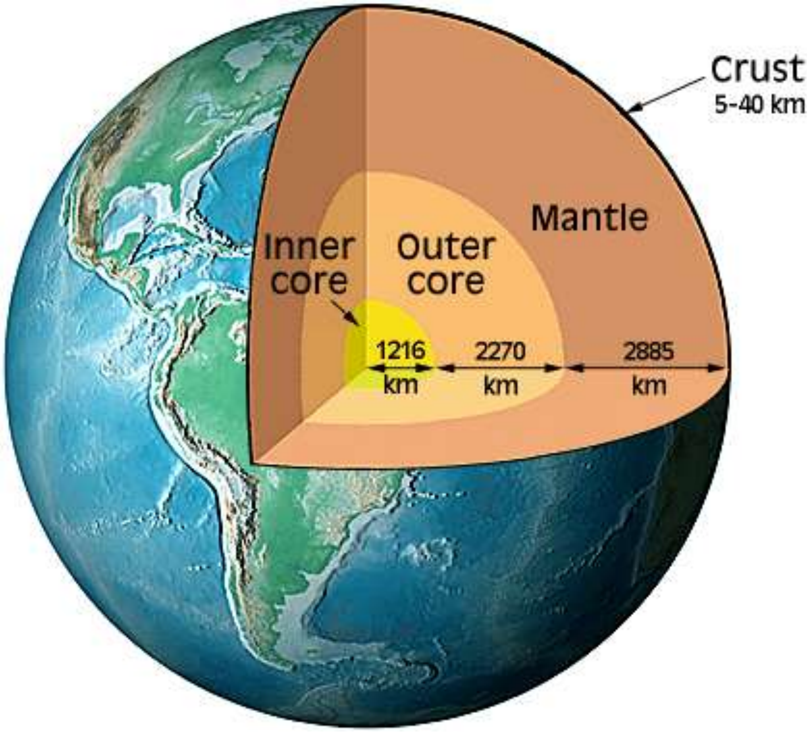
M.E Structural Engineering



EARTHQUAKE ENGINEERING

Course Overview

Introduction to Engineering Seismology

Engineering characterisation of Ground Motions

Response of Simple Systems to ground Motion

Response Spectra

Development of Design Earthquakes (Linear systems)

Seismic Analysis of Building Systems and Analytical Tools for Preliminary/Conceptual Design

Architectural considerations

Performance-based Design/ Capacity Design / Damage Tolerant Design

Applications -Moment Resisting and Braced Frames (mainly steel)

Code related Issues

Design for Drift and Lateral stability

Seismic Design of Steel, RC, Masonry and Non-Structural system components

Seismic Design of Foundation systems

Design of structures with seismic Isolation

Special topics

References:-

1. Dowrick. D.J, *Earthquake resistant design*, John wily & Sons, Chichester, U.K,1977.

2. Arnold. C and Reitherman. R, *Building configuration and seismic design,* John wily & Sons, Inc, Newyork,1976.

3. National Earthquake Hazard Reduction Program (NEHRP), Tentative provisions for seismic design of Buildings, FEMA-Publications: Federal Emergency management Agency – 312, Washington.DC, 2000.

4. EHRP Guidelines for the seismic rehabilitation of buildings, FEMA- Publications- 273, Washington.DC, 2000.

   http:/ www.degenkolb.com/fema273/intro.html.5.

5. Fundamentals of Earthquake resistant construction Ellis L. Krinitzsky, James P. Gould, Peter H. Edinger

6. **SP: 22**, *Explanatory handbook* (or) Codes for Earth quake Engineering, Special Publications, Bureau of Indian Standards, New Delhi, 1982.

7. **IS: 1893**, *Criteria for Earth quake Resistant Design of Structures* **:** BIS Bureau of Indian Standards, New Delhi, 2002.

   Part 1 *General provisions and buildings*

   Part 2* *Liquid retaining tanks – Elevated and ground supported*

   Part 3* *Bridges and retaining walls*

   Part 4* *Industrial Structures including stack like structures*

   Part 5* *Dams and embankments*

   *Pending finalization

8. **IS: 13920**, *Ductile Detailing of Reinforce Concrete Structures Subjecting to Seismic forces*, Bureau of Indian Standards, New Delhi, 1993

9. **IS: 4236**, Code of Practice for Earthquake Resistant Design and Construction of Buildings, Bureau of Indian Standards, New Delhi, 1993.

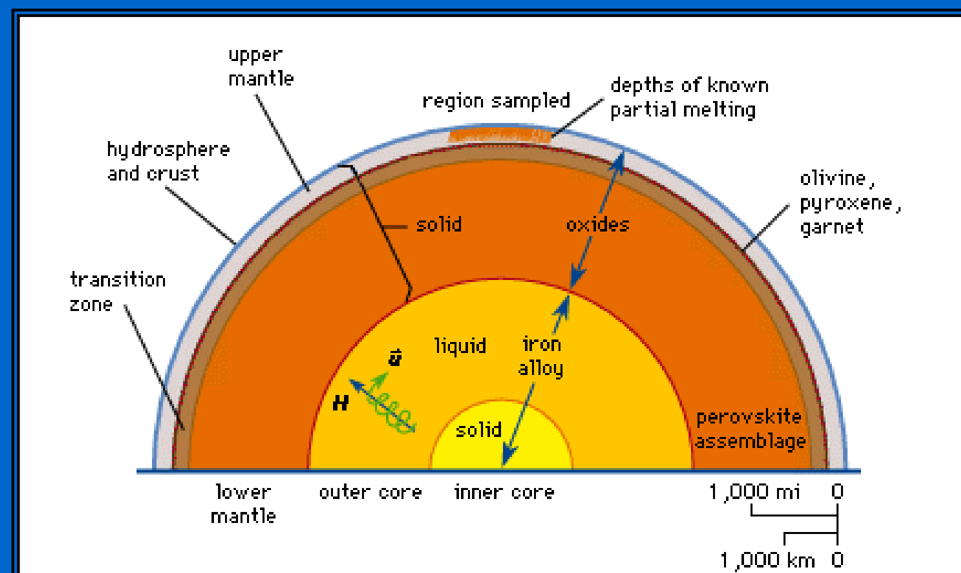
Earth

History dates back to Five billion years, the Earth was formed by a massive conglomeration of space materials.

The heat energy released by this event melted the entire planet, and it is still cooling off today.

Denser materials like iron (Fe) sank into the core of the Earth, while lighter silicates (Si), other oxygen (O) compounds, and water rose near the surface.

The earth is divided into four main layers: the inner core, outer core, mantle and crust.

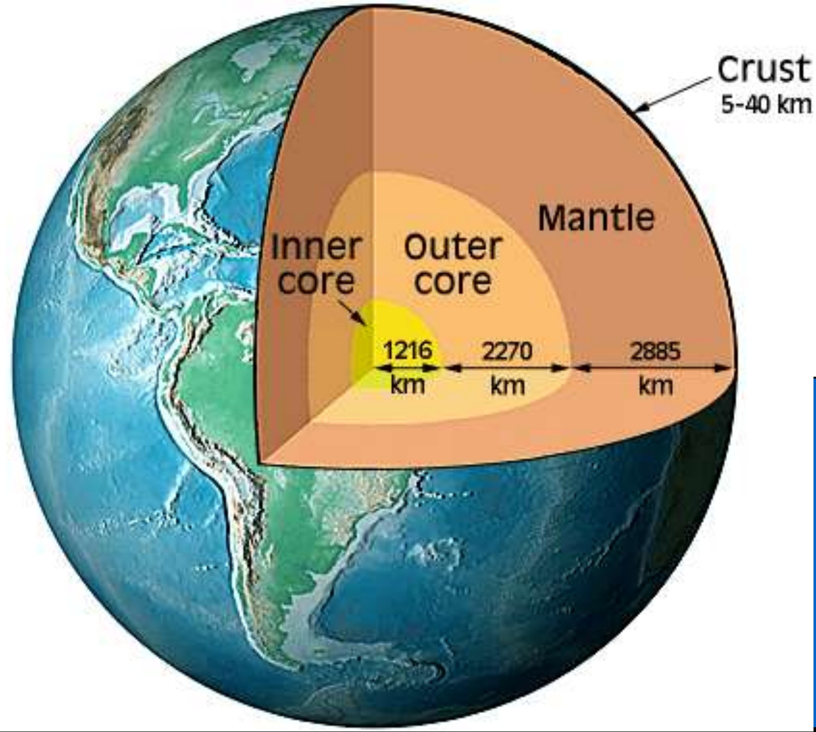


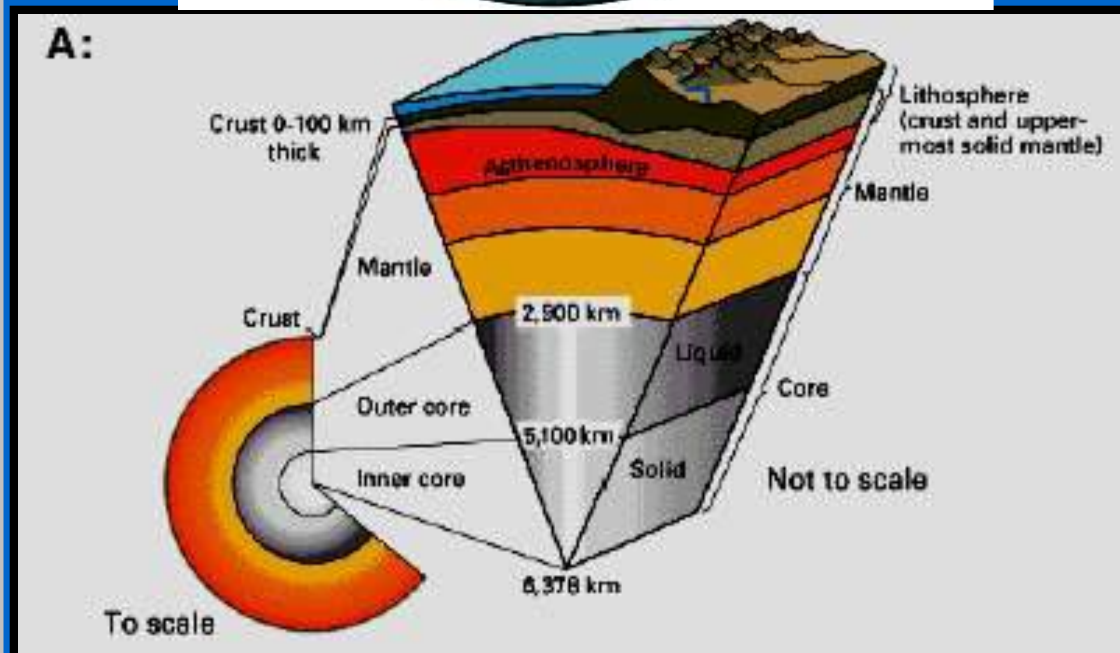
Interior of the Earth

Inner core, Outer core,mantle, and Crust. Earth's mass is in the mantle. It composed Fe, Mg, Al, Si, O_2 and other compounds. The temp is about 1000º C, the mantle is solid but can deform slowly in a plastic manner

Crust -thin layers- composed of the least dense calcium (Ca) and sodium (Na) aluminum-silicate minerals. The crust is rocky and brittle, relatively cold so it can fracture in earthquakes.

Earthquakes occur in the crust or upper mantle- ranges from earth's surface to 800 kilometers deep.





Seismology

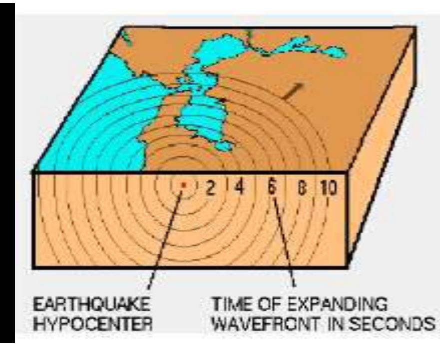
Seismic Waves

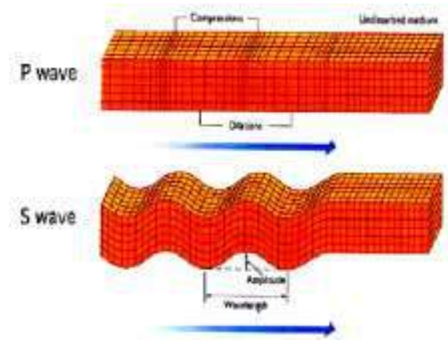
Body Waves

P-Waves and S-Waves

Surface Waves

Rayleigh and Love waves

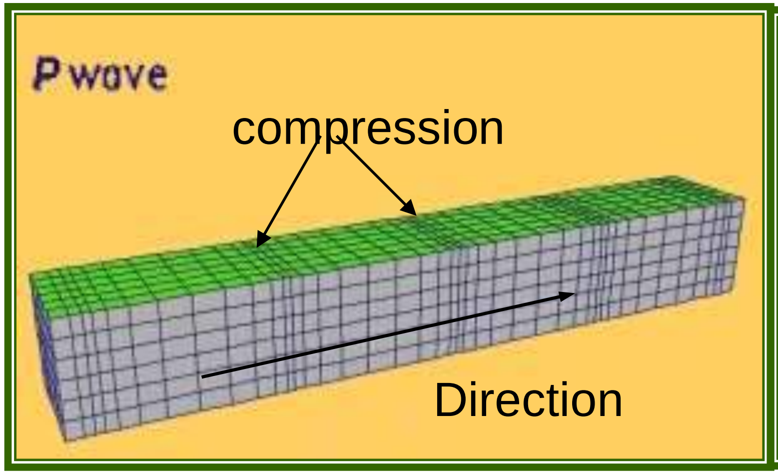


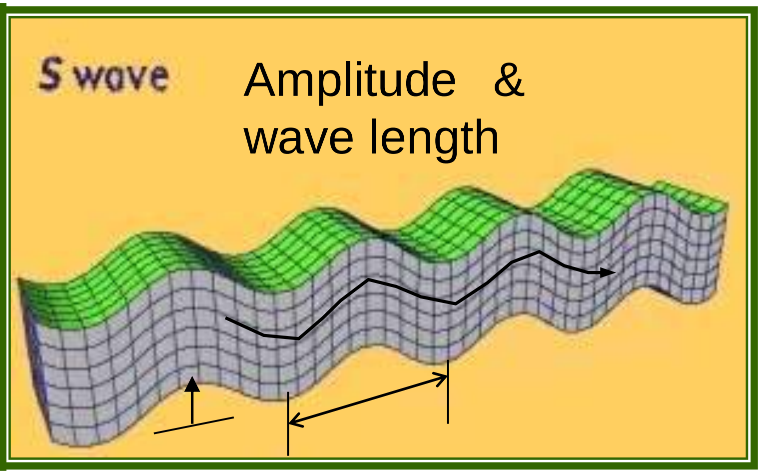


- Seismology is the branch of Geophysics concerned with the study and analysis of Earthquakes and the science of energy propagation through the Earth's crust.
- During Earthquake large amount of the energy released in the form of elastic waves which are transmitted through the earth.
- These waves are detected and recorded by seismograms, which measure, amplify and record the motion of the ground.
- Seismographs record a zig-zag trace that shows the varying amplitude of ground oscillations beneath the instrument.
- The time, locations, and magnitude of an earthquake can be determined from the data recorded by seismograph stations.

- Earthquakes generate four principal types of waves; two, known as **body waves,** travel within the Earth, whereas the other two, called **surface waves**, travel along its surface.
- Body waves are reflected and transmitted at interfaces where seismic velocity or density change, and they obey Snell's law. The two different types of body waves are: P-Waves and S-Waves
- Surface waves do not penetrate the deep interior of the earth, and are normally generated by shallow earthquakes (nuclear explosions do not generate these surface waves).
- Surface waves are larger in amplitude and longer in duration than body waves.
- Interpretation of seismograms (recorded traces of the amplitude and frequency of seismic waves) yields information about the Earth and its subsurface structure

Body waves





- Primary, or P waves or compressional or longitudinal waves

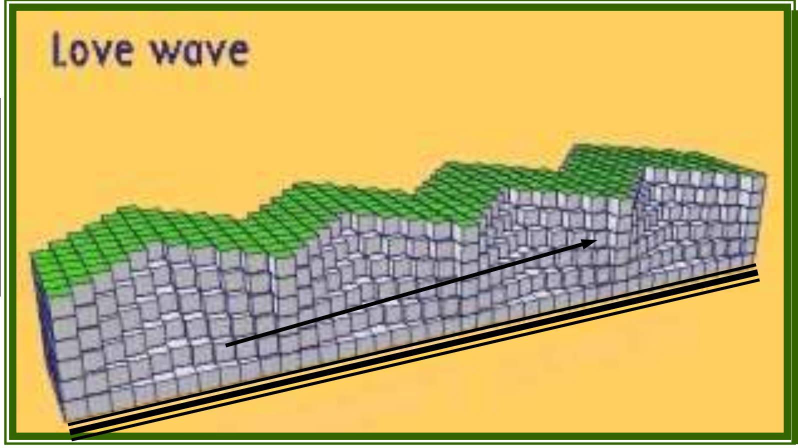
  P waves reach seismic recording station faster than the S waves.

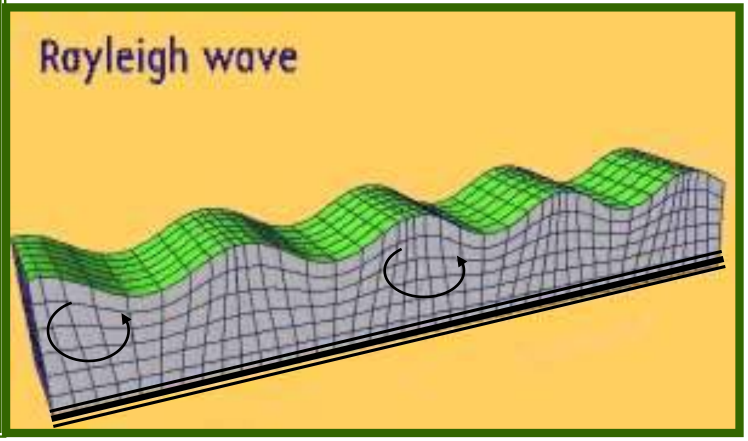
  P waves push rock particles back-and-forth motion along the path of propagation, thus stretching or compressing the rock as the wave passes any one point; these waves are like sound waves in air.

- Secondary, or S waves or transverse or shear waves

  Rock particles to move back and forth perpendicular to the direction of propagation; as the wave passes, the rock is distorted first in one direction and then in another.

Surface waves





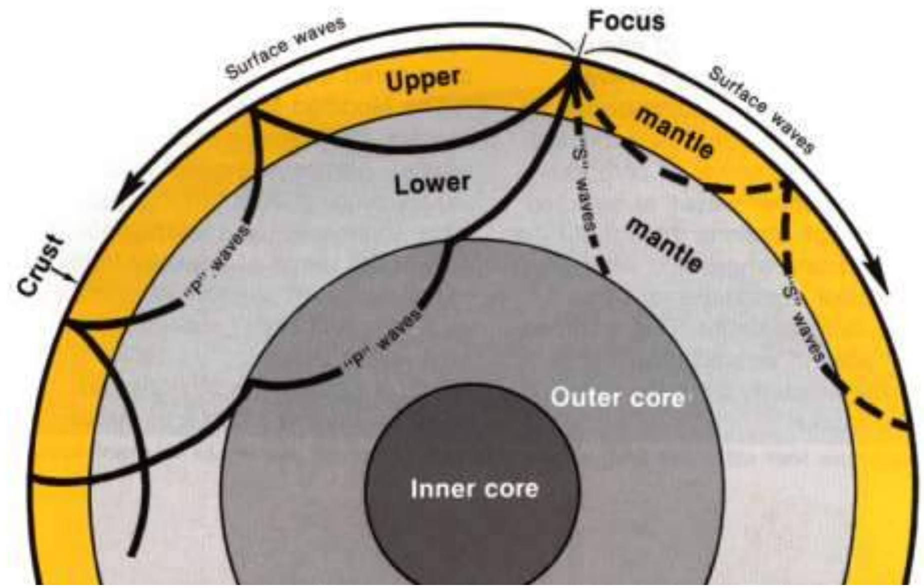
- Love waves—named after A.E. Love, who first predicted their existence

  travel faster and are propagated in a surface layer that overlies a solid rock layer with different elastic properties. It is entirely perpendicular to the direction of propagation and has no vertical or longitudinal components. The energy of Love waves spreads from the source in two directions rather than in three, and so these waves produce a strong record at seismic stations

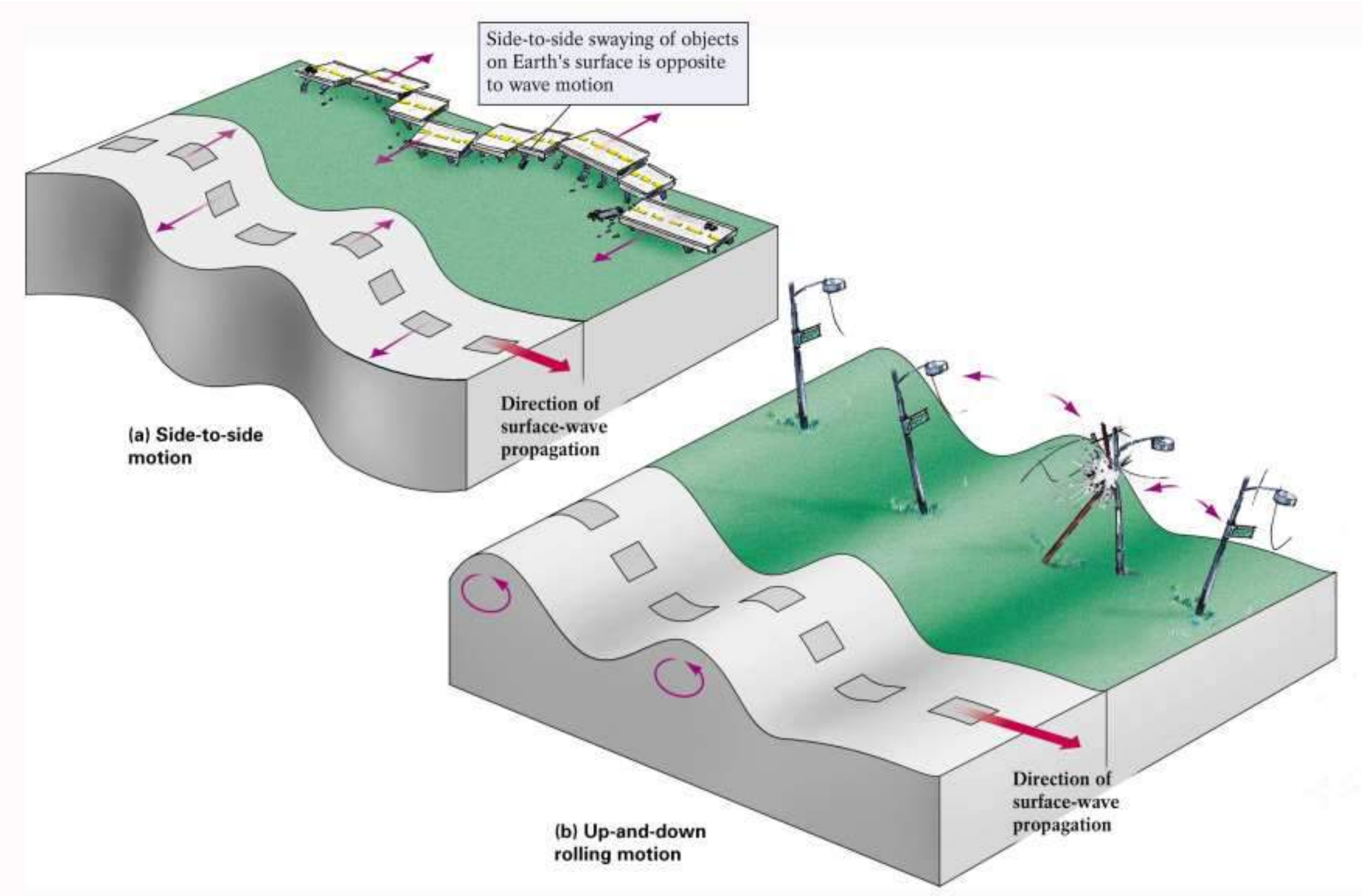
- Rayleigh waves after Lord Rayleigh, who first predicted their existence.

  travel on the free surface of an elastic solid. It has longitudinal and vertical vibration that gives an elliptical motion to the rock particles. The displacements are greatest at the surface and decrease exponentially downward. It shows varying wavelength. This wave is similar to how ocean waves propagate.

- Travel just below or along the ground's surface
- Slower than body waves; rolling and side-to-side movement
- Especially damaging to buildings



Two most common types of surface waves



Seismic Waves

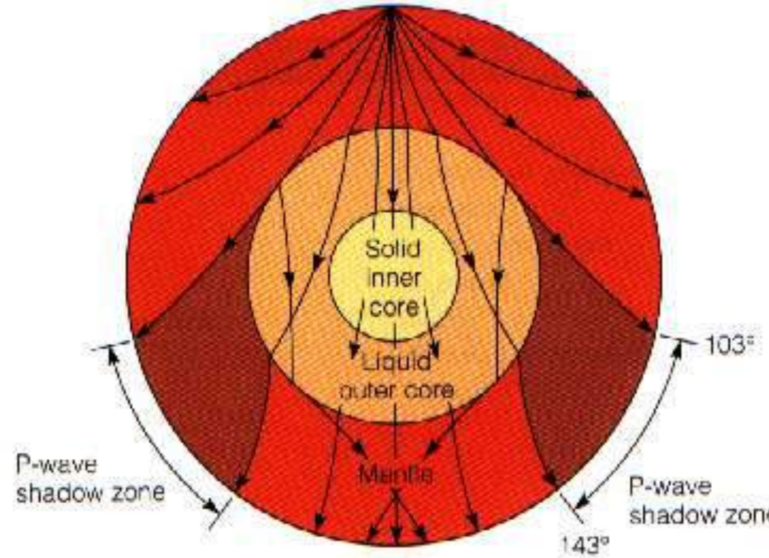
(Earthquake's energy is transmitted through the earth as seismic waves)

Two types of seismic waves

- **Body waves- transmit energy through earth's interior**
  - **Primary (P) wave- rocks vibrate parallel to direction of wave**
    - **Compression and expansion (slinky example)**
  - **Secondary (S) wave- rocks move perpendicular to wave direction**
    - **Rock shearing (rope-like or 'wave' in a stadium)**
- **Surface waves- transmit energy along earth's surface**
  - **Rock moves from side to side like snake**
  - **Rolling pattern like ocean wave**

Primary waves

- P-waves, compressional or longitudinal.
- Typical crustal velocity: 6 km/s (~13,500 mph)
- Travel through solids, liquids, or gases
- Material movement is in the same direction as wave movement
- Behavior: Cause dilation and contraction (compression) of the earth material through which they pass.
- Arrival: They arrive first on a seismogram.

