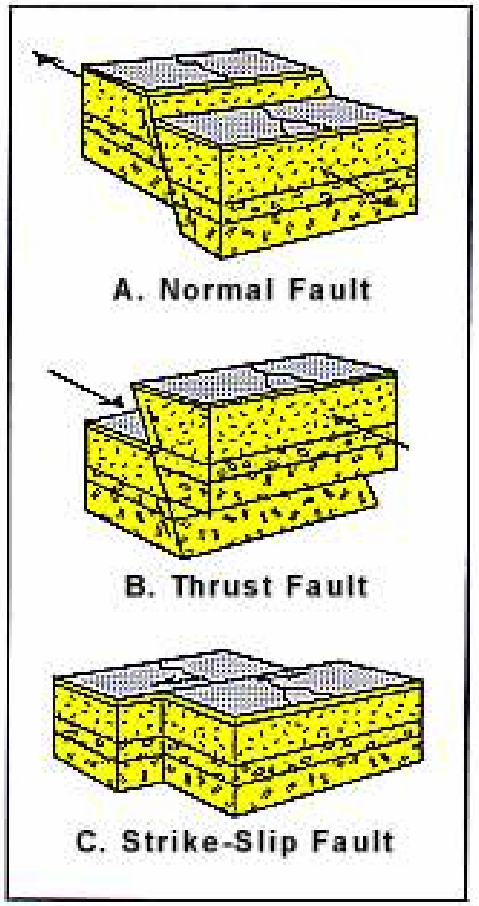
Earthquakes, Aftershocks and Seismic Waves

- An earthquake results from slow build up of strain (deformation) in rock, usually caused by the relative motion of adjacent plates.
- When a fault or volume of rock can no longer resist movement, the stored strain energy is released.
- A strong earthquake is generally followed by a sequence of aftershocks, which can continue for months.
- The aftershocks occur during a period of readjustment, in which small localized strains on the fault are released.
- **Deep focus** earthquakes usually do not have aftershocks.

- **Earthquakes cause Seismic Waves!**
- **Use to study composition of earth's interior.**



Aristotle believed earthquakes to be caused by <u>subterranean winds</u>

(Medieval MS)

Seismic Waves and Velocity

- Seismic velocity is a material property (like density).
- We distinguish between *Body and Surface waves*.
- There are two kinds of **body** waves – *P and S waves*.
  - Parallel & Senkrecht
    (German for parallel and perpendicular to travel direction) or
  - Primary & Secondary (time of arrival)
- P waves always travel *faster* than S waves.
- Seismic velocities depend on quantities like chemical composition, pressure, temperature, etc.

Faster Velocities

- Lower temperatures
- Higher pressures
- Solid phases

Slower Velocities

- Higher temperatures
- Lower pressures
- Liquid phases

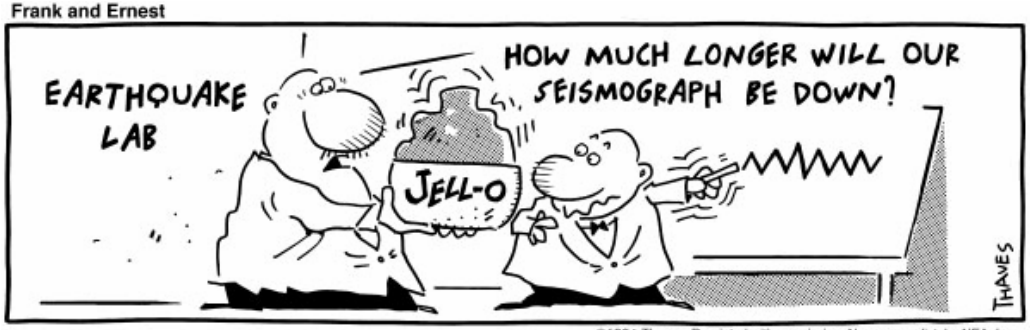
$$V_p = \sqrt{\frac{\left(\frac{4}{3}\mu + B\right)}{\rho}}$$

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

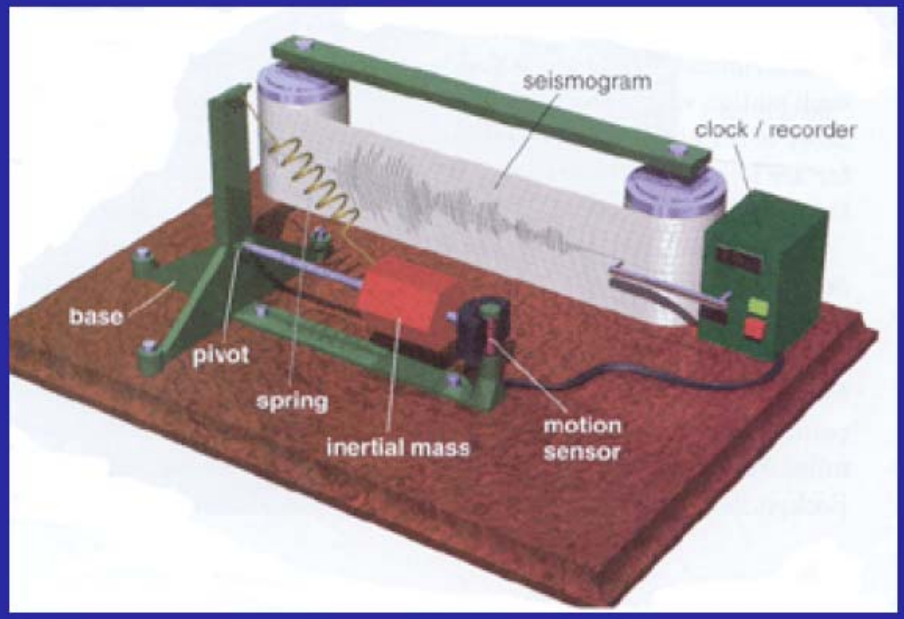
Detecting seismic waves

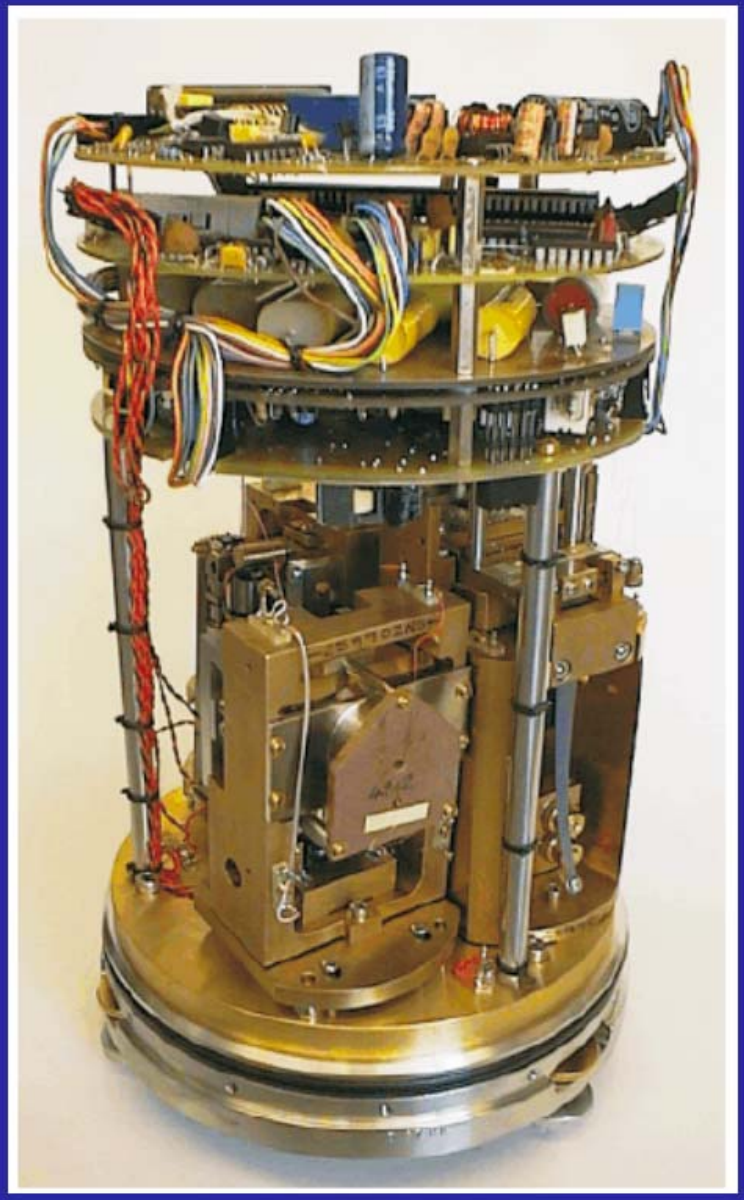
1. Use buildings–
left: copper engraving,
Calabria, Italy 1783
(Jan Kozak Collection)

