Seismic Waves - Introduction

- Stress and strain
  - Elastic constants
  - Body waves and surface waves
  - Seismic wave velocities
  - Attenuation
- Seismic rays
  - Snell's law
  - Reflection, transmission
  - Refraction, Diffraction
- Seismic sources
- Seismic recording systems

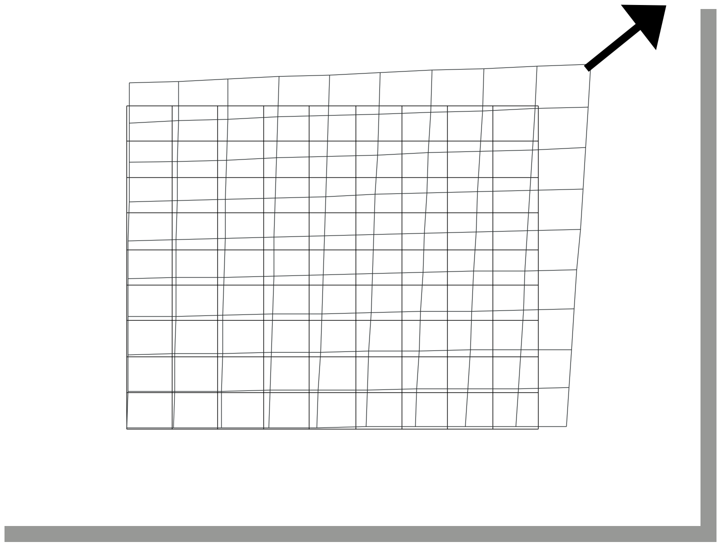
Questions

- Why do we observe waves in the Earth?
- What kind of waves are there?
- How fast do they propagate?
- What determines their speed?
- Do seismic waves vary with rock type?
- Are seismic waves attenuated?
- What waves do we use in seismic exploration?
- How are seismic waves generated (on land, at sea)?
- With what instruments can we observe seismic waves?

Stress and strain

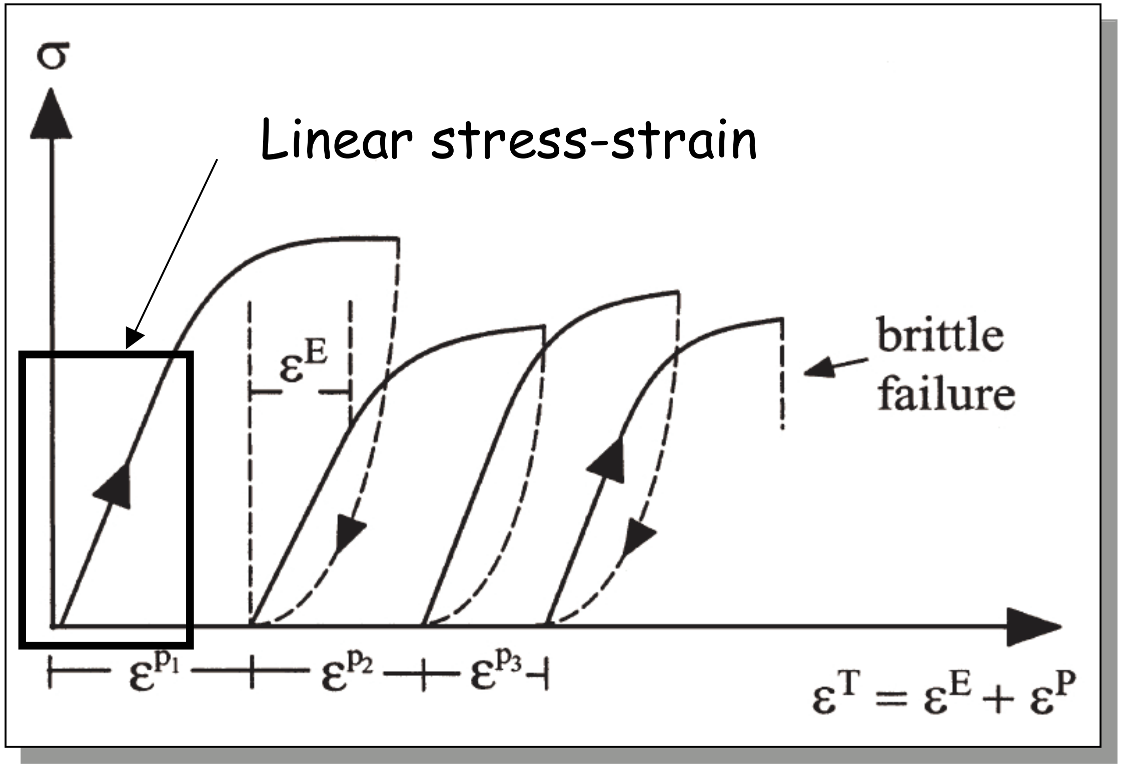
To first order the Earth' crust deforms like an elastic body when the deformation (strain) is small.

In other words, if the force that causes the deformation is stopped the rock will go back to its original form.



The change in shape (i.e., the deformation) is called strain, the forces that cause this strain are called stresses.