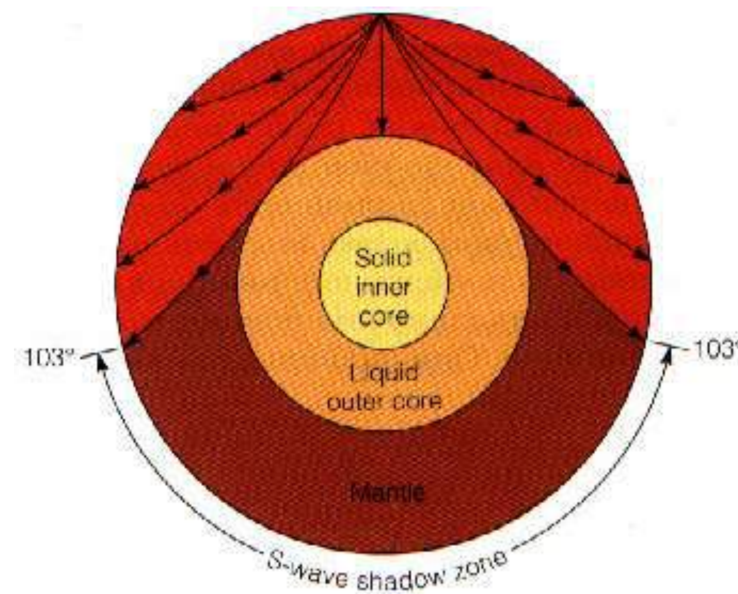


Even for P waves (which can travel all the way through) we see some changes in the path at certain points within Earth.

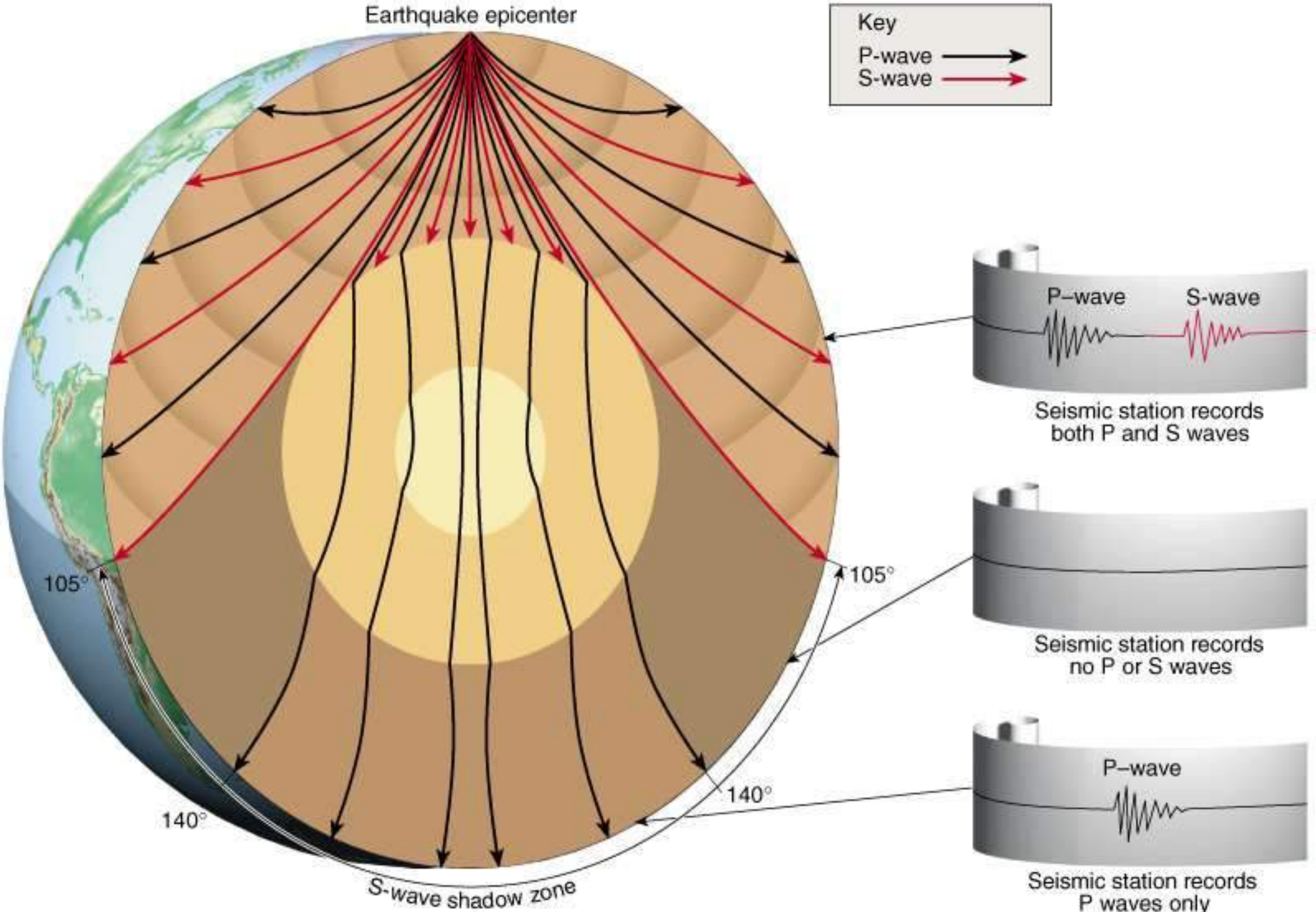
This is due to the discontinuities present at different boundaries in earth structure

Secondary waves

- S waves (secondary)
- Typical crustal velocity: 3 km/s (~6,750 mph)
- Behavior: Cause shearing and stretching of the earth material through which they pass. Generally cause the most severe shaking; very damaging to structures.
- Travel through solids only
- shear waves - move material perpendicular to wave movement
- Arrival: Second on a seismogram.

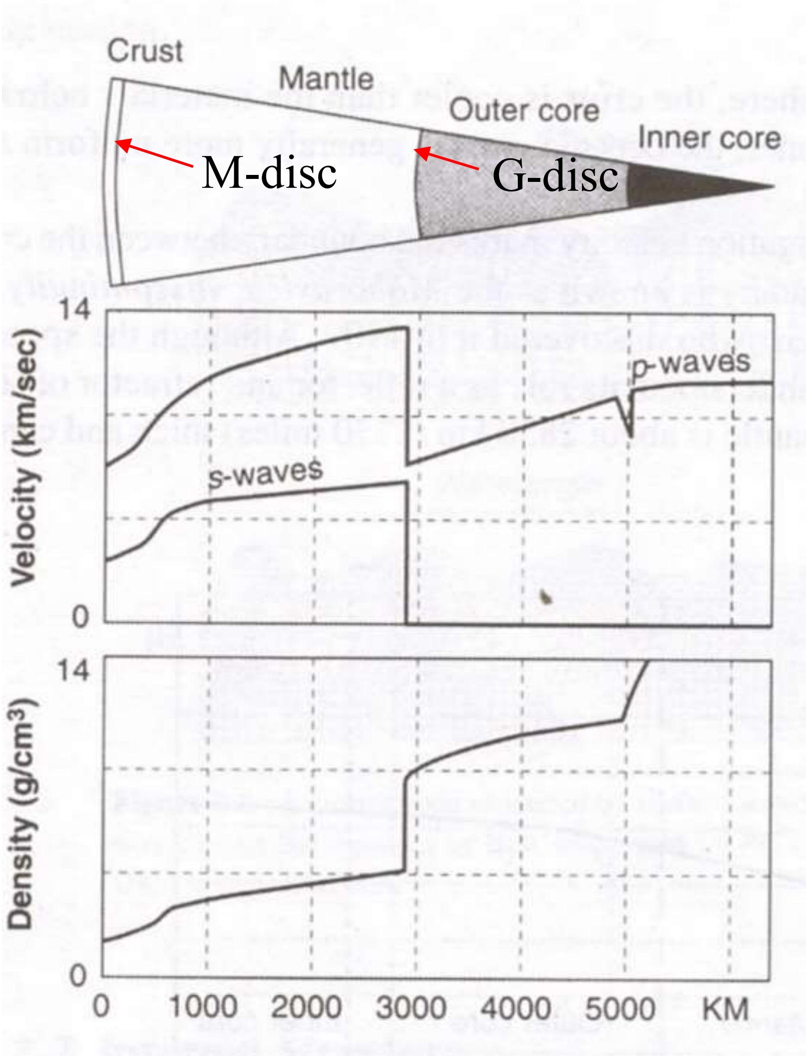


S-wave velocity drops to zero at the core-mantle boundary or *Gutenberg Discontinuity*



Shadow Zone - no earthquake waves

Variation of P and S wave velocities within the earth

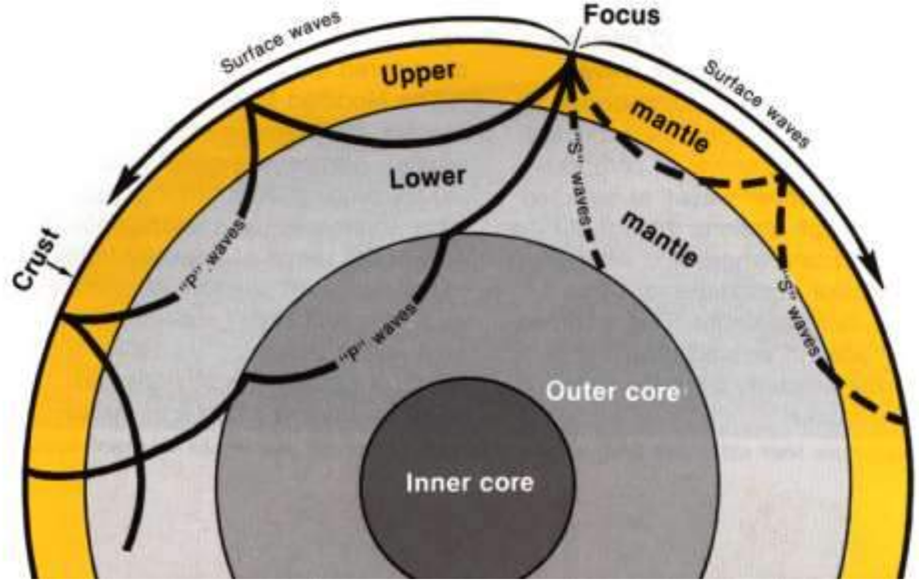


M-Disc : The Mohorovicic discontinuity

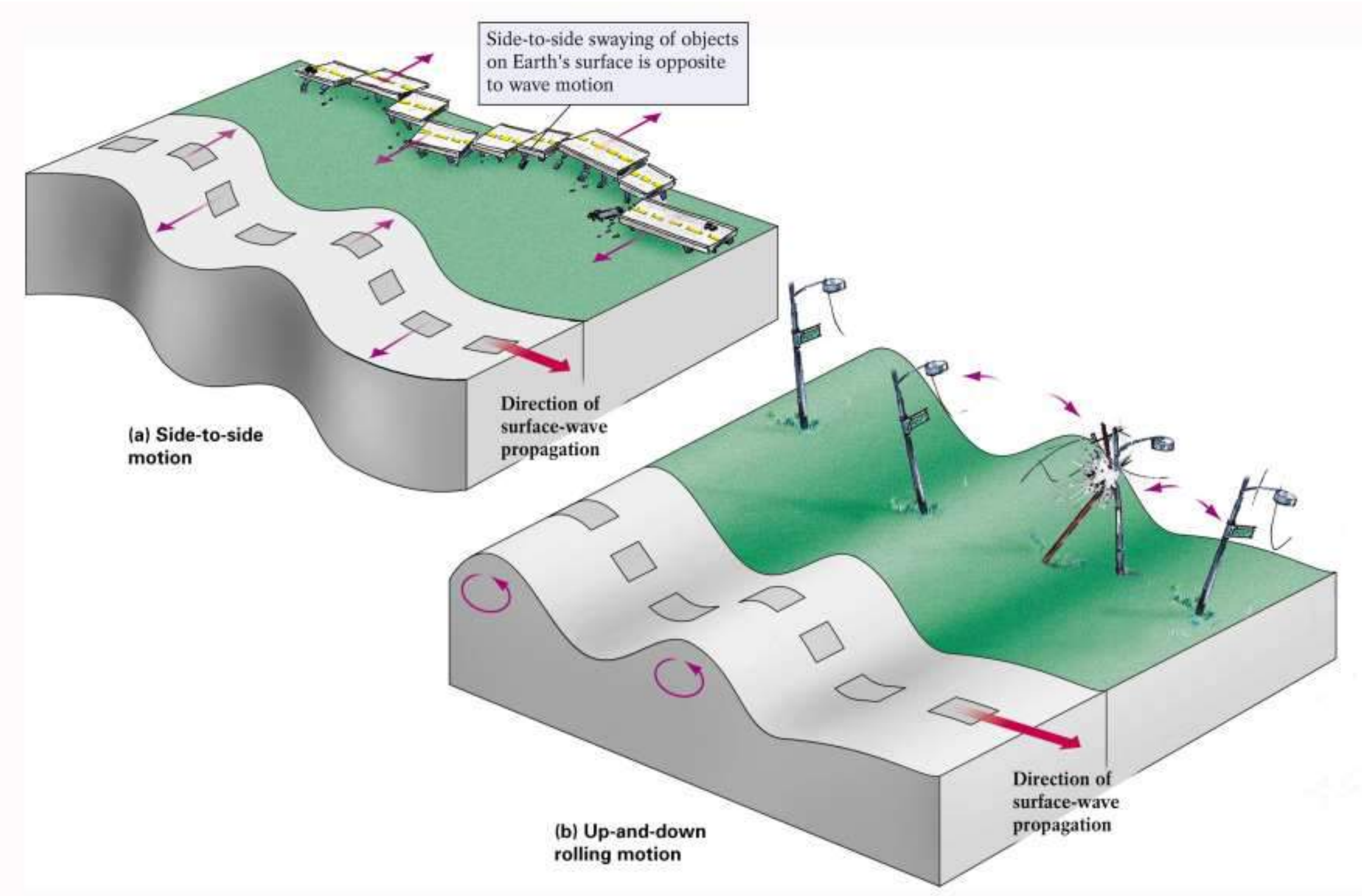
G-disc: The Gutenberg discontinuity

Surface Waves

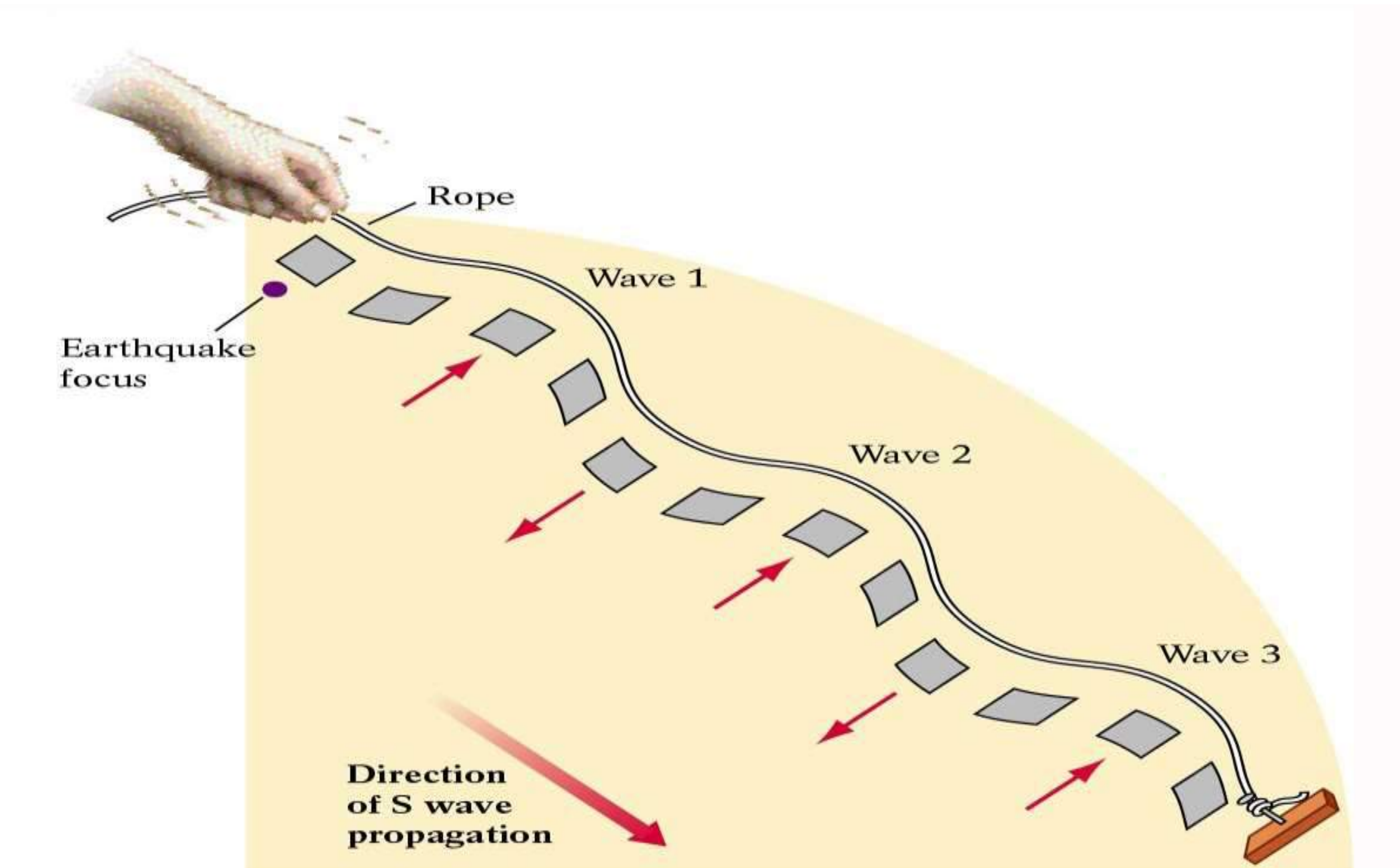
- Travel just below or along the ground's surface
- Slower than body waves; rolling and side-to-side movement
- Especially damaging to buildings



Two most common types of surface waves



Secondary Waves

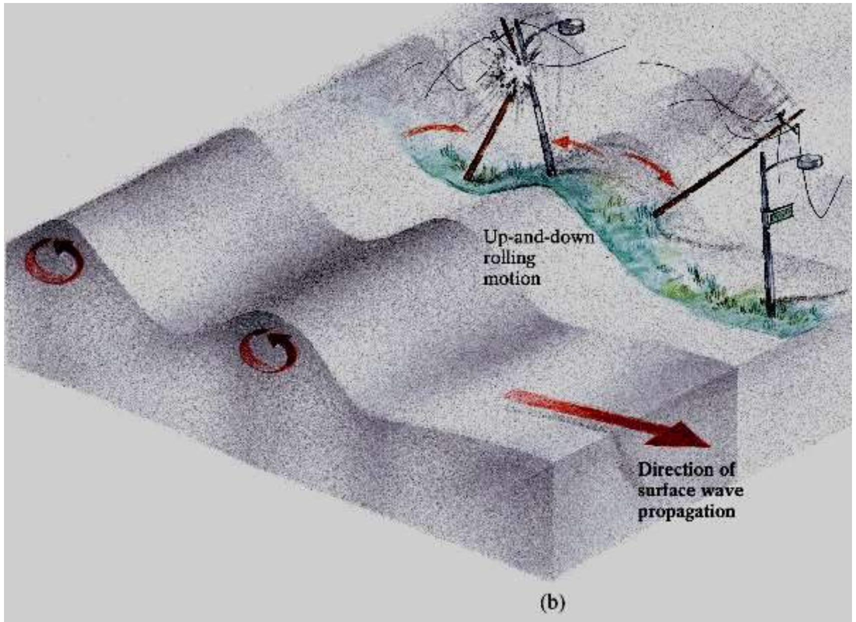


Rayleigh Waves

Typical velocity: ~ 0.9 that of the S wave

Behavior: Causes vertical together with back-and-forth horizontal motion. Motion is similar to that of being in a boat in the ocean when a swell moves past.

Arrival: They usually arrive last on a seismogram.

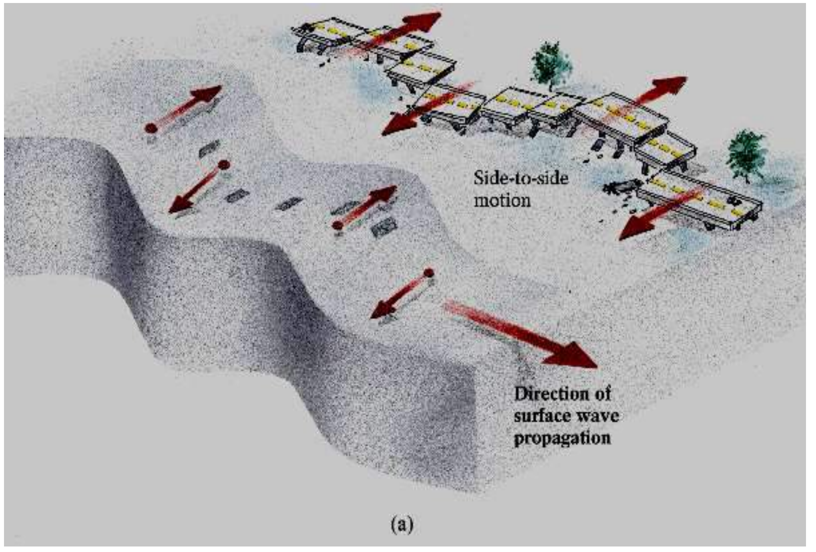


Love Waves

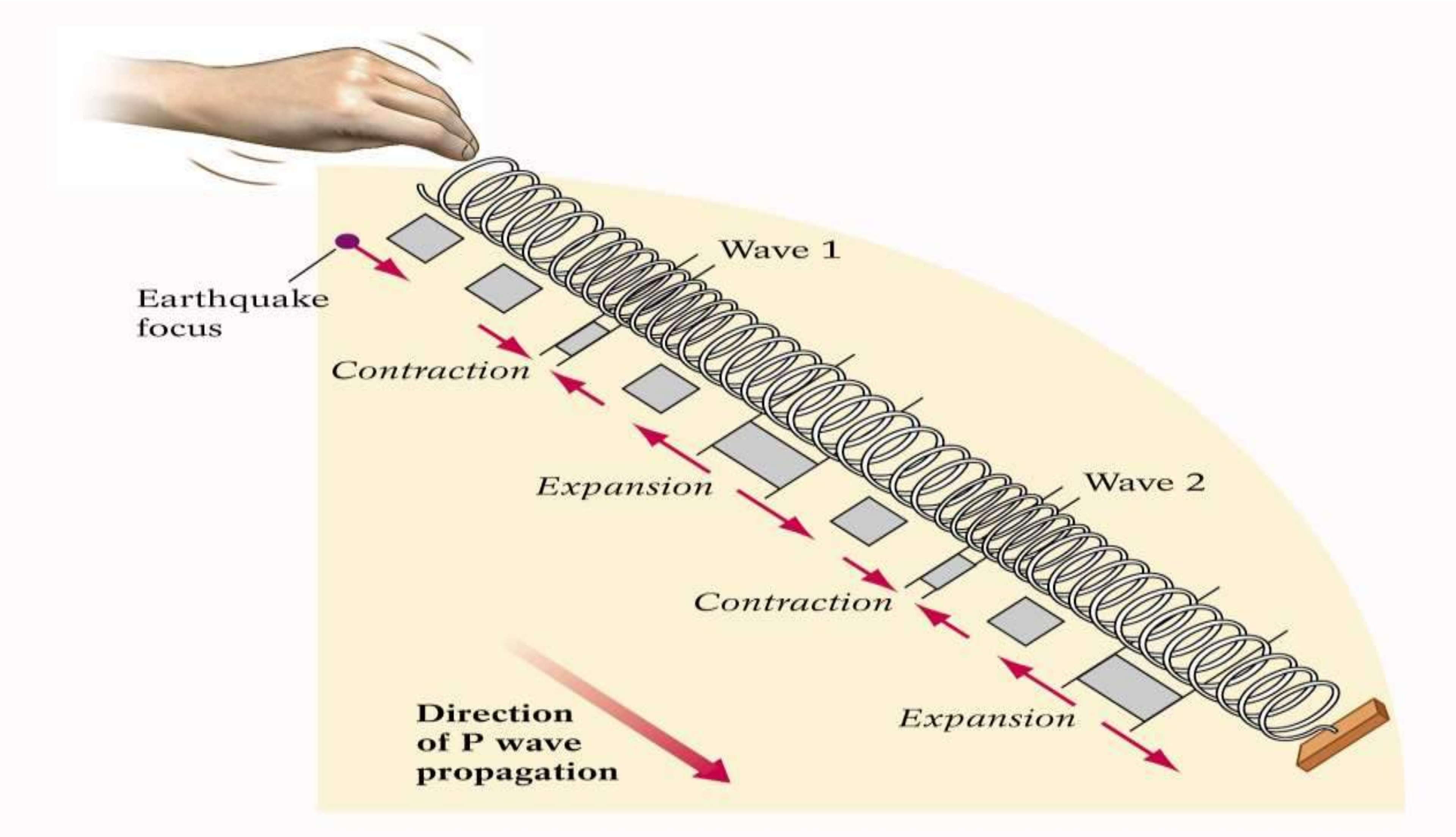
Typical velocity: Depends on earth structure, but less than velocity of S waves.

Behavior: Causes shearing motion (horizontal) similar to S waves.

