Seismic Exploration

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Introduction

- **Seismology** is a science that deals with earthquakes and with artificially produced vibrations of the earth.

I. **Earthquake Seismology**

Recordings of distant or local earthquakes are used to infer earth structure and faulting characteristics.

II. Applied Seismology

A signal, similar to a sound pulse, is transmitted into the Earth. The signal recorded at the surface can be used to infer subsurface properties.

Elasticity Theory
Stress and Strain

- A force applied to the surface of a solid body creates internal forces within the body:
- **Stress** is the ratio of applied force F to the area across which it is acts.
- **Strain** is the deformation caused in the body, and is expressed as the ratio of change in length (or volume) to original length (or volume).

Introduction

- There are two main classes of survey, Figure 1:

I. **Seismic Refraction**: the signal returns to the surface by refraction at subsurface interfaces, and is recorded at distances much greater than depth of investigation.

II. **Seismic Reflection**: the seismic signal is reflected back to the surface at layer interfaces, and is recorded at distances less than depth of investigation.

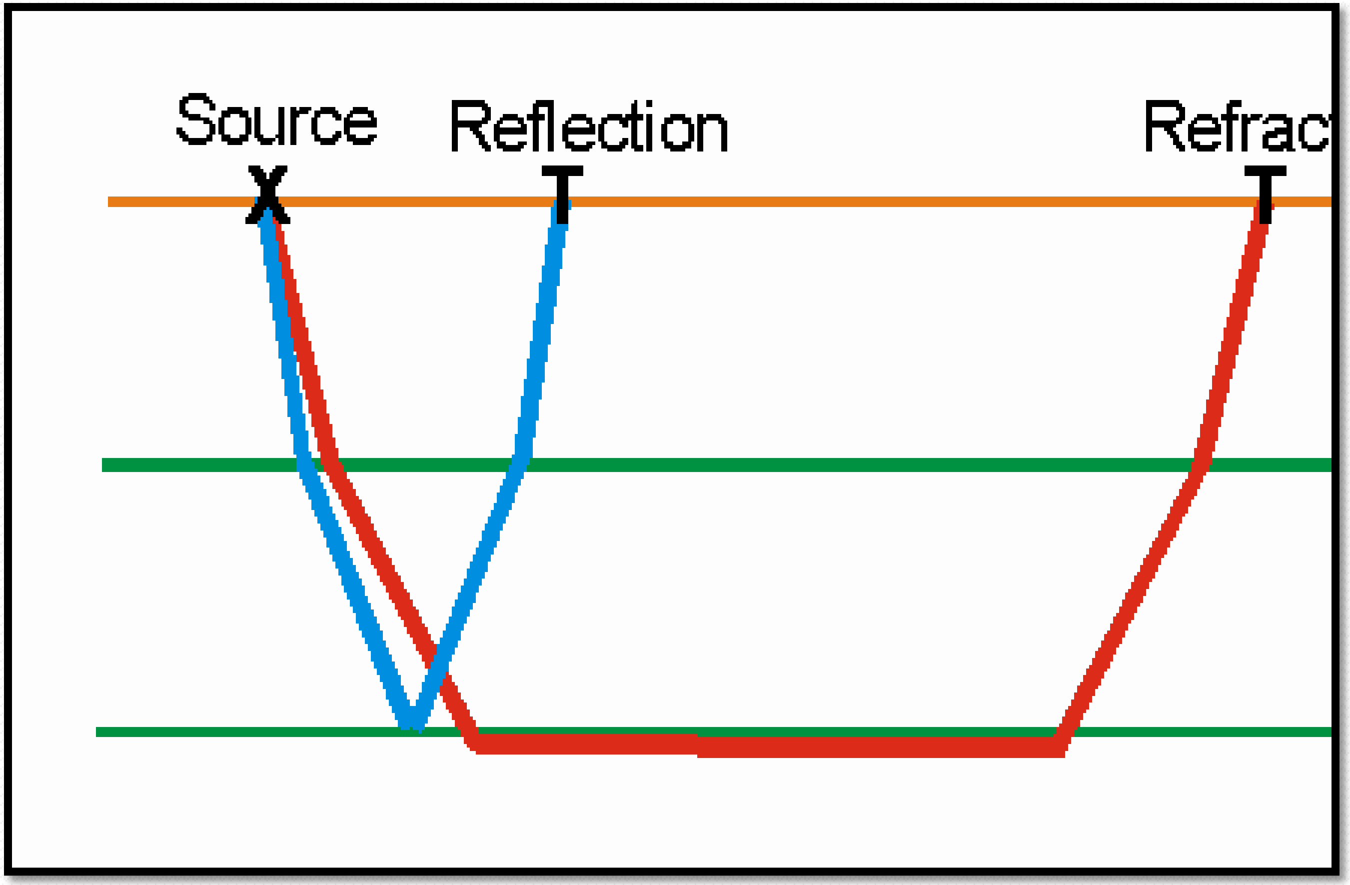


Figure 1. Types of seismic survey.