2. Below, Frank and Ernest
demonstrate modern technology



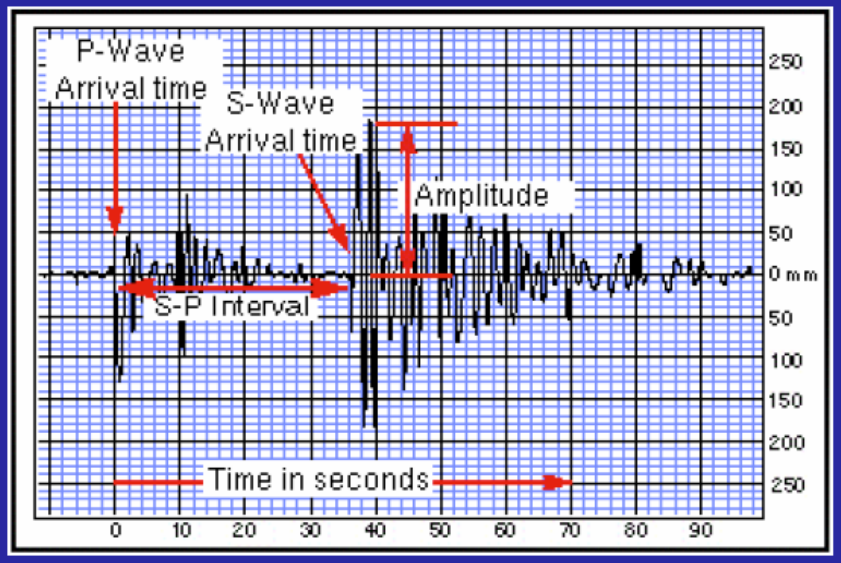
Seismograph Operation





Courtesy Güralp Instruments

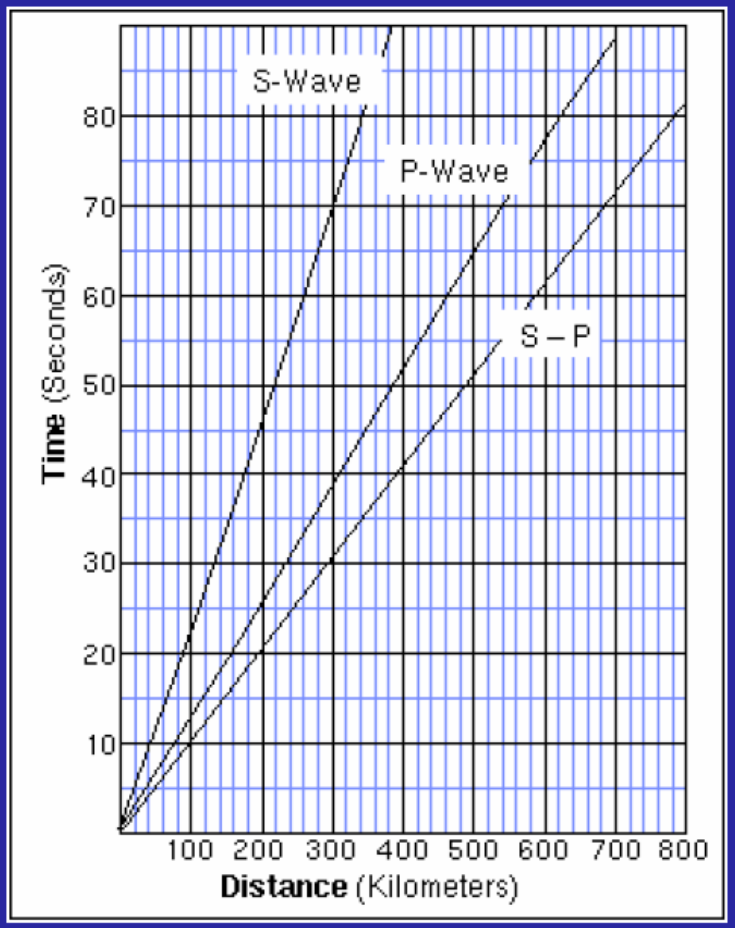
Locating earthquakes



Locating earthquakes depends on the difference in P and S wave velocity.

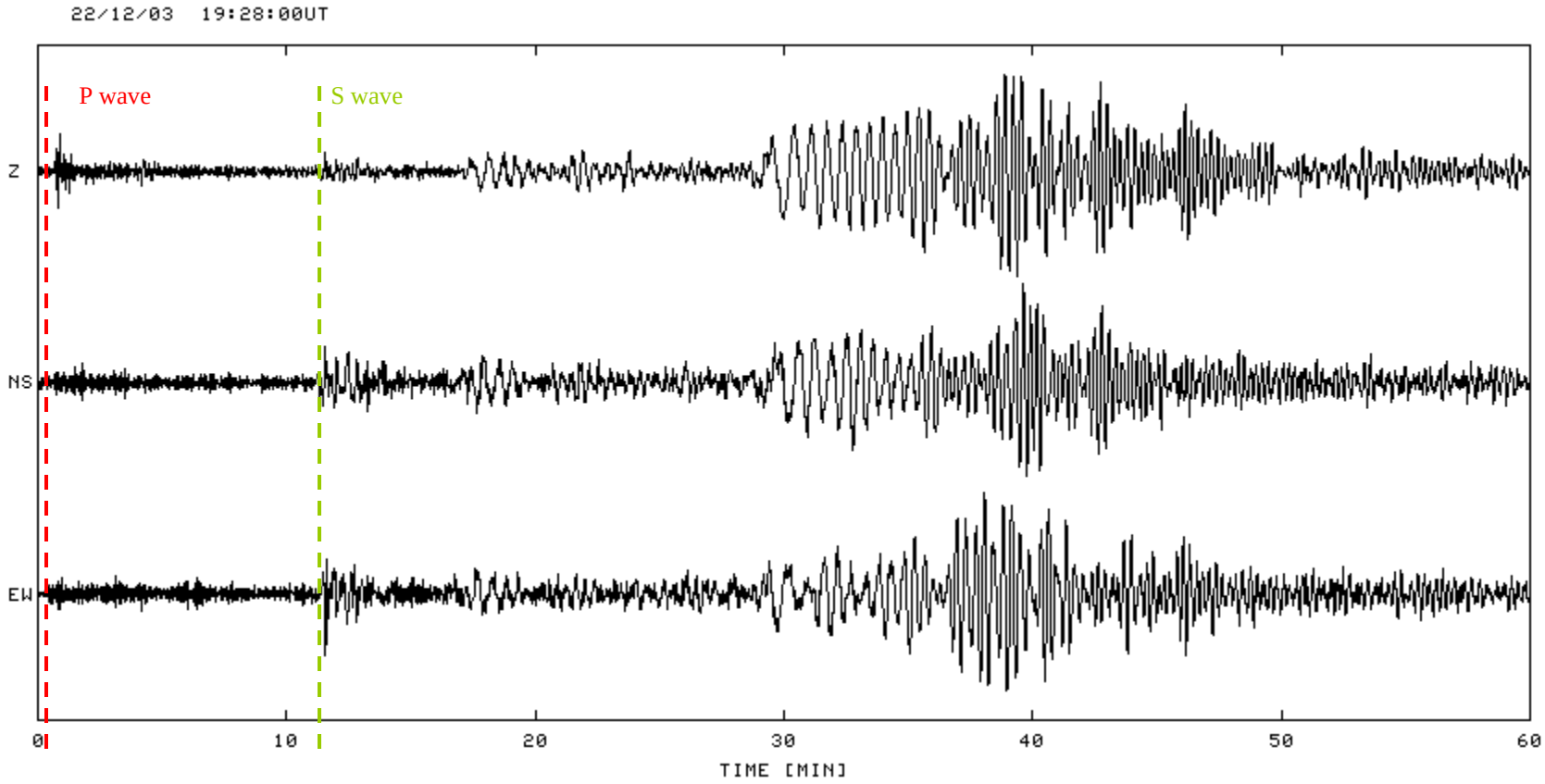
- Different seismic waves (*phases*) are identified on the recorded seismogram.

- Even if time of the earthquake (*origin time*) is not known, the difference t_s - t_p can be easily measured.

