Global Seismology

Chapter 4

- ***Earthquake:*** an event of ground shaking usually caused by the rupturing of a fault within the Earth.

- Who studies Earthquakes?
  - Seismologists
    - waves
  - Geophysicists
    - Mechanics
    - Geodesy
  - Geologists
    - Structures
    - Paleoseismology

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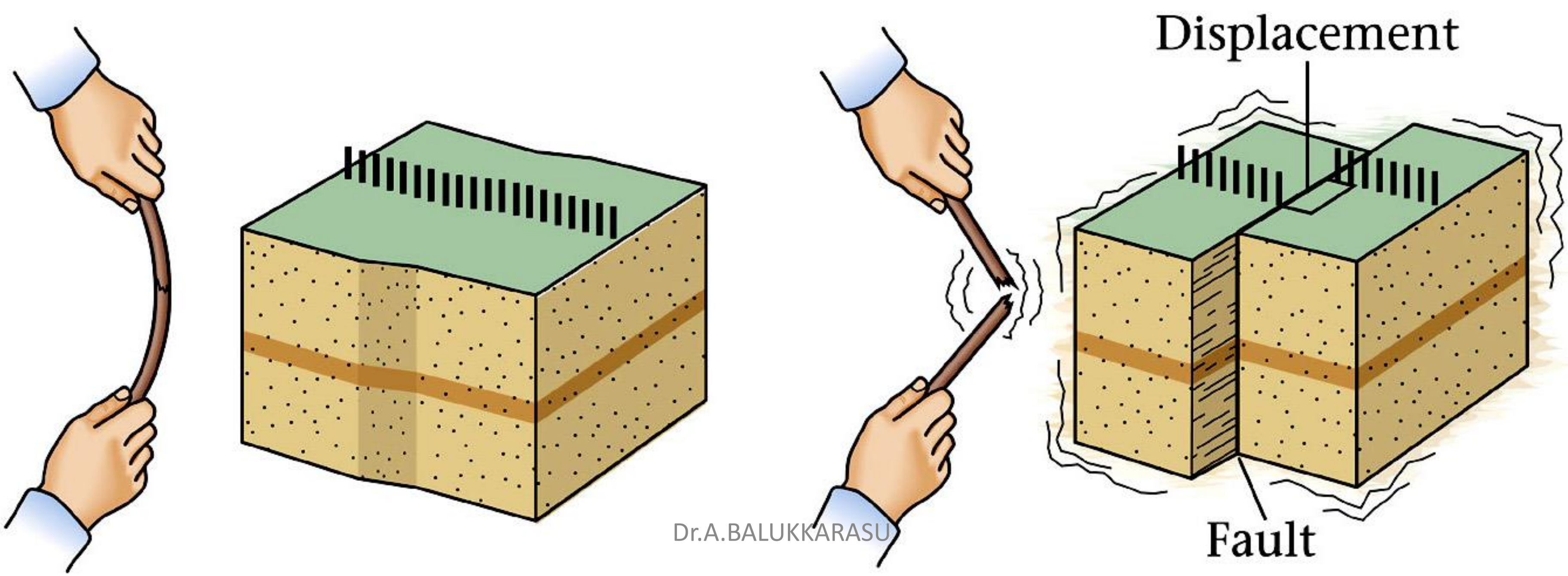
Why Do Earthquakes Occur?

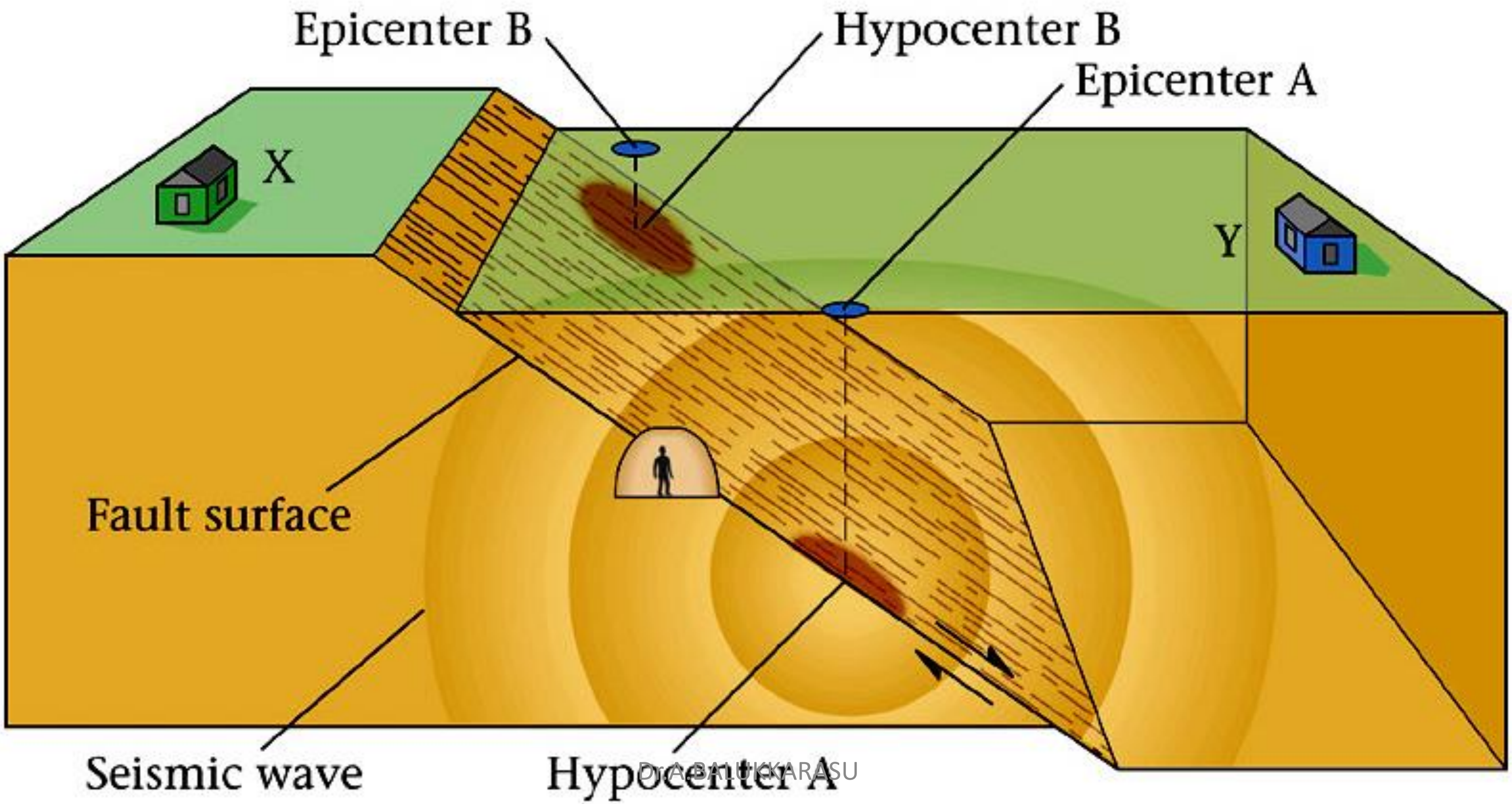
Earthquakes can occur due to:

- Sudden formation of a new fault (fracture on which sliding occurs)
- Sudden slip on an existing fault
- Movement of magma in a volcano / Explosion of a volcano
- Giant landslides (technically involves a fault)
- Meteorite impact
- Underground nuclear bomb tests



Earthquake Terminology

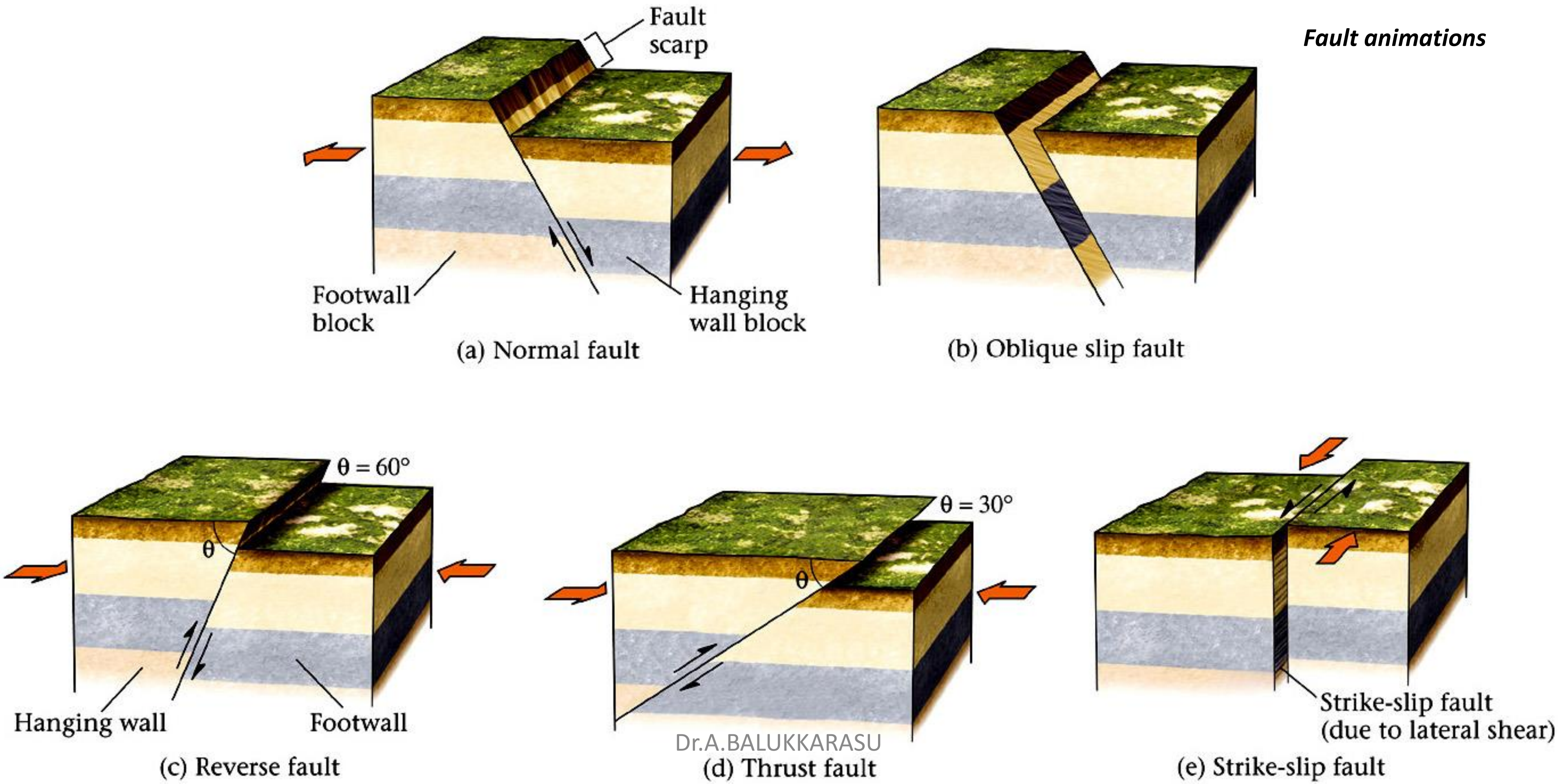
- ***Hypocenter (Focus):*** actual location of the earthquake at depth
- ***Epicenter:*** location on the surface of the Earth above the hypocenter
- ***Hanging Wall:*** top block of a fault (where a light would hang from)
- ***Footwall:*** bottom block of a fault (where you would stand)



Types of Faults

- In general, faults come in three different types: ***Normal, Reverse, and Strike-Slip***
- Shallow angle (< 30°) reverse faults are called ***thrust faults***
- Faults that have a mix of slip styles are called ***oblique slip faults***

Fault animations



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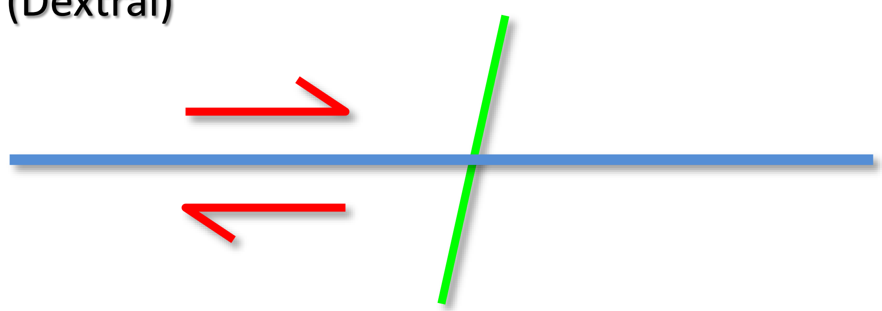
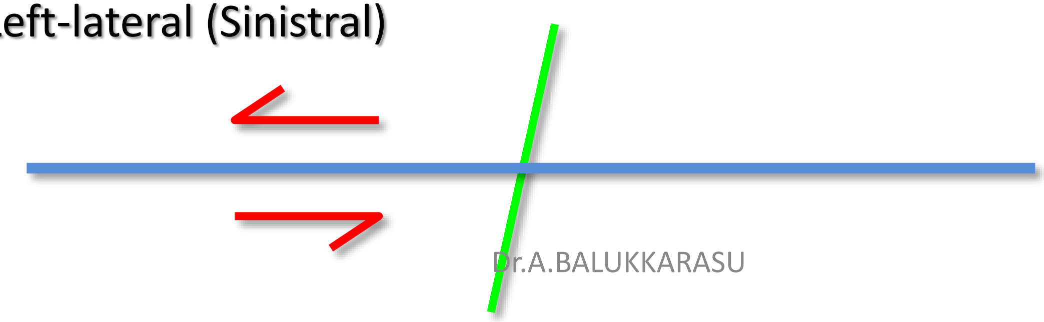
Why are there different types of faults?