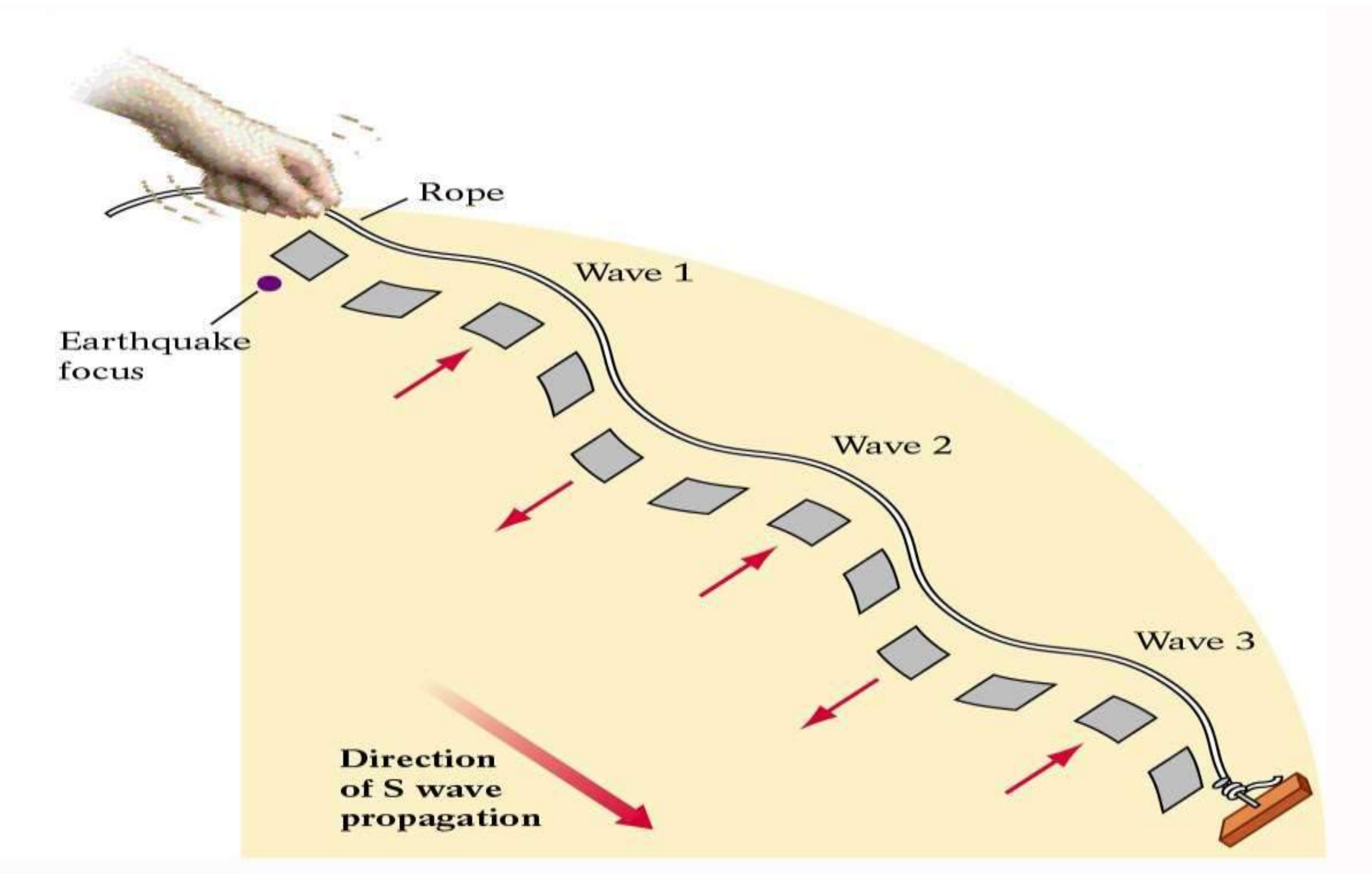
Arrival: They usually arrive after the S wave and before the Rayleigh wave.



Primary Waves



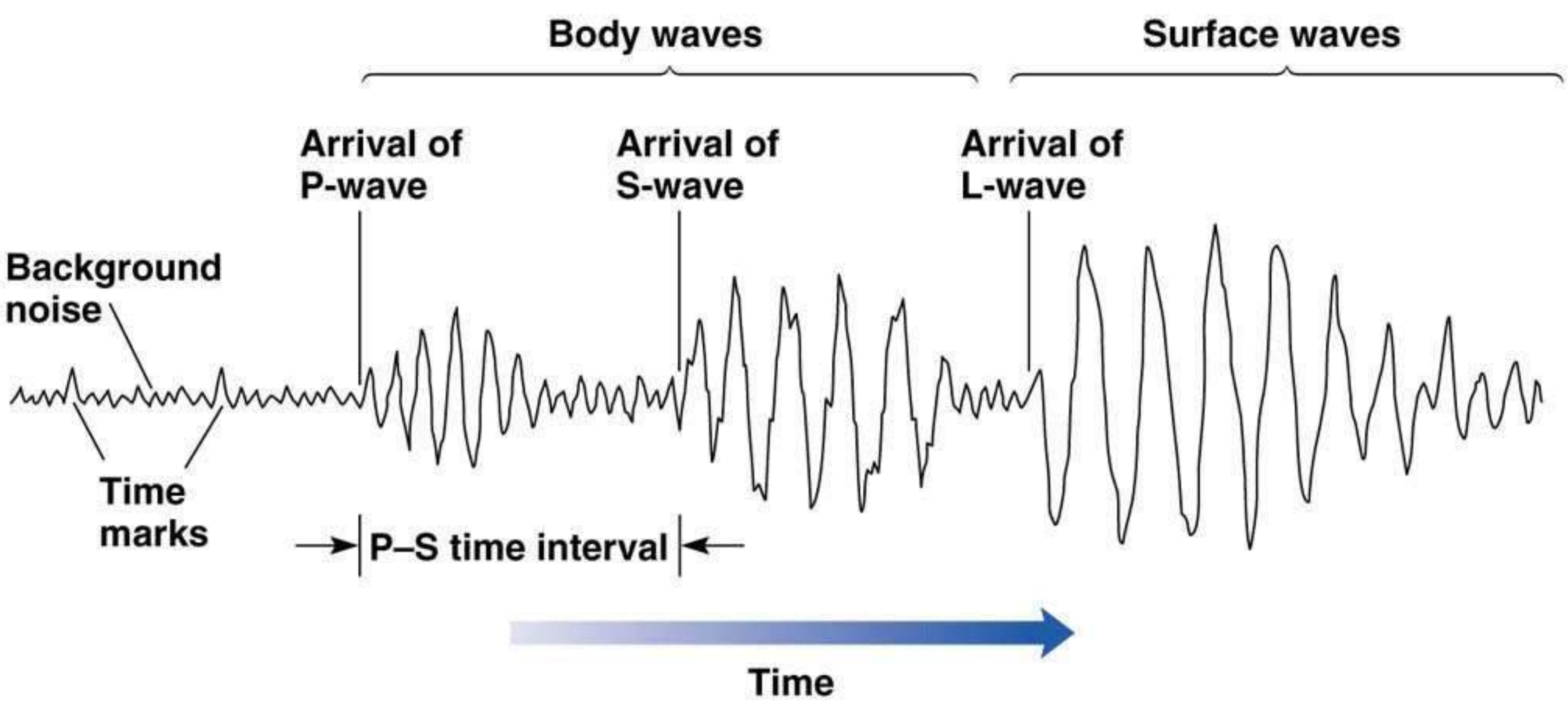
Secondary Waves



Locating an Earthquake's Epicenter

Seismic wave behavior

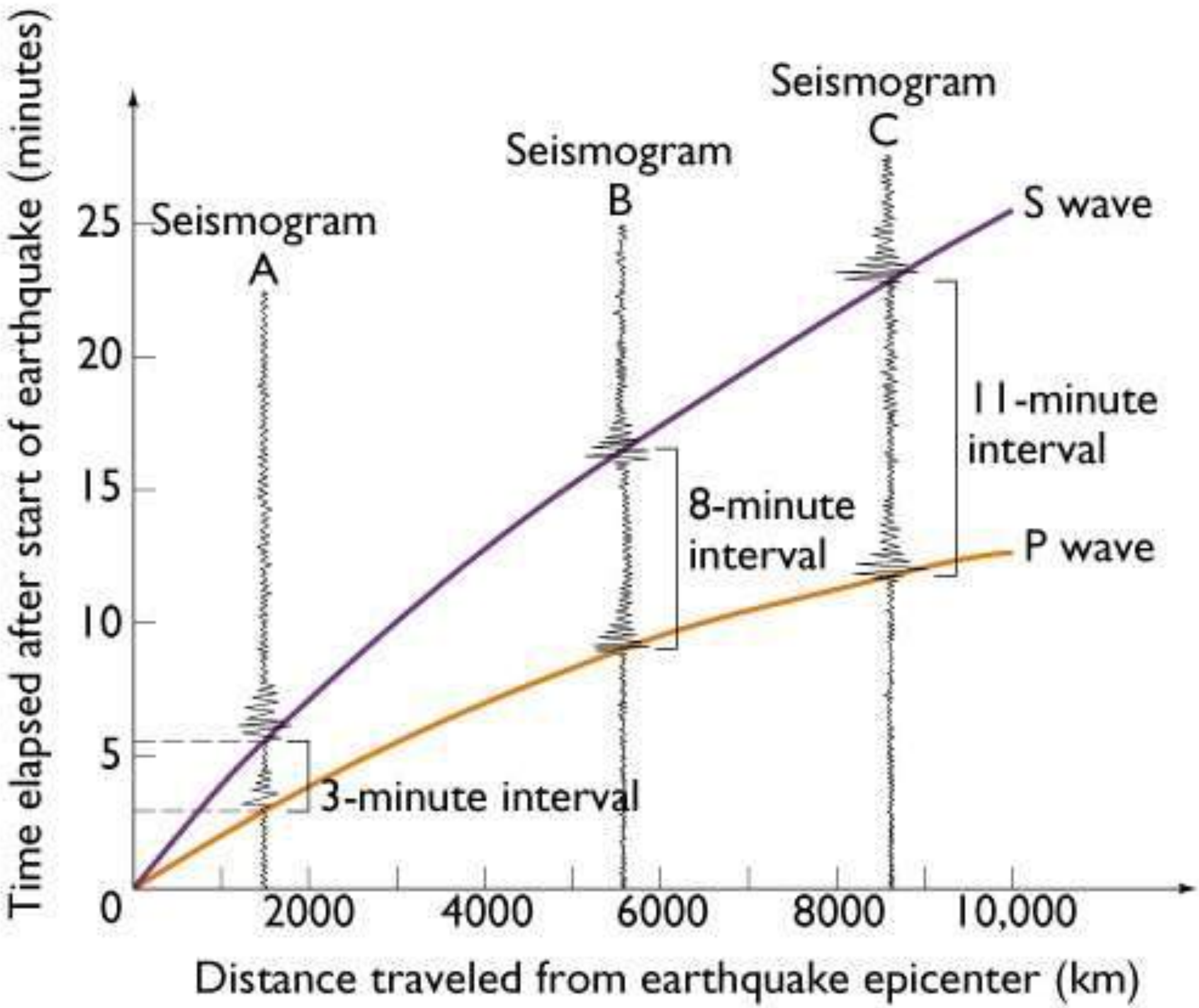
- P waves arrive first, then S waves, then L and R
- After an earthquake, the difference in arrival times at a seismograph station can be used to calculate the distance from the seismograph to the epicenter (D).



(a)

If average speeds for all these waves is known, use the S-P (S minus P) time formula: a method to compute the distance (D) between a recording station and an event.

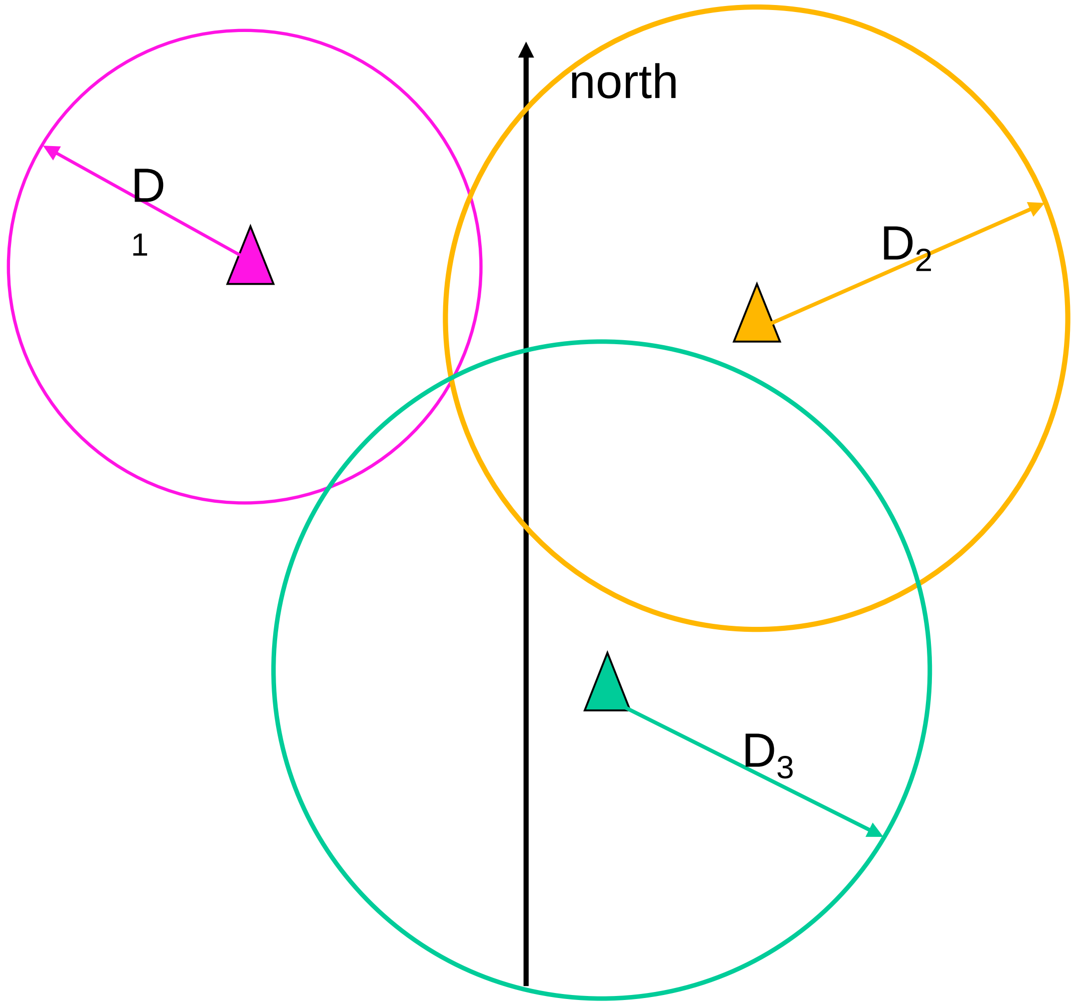
Seismic Travel-time Curve: If the speeds of the seismic waves are not known, use Travel-Time curve for that region to get the distance



1. Measure time between P and S wave on seismogram

2. Use travel-time graph to get distance to epicenter

3-circle method:



3-circle steps:

1) Read S-P time from 3 seismograms.

2) Compute distance for each event/recording station pair (D_1, D_2, D_3) using S-P time formula.

3) Draw each circle of radius D_i on map.

4) Overlapping point is the event location.

Assumption: Source is relatively shallow; epicenter is relatively close to hypocenter.

How does an earthquake occur?

Any abrupt disturbance within the Earth I.e **tectonic or volcanic in origin** and that results in the generation of elastic waves. The passage of such seismic waves through the earth often causes violent shaking at its surface.

tectonic in origin

The word tectonic is derived from the Greek word tekton, which means “builder.” **Plate tectonics** is the continual slow movement of the tectonic plates. The origin and distribution of most major earthquakes can be explained in terms of the plate tectonics theory. This theory postulates that the Earth's surface is made up of a number of large, rigid plates in lithosphere that move relative to one another and interact at their boundaries. .

volcanic in origin

any vent in the crust of the Earth from which molten rock, pyroclastic debris, and steam erupted .

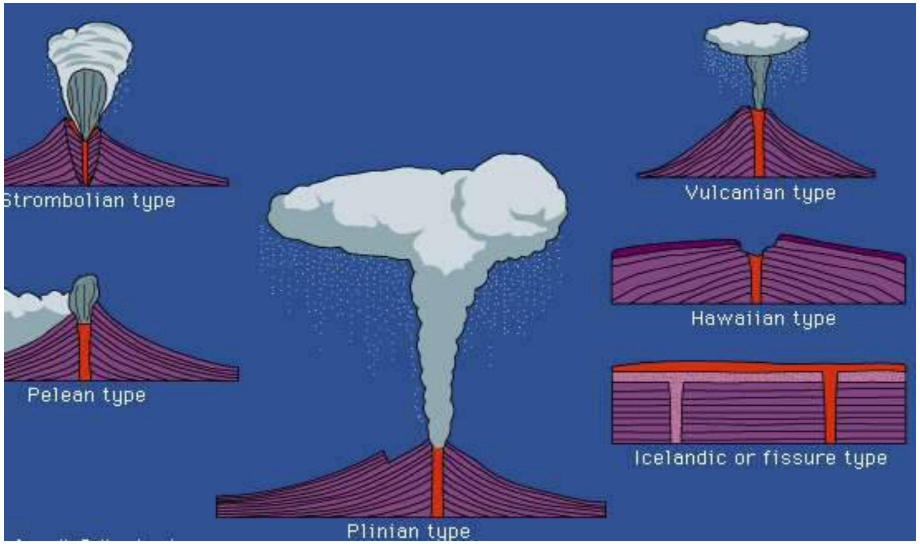
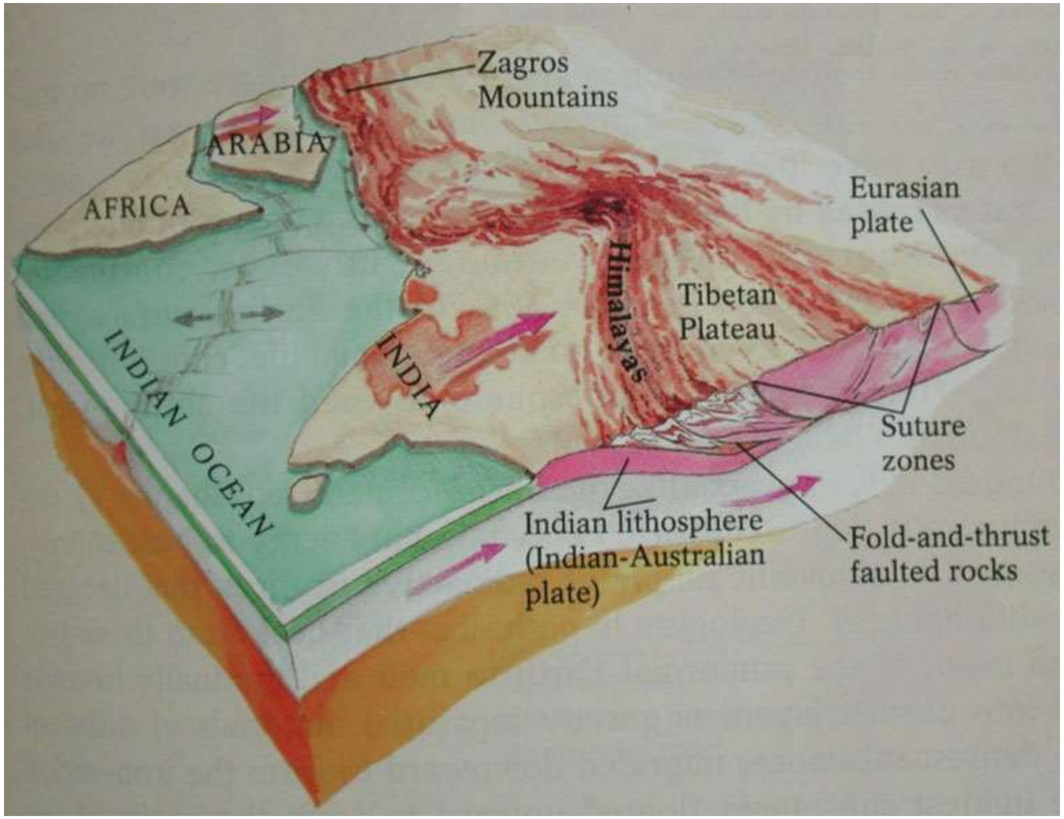


plate boundaries

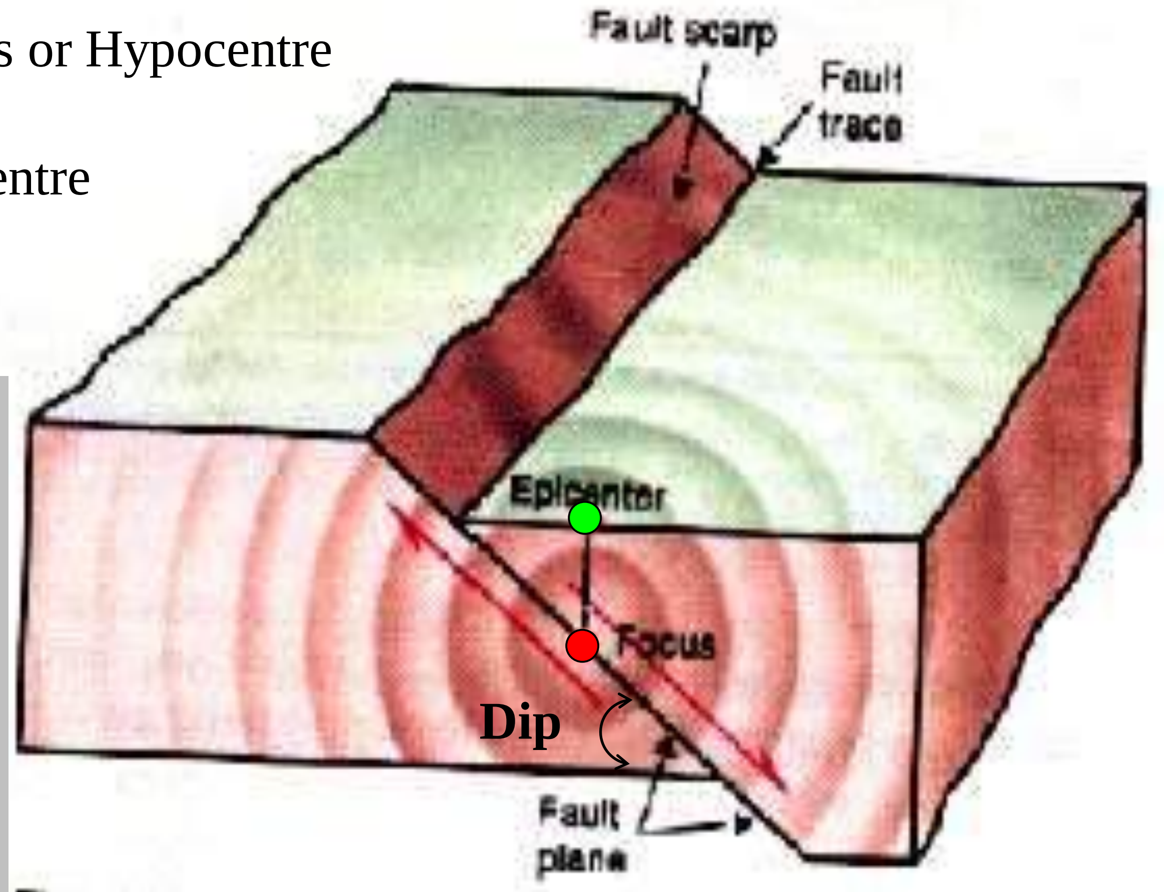


volcanic in origin

Fault, Slip ,Strike &Dip

Focus or Hypocentre

Epicentre



A fault is a fracture zone between two blocks of rock.

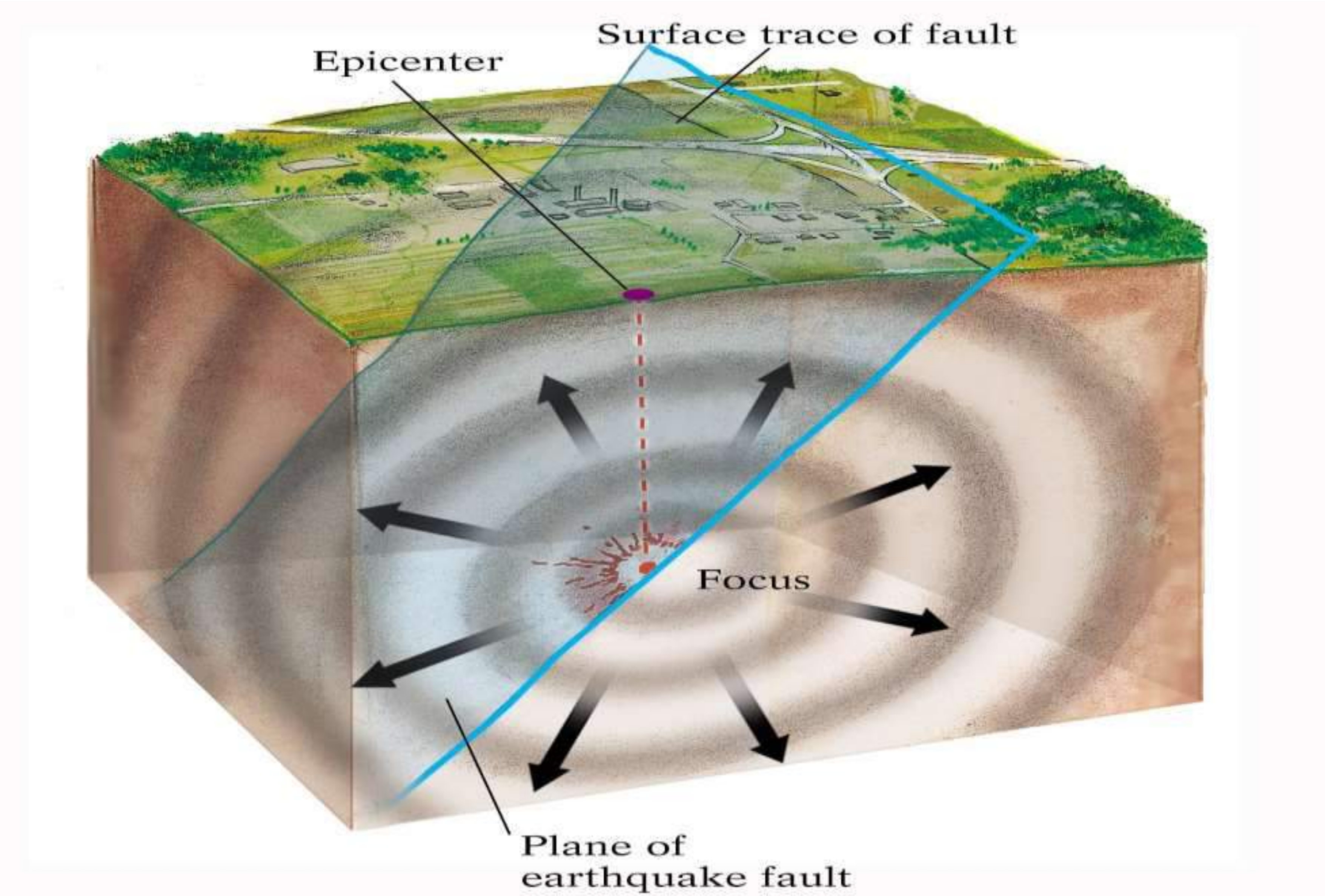
Faults allow the blocks to move relative to each other.