Linear and non-linear stress and strain

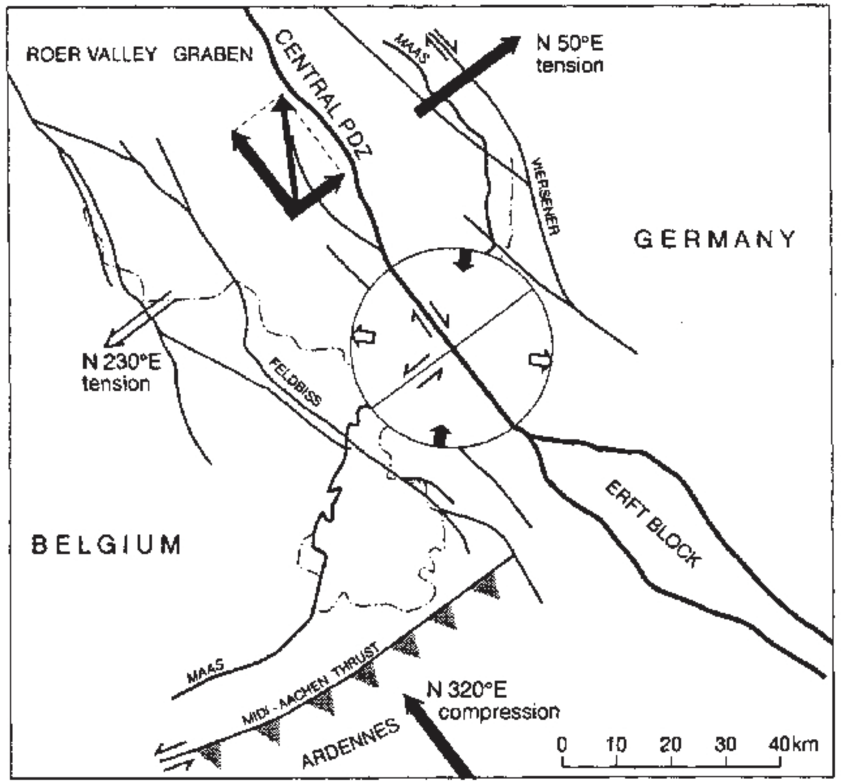


Stress vs. strain for a loading cycle with rock that breaks. In applied seismics assuming linear elasticity is usually sufficient.

Principal stress, hydrostatic stress

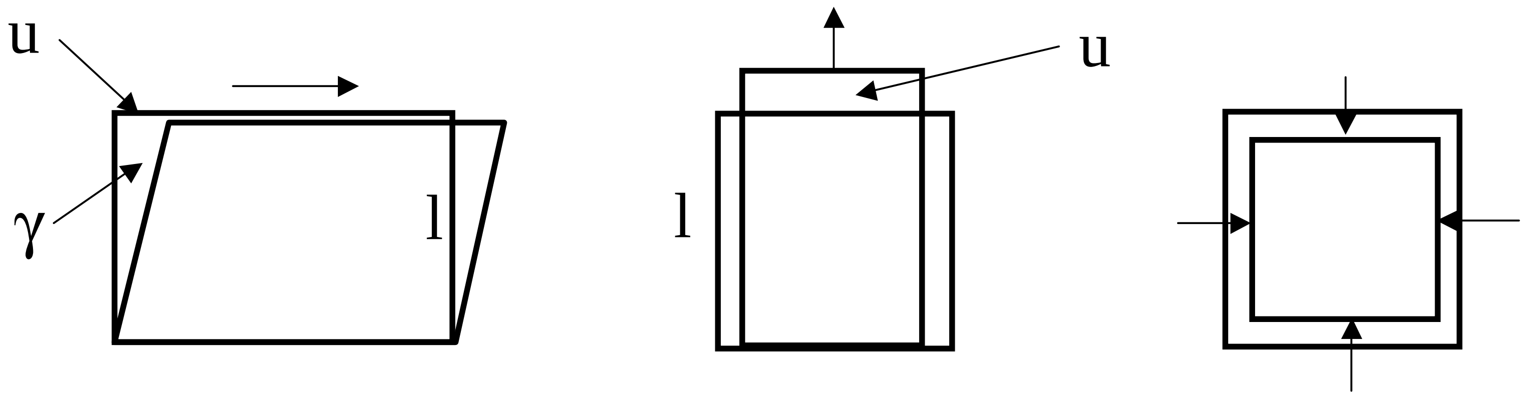
Horizontal stresses are influenced by tectonic forces (regional and local). This implies that usually there are two uneven horizontal principal stress directions.

Example: Cologne Basin



When all three orthogonal principal stresses are equal we speak of hydrostatic stress.

Elastic constants



$$\sigma_{12} = \mu\gamma \qquad \sigma_{22} = E\,\tfrac{u}{l} \qquad P = K\,\tfrac{\Delta V}{V} = K\varepsilon_{ii}$$

The elastic constants link the stresses and the strains (think of the spring constants in the 1D problem)

Stress = Elastic constants * strain

F = D * s   Hooke's Law

Elastic constants

The elastic constants describe how a material deforms when it's stressed. Unfortunately there are many different approaches. The most important are (compare with previous slide):

Young's modulus $E = \dfrac{\text{longitudinal stress } F/A}{\text{longitudinal strain } \Delta l/l}$

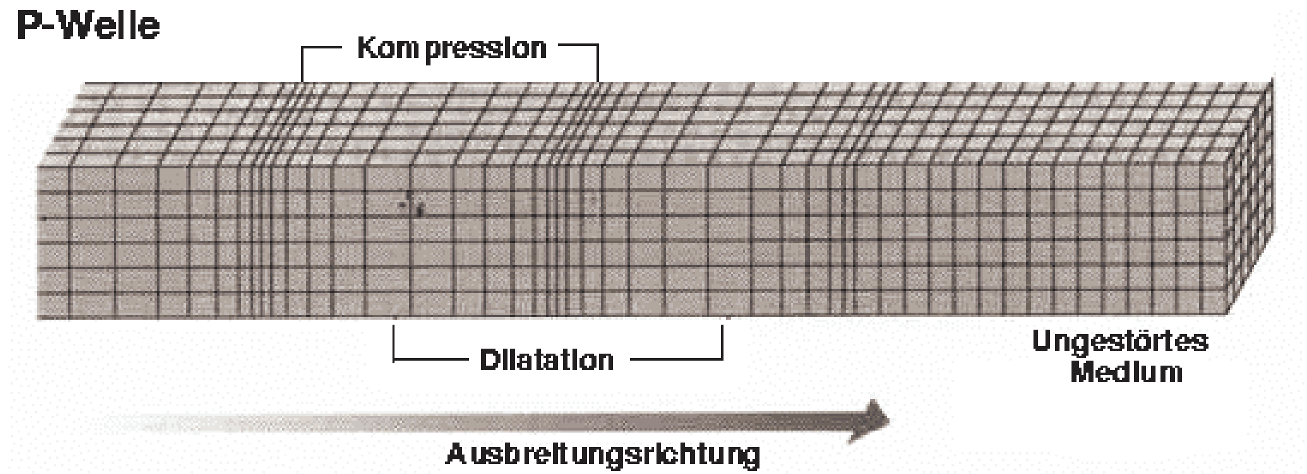
Bulk modulus $K = \dfrac{\text{volume stress } P}{\text{volume strain } \Delta V/V}$

Shear modulus $\mu = \dfrac{\text{shear stress}}{\text{shear strain } (\tan \varphi)}$

Others: Lame' parameters, Poisson's ratio, etc.