- **Normal Faults**: from stretching of or extending rock; points on opposite sides of a fault are father apart after an earthquake
- **Reverse Faults**: from contracting or squishing rock; points on opposite sides of the fault are closer together after an earthquake
- **Strike-Slip**: can form in either areas of stretching or squishing, material slides laterally past each side of the fault.
  - Described by sense of motion:
    - Right-lateral (Dextral)



    - Left-lateral (Sinistral)



Quantifying Deformation: Stress & Strain

A simplistic view…

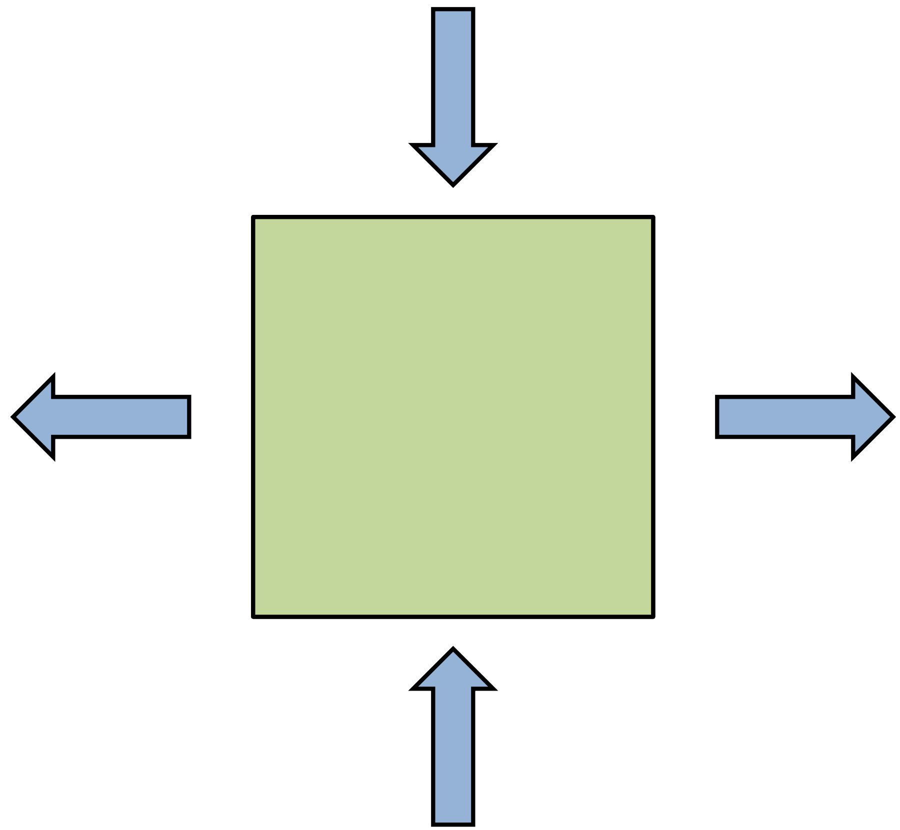
- Stress = force/area
  - So both force and area of contact are important
  - Stress [=] Pascals [=] $\mathrm{Kg \cdot m^{-1} \cdot s^{-2}}$
  - Types: tension, compression, shear

- $\mathrm{Strain} = \Delta l / l_0$
  - Measures change in size/shape (i.e. deformation)
  - Dimensionless (i.e. it is a percent).
    - Some may say, e.g., 2.5 µstrains or 3.1 nstrains
  - Types: extension/dilatation, contraction, shear

- Most scientists agree that stress causes strain
  - Chicken and egg argument

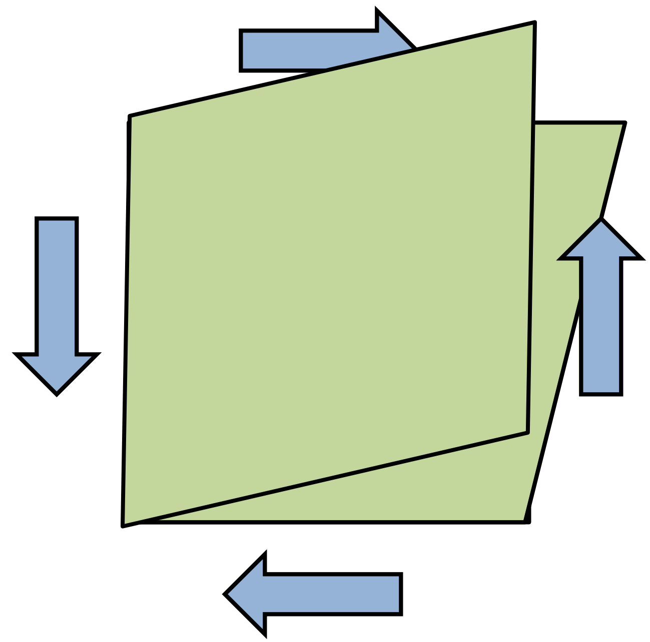
Normal Stress / Normal Strain

- A normal stress acts perpendicular to the applied surface.
- A normal strain results from a normal stress
- Deforms a square into a rectangle
  - Angles between sides remain unchanged



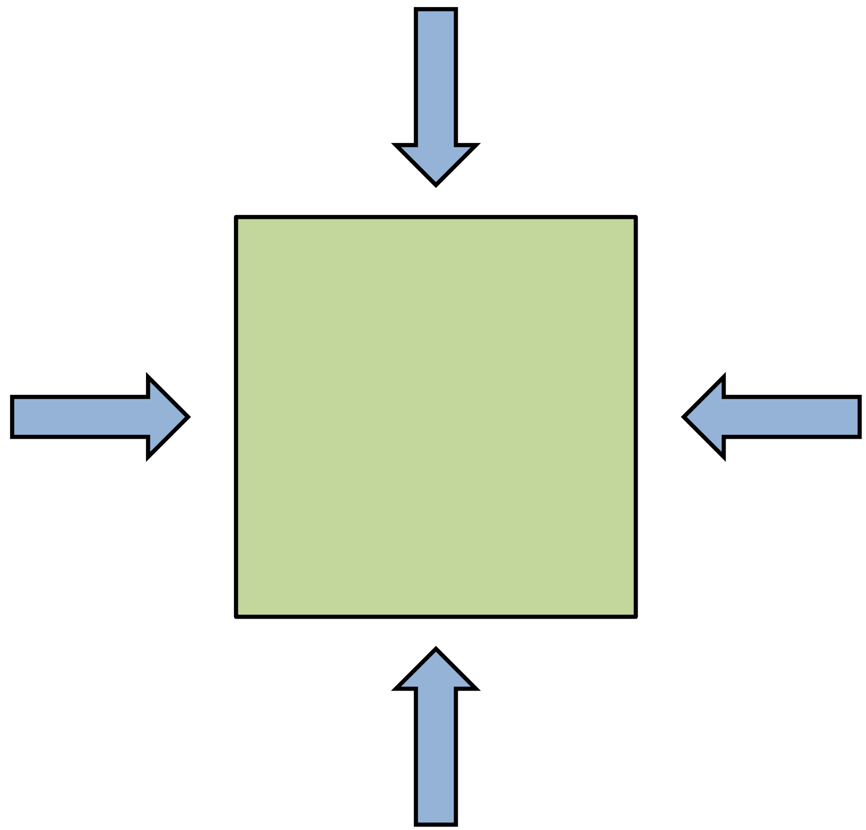
Shear Stress / Normal Strain

- A shear stress acts parallel to the applied surface.
- A normal strain results from a normal stress
- Deforms a square into a lozenge.
  - Angles between sides change.



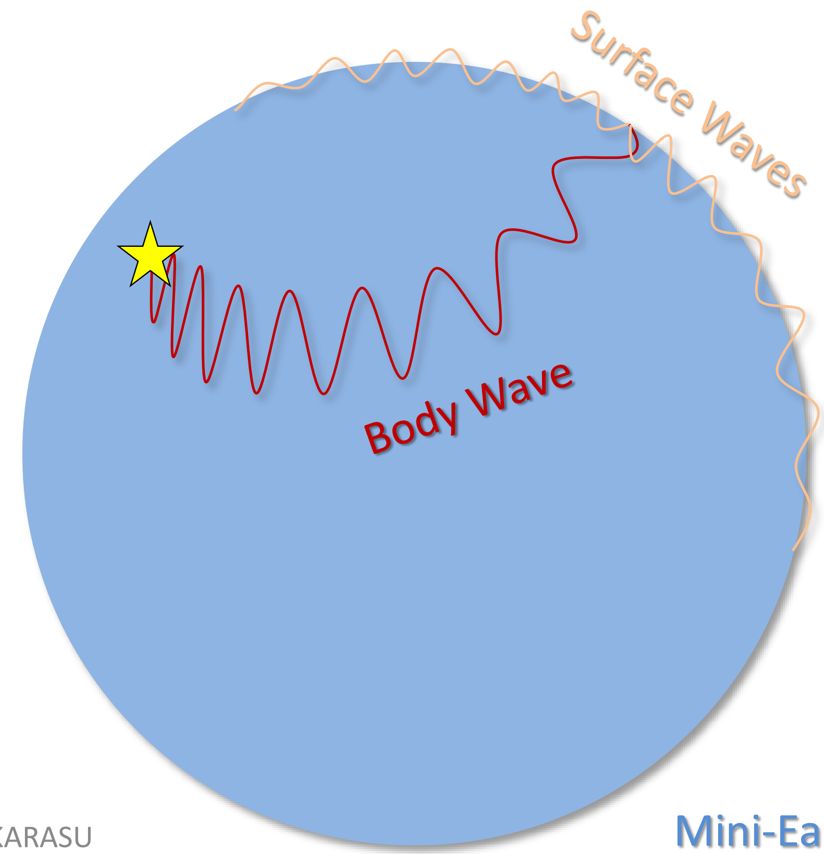
Pressure

- Pressure is a special state of stress where the stresses are equal in all directions
  - i.e. all normal stresses
  - Zero shear stress
  - Occurs in fluids (liquids/gasses)
    - E.g. air pressure
  - Causes only volumetric changes



Basic Wave Types

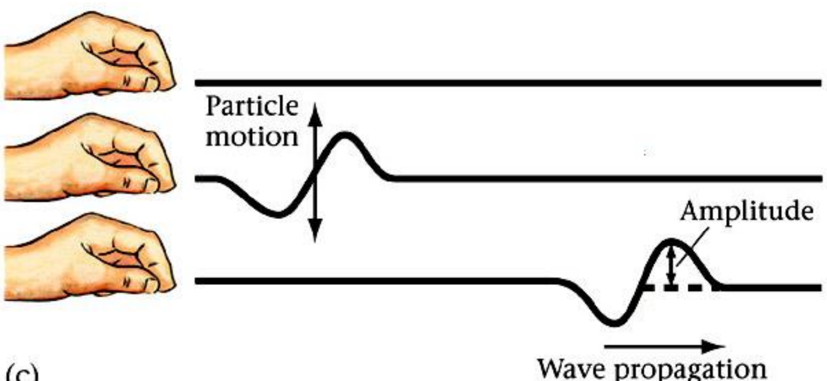
- Radiated energy that passes through the Earth during and after an earthquake are called ***seismic waves.***
- In physics, there are two basic ways to classify waves
  - Both are required to completely describe the wave type
- 1st Way: Based on what the wave is traveling through / along
  - Body wave: Motion through the interior of Earth
  - Surface wave: Motion is along the surface



Mini-Earth

Basic Wave Types

- 2nd Way: Based on how particles are moved by the wave / how the wave causes the material it is traveling through to deform
  - Compressional (Transverse) waves
    - motion of particles is in the direction of the wave
    - causes material to contract and extend
  - Shear (Longitudinal) waves
    - motion is perpendicular to wave direction
    - causes material to shear



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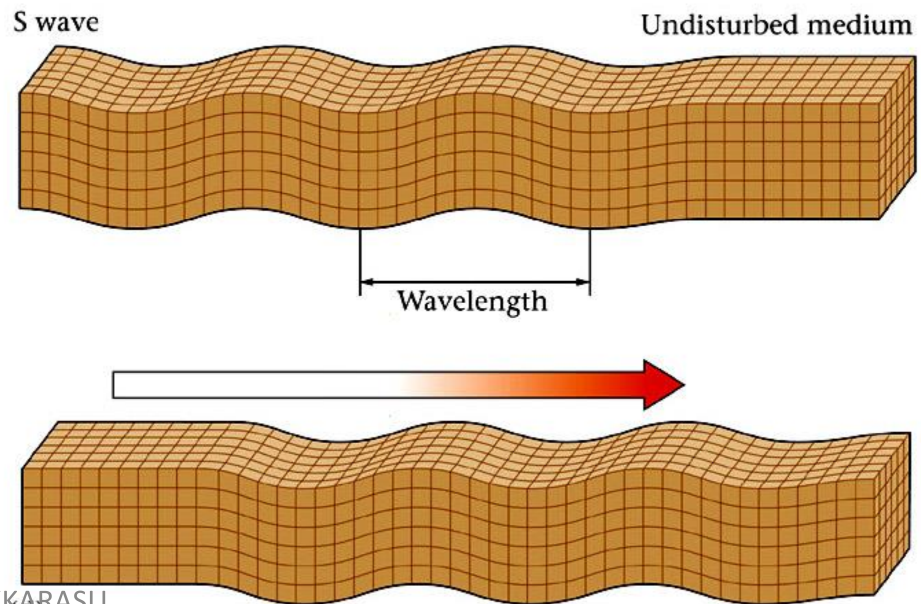

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Basic Wave Types

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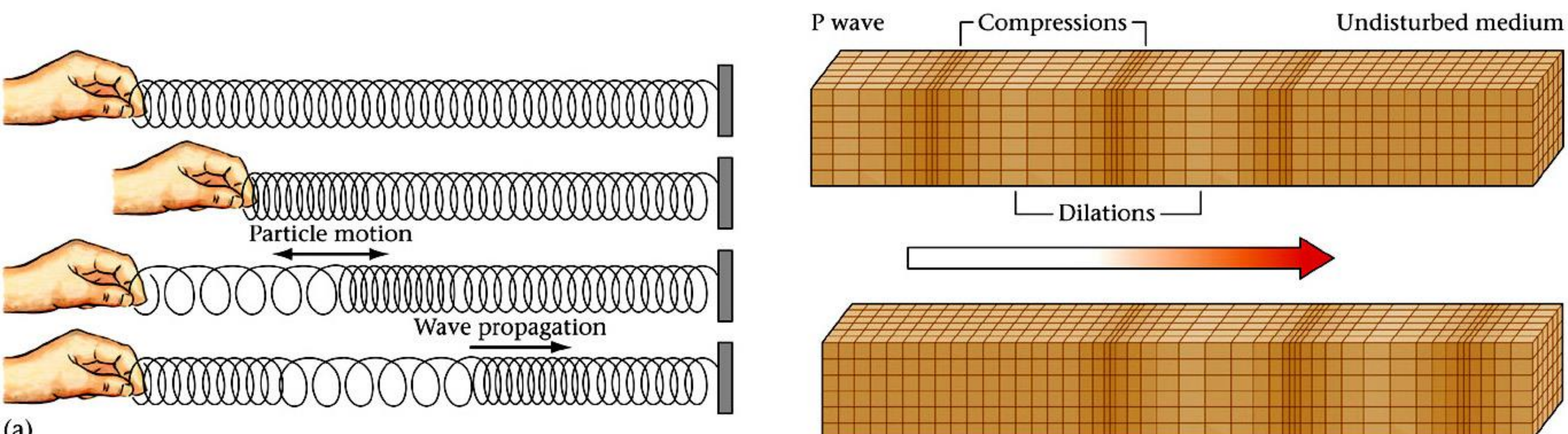
(Animation of wave types)