History of Seismology

Seismic exploration methods developed from early work on earthquakes:

- 1846: Irish physicist, Robert Mallett, makes first use of an artificial source in a seismic experiment.
- 1888: August Schmidt uses travel time vs. distance plots to determine subsurface seismic velocities.
- 1899: G.K. Knott explained refraction and reflection of seismic waves at plane boundaries.
- 1910: A. Mohorovicic identifies separate P and S waves on traveltime plots of distant earthquakes, and associates them with base of the crust, the Moho.
- 1916: Seismic refraction developed to locate artillery guns by measurement of recoil.
- 1921: ‘Seismos’ company founded to use seismic refraction to map salt domes, often associated with hydrocarbon traps.
- 1920: Practical seismic reflection methods developed. Within 10 years, the dominant method of hydrocarbon exploration.

Seismic Exploration Applications

Seismic Refraction

- Rock competence for engineering applications
- Depth to Bedrock
- Groundwater exploration
- Correction of lateral, near-surface, variations in seismic reflection surveys
- Crustal structure and tectonics

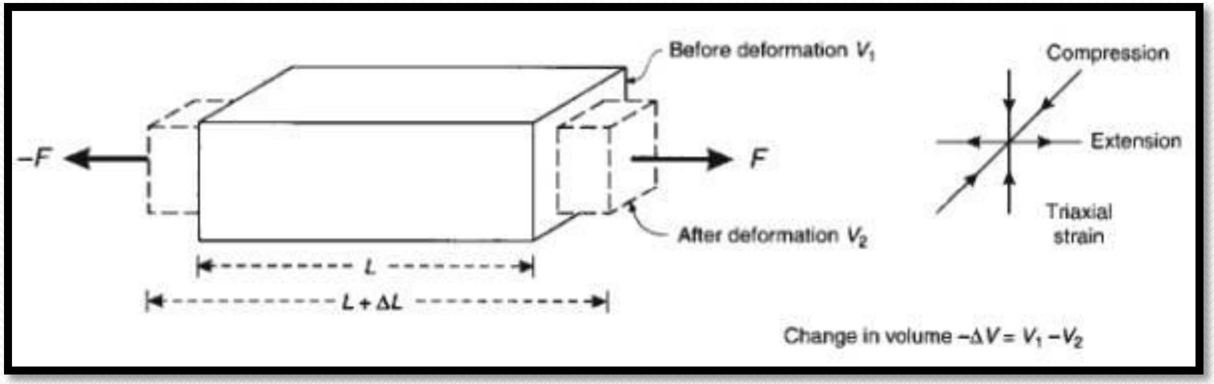
Seismic reflection

- Detection of subsurface cavities
- Shallow stratigraphy
- Site surveys for offshore installations
- Hydrocarbon exploration
- Crustal structure and tectonics

Stress and Strain

❖ **Triaxial Stress**

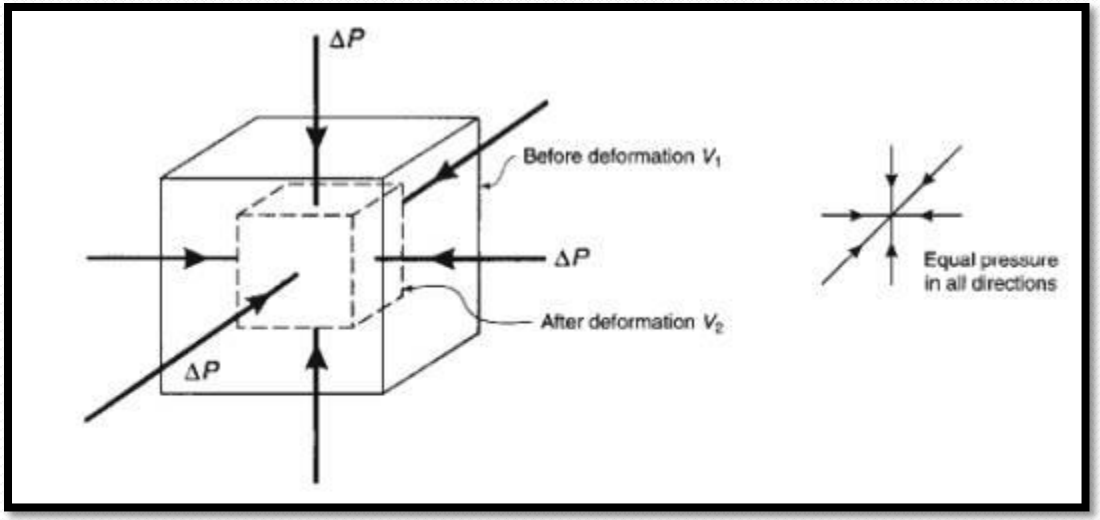
Stresses act along three orthogonal axes, perpendicular to faces of solid, e.g. stretching a bar:



Stress and Strain

Pressure

Forces act equally in all directions perpendicular to faces of body, e.g. pressure on a cube in water:

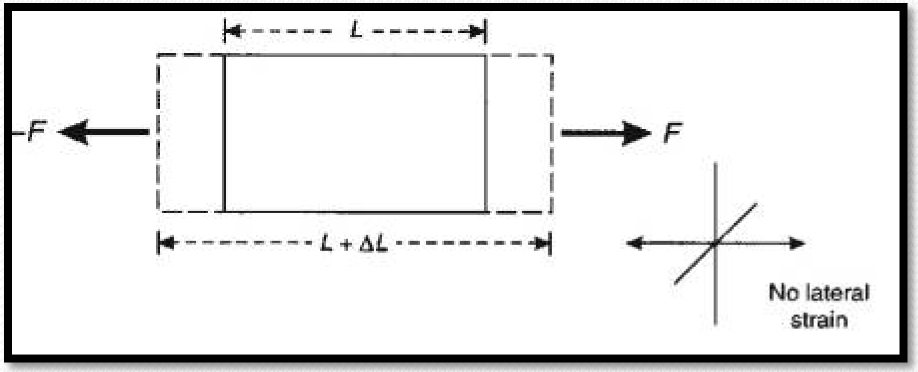


Strain Associated with Seismic Waves

- Inside a uniform solid, two types of strain can propagate as waves:
- **Axial Strain**