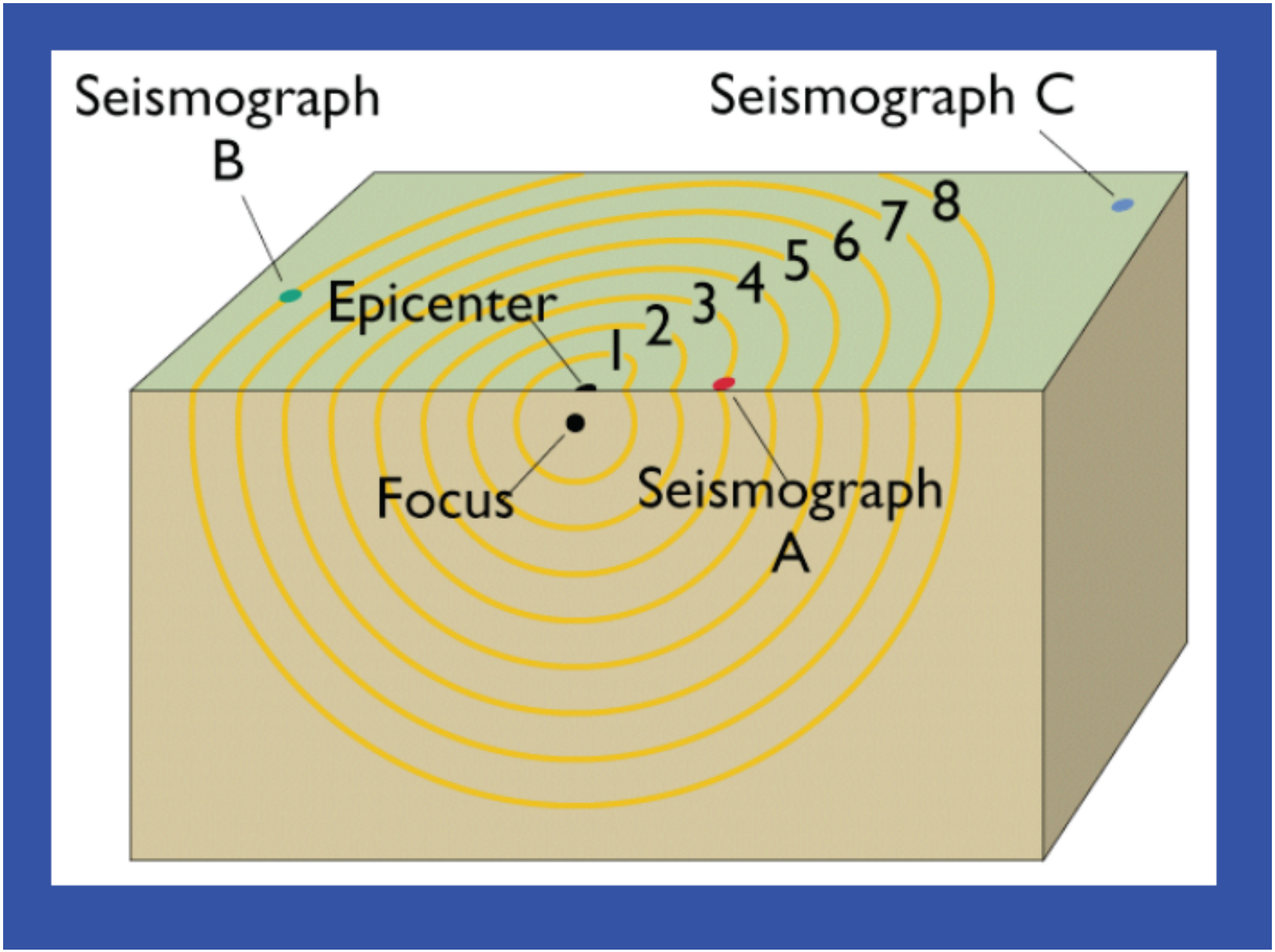


Travel time curves represent expected arrival times for waves recorded at various distances from a source.

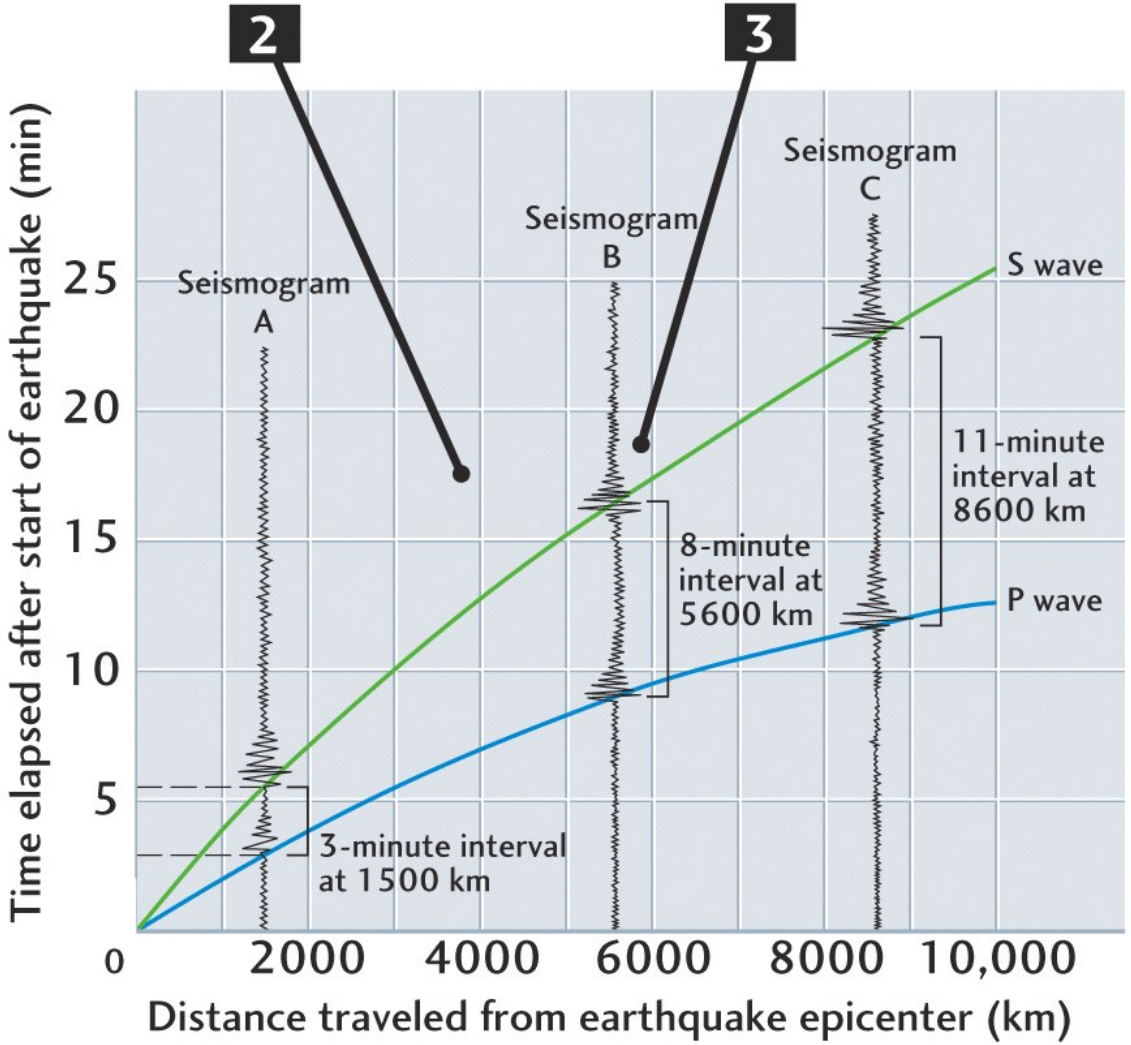
Seismogram Example
Recording along 3 axes



Three stations -> epicenter location



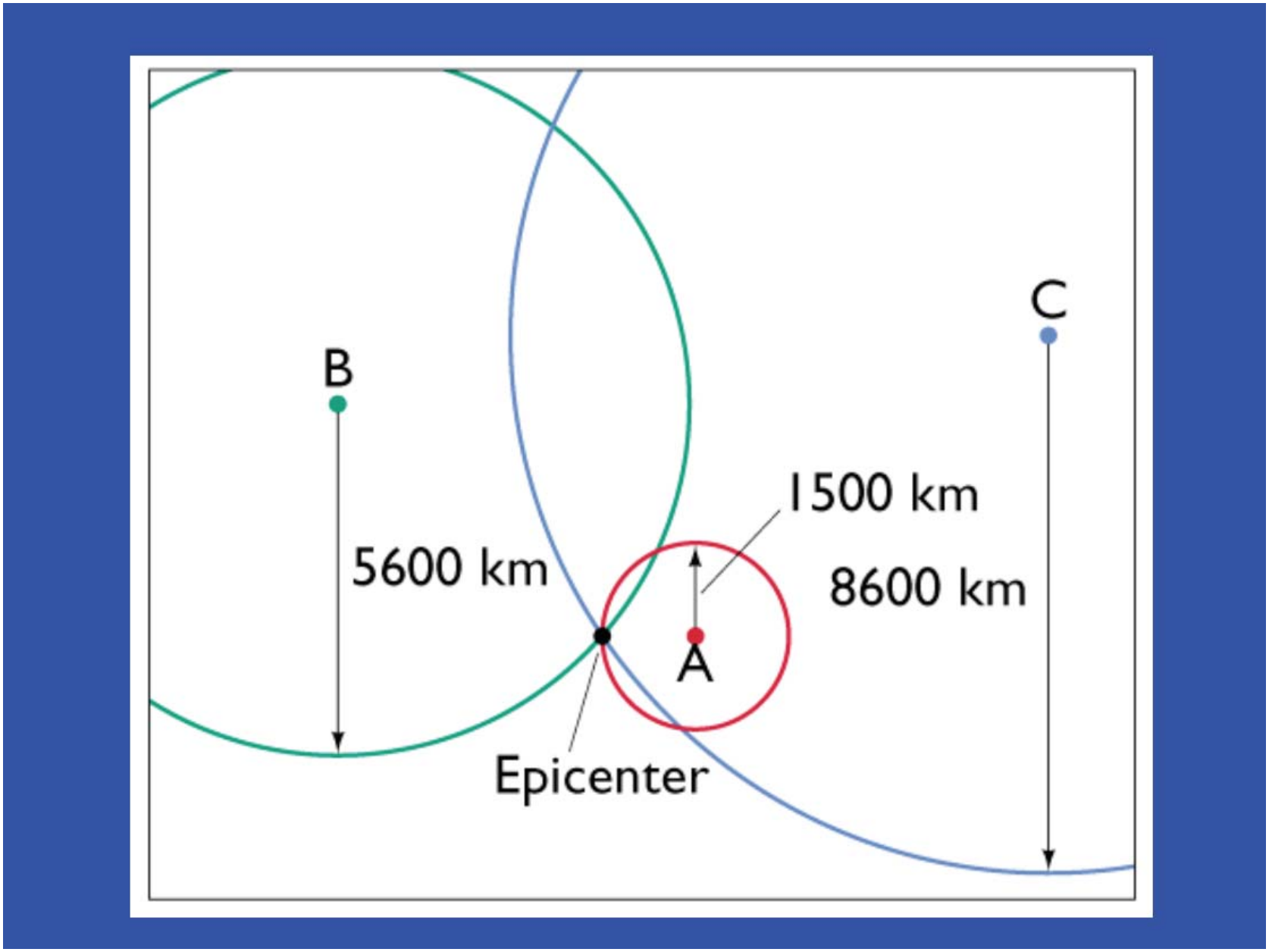
READINGS AT DIFFERENT SEISMOGRAPHIC STATIONS REVEAL THE LOCATION OF THE EARTHQUAKE EPICENTER



