

# Course review

# EXAM LOGISTICS

Date: Monday, April 20

- Time: 12:30 – 14:30 (2 hours)
- Location: E2S2 Lab 3
- The exam starts at 12:30 sharp (no delay)
- Students are strongly advised to arrive 10-15 minutes early

What to bring:

- Your ID (passport for international students, or other valid identification)
- Pens and erasers
- Simple calculator (non-programmable)

# EXAM LOGISTICS

## Allowed / Forbidden

✓ Calculator

✗ No books, notes, or electronic devices (phones, tablets, smartwatches)

## Exam structure (100 points)

Part A: Multiple choice (46 points)

Part B: Open questions (24 points)

Part C: Exercises (calculations + interpretation) (30 points)

# EXAM LOGISTICS

## Leaving the room:

- Allowed **only after 60 minutes**
- **No re-entry** once you leave

## Absence policy:

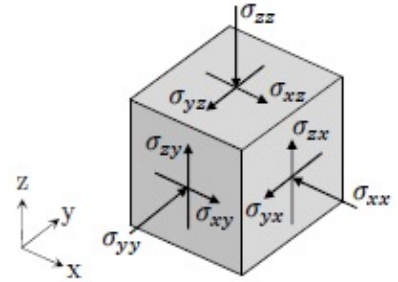
- Absence requires official documentation
- Otherwise, 30% grading penalty

# What is the stress tensor?

The stress tensor is one object that describes how forces act on a small volume from all directions. Critical clarification:

- It is NOT 9 tensors
- It is 1 tensor with 9 components

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$



# What is the stress tensor? **Physical meaning**

The stress tensor is one object that describes how forces act on a small volume from all directions. Critical clarification:

- It is NOT 9 tensors
- It is 1 tensor with 9 components

Each component answers this question:

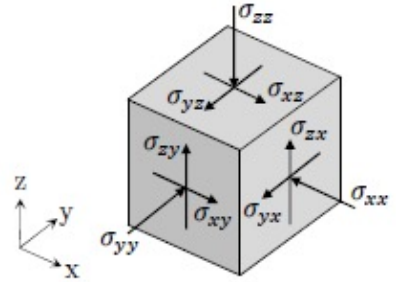
“What force acts in direction  $i$  on a surface whose normal is  $j$ ?”

Example:

$\sigma_{xx}$ : force in  $x$ -direction on a surface facing  $x$

$\sigma_{xy}$ : force in  $x$ -direction on a surface facing  $y$

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$



# Normal vs. shear stress

Normal stresses (diagonal)

$\sigma_{xx}$ ,  $\sigma_{yy}$ ,  $\sigma_{zz}$

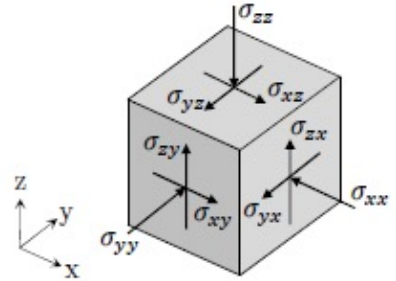
→ push or pull perpendicular to the surface

Shear stresses (off-diagonal)

$\sigma_{xy}$ ,  $\sigma_{xz}$ ,  $\sigma_{yz}$ , ...

→ act parallel to the surface (cause deformation)

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$



# What is deviatoric stress?

Imagine a rock deep underground.