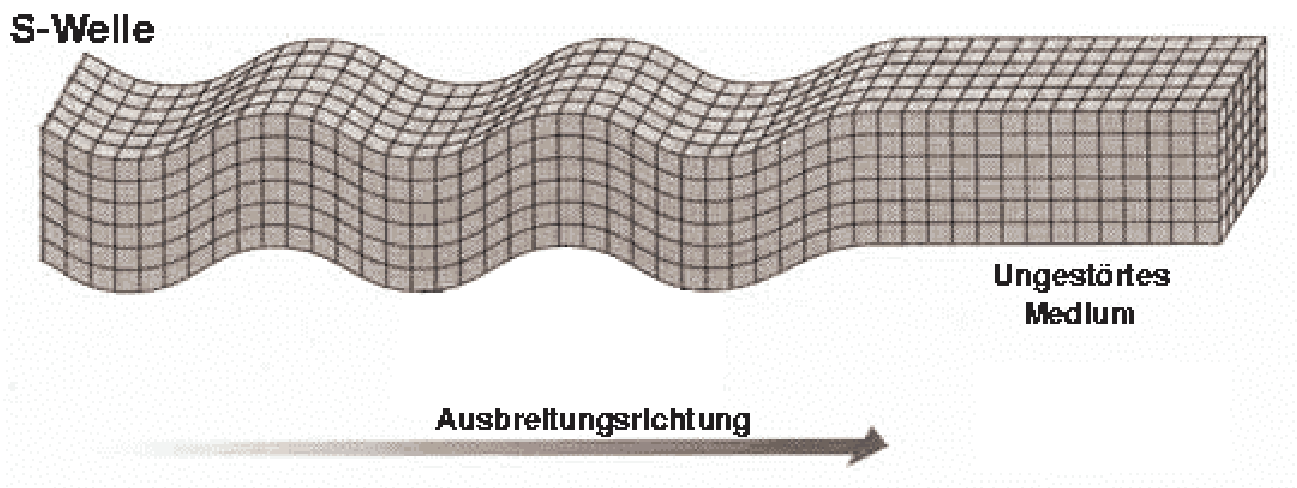
Seismic wave types
P - waves

P – primary waves – compressional waves – longitudinal waves



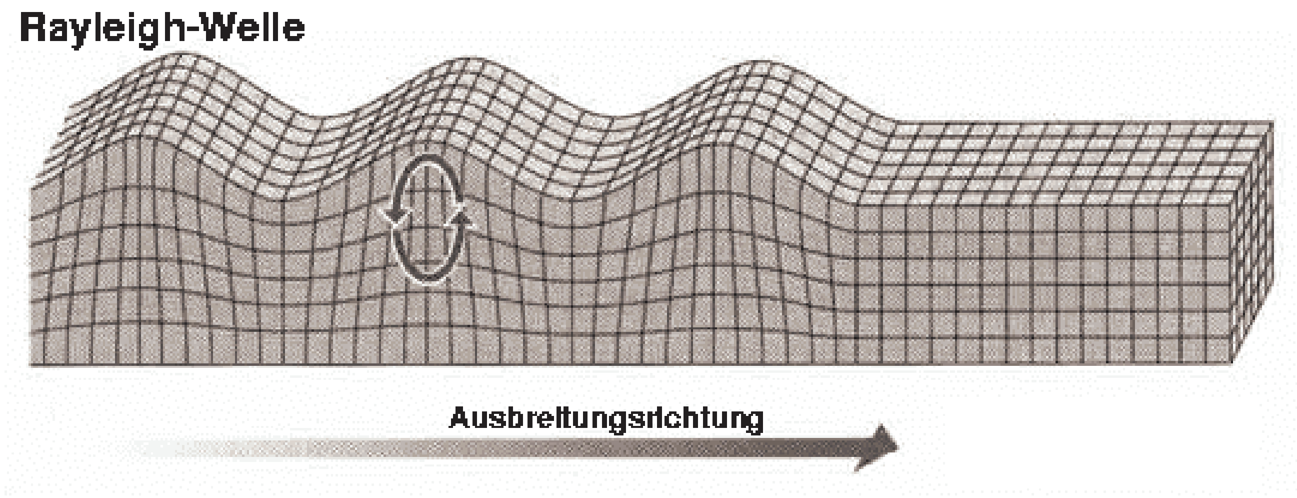
Seismic wave types
S - waves

S – waves – secondary waves – shear waves – transverse waves



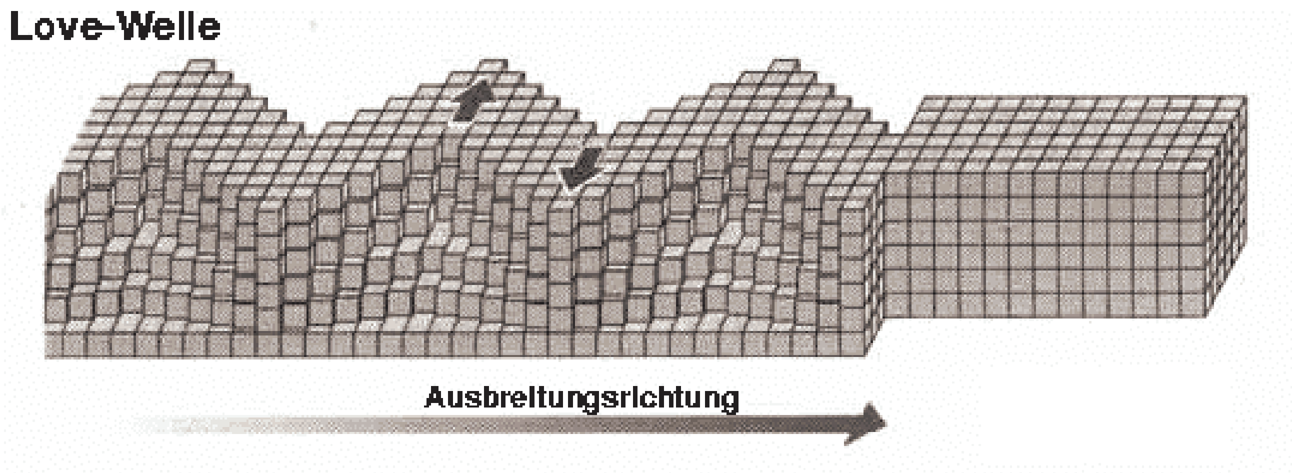
Seismic wave types
Rayleigh waves

Rayleigh waves – polarized in the plane through source and receiver – superposition of P and SV waves