Stresses act in one direction only, e.g. if sides of bar fixed:

- **Change in volume of solid occurs.**
- **Associated with P wave propagation**

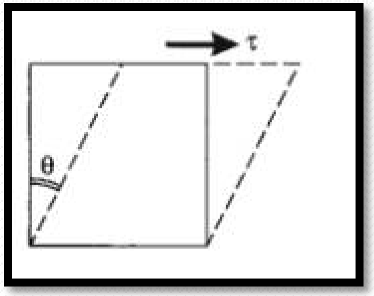


Strain Associated with Seismic Waves

- **Shear Stress**

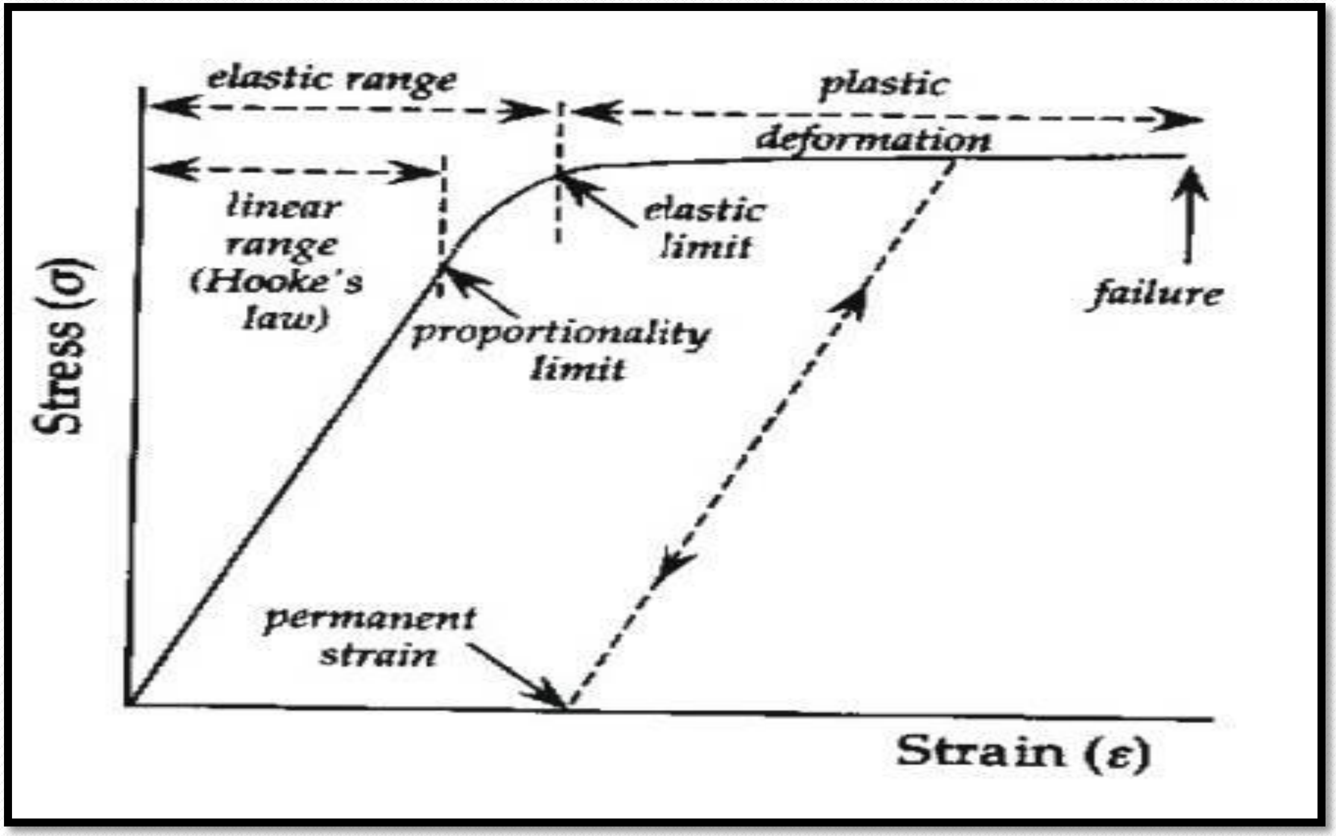
Stresses act parallel to face of solid, e.g. pushing along a table:

- No change in volume.
- Fluids such as water and air cannot support shear stresses.
- Associated with S wave propagation.



Hooke's Law

- Hooke's Law essentially states that stress is proportional to strain.
- At low to moderate strains: Hooke's Law applies and a solid body is said to behave elastically, i.e. will return to original form when stress removed.
- At high strains: the elastic limit is exceeded and a body deforms in a plastic or ductile manner: it is unable to return to its original shape, being permanently strained, or damaged.
- At very high strains: a solid will fracture, e.g. in earthquake faulting.