Case 1: pressure is the same in all directions → rock is just squeezed

Case 2: forces are different in different directions → rock deforms / fails

Key idea: Deviatoric stress = what remains after removing uniform pressure

Total stress = pressure + deviatoric stress

# What is deviatoric stress?

**If all stresses are equal:**  $\sigma_{xx} = \sigma_{yy} = \sigma_{zz}$

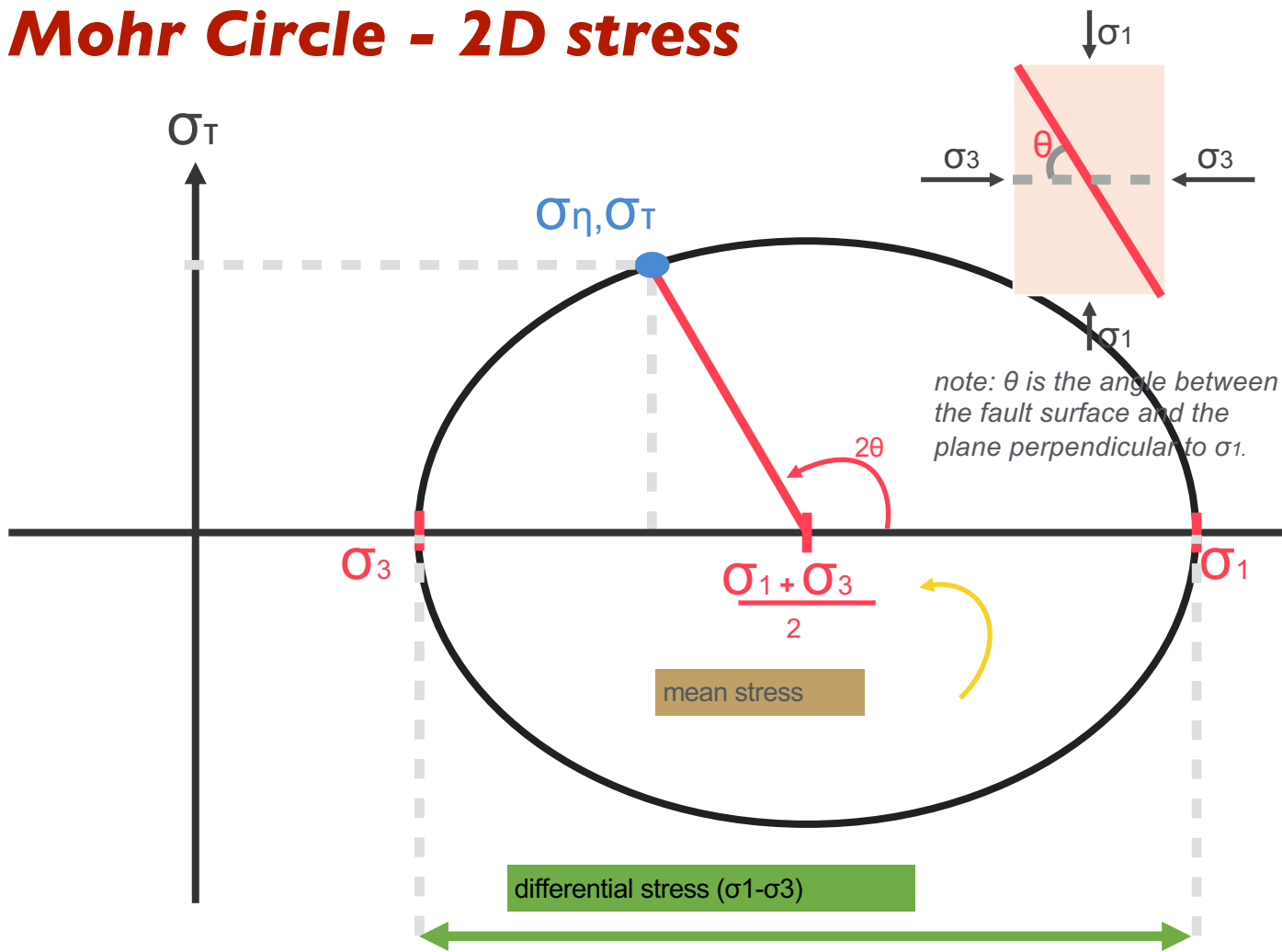
→ No shape deformation

→ Deviatoric stress = 0

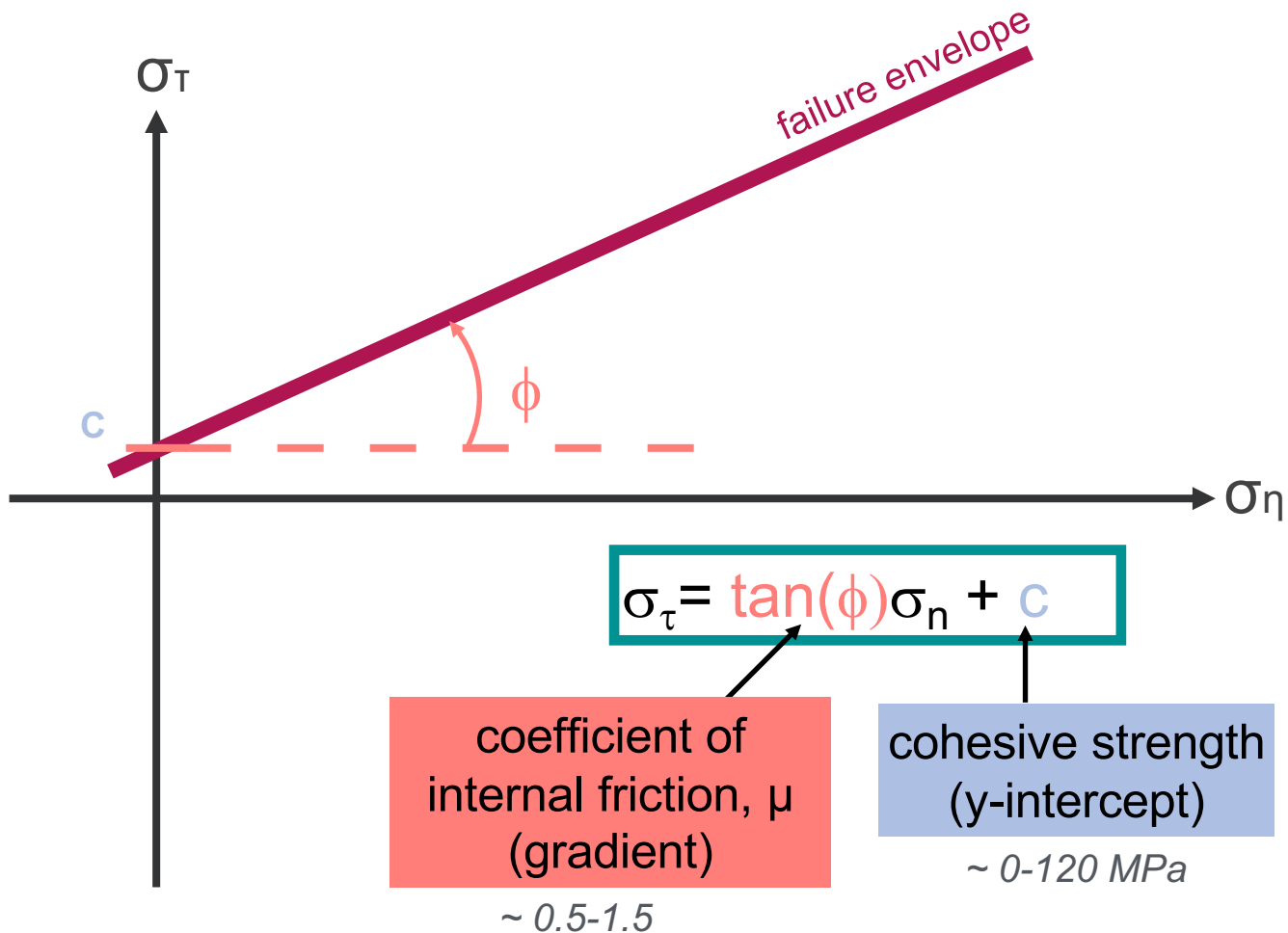
$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix} = \underbrace{\begin{pmatrix} \sigma_m & 0 & 0 \\ 0 & \sigma_m & 0 \\ 0 & 0 & \sigma_m \end{pmatrix}}_{\text{Hydrostatic Stress state}} + \underbrace{\begin{pmatrix} \sigma_{11} - \sigma_m & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} - \sigma_m & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} - \sigma_m \end{pmatrix}}_{\text{Deviatoric Stress state}}$$

Mean normal stress ( $\sigma_m$ ) or hydrostatic pressure ( $p$ ) is  $= (\sigma_{xx} + \sigma_{yy} + \sigma_{zz})/3$

