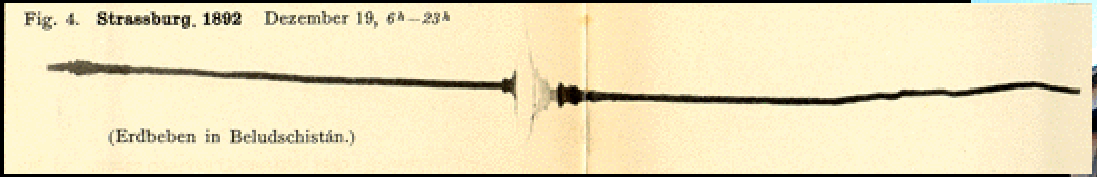
Earthquake - Elements of seismology (overview)



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What is seismology?

Seismology is science dealing with all aspects of earthquakes:

OBSERVATIONAL SEISMOLOGY

- Recording earthquakes (microseismology)
- Cataloguing earthquakes
- Observing earthquake effects (macroseismology)

ENGINEERING SEISMOLOGY

- Estimation of seismic hazard and risk
- Aseismic building

'PHYSICAL' SEISMOLOGY

- Study of the properties of the Earth's interior
- Study of physical characteristics of seismic sources

EXPLORATIONAL SEISMOLOGY (Applied seismic methods)...

The Earth and its Interior

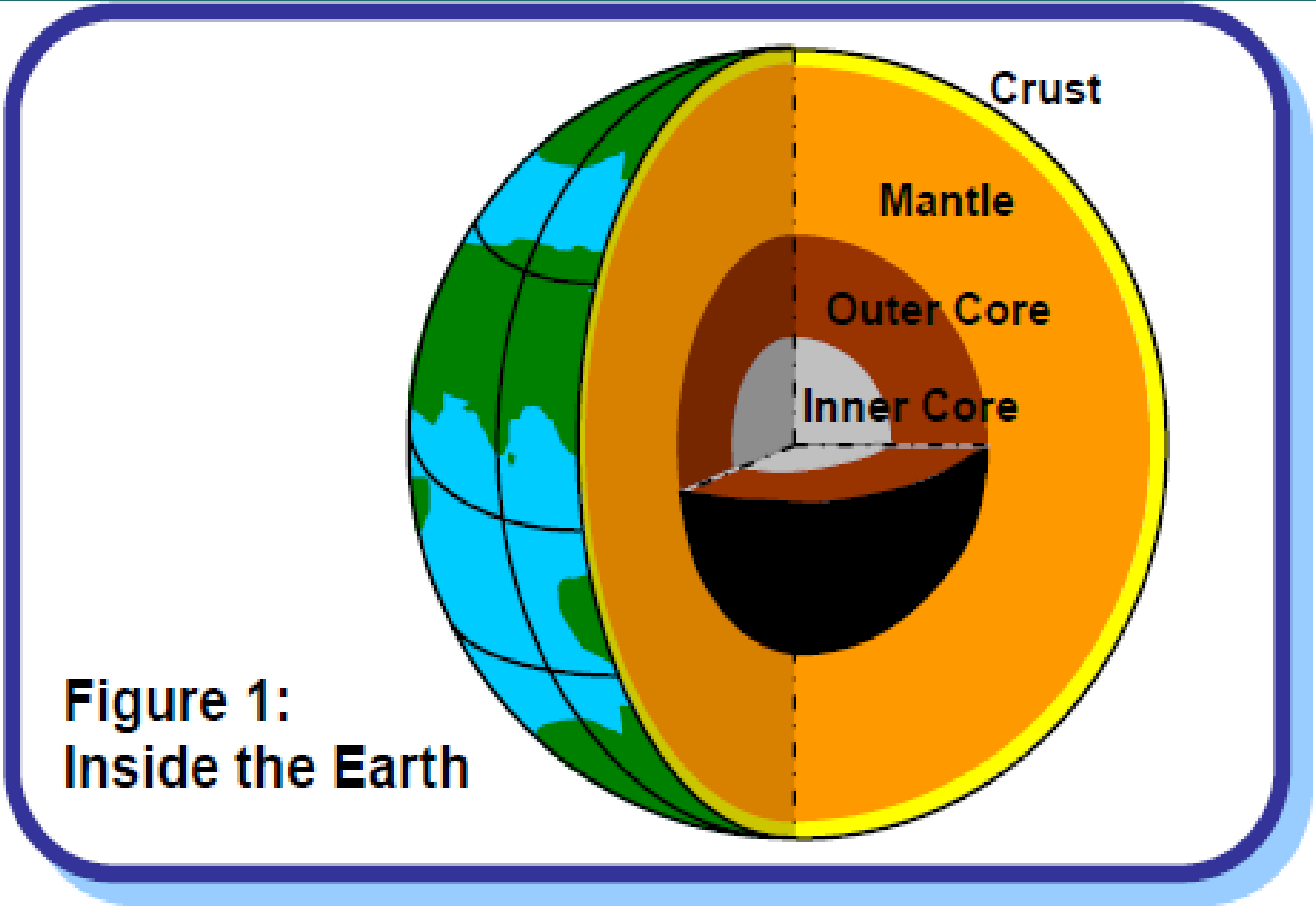
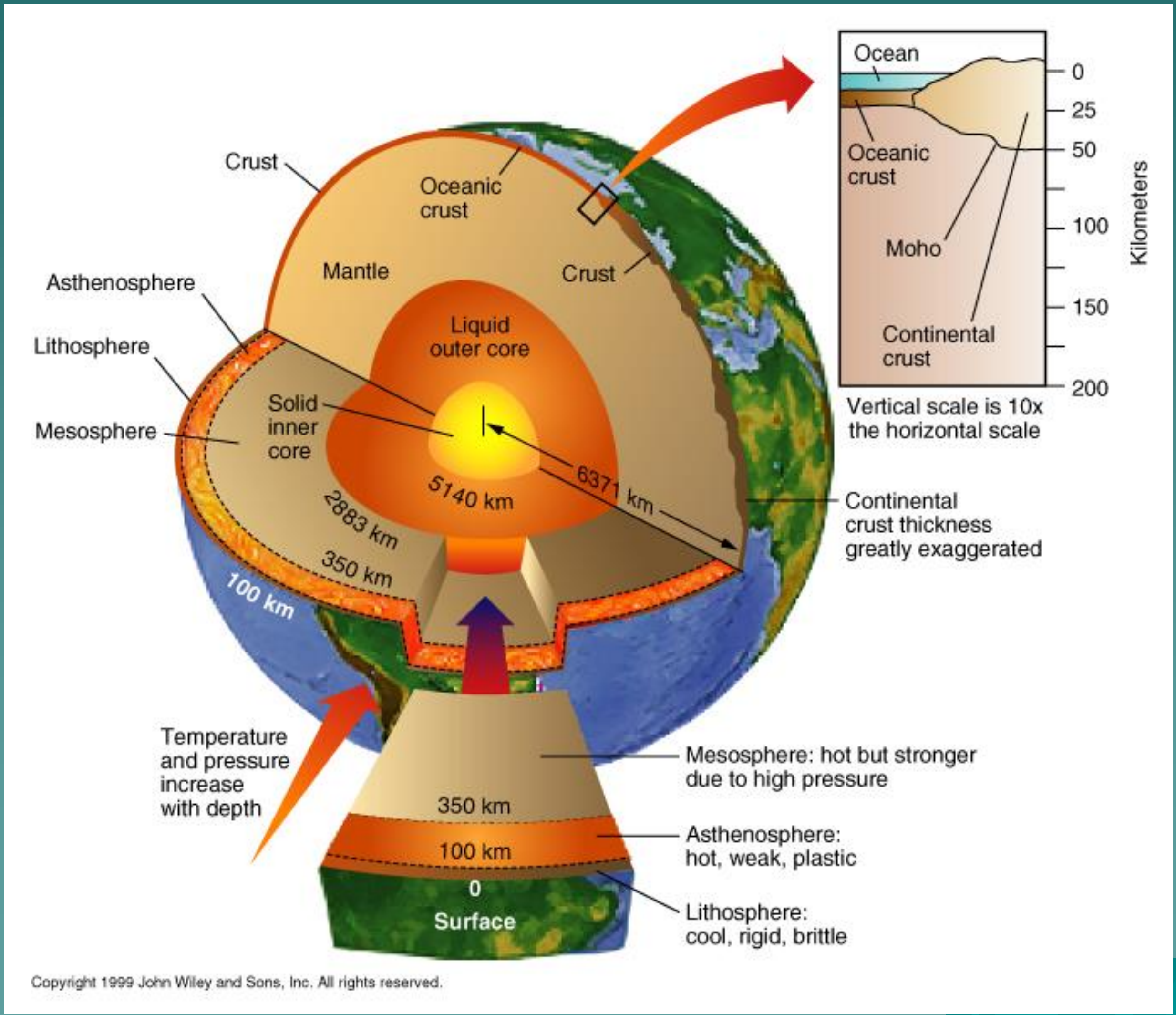