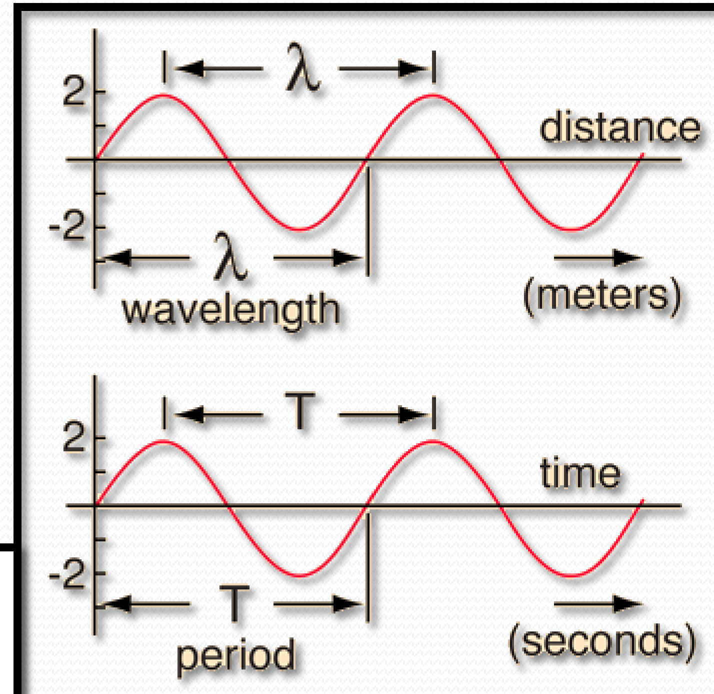


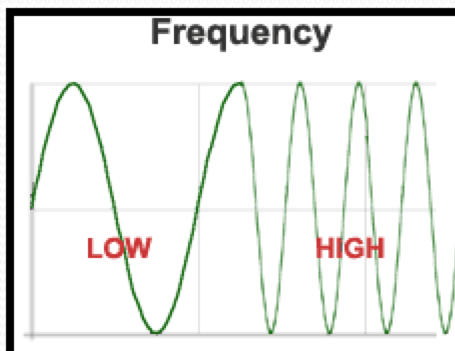
Constant of proportionality is called the modulus, and is ratio of stress to strain, e.g. Young's modulus in triaxial strain.

Seismic (Elastic) Waves

- **Waves**
- Any wave has the following properties:
- Velocity, v
- Wavelength, λ
- Frequency, f
- Period, T = 1/f

V = f λ





Seismic (Elastic) Waves

- According to propagation of the wave within the Earth and along its surface, the seismic waves can be classified into two Types:

I. **Body waves**

They propagate within the Earth.

II. **Surface Waves**

They propagate along the surface of the Earth.

Seismic Body Waves

- Seismic waves are pulses of strain energy that propagate in a solid. Two types of seismic wave can exist inside a uniform solid, Figure 2:

A) P waves (Primary, Compressional, Push-Pull)

- Motion of particles in the solid is in direction of wave propagation.
- P waves have highest speed.
- Volumetric change
- Sound is an example of a P wave.

Seismic Body Waves

- **P-waves are the most important for controlled source seismology because**
- They arrive first making them easier to observe.
- It is difficult to create a shear source, explosions are compressional.

Seismic Body Waves

B) S waves (Secondary, Shear, Shake)

- Particle motion is in plane perpendicular to direction of propagation.
- If particle motion along a line in perpendicular plane, then S wave is said to be plane polarised: SV in vertical plane, SH horizontal.
- No volume change
- S waves cannot exist in fluids like water or air, because the fluid is unable to support shear stresses.