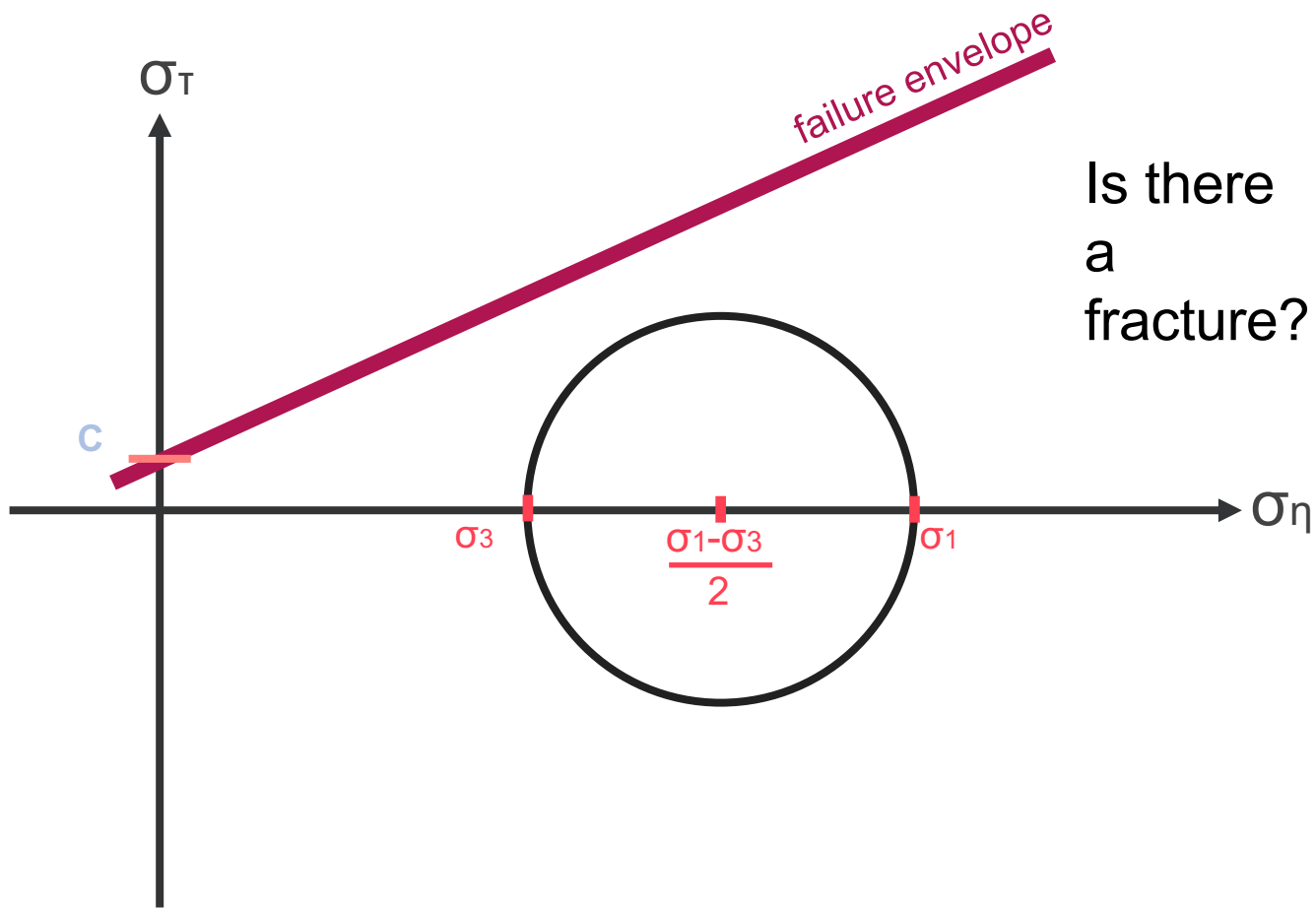
# Mohr Circle - 2D stress



# Mohr-Coulomb Fracture

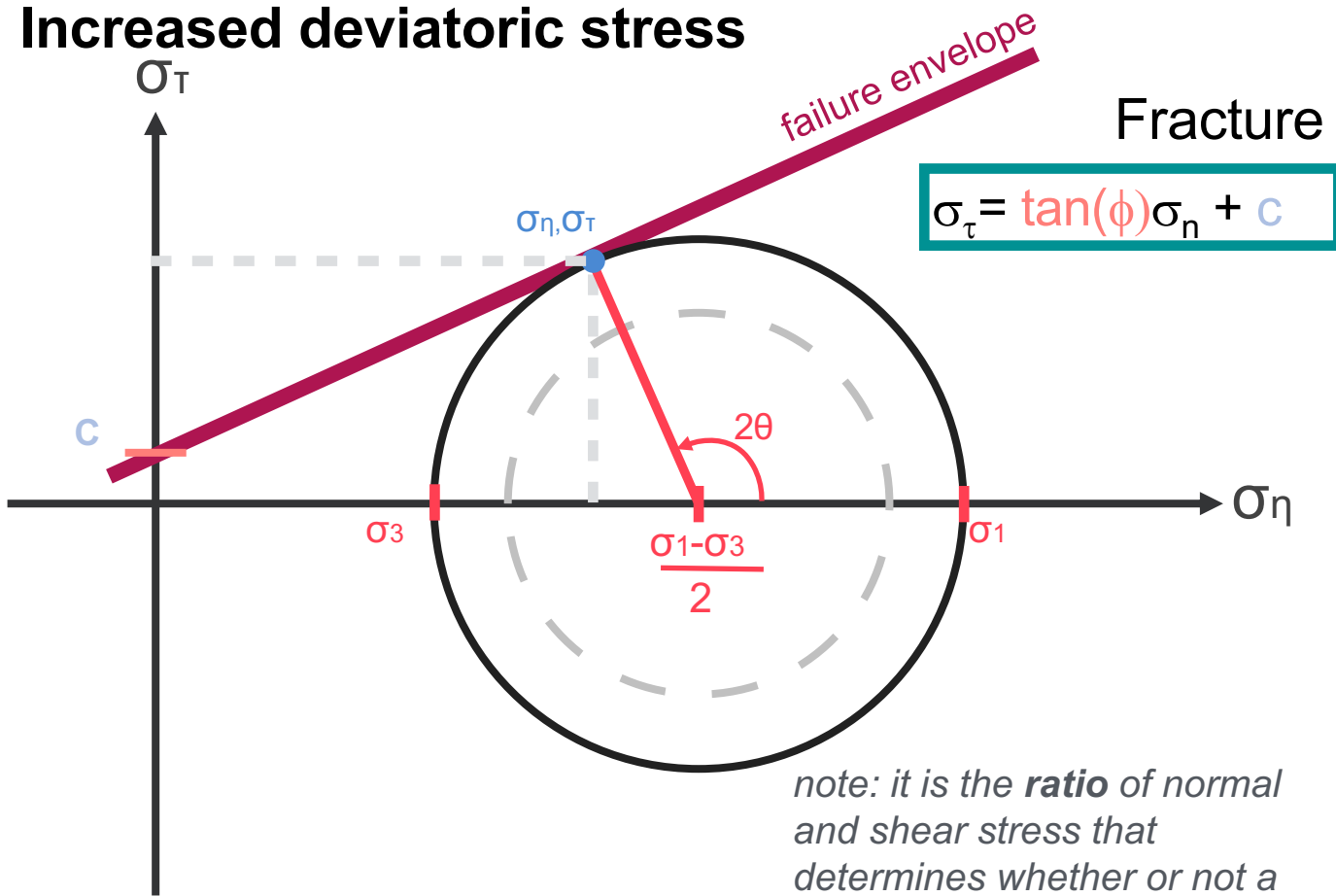


# Mohr-Coulomb Fracture



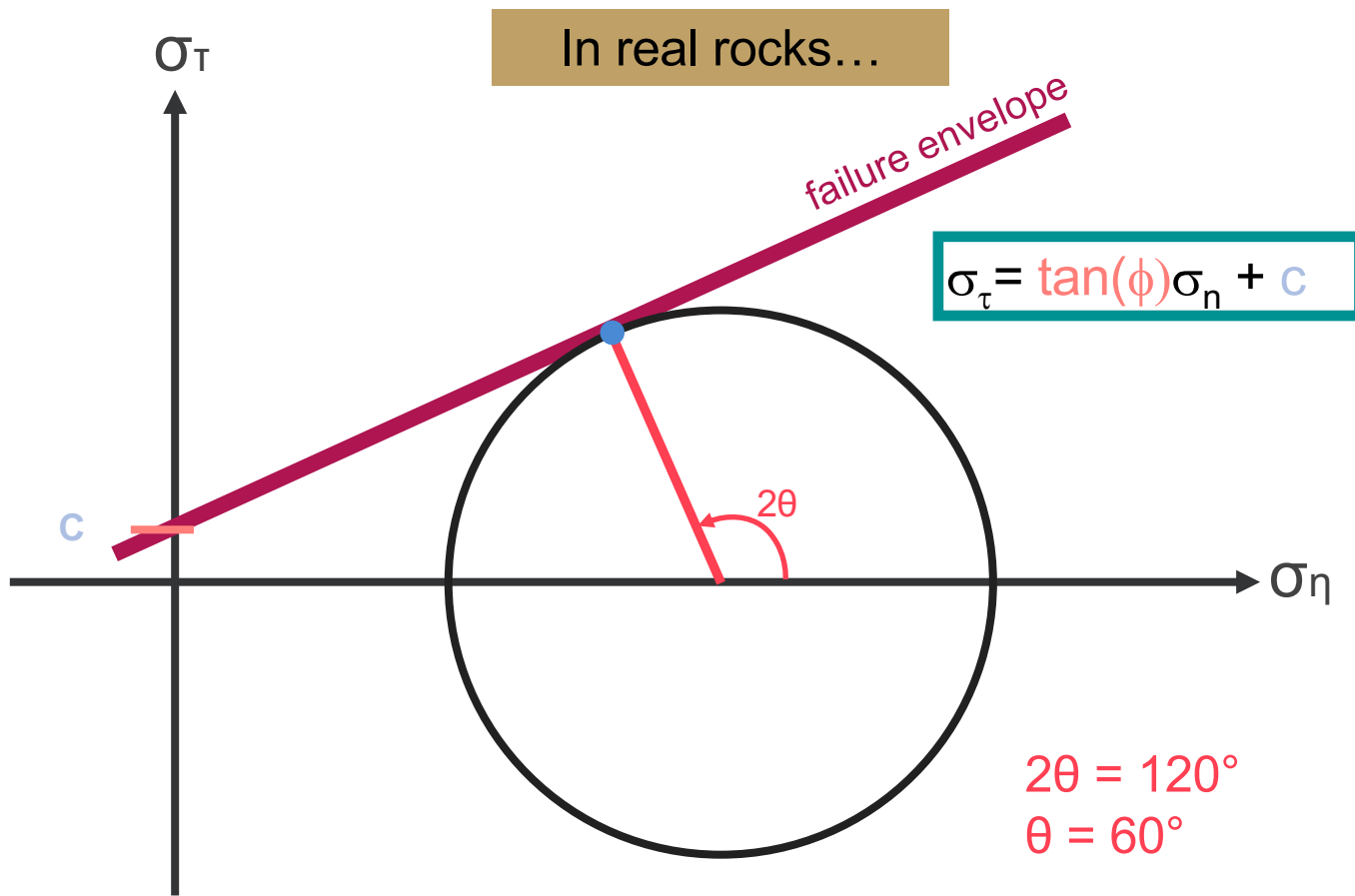
# Mohr-Coulomb Fracture

Increased deviatoric stress



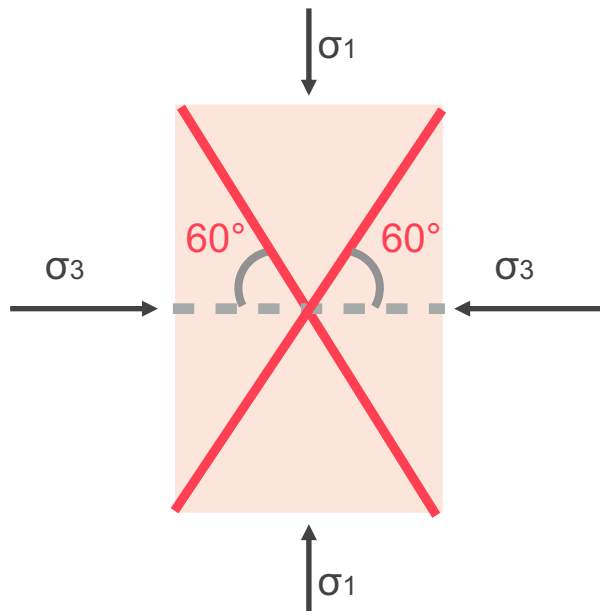
*note: it is the **ratio** of normal and shear stress that determines whether or not a rock breaks.*

# Mohr-Coulomb Fracture

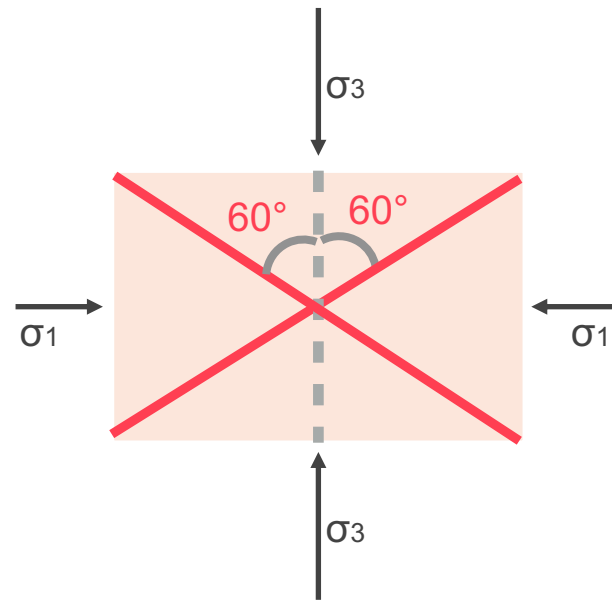


# Mohr-Coulomb Fracture

In real rocks,  $\theta \sim 60^\circ$



Normal faults



Reverse faults

# Bouguer anomaly – what is the reference?

*A Bouguer anomaly is the difference between measured gravity and a theoretical reference Earth.*

What is the reference? The reference is not the raw measurement, but a model where the Earth is smooth, symmetric, and has no local structures.

**What we do step-by-step:** Measure gravity in the field → “g\_measured”

Then, remove predictable effects: latitude correction, free-air correction (elevation), Bouguer correction (mass between station and sea level)...

**Bouguer anomaly = g\_measured – g\_reference**

where g\_reference = gravity of an ideal, uniform Earth

# Bouguer anomaly – what is the reference?

$$\text{Bouguer anomaly} = g_{\text{measured}} - g_{\text{reference}}$$

where  $g_{\text{reference}}$  = gravity of an ideal, uniform Earth

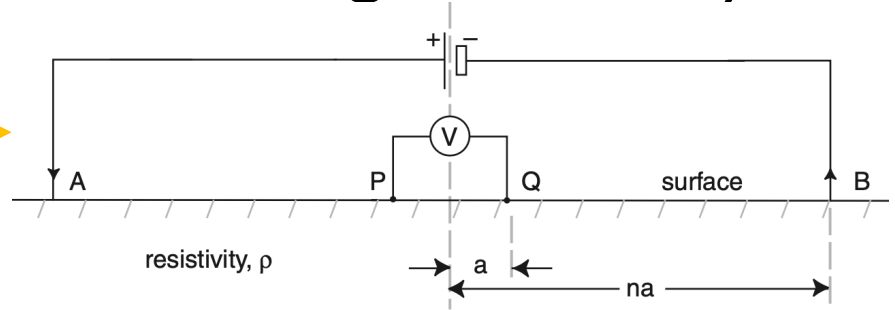
Physical meaning

- Positive anomaly → excess mass (higher density)
- Negative anomaly → deficit of mass (lower density)