(a) (b)

Types of Seismic Waves

Earthquakes produce four main types of waves

- ***Body Waves:***
  - ***P-waves*** - compressional body waves
    - Think “primary” or “push-pull” waves
  - ***S-waves*** - shear body waves
    - Think “secondary” or “shear” or “shake” waves

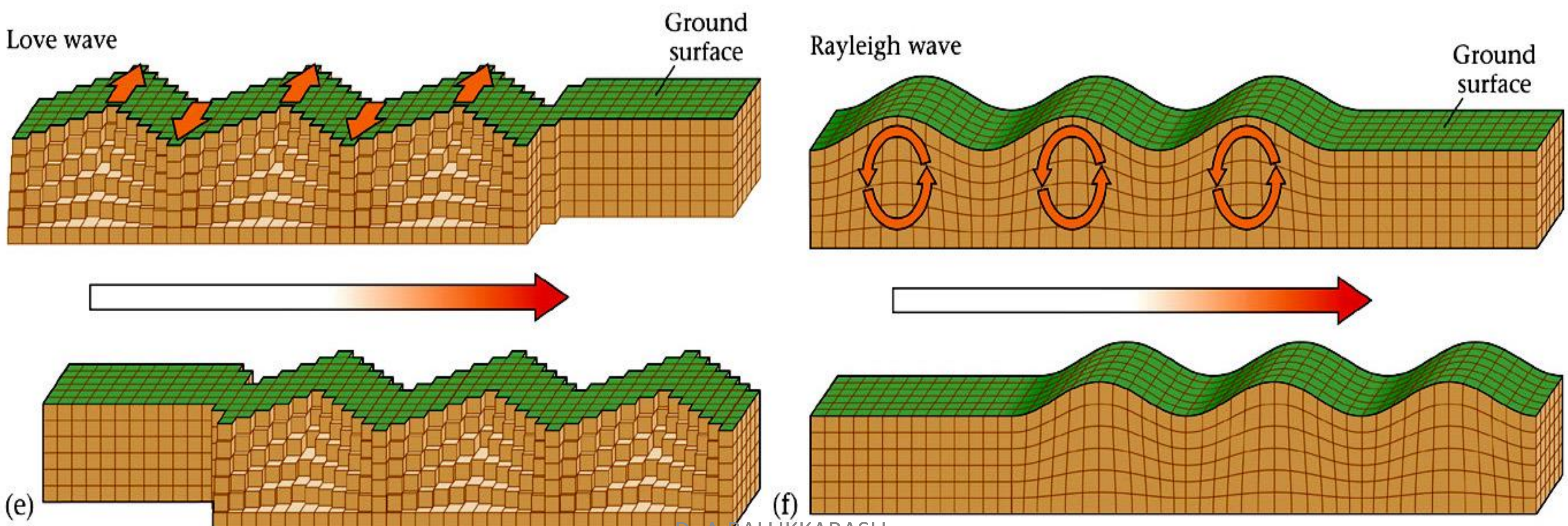
- **Surface Waves:**
  - ***R-waves*** – (Rayleigh, named for a physicist) surface shear waves that make the ground move up and down in a retrograde elliptical pattern.
  - ***L-waves*** – (Love, named for a seismologist) surface shear waves that cause the ground to move horizontally back and forth (like a snake).

- There are no surface compressional waves

L-waves vs. R-waves

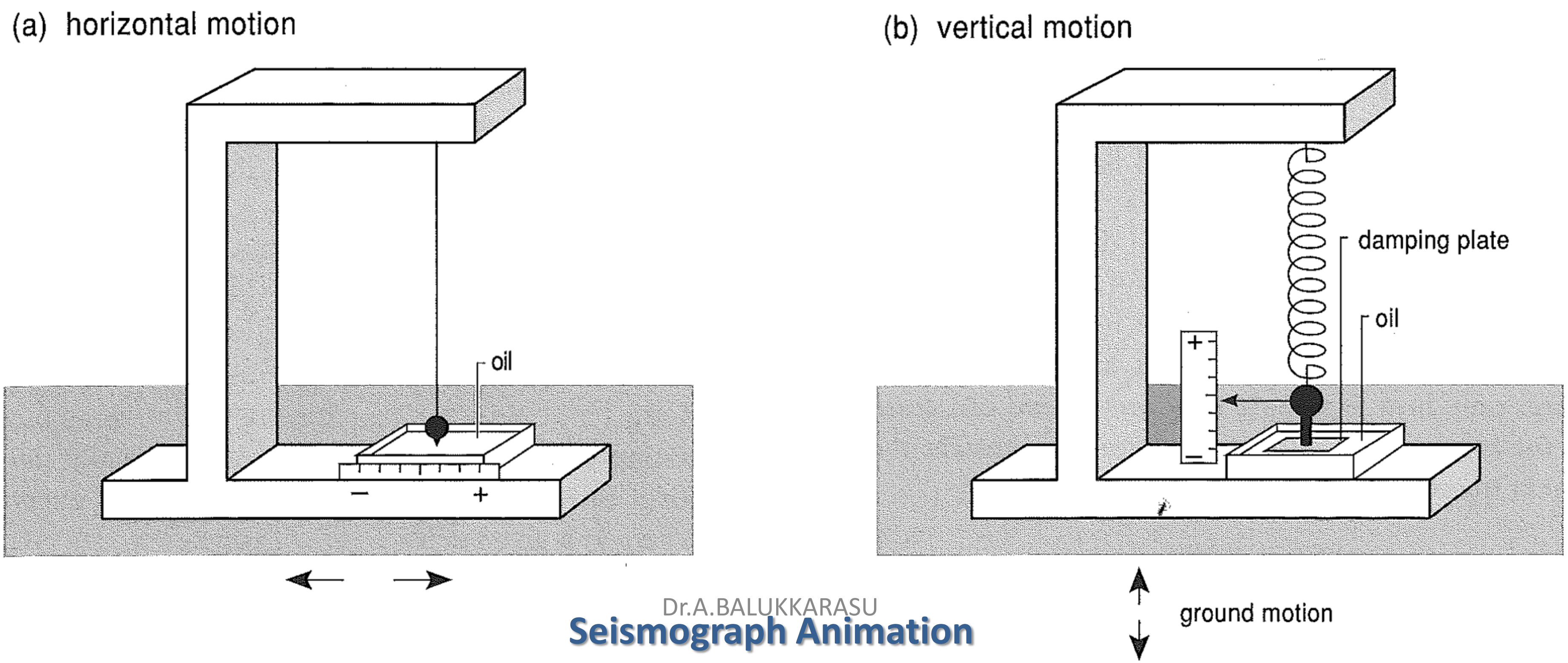
- L-waves – horizontal motion
- R-waves – retrograde elliptical motion in the vertical plane
- Surface waves do most of the damage in earthquakes

- How do we measure ground motion?



Measuring Seismic Waves

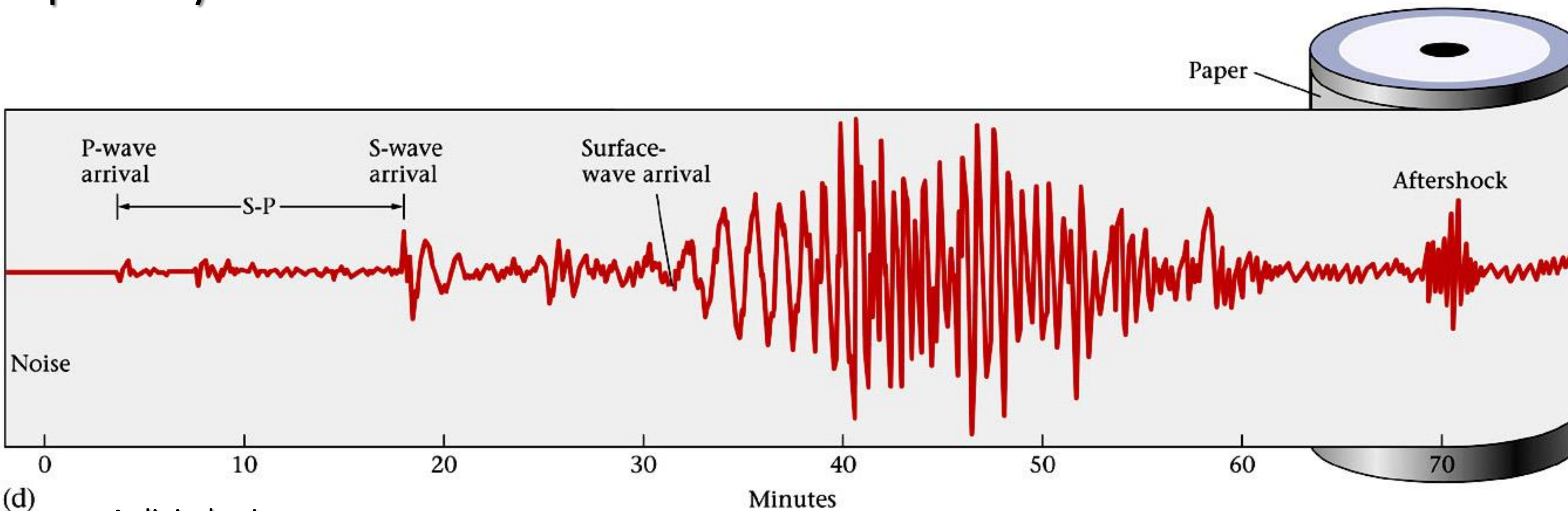
- Seismologists use **seismographs** or **geophones** to measure the ground accelerations of the Earth.
- Seismographs work because the Earth moves but the bob doesn't
- The record that the seismograph writes to is called a **seismogram**, which records the **arrival times** of seismic waves
- To minimize oscillations, a dampening fluid (e.g. oil) is used.



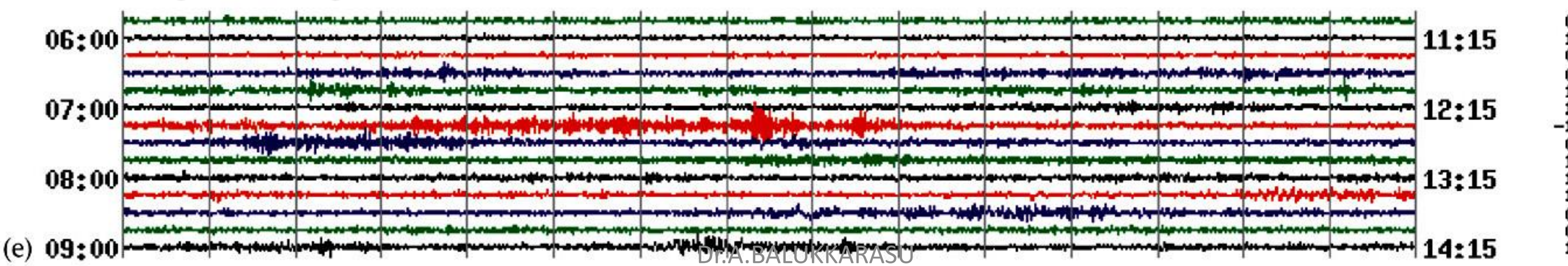
Seismograph Animation

Seismogram

- On a ***seismogram*** (the record created by a seismograph), we see the arrival times of the various seismic waves.
- P-waves, first,
- S-waves next,
- possibly aftershocks