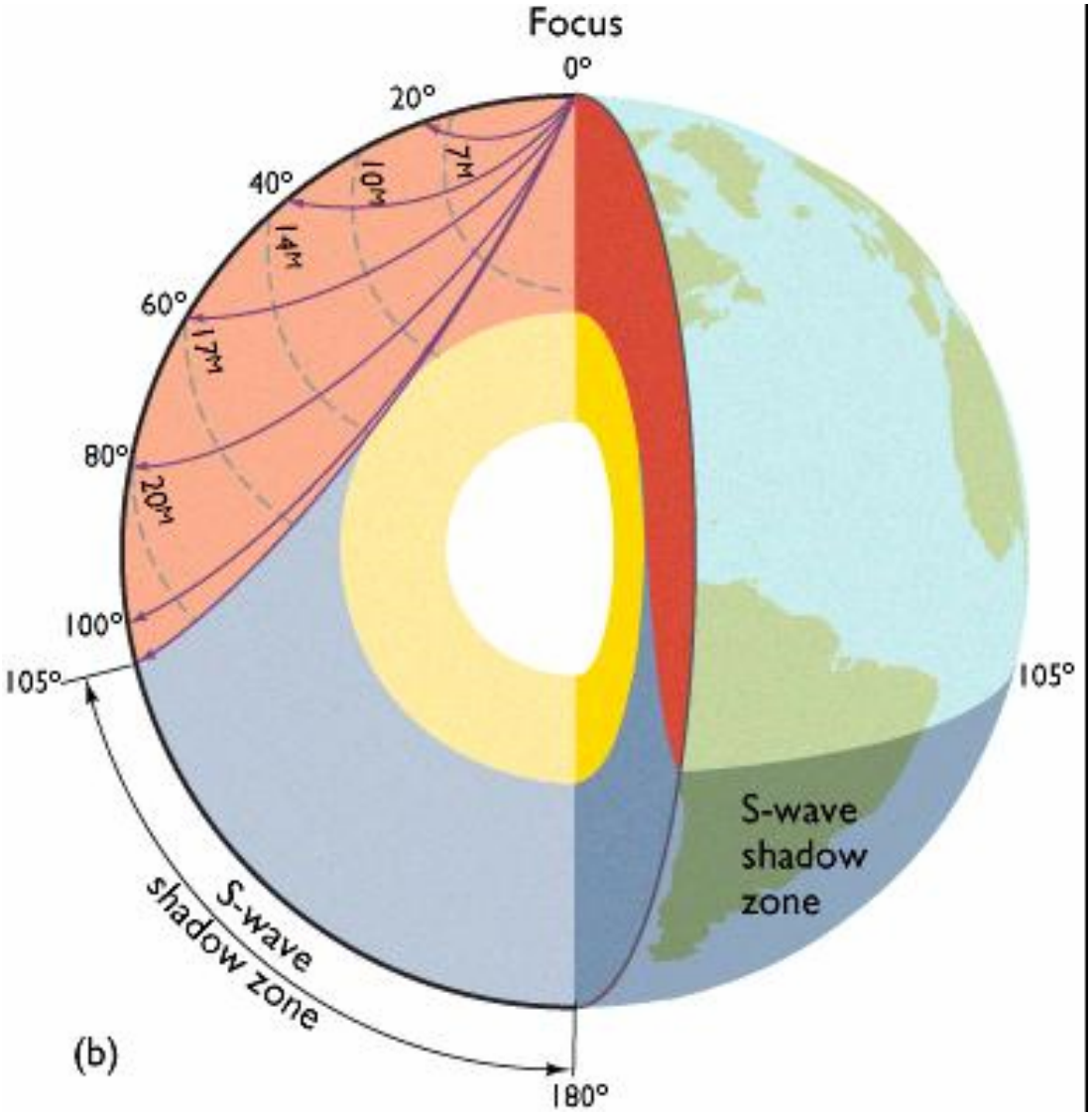
Three distances:
1500, 5600, 8600 km

Convert to location
by triangulation

Triangulation: intersection of spheres



S-wave shadow zone (discovered ~1900)

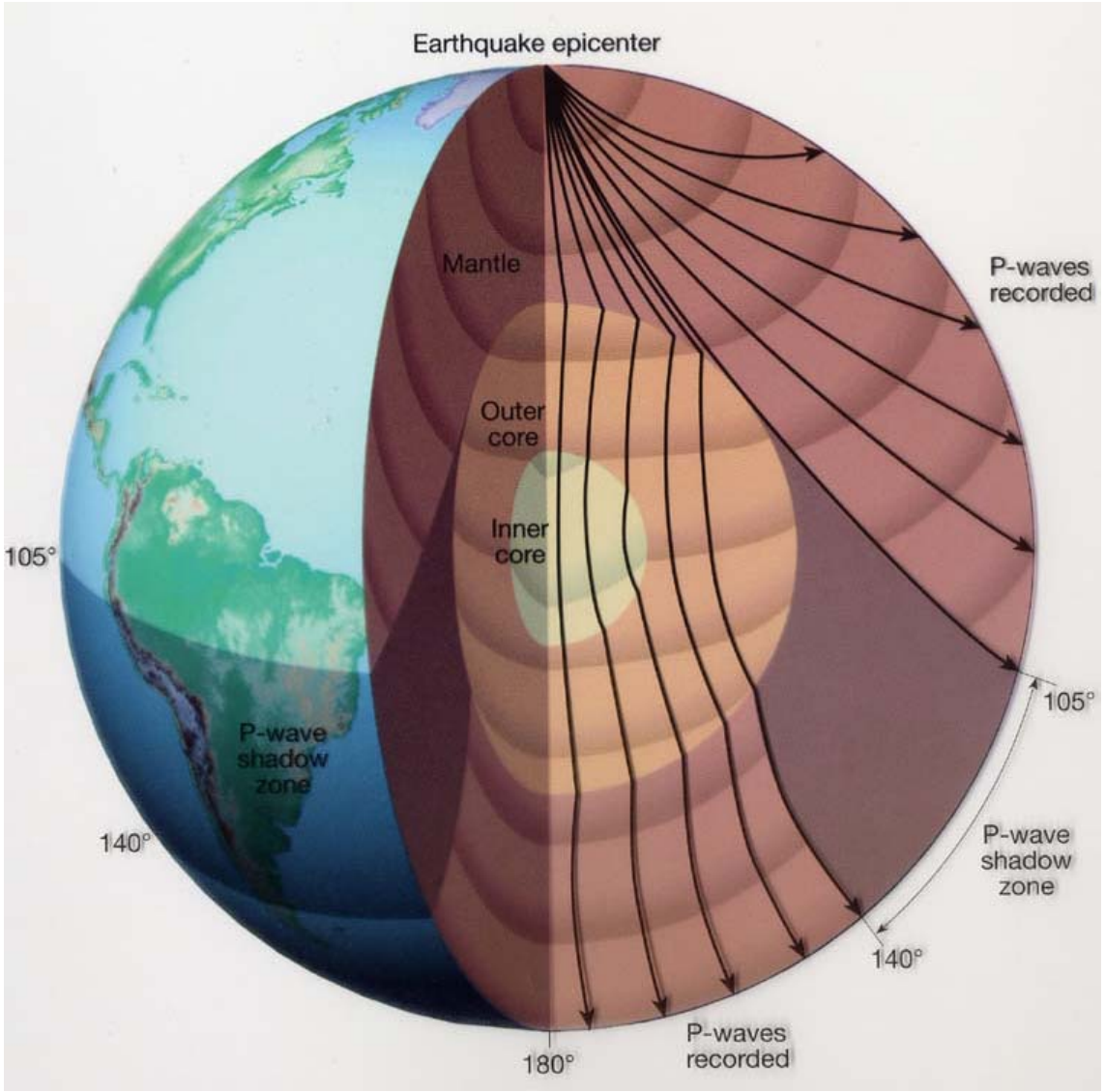


One explanation:

Fluids do not support shear waves

Is the earth's core molten?

P-wave shadow zone (discovered ~1916)