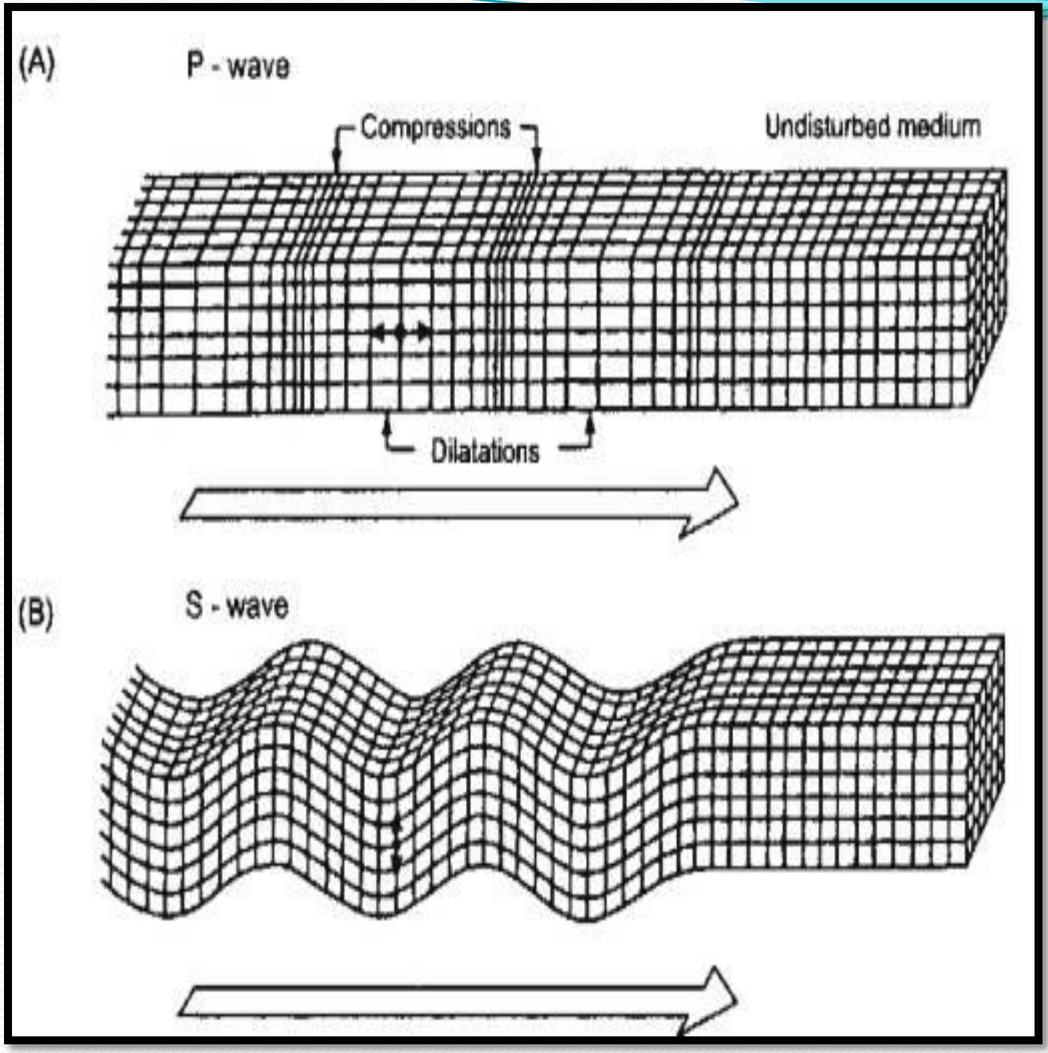


Figure 2. Seismic Body Waves

Seismic Surface Waves

- No stresses act on the Earth's surface (<u>Free surface</u>), and two types of surface wave can exist, Figure 3. They are mainly a source of noise for us.
- **A) Rayleigh waves**
- Propagate along the surface of Earth
- Amplitude decreases exponentially with depth.
- Near the surface the particle motion is retrograde elliptical.
- Rayleigh wave speed is slightly less than S wave: ~92% V_S.

Seismic Surface Waves

B. Love waves

- Occur when a free surface and a deeper interface are present, and the shear wave velocity is lower in the top layer.
- Particle motion is SH, i.e. transverse horizontal
- Dispersive propagation: different frequencies travel at different velocities, but usually faster than Rayleigh waves.

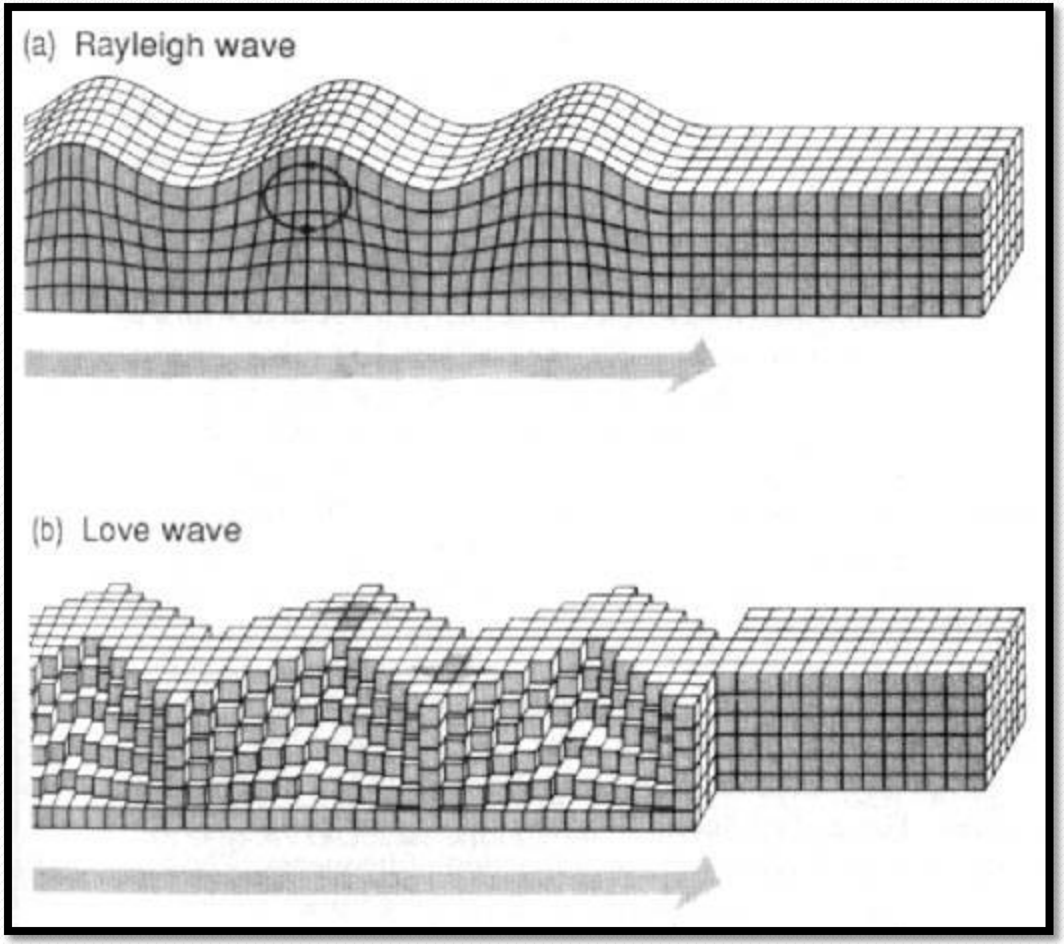
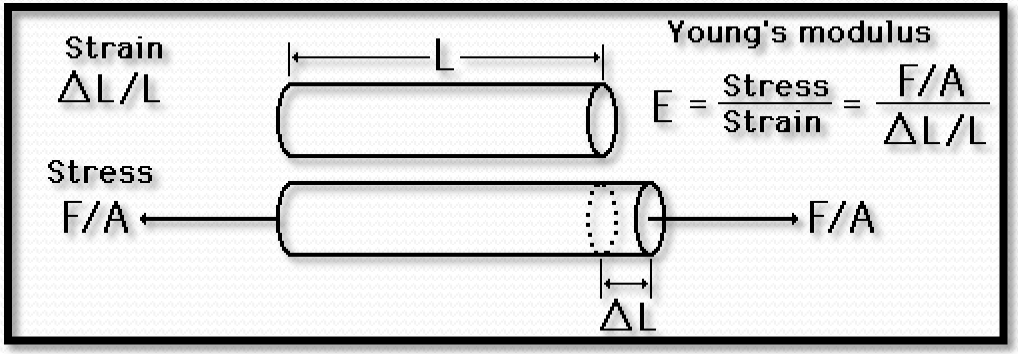