***REMEMBER: The Bouguer anomaly tells you how much the real Earth deviates from an ideal, uniform Earth due to subsurface density variations.***

# Electric resistivity: What happens when we increase electrode spacing? Setup (Schlumberger method)

Schlumberger



When electrodes are close  $\rightarrow$  current stays near the surface

When electrodes are far apart  $\rightarrow$  current penetrates deeper

Why? Current does not travel straight down, it spreads in curved paths (like a bulb). Increasing spacing forces current to: 1. travel longer paths; 2. sample larger volumes; 3. reach greater depths

*Increasing electrode spacing increases depth penetration because the injected current spreads over a larger volume and becomes sensitive to deeper parts of the subsurface.*

# Magnetic anomalies: Positive, Negative, Symmetric

## Symmetric anomaly

### Case 1: Real Earth (what we actually measure)

Earth's magnetic field is **inclined** (not vertical)

The body is magnetized along this inclined field

Result?

The anomaly is **asymmetric**

It has a **dipole shape** (positive + negative)

The peak is **shifted away from the source**

# Magnetic anomalies: Positive, Negative, Symmetric

**Simplified conditions** – symmetry occurs if:

The magnetic field is vertical, or

The data are mathematically transformed to simulate a vertical field (reduction to the pole)

Result?

The anomaly becomes symmetric

A single peak is centered directly above the body

Magnetic anomalies are symmetric only when the field is vertical; otherwise, they are asymmetric due to the inclined Earth field.