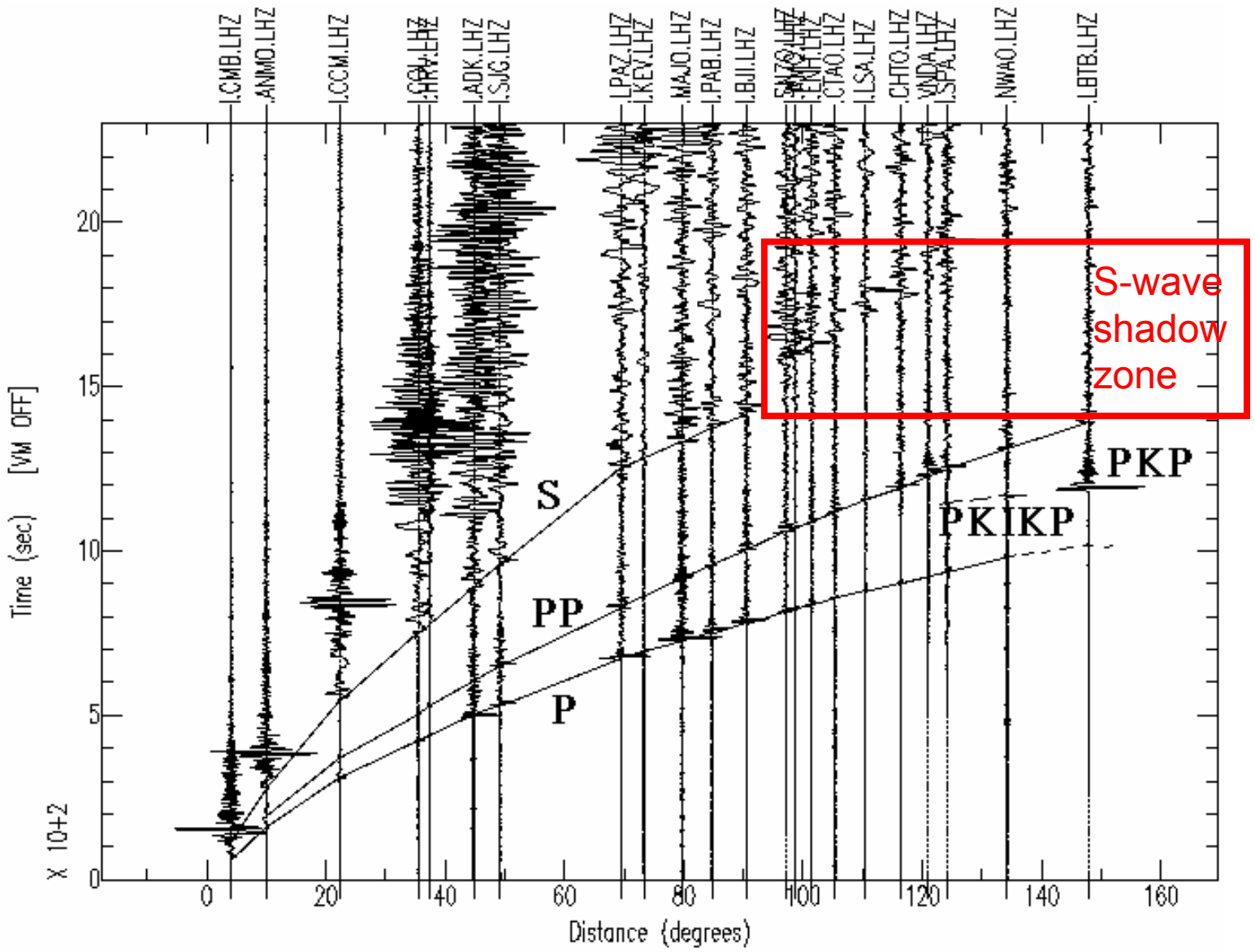


One explanation: waves are *refracted* by changes in velocity at a discontinuity

Well understood for light waves. Less well studied for sound.

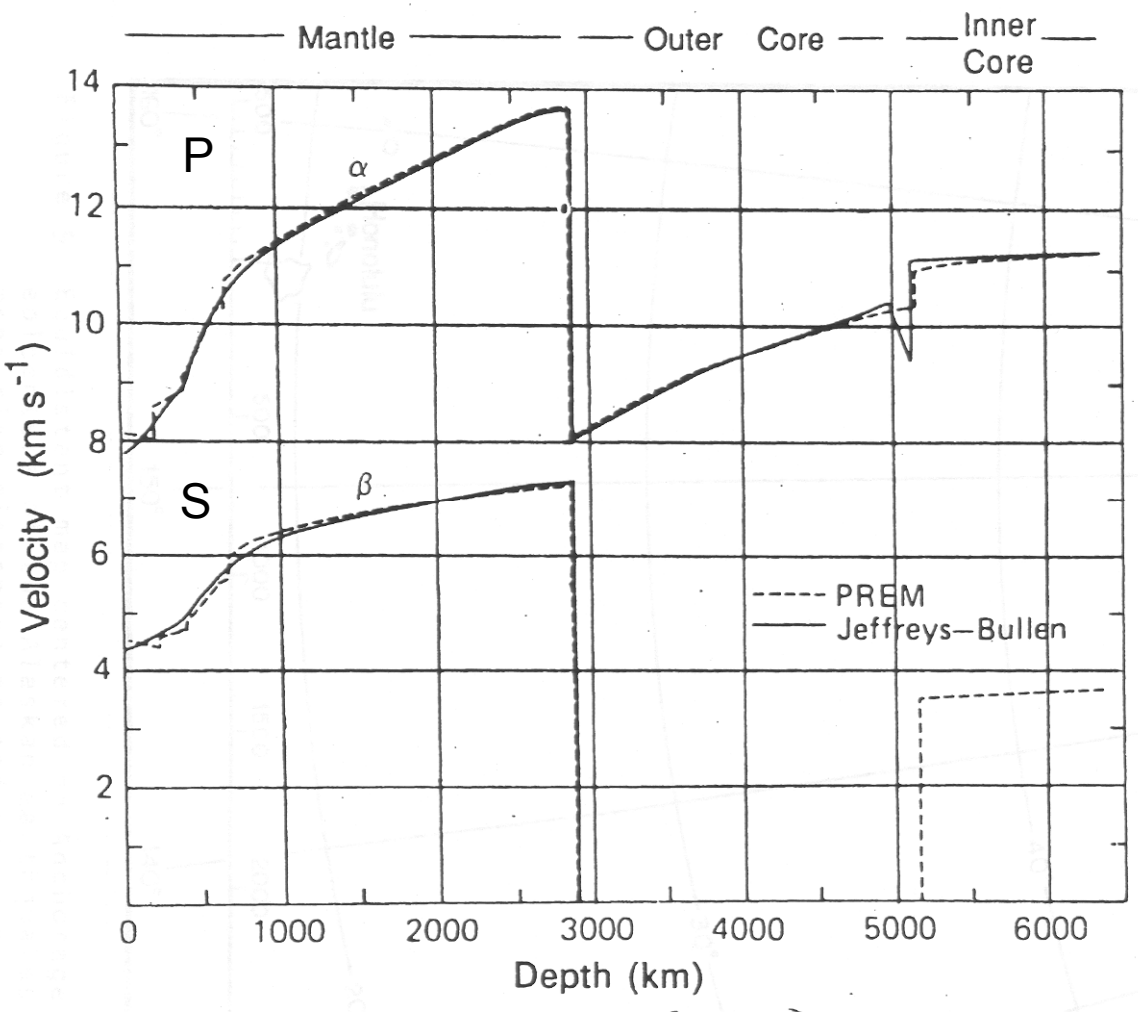
Inner core discovered in 1936: Reflections!

Some actual recordings



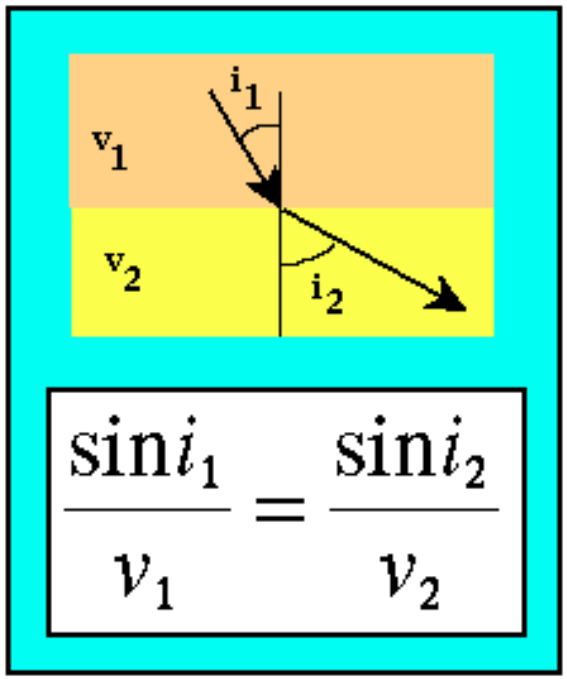
http://lasker.princeton.edu/ScienceProjects/curr/waves/waves_fig8b.gif

Seismic Velocity-Depth Model for Whole Earth

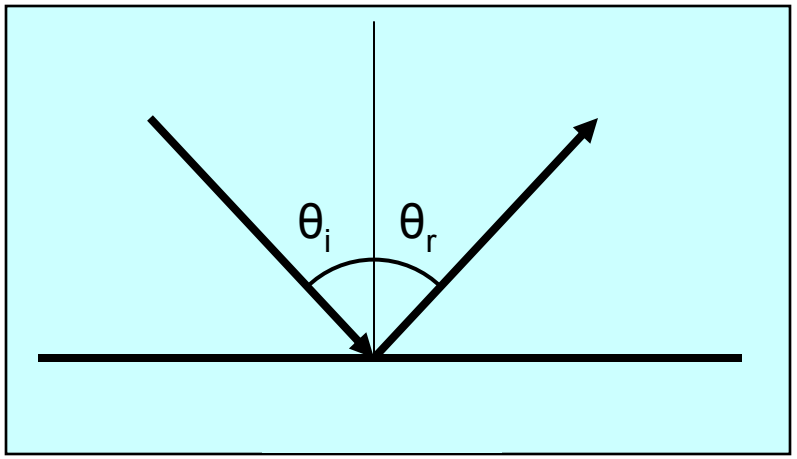


- Pressure and temperature increase as we go deeper into the earth
- These have opposite effects on seismic velocity
- Seismic velocity tends to increase with depth (increasing pressure)
- Exceptions include regions of partial melt (LVZ-asthenosphere), and total melt (the outer core)
- What is the relationship of seismic velocities with density?

