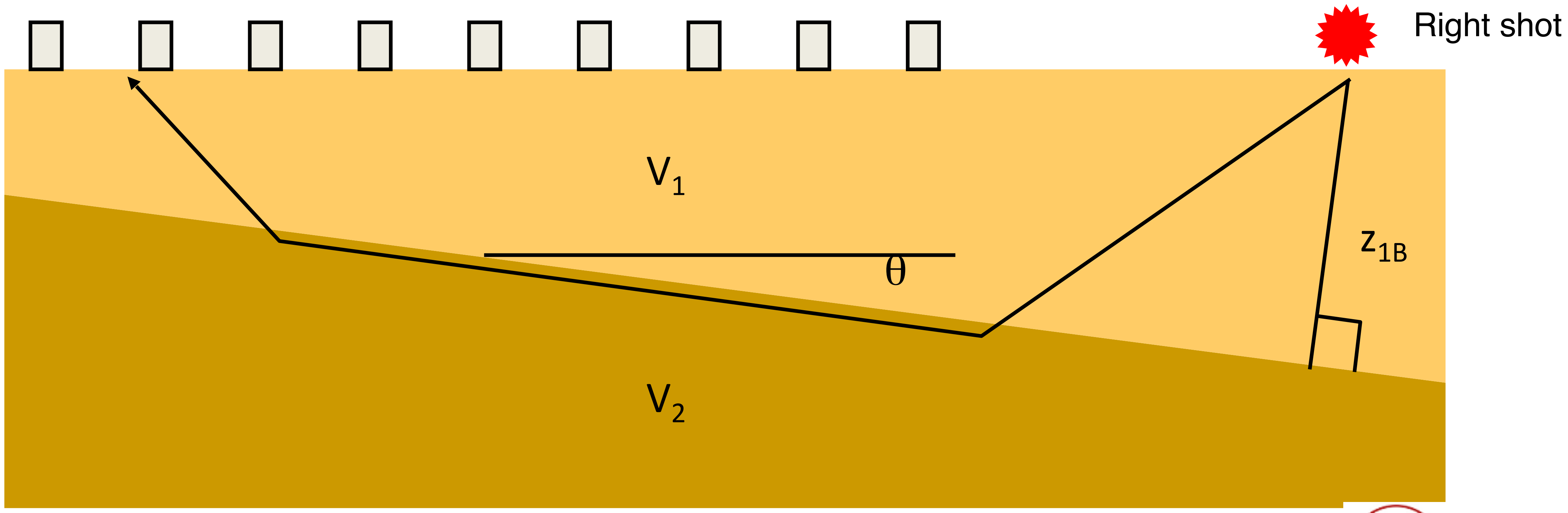
≠ T0

≠ H



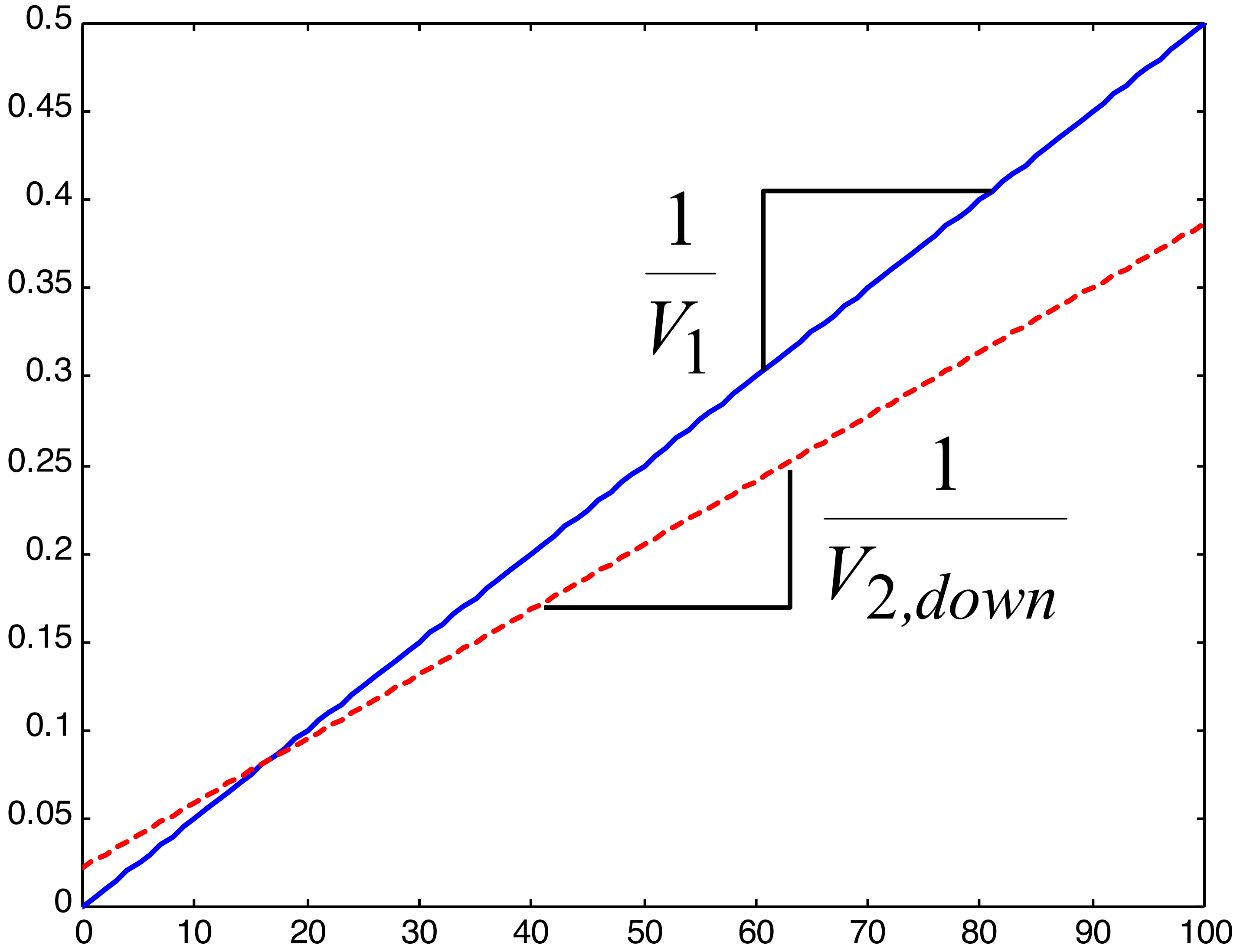
Seismic Refraction





DIPARTIMENTO DI GEOSCIENZE

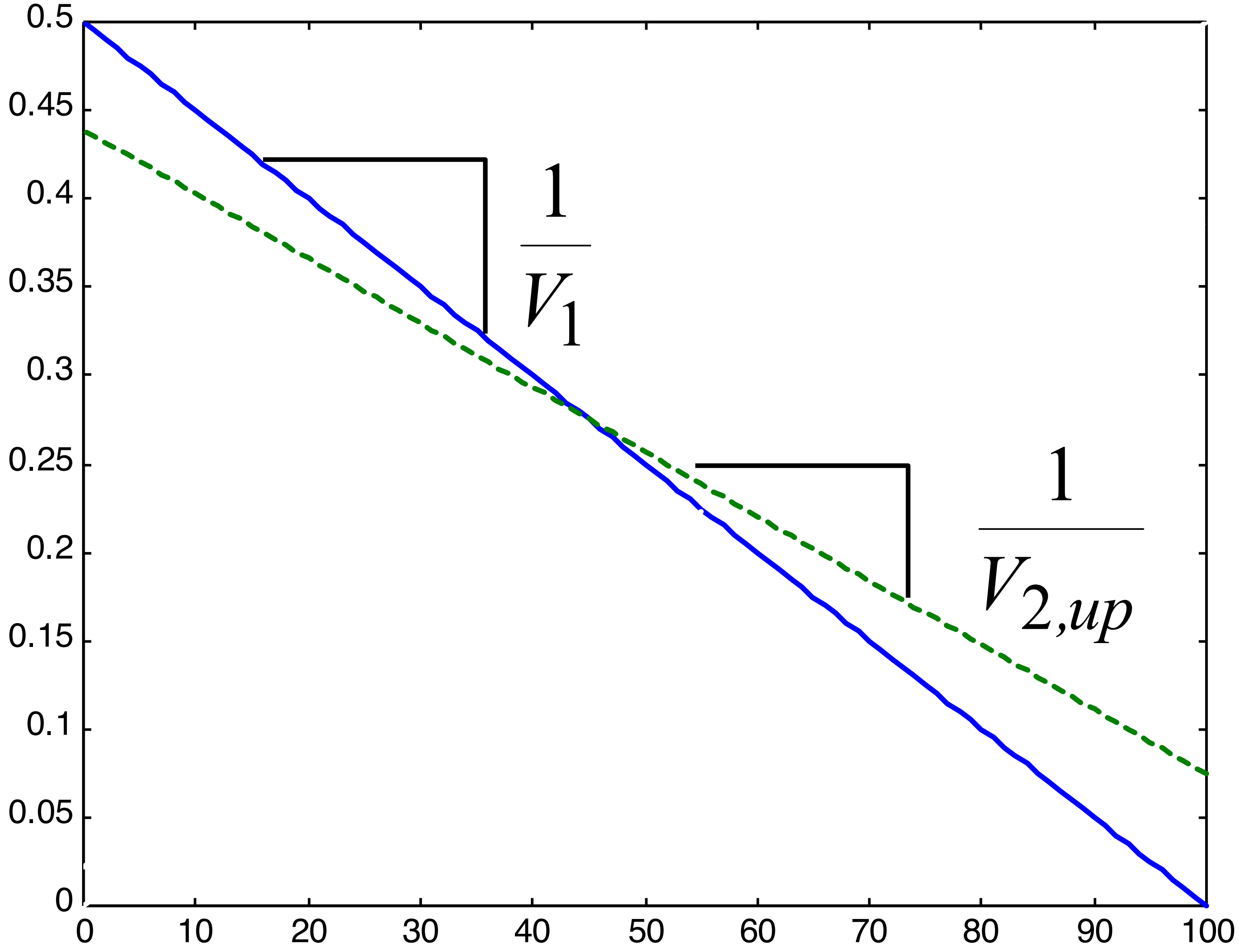
Seismic Refraction



Left shot

Right shot

Seismic Refraction



Right shot

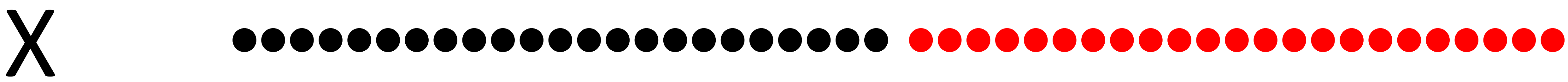
Seismic Refraction

$$\left.\begin{aligned} i_c + \theta &= \sin^{-1}\left(\frac{V_1}{V_{2,down}}\right) \\ i_c - \theta &= \sin^{-1}\left(\frac{V_1}{V_{2,up}}\right) \end{aligned}\right\}$$