# Magnetic Anomalies: Positive, Negative, Symmetric

*What is a magnetic anomaly? A magnetic anomaly is the difference between the magnetic field measured at a given location and the value predicted at that same location by the reference Earth field.*

## **Positive anomaly**

- measured field is stronger than the background
- caused by rocks that add magnetization in the same direction as Earth's field

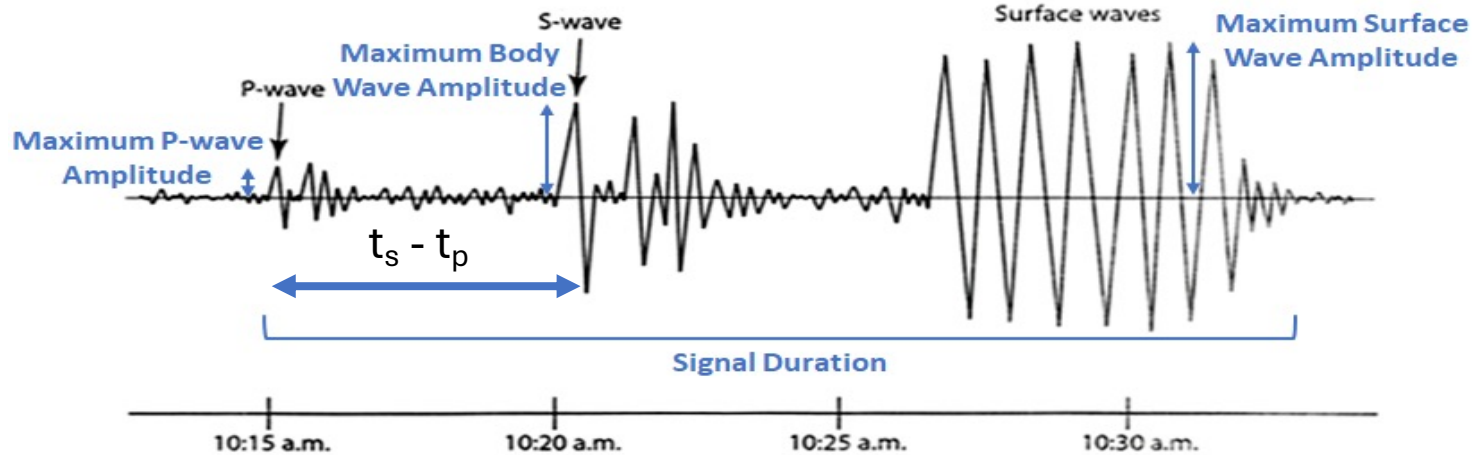
## **Negative anomaly**

- measured field is weaker than the background
- caused by rocks magnetized opposite to Earth's field (remanent magnetization)

# Earthquake location using triangulation

## General rule of thumb:

Distance to the earthquake = 8 x (arrival time of S – arrival time of P) kilometres

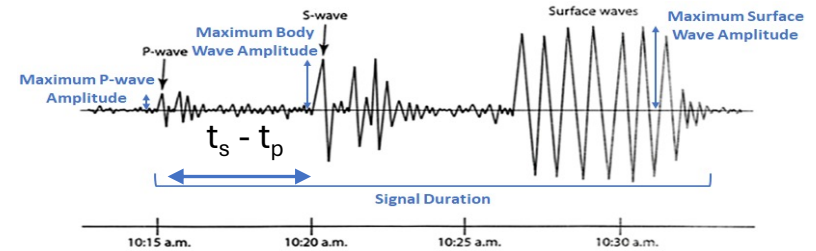
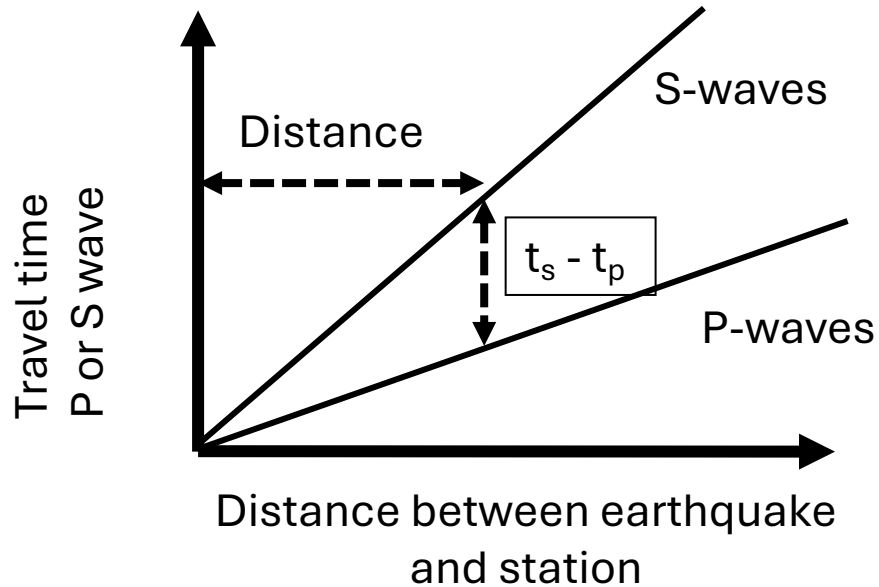


$$t_s = t_0 + \frac{D}{V_s} \quad t_p = t_0 + \frac{D}{V_p} \quad D = (t_s - t_p) \frac{V_s V_p}{V_p - V_s} \quad D \sim (t_s - t_p) \times 8$$

We expect you to know this! We will not give these equations in the exam

# Determining EQ location:

We can pick the arrival time of P and S waves at different seismometers around the world and use it to calculate distance to the earthquake.

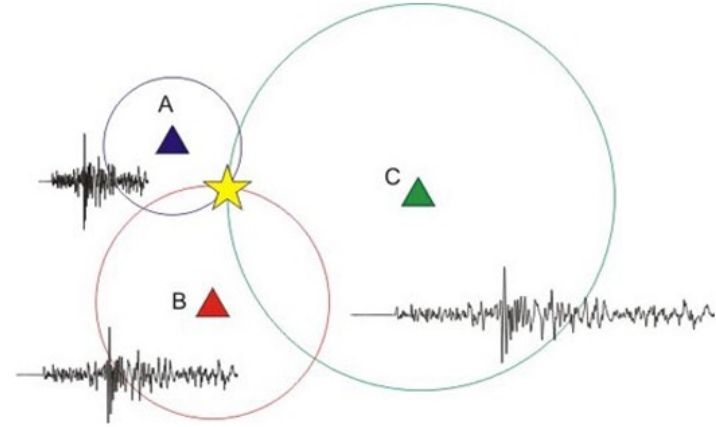
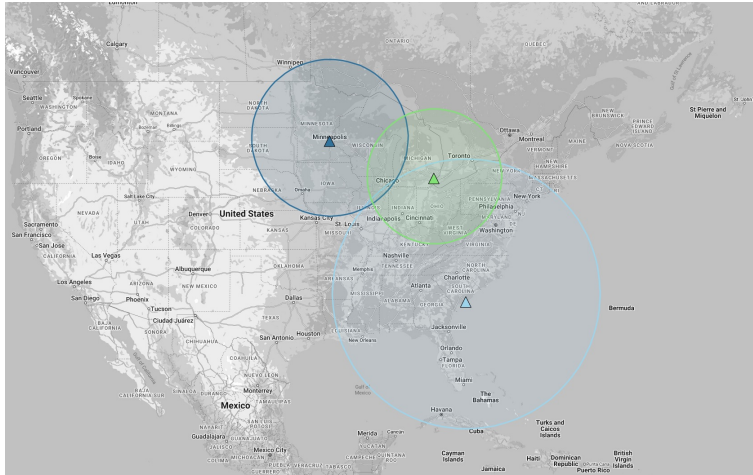