Figure 1:
Inside the Earth

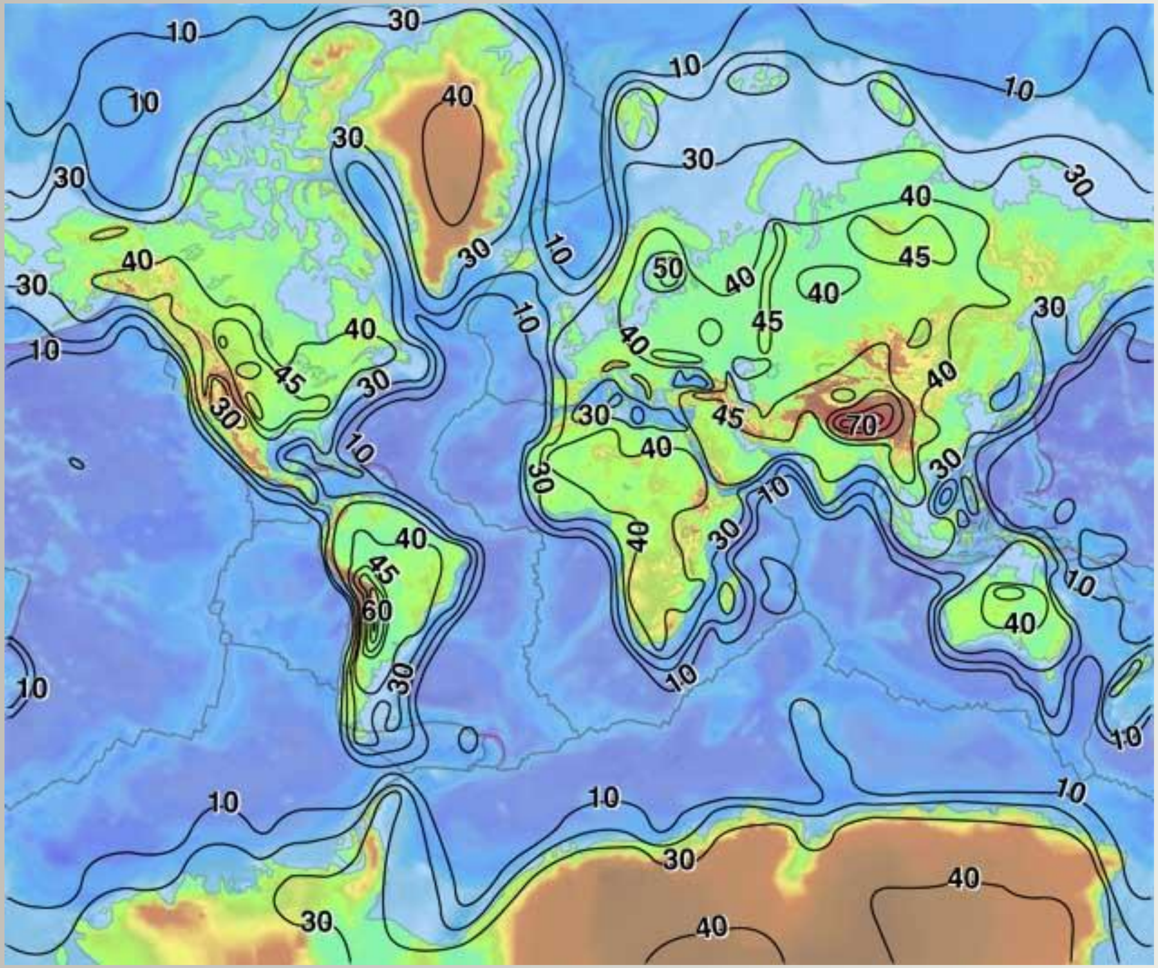
To see how earthquakes really occur, we first need to learn about constitution of the Earth!