Two Equations – Two Unknowns

$$\sin i_c = \frac{V_1}{V_2}$$

Seismic Refraction



Source

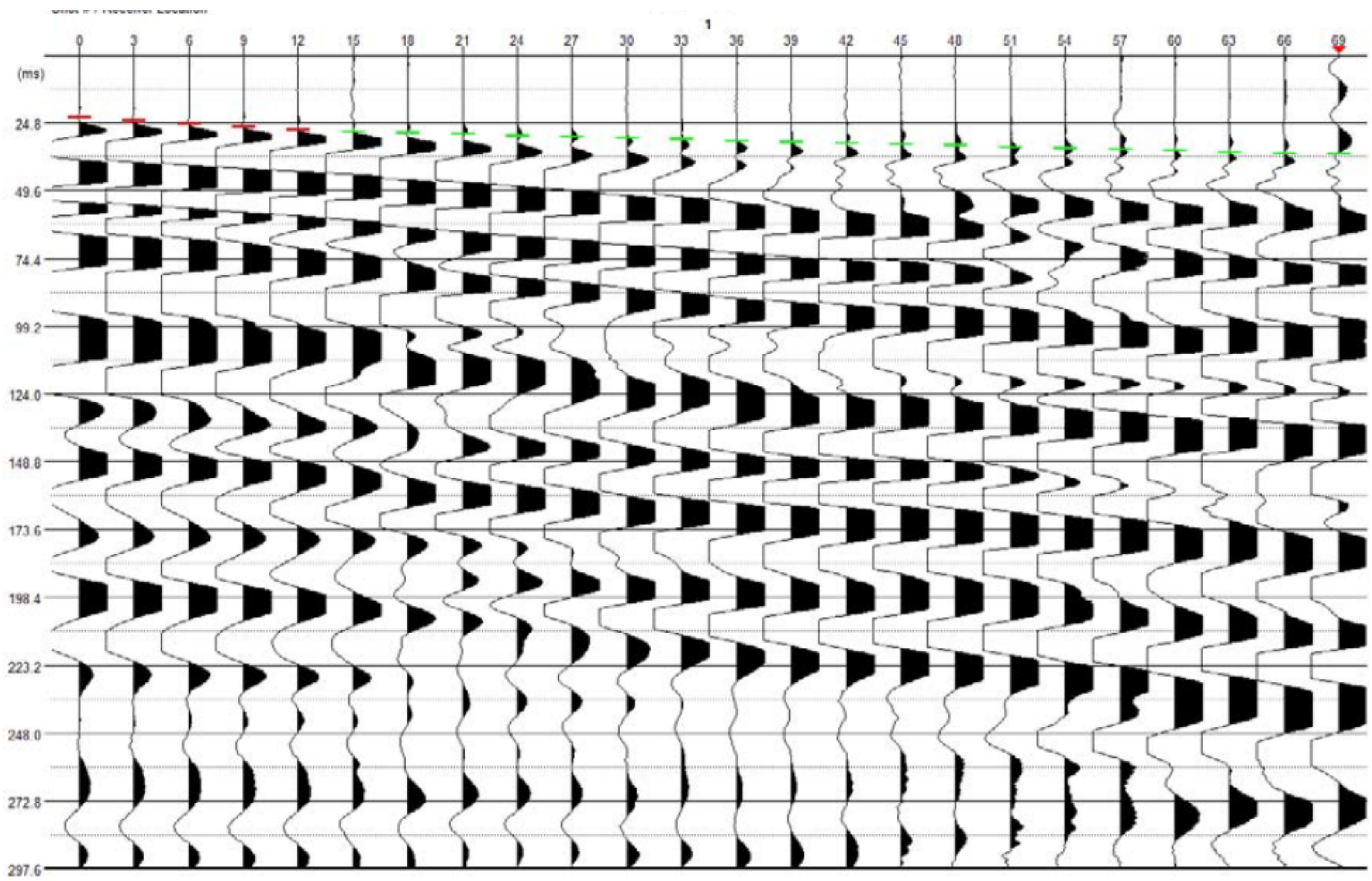
24 receivers @ 3 m spacing

24 receivers @ 3 m spacing

X

Shot 1

Shot 2

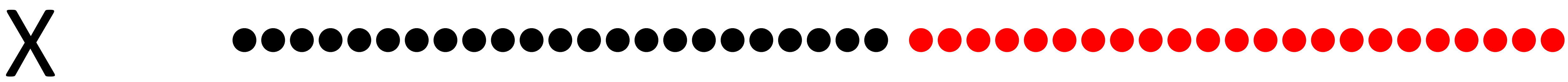


Seismic Refraction

Source

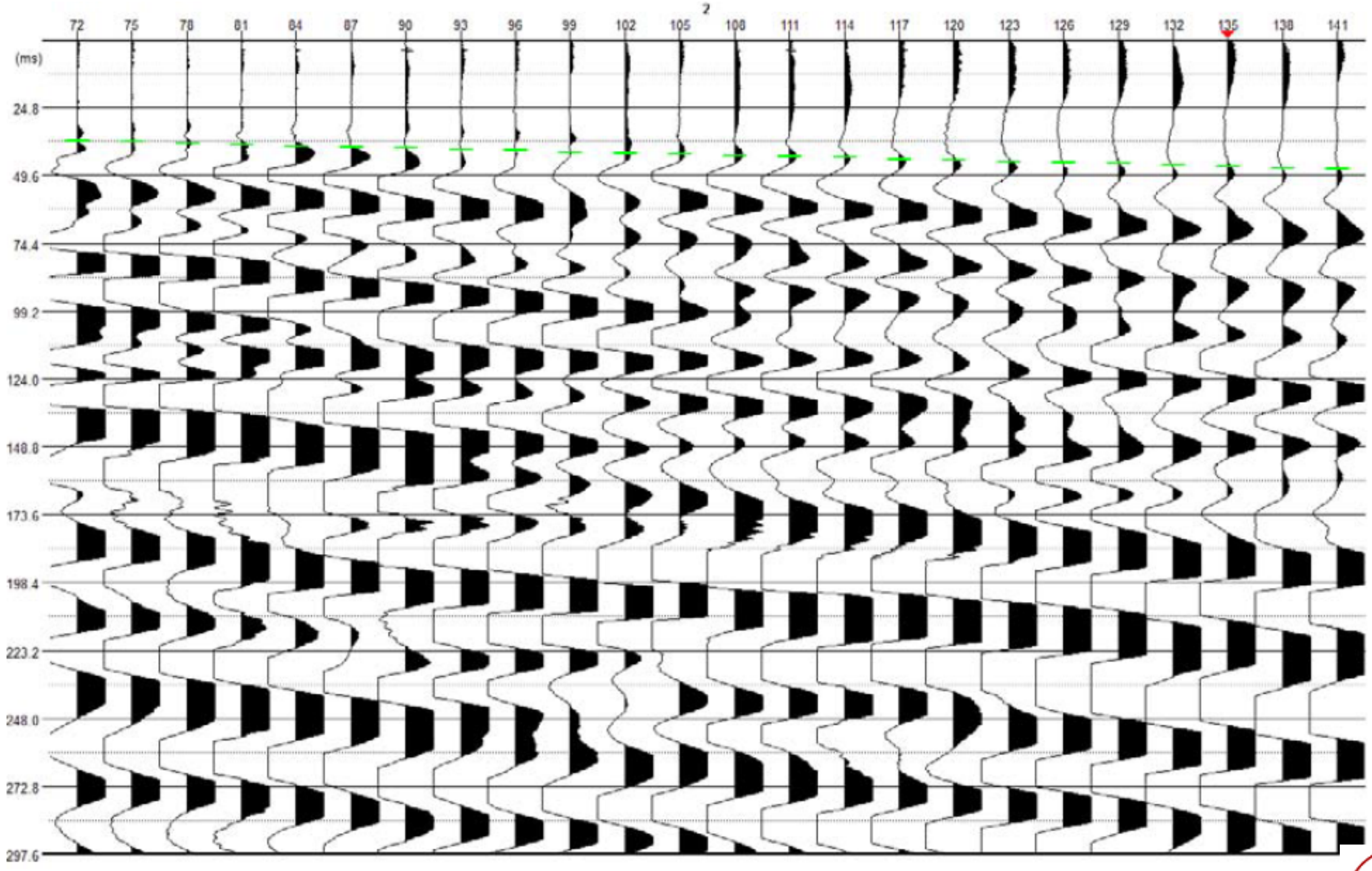
24 receivers @ 3 m spacing

24 receivers @ 3 m spacing

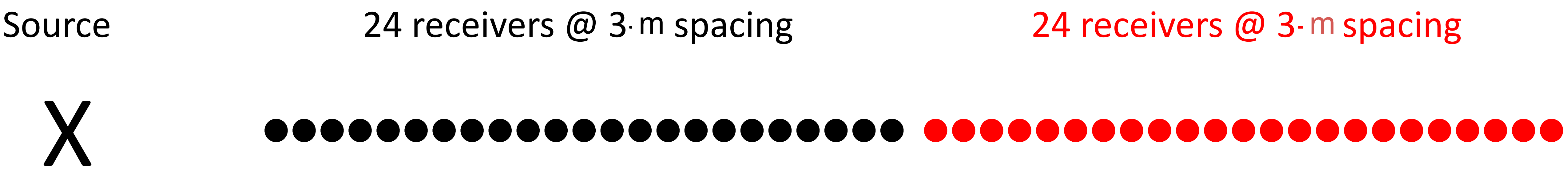


Shot 1

Shot 2



Seismic Refraction



Source

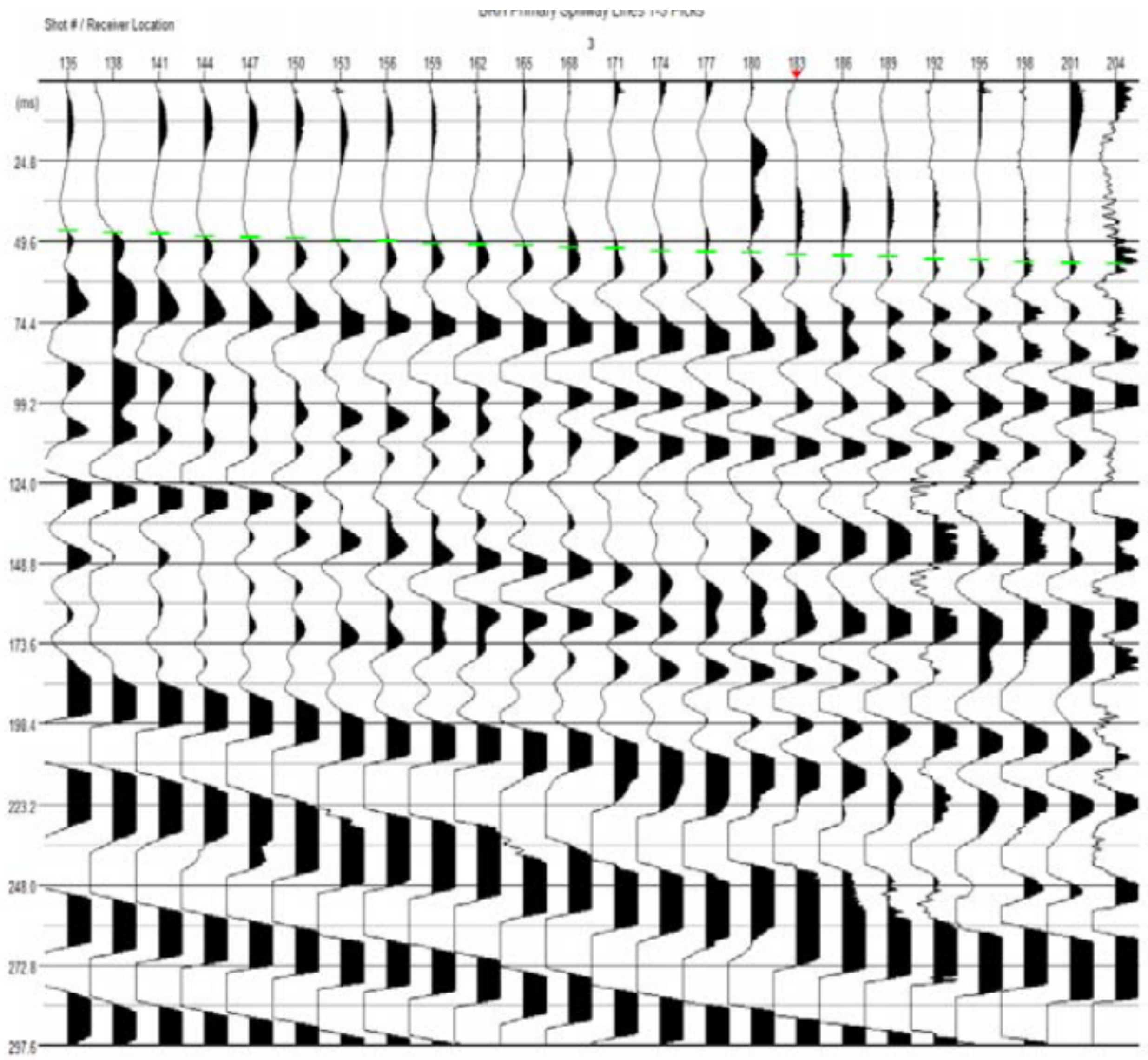
24 receivers @ 3 m spacing

24 receivers @ 3 m spacing

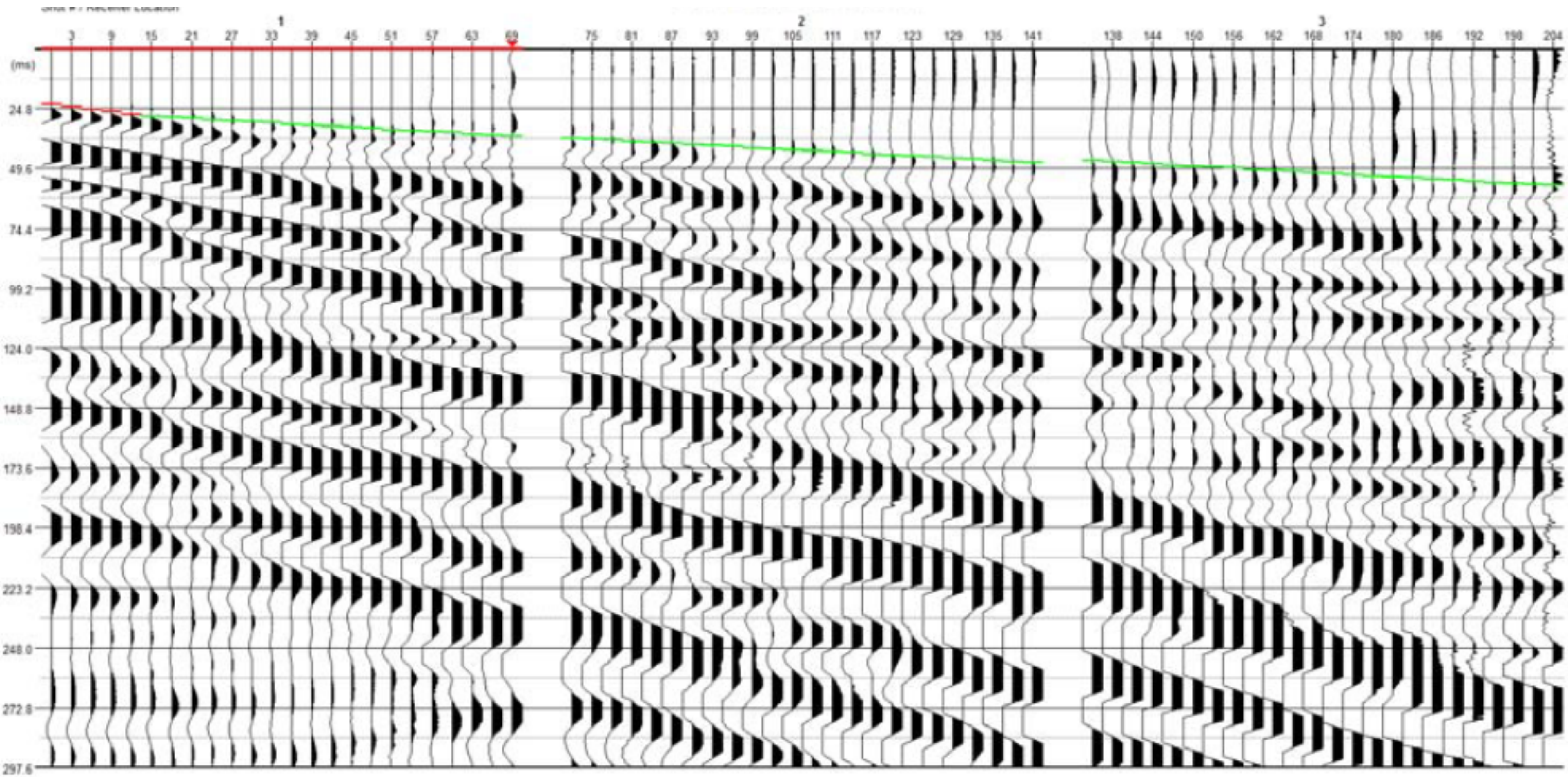
X

Shot 2

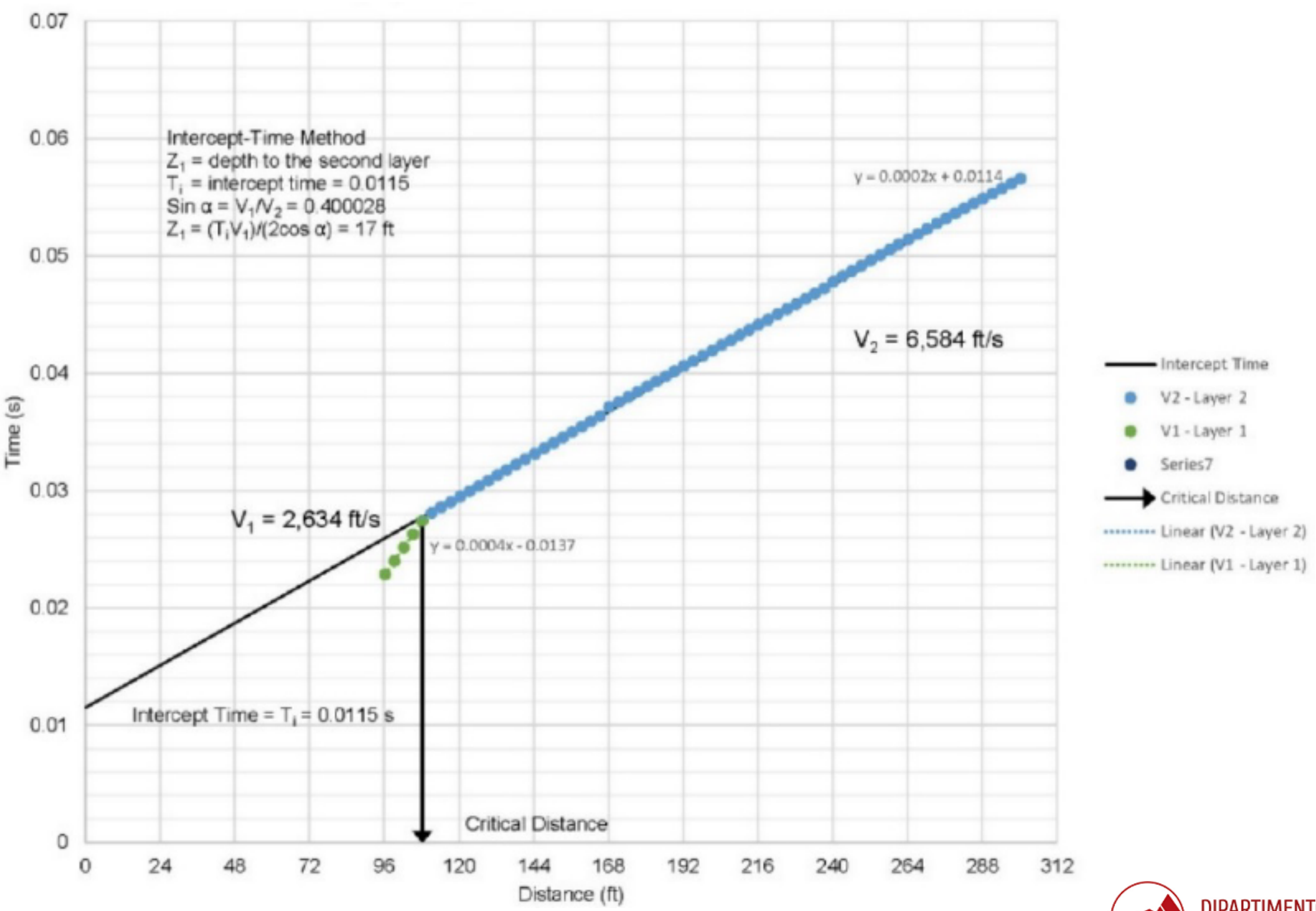
Shot 3



Seismic Refraction



Seismic Refraction



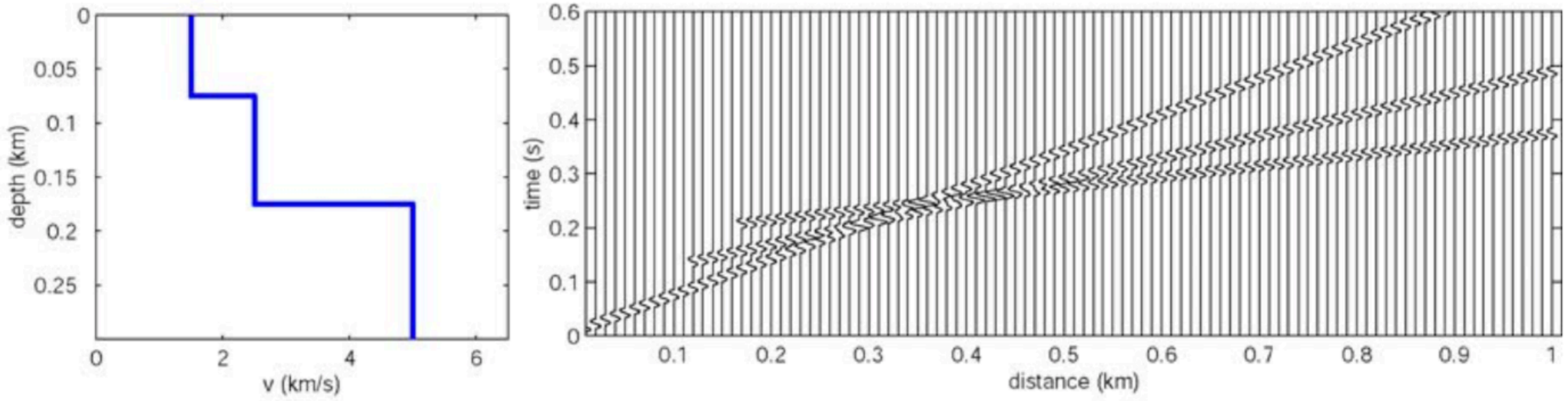
DIPARTIMENTO DI GEOSCIENZE

Seismic Refraction

C3.2 Seismic refraction - with a low velocity zone (LVZ)

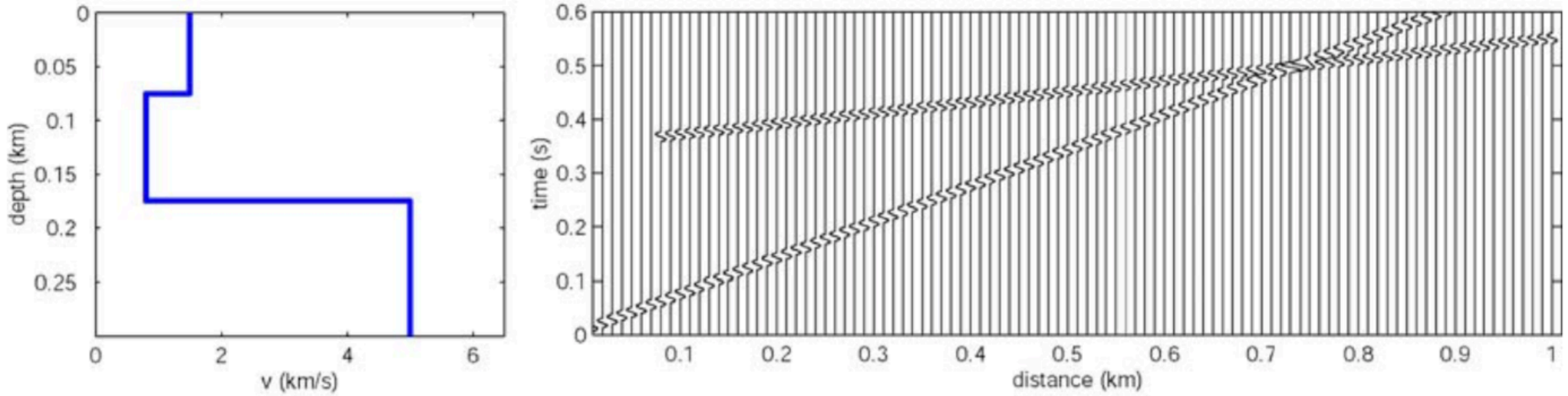
3 layers

(a) 3-layer model with no LVZ



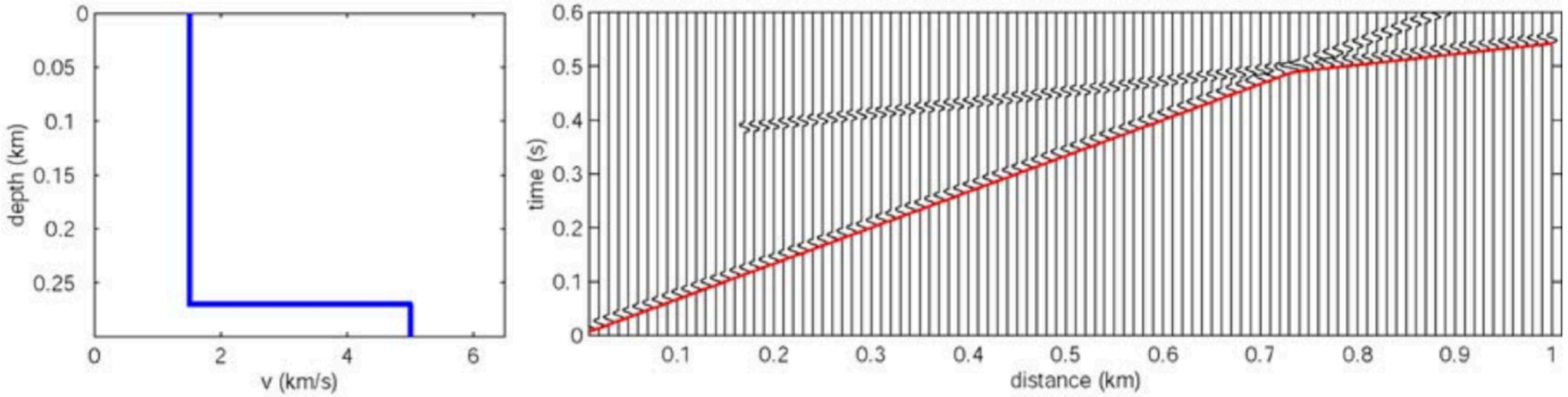
Hidden layer limit (low velocity Zone LVZ)

(b) 3-layer model with LVZ



2 layers

(c) Interpretation of first arrivals from (b)



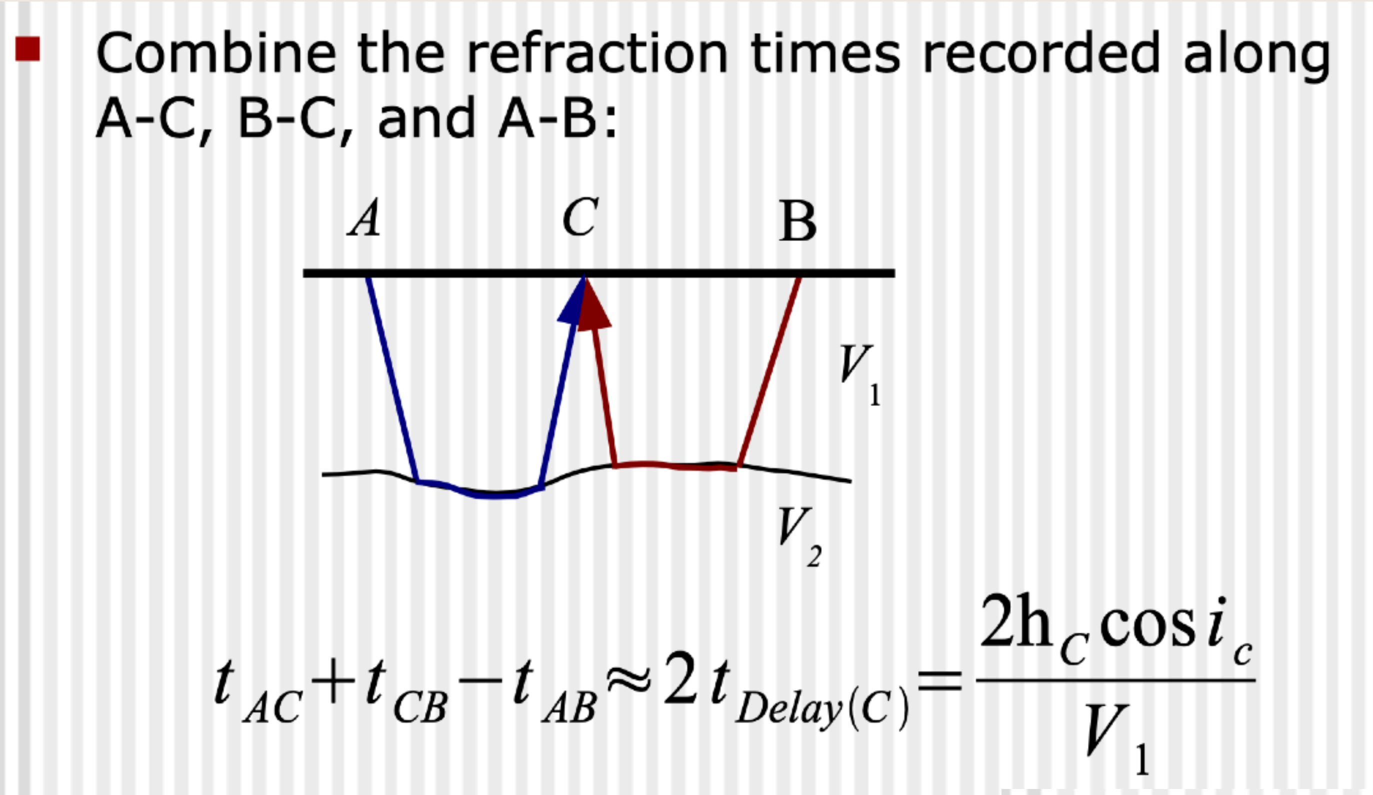
Seismic Refraction

- Time Intercept and Crossover Distance Methods (planar refractors)
- Common Reciprocal Methods (non-planar refractors)
  - Plus-Minus Method
  - ABC Method
  - Hagiwaras Method
- Generalized Reciprocal Methods (non-planar refractors)
  - Delay Time Method
  - Hales Method

Reciprocal methods= you need reversal shots!