A digital seismogram



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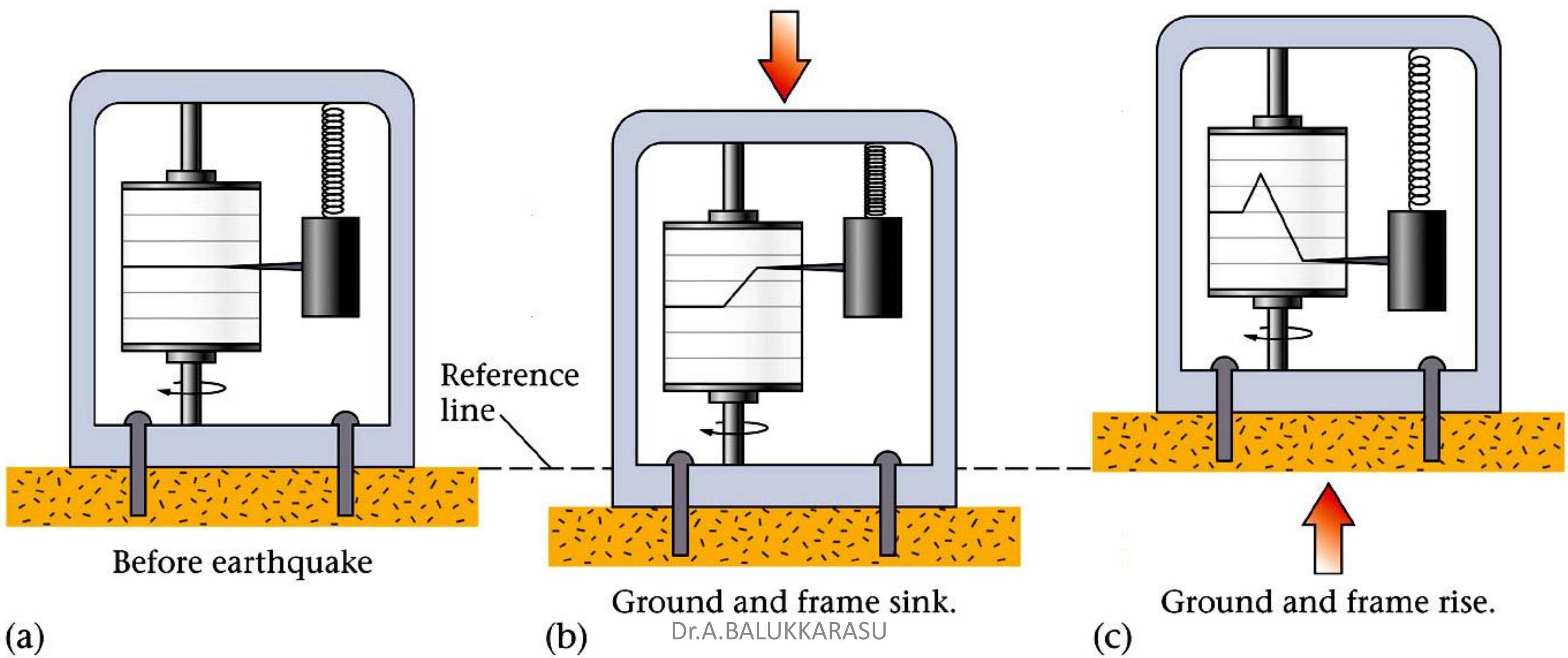
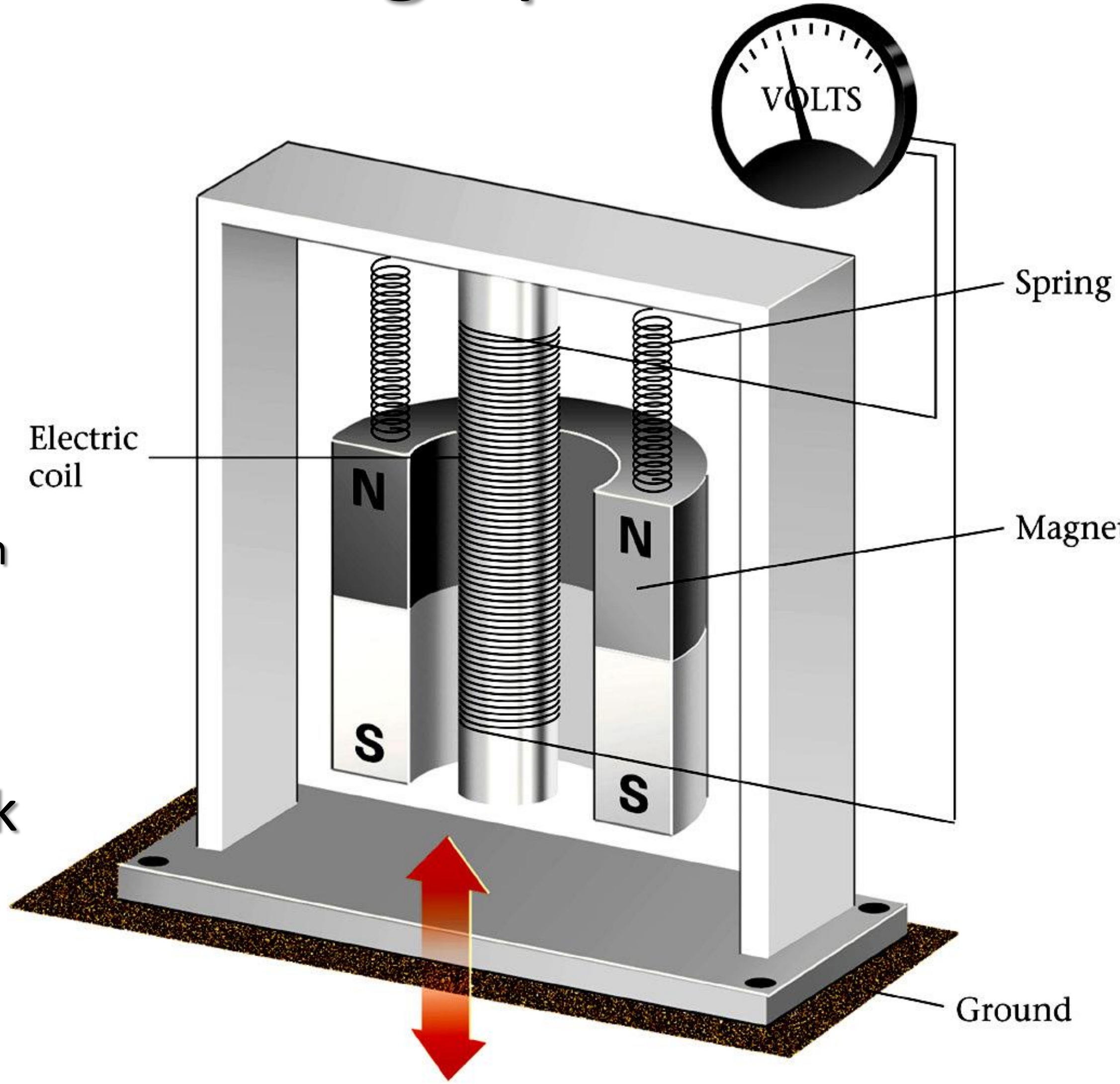
Seismograph in Action

- As the ground moves down, the seismogram records a positive slope.
- Large magnitude earthquakes are hard to measure with stations near the epicenter, because motions are so large that the needle essentially goes off the paper (e.g. the M_w9.1 great Sumatra earthquake)



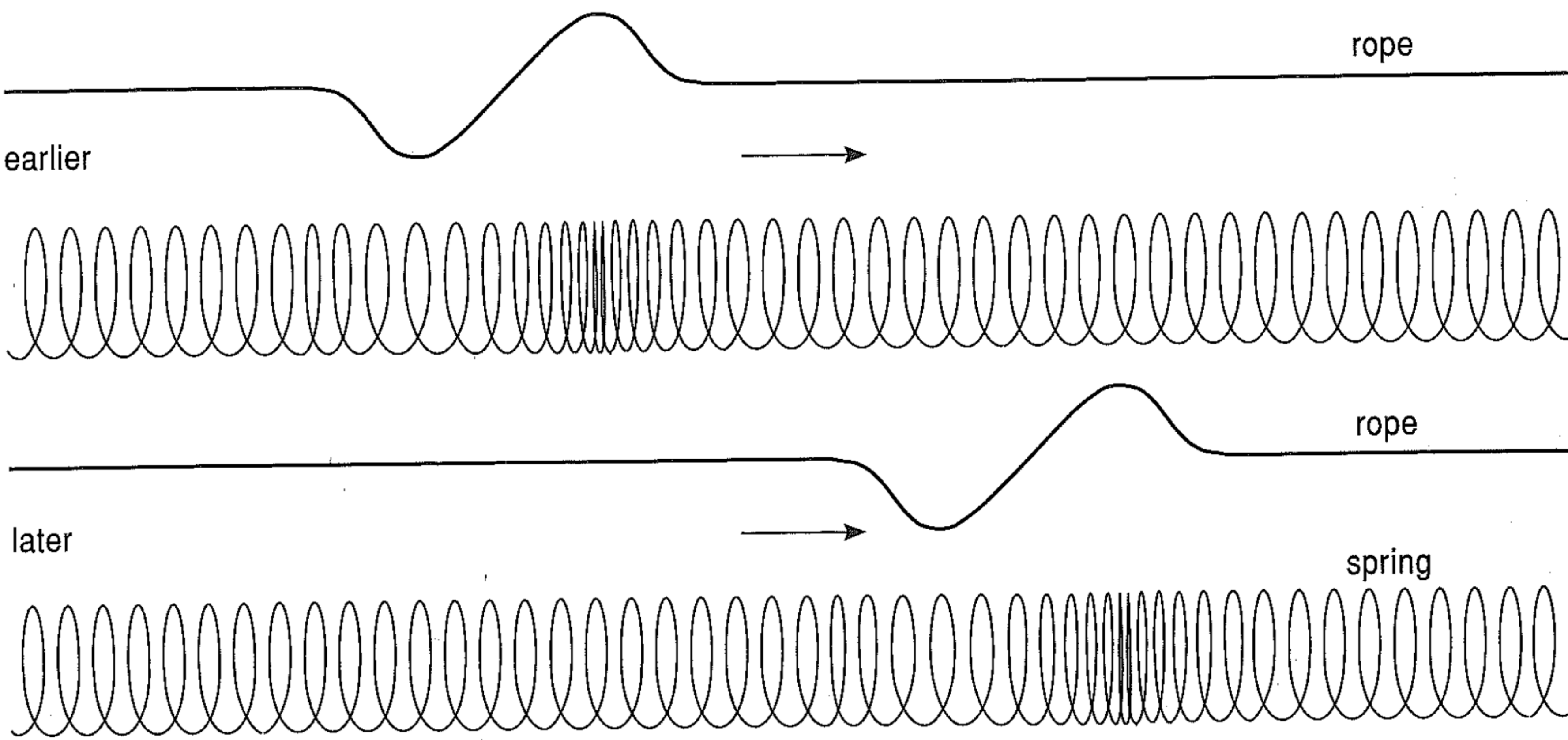
Modern Seismographs

- Use the same principles but use a coil of wire inside a magnet
- Motions induce a current that is measured by a computer
- Modern seismographs can
  - measure motions of a millionth of a millimeter
    - ~10x diameter of a typical atom
  - Detect a person walking at 1 km distance
- The global seismic network is calibrated so that all devices generate compatible data



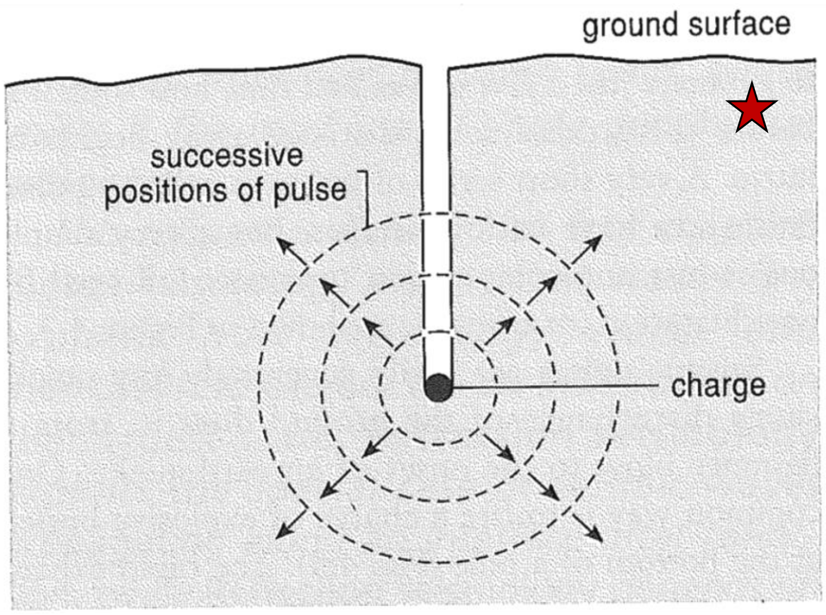
Seismic Pulses

- How does seismic energy move?
- A simple way to understand this is to consider a pulse.
  - **Pulse**: A very short series of waves
    - But the Earth is 3D!



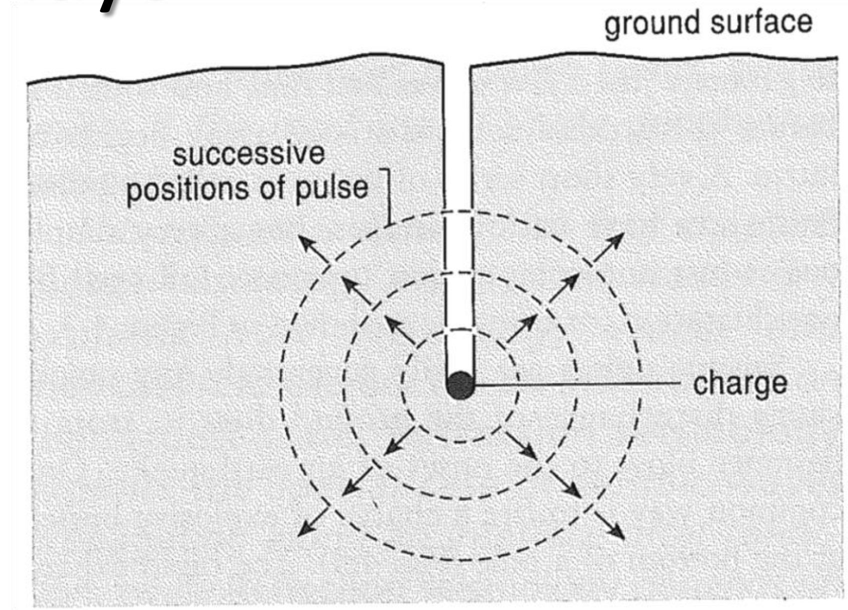
Seismic Wave Fronts

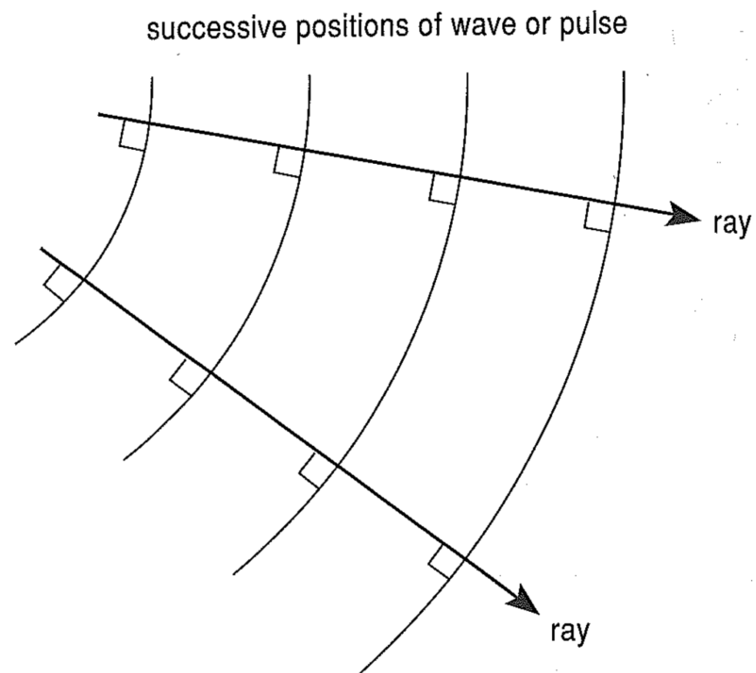
- Seismic sources radiate pulses of energy in all directions (spherically) from a source point. E.g.
  - pebble into water
  - explosion
- **Wave front**: The boundary between the energy pulse and the material that has not yet received the energy
- If we are only interested in what happens in one direction
  - We can just study part of the wave front :: **Seismic ray**