Seismic wave types
Love waves

Love waves – transversely polarized – superposition of SH waves in layered media



Seismic wave velocities

Seismic wave velocities v strongly depend on

- rock type (sediment, igenous, volcanic)
- porosity
- pressure and temperature
- pore space content (gas, liquid)

$$v = \sqrt{\frac{ElasticModuli}{Density}}$$

Seismic wave velocities
P-waves

Material	V_p (km/s)
Unconsolidated material	
Sand (dry)	0.2-1.0
Sand (wet)	1.5-2.0
Sediments	
Sandstones	2.0-6.0
Limestones	2.0-6.0
Igneous rocks	
Granite	5.5-6.0
Gabbro	6.5-8.5
Pore fluids	
Air	0.3
Water	1.4-1.5
Oil	1.3-1.4
Other material	
Steel	6.1
Concrete	3.6

Seismic wave velocities
shear waves

The relation between P-waves velocities and shear wave velocities is often described by the v_P/v_s ratio or Poisson's ratio.

A commonly used assumption for crustal rocks is:

$v_P/v_s = sqrt(3) \approx 1.7$

This corresponds to the Poisson ratio σ

$\sigma = 0.25$

With the relation:

$$\frac{v_p}{v_s} = \left[\frac{2(1-\sigma)}{(1-2\sigma)} \right]^{1/2}$$

Fluids or gas in rocks strongly influence the v_P/v_s ratio that is one of the most important diagnostics in seismic exploration!

Seismic velocities and density
Porosity

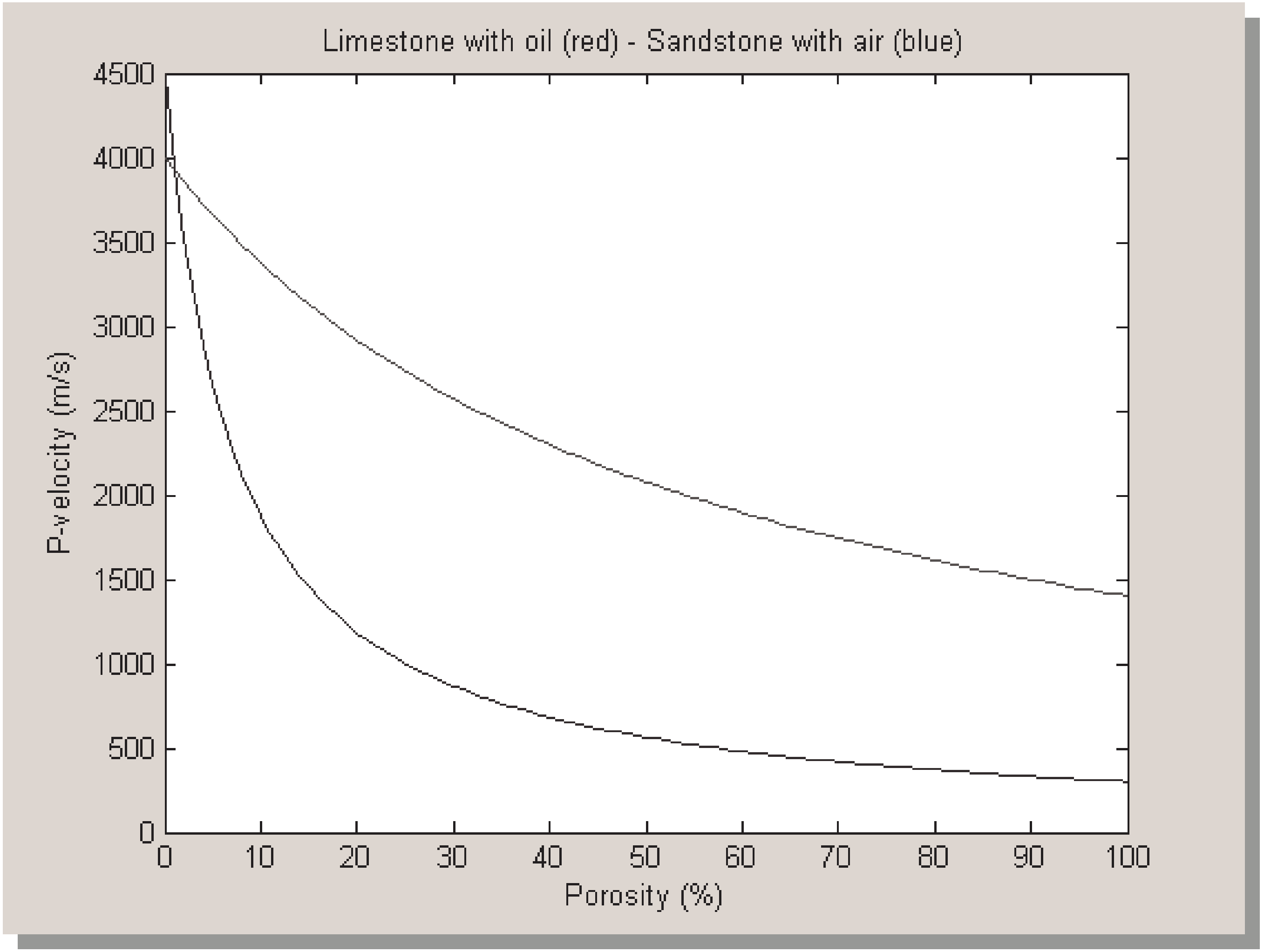
We want to quantify the effect of porosity Φ on the seismic wave velocity and density. With ρ_b the bulk density, ρ_f the pore fluid density and ρ_m the rock matrix density:

$$\rho_b = \rho_f \Phi + (1 - \Phi)\rho_m$$

... and a corresponding relation exists for P-velocity

$$\frac{1}{v_b} = \frac{\Phi}{v_f} + \frac{(1 - \Phi)}{v_m}$$

Seismic velocities and density
Porosity



Attenuation

Propagating seismic waves loose energy due to

- geometrical spreading

  e.g. the energy of spherical wavefront emanating from a point source is distributed over a spherical surface of ever increasing size

- intrinsic attenuation

  elastic wave propagation consists of a permanent exchange between potential (displacement) and kinetic (velocity) energy. This process is not completely reversible. There is energy loss due to shear heating at grain boundaries, mineral dislocations etc.