Seismic Refraction

Common Reciprocal Methods : ABC method

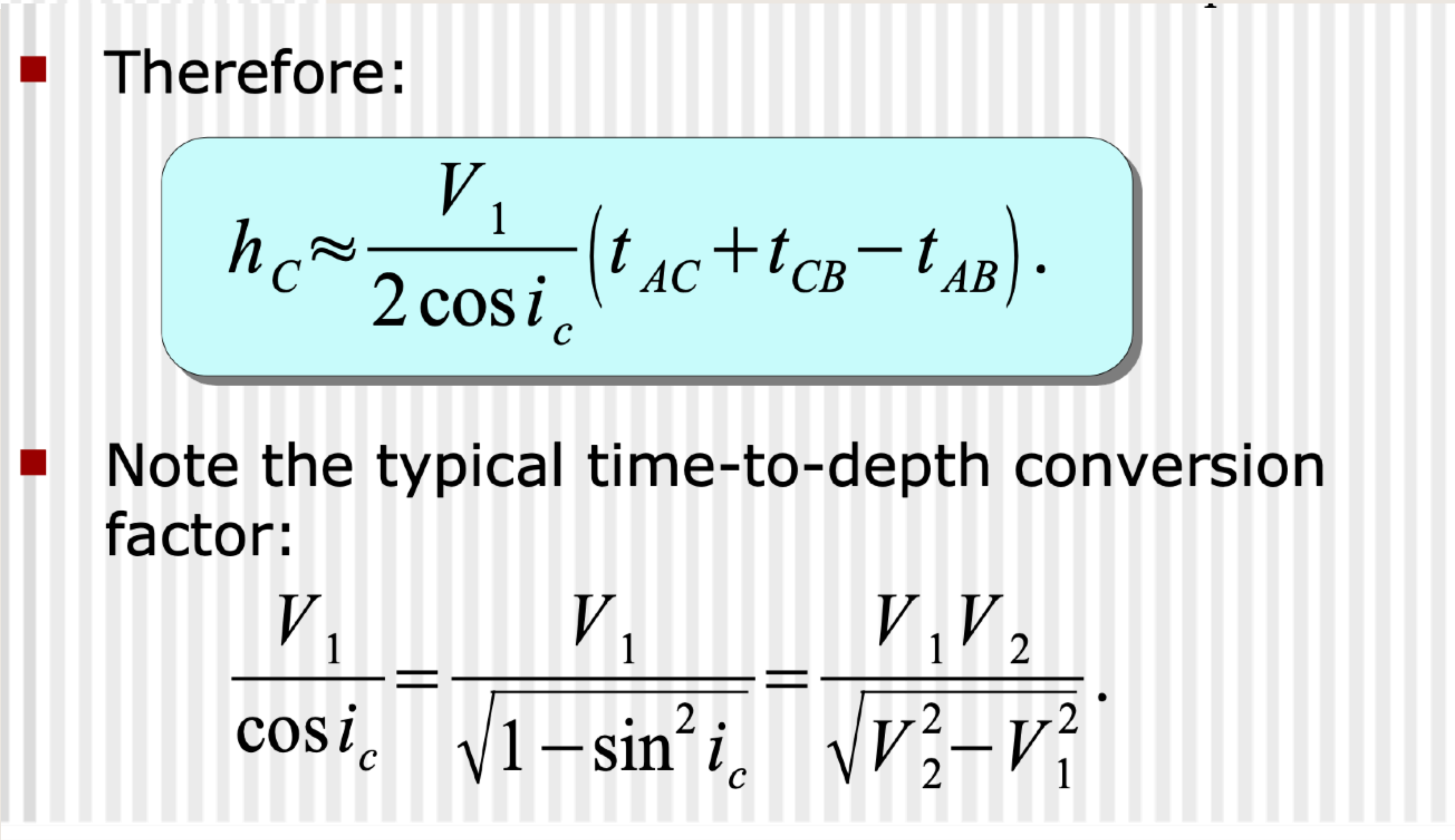


- Combine the refraction times recorded along A-C, B-C, and A-B:

$$t_{AC}+t_{CB}-t_{AB}\approx 2t_{Delay(C)}=\frac{2h_C\cos i_c}{V_1}$$

The ABC method

Get the thickness in C (Hc) (Knowing velocities)



- Therefore:

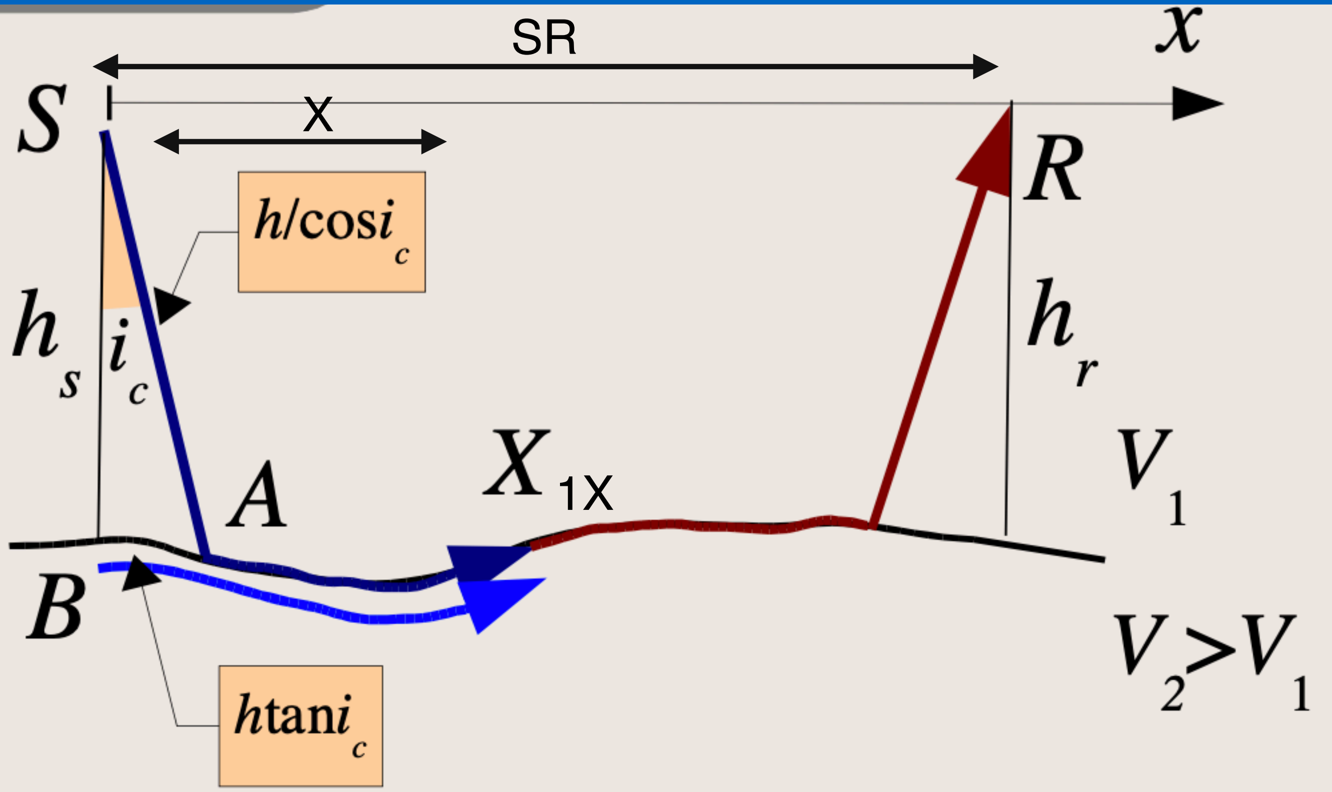
$$\boxed{h_C\approx\frac{V_1}{2\cos i_c}\left(t_{AC}+t_{CB}-t_{AB}\right).}$$

- Note the typical time-to-depth conversion factor:

$$\frac{V_1}{\cos i_c}=\frac{V_1}{\sqrt{1-\sin^2 i_c}}=\frac{V_1V_2}{\sqrt{V_2^2-V_1^2}}.$$

Knowing arrival times in A, B, C and Velocities, you get HC

Seismic Refraction
Delay Time method



Consider a nearly horizontal, shallow interface with strong velocity contrast (a typical case for weathering layer).

In this case, we can separate the times associated with the source and receiver vicinities:

$$t_{SR} = t_{SX} + t_{XR}.$$

Relate the time t_{sx} to a time along the refractor, t_{BX}

$$t_{SX} = t_{SA} - t_{BA} + tB_X = t_{Sdelay} + X/V_2$$

$$t_{S\ Delay} = \frac{SA}{V_1} - \frac{BA}{V_2} = \frac{h_s}{V_1 \cos i_c} - \frac{h_s \tan i_c}{V_2} = \frac{h_s}{V_1 \cos i_c}(1 - \sin^2 i_c) = \frac{h_s cos i_c}{V_{1.}}$$

Note that $V_2 = V_1/\sin i_c$

Thus, source and receiver *delay times* are:

You can retrieve h

$$t_{S\ ,R\ Delay} = \frac{h_{s\ ,r} cos i_c}{V_{1.}}$$

and

$$t_{SR} = t_{S\ Delay} + t_{R\ Delay} + \frac{SR}{V_{2.}}$$

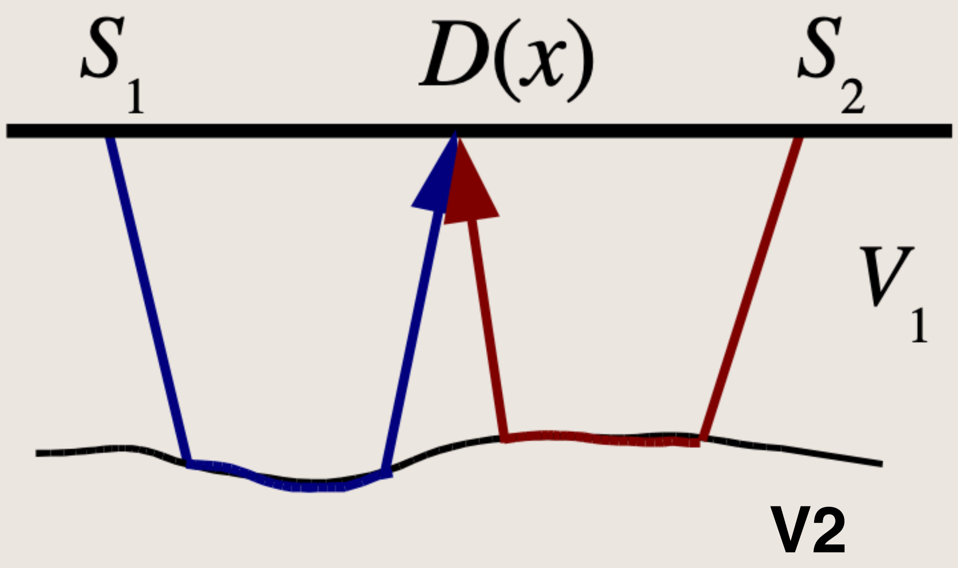
You can retrieve V2

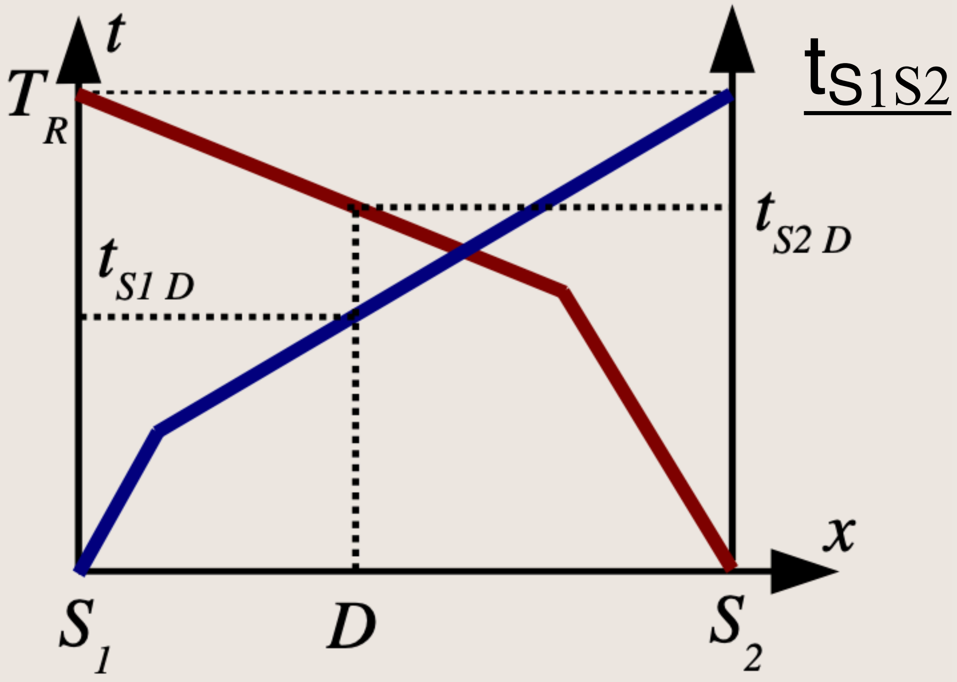
Seismic Refraction

Plus-Minus Method

Assume that we have recorded two headwaves in opposite directions, and have estimated the velocity of overburden, V_1.

- <u>How can we map the refracting interface?</u>



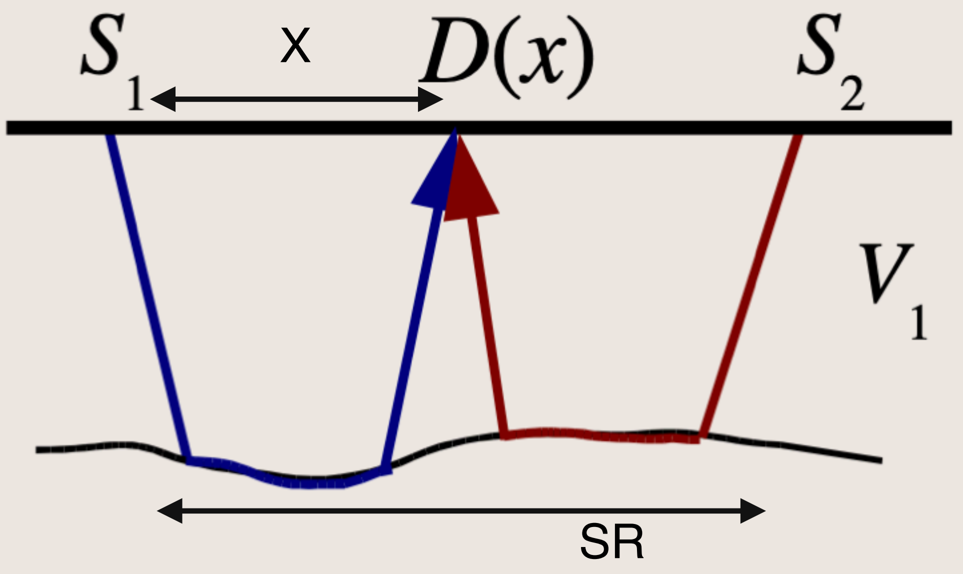


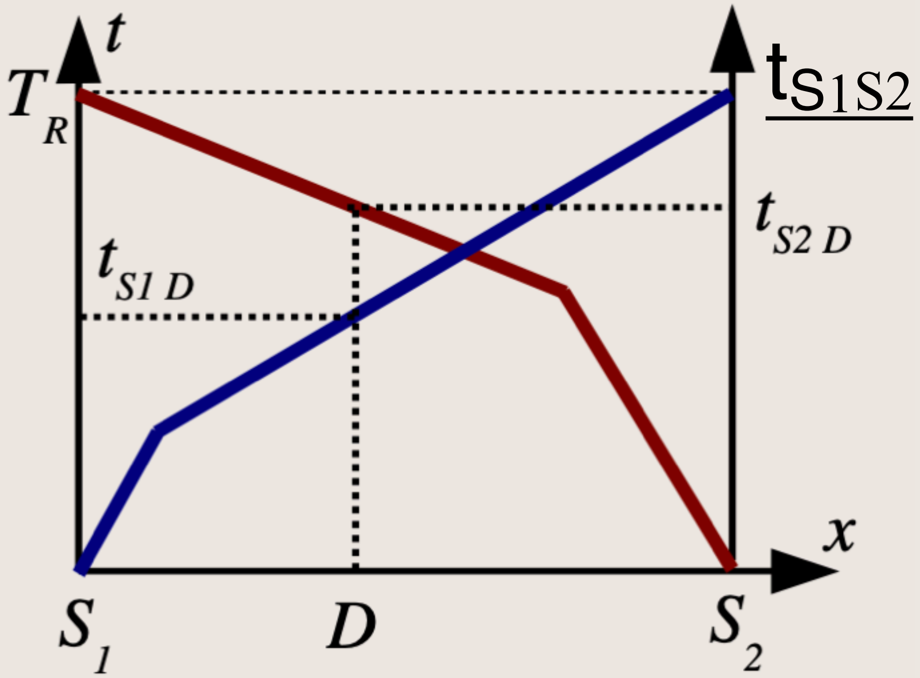
Solution:

We want to estimate Delay time in D (Td) to get thickness below point D, and Velocities of refractor V2

Seismic Refraction

Plus-Minus Method





Solution:

- Profile $S_1 \rightarrow S_2$: $t_{S_1 D} = \frac{x}{V_2} + t_{S_1} + t_D;$

$$t_{SR} = t_{S\,Delay} + t_{R\,Delay} + \frac{SR}{V_{2.}}$$

- Profile $S_2 \rightarrow S_1$: $t_{S_2 D} = \frac{(SR - x)}{V_2} + t_{S_2} + t_{D.}$

- Form PLUS travel-time:

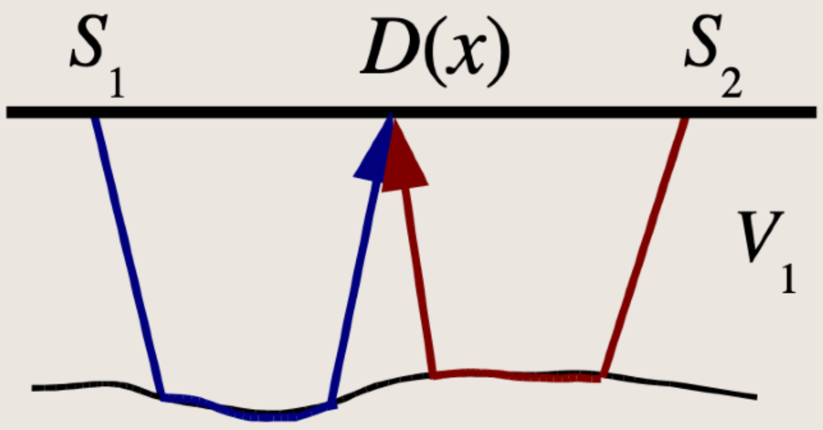
$$t_{PLUS} = t_{S_1 D} + t_{S_2 D} = \frac{SR}{V_2} + t_{S_1} + t_{S_2} + 2t_D = t_{S_1 S_2} + 2t_{D.}$$

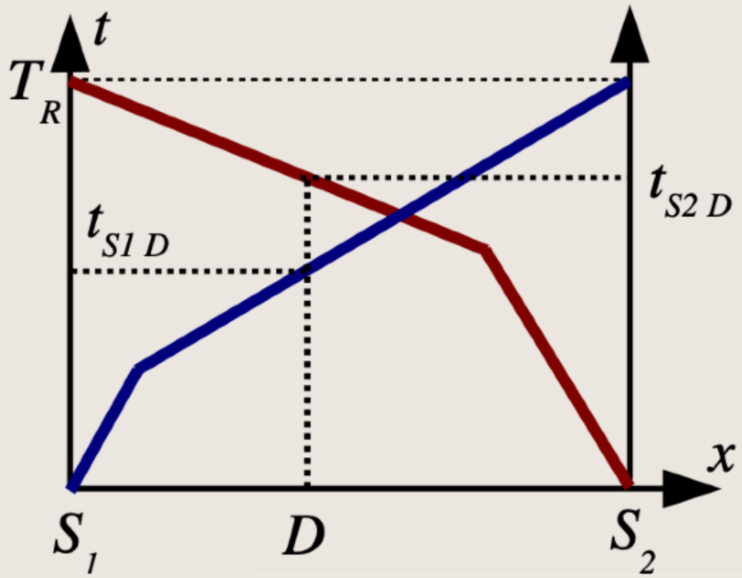
Hence: $t_D = \frac{1}{2}\left(t_{PLUS} - t_{S_1 S_2}\right).$

- To determine i_c (and depth), still need to find V_2.

Seismic Refraction

Plus-Minus Method





To determine V_2:

- Form MINUS travel-time:

this is a constant!

$$t_{MINUS} = t_{S_1 D} - t_{S_2 D} = \frac{2x}{V_2} \boxed{- \frac{SR}{V_2} + t_{s_1} - t_{s_2}}.$$

Hence:

$$\boxed{slope\left[t_{MINUS}(x)\right] = \frac{2}{V_2}.}$$

Plotting **$t_{S_1D} - t_{S_2D}$**

***vs* 2x give you the slope**

= *$1/v2$*

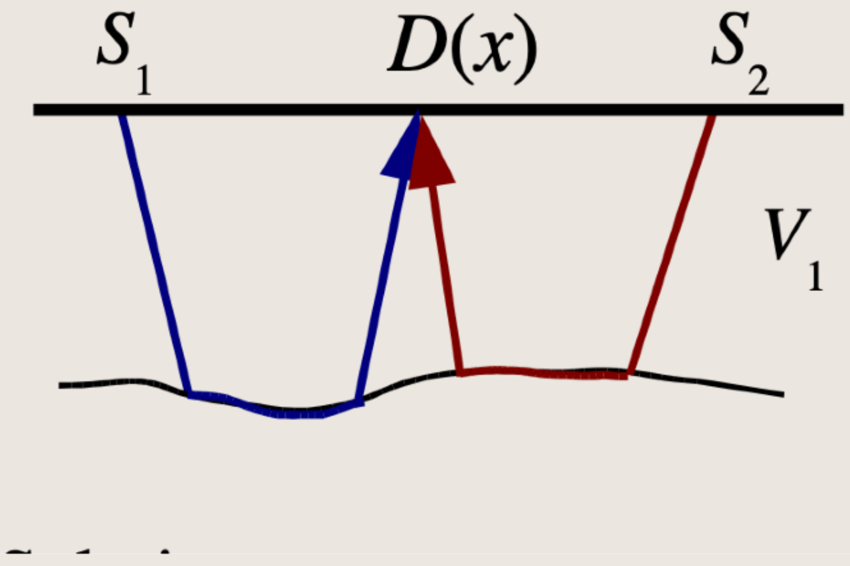
(For several geophones)

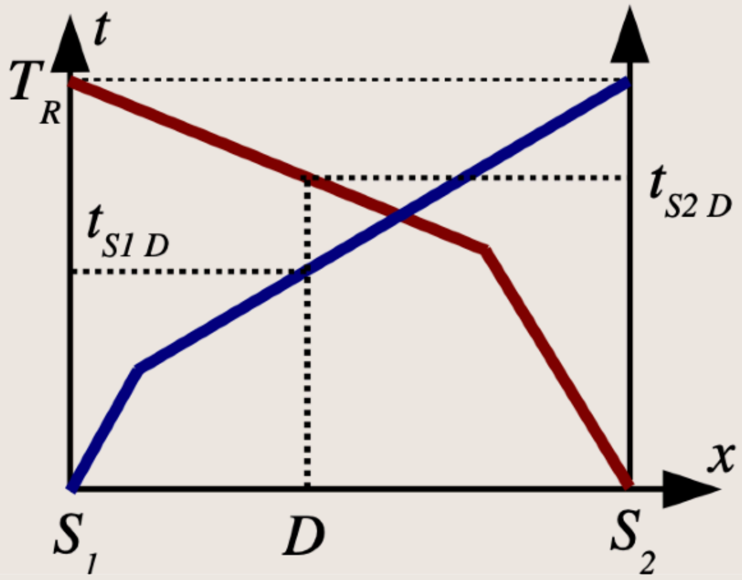
Seismic Refraction

Plus-Minus Method

Note that $V_2=V_1/\sin i_c$

$$t_D = \frac{h_D \cos i_c}{V_1}$$





$$slope\left[t_{MINUS}(x)\right]=\frac{2}{V_2}.$$

You have **(V1),V2**,, *ic* and can retrieve **Hd** (thickness below D) for each geophones