This movement may occur rapidly, in the form of an earthquake - or may occur slowly, in the form of creep.

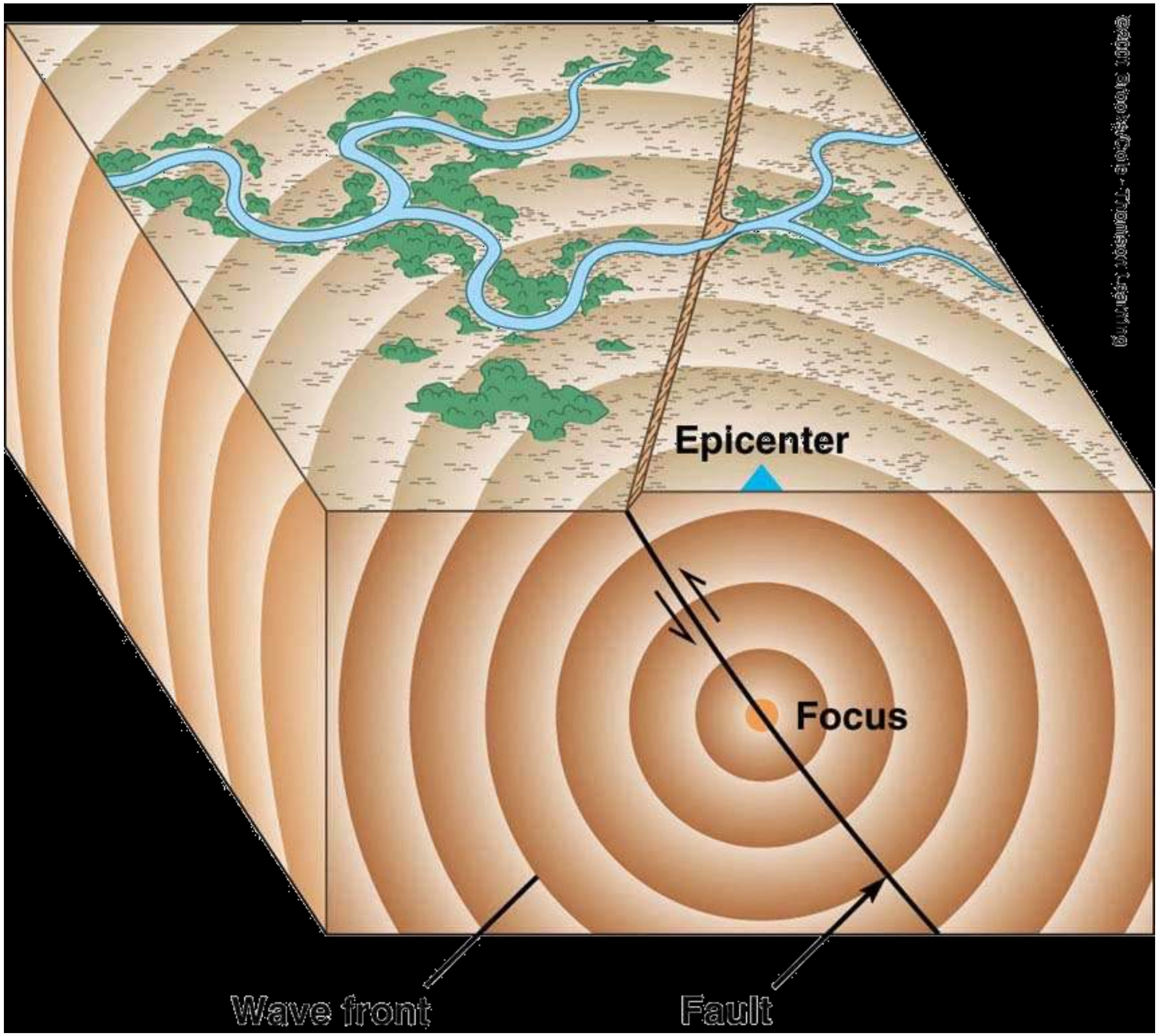
Faults may range in length from a few millimeters to thousands of kilometers. During an earthquake, the rock on one side of the fault suddenly slips with respect to the other. The fault surface can be horizontal or vertical or some arbitrary angle in between.

Earth scientists use the angle of the fault with respect to the surface known as the **dip**

Release of Accumulated energy



The Focus and Epicenter of an Earthquake



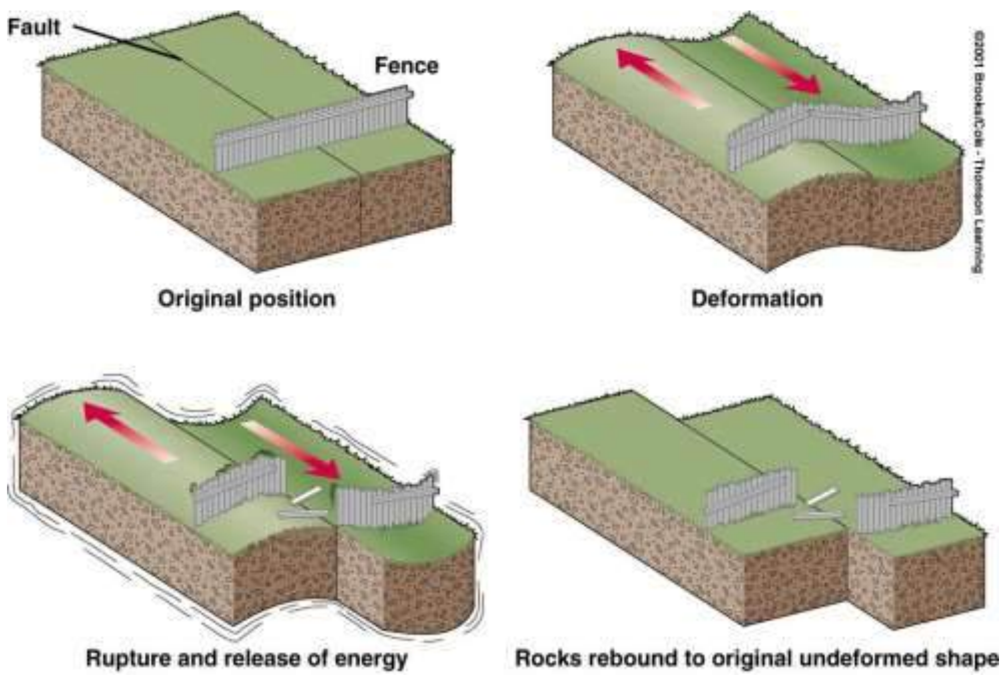
The point within Earth where faulting begins is the focus, or hypocenter

The point directly above the focus on the surface is the epicenter

Elastic Rebound Theory

Elastic Rebound Theory

Rocks bend under stress while storing elastic energy. When the strain in the rocks exceeds their strength, breaking will occur along the fault. Stored elastic energy is released as the earthquake. Rocks“snap back”, or rebound to their original condition.



Types of Faults

Types of Faults

The faults are classified based on the **direction of slip** along the fault

Dip-Slip Faults

Faults which move along the direction of the dip plane and are described either normal or reverse, depending on their motion.

Strike –Slip Faults

which move horizontally and are classified either right-lateral or left-lateral.

oblique-slip faults

Faults show both dip-slip and strike-slip motion are known as oblique-slip faults.

Normal earthquakes occur on normal faults

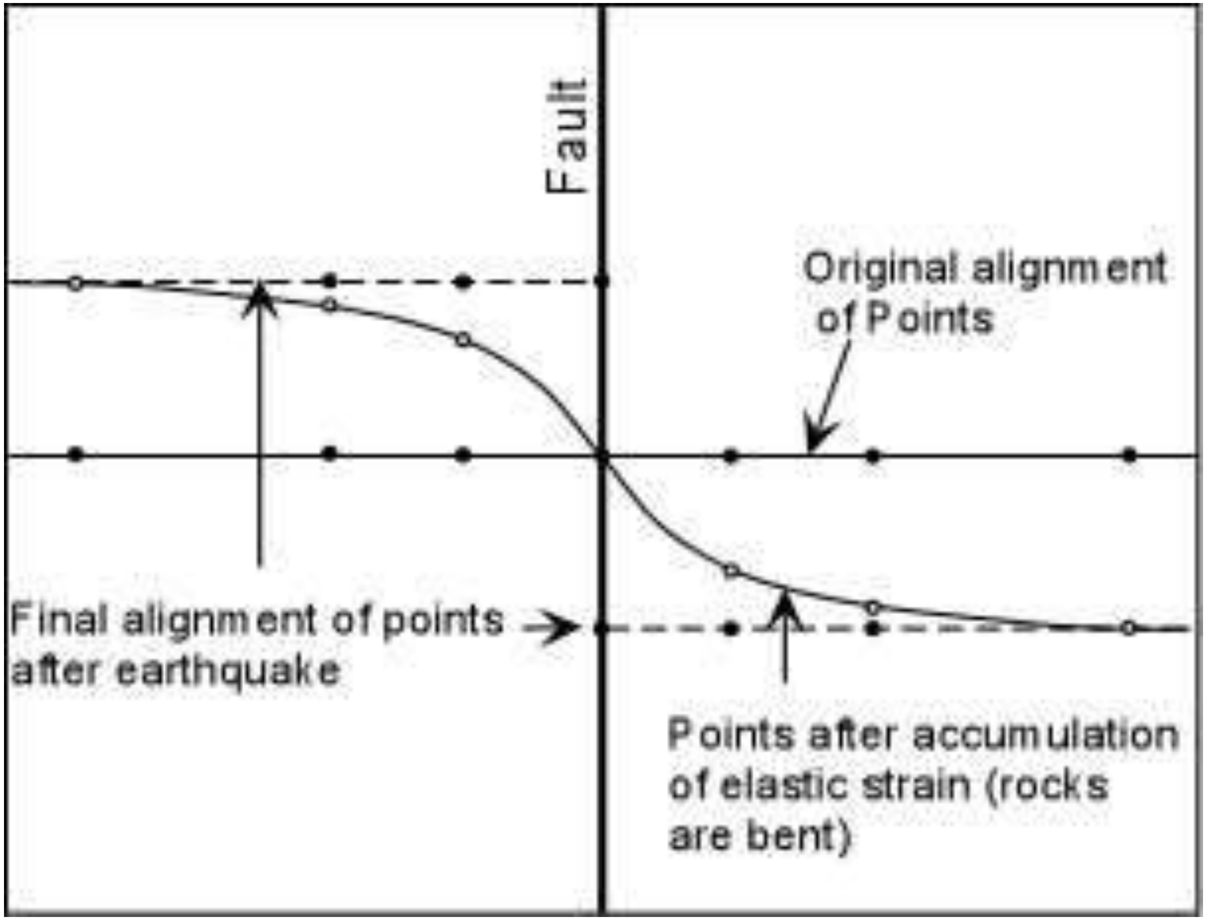
Thrust earthquakes occur on thrust or reverse faults

Elastic Rebound Theory

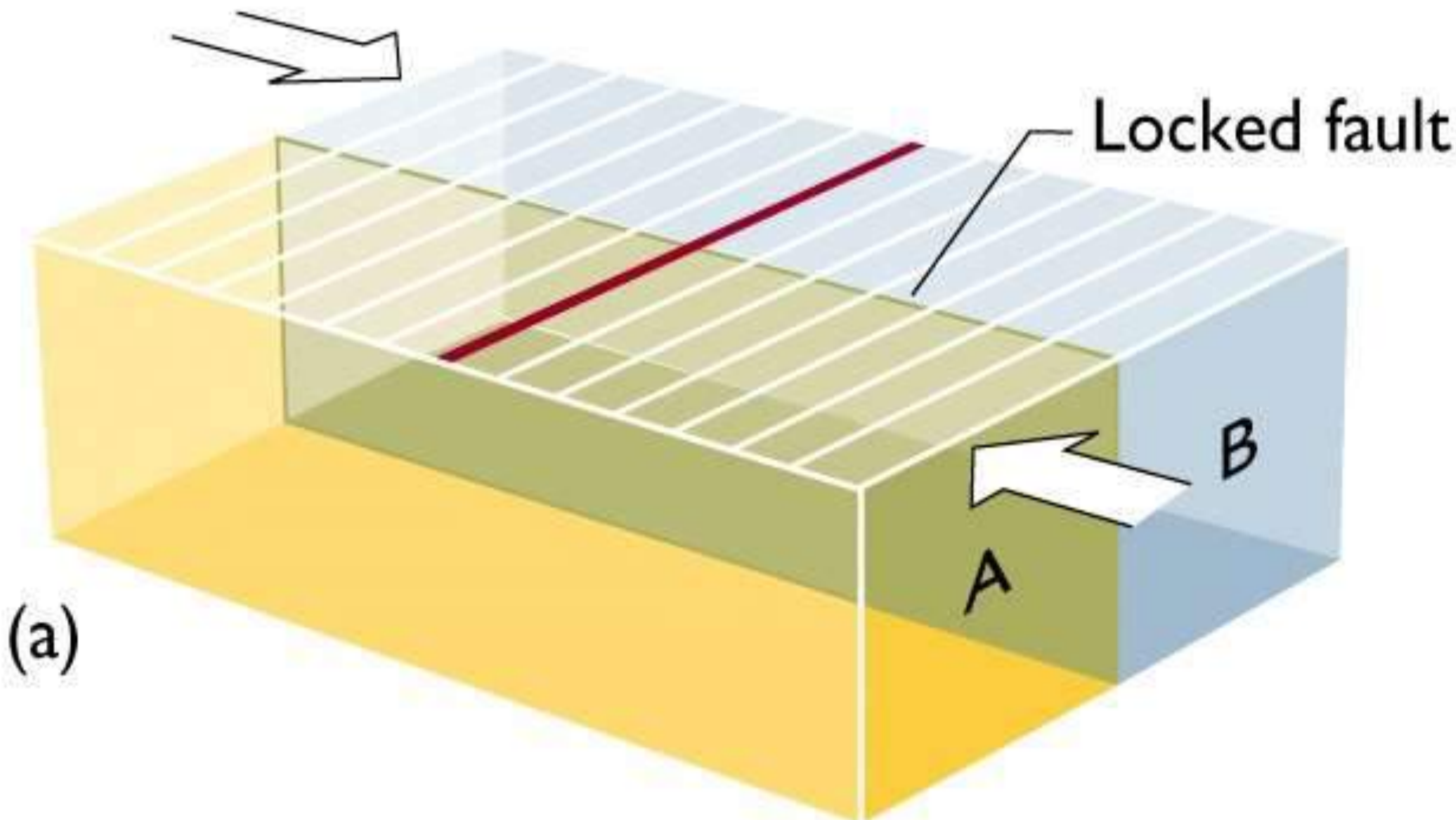
This theory was discovered by making measurements at a number of points across a fault.

Prior to an earthquake it was noted that the rocks adjacent to the fault were bending. These bends disappeared after an earthquake suggesting that the energy stored in bending the rocks was suddenly released during the earthquake.

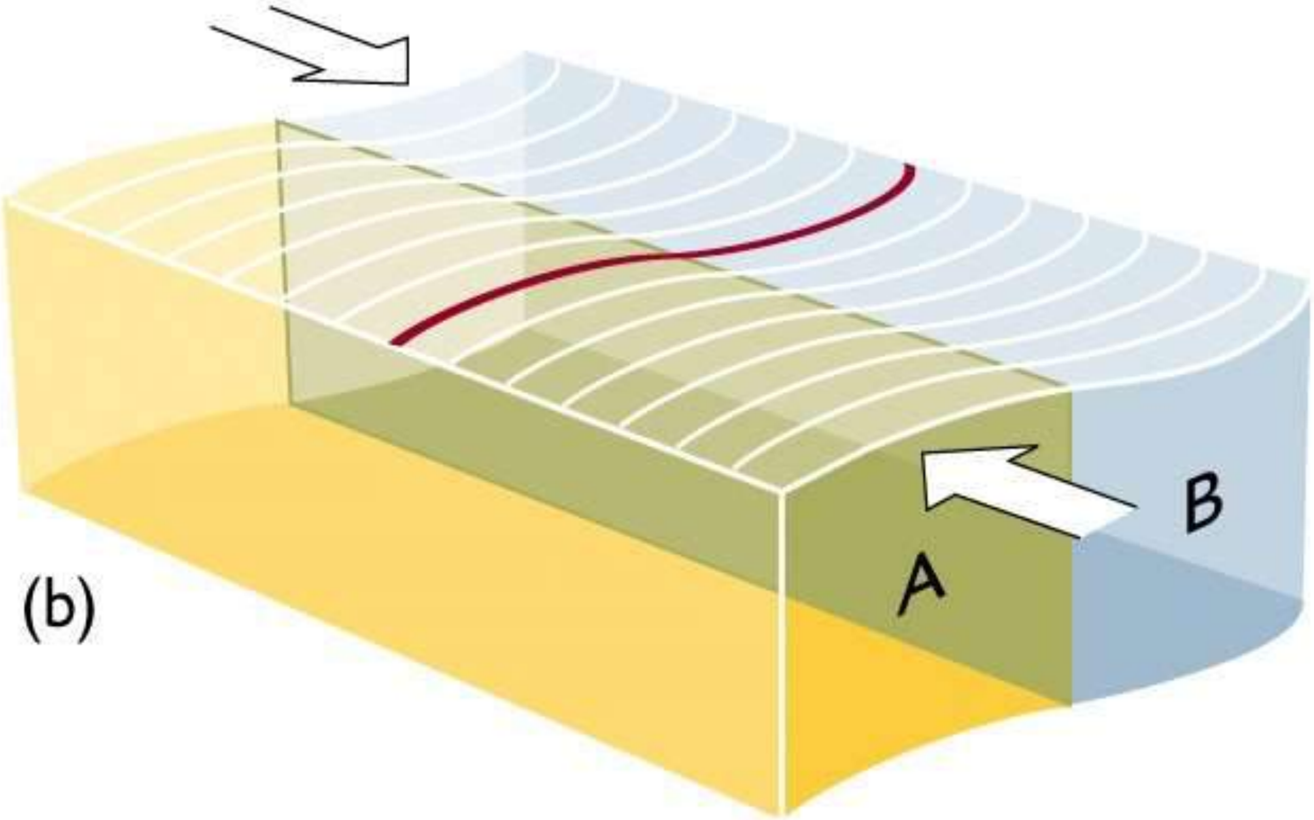
Elastic Rebound Theory



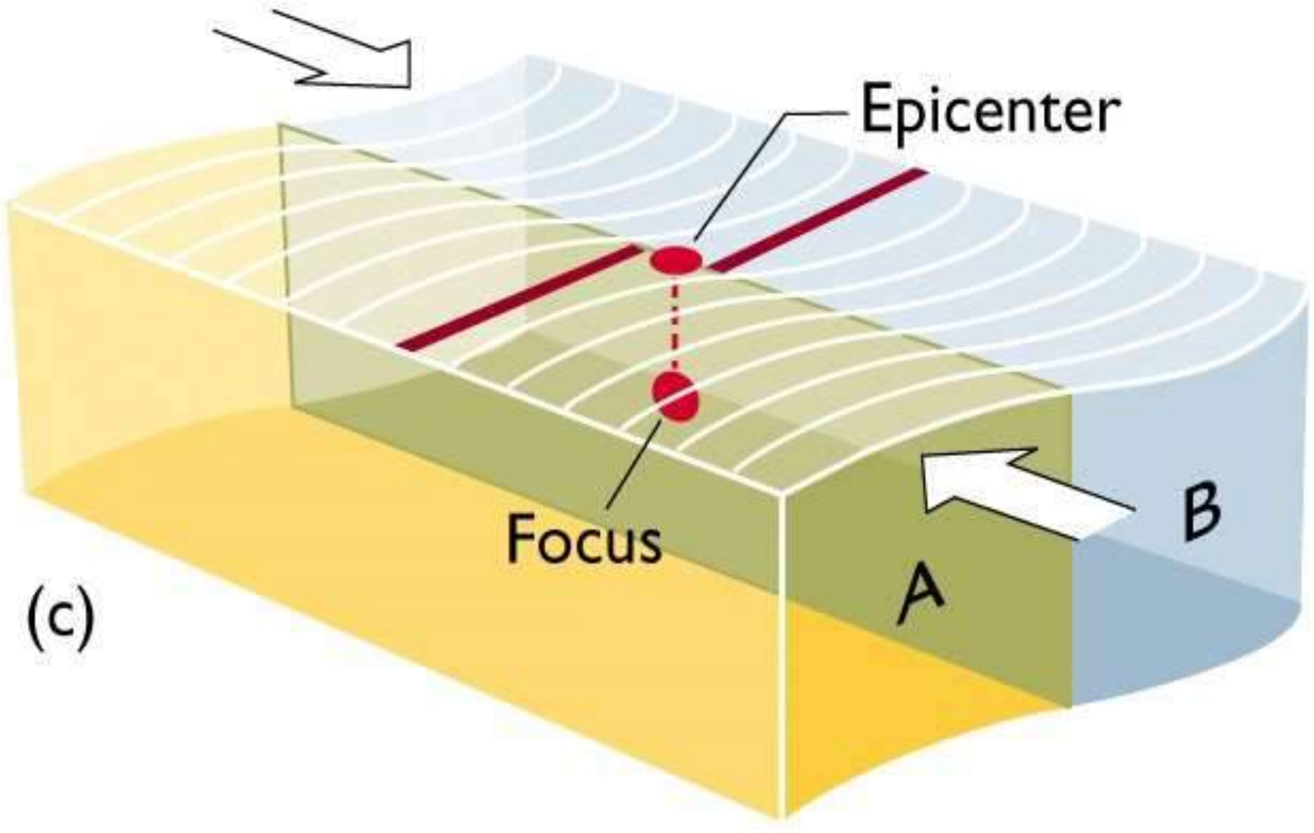
Sequence of elastic rebound: Stresses



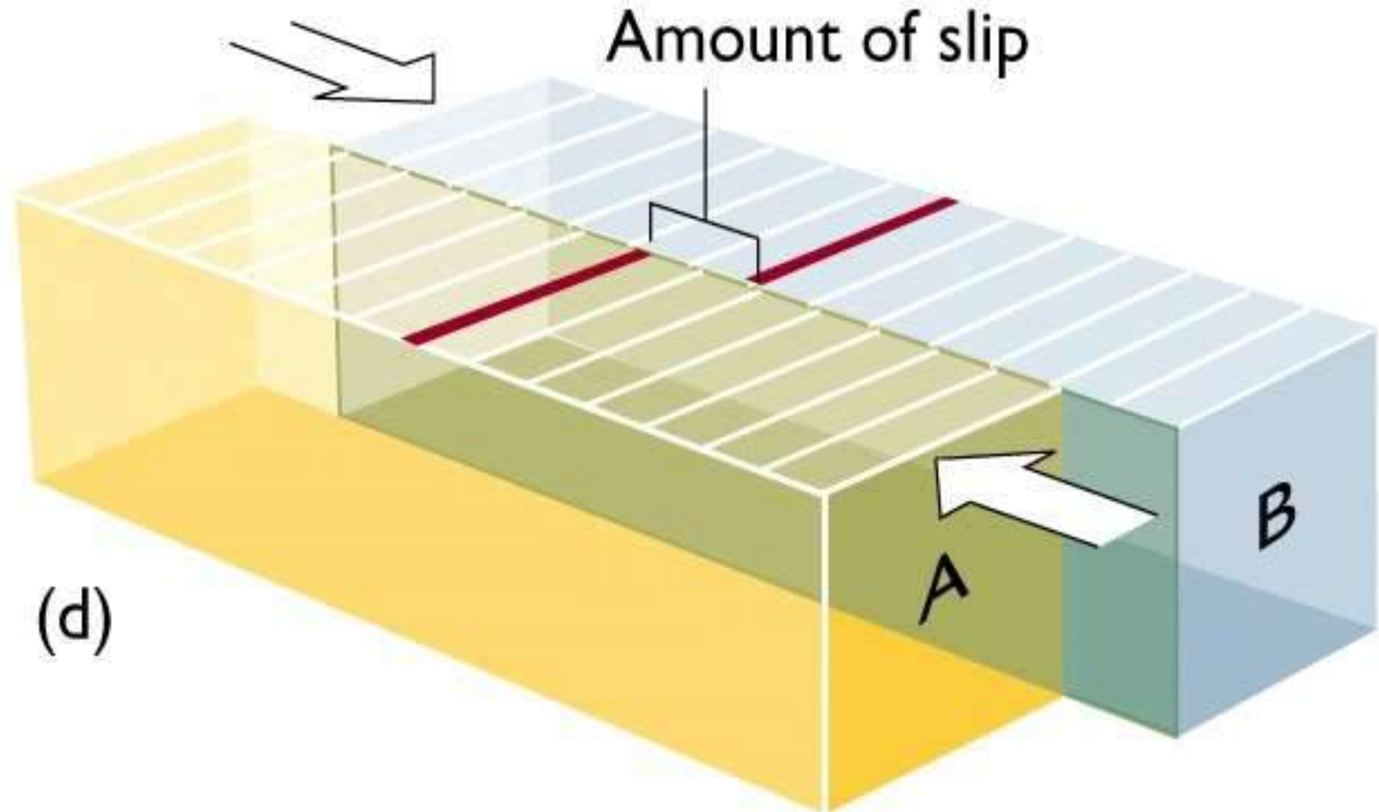
Sequence of elastic rebound: Bending



Sequence of elastic rebound: Rupture



Sequence of elastic rebound: Rebound



Sudden Slip by Elastic Rebound

Stresses (force/area) are applied to a fault.