- scattering attenuation

  whenever there are material changes the energy of a wavefield is scattered in different phases. Depending on the material properties this will lead to amplitude decay and dispersive effects.

Geometrical spreading

Decay of wavefront amplitude/energy for spherical waves

- Energy

    Decay is proportional to $1/r^2$

- Amplitude

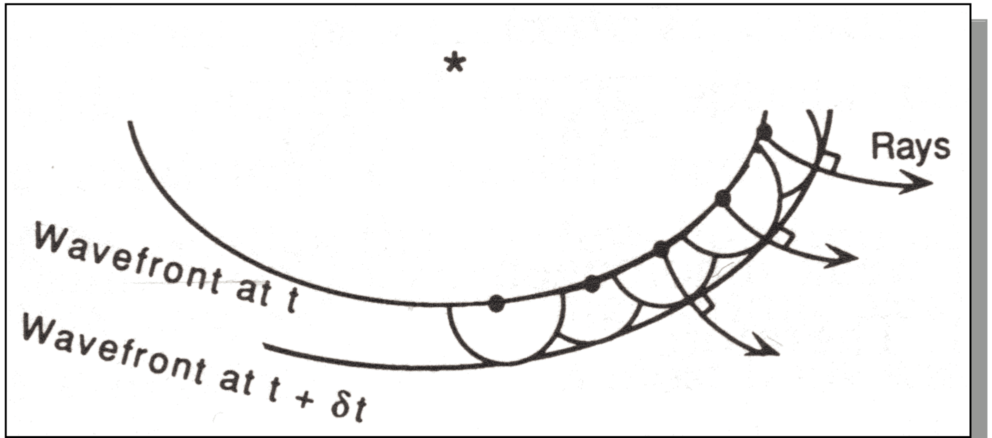
    Decay is proportional to $1/r$

Attenuation Q

Attenuation of seismic wave s if usually desribed by the attenuation factor Q. Q is the energy loss per cycle. Q is usually different for P and S waves. Why?

Rock Type	Q_p	Q_S
Shale	30	10
Sandstone	58	31
Granite	250	70-250
Peridotite	650	280
Midmantle	360	200
Lowermantle	1200	520
Outer Core	8000	0

Seismic rays



Huygens principle states that each point on the wavefront serves as a secondary source. The tangent surface of the expanding waves gives the wavefront at later times. Rays are the trajectories perpendicular to the wavefronts.

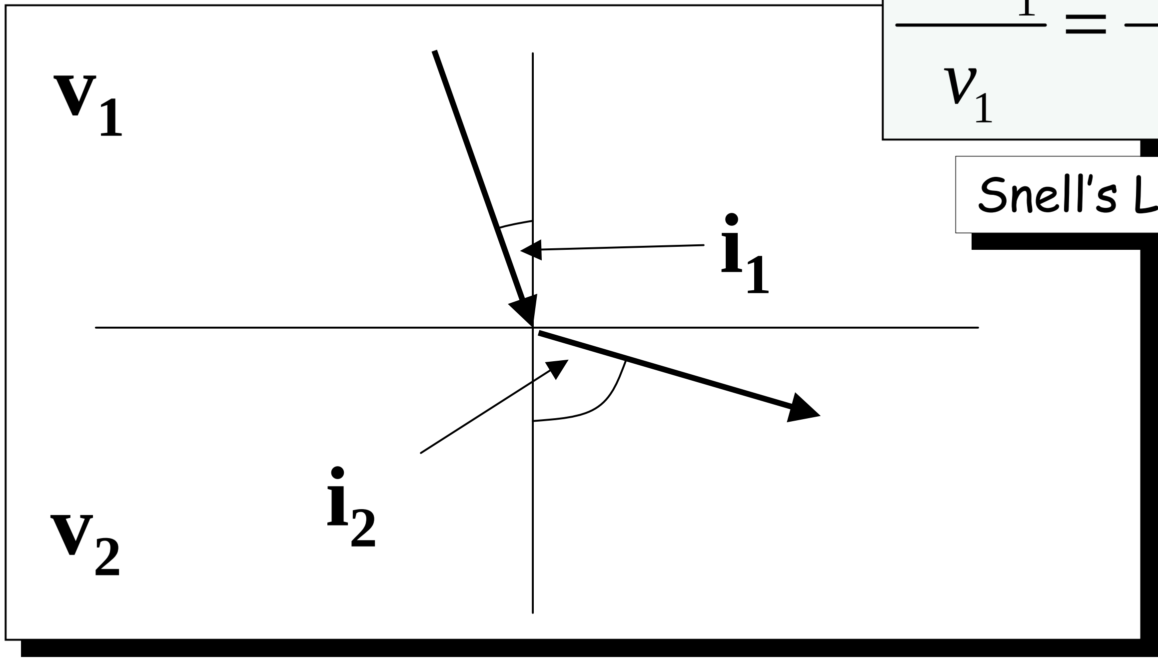
Fermat's principle and Snell's law ray transmission

Fermat's principle governs the geometry of the ray path. The ray will follow *a minimum-time* path. From Fermat's principle follows directly Snell's Law

$$\frac{\sin i_1}{v_1} = \frac{\sin i_2}{v_2}$$

Snell's Law

$V_2 > V_1$



Reflection and transmission at boundaries vertical incidence

An importance notion in seismic reflection studies is the impedance. It is the product of density ρ and P-wave (or S-wave) velocity $v_{P/S}$. It is usually denoted by Z