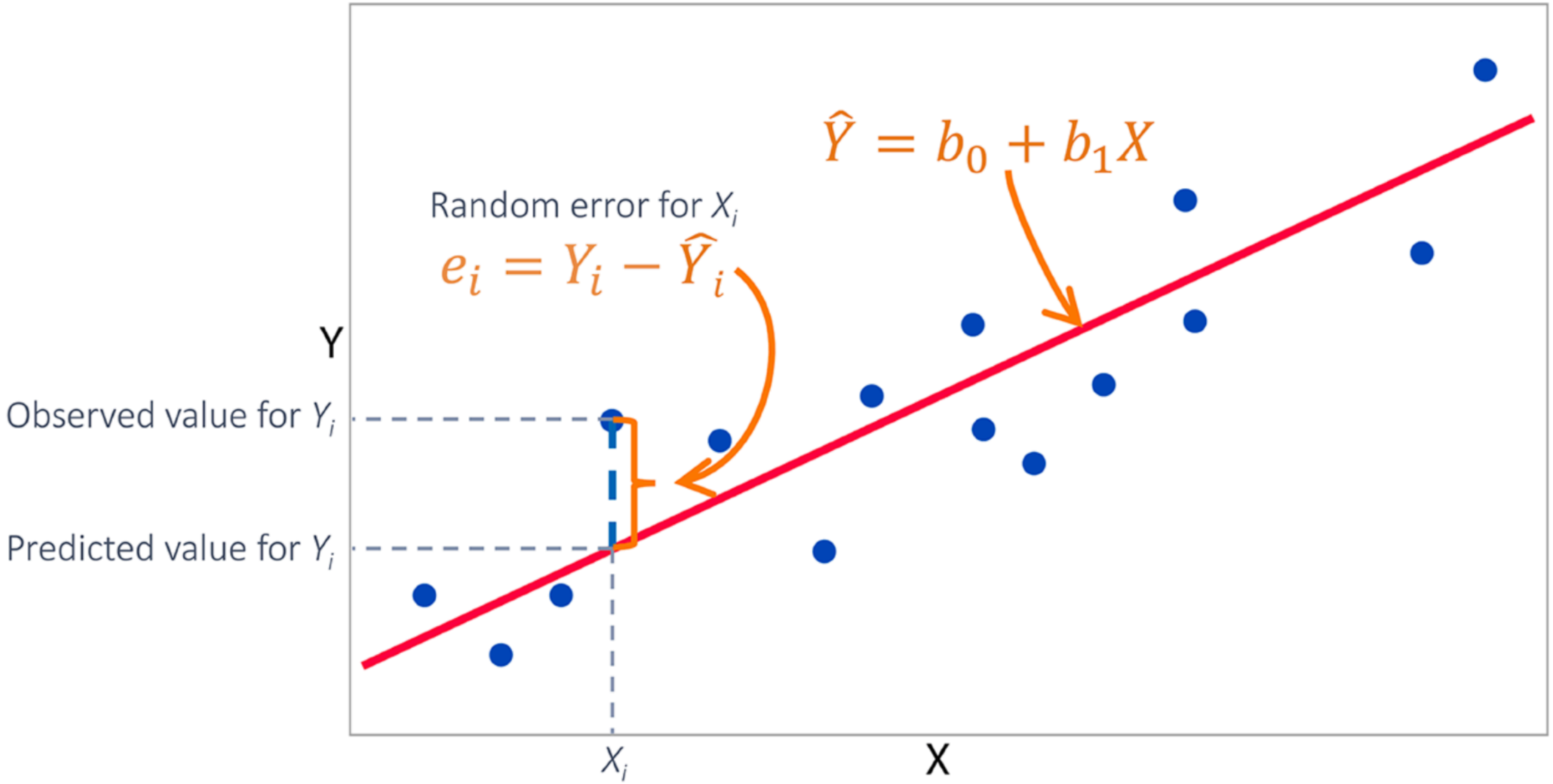
Seismic Refraction

Plus-Minus Method

- The slope is usually estimated by using the *Least Squares method*.

Seismic Refraction

Least square regression



If we add up all of the errors, the sum will be zero. To measure overall error we square the errors and find a line that minimizes this sum of the squared errors.

$$\sum {e_t}^2 = \sum (Y_i - \overline{Y}_i)^2$$

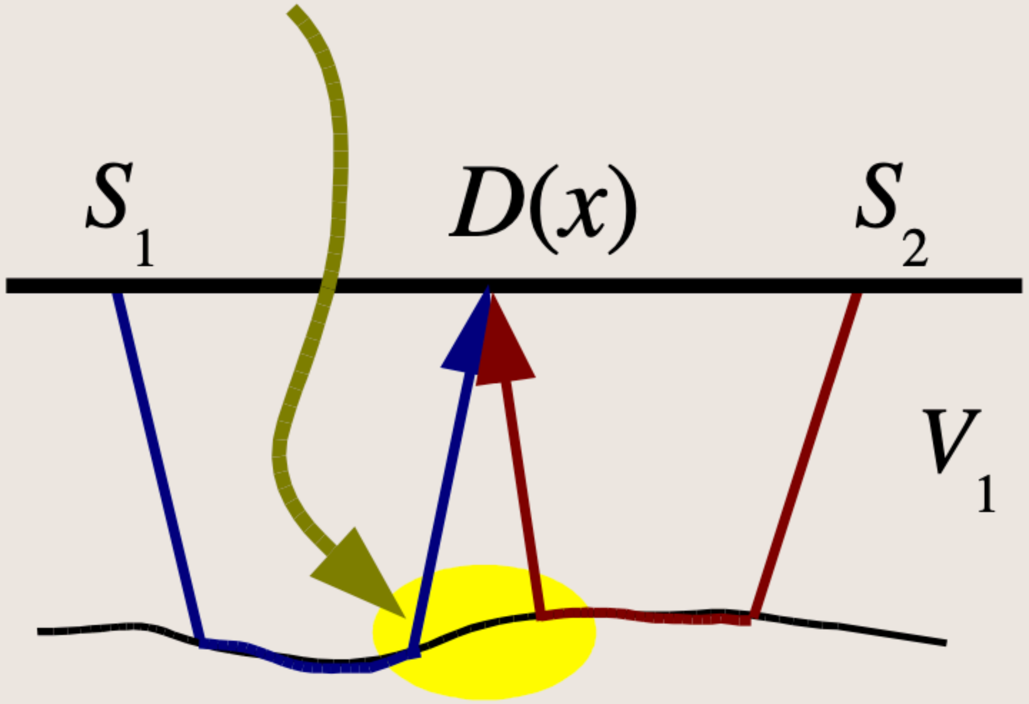
The method of least squares finds values of the intercept and slope coefficient that minimize the sum of the squared errors.

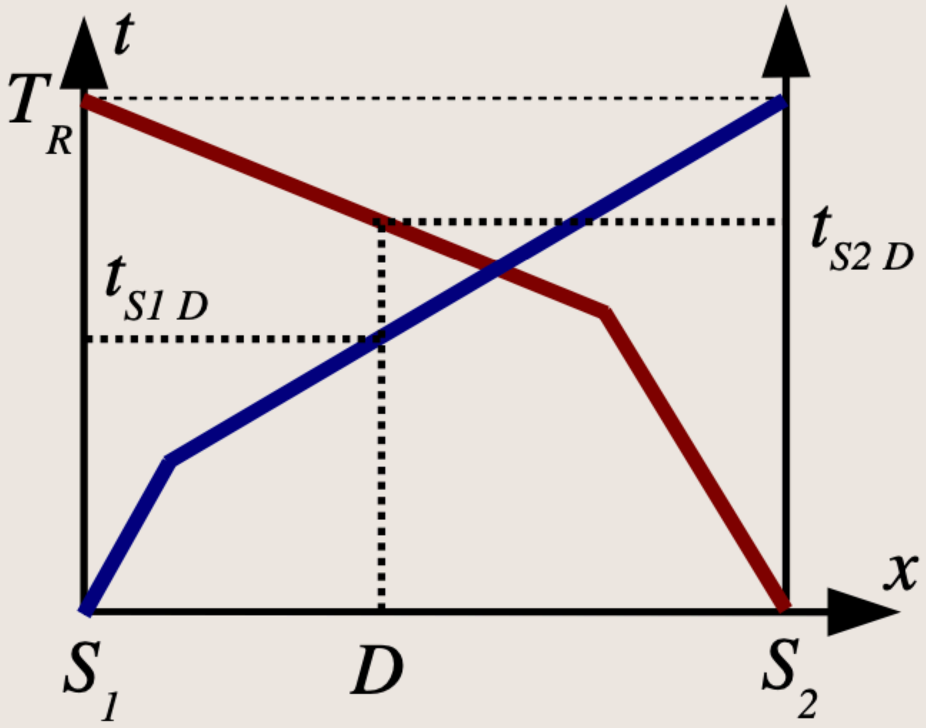
Seismic Refraction

Plus-Minus Method

- The slope is usually estimated by using the *Least Squares method*.

Drawback of this method – averaging over the pre-critical region.





DIPARTIMENTO DI GEOSCIENZE

Seismic Refraction
Generalised Reciprocal Method

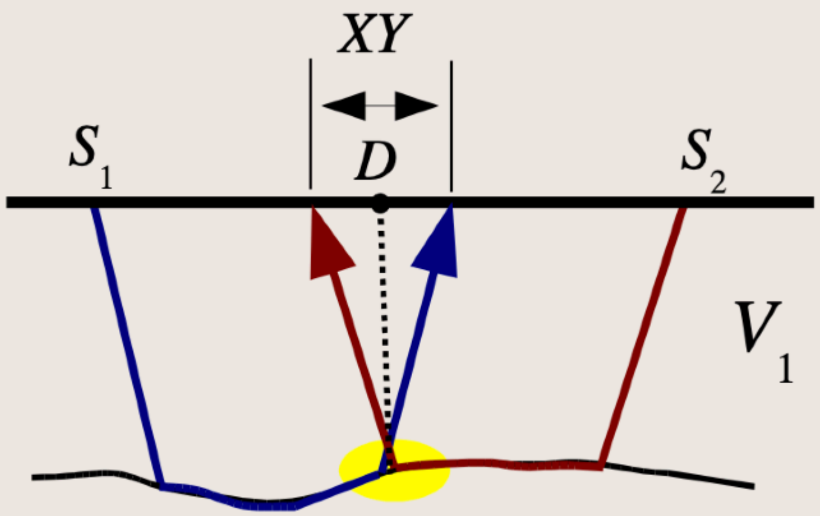
Introduces offsets ('*XY*') in travel-time readings in the forward and reverse shots;

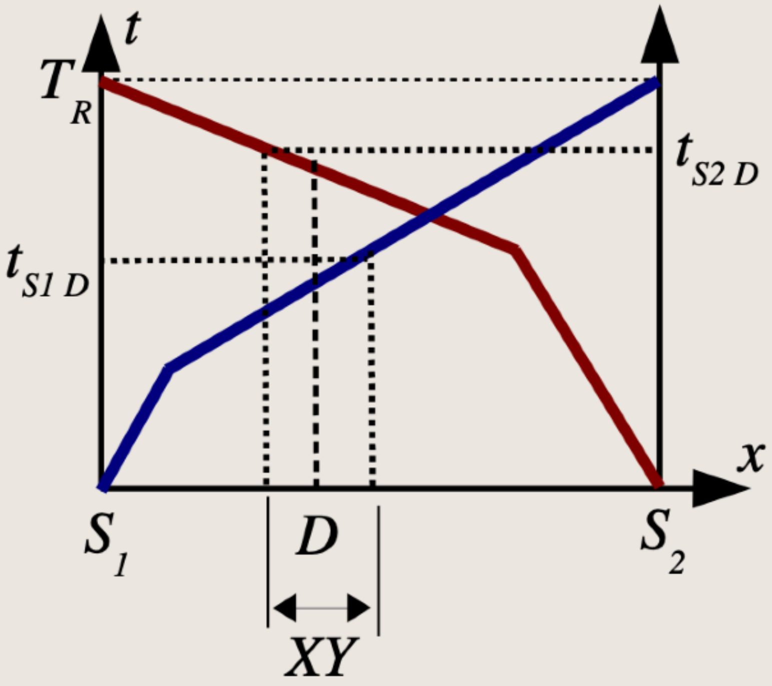
- so that the imaging is targeted on a compact interface region.

Proceeds as the plus-minus method;

Determines the '*optimal*' *XY*:

1) Corresponding to the most linear *time-depth function*;
2) Corresponding to the *most detail* of the refractor.





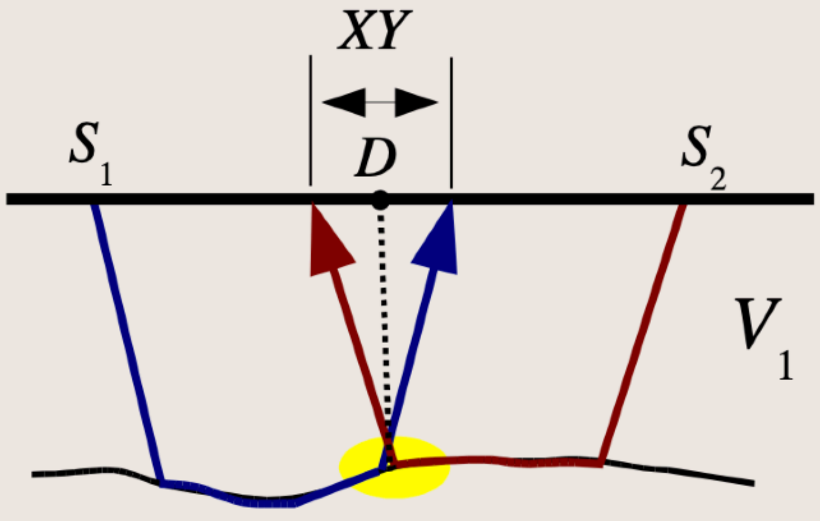
The *velocity analysis function*:

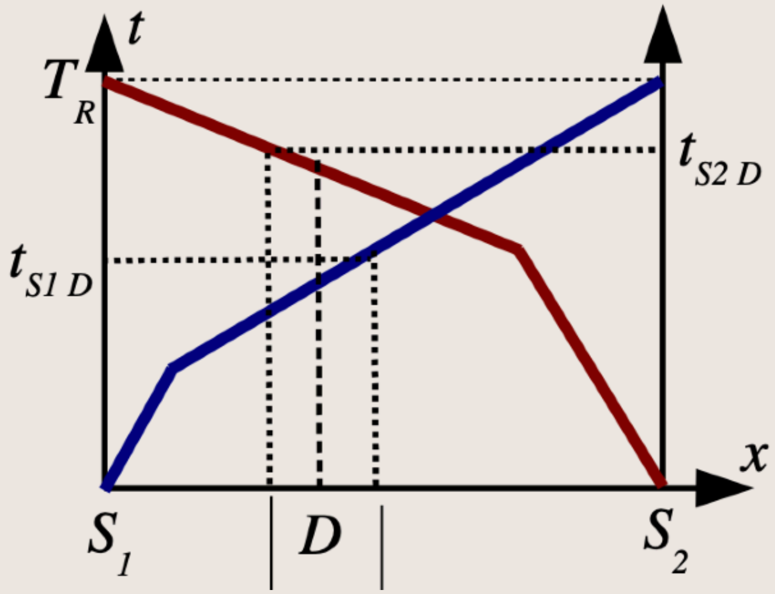
$$t_V = \frac{1}{2}\left(t_{S_1 D} - t_{S_2 D} + t_{S_1 S_2}\right),$$

should be linear, slope $= 1/V_2$;

Seismic Refraction

Generalised Reciprocal Method





The *time-depth function*:

$$t_D = \frac{1}{2}\left(t_{S_1 D} + t_{S_2 D} - t_{S_1 S_2} - \frac{XY}{V_2}\right).$$

this is related to the desired image:

$$h_D = \frac{t_D V_1 V_2}{\sqrt{V_2^2 - V_1^2}}$$

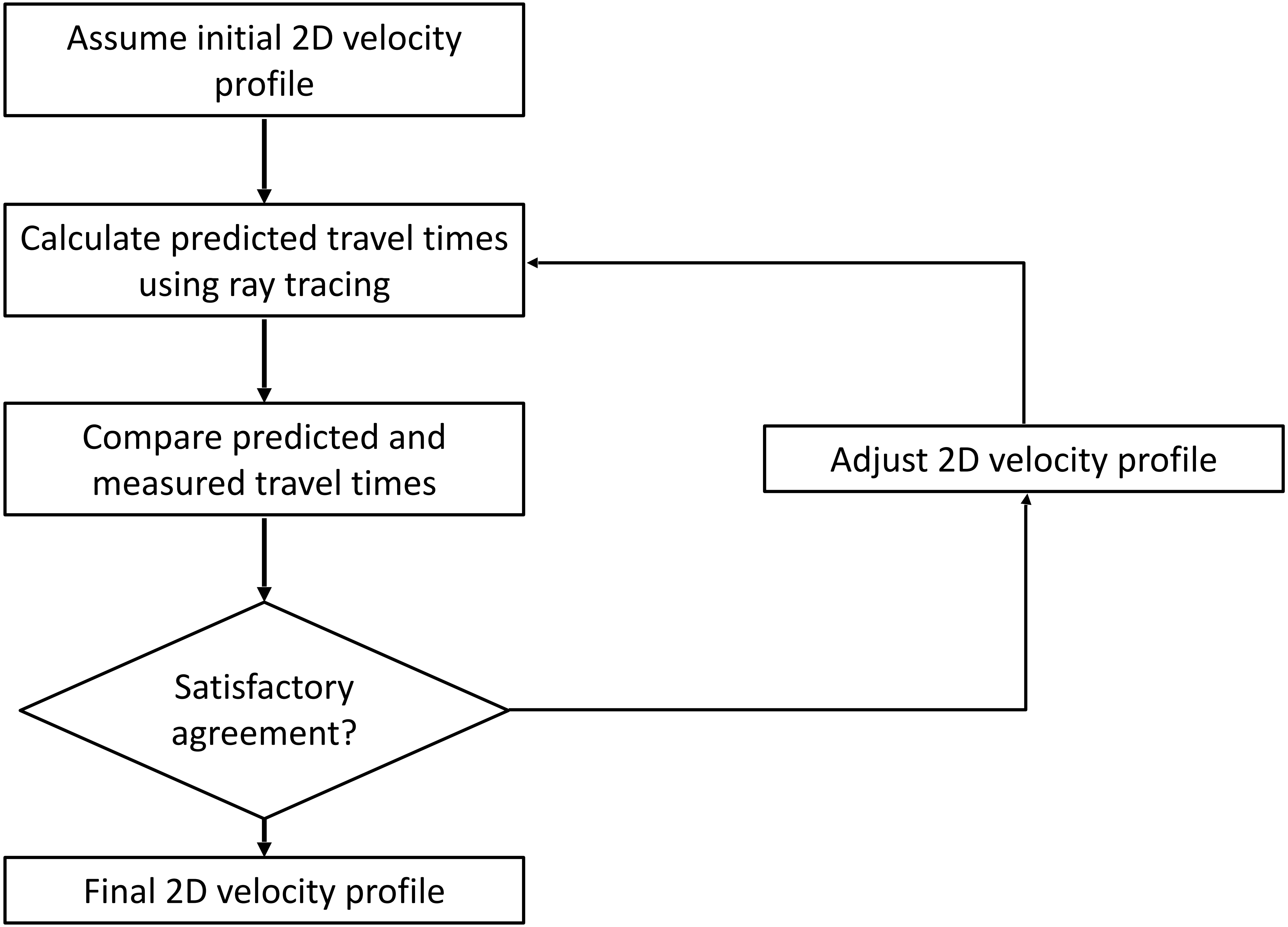
Seismic Refraction

- The two-dimensional (2D) velocity structure is estimated by minimizing the difference between predicted and observed first-arrival travel times (i.e., an **inversion** procedure).

↓

Computational
Refraction tomography

Seismic Refraction



Assume initial 2D velocity profile

Calculate predicted travel times using ray tracing

Compare predicted and measured travel times

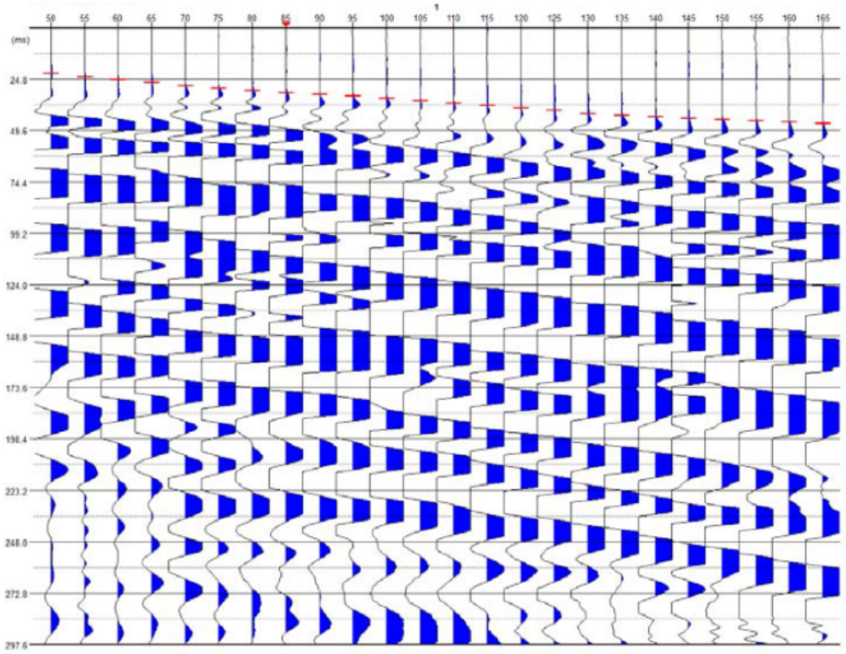
Satisfactory agreement?