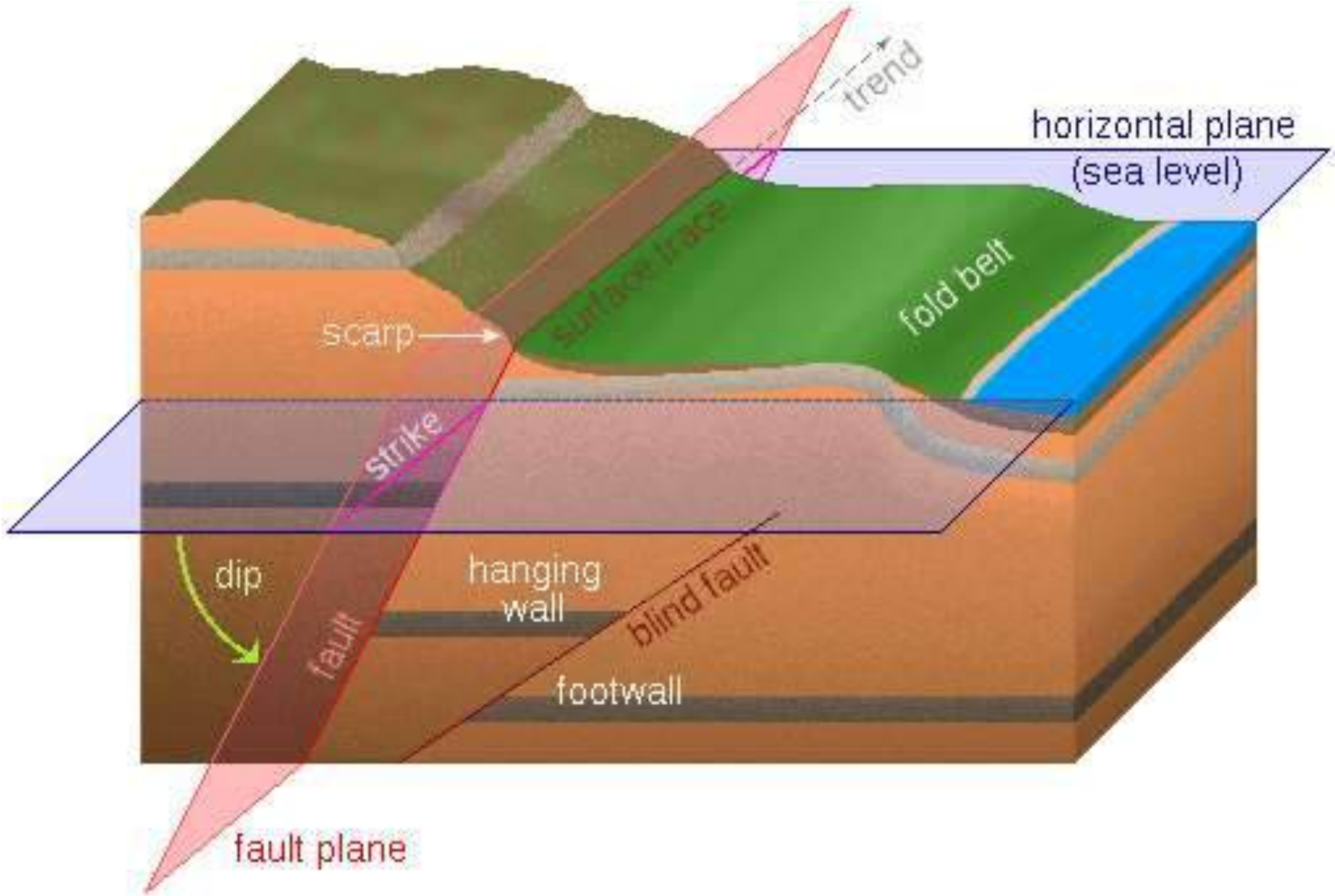
Strain (deformation) accumulates in the vicinity of friction-locked faults.

Strain accumulation reaches a threshold and fault slips suddenly

Rupture (slip) continues over some portion of the fault. Slip is the distance of displacement along a fault.

Fault

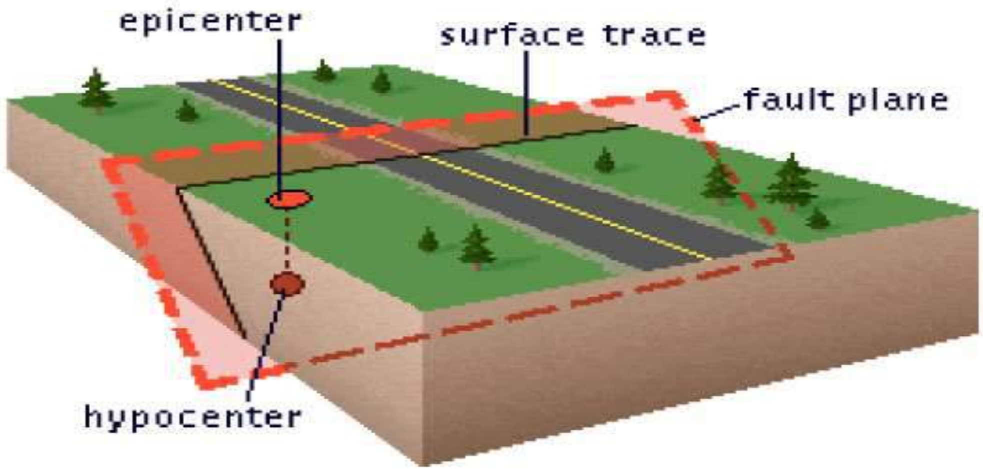
A fracture (crack) in the earth, where the two sides move past each other and the relative motion is parallel to the fracture.

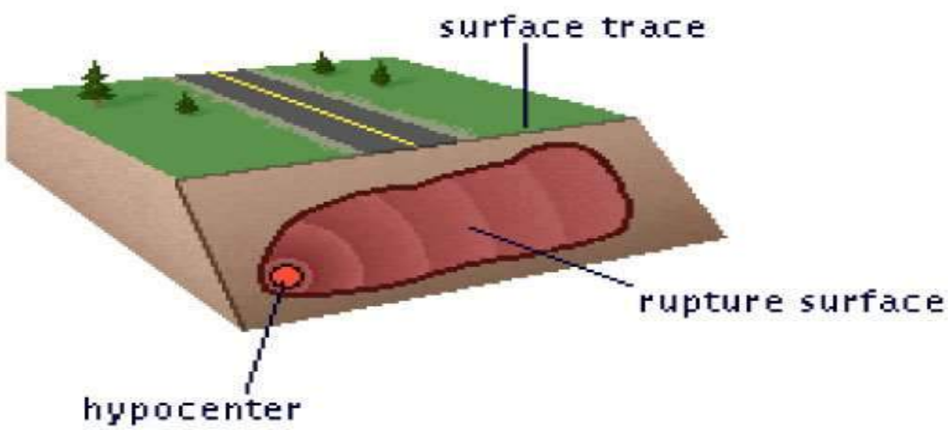


90˚ dip = vertical fault plane

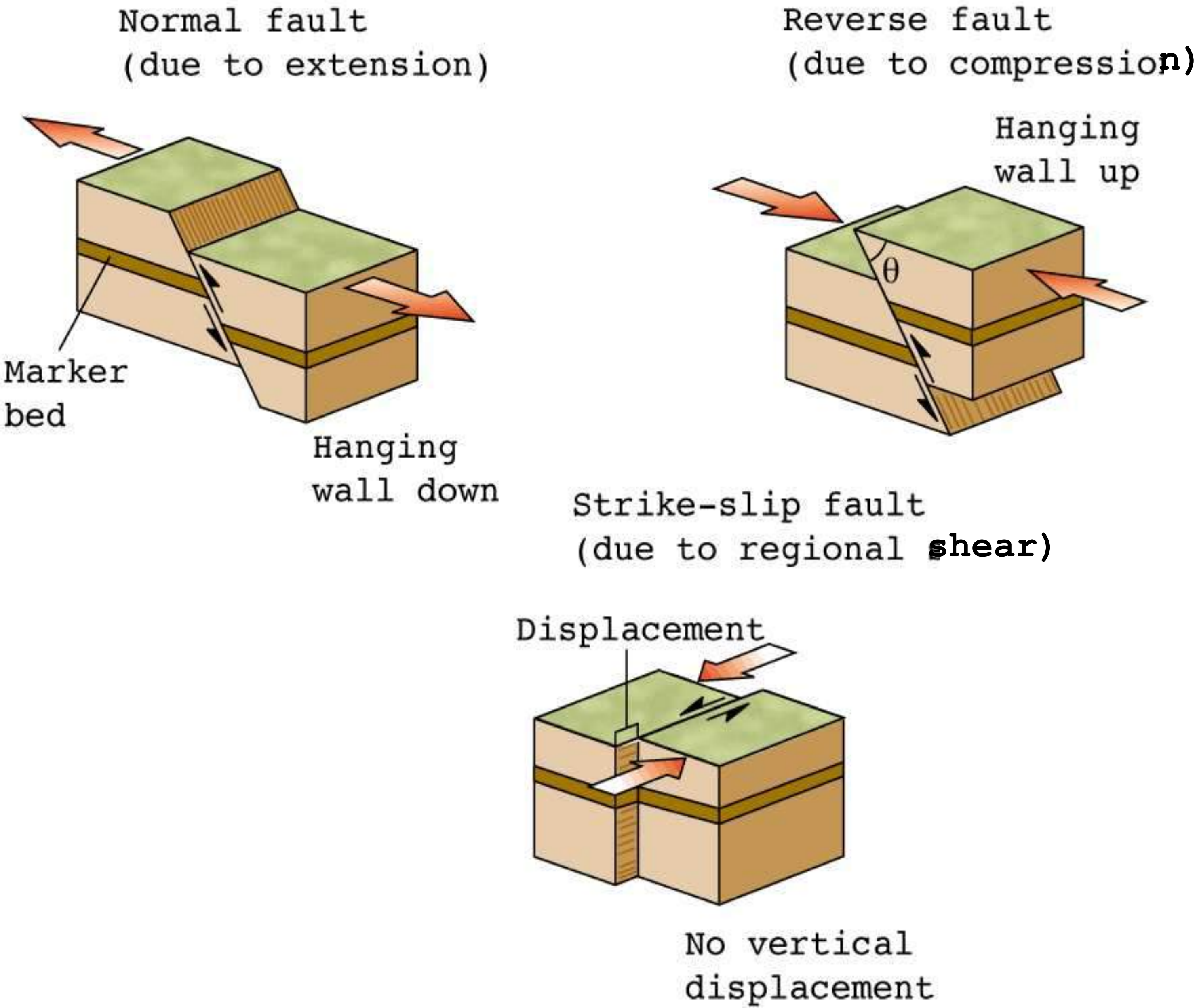
0˚ strike = north parallel fault plane

Surface Trace of a fault

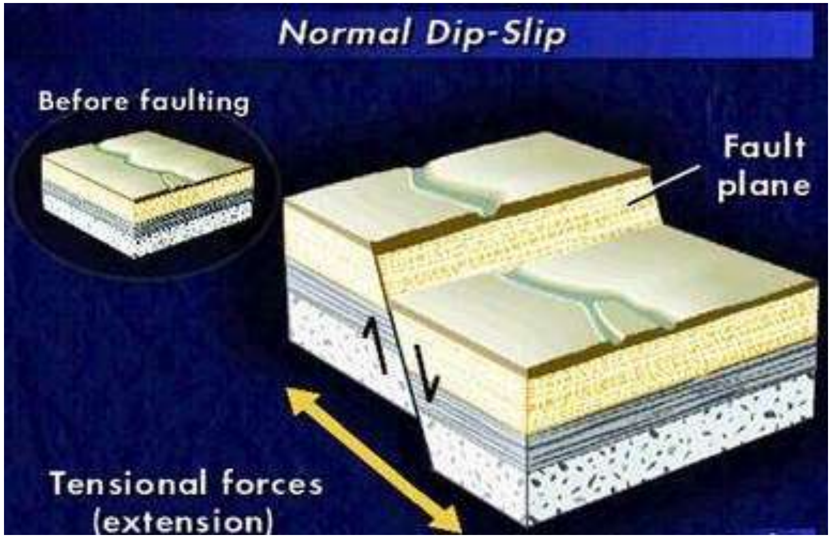




Different Fault Types

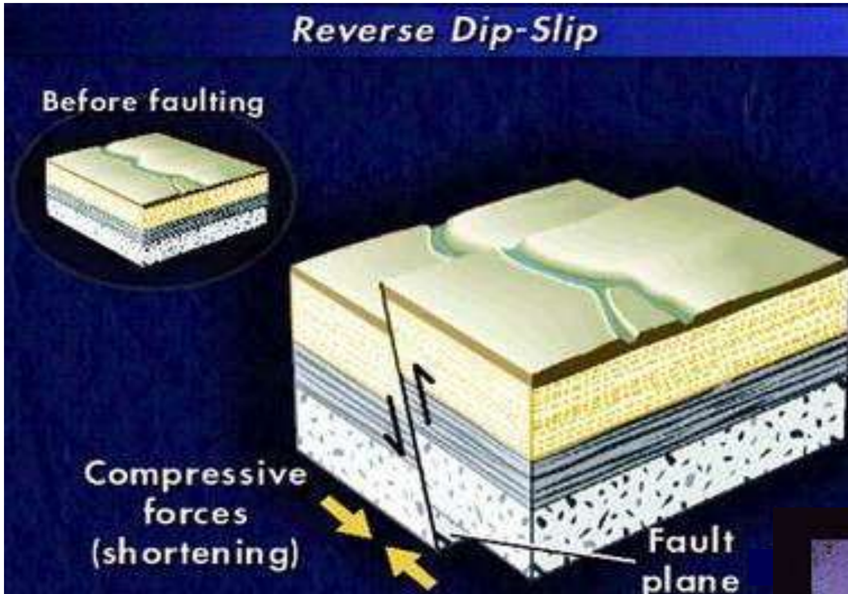


Normal Dip-slip fault

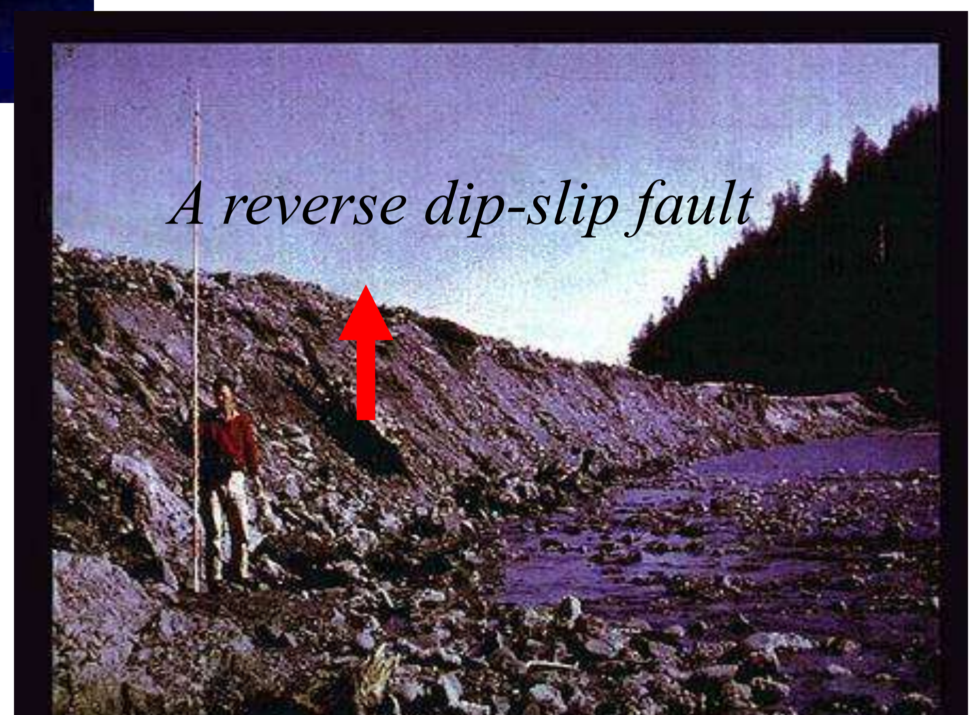


hanging wall moves down

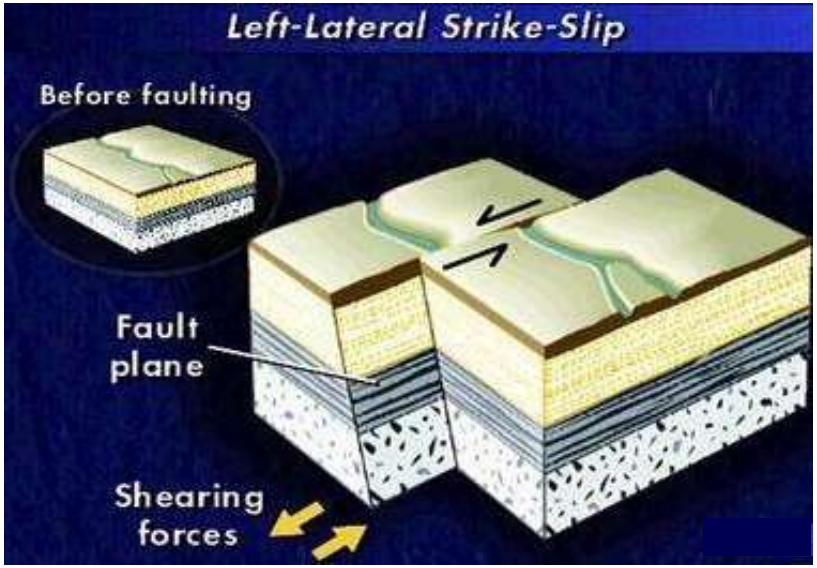
Reverse Dip-slip fault



Hanging wall moves up
This is also called a **Thrust Fault**.