- < 100 km : local eq
- 100 to 1400 km: regional eq
- >1400 km: teleseismic eq

# Recall..

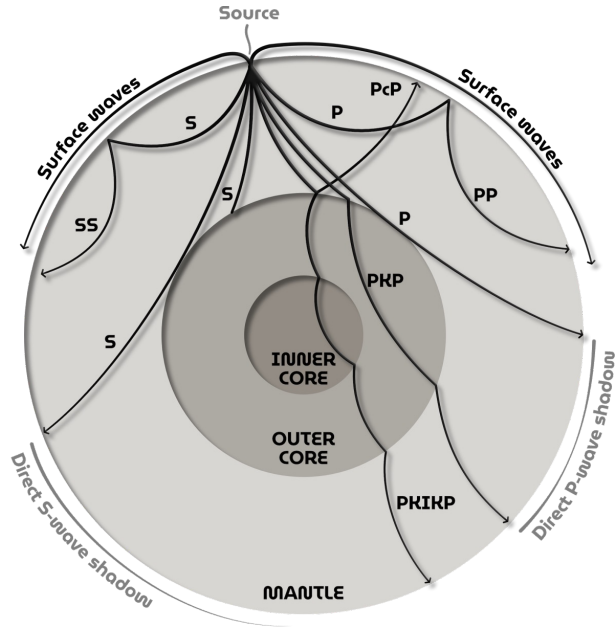
More stations will help us determine the location more accurately, it reduces uncertainty. Recall the **tutorial exercise** that we did!

Also, recall our answers for location depends on the assumptions we made during the calculations (like the velocity model). Other errors can come from instruments, measurement errors, etc

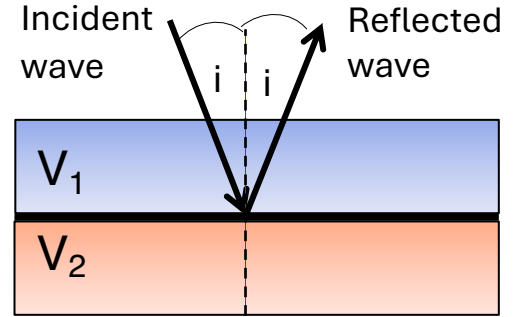


# Refraction causes bending of waves

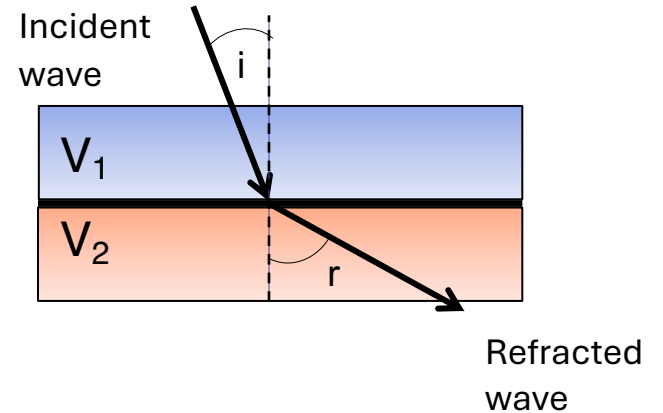
Seismic rays don't continue as a straight line. When they meet a rock with different properties, they will **bend**.



## Reflection

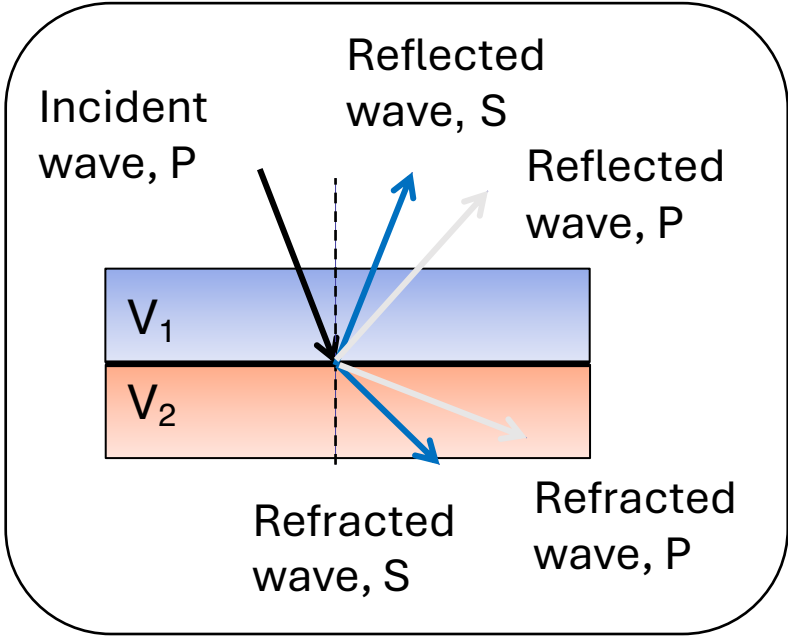
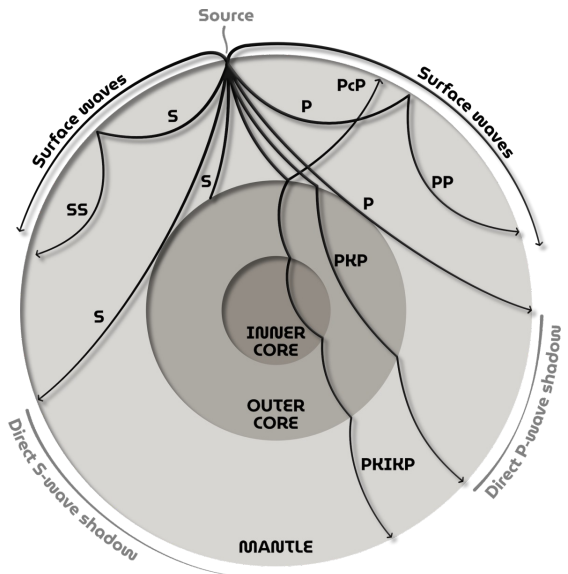


## Refraction



# Mode conversion

Energy from one wave type can be converted to another wave type at a boundary.  
Remember: All of these waves are always created at a boundary



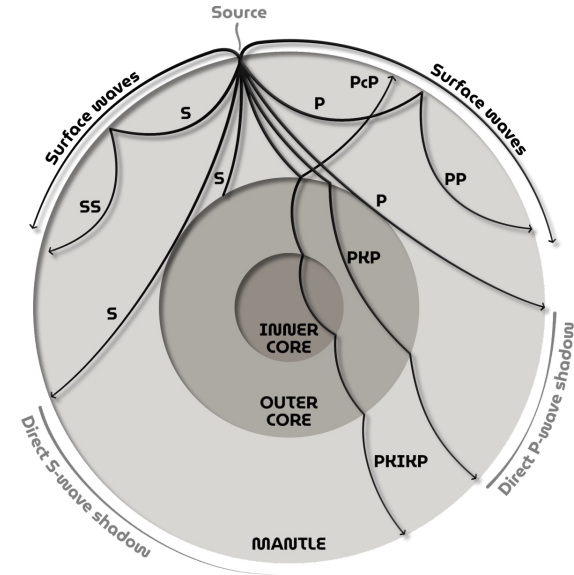
# Mode conversion

## Some key phases:

- PcP P reflection from CMB
- PKP ray through outer core
- PKiKP reflection from inner core
- PKIKP ray through inner core
- SKS S through mantle, as P through outer core
- ScP S through mantle, reflected P from CMB