Final 2D velocity profile

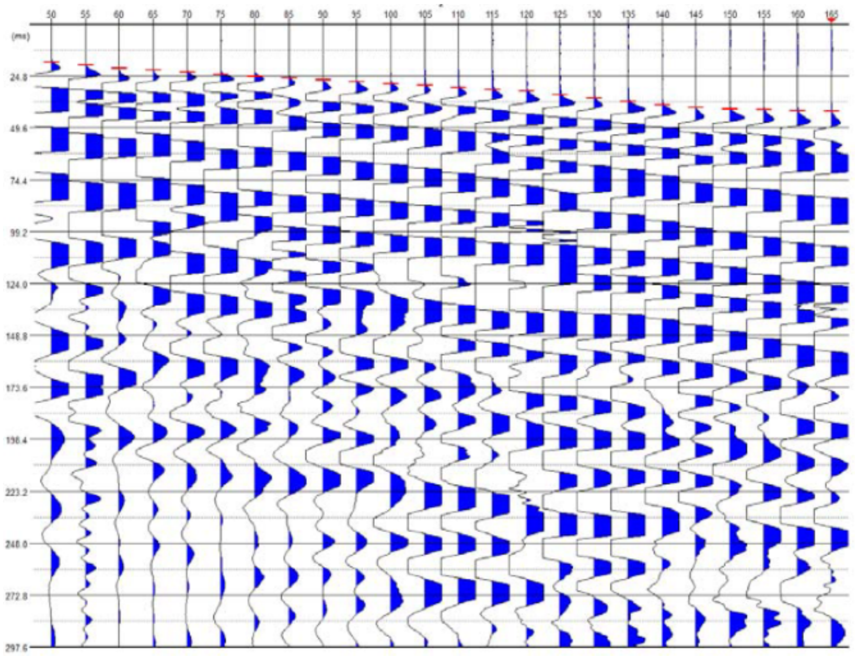
Adjust 2D velocity profile

Seismic Refraction Examples

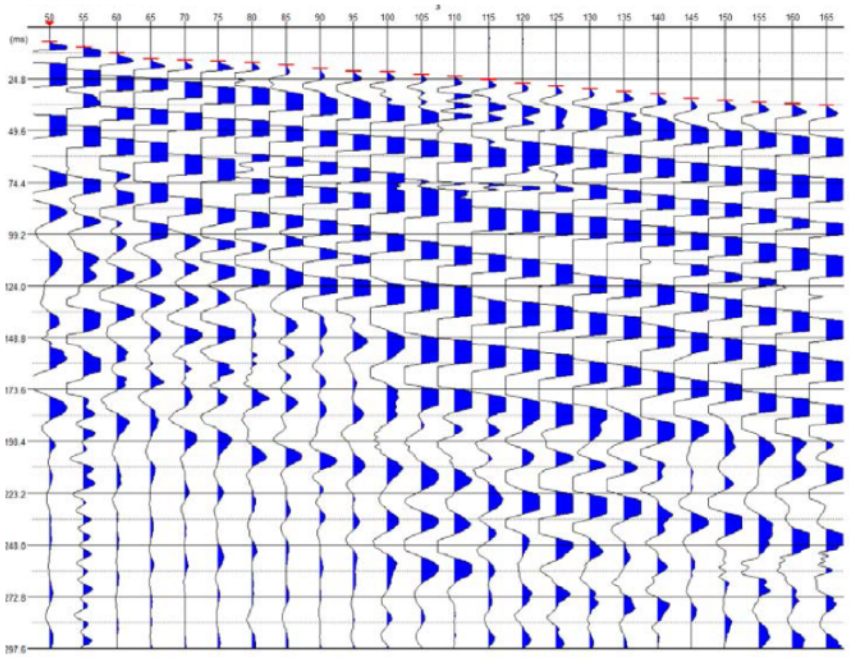
Shot 1



Shot 2



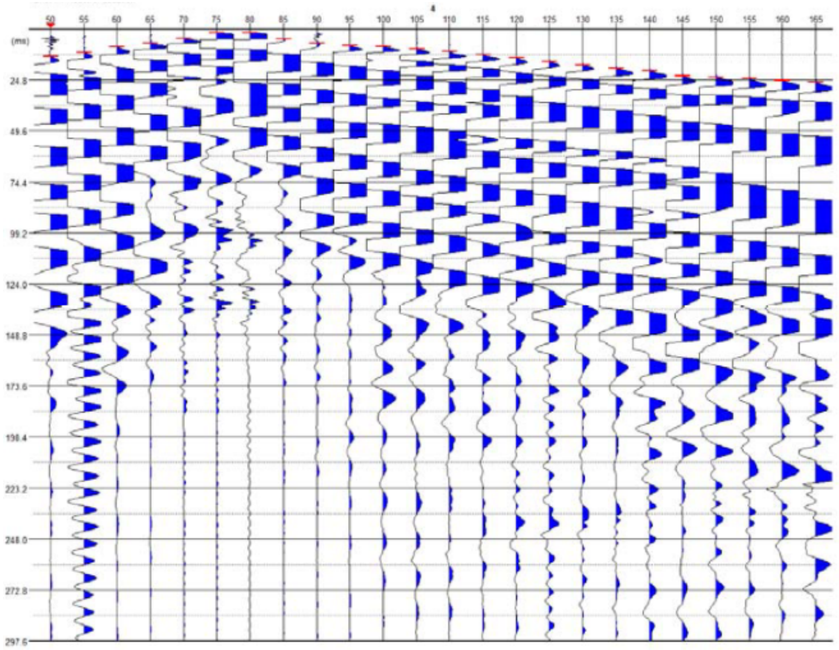
Shot 3



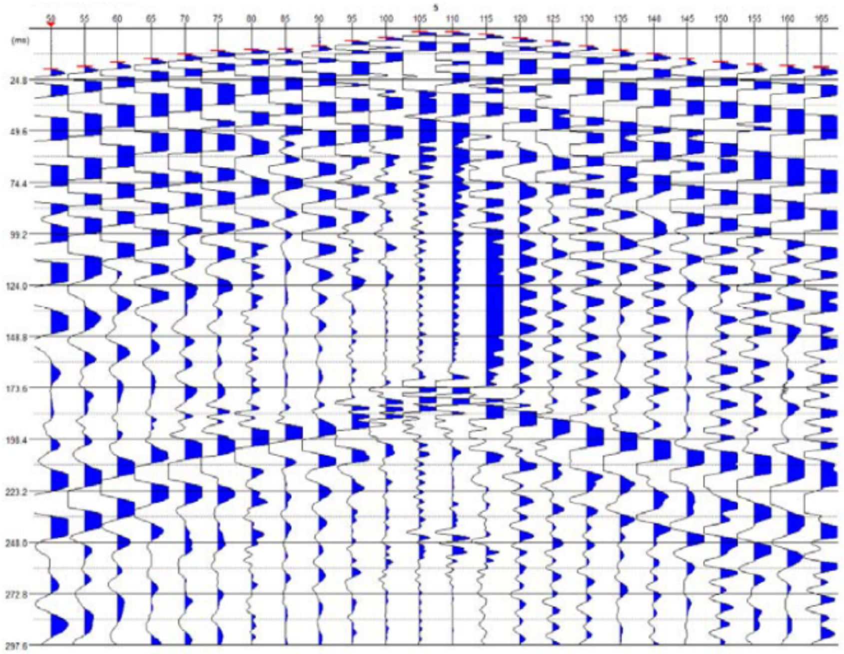
DIPARTIMENTO
DI GEOSCIENZE

Seismic Refraction

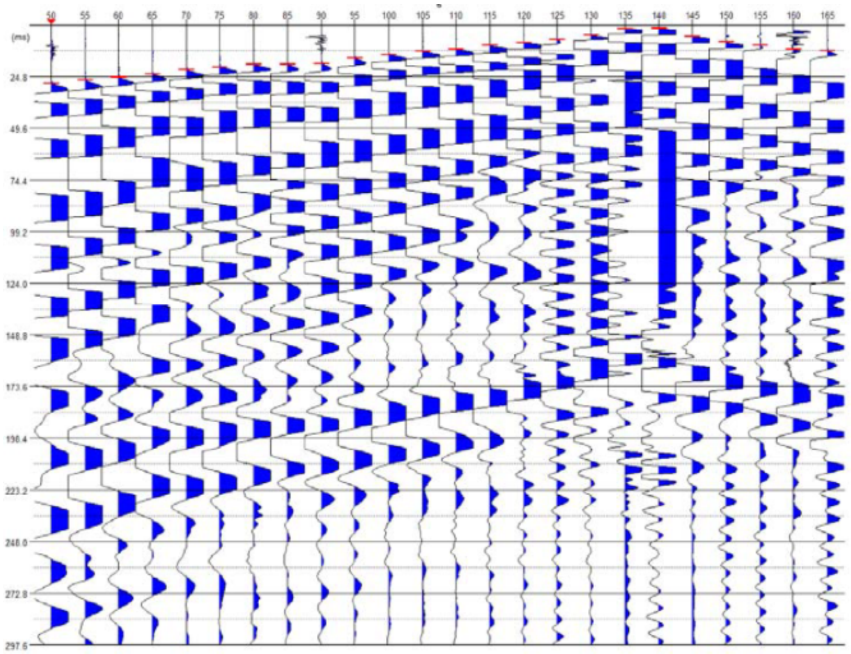
Shot 4



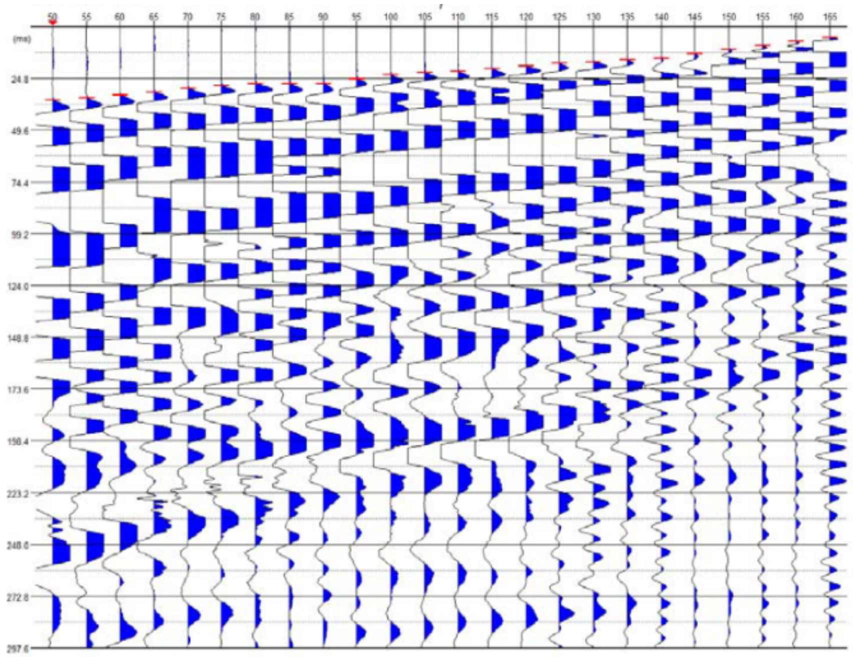
Shot 5

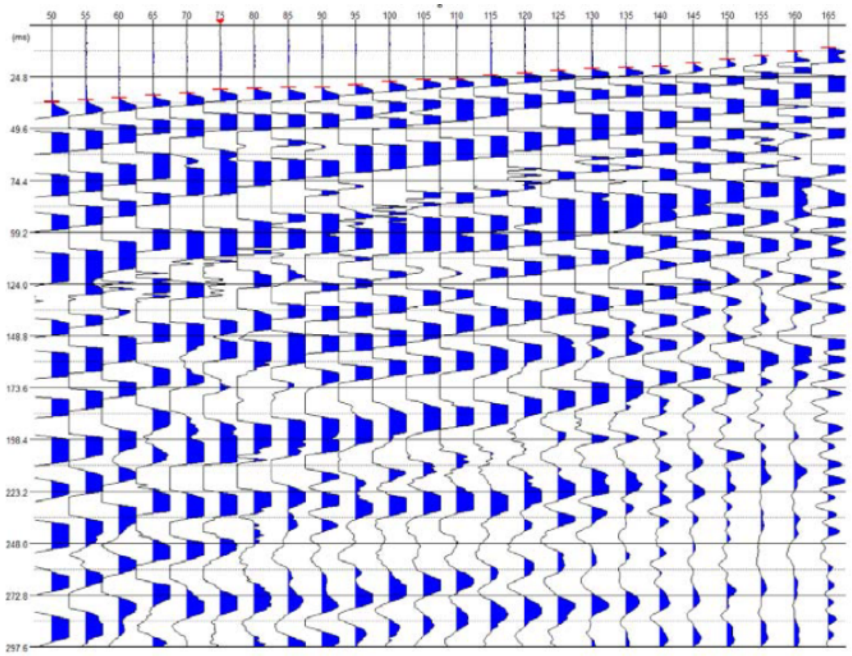


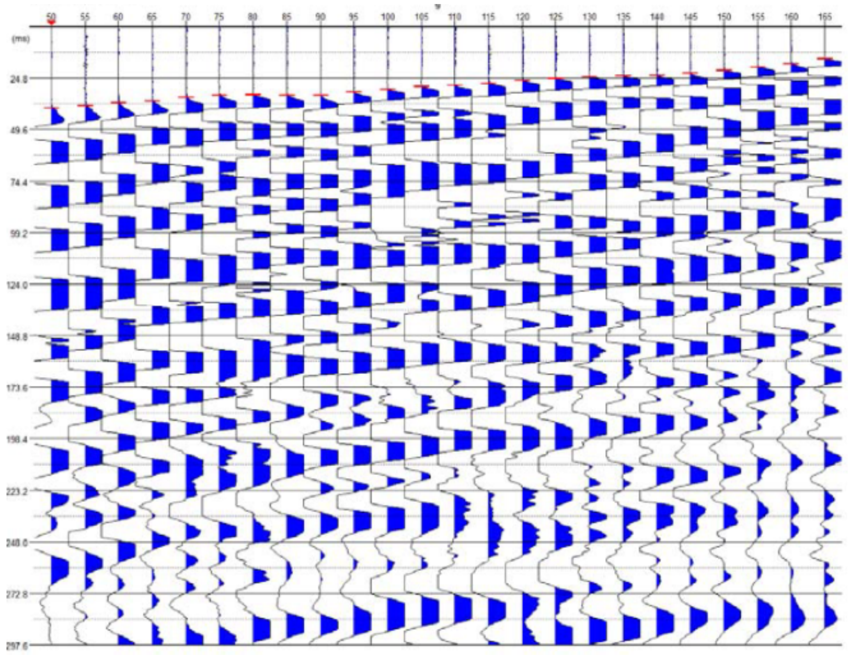
Shot 6



Seismic Refraction

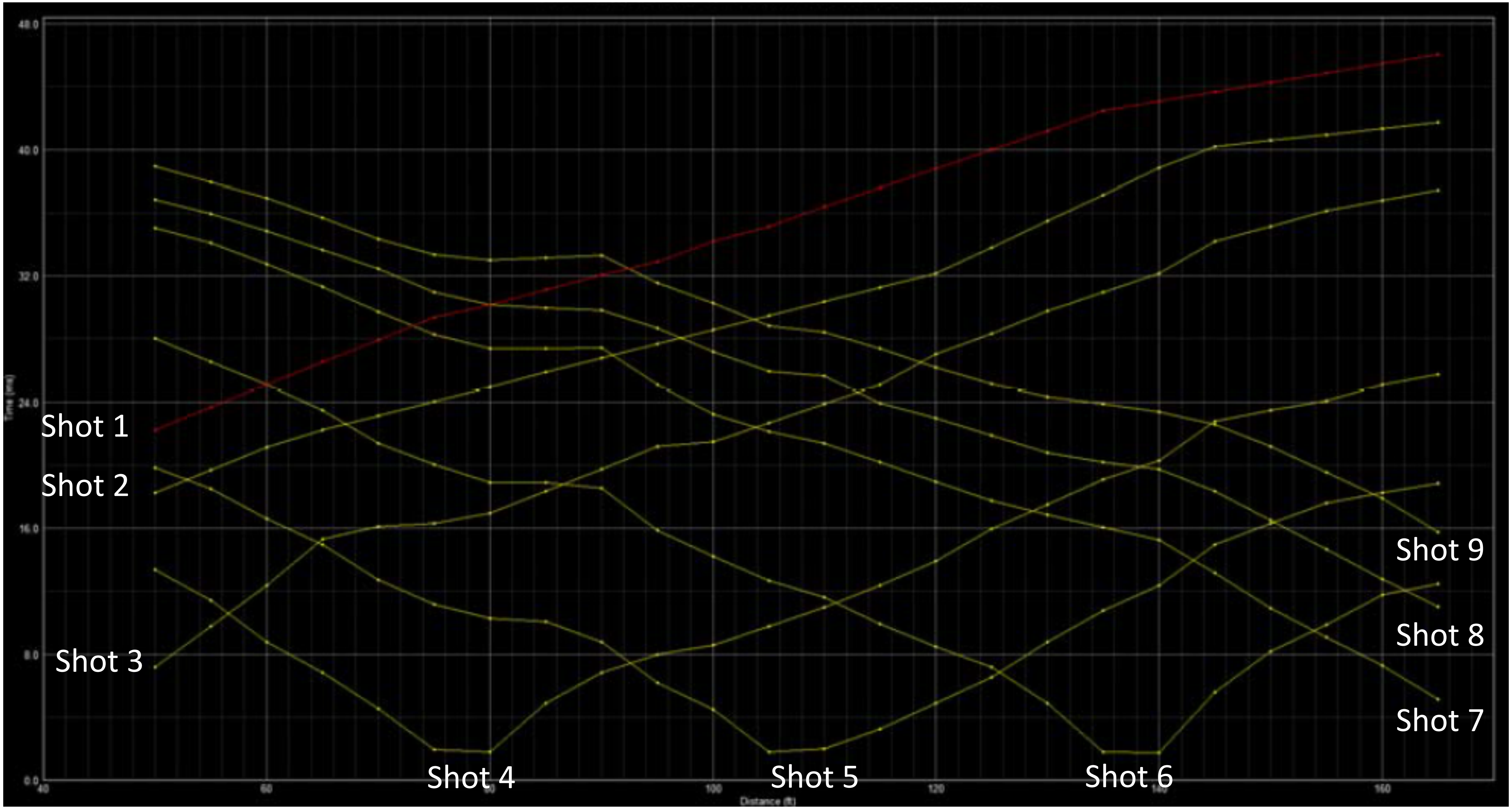

Shot 7


Shot 8


Shot 9

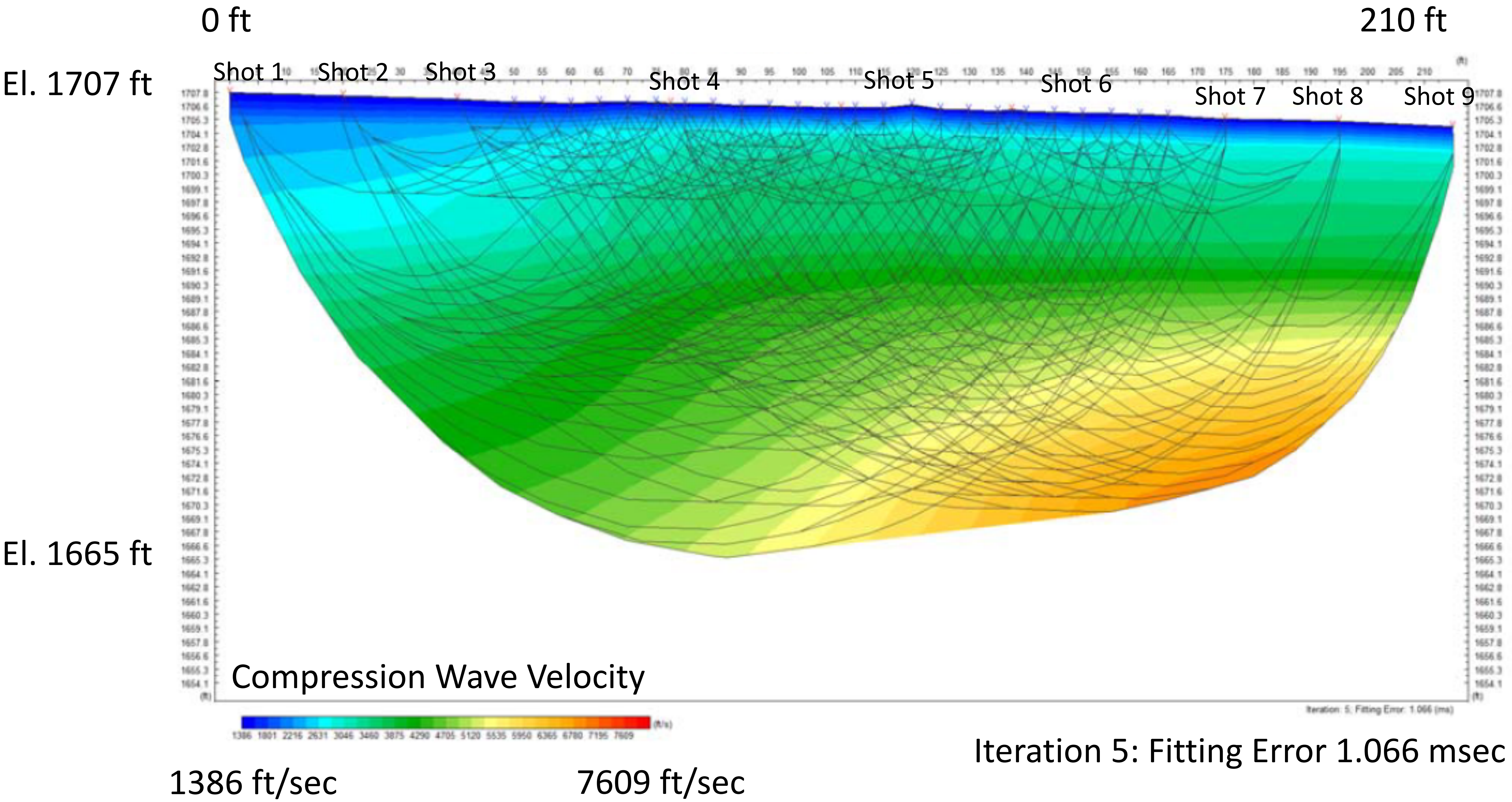
DIPARTIMENTO
DI GEOSCIENZE

Seismic Refraction



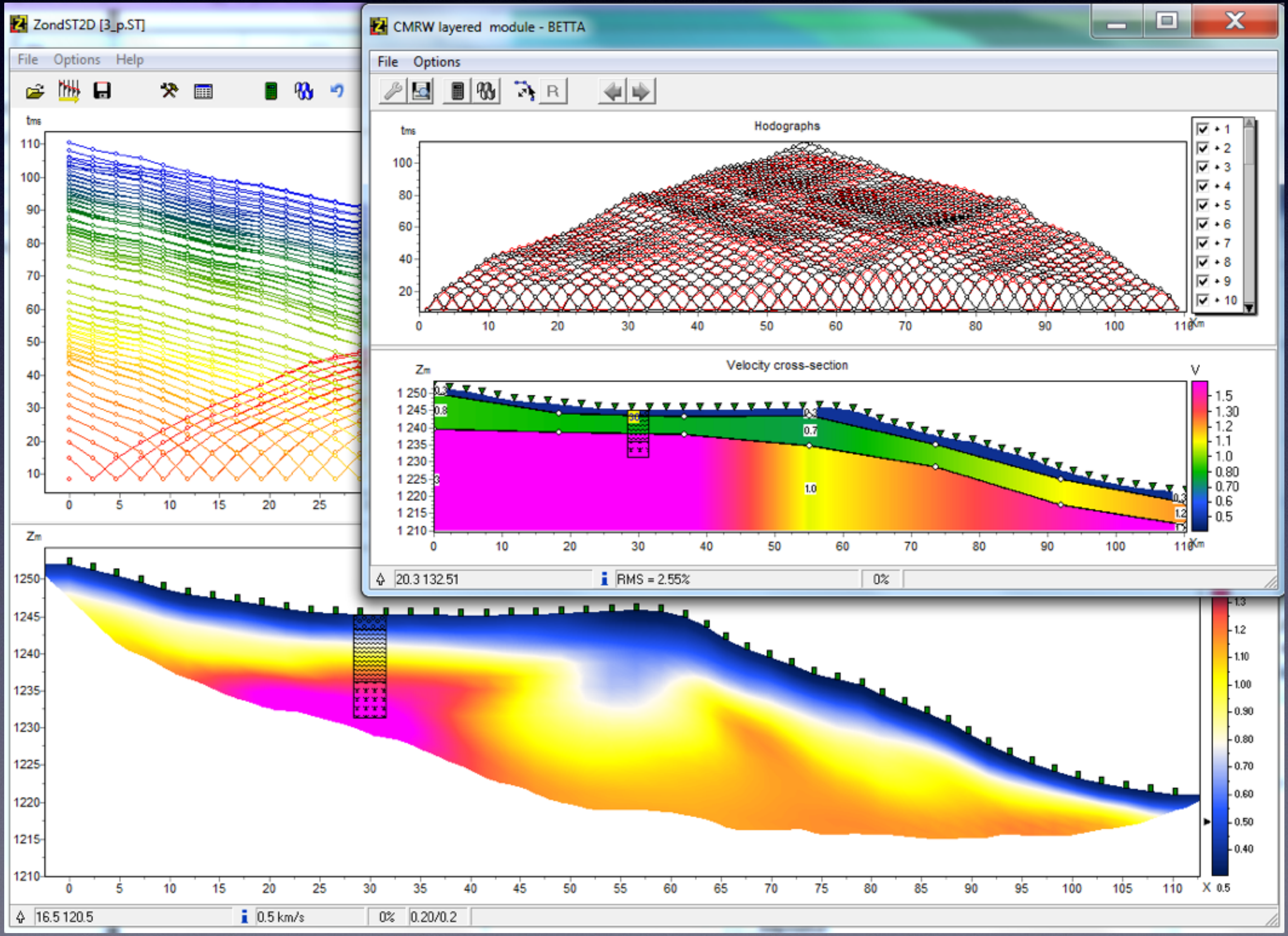
DIPARTIMENTO
DI GEOSCIENZE

Seismic Refraction



REFRACTION SEISMIC

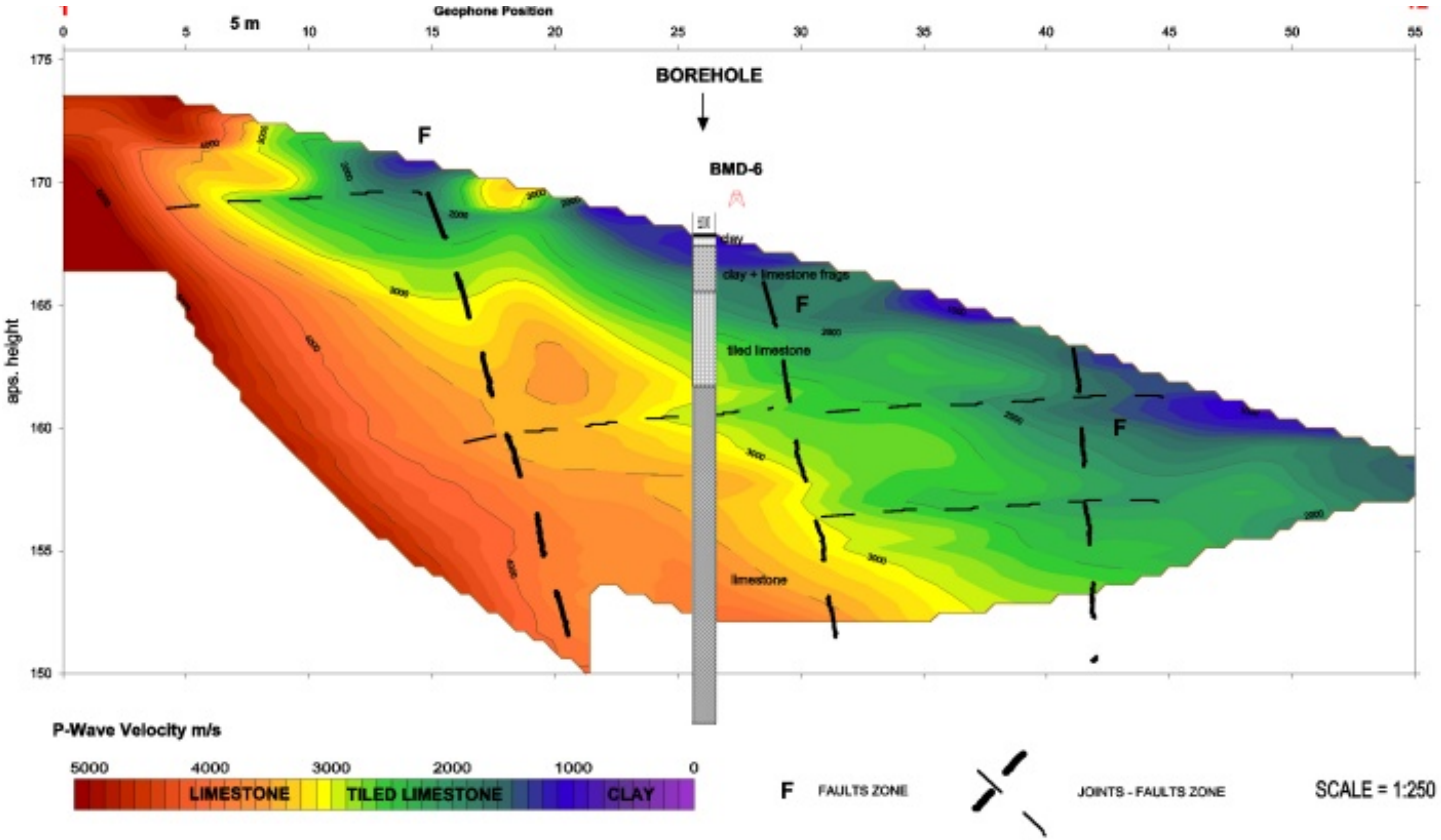