The Three Major Chemical Radial Divisions

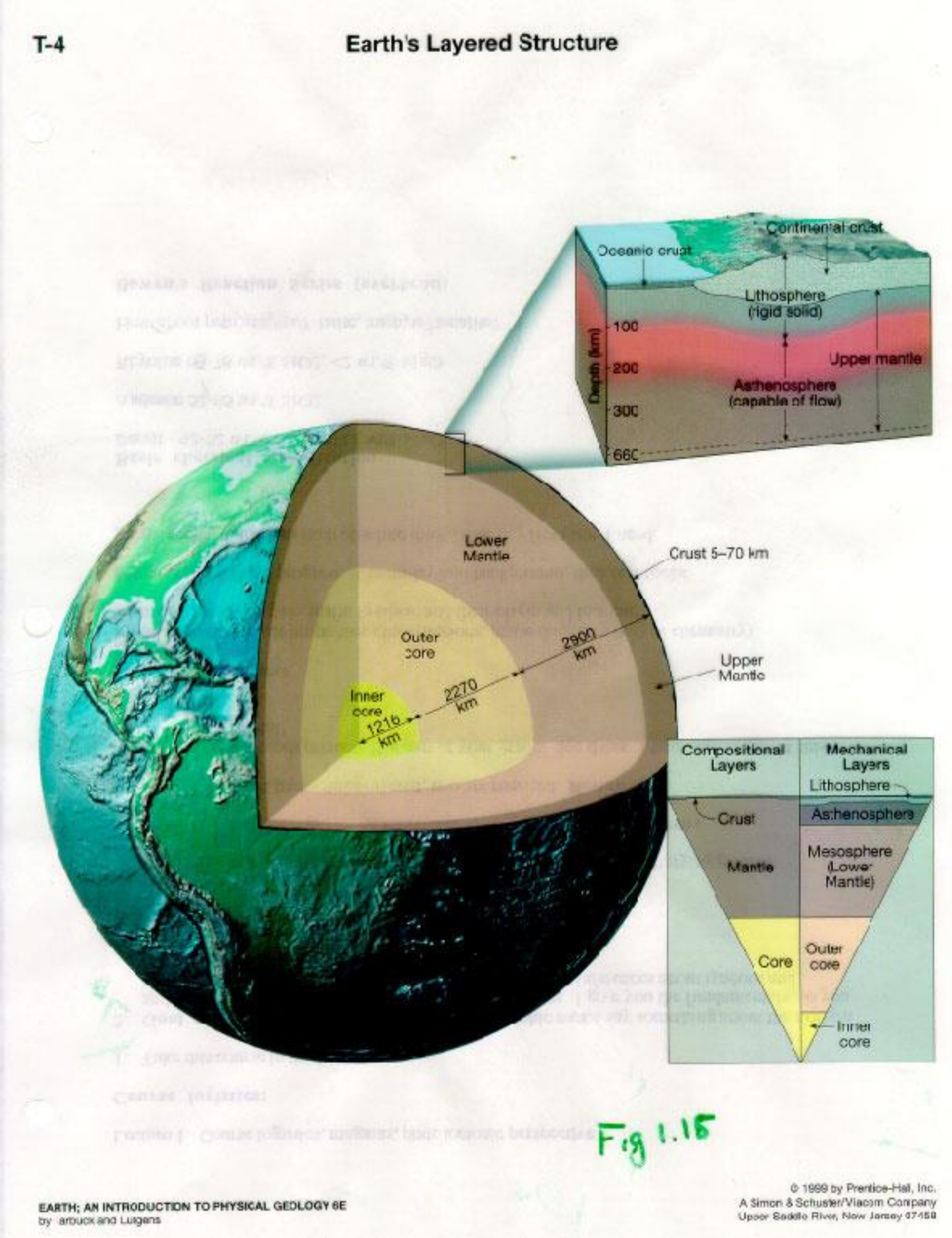


- Crust
- Mantle
- Core

Crustal thickness



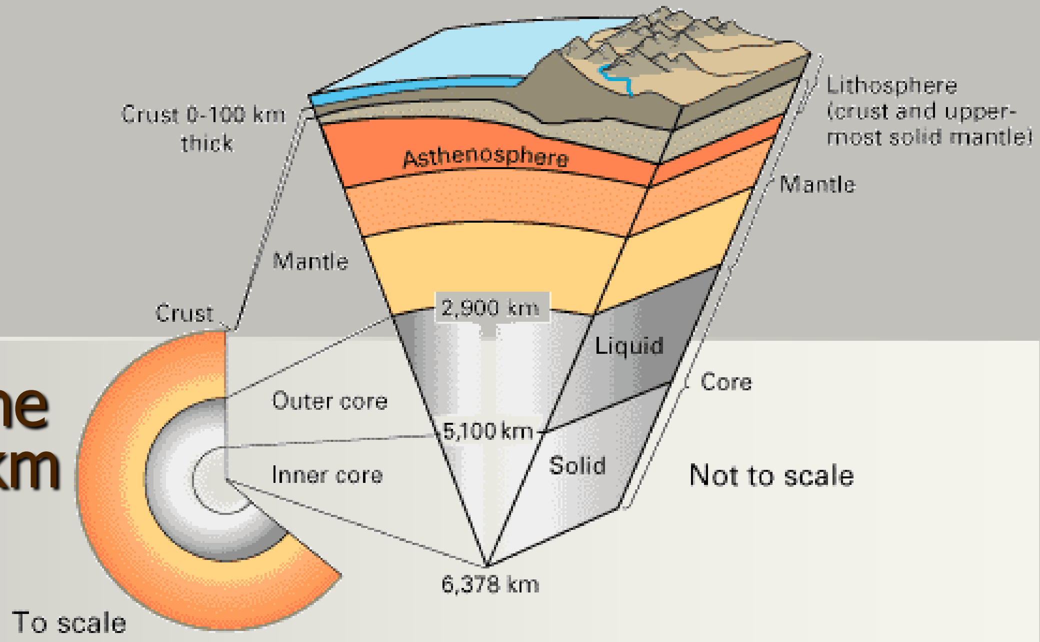
http://quake.wr.usgs.gov/research/structure/CrustalStructure/index.html



Mechanical Layers:

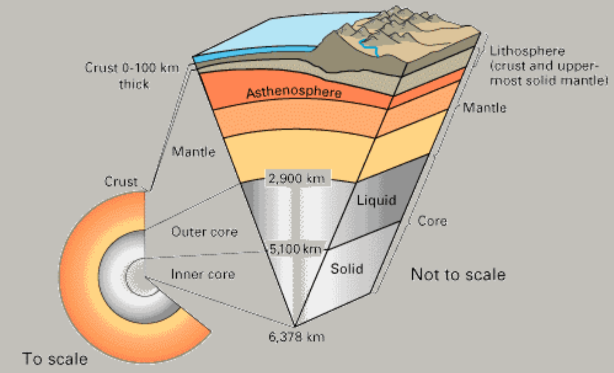
1. Lithosphere
2. Asthenosphere
3. Mesosphere

Litosphere



- The *lithosphere* is the uppermost 50-100 km of the Earth.
- There is not a strict boundary between the lithosphere and the asthenosphere as there is between the crust and mantle.
- It consists of both crust and upper parts of mantle.
- It behaves rigidly, like a solid, over very long time periods.

Astenosphere



- The asthenosphere exists between depths of 100-200 km.
- It is the weakest part of the mantle.
- It is a solid over short time scales, but behaves like a fluid over millions of years.
- The asthenosphere decouples the lithosphere (**tectonic plates**) from the rest of the mantle.

The Earth and its Interior

- The differentiated Earth consists of the *Inner Core (radius ~1290km), the Outer Core (thickness ~2200km), the Mantle (thickness ~2900km) and the Crust (thickness ~5* to 40*km). Figure 1 shows these layers.*
- *The Inner Core* is solid and consists of heavy metals (*e.g., nickel and* iron),
- while the Crust consists of light materials (*e.g.,* basalts and granites).
- The Outer Core is liquid in form and the Mantle has the ability to flow.
- At the Core, the temperature is estimated to be *~2500°C, the pressure ~*4 million *atmospheres and density ~13.5 gm/cc*

Plate tectonics

PLATE TECTONICS theory is very young (1960-ies)

It provides answers to the most fundamental questions in seismology:

- ❖ Why earthquakes occur?
- ❖ Why are earthquake epicenters not uniformly distributed around the globe?
- ❖ At what depths are their foci?

Tectonic forces

- The interior of the Earth is dynamic – it cools down and thus provides energy for convective currents in the outer core and in the astenosphere.