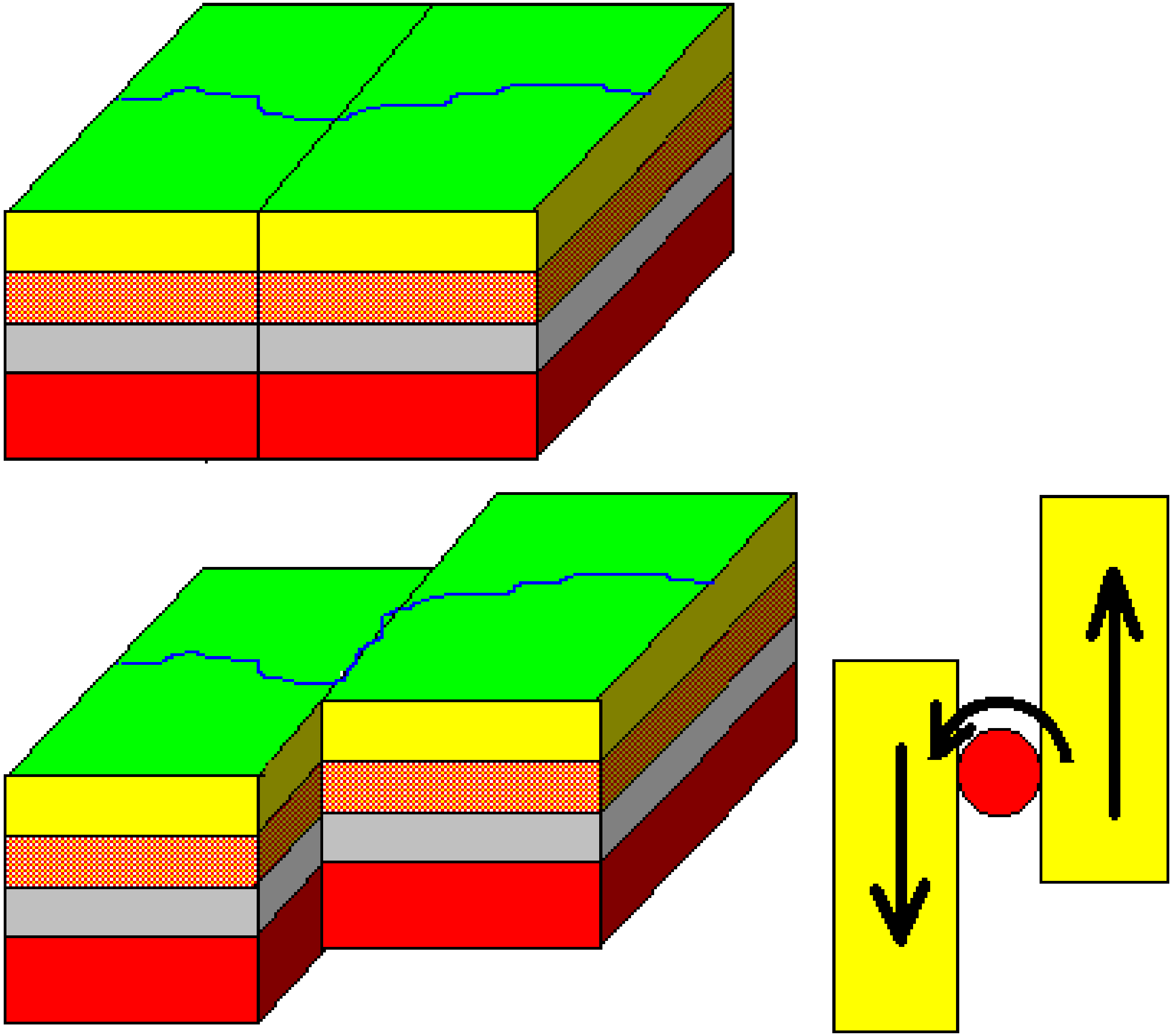


Strike-slip fault

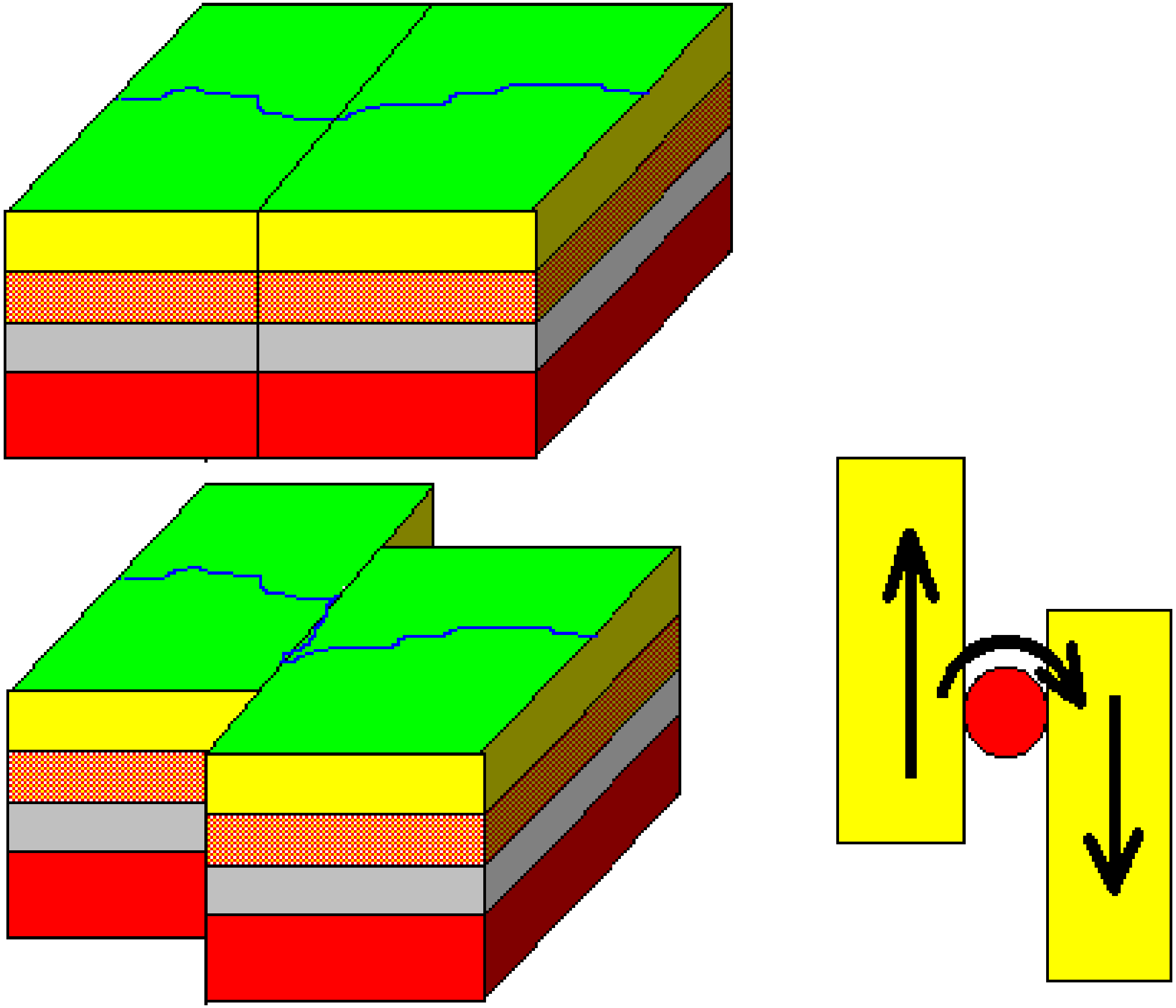


Displacement in horizontal direction

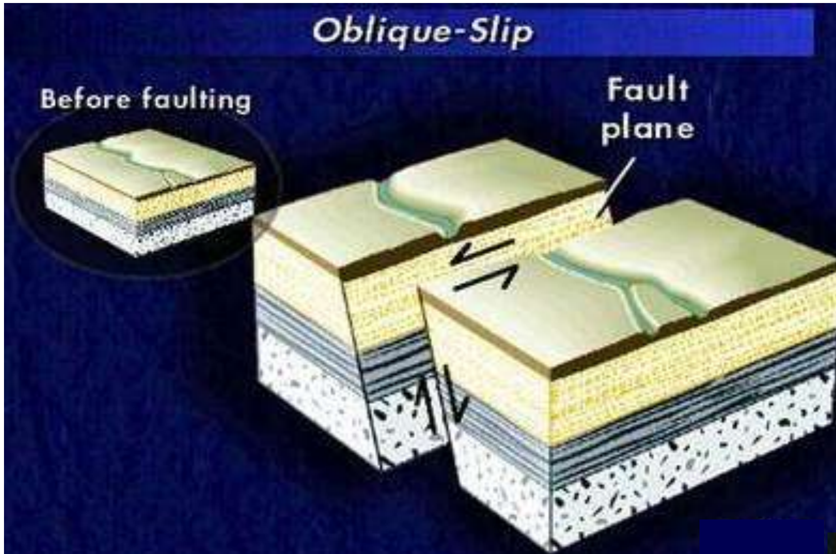
Strike-Slip Fault – Left Lateral



Strike-Slip Fault – Right Lateral

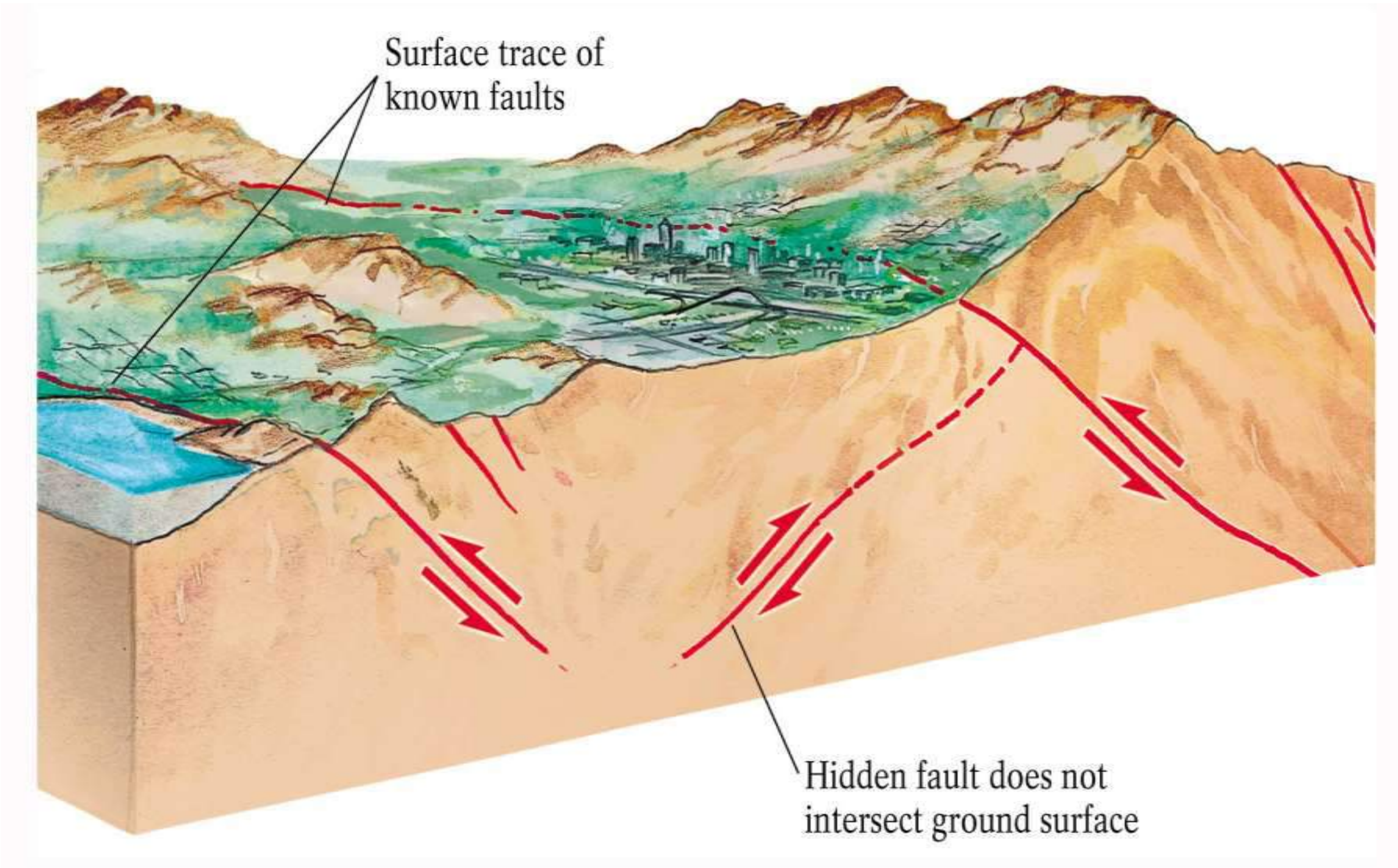


Oblique-slip fault



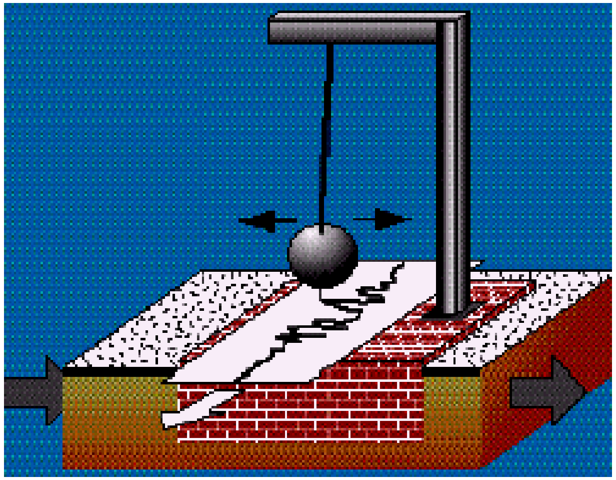
Displacement in both vertical and horizontal directions

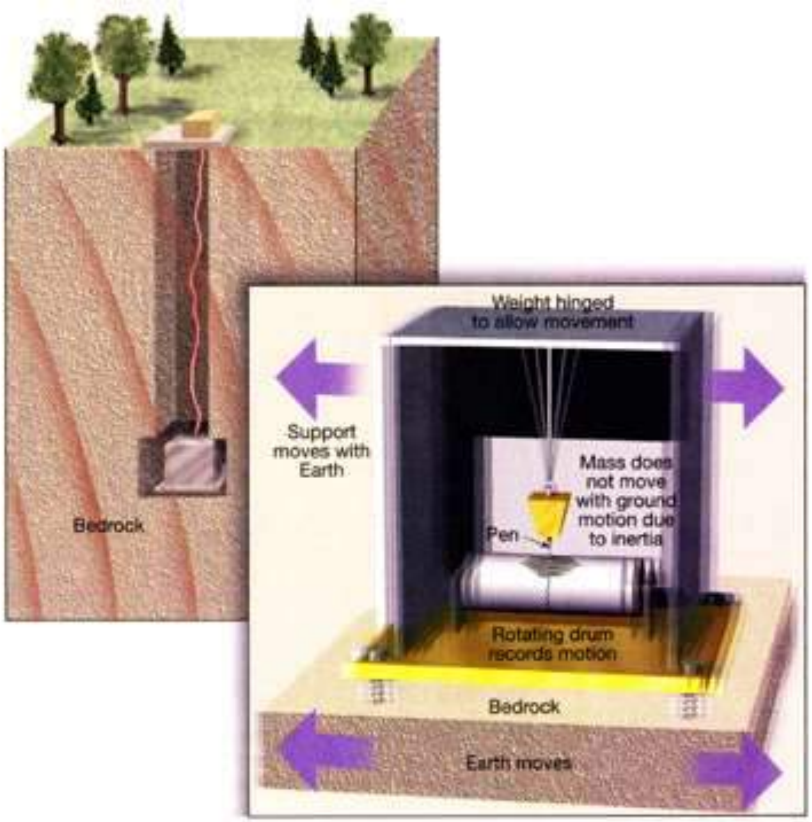
Blind/Hidden faults



seismograms

The study of earthquake waves, Seismology, dates back almost 2000 years to the Chinese Seismographs, instruments that record seismic waves. The first seismograph called Di-Dong-Di was invented by Cheng Heng (132 A.D.).



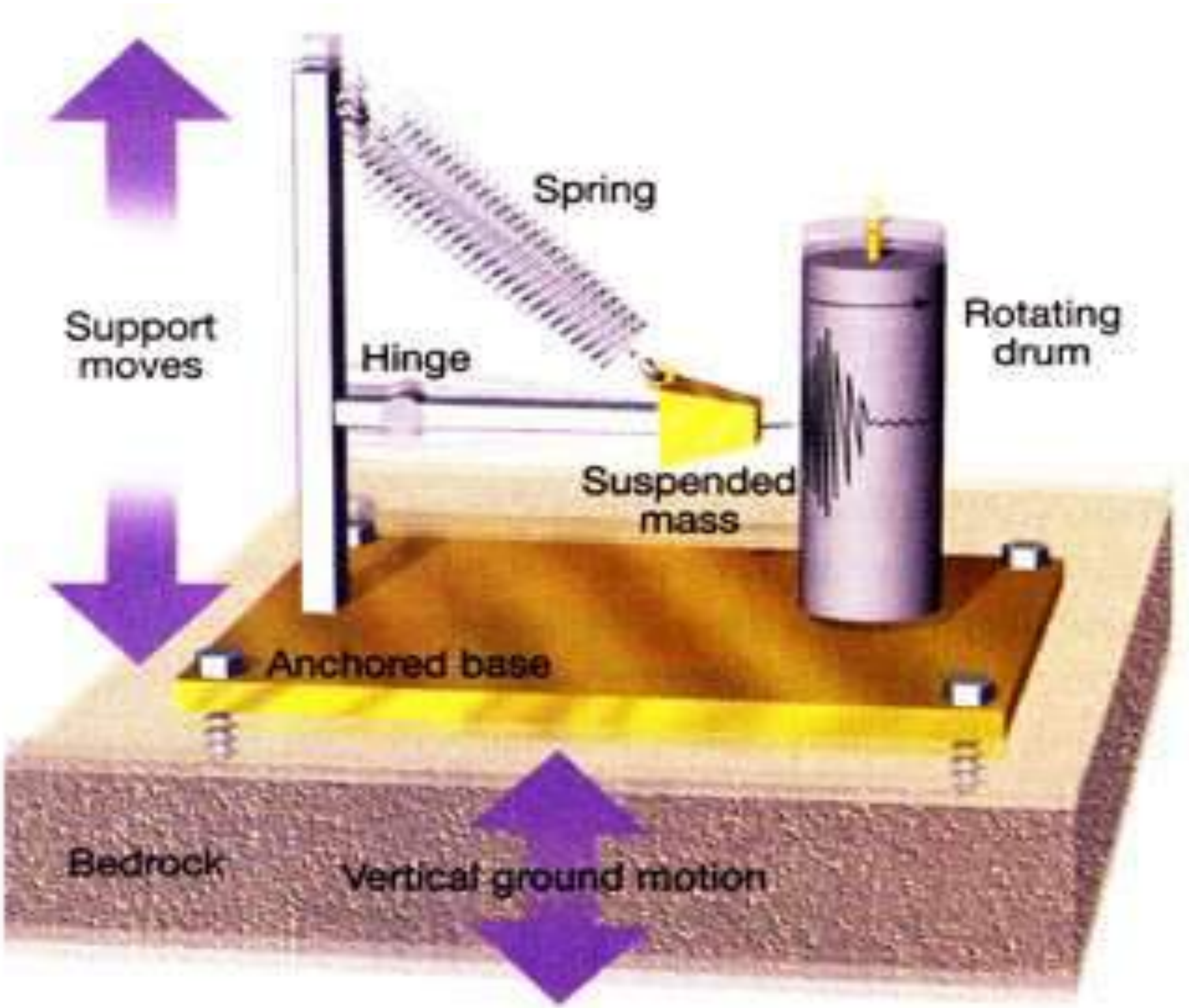


Modern Seismograph (Horizontal)

Spring mounted: seismograph records vertical motion.

Pendulum-mounted: records horizontal motion.

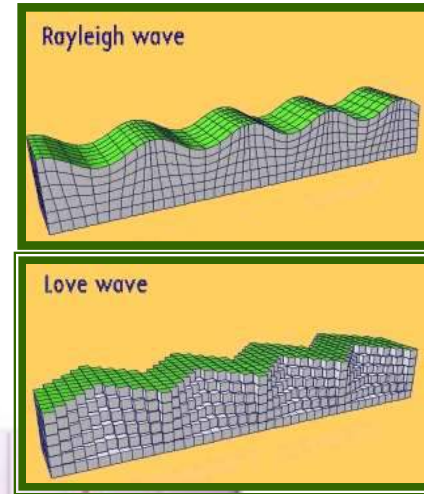
Modern Seismograph (Vertical)

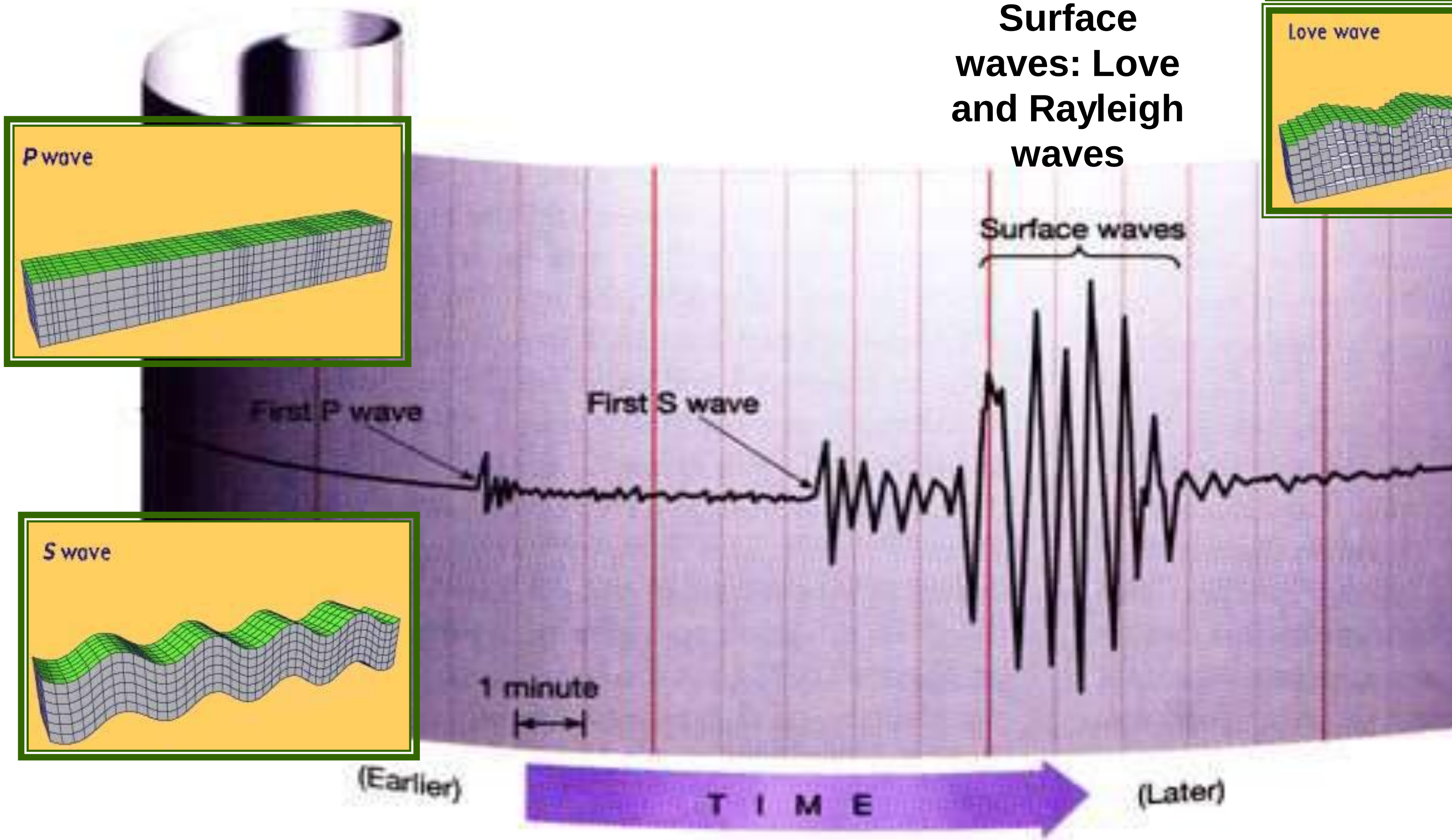


Seismogram

Body waves: P and S waves

Surface waves: Love and Rayleigh waves





Magnitude:

Earthquake magnitude is measured in Richter scale magnitude, named after geophysicist Charles F. Richter of CIT, California, who developed in 1935.

Magnitude = $Log_{10}(A_{max})$; Amax = max. amplitude in microns(10^{-3}m) recorded by a seismograph

The magnitude number is assigned to an earthquake on the basis of amount of ground displacement or amount of strain energy released at the source, which is measured by a seismograph.

It is a mathematical device to measure the size of earthquakes.i.e the logarithm of the amplitude of waves recorded on a seismogram at a certain period.

The Richter Scale is not used to express damage.

Seismic Intensity

Richer Scale

Intensity:

- It is a measure of the shaking and damage caused by the earthquake, and this value changes from location to location.
- Adjustments are included for the variation in the distance between the various seismographs and the epicenter of the earthquakes.

- On the Richter Scale, magnitude is expressed in whole numbers and decimal fractions.
- For example, a magnitude 5.3 might be computed for a moderate earthquake, and a strong earthquake might be rated as magnitude 6.3.
- Because of the logarithmic basis of the scale, each whole number increase in magnitude represents a tenfold increase in measured amplitude; as an estimate of energy, each whole number step in the magnitude scale corresponds to the release of about 31 times more energy than the amount associated with the preceding whole number value.
- Recently, another scale called the moment magnitude scale has been devised for more precise study of great earthquakes.
- Great earthquakes, such as the 1964 Good Friday earthquake in Alaska, have magnitudes of 8.0 or higher.
- Sensitive seismographs, which greatly magnify these ground motions, can detect strong earthquakes from sources anywhere in the world

Magnitude and Intensity

Intensity

How Strong Earthquake Feels to Observer

- Qualitative assessment of the kinds of damage done by an earthquake
- Depends on distance to earthquake & strength of earthquake
- Determined from the intensity of shaking and damage from the earthquake

Magnitude

Related to Energy Release.

- Quantitative measurement of the amount of energy released by an earthquake
- Depends on the size of the fault that breaks
- Determined from Seismic Records

Measuring Earthquakes

Seismogram is visual record of arrival time and magnitude of shaking associated with seismic wave. Analysis of seismogram allows measurement of size of earthquake.

Mercalli Intensity scale

- Measured by the amount of damage caused in human terms- I (low) to XII (high); drawback: inefficient in uninhabited area

Richter Scale- (logarithmic scale)

- Magnitude- based on amplitude of the waves
- Related to earthquake total energy

Intensity

How Strong Earthquake Feels to Observer

Depends On:

Distance to Quake

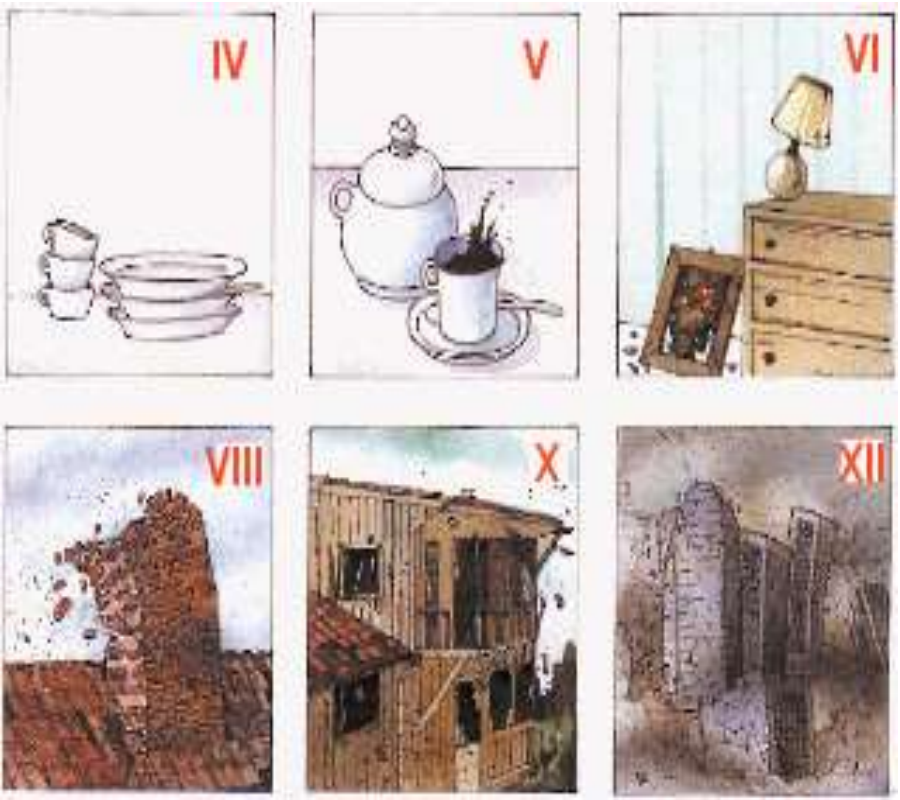
Geology

Type of Building

Observer!

Varies from Place to Place

Modified Mercalli Scale- 1 to 12



Modified Mercalli Scale		Richter Magnitude Scale
I	Detected only by sensitive instruments	1.5
II	Felt by few persons at rest, especially on upper floors; delicately suspended objects may swing	2
III	Felt noticeably indoors, but not always recognized as earthquake; standing autos rock slightly, vibration like passing truck	2.5
IV	Felt indoors by many, outdoors by few, at night some may awaken; dishes, windows, doors disturbed; motor cars rock noticeably	3
V	Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects	3.5, 4
VI	Felt by all, many frightened and run outdoors; falling plaster and chimneys, damage small	4.5
VII	Everybody runs outdoors; damage to buildings varies depending on quality of construction; noticed by drivers of automobiles	5
VIII	Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected; drivers of autos disturbed	5.5
IX	Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken	6, 6.5
X	Most masonry and frame structures destroyed; ground cracked, rails bent, landslides	7
XI	Few structures remain standing; bridges destroyed, fissures in ground, pipes broken, landslides, rails bent	7.5
XII	Damage total; waves seen on ground surface, lines of sight and level distorted, objects thrown up into air	8

Earthquake Magnitude

- M_L - Local (Richter) magnitude
- M_W - Seismic Moment magnitude
- M_S - Surface wave magnitude
- $M_{\mathbf{B}}$- Body wave magnitude

Richter Scale

Richter Scale

- Amplitude scale is logarithmic (10-fold increase for every whole number increase)
- Scale 1 ---- 0.001 mm; 2---- 0.01 mm; 5---- 10mm; 7---- 1 meter
- Earthquake Energy: Each whole number represents a 33-fold increase in Energy; Energy difference between 3 & 6 means ~1000 times
- Drawbacks:
  - Based on Antiquated Wood-Anderson Seismographs
  - Measurment Past Magnitude 7.0 ineffective – Requires Estimates

Local Magnitude of Earthquake

Magnitude

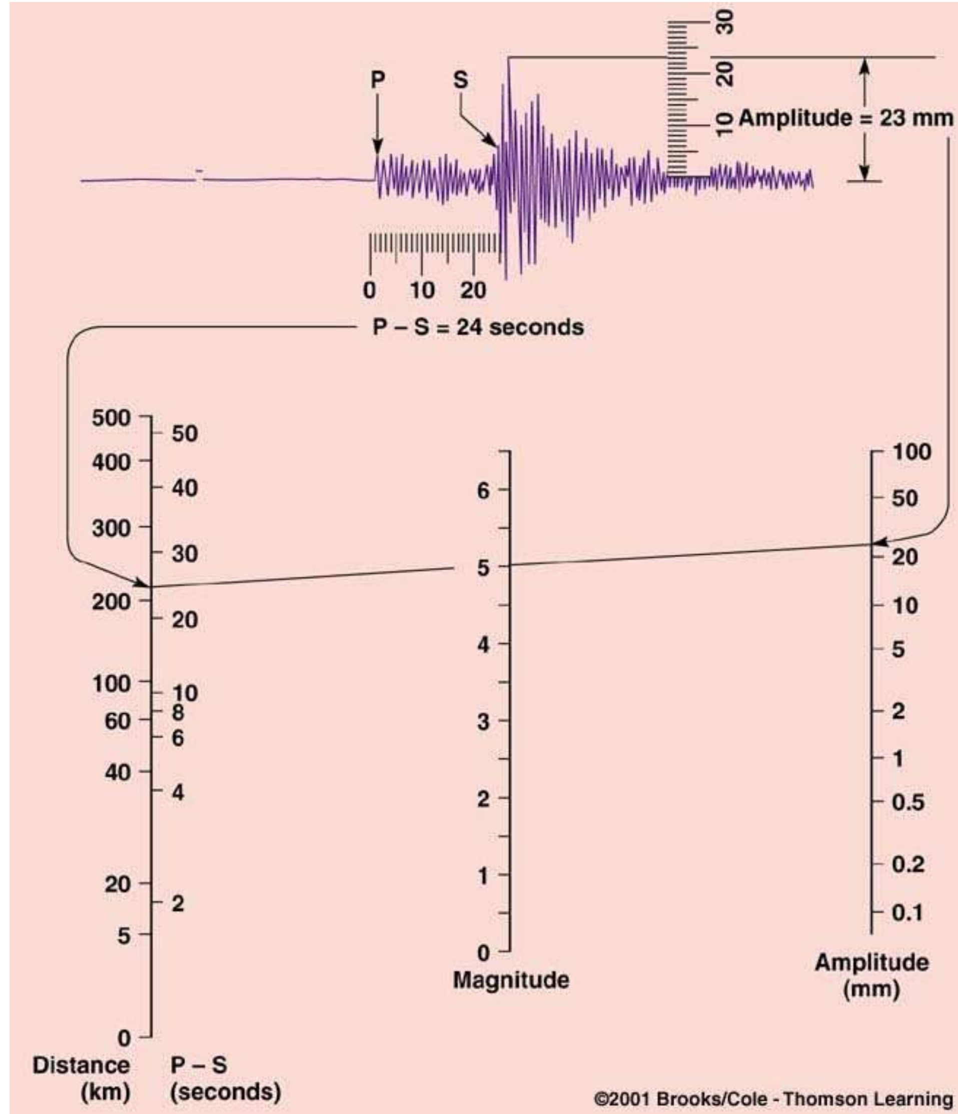
- Richter scale measures the magnitude of an earthquake, based on seismogram independent of intensity
- Amplitude of the largest wave produced by an event is corrected for distance and assigned a value on an open-ended logarithmic scale
- The equation for Richter Magnitude is:

$$\boldsymbol{M_L = \log_{10} A(mm) + (Distance\ correction\ factor)}$$

Here A is the amplitude, in millimeters, measured directly from the photographic paper record of the Wood-Anderson seismometer, a special type of instrument. The *distance factor* comes from a table given by Richter (1958).