Figure 3. Types of Seismic Surface Waves

Elastic moduli

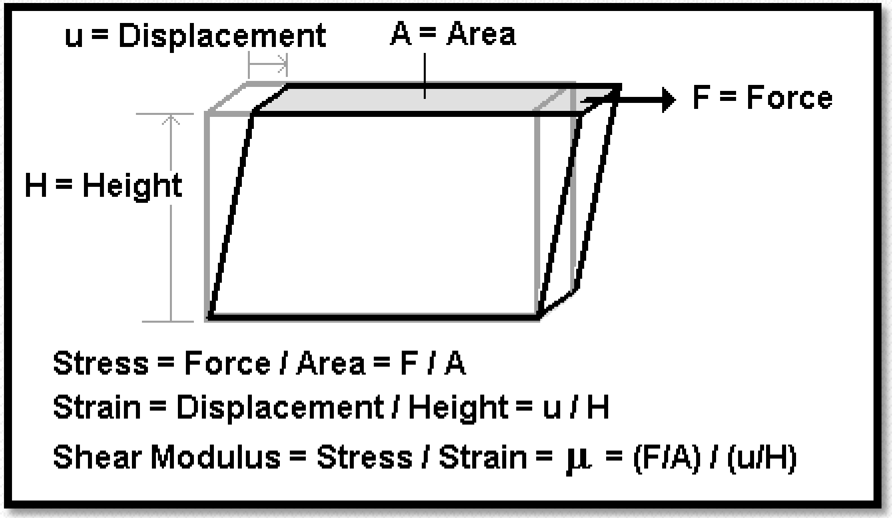
- They describe the physical properties of the rock and determine the seismic velocity.
- Young's modulus



Elastic moduli

- Shear modulus, μ

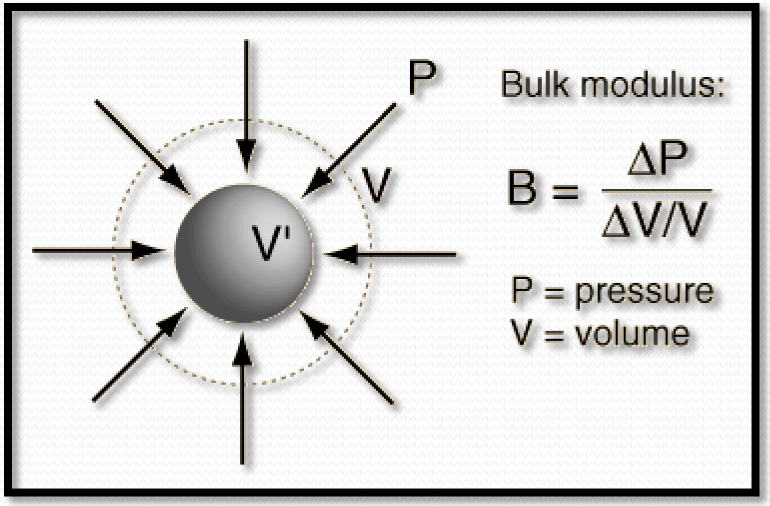
Force per unit area to change the shape of the material.