## Naming:

- P = P wave in mantle
- S = S wave in mantle
- K = P wave in outer core
- I = P wave in inner core
- i = P wave reflected from inner core boundary (ICB)
- c = P wave reflected from core mantle boundary (CMB)



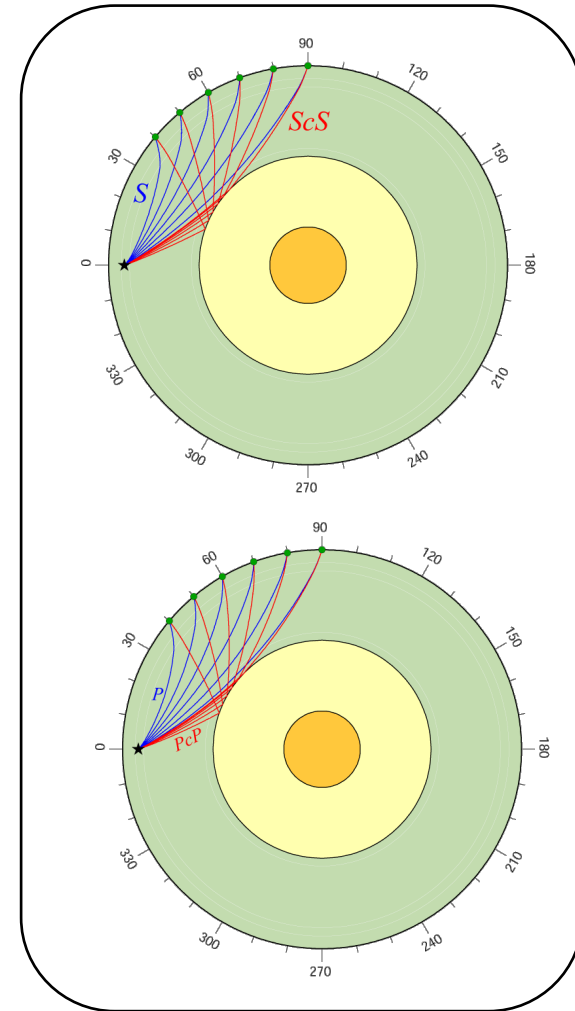
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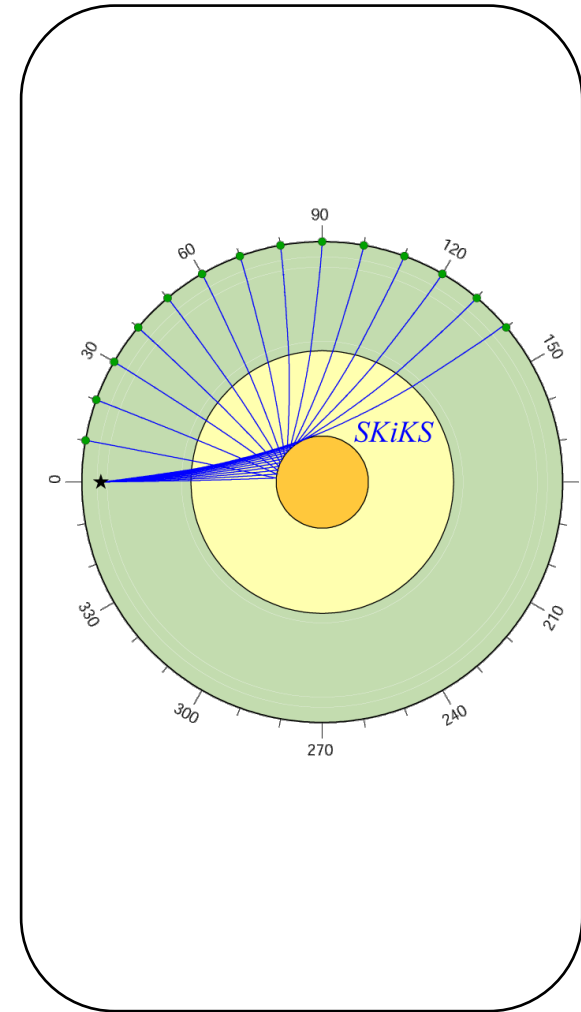
# Question

## Some key phases:

- PcP P reflection from CMB  
PKP ray through outer core  
PKiKP reflection from inner core  
PKIKP ray through inner core  
SKS S through mantle, as P  
through outer core  
ScP S through mantle, reflected  
P from CMB

## Naming:

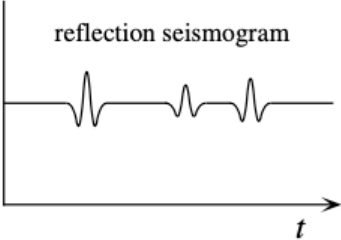
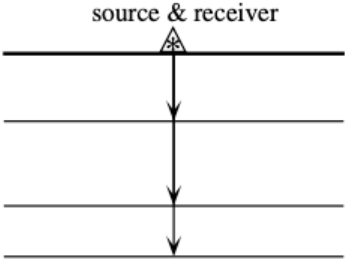
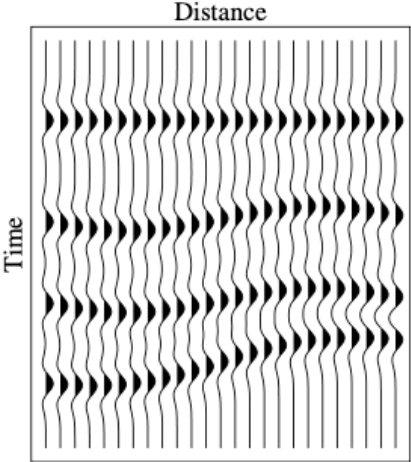
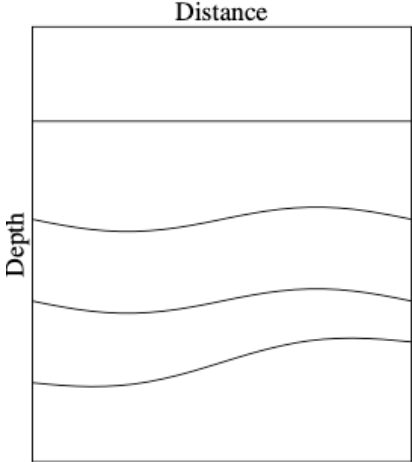
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S = S wave in mantle  
K = P wave in outer core  
I = P wave in inner core  
i = P wave reflected from  
inner core boundary  
(ICB)  
c = P wave reflected  
from core mantle  
boundary (CMB)