Richter’s Local Magnitude

Right side diagram (nomogram) demonstrates how to use Richter's original method to measure a seismogram for a magnitude estimate After you measure the wave amplitude you have to take its logarithm and scale it according to the distance of the seismometer from the earthquake, estimated by the S-P time difference. The S-P time, in seconds, makes Δt. The equation behind this nomogram, used by Richter in Southern California, is:



$$M_L = \log_{10}A(mm) + 3\log_{10}[8\,\Delta t\,(\mathrm{sec})] - 2.93$$

Richter Scale: Related to intensity

- M=1 to 3: Recorded on local seismographs, but generally not felt
- M= 3 to 4: Often felt, no damage
- M=5: Felt widely, slight damage near epicenter
- M=6: Damage to poorly constructed buildings and other structures within 10's km
- M=7: "Major" earthquake, causes serious damage up to ~100 km (recent Gujarat earthquake).
- M=8: "Great" earthquake, great destruction, loss of life over several 100 km
- M=9: Rare great earthquake, major damage over a large region over 1000 km

Surface Wave Magnitude

Richter's local magnitude does not distinguish between different types of waves.

At large distances from epicenter, ground motion is dominated by surface waves.

Gutenberg and Richter (1936) developed a magnitude scale based on the amplitude of Rayleigh waves.

Surface wave magnitude $\mathbf{M_s = \log_{10}A + 1.66\,\log_{10}\Delta + 2}$

A = Maximum ground displacement in micrometers

Δ= Distance of seismograph from the epicenter, in degrees.

Surface wave magnitude is used for shallow earthquakes

Body Wave Magnitude

For deep focus earthquakes, reliable measurement of amplitude of surface waves is difficult.

Amplitudes of P-waves are not strongly affected by focal depth. Gutenberg (1945) developed a magnitude scale based on the amplitude of the first few cycles of P- waves, which is useful for measuring the size of deep earthquakes.

Body wave magnitude $\mathbf{M_b = \log_{10}A - \log_{10}T + 0.01\,\Delta + 5.9}$

A = Amplitude of P-waves in micrometers

Δ= Distance of seismograph from the epicenter, in degrees.

Seismic - Moment Magnitude

A Seismograph Measures Ground Motion at One Instant But --

A Really Great Earthquake Lasts Minutes

Releases Energy over Hundreds of Kilometers

Need to Sum Energy of Entire Record

Moment magnitude scale based on seismic moment (Kanamori, 1977) and doesn't depend upon ground shaking levels.

It's the only magnitude scale efficient for any size of earthquake.

Moment Magnitude

Moment-Magnitude Scale

– Seismic Moment = Strength of Rock x Fault Area x Total amount of Slip along Rupture

$$M_0 = \mu\ A\ D$$

Moment Magnitude $M_w = 2/3 \times [\log_{10} M_0(\text{dyne-cm}) - 16]$

– Measurement Analysis requires Time

Seismic Energy

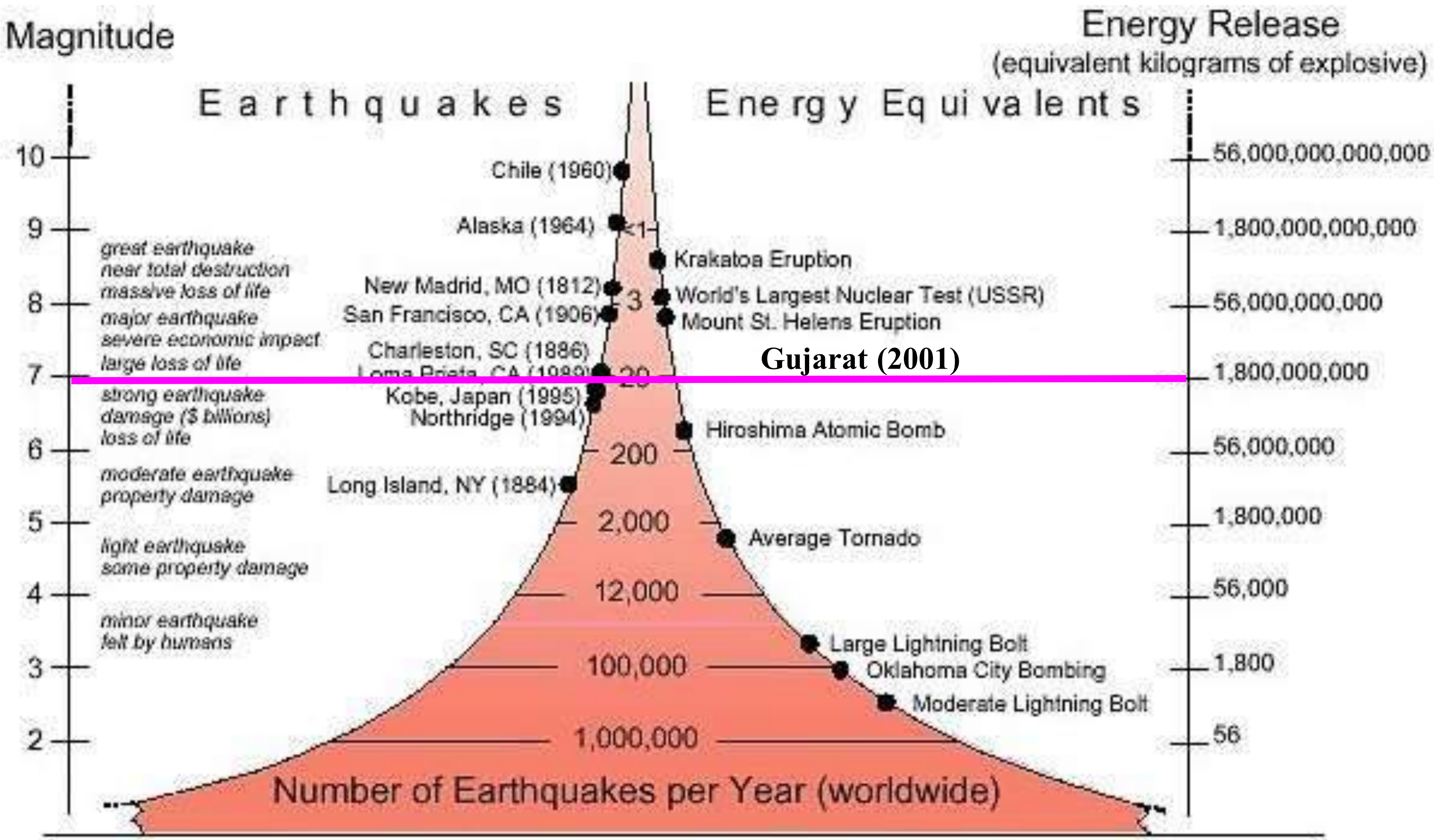
Both the magnitude and the seismic moment are related to the amount of energy that is radiated by an earthquake. **Dr.** Gutenberg and Richter 1956), developed a relationship between magnitude and energy. Their relationship is:

$$\log E_S = 11.8 + 1.5M_s$$

Energy E_S in **erg**s from the surface wave magnitude M_s. E_S is not the total ``intrinsic" energy of the earthquake, transferred from sources such as gravitational energy or to sinks such as heat energy. It is only the amount radiated from the earthquake as seismic waves, which ought to be a small fraction of the total energy transfered during the earthquake process.

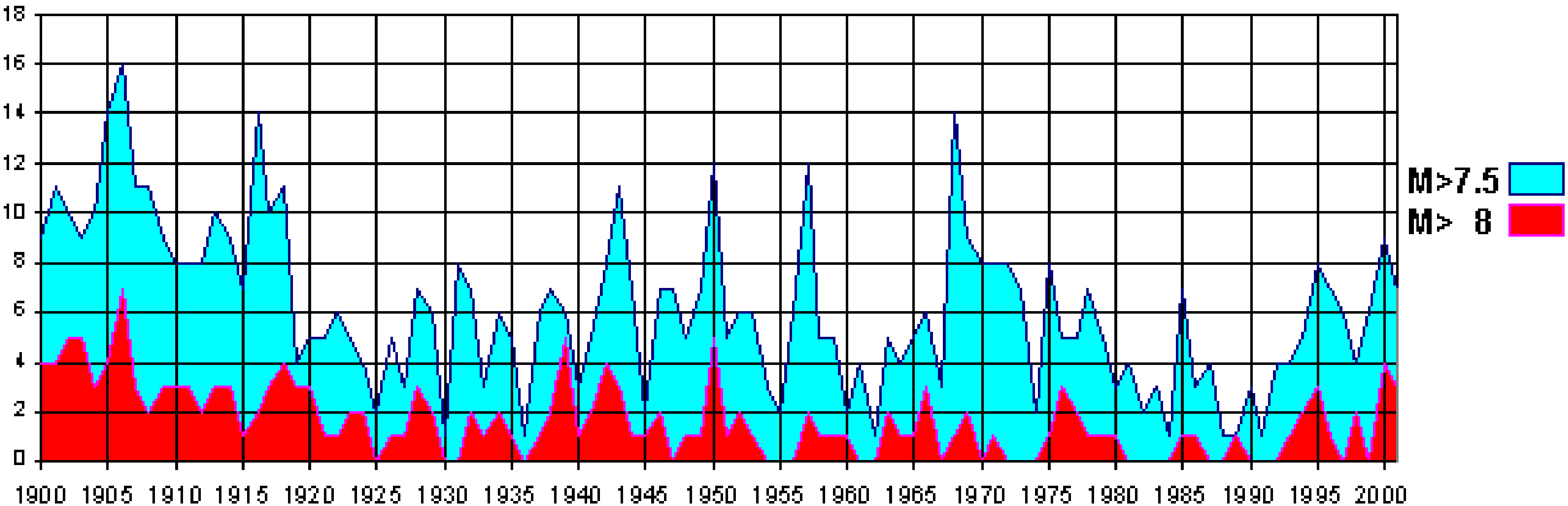
This figure was produced in cooperation with the US Geological Survey, and the University of Memphis private foundations

Local Magnitude - Seismic Energy correlation



Size of an earthquake using the Richter's Local Magnitude Scale is shown on the left hand side of the figure above. The larger the number, the bigger the earthquake. The scale on the right hand side of the figure represents the amount of high explosive required to produce the energy released by the earthquake.

Frequency of earthquakes



Strong Ground Motion

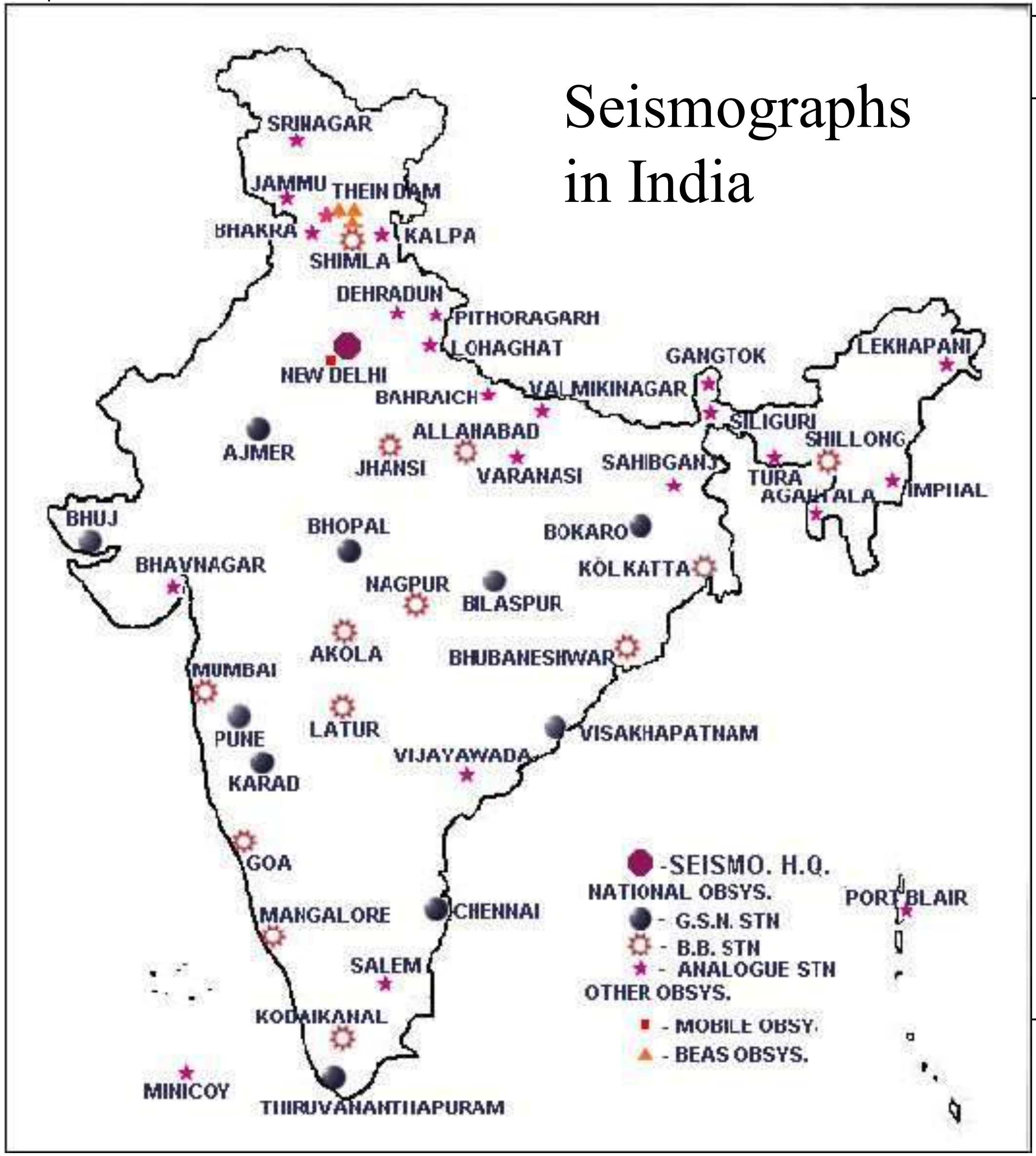
Evaluation of the effects of earthquakes requires the study of ground motion

Engineering Seismology deals with vibrations related to earthquakes, which are strong enough to cause damage to people and environment

The ground motions produced by earthquakes at any particular point have 3 translational and 3 rotational components.

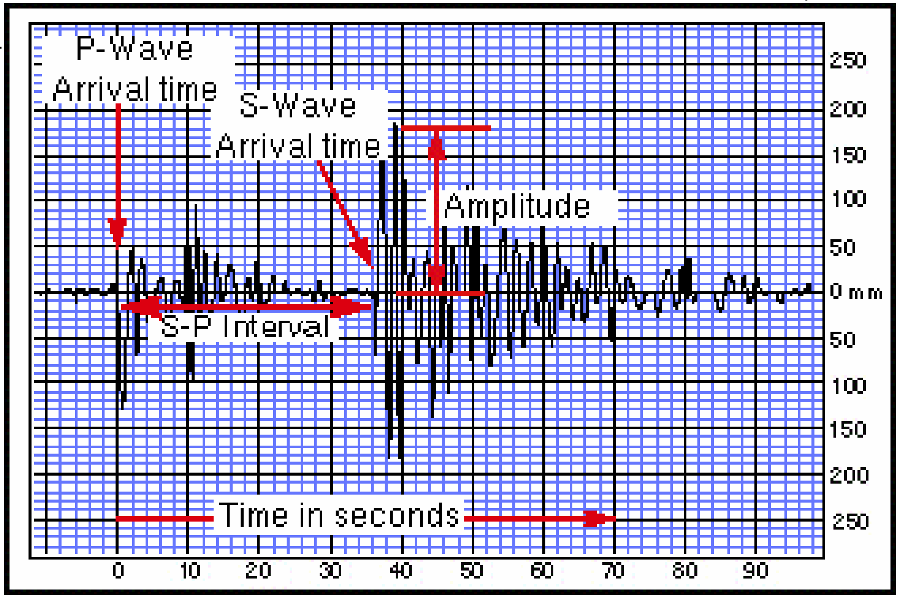
In practice, generally translational components of ground motion are measured and the rotational components are ignored.

Strong motion seismographs



- Designed to pickup strong, high-amplitude shaking close to quake source
- Most common type is the accelerometer
- Directly records ground acceleration
- Recording is triggered by first waves
- Difficult to differentiate P,S and surface waves

Seismogram interpretation



Seismograms can provide information on
- epicenter location
- Magnitude of earthquake
- source properties

Most seismograms will record P, S & surface waves

First arrival is P wave

After a pause of several seconds/10s seconds the higher amplitude S wave arrives

Defines S-P interval

- surface waves follow and may continue for tens of seconds
- surface waves are slower but persist to greater distances than P & S waves

Wave terminology

Wave amplitude

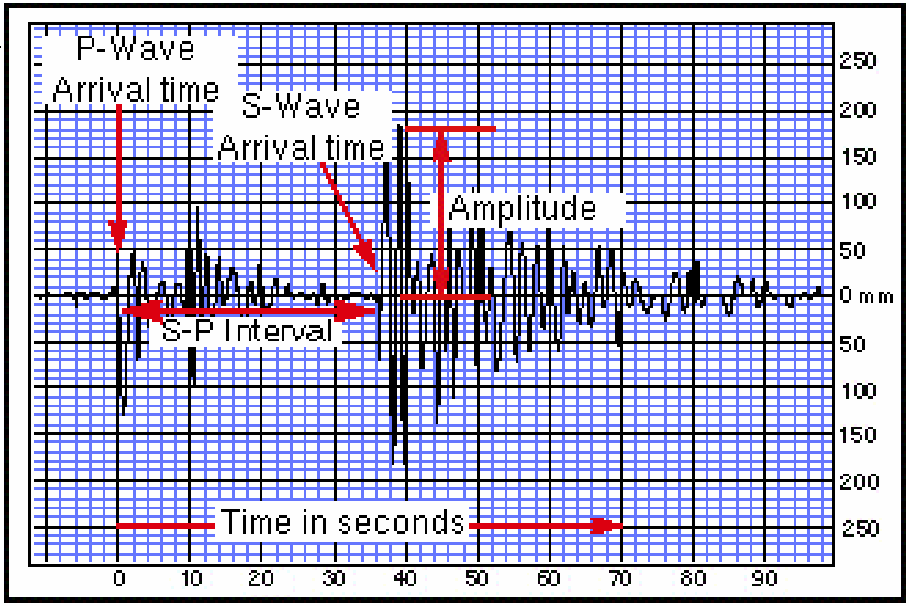
- **height of a wave above its zero position**

Wave period

- **time taken to complete one cycle of motion**

Frequency

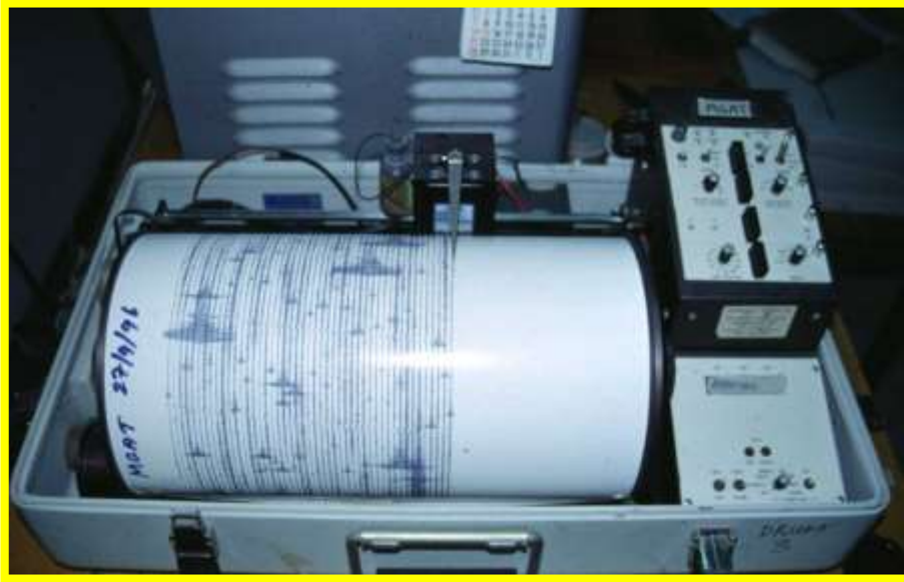
- **number of cycles per second (Hertz)**
- **felt shaking during quake has frequencies from 20 down to 1 Hertz**



Human ear can detect frequencies down to 15 Hz

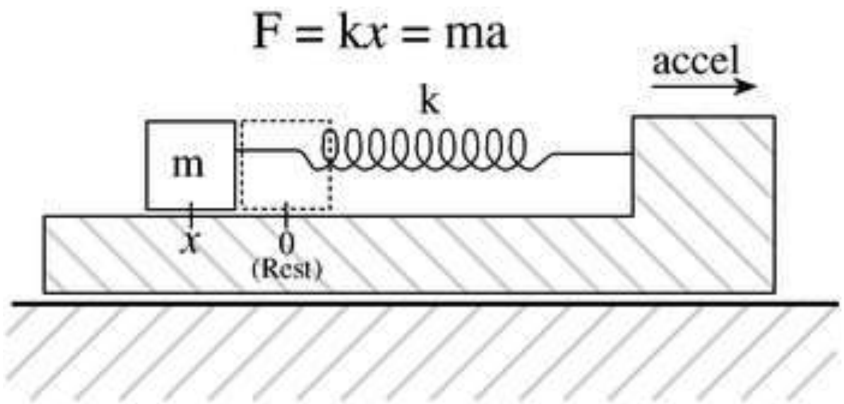
Ground Motion Recording

The actual ground motion at a given location is derived from instrumentally recorded motions. The most commonly used instruments for engineering purposes are strong motion accelerographs/ accelerometers. These instruments record the acceleration time history of ground motion at a site, called an accelerogram.



By proper analysis of a recorded accelerogram to account for instrument distortion and base line correction, the resulting corrected acceleration record can be used by engineers to obtain ground velocity and ground displacement by appropriate integration.

Accelerometer



Types of Accelerometers:

Electronic : transducers produce voltage output

Servo controlled: use suspended mass with displacement transducer

Piezoelectric: Mass attached to a piezoelectric material, which develops electric charge on surface.

Principle: An acceleration *a* will cause the mass to be displaced by ma/k or alternatively, if we observe a displacement of *x*, we know that the mass has undergone an acceleration of kx/m.

Generally accelerometers are placed in three orthogonal directions to measure accelerations in three directions at any time. Sometimes ***geophones*** (velocity transducers) are attached to accelerometers to measure the seismic wave velocities.

Ground Motion Parameters

An earthquake history can be described using ***amplitude***, ***frequency content***, and ***duration***.

Amplitude: The most common measures of amplitude are

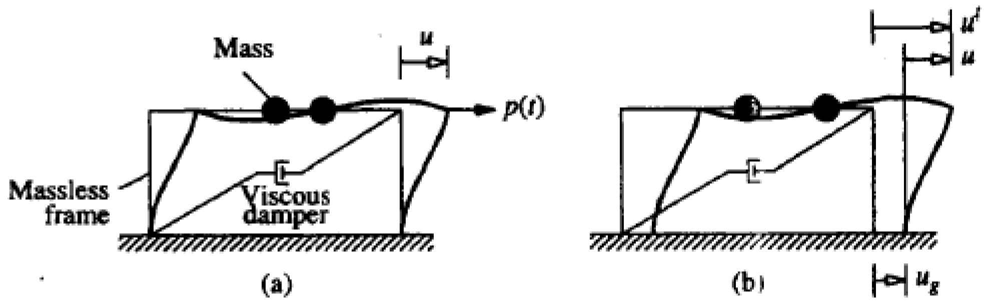
PGA: Peak ground acceleration (Horizontal- PHA & Vertical- PVA)
EPA: Effective peak acceleration
PGV: Peak ground velocity (PHV & PVV)
EPV: Effective peak velocity
PGD: Peak ground displacement

Frequency Content: The frequency content of an earthquake history is often described using Fourier Spectra, Power spectra and response spectra.

Duration: The duration of an earthquake history is somewhat dependent on the magnitude of the earthquake.

Measurement of ground acceleration

A seismograph can be illustrated by a mass-spring-dashpot single degree of freedom system.



The response of such system for shaking is given by

Where *u* is the trace displacement (relative displacement between seismograph and ground), u_g is the ground displacement, c is the damping coefficient, k is the stiffness coefficient.