Seismic Rays

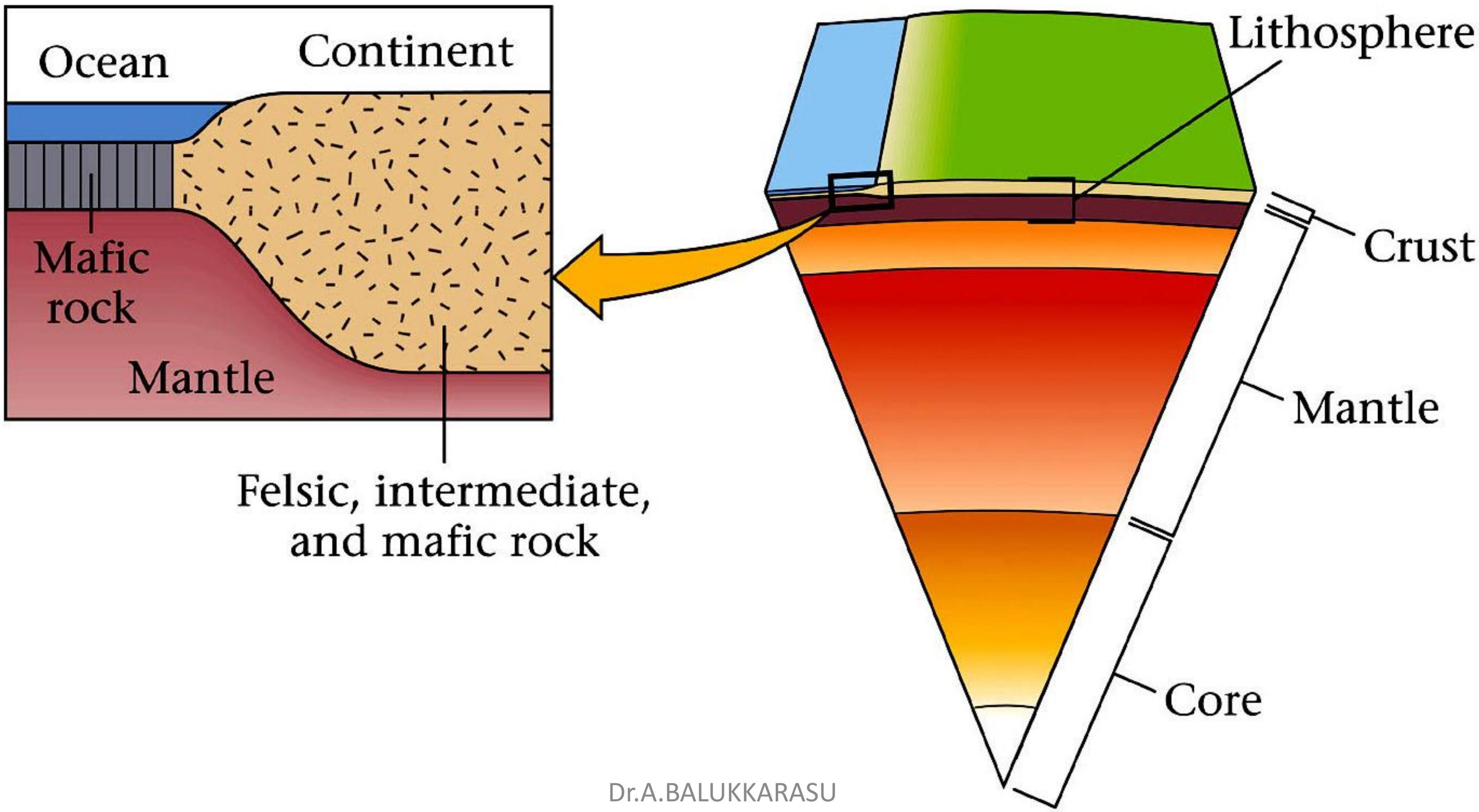
- **Ray**: The path of a tiny portion of the wave front
  - Perpendicular to wave front
  - Easier to understand
  - Most of seismology involves rays, although we understand that wave fronts are what is really occurring.





Using Earthquakes to See Inside the Earth

- Using what we have learned (and will learn now) about seismic waves, we can now look at how the various layers of the Earth were discovered and some of their properties.



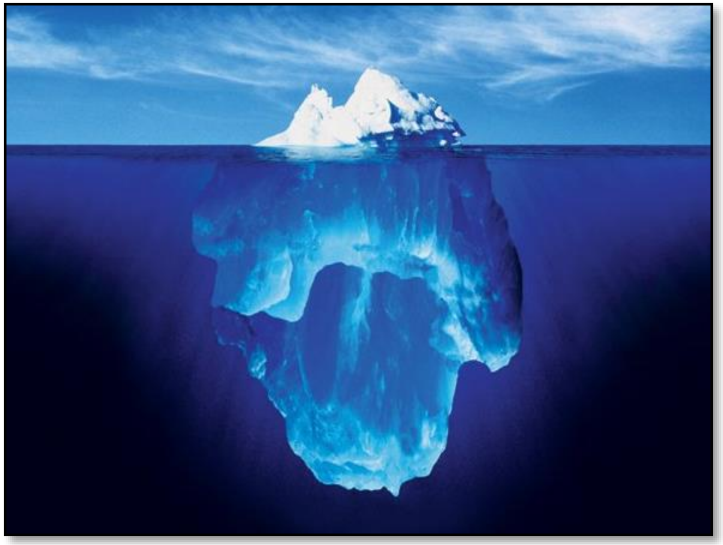
A Layered Earth

- We live on the thin outer skin of Earth.
- Early perceptions about Earth's interior were wrong.
  - Open caverns filled with magma, water, and air.
  - Furnaces and flames.
- We now know that Earth is comprised of layers.
  - The Crust.
  - The Mantle.
  - The Core.
    - Outer Core.
    - Inner Core.
- Some basic rules of physics give some clues…

From Milton's "Paradise Lost"

Earth's Density

- Earth's Density gives us clues about its internal structure

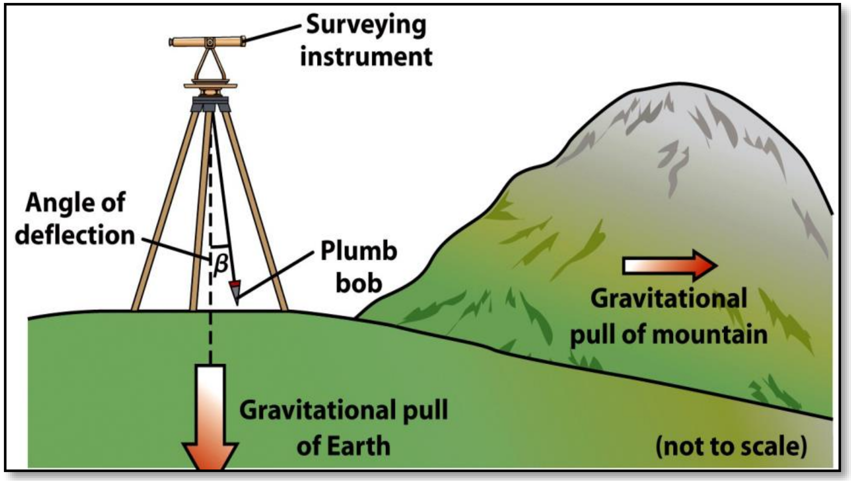


- ***Density = Mass/Volume***
  - Measures how much mass is in a given volume.
  - Expressed in units of mass/volume e.g. g/cm^3
  - Ice floats…why?

- Estimates of earth's mass and volume give a whole earth density of ~5.5 g/cm^3

- Typical rocks at the surface of the Earth have a density of 2.0-2.5 g/cm^3

- ***What does this require of the density of material in the Earth's interior?***



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Earth’s Density

Earth’s shape as a clue to the internal structure of the Earth

If density increased gradually and uniformly towards the center, a significant portion of Earth’s mass would be near the outer edges….

Then ***centrifugal*** force (not centripetal) would cause the planet to flatten into a disk.

This has (obviously) not happened…

- But Earth does slightly bulge at the equator (~0.033 %)

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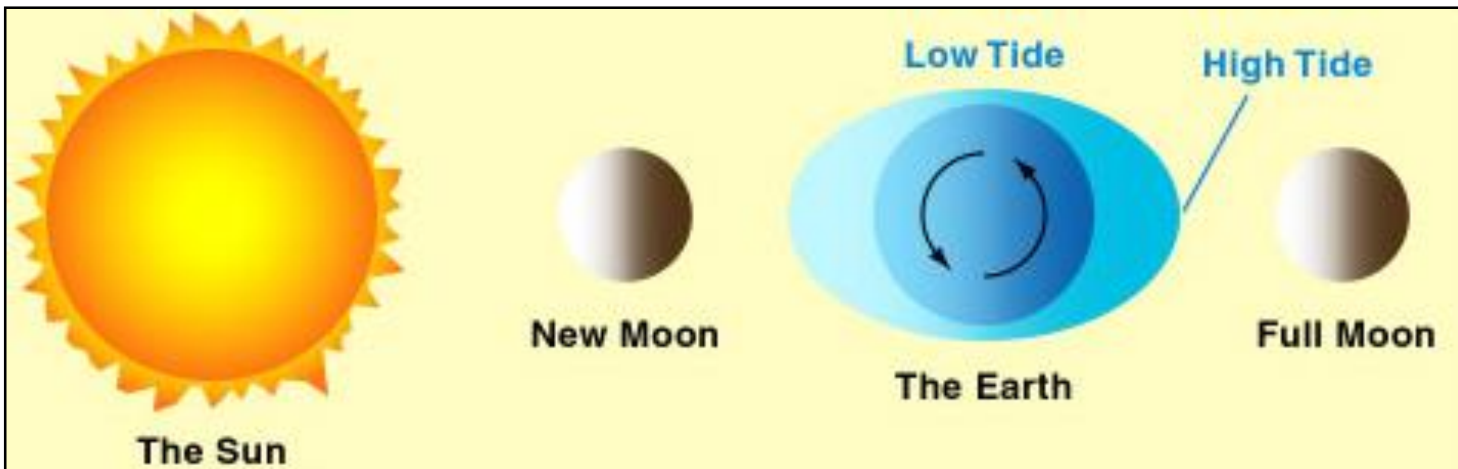
Earth's Layers

Earth's shape as a clue to the layering of the earth

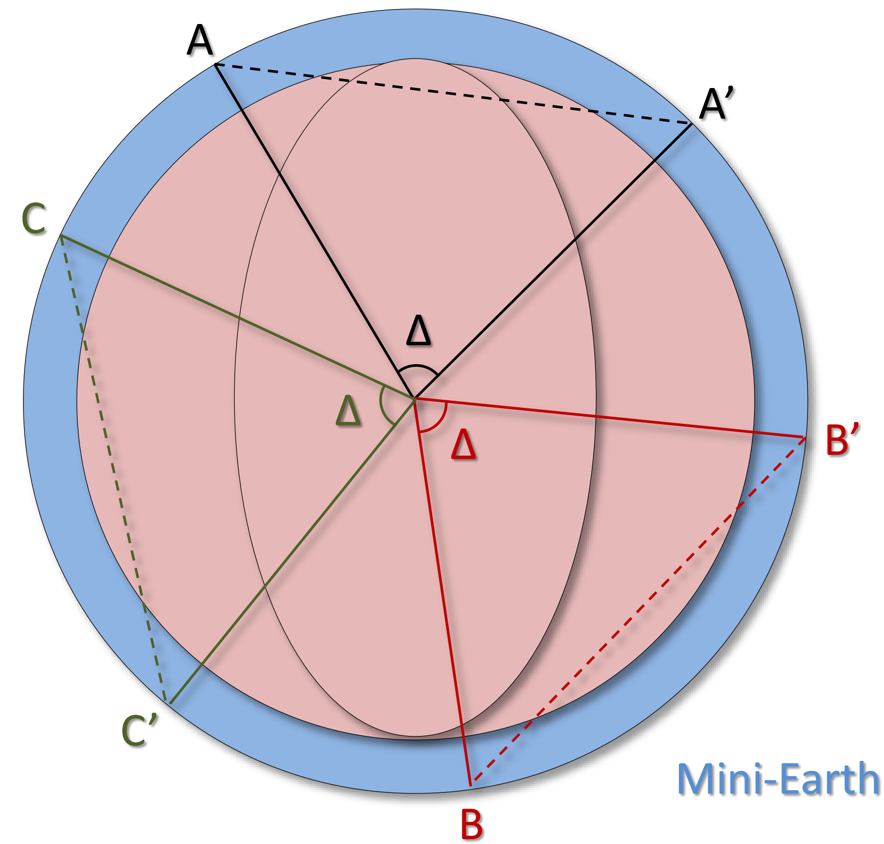
- If the Earth consisted of a thin solid shell over a thick liquid center, then the surface would rise and fall with tides like the ocean – This does not happen; only the oceans rise and fall.



- Thus, the Crust does not float over a liquid interior

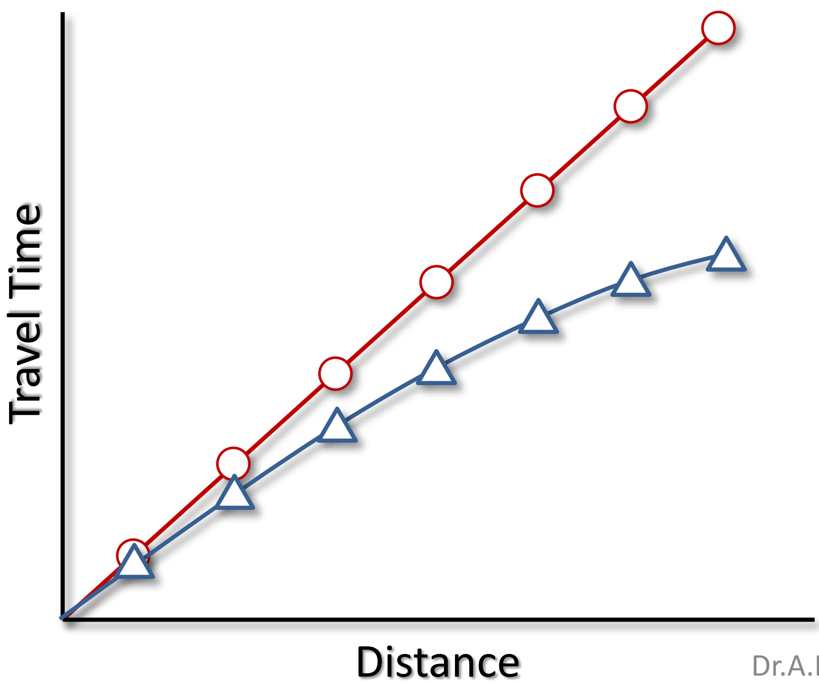
Is Earth's Interior Spherically Symmetrical?

- To test this question:
  - Look at arrival times from stations at equal distances from each other
  - Seismologists commonly measure distance by **epicentral angle**, Δ, the angle subtended at Earth's center
  - Measurements like this show that for any given epicentral angle, travel times are ~constant regardless of starting location.
  - So, this means that Earth must be spherically layered.



Do Seismic Velocities Vary with Depth?