Dozens of shot, dozen of ray paths **Software** *Seismic tomography*



Velocities fields
In 2D -3D

Seismic Tomography

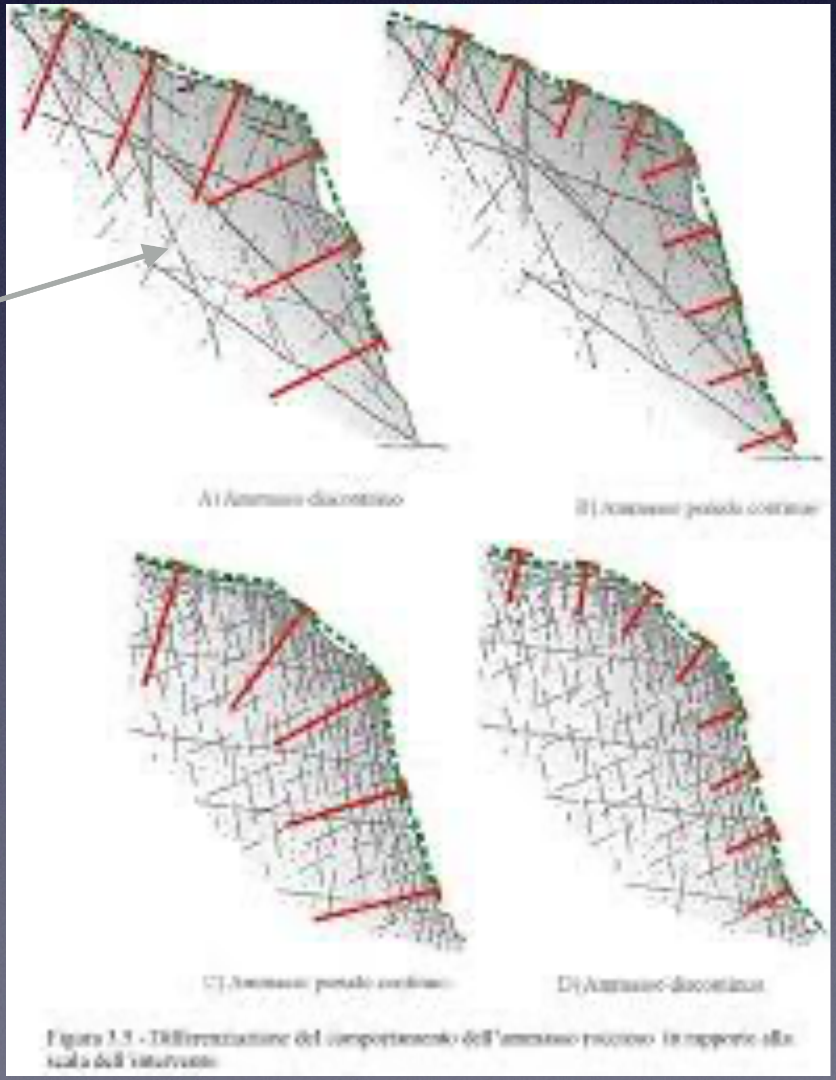
2D section of velocities distribution



Vp

Do I need this course ?

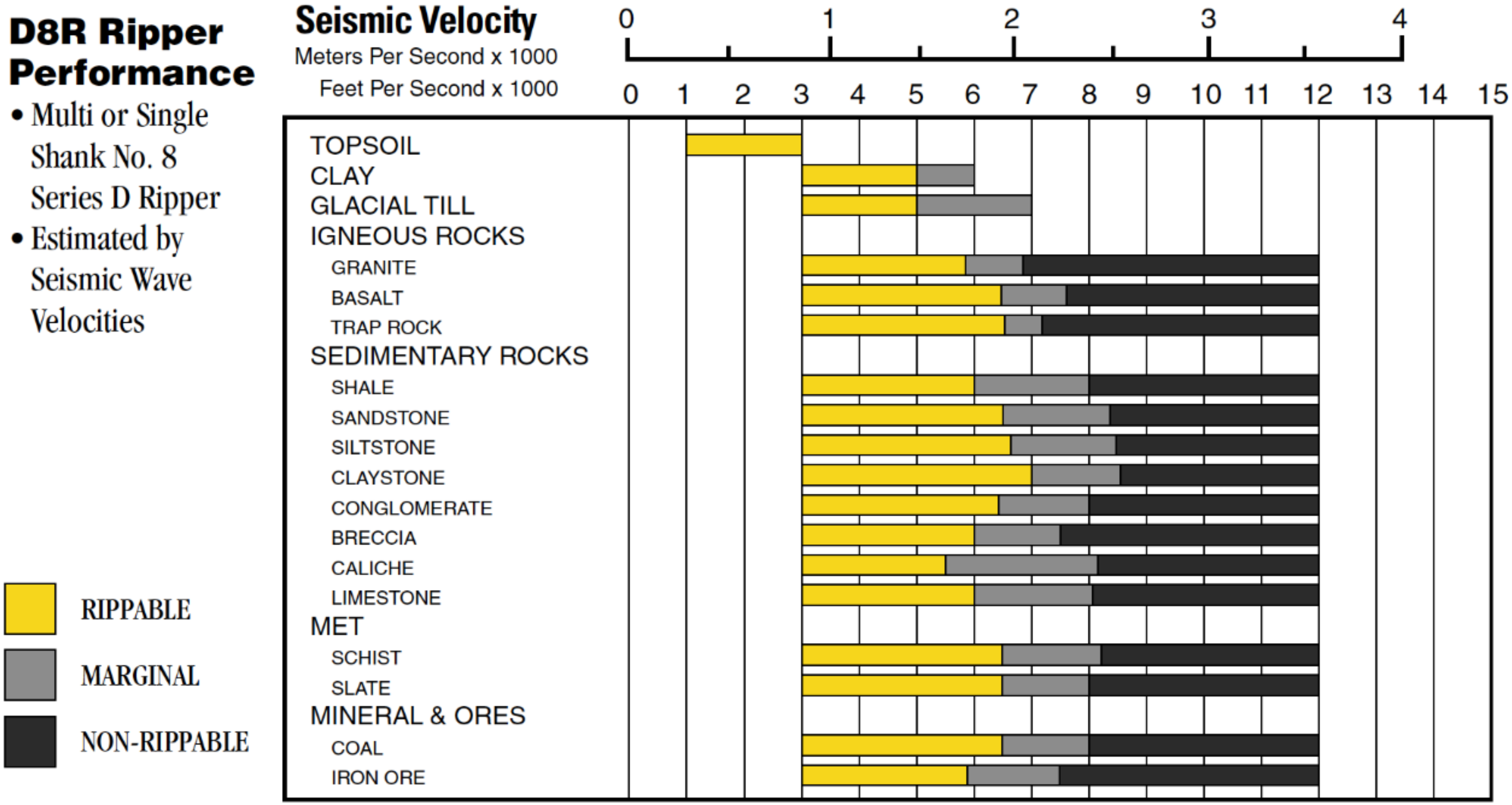
Practical problem:
Design a classical net
defence for rock falls



Nails must be anchored
in the solid rock
underneath debris…

How to do?

Seismic Refraction



D8R Ripper Performance

- Multi or Single Shank No. 8 Series D Ripper
- Estimated by Seismic Wave Velocities

Source: Caterpillar

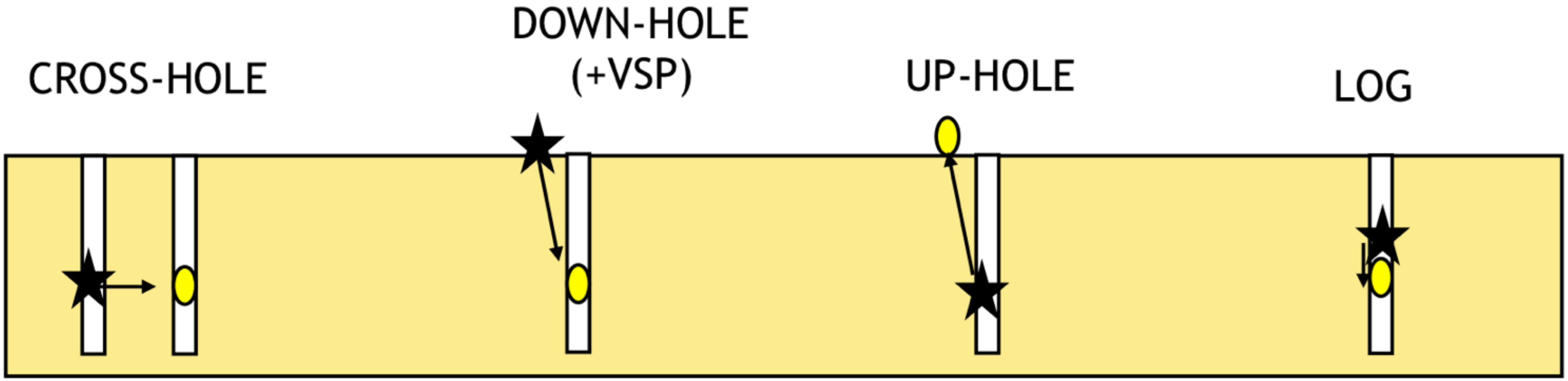
Seismic Methods

Refraction seismic

- *Depth of penetration limited* (*Depth* ≈ 1/3 array lenght)
- *Good Resolution (f* (λ, Source, dx, etc.))
- *Logistic and processing easy*
- *Both in P wave and S wave (harder logistic)*

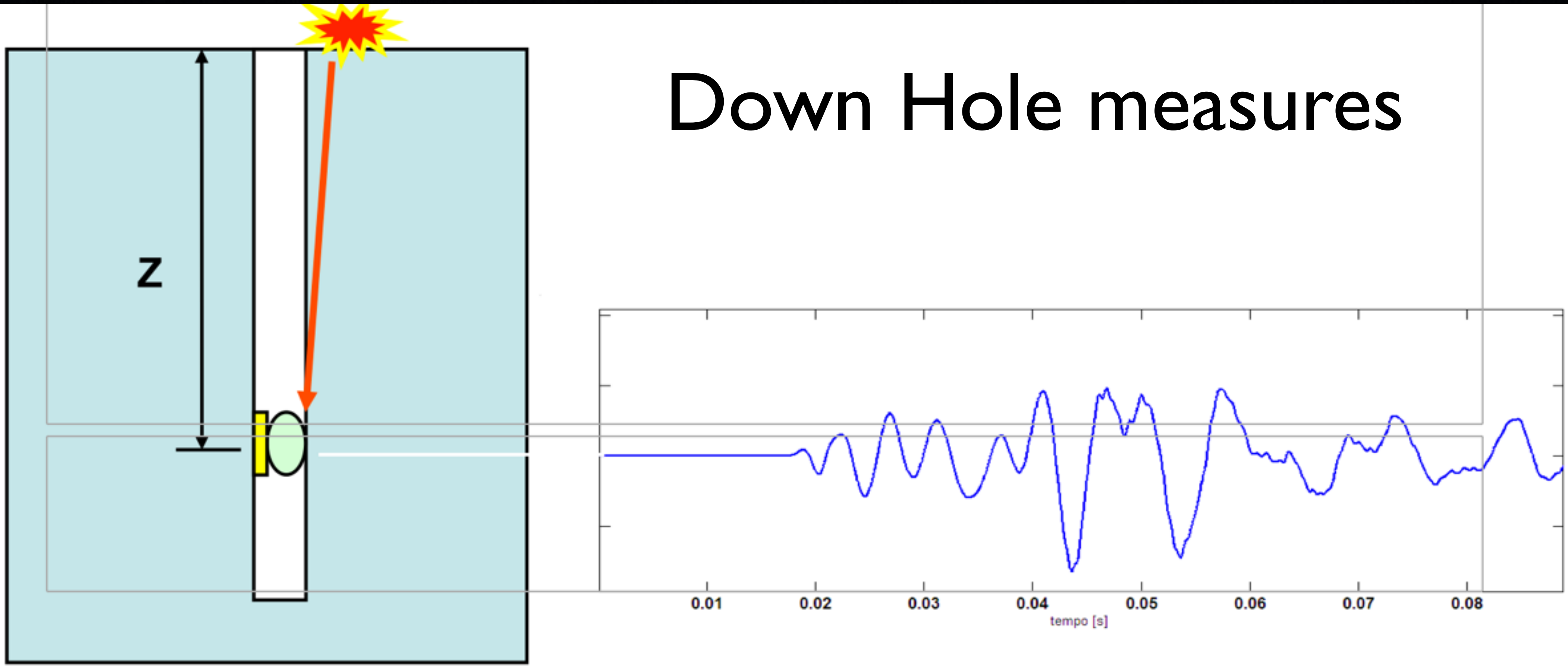
Blind to inversion velocity!