Elastic moduli

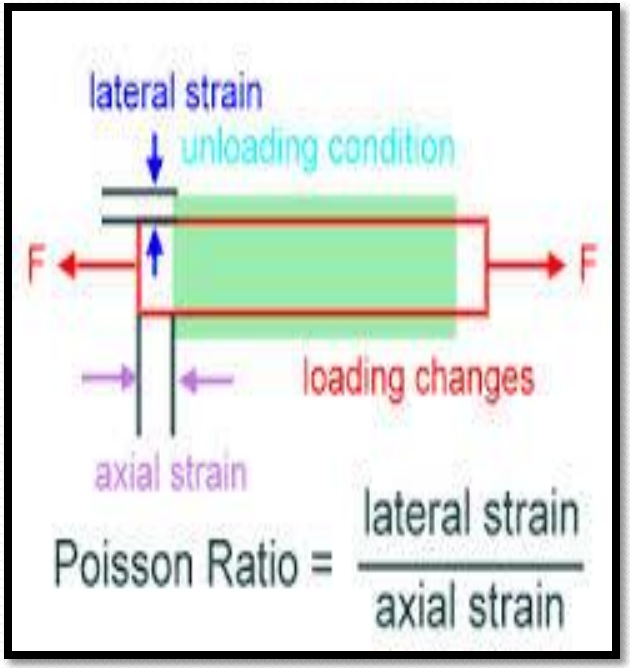
- Bulk modulus, κ

Ratio of increase in pressure to associated volume change. Always positive.



Elastic moduli

- Poisson's ratio



Seismic Wave Velocities

- The velocity of seismic waves is related to the elastic properties of solid, i.e. how easy it is to strain the rock for a given stress.
- It depends on **density**, **shear modulus**, and **axial modulus.**
- Velocity of wave propagation is NOT velocity at which particles move in solid (~ 0.01 m/s).

Relations of P and S waves Velocity with density and Elastic Moduli

- **P- and S- velocities**

$$v_p = \sqrt{\frac{K + (4/3)\mu}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}.$$

- Where
- V_P is P-wave velocity
- V_S is S-wave velocity
- K is the bulk modulus
- μ is the shear (or rigidity) modulus
- ρ is the density

Relations of P and S waves Velocity with density and Elastic Moduli

- **For liquids and gases** $\mu = 0$**, therefore**
- $\rightarrow V_S = 0$ and V_P is reduced in liquids and gases
- $\rightarrow$ Highly fractured or porous rocks have significantly reduced V_P
- **The bulk modulus,** κ **is always positive,** therefore $V_S < V_P$ always

Factors affecting velocity

- Seismic velocities vary with

I. **mineral content**

II. lithology

III. porosity

IV. pore fluid saturation

V. pore pressure

VI. to some extent temperature.

Factors affecting velocity

1. **Density** – velocity typically increases with density.

2. Porosity and **fluid saturation**

- Increasing porosity reduces velocity.
- Filling the porosity with fluid increases the velocity.

$$\frac{1}{Vsat.} = \frac{\varphi}{VF} + \frac{1-\varphi}{VM}$$

Where

Φ is the porosity.

V_F is fluid velocity

V_M is material velocity

V_{sat} is saturated material

Factors affecting velocity

- **Poisson's ratio** – related to V_P/V_S

This is used to distinguish between rock/sediment types. It is usually more sensitive than just V_P alone.

The significant variations of the seismic velocities in sediments are usually due to porosity variations and water saturation. Water saturation has no effect on V_S (for low porosities) but a significant effect on V_P.

Factors affecting velocity

1. P wave velocity as function of age and depth

$$V = 1.47(ZT)^{1/6}$$

where Z is depth in km and T is geological age in millions of years (Faust, 1951).

Factors affecting velocity

❖ 2. Time-average equation

$$\frac{1}{V} = \frac{\phi}{V_f} + \frac{1-\phi}{V_m}$$

where ϕ is porosity, V_f and V_m are P wave velocities of pore fluid and rock matrix respectively (Wyllie, 1958).

- Usually $V_f \approx 1500$ m/s, while V_m depends on lithology.
- If the velocities of pore fluid and matrix known, then porosity can be estimated from the measured P wave velocity.