- To test this question:
  - Look at arrival times from stations at varying distances from each other
  - If velocity is uniform with depth…
    - Distance will be linearly related to time; waves will be traveling in straight lines
  - Global measurements show…
    - Travel times are not linearly related to distance
    - Velocity is not uniform with depth; waves do not travel in straight lines
      - Velocity must increase with depth



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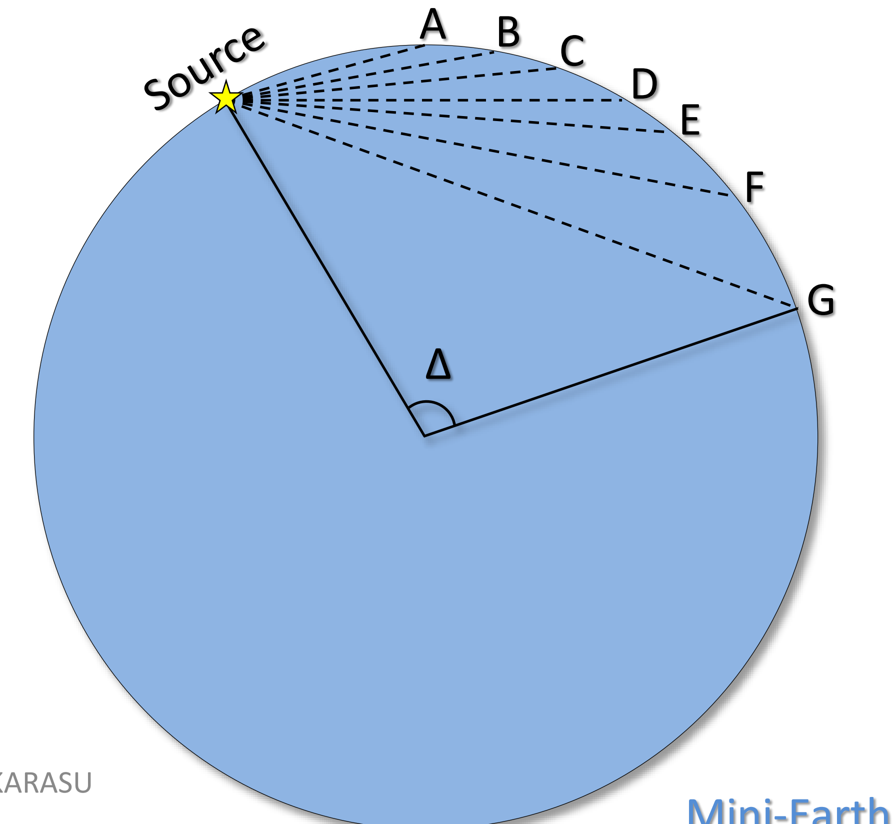


What Controls Seismic Velocities?

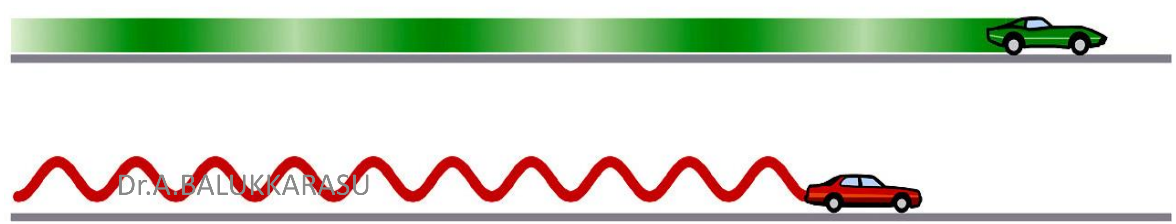
- A typical seismic wave:
  - Wavelength, λ = 200 m
  - Freqency, f = 10 Hz (s^{-1})
- v = f λ
  - Velocity, v = 2 km/s
- Velocities of P- and S-waves are different
  - μ = Shear Modulus
  - K = Bulk Modulus
  - ρ (rho) = Density
  - Which is faster?
  - What are moduli?
  - Given that seismic velocities in sandstone are ~3.5 km/s and ~8 km/s in peridotite, how can this make sense?

P-wave velocity

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

S-wave velocity

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



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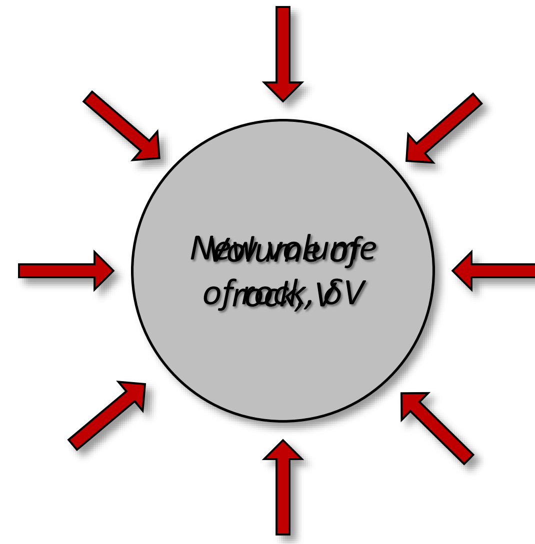
Elastic Moduli

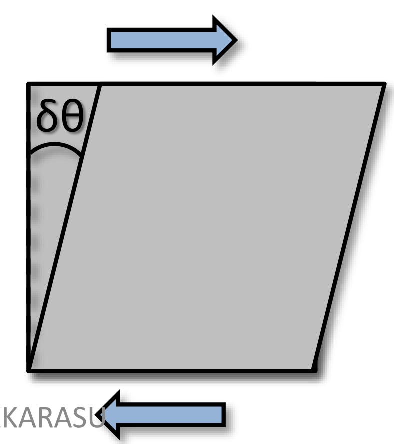
- Elastic Moduli measure a material's constitutive properties
  - i.e. the mathematical relationship between stress and strain.
- For elastic materials, only two are needed to completely define behavior.
  - Bulk Modulus, K:
    resistance to volumetric strain or "compressibility"

$$K = -\frac{P}{\left(\frac{\partial V}{V}\right)}$$



  - Shear Modulus, μ (sometimes, G):
    resistance to shear strain or the resistance to "shape change"

$$\mu = \frac{\tau}{\delta\theta} = \frac{shearStress}{shearStrain}$$



  - Because liquids have no shear resistance, their $\mu = 0$

Seismic Velocities and Moduli

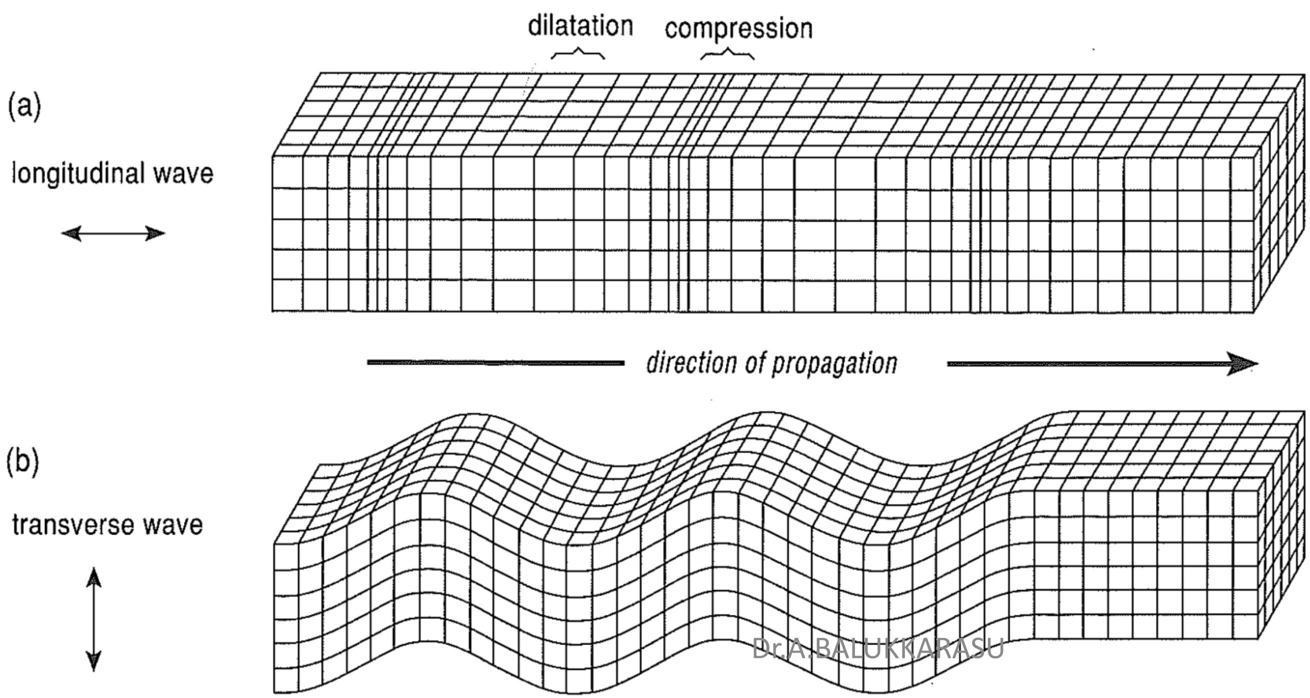
- Given the equations for seismic velocity
  - Why does v_s depend on μ?
  - Why does v_p depend on μ and K?
  - What is v_s in a liquid? Why?
  - What is v_p in a liquid? Why?
  - In a partial melt:
    - What happens to v?
    - Which wave will be slowed the most? Why?

P-wave velocity

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

S-wave velocity

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



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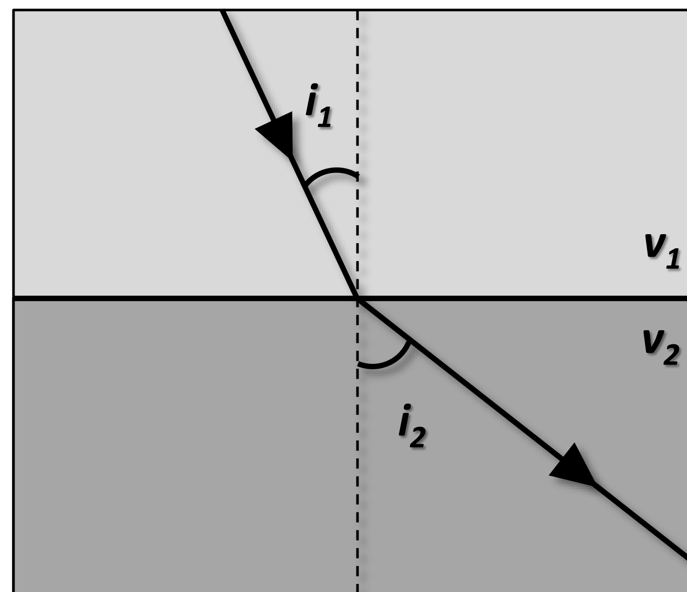
Finding Ray Paths :: Refraction

- Just like light, seismic rays refract, or bend, when they encounter a medium of different seismic velocity
- Refraction is quantified by Snell's Law

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

  - I = angle of incidence
    - Measured normal to interface
  - v = seismic velocity of material
- At some value of *i*, i_{crit}, the wave is completely reflected

An orangutan spear fishing



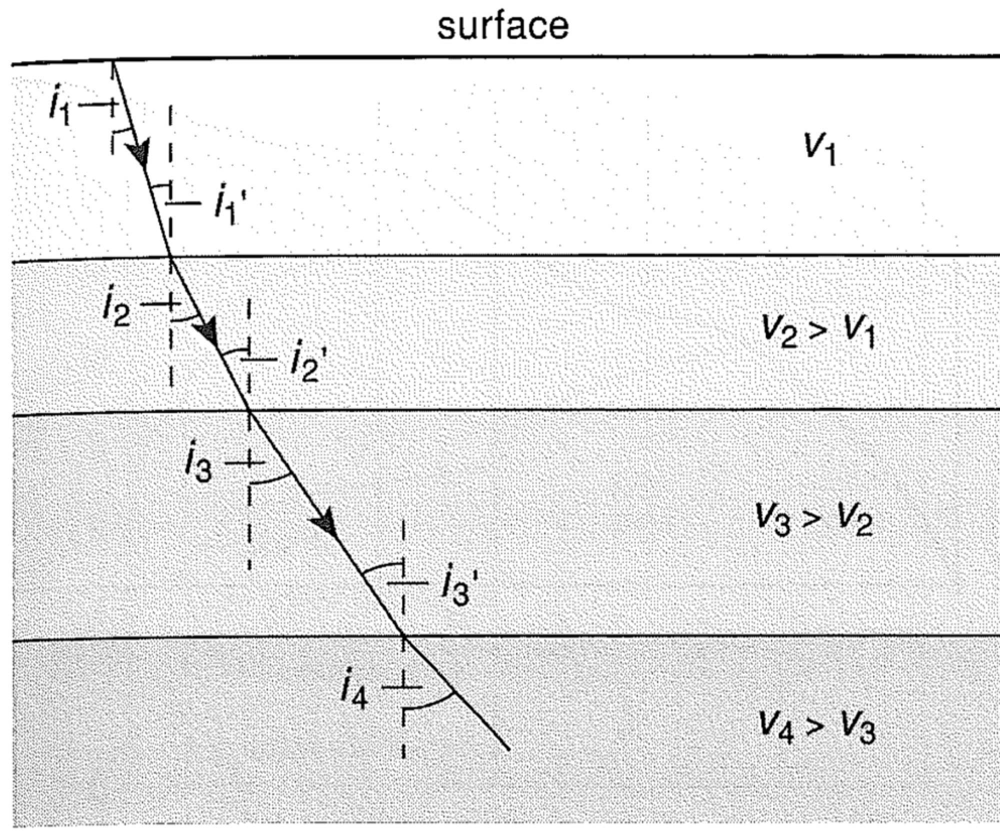
$v_1 < v_2$

Refraction Through Multiple Layers

- Snell's law can be applied to multiple layers

$$\frac{\sin i_1}{v_1} = \frac{\sin i_2}{v_2} = \frac{\sin i_3}{v_3}$$

- Snell's law also applies to reflected rays
    - we'll cover this later

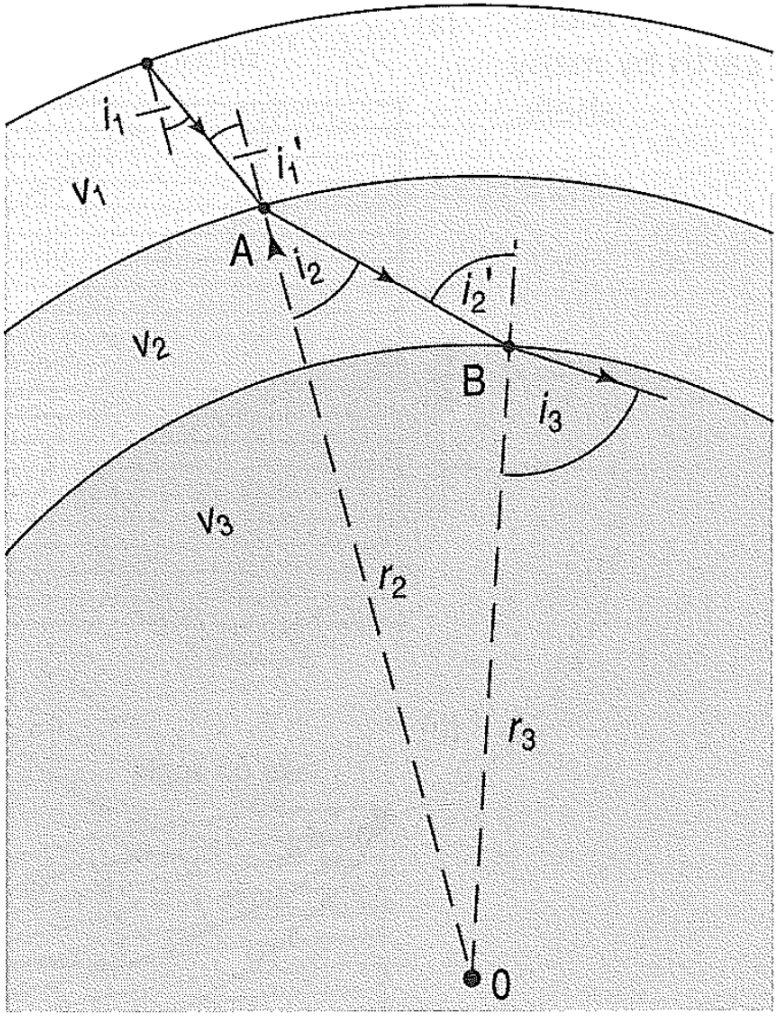


Refraction Through Curved Layers

- When dealing with large epicentral distances
  - Must account for the Earth being spherical
  - Snell's Law can be derived for spherical layers