- Additional energy comes from radioactive decay…

Plate Tectonics

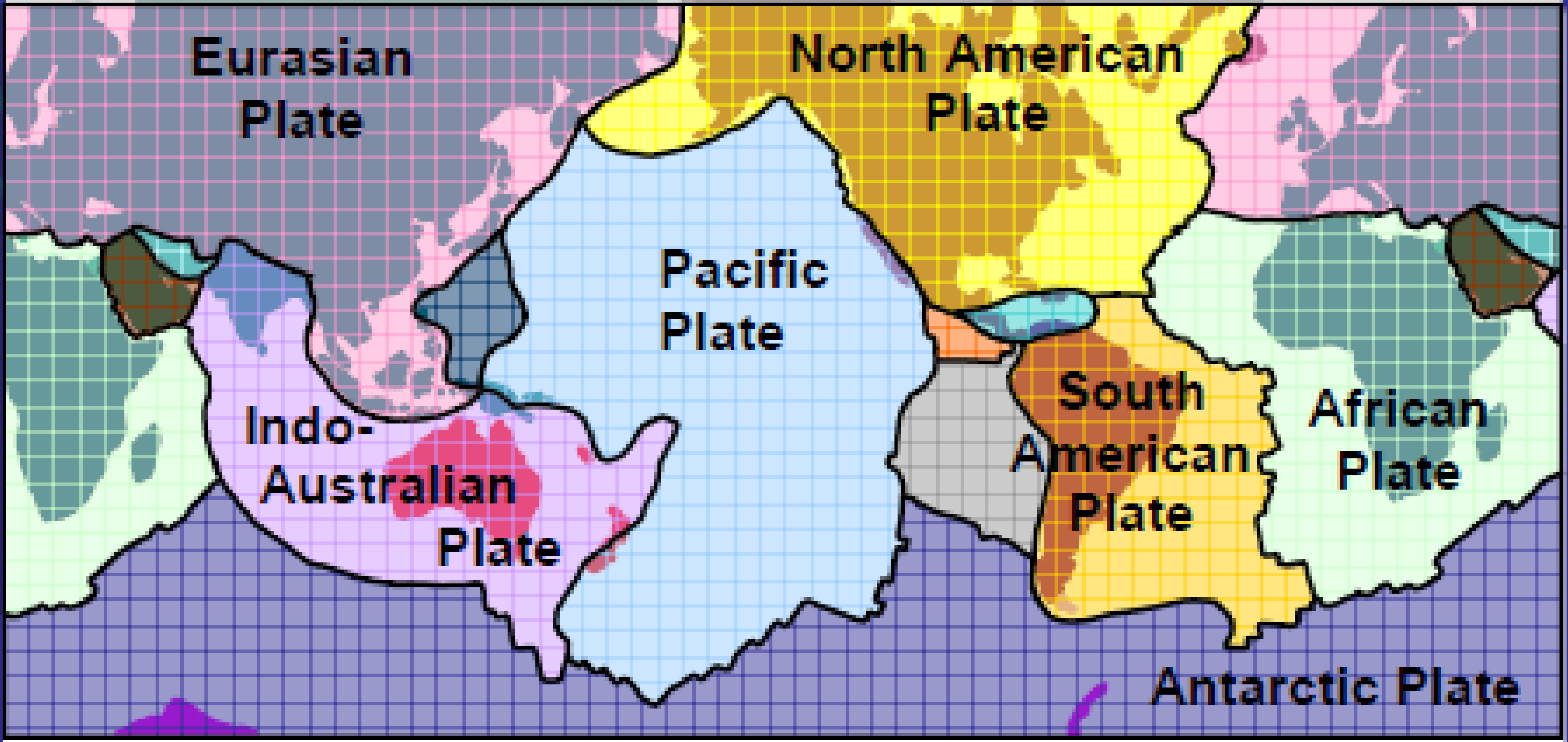
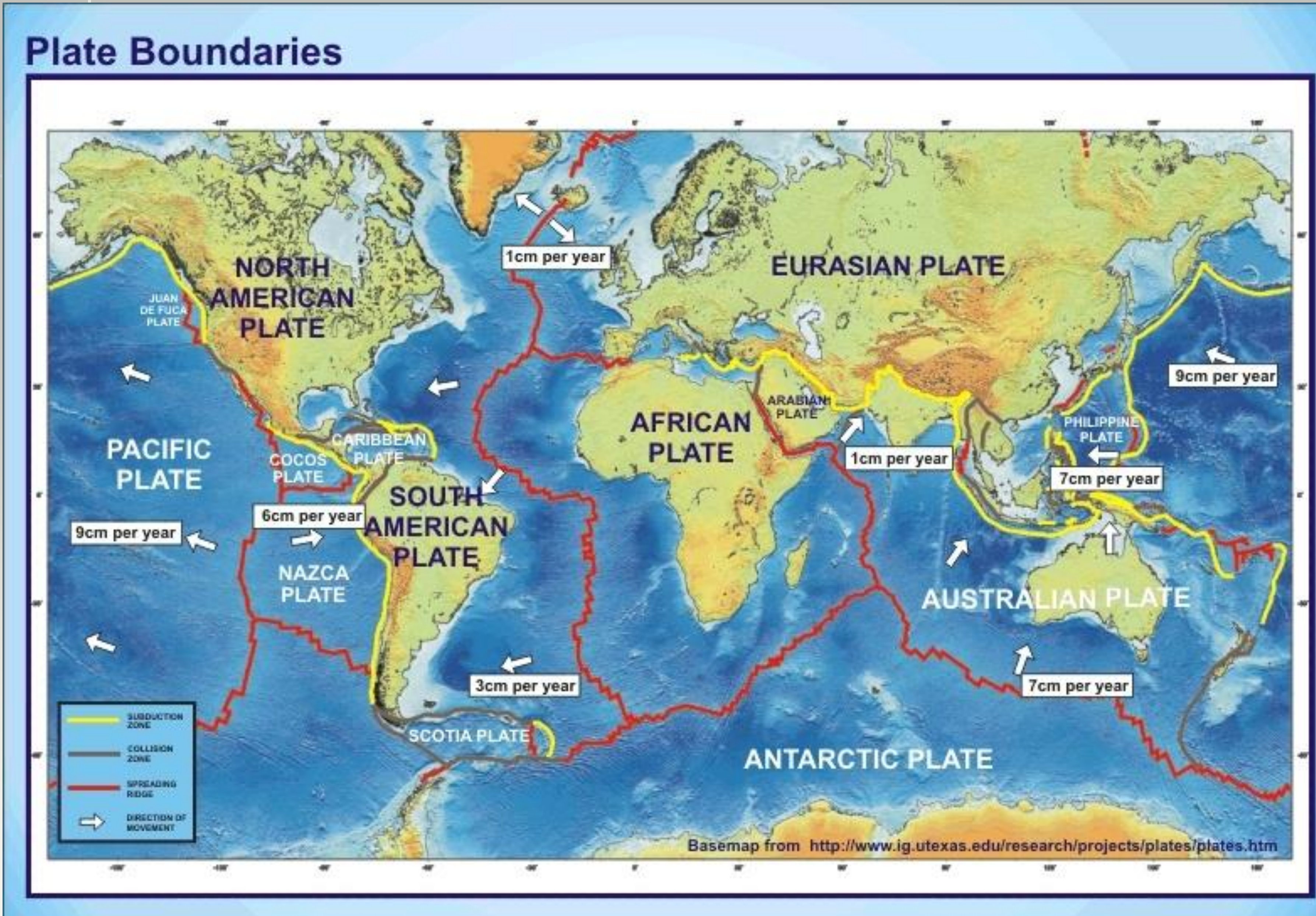