Measurement of ground acceleration

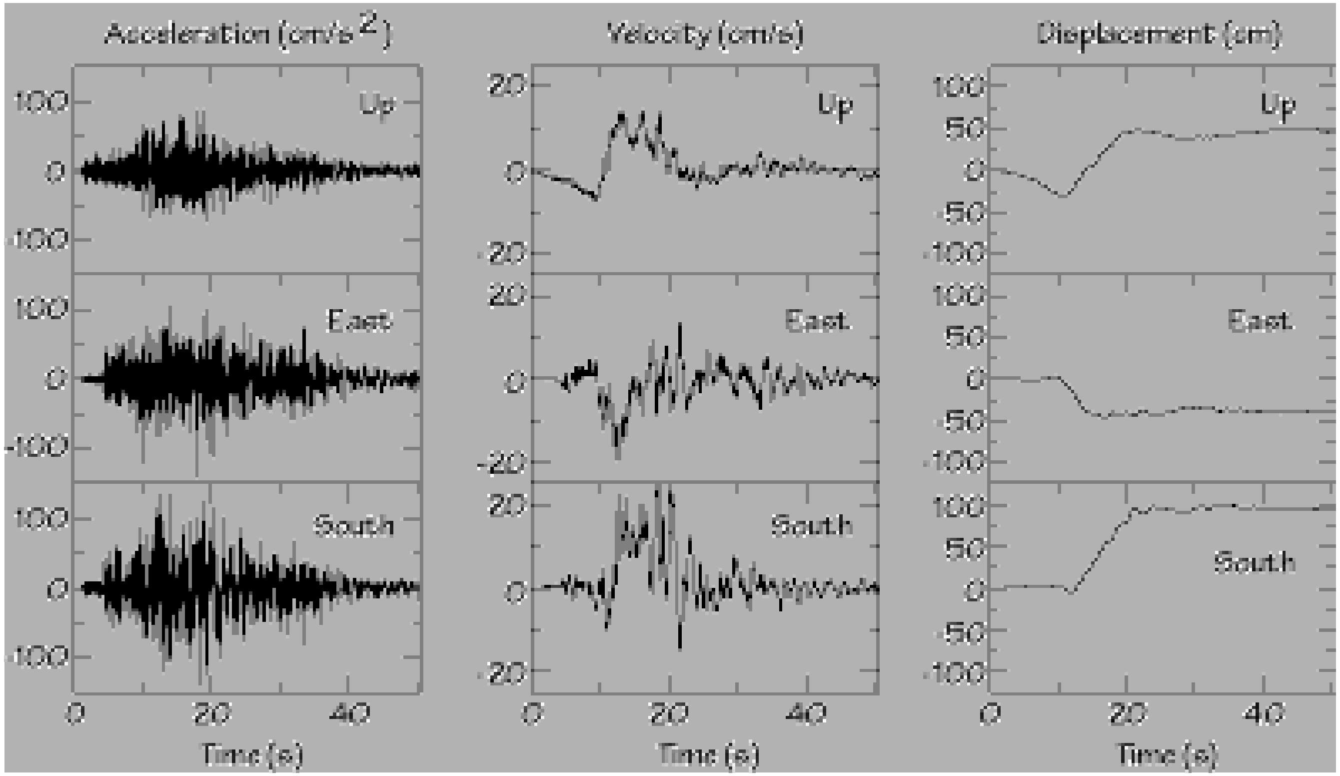
If the ground displacement is simple harmonic at a circular frequency ω_g , the ground acceleration amplitude is calculated from the trace displacement amplitude using the equation:

Where ω_0 is the undamped natural circular frequency

β is tuning ratio, given by ω_g / ω_0

ξ Is damping ratio, given by

Amplitude Parameters



From the time histories of acceleration, velocity and displacement are obtained by integrating the acceleration records. All other amplitude parameters are calculated from these time histories.

Amplitude Parameters

Effective Acceleration: The acceleration which is effective in causing structural damage. This depends on size of loaded area, weight, damping and stiffness properties of structure and its location with respect to epicenter.

Sustained Maximum Acceleration: The absolute values of highest accelerations that sustained for 3 and 5 cycles in acceleration time history are defined as 3-cycle sustained and 5-cycle sustained accelerations respectively.

Frequency Content Parameters

The frequency content of an earthquake history is often described using Fourier Spectra, Power spectra and response spectra.

Fourier Spectra

A periodic function (for which an earthquake history is an approximation) can be written as

where c_n and ϕ_n are the *amplitude* and *phase angle* respectively of the n^{th} harmonic in the Fourier series.

Frequency Content Parameters

The *Fourier amplitude spectrum* is a plot of c_n versus ω_n

- Shows how the amplitude of the motion varies with frequency.
- Expresses the frequency content of a motion

The *Fourier phase spectrum* is a plot of ϕ_n versus ω_n

- Phase angles control the times at which the peaks of harmonic motion occur.
- Fourier phase spectrum is influenced by the variation of ground motion with time.

Fourier Amplitude Spectrum

The Fourier amplitude spectra of actual earthquakes are often plotted on logarithmic scales, so that their characteristic shapes can be clearly distinguished from the smoothed curves.

Two frequencies that mark the range of frequencies for largest Fourier acceleration amplitude are corner frequency (f_c) and cutoff frequency (f_{max})

Fourier Amplitude (log)

f_c f_{max}

Frequency (log)

f_c is a very important parameter because it is inversely proportional to the cube root of seismic moment, thus indicating that large earthquakes produce greater low-frequency motions.

Frequency Content Parameters

Power Spectra

The power spectrum is a plot of $G(\omega)$ versus ω_n. The power spectrum density (PSD) function is defined by the following equation and is closely related to the Fourier amplitude spectrum:

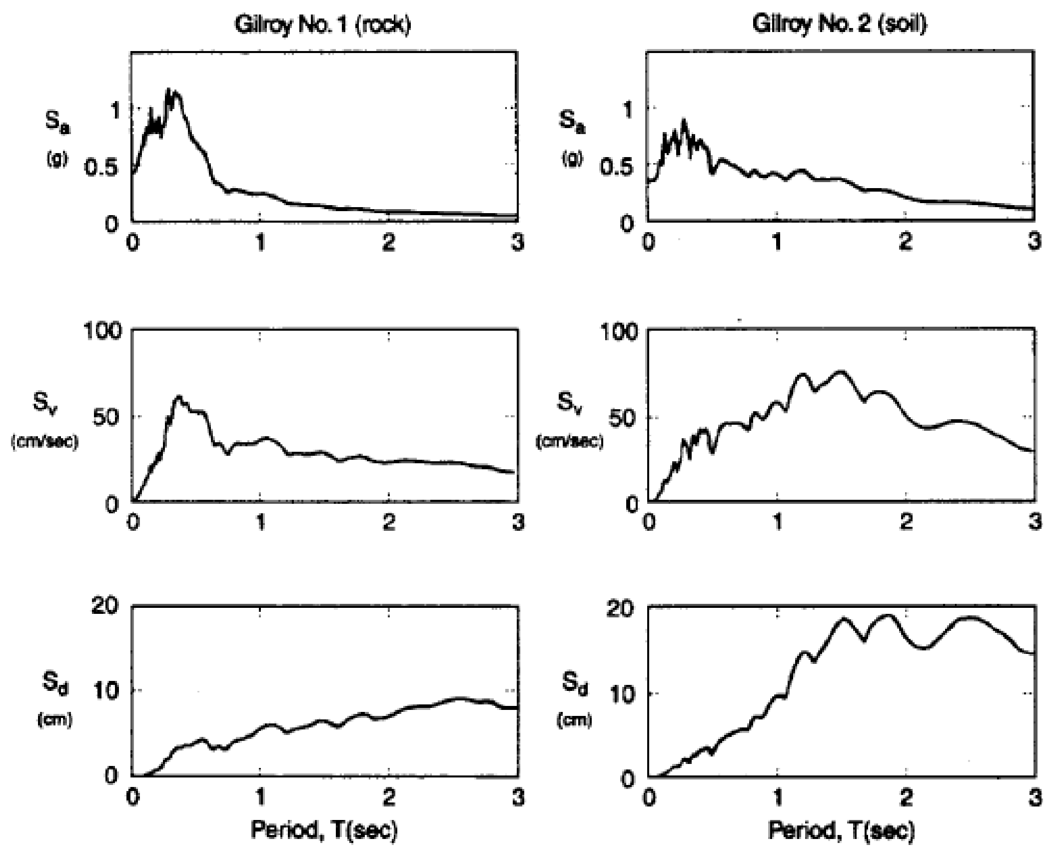
where G(ω) is the PSD, T_d is the duration of the ground motion, and c_n is the *amplitude* of the n^{th} harmonic in the Fourier series. PSD function is used to characterize an earthquake history as a random process.

Frequency Content Parameters

Response Spectra

The response spectrum describes the maximum response of a SDOF oscillator to a particular input motion as a function of frequency and damping ratio.

The response spectra from two sites (one rock and the other soil) are shown in figure.



Duration

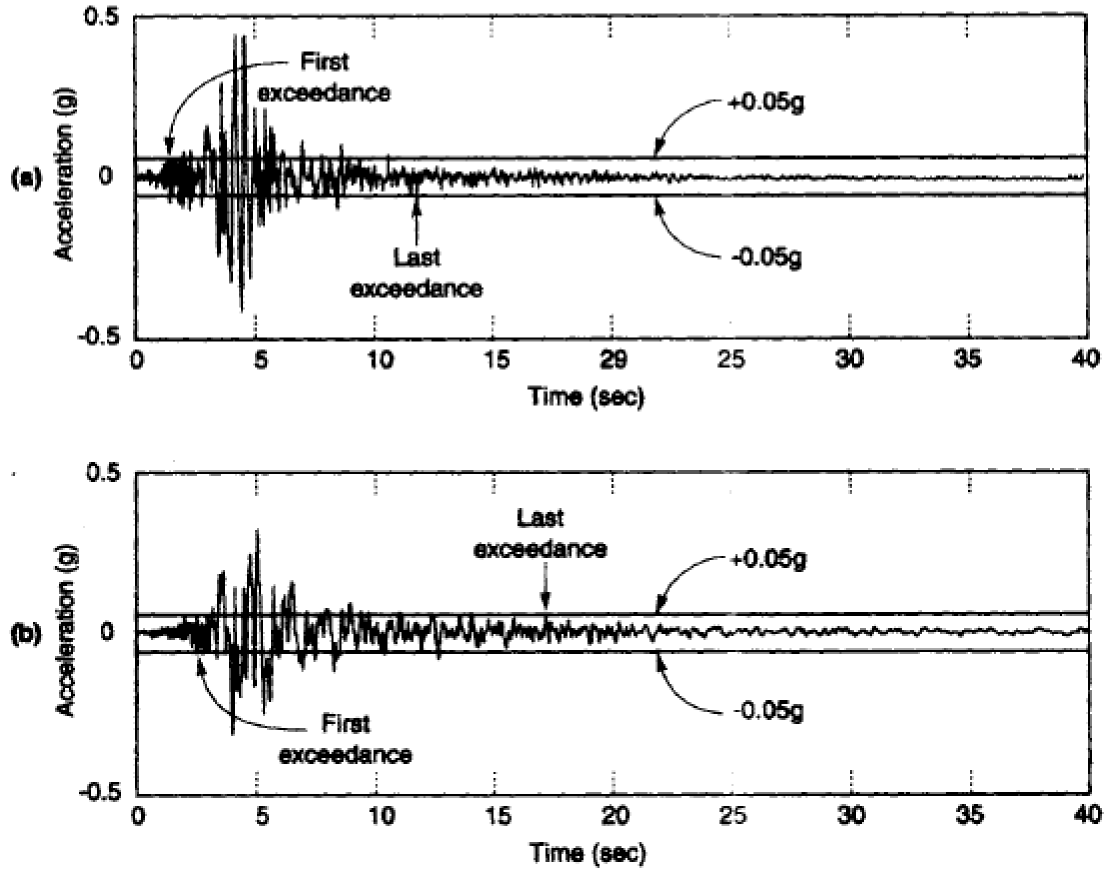
Duration of an earthquake is very important parameter that influences the amount of damage due to earthquake. A strong motion of very high amplitude of short duration may not cause as much damage to a structure as a motion with moderate amplitude with long duration can cause. This is because the ground motion with long duration causes more load reversals, which is important in the degradation of stiffness of the structures and in building up pore pressures in loose saturated soils.

Duration represents the time required for the release of accumulated strain energy along a fault, thus increases with increase in magnitude of earthquake.

Relative duration does not depend on the peak values. It is the time interval between the points at which 0.05% and 0.95% of the total energy has been recorded.

Duration

Bracketed duration is the measure of time between the first and last exceedence of a threshold acceleration 0.05 g.



Other Spectral Parameters

SI** - **The Spectrum Intensity is defined as the integral of the psuedo-Spectral velocity curve (also known as the velocity response spectrum), integrated between periods of 0.1 - 2.5 seconds. These quantities are motivated by the need to examine the response of structures to ground motion, as many structures have fundamental periods between 0.1 and 2.5 sec. The SI can be calculated for any structural damping ratio.

Dominant frequency of ground motion **(F_d)** is defined as the frequency corresponding to the peak value in the amplitude spectrum. Thus, **F_d** indicates the frequency for which the ground motion has the most energy. The amplitude spectrum has to be smoothed before determining **F_d**.

Other Spectral Parameters

***Predominant Period* (T$_p$)**: Period of vibration corresponding to the maximum value of the Fourier amplitude spectrum. This parameter represents the frequency content of the motion. The predominant period for two different ground motions with different frequency contents can be same, making the estimation of frequency content crude.

Fourier Amplitude

GM1

GM2

T_p

Period

***Bandwidth* BW** - of the dominant frequency; measured where the amplitude falls to 0.707 (1 /sq. root 2) of the amplitude of the dominant frequency. Again, this is based on a smoothed amplitude spectrum.

T_p is same for the two ground motions, though the frequency content is different

Spatial variability of ground motions

The ground motion parameters at any site depend upon the magnitude of earthquake and the distance of the site from epicenter.

The ground motion parameters measured at a site have been used to develop empirical relationships to predict the parameters as functions of earthquake magnitude and source-to-site distance. But these predictions are not accurate.

For structures that extend over considerable distance (such as bridges and pipelines), the ground motion parameters will be different at different part of the structure, causing differential movement of the supports. Local variation of ground motion parameters need to be considered for the design of such structures.

Earthquake Depth

Earthquakes usually occur at some depth below the ground

Surface. The depth can also be calculated from seismograph records

Earthquake foci are described as:

Shallow: less than 70 km depth

Intermediate: 70 - 300 km depth

Deep: 300 - 700 km depth

90% of earthquake foci are less than 100 km deep

Large earthquakes are mostly at < 60 km depth

No earthquakes occur deeper than 700 km

Predicting Earthquakes

Strange Animal Behavior

stress in the rocks causes tiny hairline fractures to form, the cracking of the rocks evidently emits high pitched sounds and minute vibrations imperceptible to humans but noticeable by many animals.

Foreshocks

unusual increase in the frequency of small earthquakes before the main shock

Changes in water level

porosity increases or decreases with changes in strain

Seismic Gaps

based of the chronological distribution of major earthquakes

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Seismic Gaps

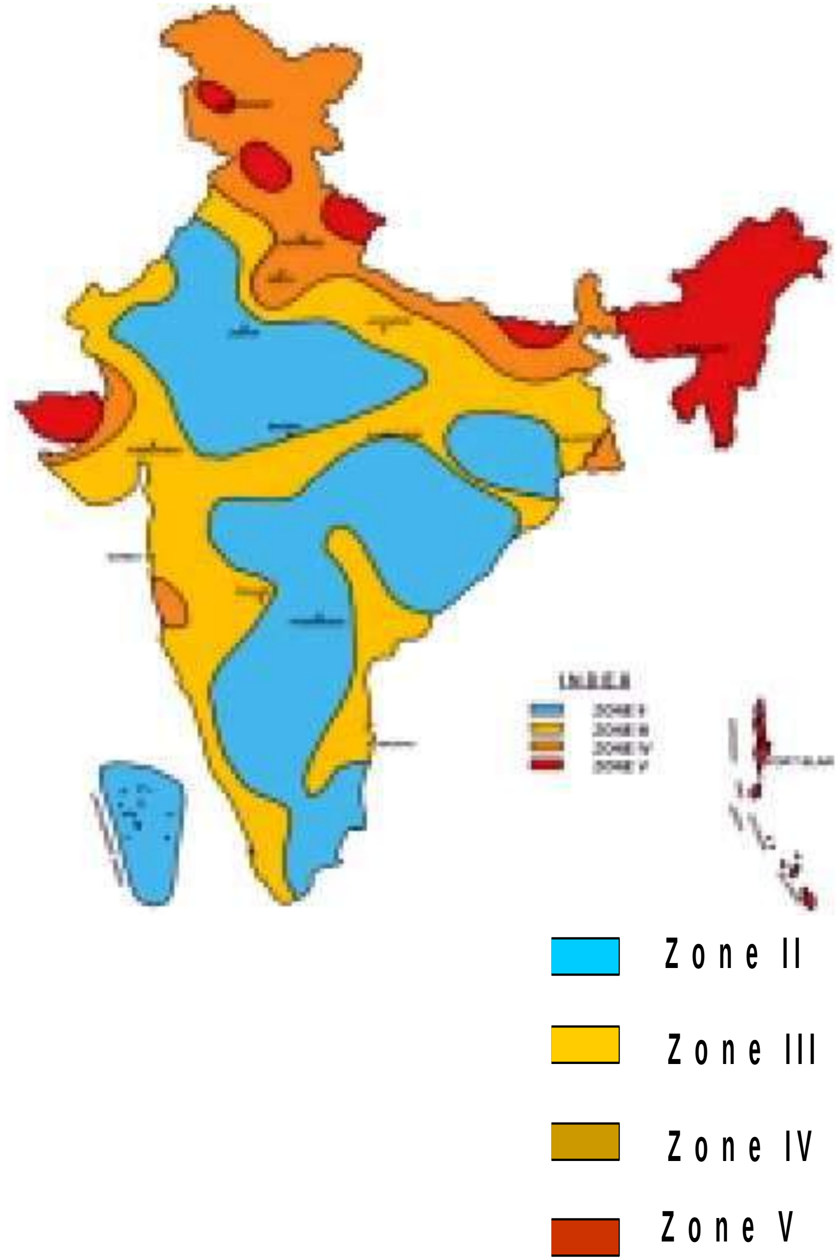
based of the chronological distribution of major earthquakes

Revised Seismic zone map of India (IS: 1893 - 2002)

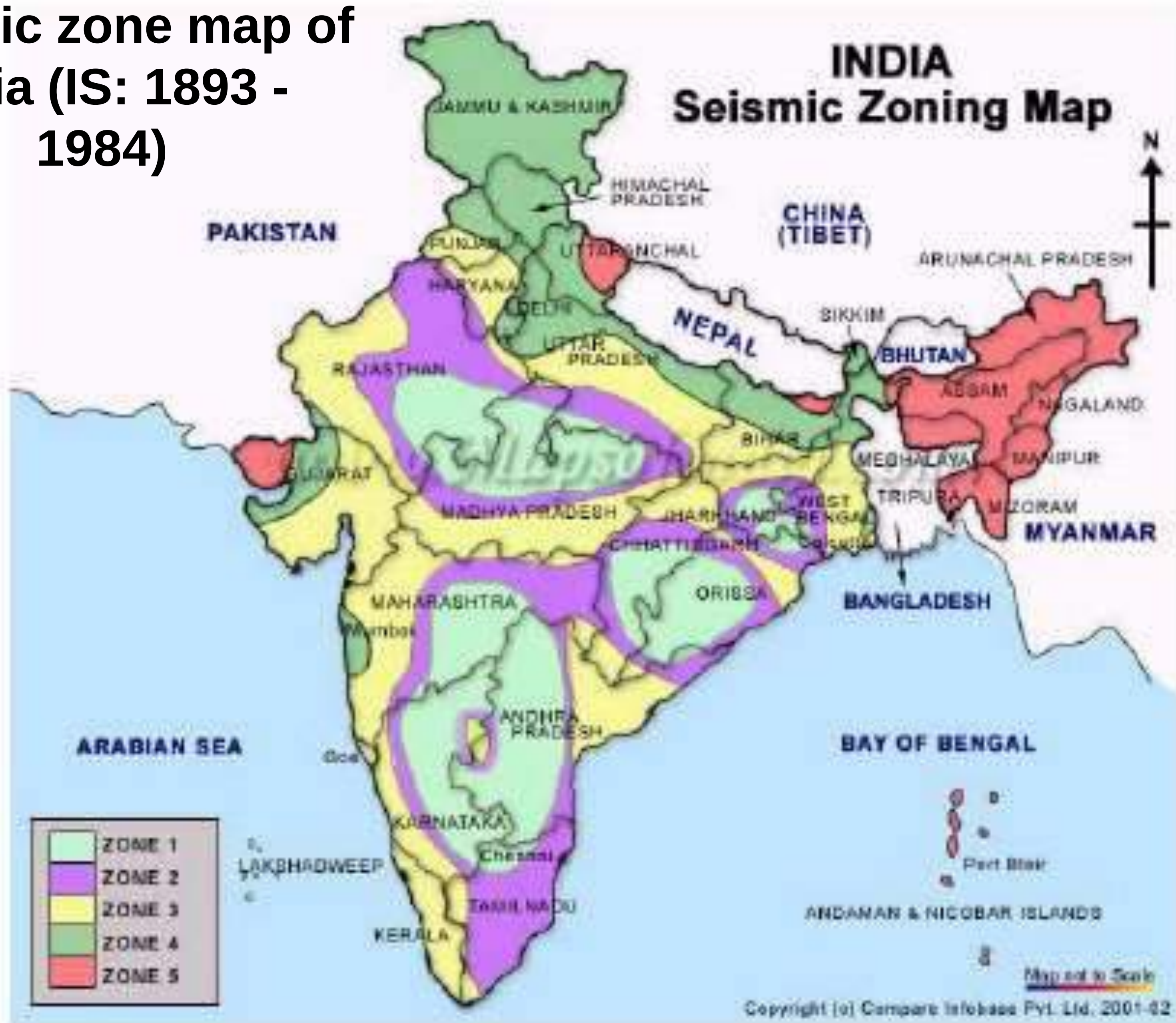
Indian Sub-continent Four seismic zones with different level of ground shaking as per IS: 1893 – 2002

Madras will come under seismic zone III currently earlier zone II

maximum Modified Mercalli (MM) intensity of seismic shaking expected in zones are *VI*, *VII*, *VIII*, and *IX and higher*, respectively



Seismic zone map of India (IS: 1893 - 1984)



PROTECTING AGAINST EARTHQUAKE DAMAGE

- Prepare a **Seismic Risk Map** for the globe which identifies rock types, liquefaction potential, landslide potential.

- Extensive geologic surveying has to be done to identify all active faults, including hidden faults.

- **Earthquake Resistant Design** of Structures
  Enact building codes to design and build earthquake-resistant structures in high seismic risk areas. Practice good deatilng
  Use good quality building materials: wood, steel and reinforced concrete are preferred as they tend to move with the shaking ground.

- Critical facilities such as nuclear power plants and dams should be built on stable ground and as far as possible from active faults.

Earthquake Ground Motion (GM)

The earthquake GM can be expressed either by

- i) specifying a level of shaking that has a certain probability of occurrence (probabilistic approach)
- or
- ii) in terms of the maximum shaking expected for a given earthquake source fault (deterministic approach)

Therefore for design,the level of GM is expressed in terms of response spectra (i.e simulated recordings of earthquake motions)

Seismic Hazard Levels

3 levels of seismic hazard are used to define ground shaking

Serviceability Earthquake **Ground motion with a 50% chance of being exceeded in a 50-year period**

Design Earthquake: **Ground motion with a 10% chance of being exceeded in a 50-year period**

Maximum Considered Earthquake: **Maximum level of ground motion expected with a 5% chance of being exceeded in a 50-year period.**

Ground Acceleration

- Number of empirical relations available in literature to correlate shaking intensity with Peak Ground Acceleration (PGA)

- Notice that the table gives
  - Average values of PGA; real values may be higher or lower
  - There is considerable variation even in the average values by different empirical relations.

Ground Acceleration

- **ZPA** stands for **Zero Period Acceleration**.
  - Implies max acceleration experienced by a structure having zero natural period (T=0).
- An infinitely rigid structure
  - Has zero natural period (T=0)
  - Does not deform:
    - No relative motion between its mass and its base
    - Mass has same acceleration as of the ground
- Hence, ZPA is same as Peak Ground Acceleration

Uniform Building Code

- Uniform Building Code was one of the three prominent building codes in the USA
  - Now, all three codes are merged into International Building Code (IBC)
- The trend in the USA is to revise the codes every three years:
  - UBC1994, UBC1997, IBC2000

International Building Code

- Note that the IBC is a US code even though its name implies International
- Interestingly IBC lists prominent cities around the world with their equivalent IBC seismic zone
  - For instance, Delhi, Mumbai, ….

Response Spectrum

- During ground shaking, one can measure ground acceleration versus time (accelerogram) using an accelerograph
  - Accelerograph is the instrument
  - Accelerogram is the record obtained from it
    - Accelerogram is the variation of ground acceleration with time (also called time history of ground motion)

Earthquake Level

- Maximum Credible Earthquake (MCE):
  - Largest reasonably conceivable earthquake that appears possible along a recognized fault (or within a tectonic province).
  - It is generally an *upper bound* of expected magnitude.
  - Irrespective of return period of the earthquake which may range from say 100 years to 10,000 years.
  - Usually evaluated based on geological evidence

Earthquake Level (contd…)

- Other terms used in literature which are **somewhat** similar to max credible EQ:
  - Max Possible Earthquake
  - Max Expectable Earthquake
  - Max Probable Earthquake
  - Max Considered Earthquake

Time History Analysis

- Dynamic analysis can be done in a number of ways, e.g.
  - Time history analysis
  - Response spectrum analysis
- Time history analysis is a more sophisticated analysis
  - Rarely used for design of ordinary structures.
- Interested persons may learn it from books on Structural Dynamics.

Structural wall System

- Structural walls- An efficient lateral force resisting system (up to 20 stories, it is matter of choice)
- Beyond 20 stories, it may become imperative due to i) economy ii) control lateral deflection
- The basic criteria to satisfy the shear walls are,

  stiffness,strength and ductility.

Dual System

- Consider buildings with shear walls and moment resisting frames.
- In 1984 version of the code, Table 5 (p. 24) implied that the frame should be designed to take at least 25% of the total design seismic loads.

Dual System (contd…)

- In the new code several choices are available to the designer:
  - When conditions of Cl. 4.9 are met: **dual system.**
    - Example 1: Analysis indicates that frames are taking 30% of total seismic load while 70% loads go to shear walls. Frames and walls will be designed for these forces and the system will be termed as dual system.
    - Example 2: Analysis indicates that frames are taking 10% and walls take 90% of the total seismic load. To qualify for dual system, design the walls for 90% of total load, but design the frames to resist 25% of total seismic load

Dual System (contd…)

- Conditions of Cl. 4.9 are not met. Here, two possibilities exist (see Footnote 4 in Table 7, p. 23):
  - Frames are not designed to resist seismic loads. The entire load is assumed to be carried by the shear walls. In Example 2 above, the shear walls will be designed for 100% of total seismic loads, and the frames will be treated as gravity frames (i.e., it is assumed that frames carry no seismic loads)
  - Frames and walls are designed for the forces obtained from analysis, and the frames happen to carry less than 25% of total load. In Example 2 above, the frames will be designed for 10% while walls will be designed for 90% of total seismic loads.

Dual System (contd…)

- Clearly, the dual systems are better and are designed for lower value of design force.
- See Table 7 (p. 23) of the code. There is different value of response reduction factor (R) for the dual systems.