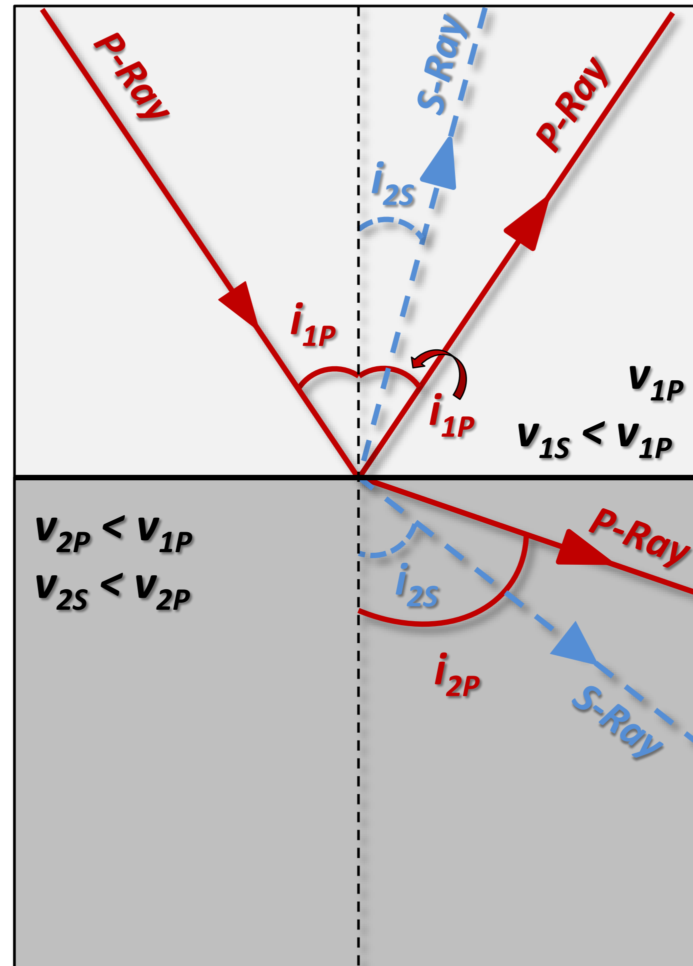
$$\frac{r_1 \sin i_1}{v_1} = \frac{r_2 \sin i_2}{v_2} = \frac{r_3 \sin i_3}{v_3} = p$$

- P = is the "ray parameter"
  - Has the same value along the entire path of any given ray assuming:
    - v, i, and r are measured at the same place

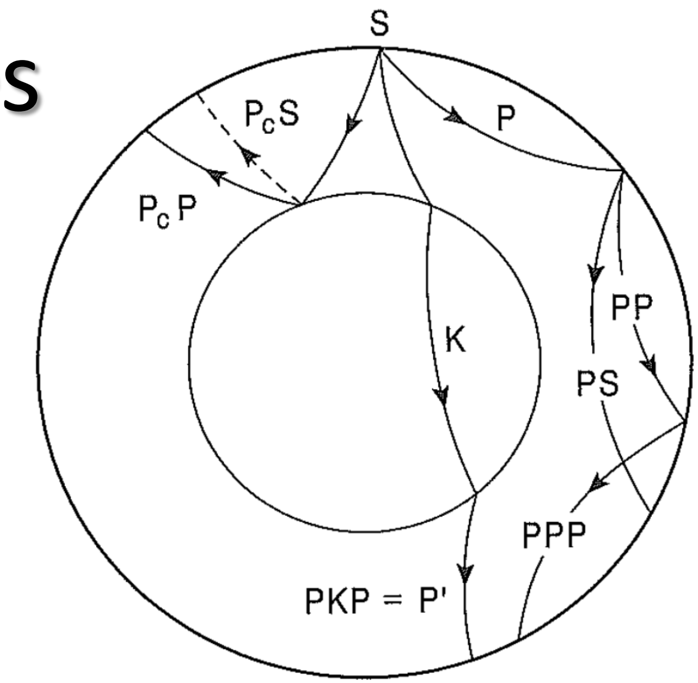


Reflection, Conversion, and Snell's Law

- Snell's Law applies to reflected rays
- Conversion: when a ray meets an interface, new rays are typically created
  - A P-wave can generate reflected P-waves, and S-waves as well as refracted P-waves and S-waves
    - Same is true for S-waves
- Snell's law also applies to converted rays that are:
  - Reflected $$\frac{\sin i_{1P}}{v_{1P}} = \frac{\sin i_{1S}}{v_{1S}}$$
  - Refracted $$\frac{\sin i_{1P}}{v_{1P}} = \frac{\sin i_{2S}}{v_{2S}}$$



Wave Phases

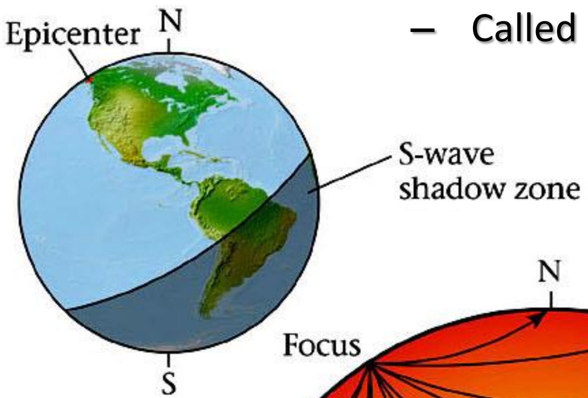


- On the global scale, waves converted from reflection or refraction with the major layers of the Earth are called **phases**.
- PS
  - begins as P-wave
  - reflected off of the surface
  - converted to S-wave
- S_cP
  - Begins as S-wave
  - reflected off outer core
  - Converted to P-wave
- i
  - Reflected off the outer core/inner core boundary
- K
  - P-wave in the outer core
- I
  - P-Wave in the inner core
- J
  - S-Wave in the inner core
- Test: What is SKJKP?
- Why is PSKIKP not possible?

The S-wave Shadow Zone

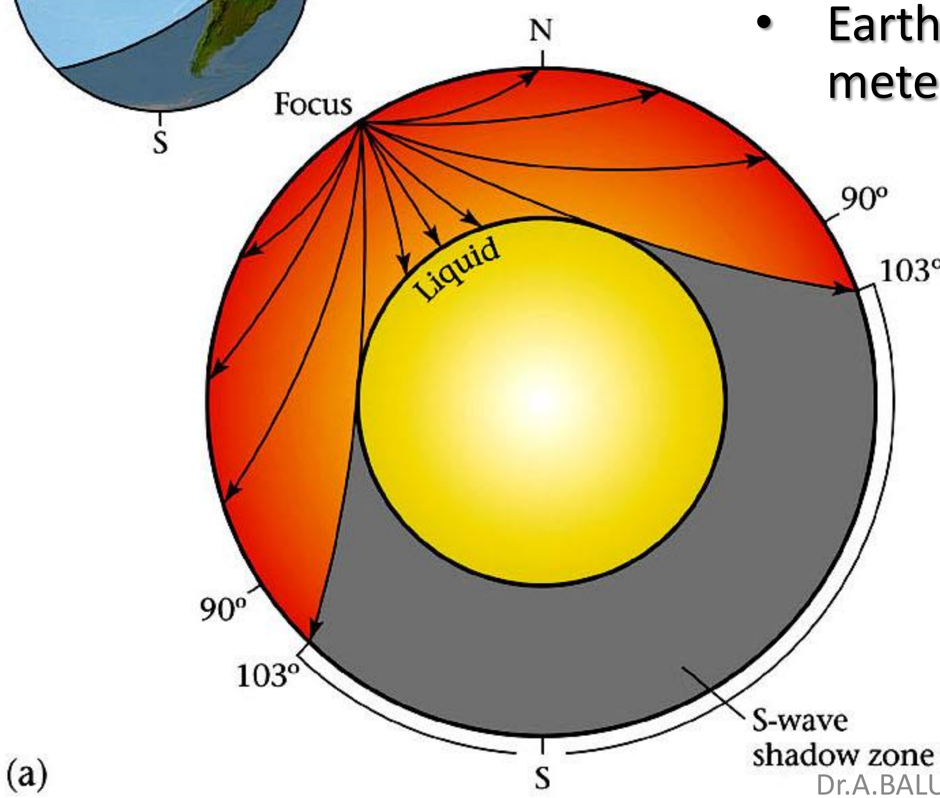
- If velocity gradually increased with depth
  - waves would be recorded at all stations globally

- Seismic waves are not recorded at all seismic stations world wide
  - Called "shadow zones"



- S-waves only reach stations that are within epicentral angles of < 103° of the epicenter.

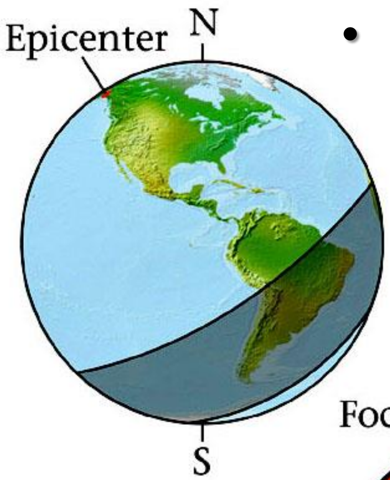
- Earth's core is made of an iron alloy based on meteorites



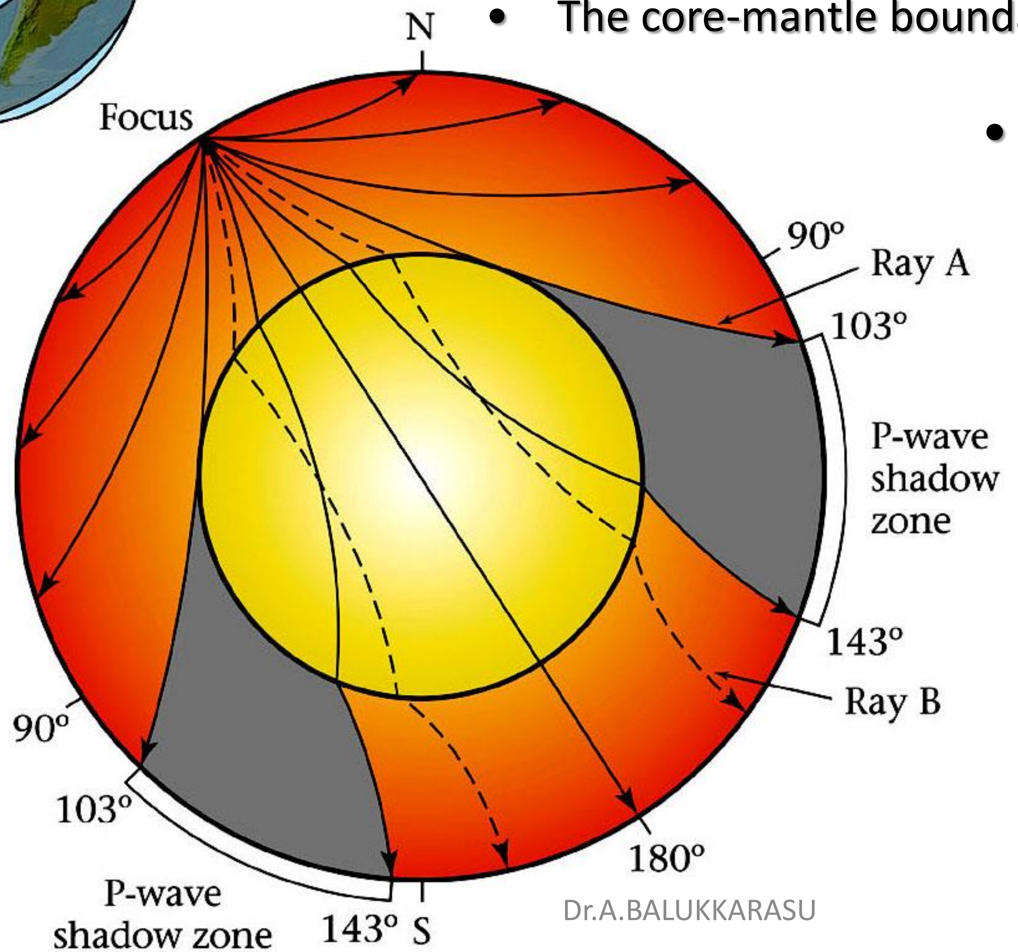
- The S-wave shadow zone is a direct consequence of the liquid outer core.

- Seismologists have since discovered that P-waves reflect off of a discontinuity within the core suggesting a two-layer core.