Complications: *Boundaries in 3-D*
Snell's Law and Law of Reflection



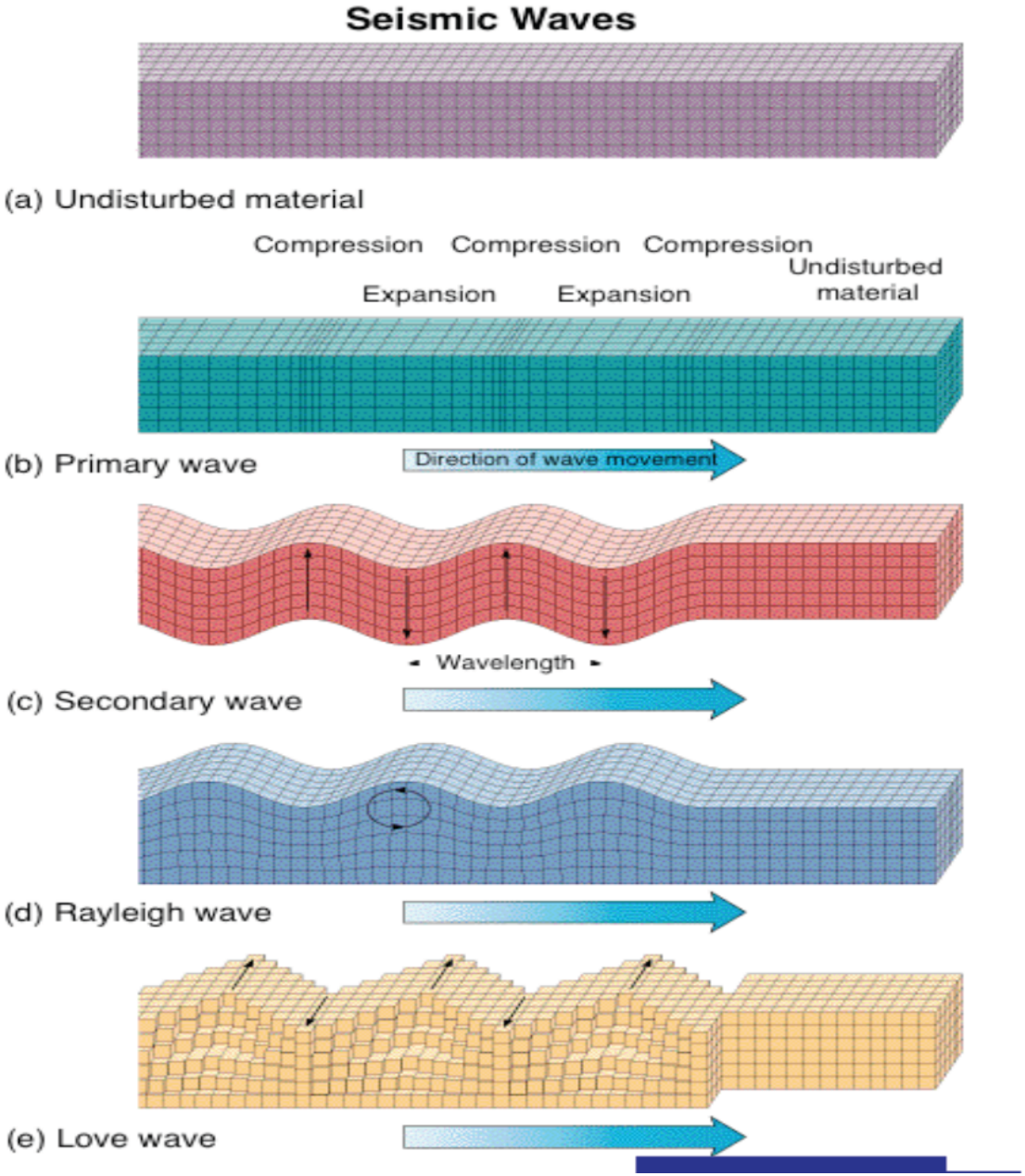
- *Snell's Law* governs the path by which a wave would take the least amount of time to propagate between two fixed points. V_1 and V_2 are the wave velocities in the two materials.
- Here, $V_2 > V_1$
- *Reflections:* angle of incidence = angle of reflection



Surface Waves-
Yet Another added complication

- Surface waves propagate along a boundary surface.
- Surface waves are larger in amplitude and longer in duration than body waves.
- Surface waves propagate at a speed lower than body waves and are recorded after the P and S waves.
- There are two types of surface waves: Rayleigh and Love waves.
- Rayleigh waves are denoted by LR or R, and Love waves are denoted by LQ or Q (L for long; R for Rayleigh; Q for Querwellen, German, 'transverse waves').
- Surface wave amplitudes decay exponentially with depth.

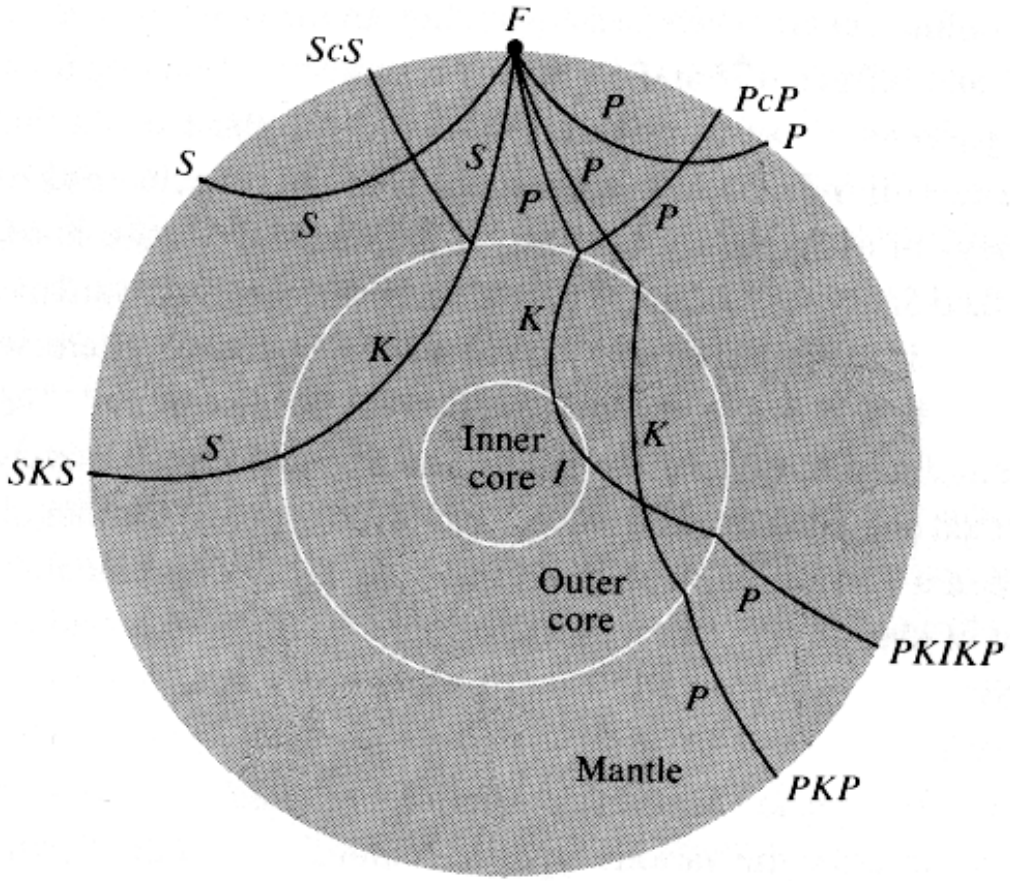
Body versus Surface Waves



Wave resulting from the interaction of P and S waves with the free surface.

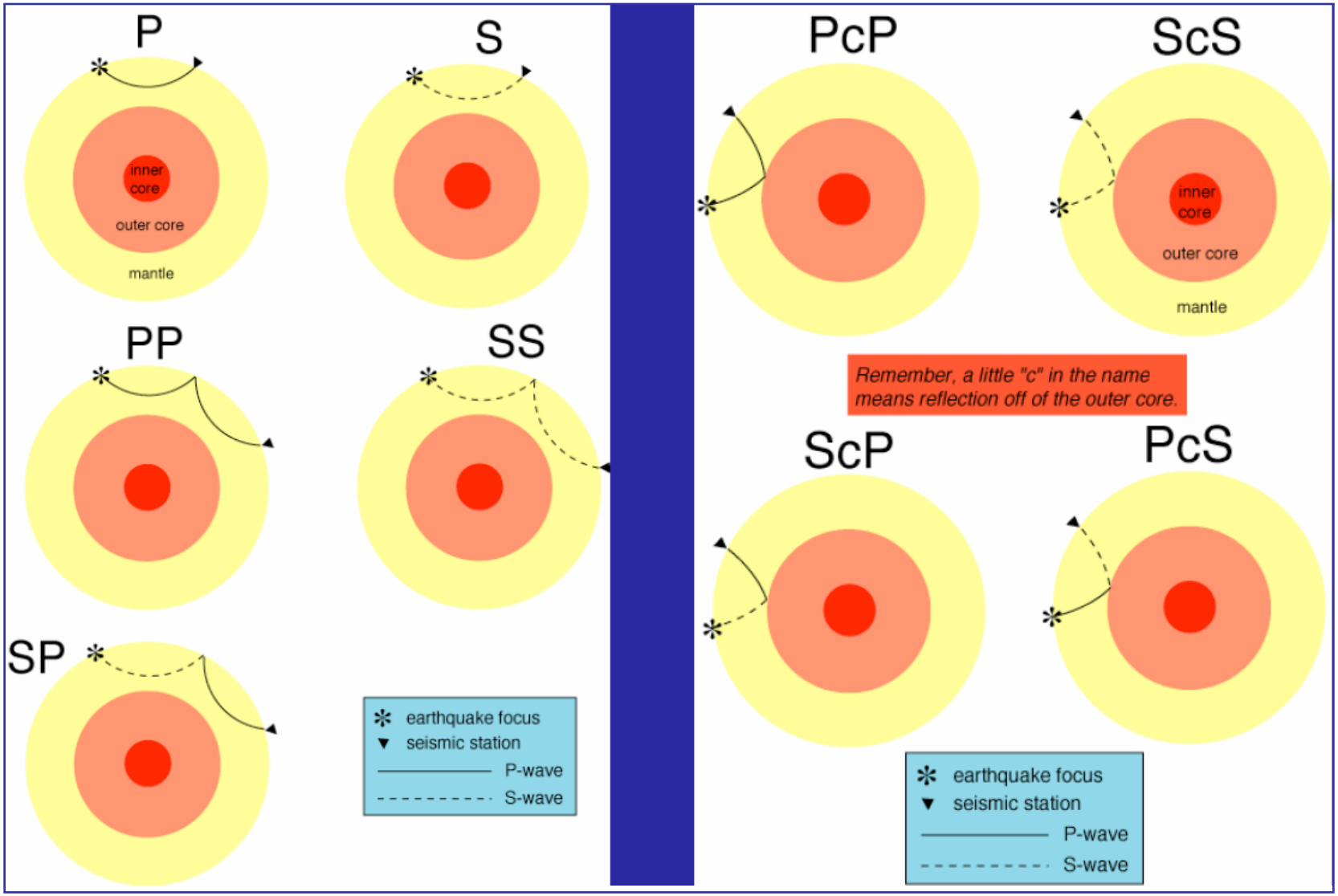
Their wave motion is confined to and propagating along the surface of the body