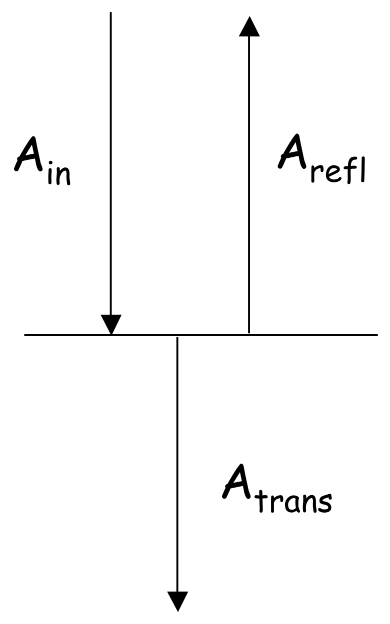
$Z = \rho * v_P$

The reflection (transmission) coefficients at an interface are given as the ratio of reflected (transmitted) to incoming wave amplitude

$R = A_{refl}/A_{in}$

$T = A_{trans}/A_{in}$

interface



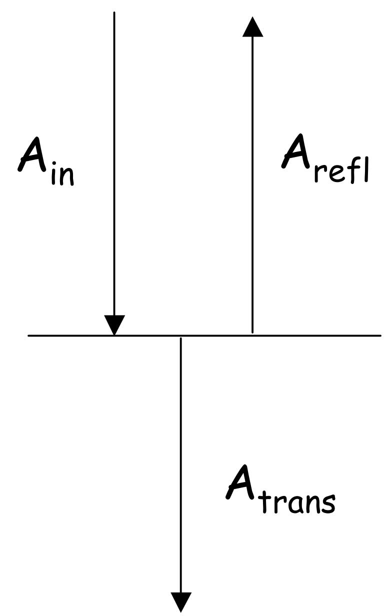
Reflection and transmission at boundaries vertical incidence

For normal (vertical) incidence the reflection coefficient is given as:

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

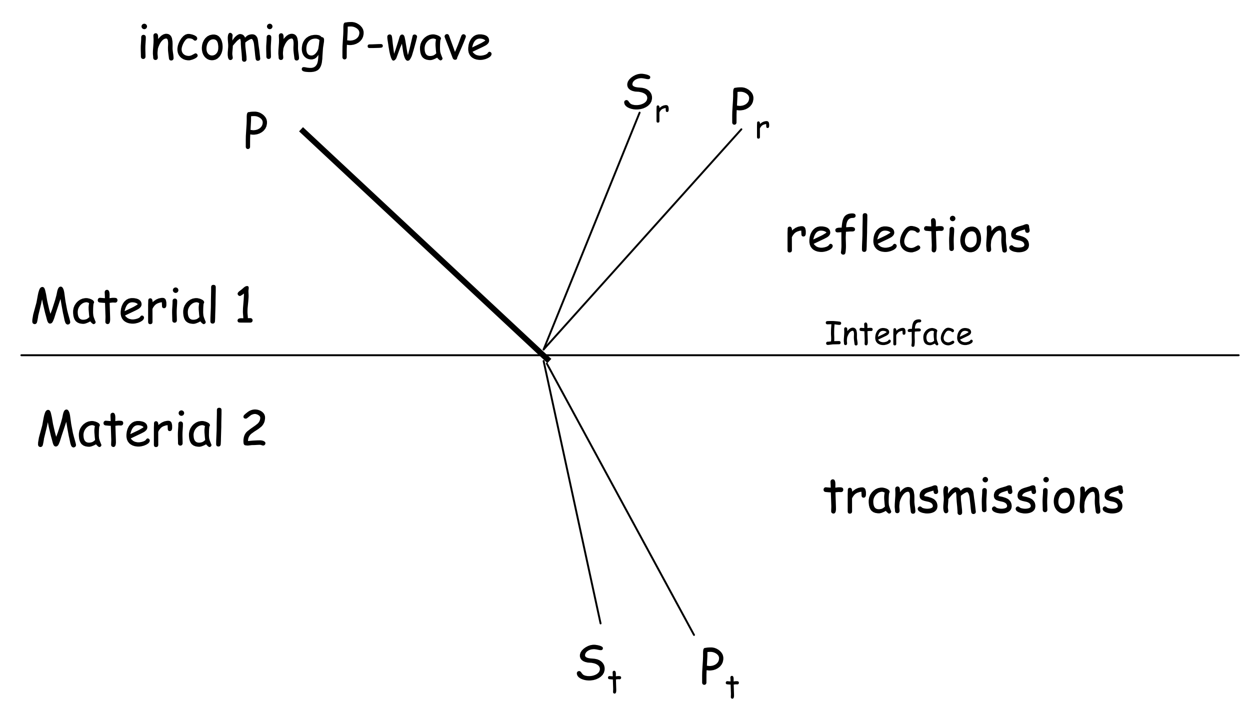
the transission coefficient is given as:

$$T = \frac{2\rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} = \frac{2Z_1}{Z_2 + Z_1}$$