Factors affecting velocity

Nafe-Drake Curve

- **Density and velocity**

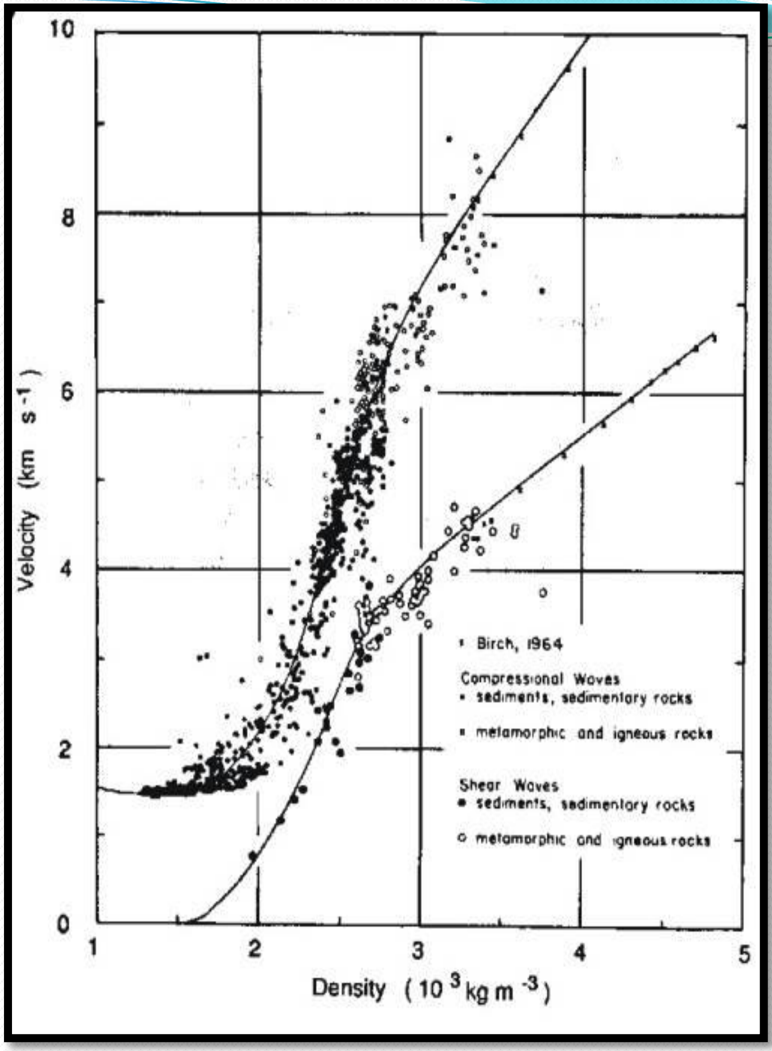
  Nafe -Drake curve

  This curve has been approximated using the expression

$$\rho = a\, V_P^{1/4}$$

(a is a constant: 1670 when ρ in km/m³ and V_P in km/s).

- Crossplotting velocity and density values of crustal rocks gives the Nafe-Drake curve after its discoverers.



Nafe-Drake Curve

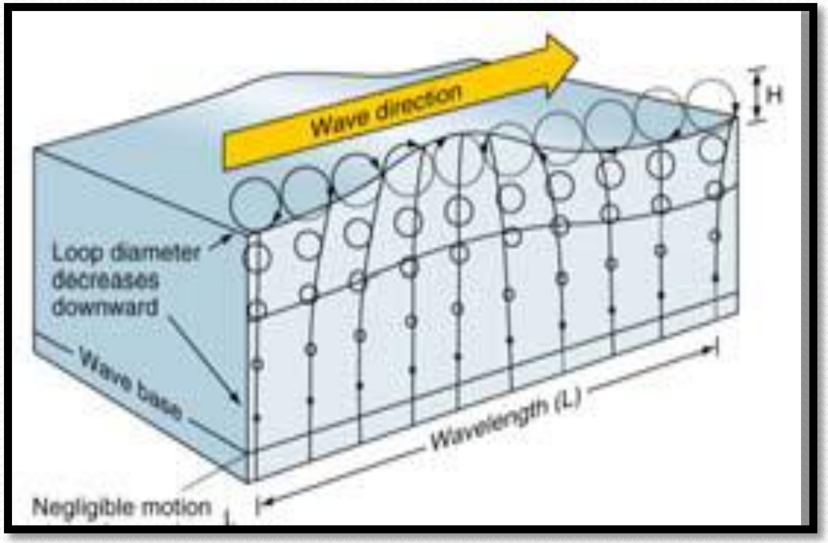
Table 4.2 Examples of P-wave velocities

Material	V_p (m/s)
Air	330
Water	1450–1530
Petroleum	1300–1400
Loess	300–600
Soil	100–500
Snow	350–3000
Solid glacier ice*	3000–4000
Sand (loose)	200–2000
Sand (dry, loose)	200–1000
Sand (water saturated, loose)	1500–2000
Glacial moraine	1500–2700
Sand and gravel (near surface)	400–2300
Sand and gravel (at 2 km depth)	3000–3500
Clay	1000–2500
Estuarine muds/clay	300–1800
Floodplain alluvium	1800–2200
Permafrost (Quaternary sediments)	1500–4900
Sandstone	1400–4500
Limestone (soft)	1700–4200
Limestone (hard)	2800–7000
Dolomites	2500–6500
Anhydrite	3500–5500
Rock salt	4000–5500
Gypsum	2000–3500
Shales	2000–4100
Granites	4600–6200
Basalts	5500–6500
Gabbro	6400–7000
Peridotite	7800–8400
Serpentinite	5500–6500
Gneiss	3500–7600
Marbles	3780–7000
Sulphide ores	3950–6700
Pulverised fuel ash	600–1000
Made ground (rubble etc.)	160–600
Landfill refuse	400–750
Concrete	3000–3500
Disturbed soil	180–335
Clay landfill cap (compacted)	355–380

* Strongly temperature dependent (Kohnen 1974)

Velocity sensitivity

- The amplitude of wave motion decreases with depth
- → Related to depth/wavelength
- → Longer wavelengths sample deeper



Velocity sensitivity

- Seismic velocity generally increases with depth.
- Surface waves are **dispersive**, which means their velocity is dependent on their wavelength. This is because longer wavelength sample deeper where the velocity is greater.
- Also, if velocity increases with depth longer wavelengths arrive first.

Textbooks

Kearey, P., Brooks, M. and Hill, I. (2002) An introduction to Geophysical Exploration. 3rd edition, Blackwell Science Ltd, UK, 261p.