Reflection, transmission and MODE CONVERSION: Possible Ray Paths for Seismic Waves Penetrating the Earth

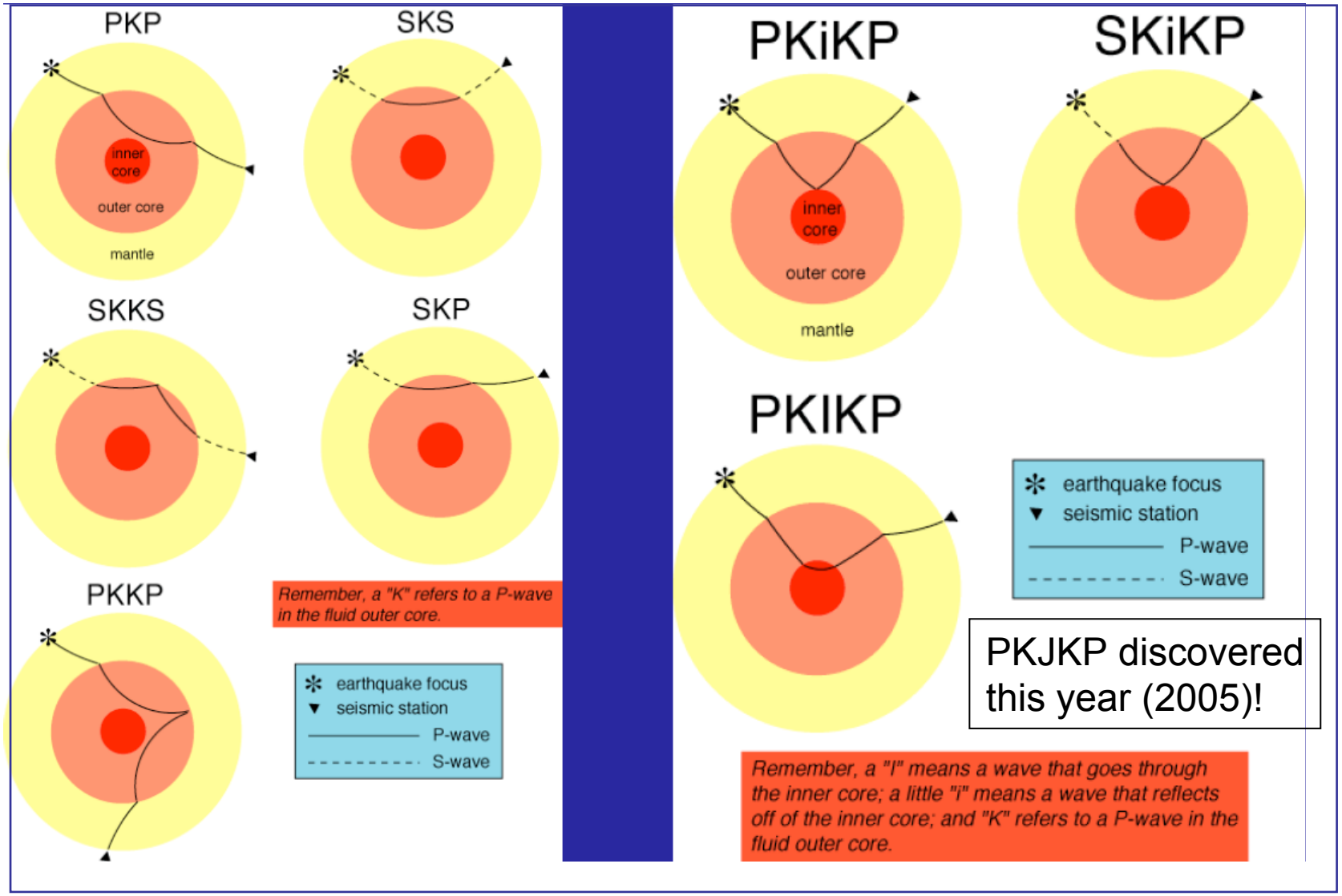


- In the mantle and inner core, the velocities increase with depth, so the ray bends away from the normal
- At the mantle-outer core (fluid) boundary the decrease in velocity causes those rays refracted into the core to bend towards the normal
- ***mode conversion:*** **P and S-waves can interconvert at a boundary due to "surface" waves!**
- However, **mode conversion is inefficient** -> small transmission coefficients, low amplitude

Nomenclature: direct and reflected paths



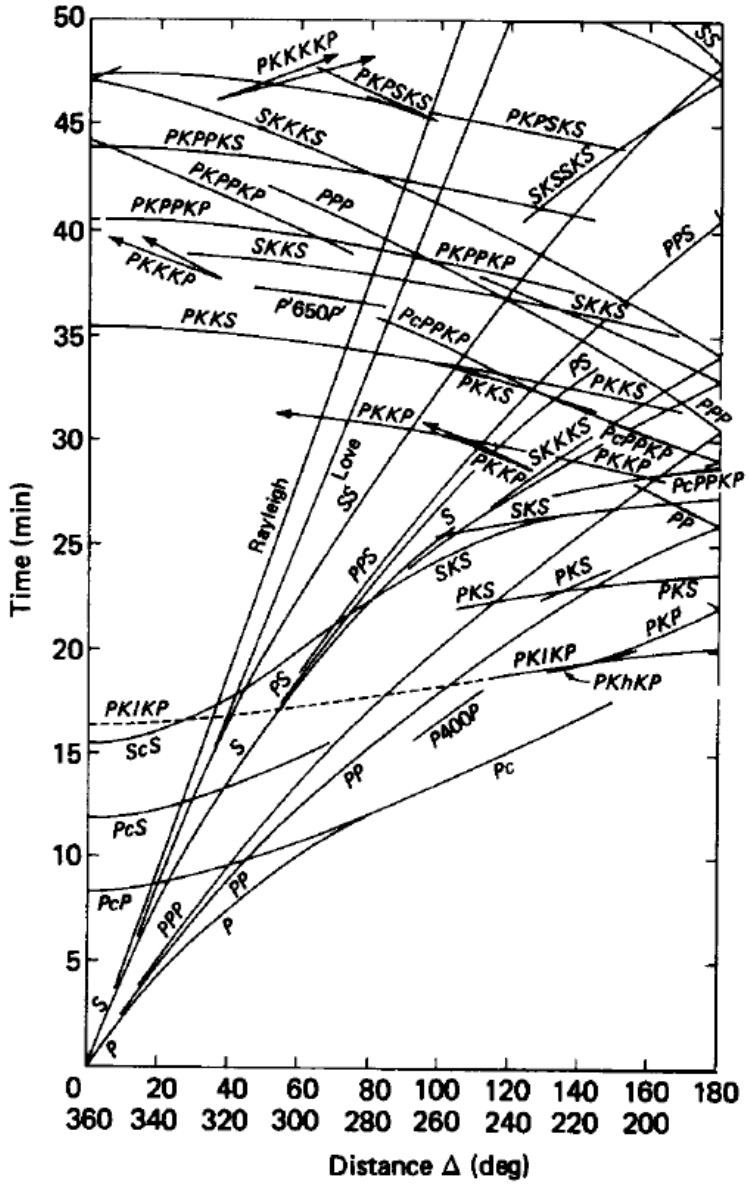
Nomenclature : passage through core



Seismic Velocity and Travel Times

- *Travel time* of a seismic wave is the time taken to travel from the focus of the earthquake to the seismometer
- Seismologists use the travel time curve to identify *seismic phases* (P, S, etc.) by determining when they will arrive on a seismogram given how far away the earthquake epicenter is from the station. It can also be used in reverse.
- One way to determine the structure of the earth's interior is to analyze the variations in the travel times of seismic waves:
  - Earthquake occurs and generates seismic waves
  - Earthquake is identified and located
  - Travel times of seismic waves are compared to times computed from a **reference model (PREM)**
  - Anomalous travel times are converted to heterogeneities (temperature, density, fluid phase) inside the earth (inverse modeling)