Figure 3:
Major Tectonic Plates on the Earth's surface

Major tectonic plates



Convection

Convection in the astenosphere enables tectonic processes – **PLATE TECTONICS**

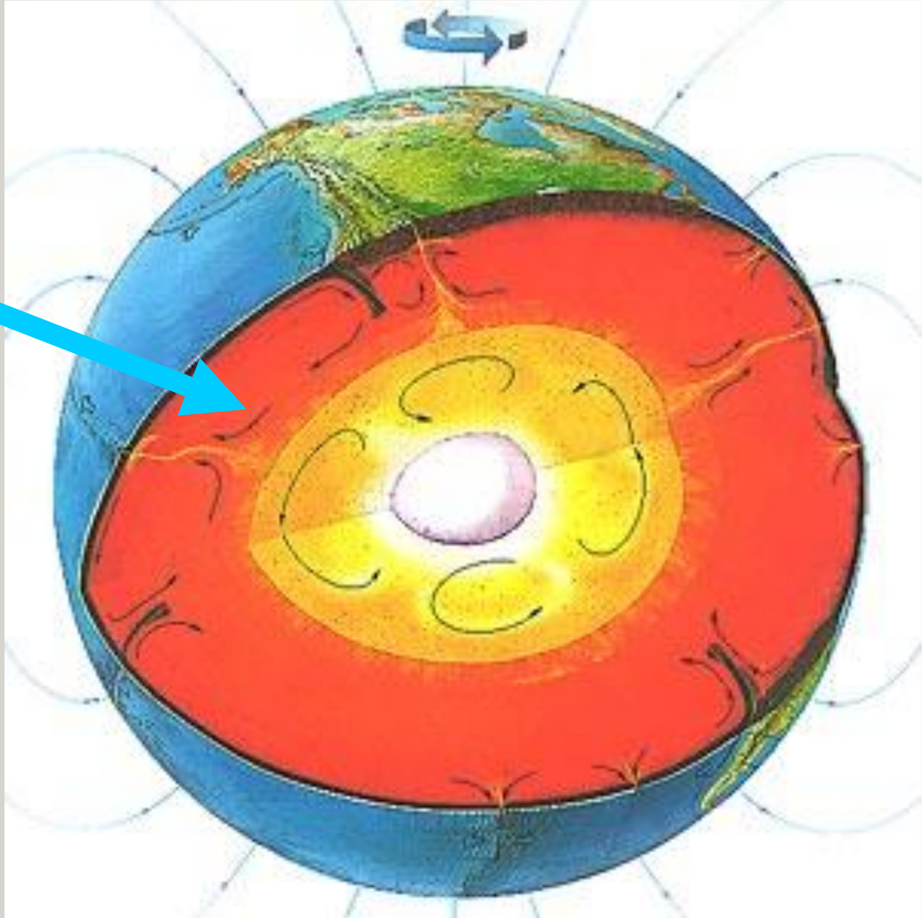


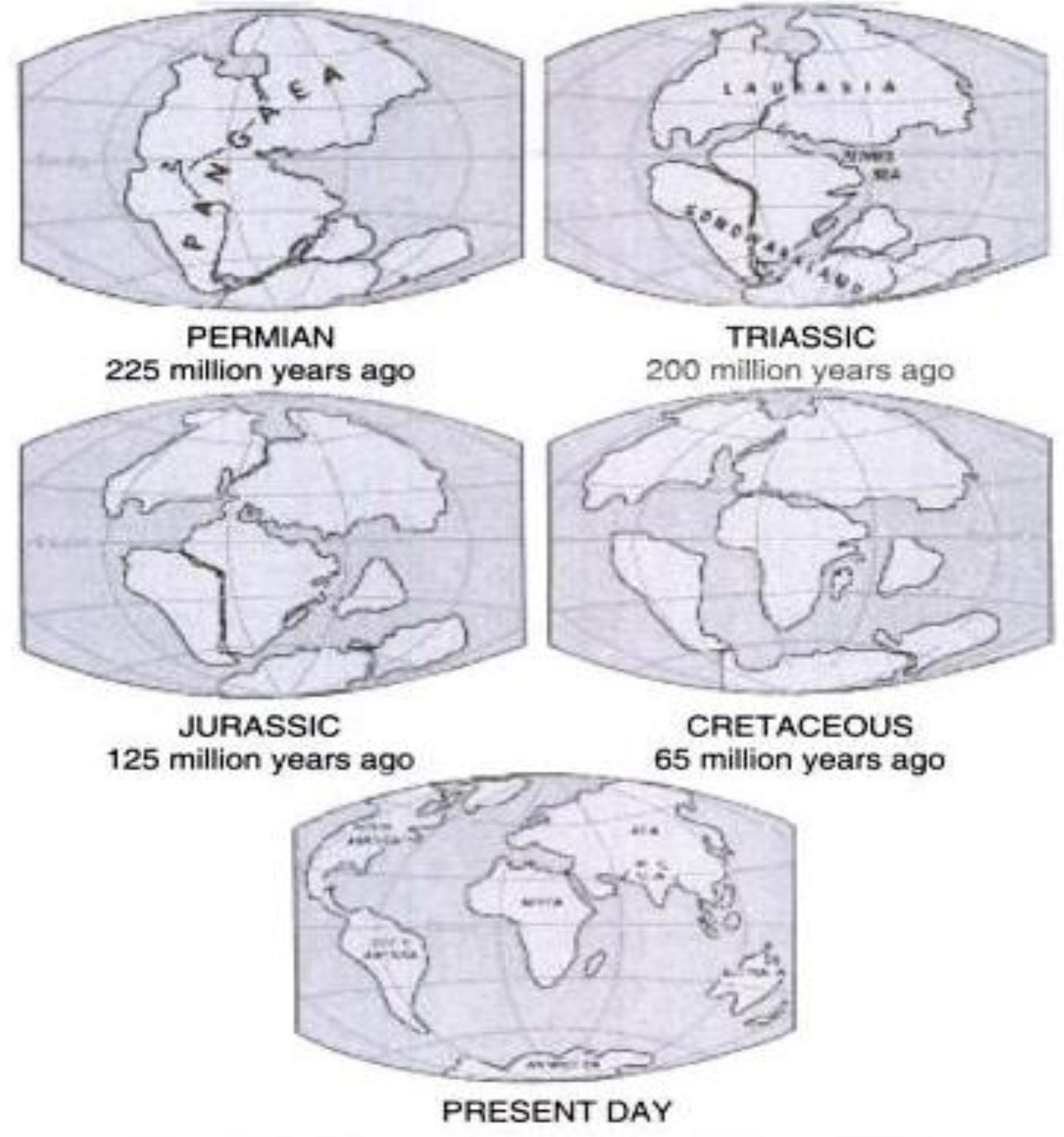
Plate Tectonics

- The convective flows of Mantle material cause the Crust and some portion of the Mantle, to slide on the hot molten outer core. This sliding of Earth's mass takes place in pieces called *Tectonic Plates.*
- *The surface* of the Earth consists of seven major tectonic plates and many smaller ones (Figure 3). These plates move in different directions and at different speeds from those of the neighbouring ones.
- Sometimes, the plate in the front is slower; then, the plate behind it comes and collides (and *mountains are formed).*
- *On the other* hand, sometimes two plates move away from one another (and *rifts are created).*

Plate Tectonics

- *In another case, two* plates move side-by-side, along the same direction or in opposite directions.
- These three types of inter-plate interactions are the *convergent, divergent and transform*
- boundaries (Figure 4), respectively.
- The convergent boundary has a peculiarity (like at the Himalayas) that sometimes neither of the colliding plates wants to sink.
- The relative movement of these plate boundaries varies across the Earth; on an average, it is of the order of a couple to tens of *centimeters per year.*

Continental Drift Theorey



Continental Drift
PERMIAN

- About 225-250 million years ago, there was only one super continent(land) called PANGEA and only one universal ocean called PANTHALASA
- Pangea had an area of 150 million sq.km and it spread more or less equally between two hemispheres.
- It consists of north America(with green land) and Eurasia (without India and Arabia) in extreme north
- Below it, South America and Africa(with Arabia)
- Further down, Antarctica, Australia and India