Borehole seismic



Borehole seismic

Down Hole measures

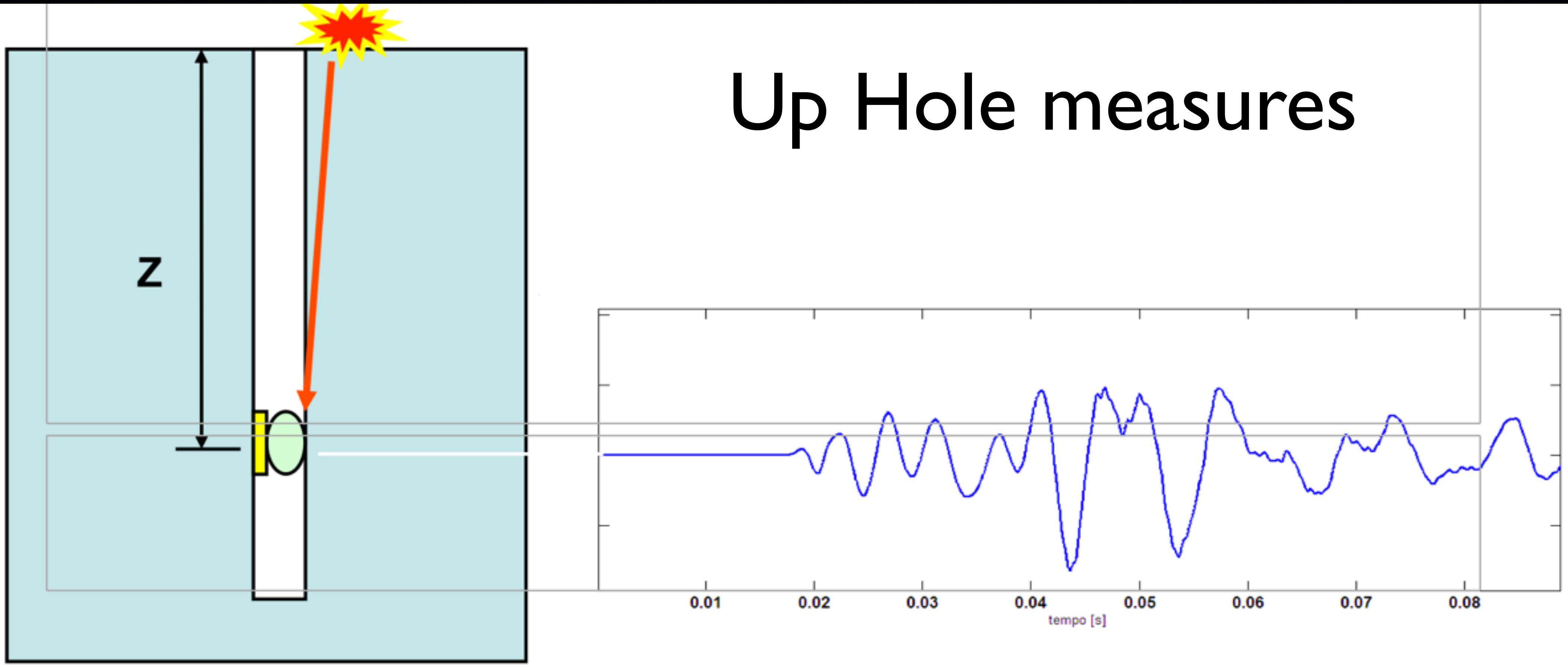


principles

Generate waves at the surface and measure time arrivals with receivers placed in the borehole at several depth. Compute the velocity of the ray path

Borehole seismic

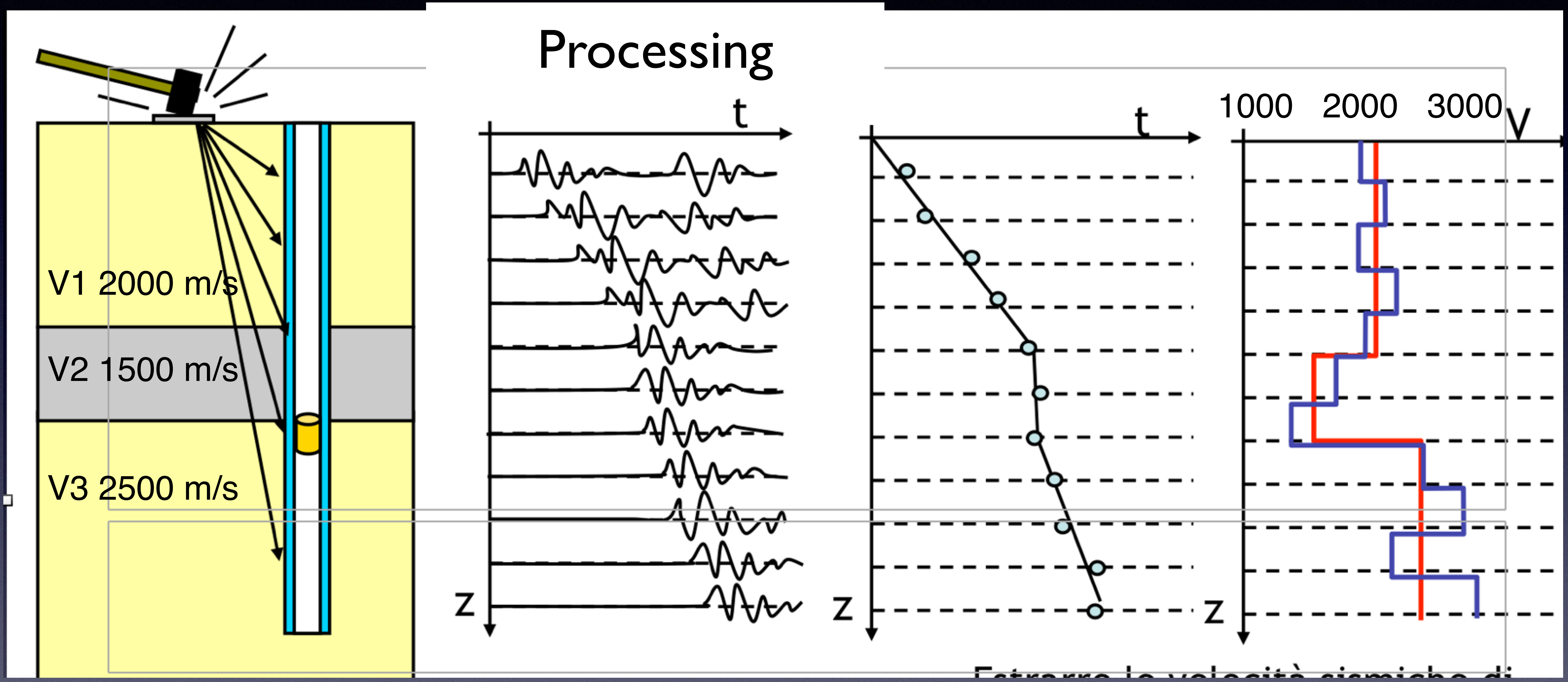
Up Hole measures



principles

Several shots in the borehole keeping fixed a receiver

Borehole seismic


Processing

Acquisition methods

1. SEISMIC WAVE SOURCES

2. RECEIVERS OF MOTION (Geophones)

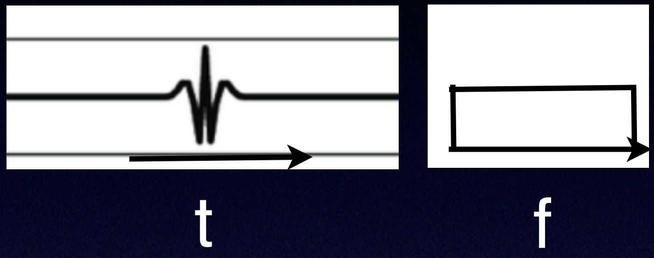
3. RECORDING (Seismograph)

1. SEISMIC WAVE SOURCES

Must be:

- POWERFUL

(Narrow in time, wide in frequency)
$<< \lambda$



$\lambda = v/f$

- RIPETIBLE

To perform stack (sum) of the single and increase the signal/noise ratio

Sources → IMPULSIVE

Sources → VIBROTIONAL

1. SEISMIC WAVE SOURCES

Sledge Hammer

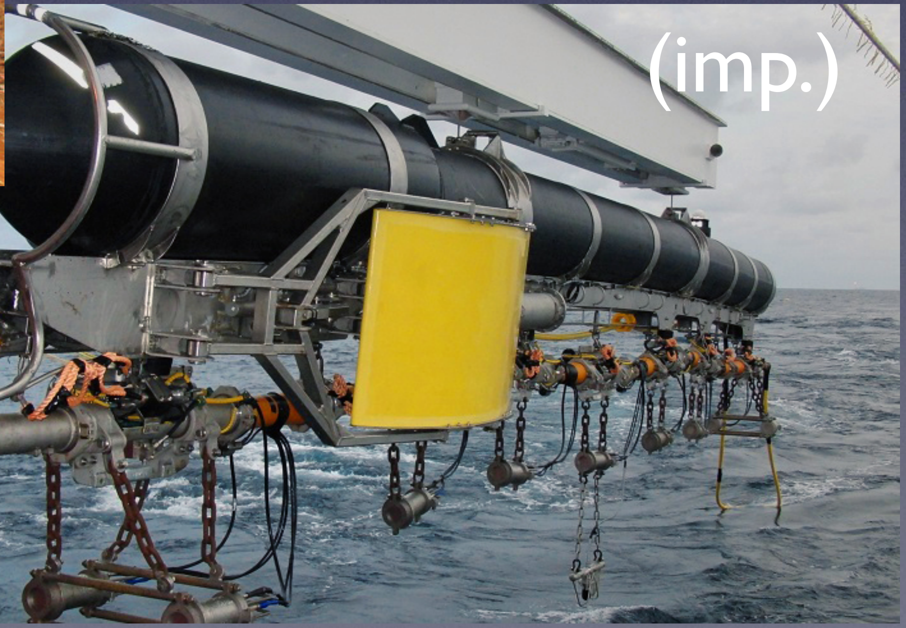
(Impulsive)

Vibroseis

(vibro)

Air gun (sea)

(imp.)



1. SEISMIC WAVE SOURCES

Accelerated
Mass (imp)

f =*m***a*

Seismic gun (imp)

Explosive (imp)

1. SEISMIC WAVE SOURCES

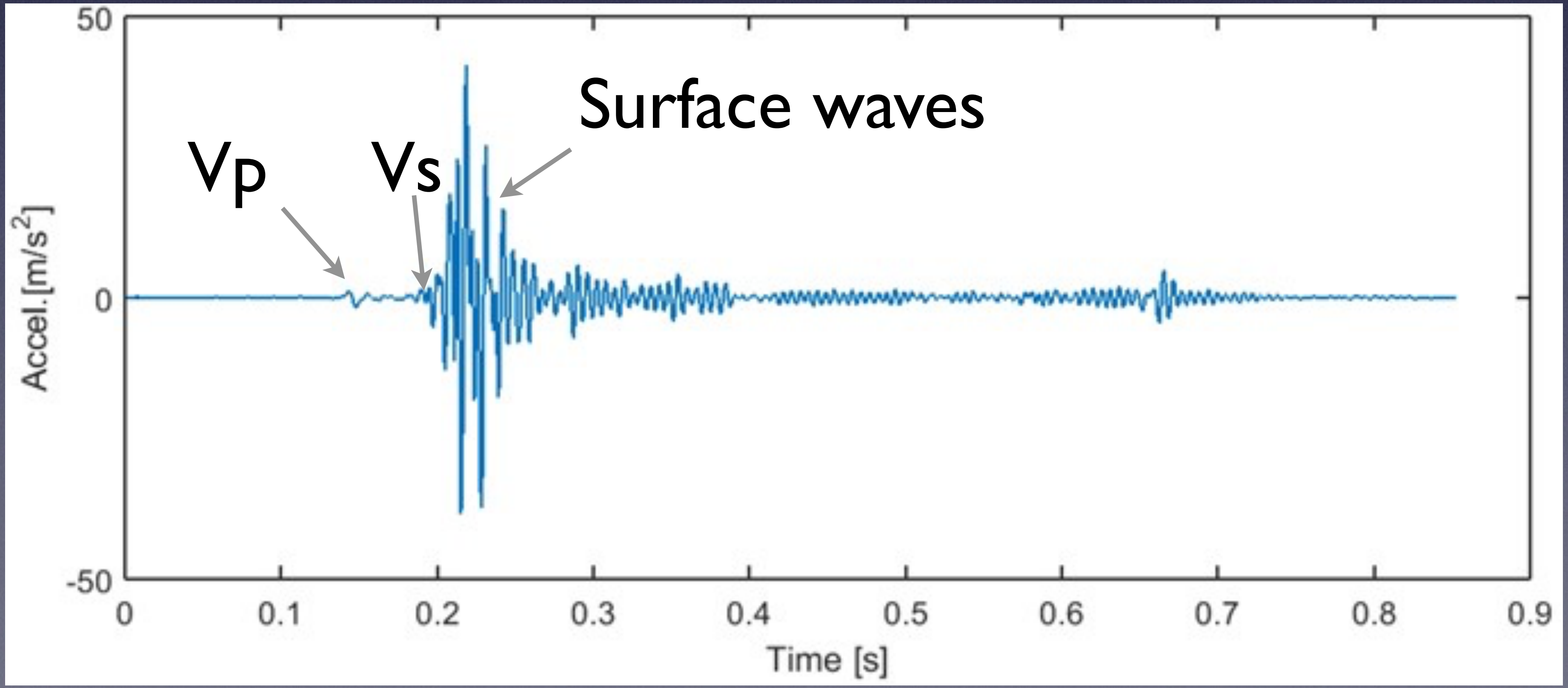
30kg tnt

Seismic

1. SEISMIC WAVE SOURCES

IMPULSIVE

Seismic trace
We want collect



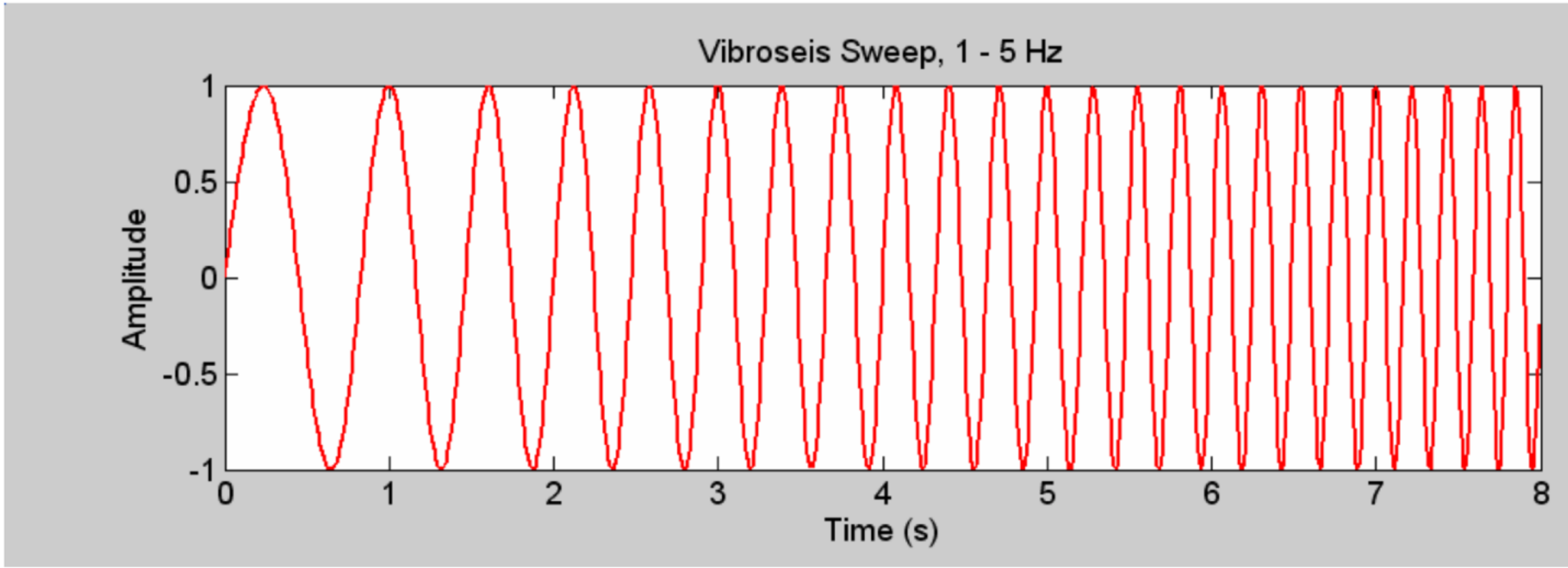
Seismic

1. SEISMIC WAVE SOURCES

Vibrational

VIBROSEIS TRUCK
(Leader of industrial reflection surveys)

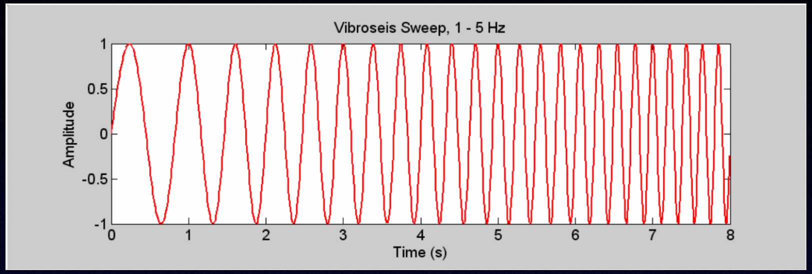
Source of vibration with constant replicable signals
(Called the **sweep**)



e,g, 1Hz -5 Hz 8 seconds sweep

1. SEISMIC WAVE SOURCES

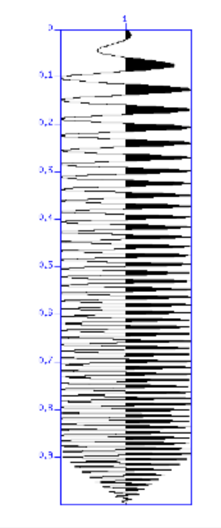
Vibrational



VIBROSEIS

Convolution

$$u(t) = sw(t)*e(t)$$



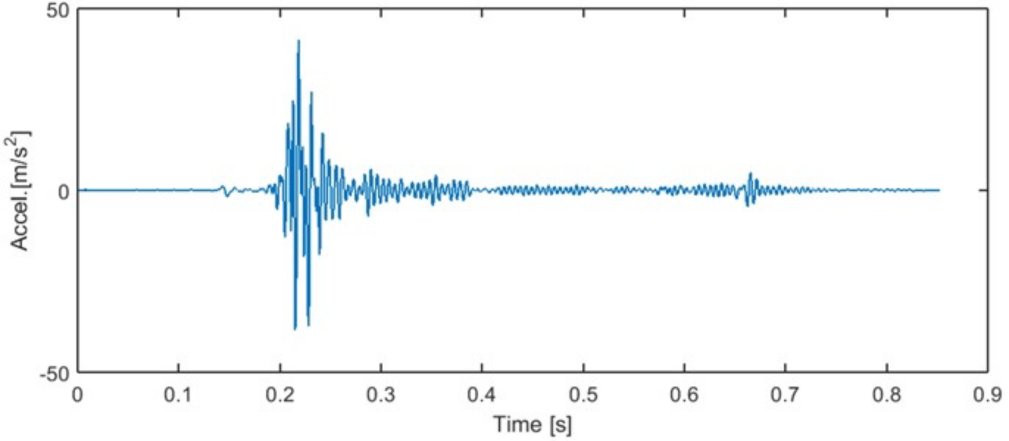
Recorded Seismogram

Sweep

Earth Filter

Trace target

$s(t)$



?

I. SEISMIC WAVE SOURCES

VIBROSEIS

Cross -correlation

$$s(t) = sw(t) \star u(t)$$

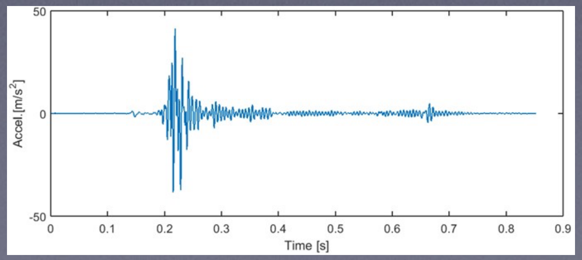
Correlated Seismogram

Sweep

Recorded seismogram

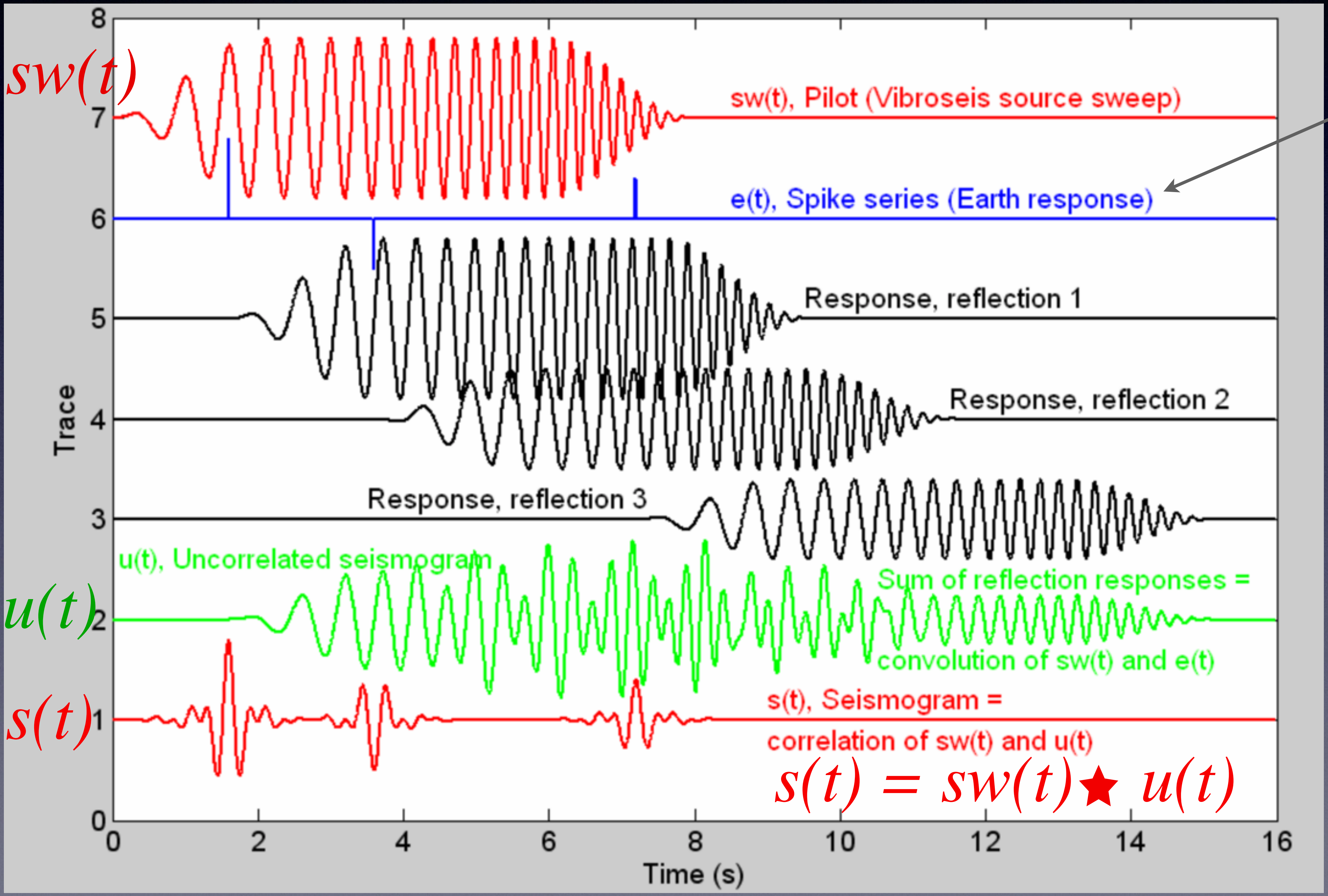
Cross correlation of the Sweep (source) with the recorded signal