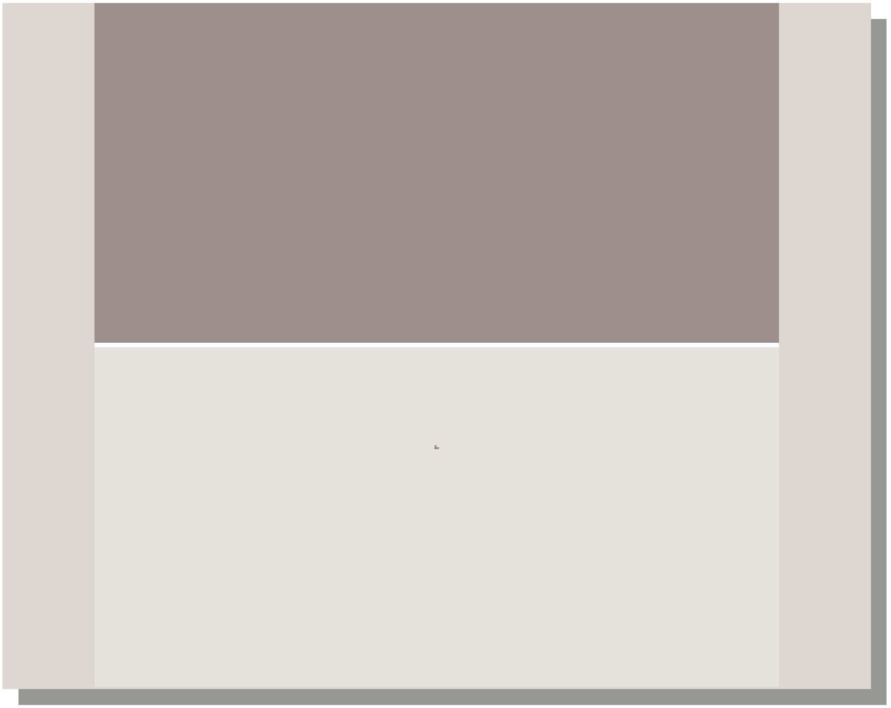


Reflection and transmission at boundaries oblique incidence - conversion

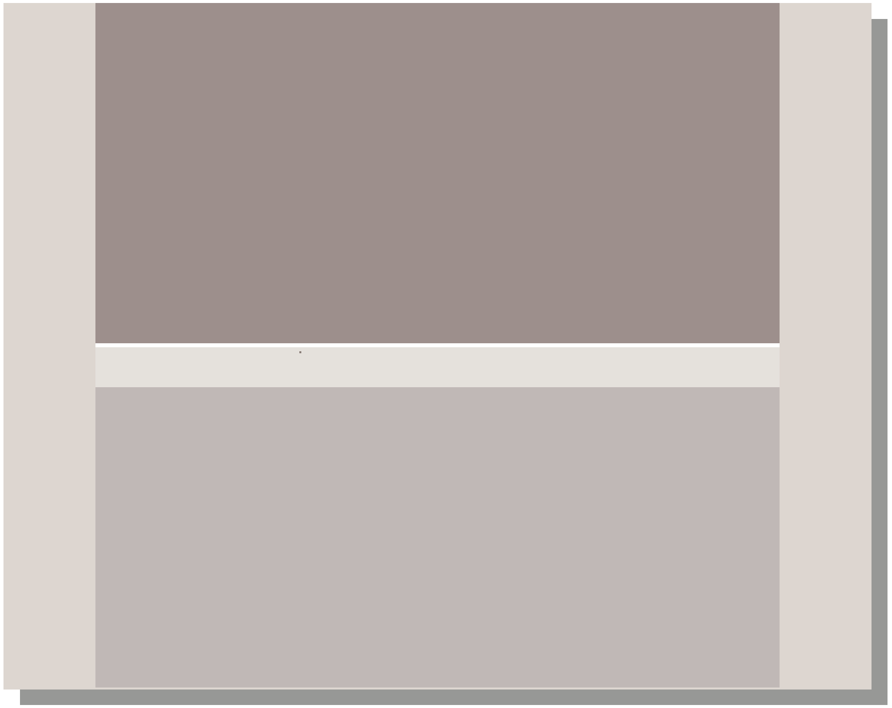
P waves can be converted to S waves and vice versa. This creates a quite complex behavior of wave amplitudes and wave forms at interfaces. This behavior can be used to constrain the properties of the material interface.



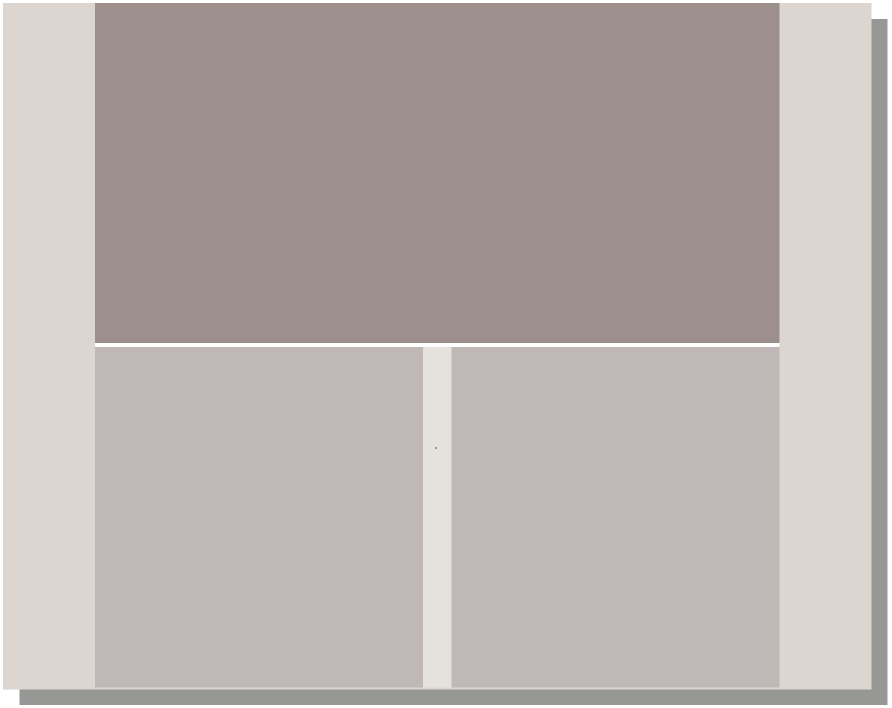
Snapshots and seismograms: homogeneous media