# Zero-offset

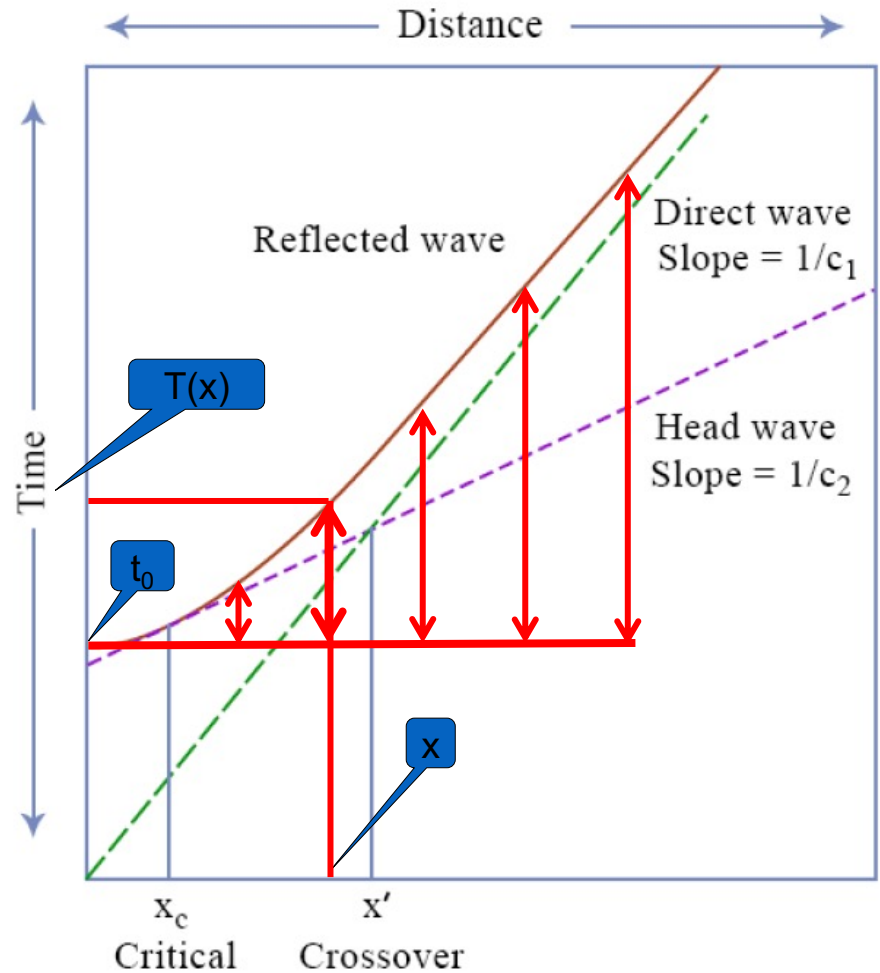
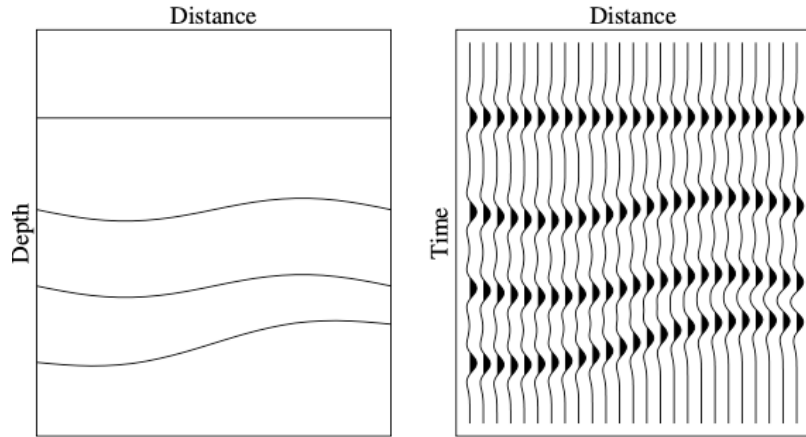
*Offset refers to the distance between the source and receiver.*

*When the source and the receiver are co-located, you get zero-offset section*



# Normal Move Out

*The difference between travel time at  $x=0$ , “ $t_0$ ”, and the travel time at any other distance  $x$ , is called the Normal MoveOut (NMO) time  $t_{NMO}$*



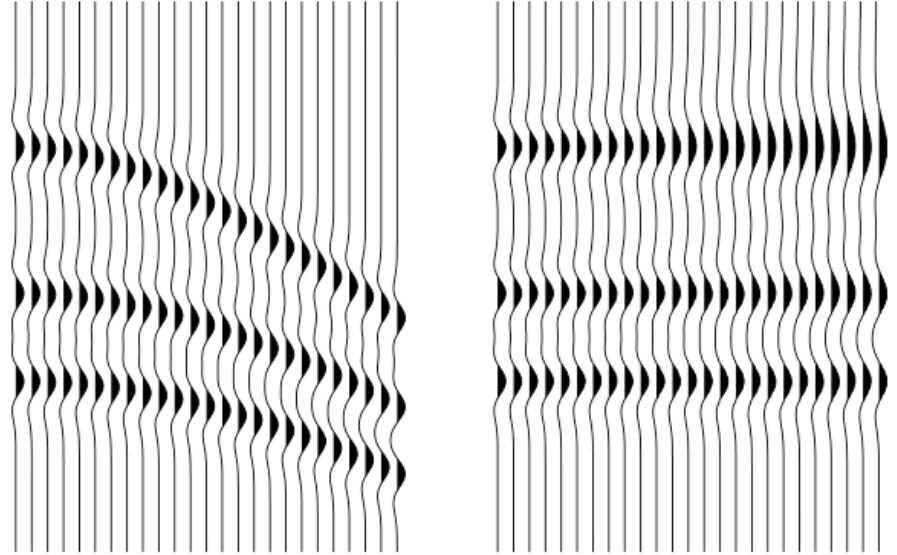
## Normal Move Out

The difference between travel time at  $x=0$ , “ $t_0$ ”, and the travel time at any other distance  $x$ , is called the Normal MoveOut (NMO) time  $t_{NMO}$

$$t_{NMO} = T(x) - t_0$$

The curvature of a reflection on a T-X plot is controlled by the velocity above it

**The NMO corrected records can then be stacked to produce a single composite zero-offset record.**



# Ask yourselves these questions before the exam...

**Broadly: How does seismics/GPR work? (physics involved). Some examples of important questions (not exhaustive):**

1. Seismic sources and receivers
2. How does reflection (seismic impedance) and refraction (Snell's law) work?
3. Snell's law  $\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$
4. Reflection coefficient calculation and analysis for seismic and GPR (formula will be given).
5. Critical angle, critical distance, cross-over distance
6. How does survey design impact the results?
7. Difference between the methods.
8. Relationship between velocity, frequency, and wavelength in GPR.
9. Depth vs resolution trade off.

**In a seismic survey, a reflection is weak. What is the most likely reason?**

- A. The boundary separates materials with similar physical properties**
- B. The source energy is too high**
- C. The wave velocity is constant with depth**
- D. The recording time is too long**

In a gravity survey, a positive anomaly typically indicates:

- A. A region of lower density
- B. A region of higher density
- C. A region of higher temperature
- D. A region of lower pressure

What property primarily controls the propagation velocity of electromagnetic waves in GPR?

A. Density

B. Electrical resistivity

C. Relative permittivity

D. Pressure

In an electrical resistivity survey, a high measured resistivity usually suggests:

A. Water-saturated materials

B. Clay-rich materials

C. Dry or resistive materials

D. High conductivity zones

When a seismic wave passes from a slower medium into a faster medium, the refracted wave:

- A. Bends toward the normal
- B. Bends away from the normal
- C. Stops propagating
- D. Changes frequency

What happens to electrical current flow when it encounters a resistive body in the subsurface?

- A. It passes straight through unchanged
- B. It accelerates
- C. It is deflected around the body
- D. It stops completely

In plate tectonics, ridge push is best described as:

- A. A force pulling plates into subduction zones
- B. A force pushing plates away from mid-ocean ridges
- C. A force generated by Earth's rotation
- D. A force caused by seismic waves