The P-Wave Shadow Zone



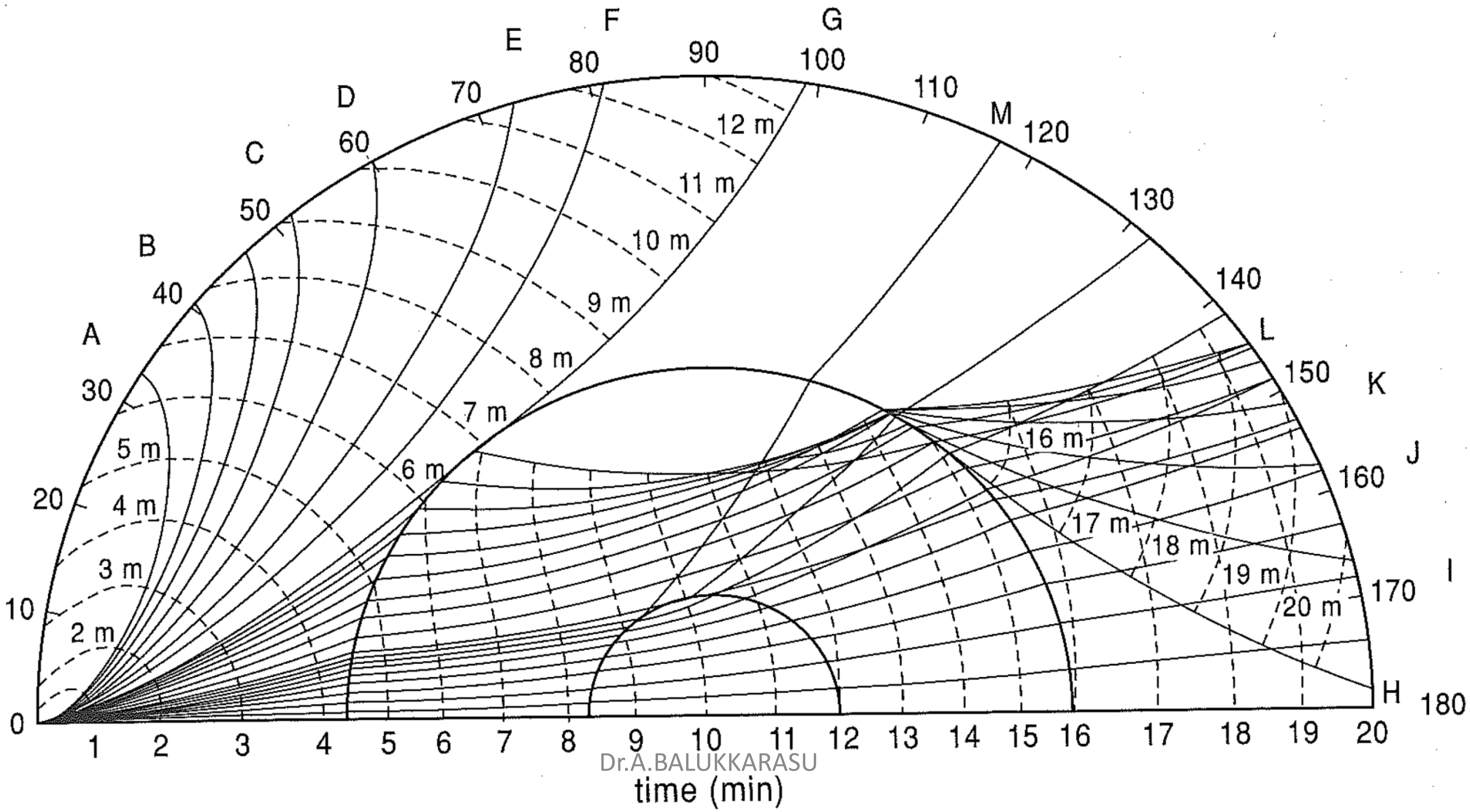
- P-waves also do not reach all stations globally
  - P-wave shadow zone is between 103° and 143°
- This can be easily explained by a large seismic velocity discontinuity at depth
  - The core-mantle boundary



- This means that seismic velocities in the core must be slower on average than the lower mantle.

How Long Does it Take?

- Seismic waves can travel through Earth in a matter of minutes!
- **Teleseismic**: Rays that arrive at > 18^{o} away from their source.
  - Spend little time in the crust
  - Useful for investigating the deep Earth



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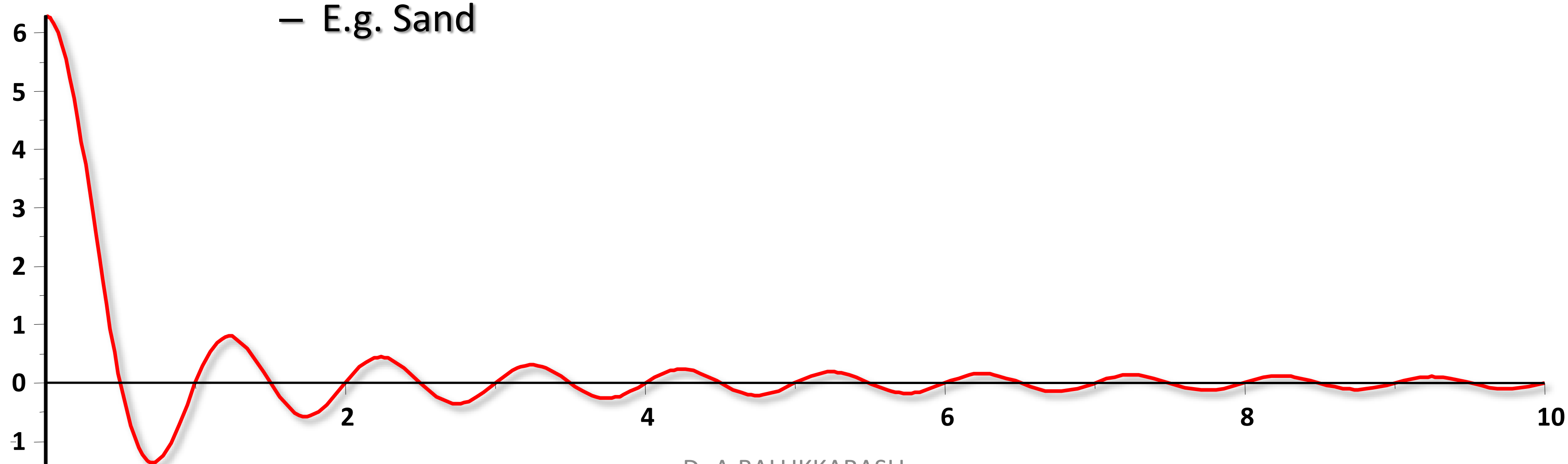
Attenuation

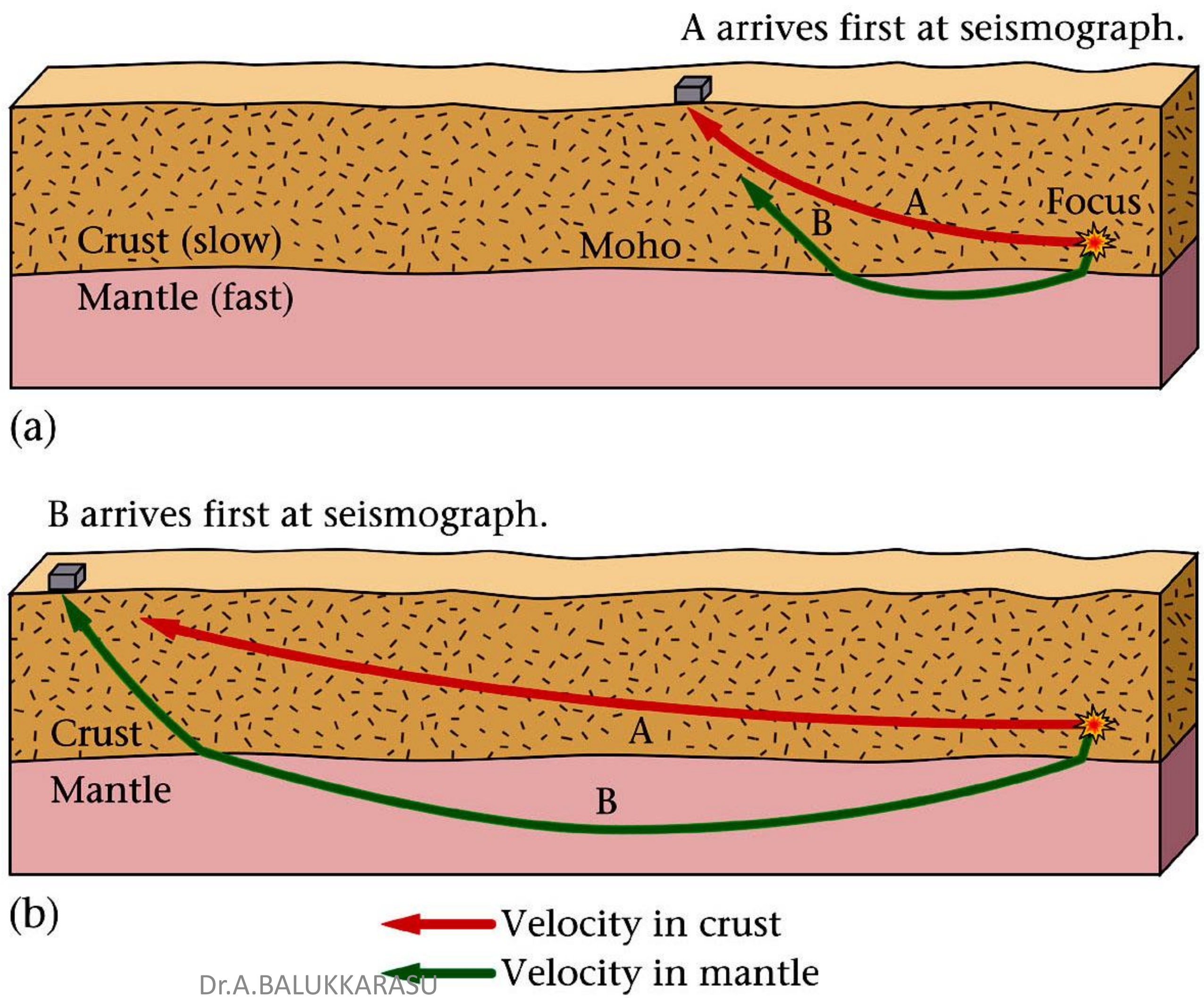
- Wave amplitudes generally decrease away from their source
  - Energy is spread over larger volume as the wave front expands
- **Attenuation**: the gradual loss of intensity (amplitude) of a wave as it travels through a medium
  - Causes of attenuation in seismic waves:
    - Encountering liquids or partial melts
      - E.g. the low velocity zone
    - Encountering unconsolidated (or non-elastic) material
      - E.g. Sand



Refraction, Velocity and Arrival Times = Moho Discovery

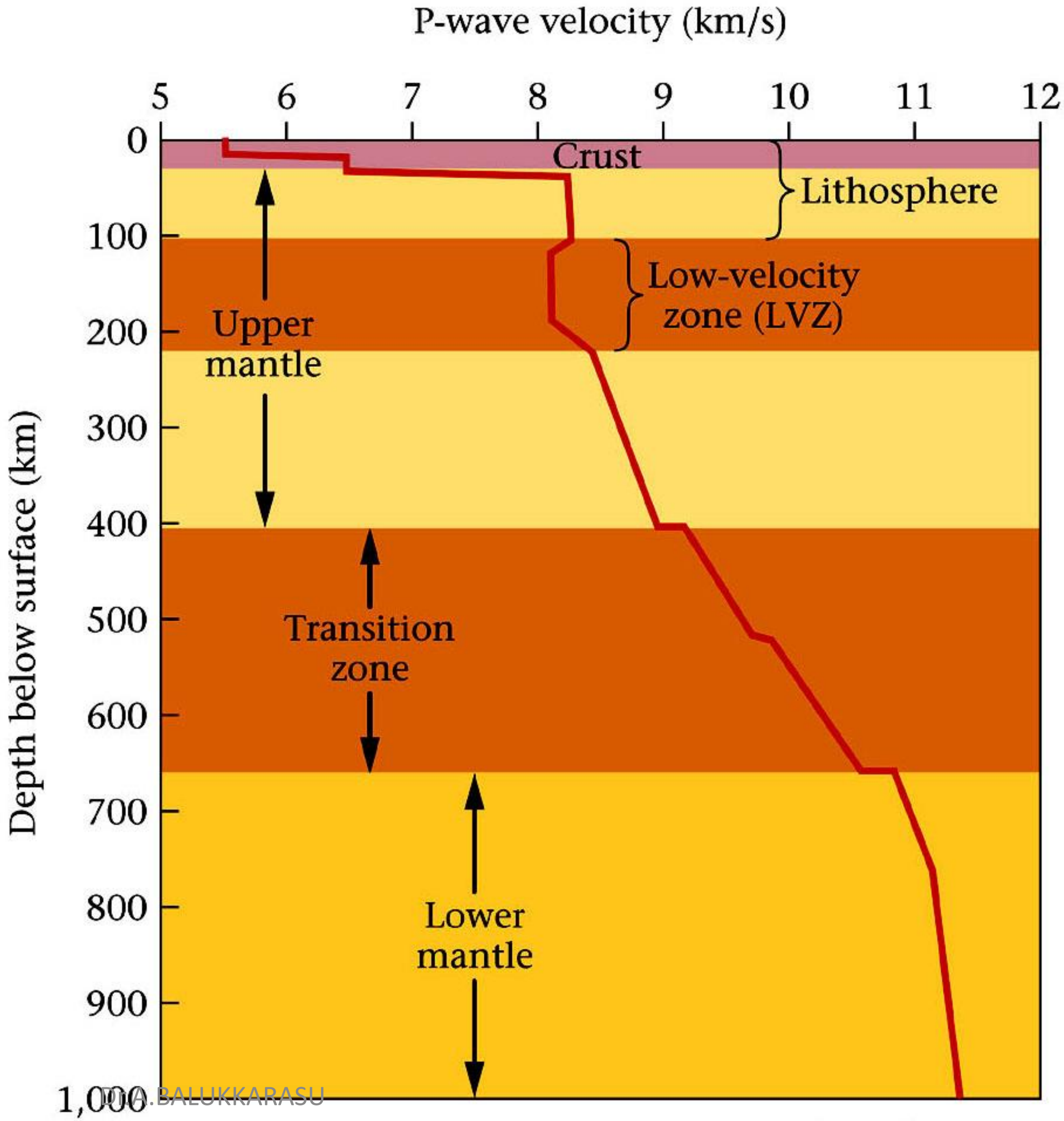
- Seismic waves travel faster through the mantle than the crust
- In 1909, Andrija Mohorovičić discovered that waves first arriving at seismic stations within 200 km of an epicenter had an average velocity of 6 km/s

- Stations > 200 km away
  - average wave speed 8 km/s
- To explain this
  - nearby stations received waves that only went through the crust
  - far away stations received waves that travel through the mantle.
- The crust mantle boundary is now called the ***Moho***, in honor of this discovery



Velocity of P-Waves at Depth

- Mantle rock = Peridotite
  - Ultramafic rock, mostly olivine
- In general, seismic velocity increases with depth.
- In oceanic crust
  - low-velocity zone at ~100-200 km depth.
- At this depth (pressure) and temperature
  - peridotite partially melts < 2%
- This zone permits the movement of oceanic plates.
- Below the LVZ
  - velocities increase until the core mantle boundary



Seismic Velocity vs. Depth for the Whole Earth

- Over the past hundred years, seismologists have created a pretty robust picture of seismic velocities at various depths within the Earth.