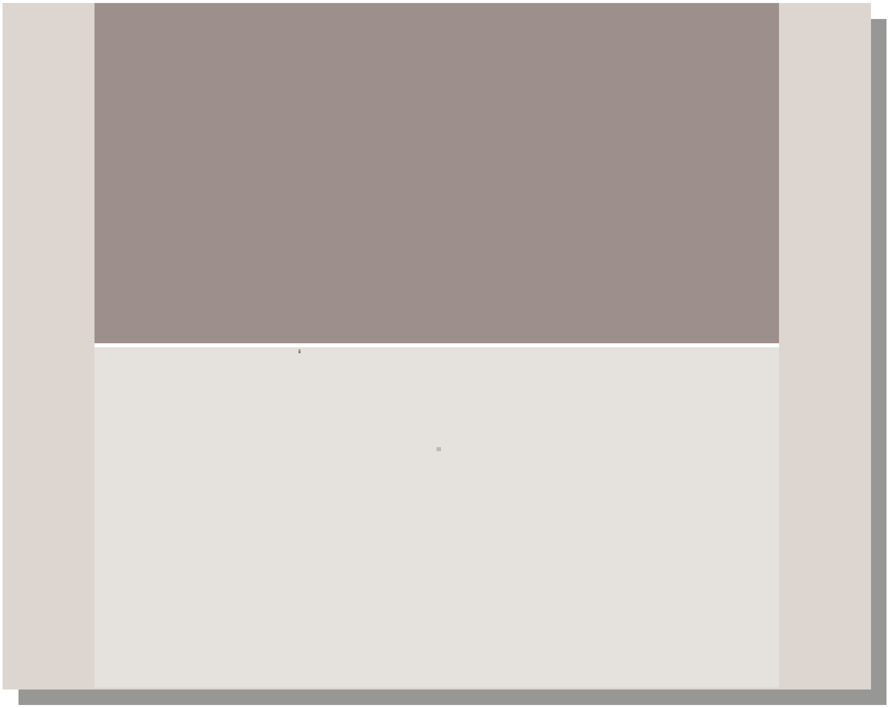
Snapshots and seismograms: surface low-velocity layer



Snapshots and seismograms: fault zone



Snapshots and seismograms: point scatterer



Seismic sources

Requirements for seismic sources:

- Produce enough energy in wide enough frequency band
- Energy focused for specific wave type (P or S)
- Repeatable source waveform
- Safe, efficient, environmentally acceptable

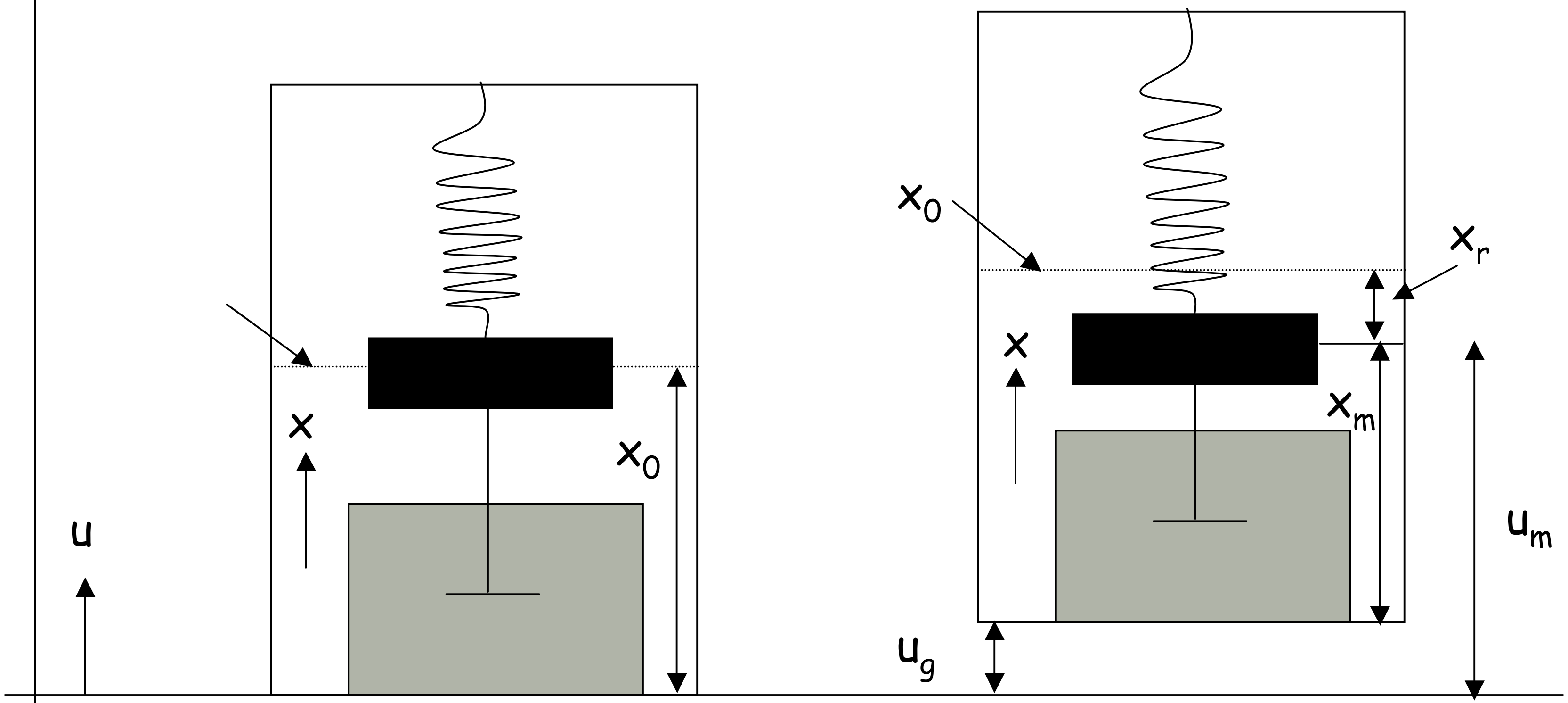
Typical sources are:

- Explosive sources (shallow boreholes)
- Vibroseis®
- Airguns (marine surveys)

Seismic transducers

- Seismometers measure the three components of ground motion (usually ground velocity)
- Hydrophones are used in marine surveys and measure pressure
- OBSs (ocean bottom seismometers) are often combinations of hydrophones and seismometers.

Seismometer



u	ground displacement
x_r	displacement of seismometer mass
x_0	mass equilibrium position

Summary

- Wave propagate in the Earth due to the elastic properties of its materials.
- For seismic exploration the most important wave types are P and S waves.
- Waves are reflected and transmitted by internal interfaces
- Seismic wave velocities are important discriminants for rock types and changes in lithology
- Wave velocities are affected by density, rock type, porosity, pore space content
- Seismic waves loose energy through geometrical spreading, attenuation and scattering