Impulsive signal



1. SEISMIC WAVE SOURCES

VIBROSEIS



$$s(t) = sw(t) \star u(t)$$

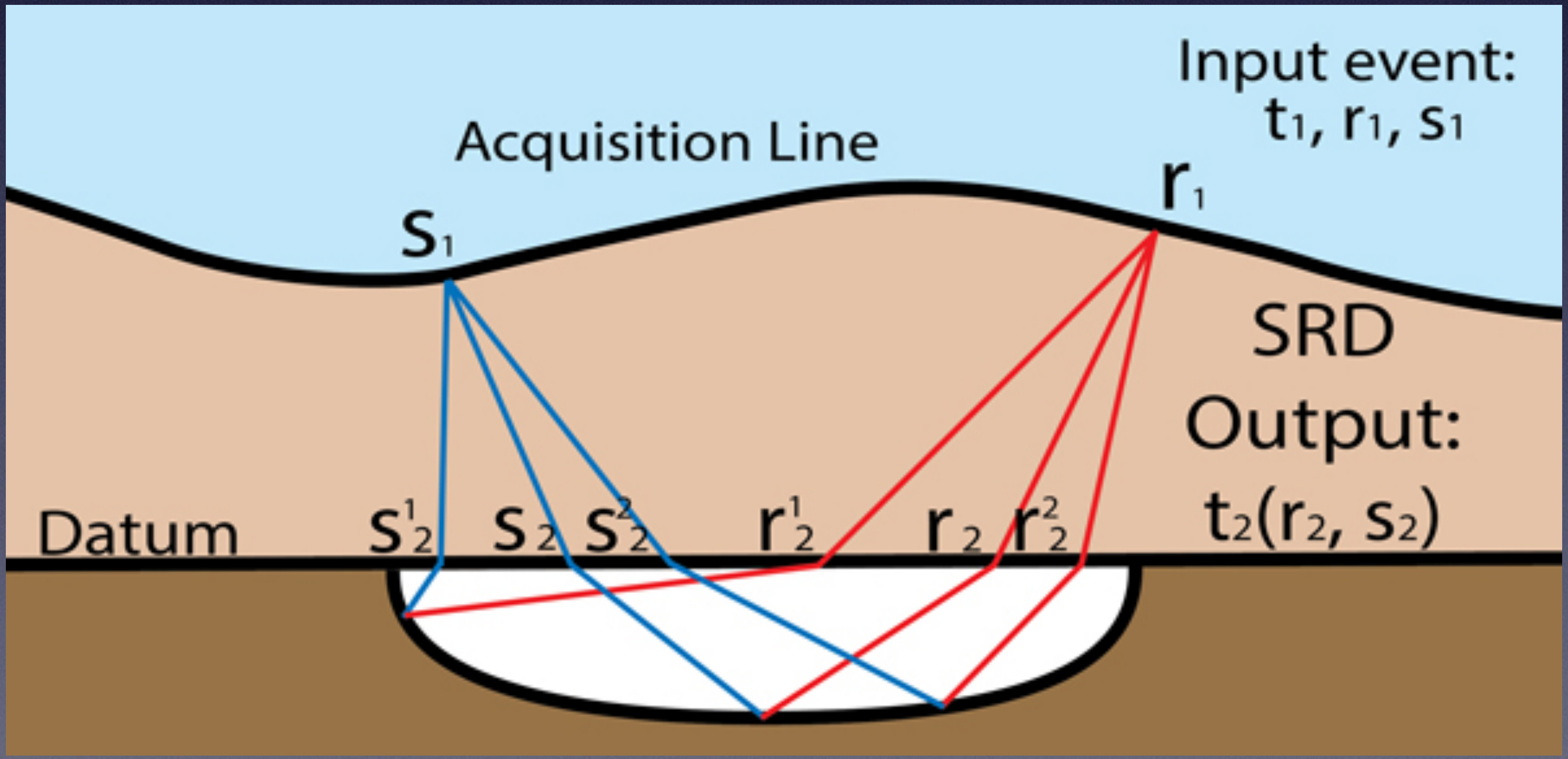
Examples with 3 Layers

1. SEISMIC WAVE SOURCES

Increase source quality

Better to put source in depth, avoiding weathered layer that attenuates the signal

+ Energy
- Attenuation



Topography is relevant

In case you can refer to a unique
Topo
(DATUM
Static correction)

1. SEISMIC WAVE SOURCES

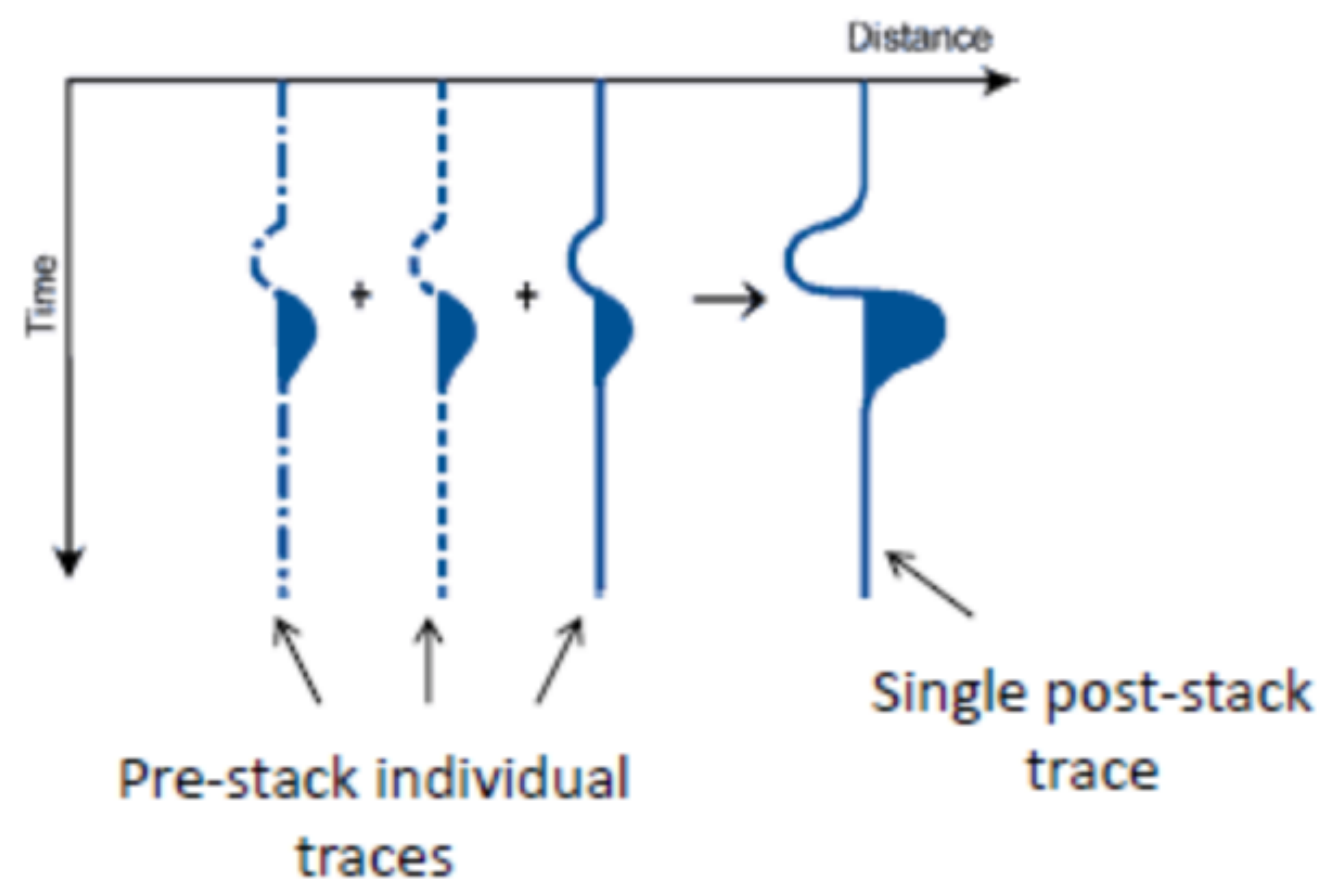
Increase source quality

Execute repeated measurements to sum all the recorded signals

STACKING

Signal is in phase, noise no!

Increase signal to noise ratio (S/N)

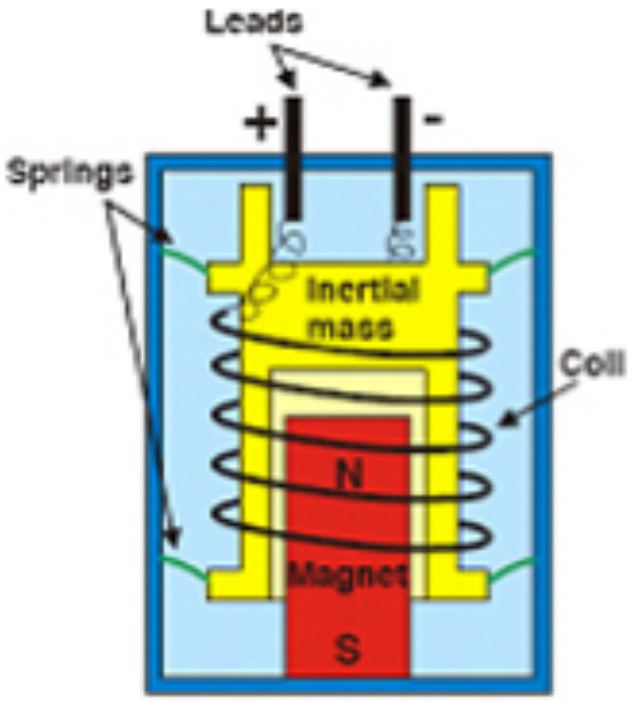


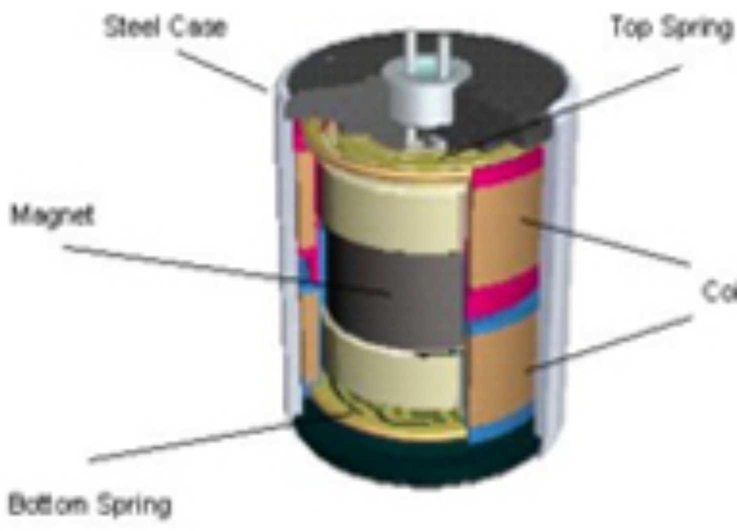
Help the picking

Seismic

RECEIVERS

GEOPHONES





They are **velocimeters** that convert the displacement velocity
In voltage (Faradays law)
For greater shaking also accelerometer are used

RECEIVERS

GEOPHONES

1.BOREHOLE SEISMIC

Down Hole

BOREHOLE GEOPHONE

It is crucial the contact between sensors and borehole:

clipping operation.

Seismic

GEOPHONES

RECEIVERS

Surface ones

- vertical

- Horizontal

- Tri-components

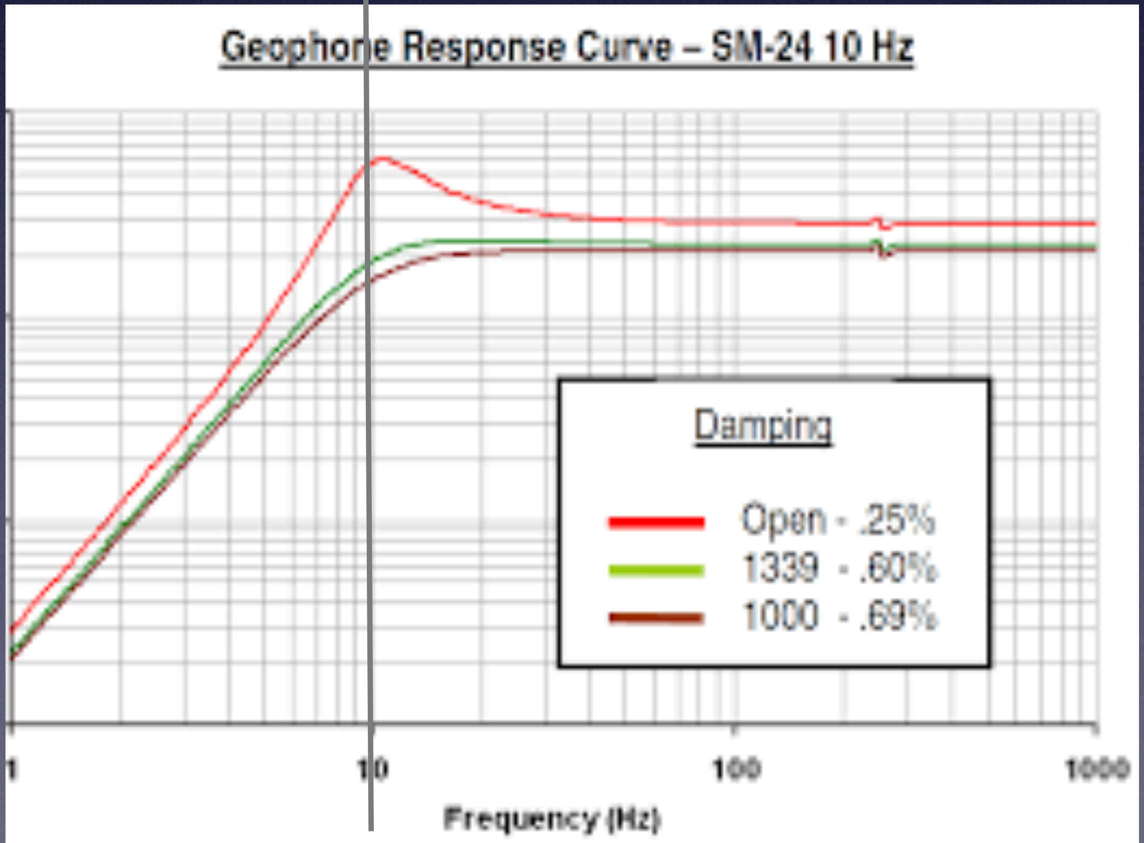
RECEIVERS

GEOPHONES

They are divided in base of the frequency response

NATURAL (CORNER) FREQUENCY OF THE GEOPHONE

Corner Freq.



Transfer function (Instrumental response) of a geophone

They are the high-pass filters

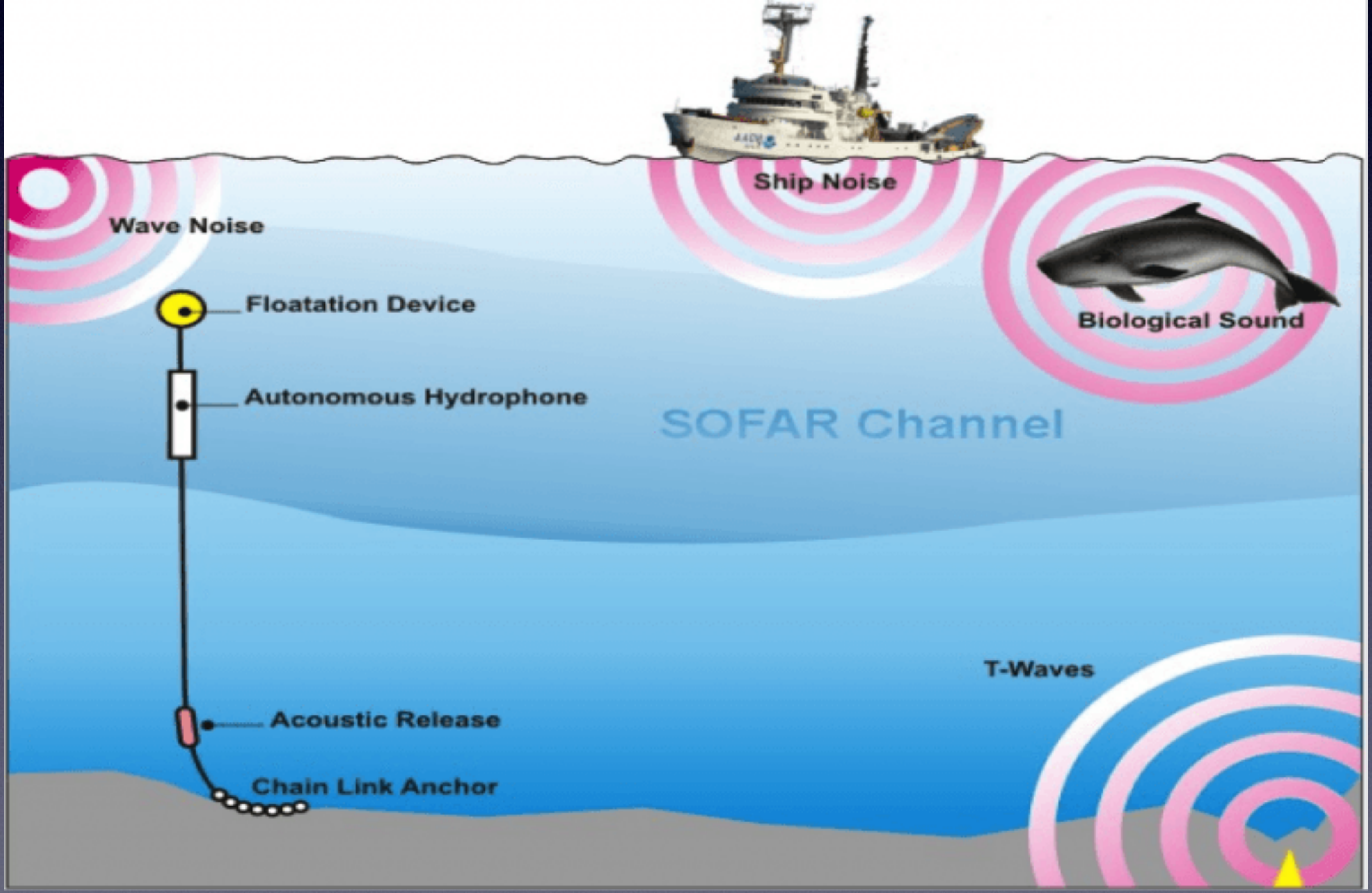
VERY IMPORTANT THE CORRECT CHOICE:
E.g. refraction: 50-100 Hz
SW: 4 Hz

Seismic

RECEIVERS

GEOPHONES

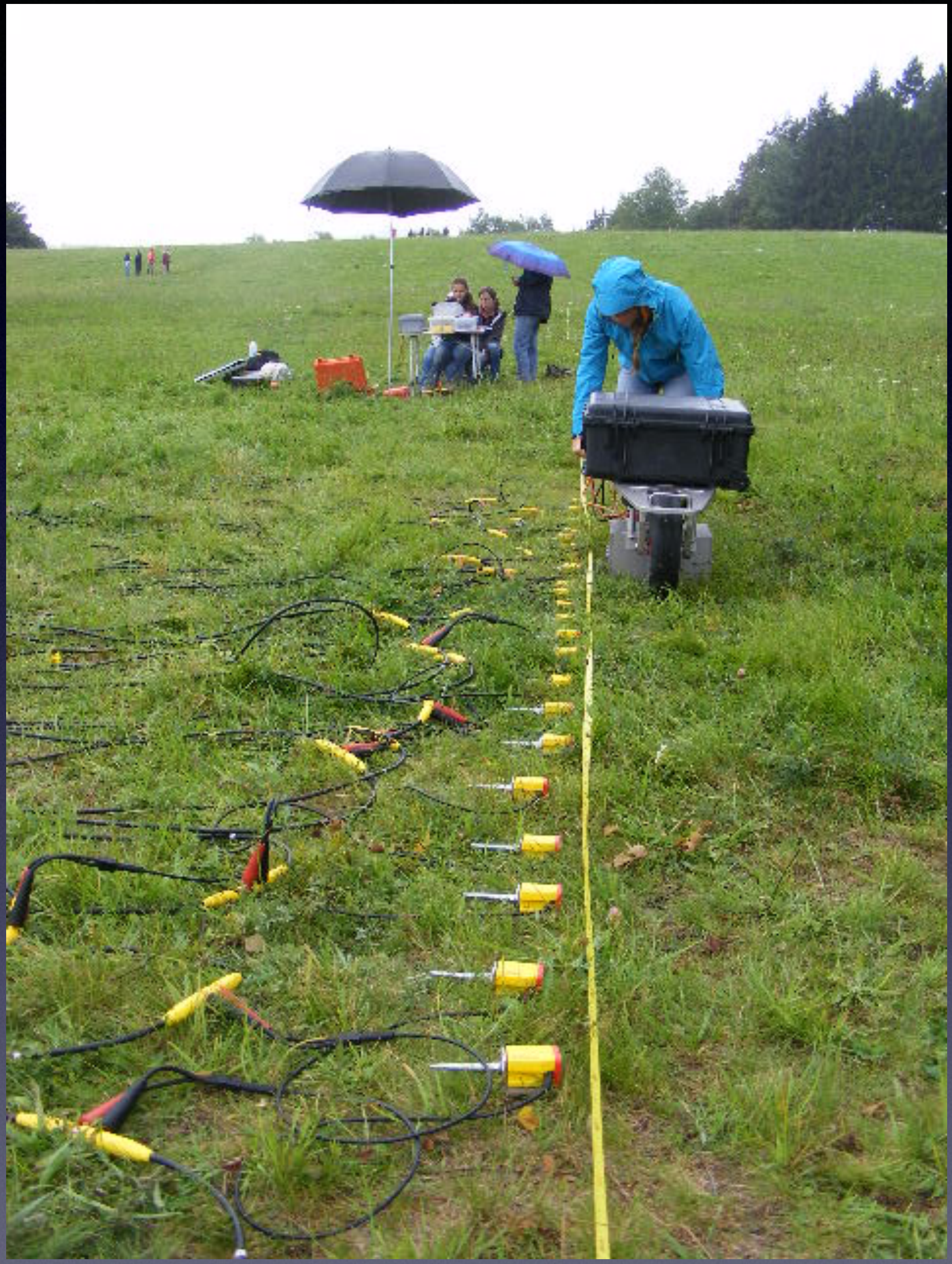
In sea HYDROPHONES



From 4 Hz to
Very high frequency

Seismic

RECEIVER INSTALLATION



USUALLY equal-spaced
Array

<< dx (spacing) >> Resolution

>> x (total lenght) >> Penetration

A compromise between numbers of receivers, spacing, total length, <u>power of the source</u>

RECEIVER INSTALLATION

- Planted

- drilled in holes

- Leaning on pavement….

Seismic

3. RECORDED (SEISMOGRAPH)

Digital
(16-24 bit)

Multi-channels
(24-48- n....)

COMPLEX AND EXPANSIVE INSTRUMENTS

Seismic Logistic

Methods	GEOPHONES	RESOLUTION	DEPTH
Refraction	24- N	cm -m	m - Km

COST: - Geophones 100 $
- cables 5k $
-Seismograph 24 nodes 25k$