Jeffreys-Bullen Travel Time Curve for Earthquake Focus at the Surface

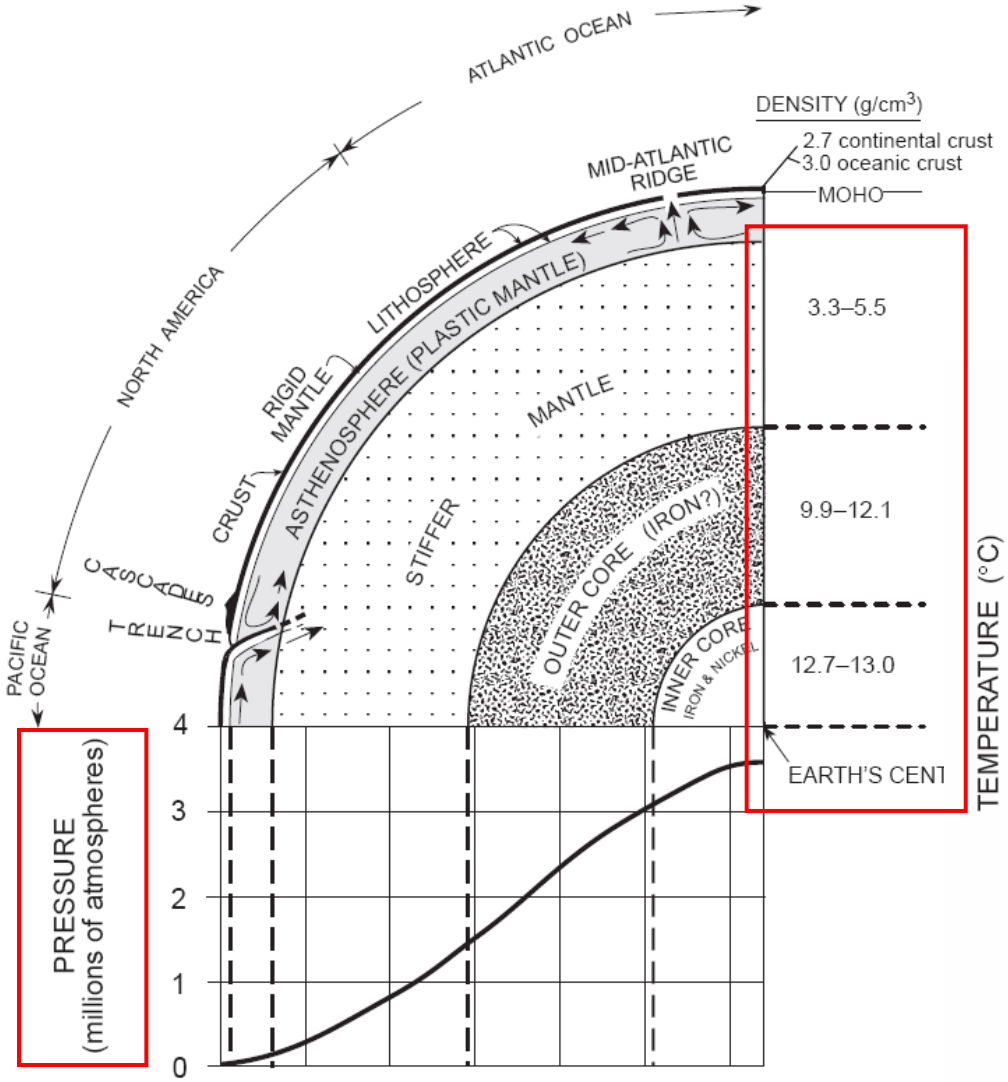


The result of years of concentrated data collection effort combined with careful statistical analysis

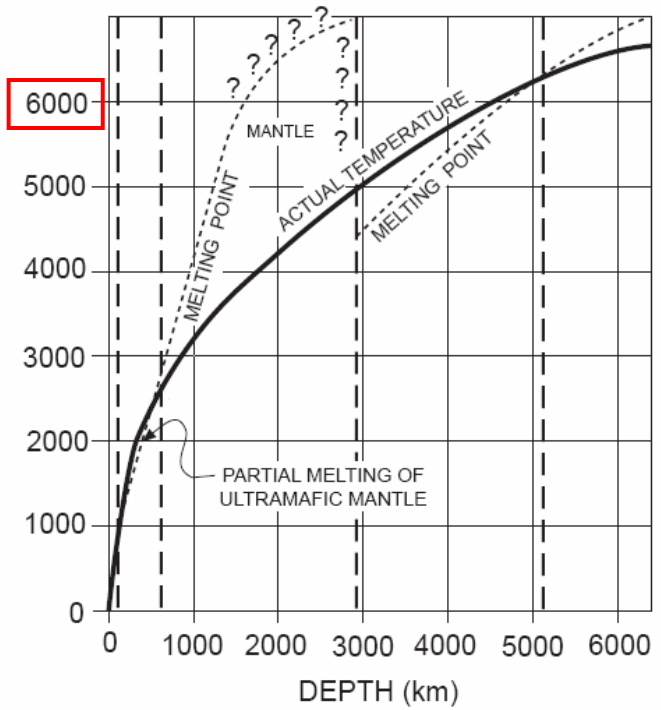
Slide right or left on the graph below until that amount of time (vertical axis) fits on the curves representing the seismic phases identified on the seismogram

Epicentral distance (1 degree = 111 km) is the angle, subtended by the earthquake epicenter and seismometer, at the center of the earth (Bullen and Bolt, 1985)

Preliminary Reference Earth Model

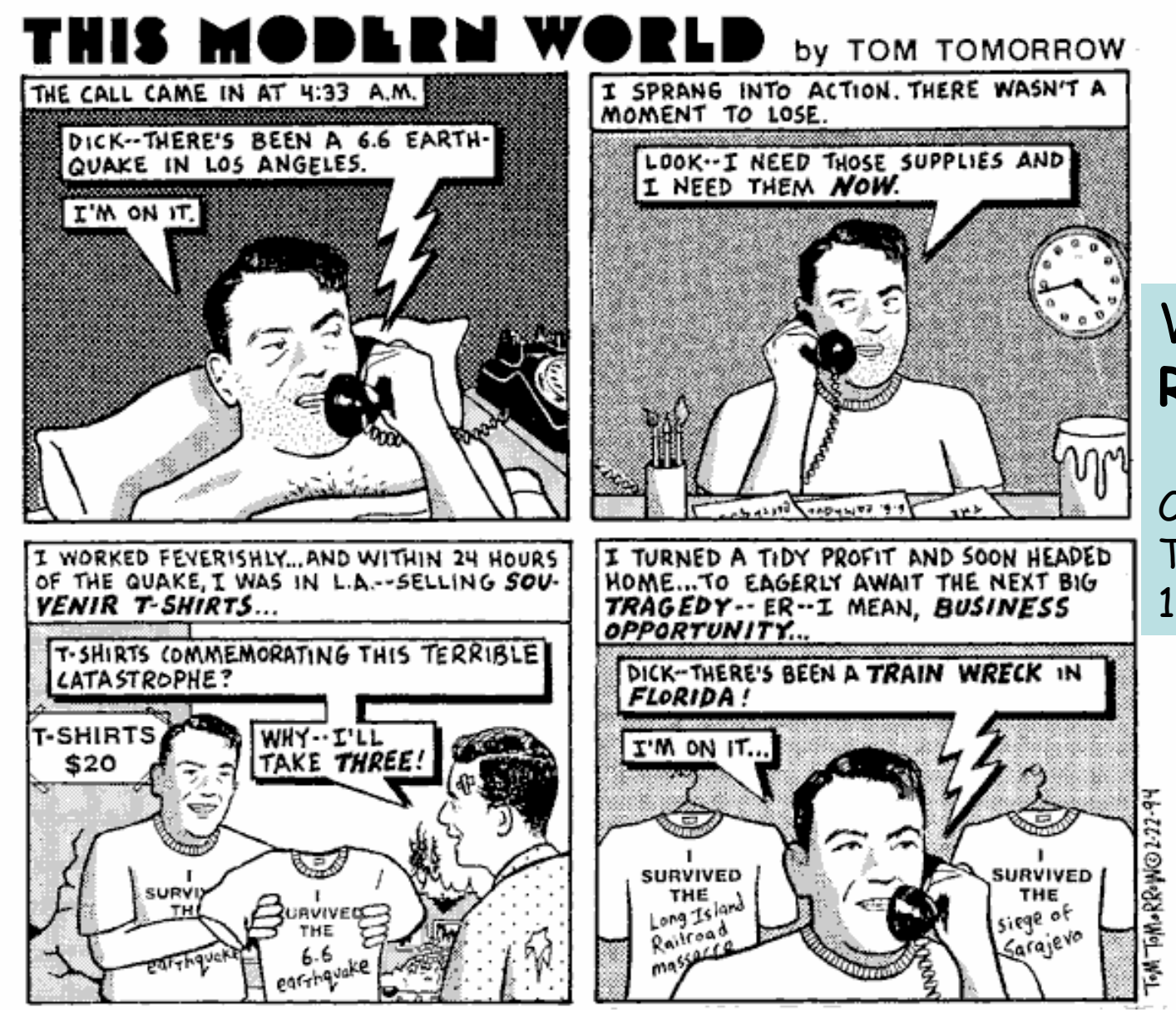


– PREM –
the "Standard Model"
of Geophysics



*Surface temp of sun ~ 6000° C

What to do about earthquakes?



Well,
Rely on FEMA!

Courtesy of
Tom Tomorrow,
1994