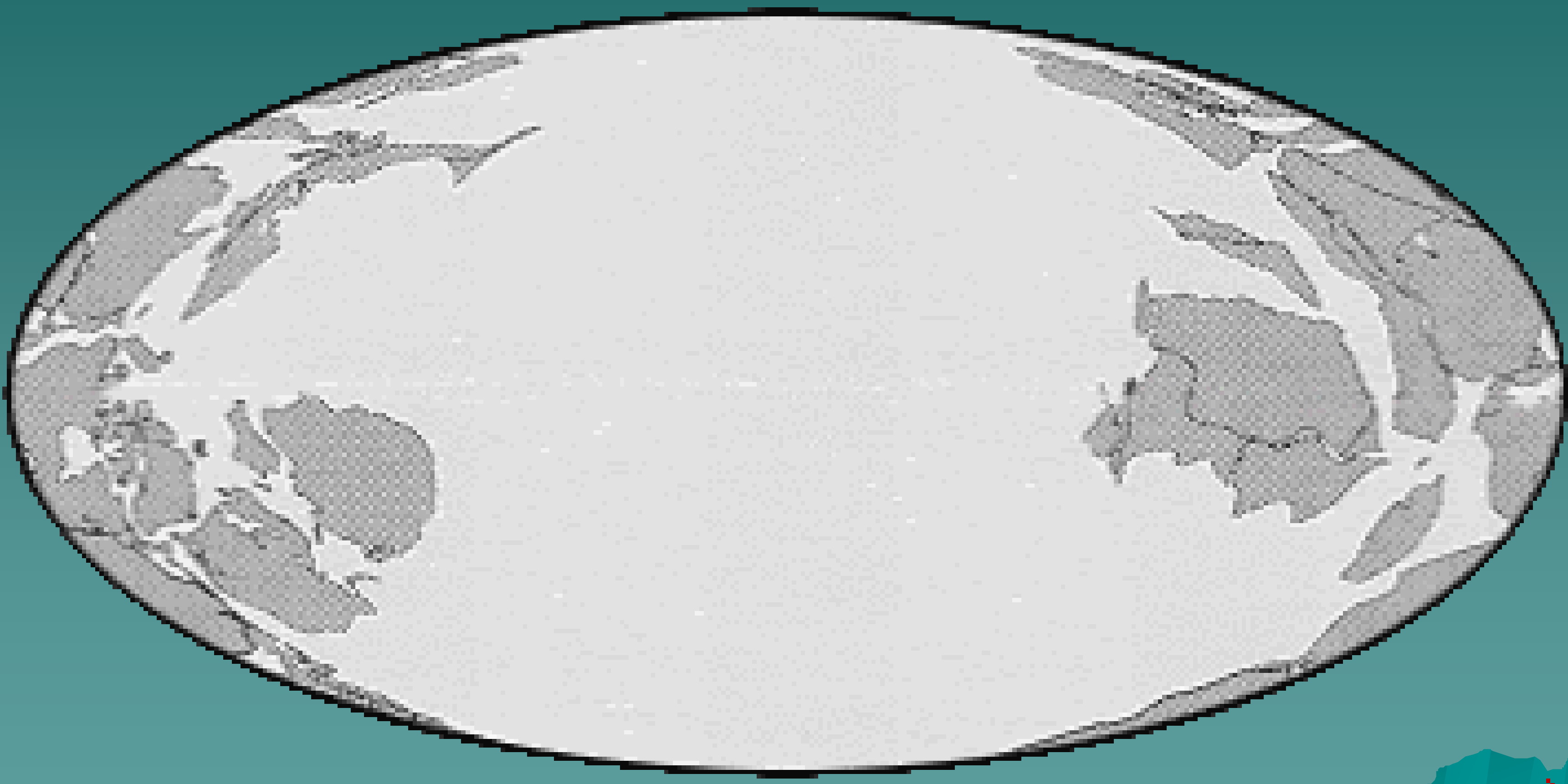
Continental Drift
TRIASSIC

- It broke in late TRIASSIC (geological age) by two drifts.
- The northern rift cut the pangea from East-West and created Laurasia in the north and Gondwana in the south
- The southern rift divided the Gondwana and opened up the Indian ocean

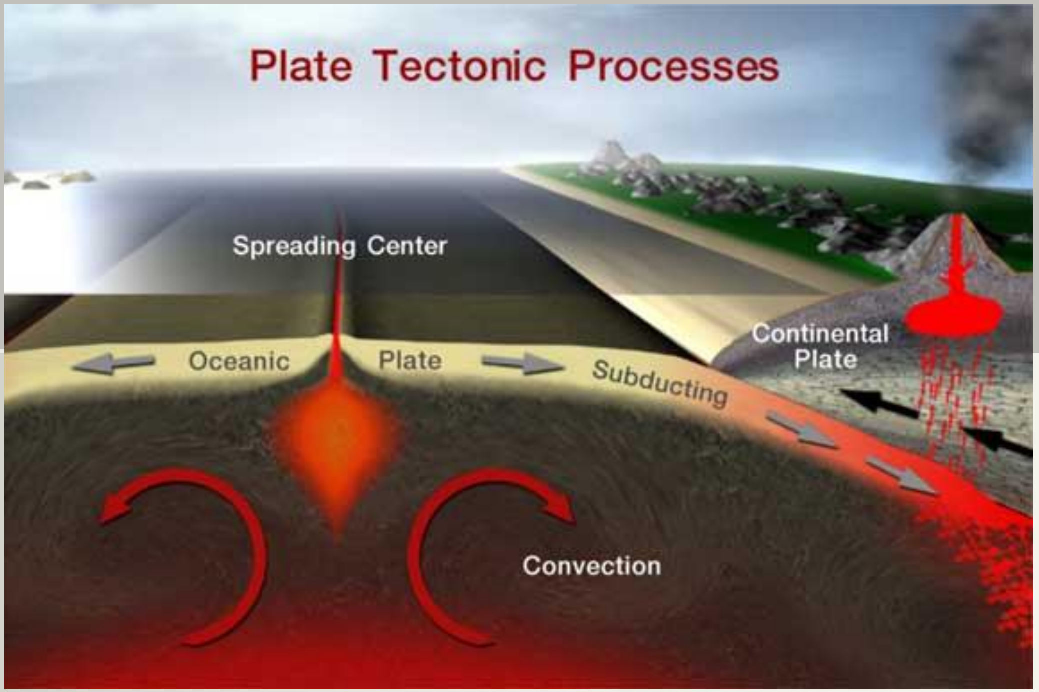
Continental Drift

CRETACEOUS

- Some 65 million years ago, North America separated from Eurasia and South America from Africa.
- Later the two Americas were united by the Isthmus of Panama, While Australia separated from Antarctic's and moved northwards
- About 20 million years ago. Arabia split from Africa to merge into Asia. This brought into existence the Red Sea and Gulf of Aden.
- India moved northwards and finally joined South Asia about 45 million years ago



Tectonic plates

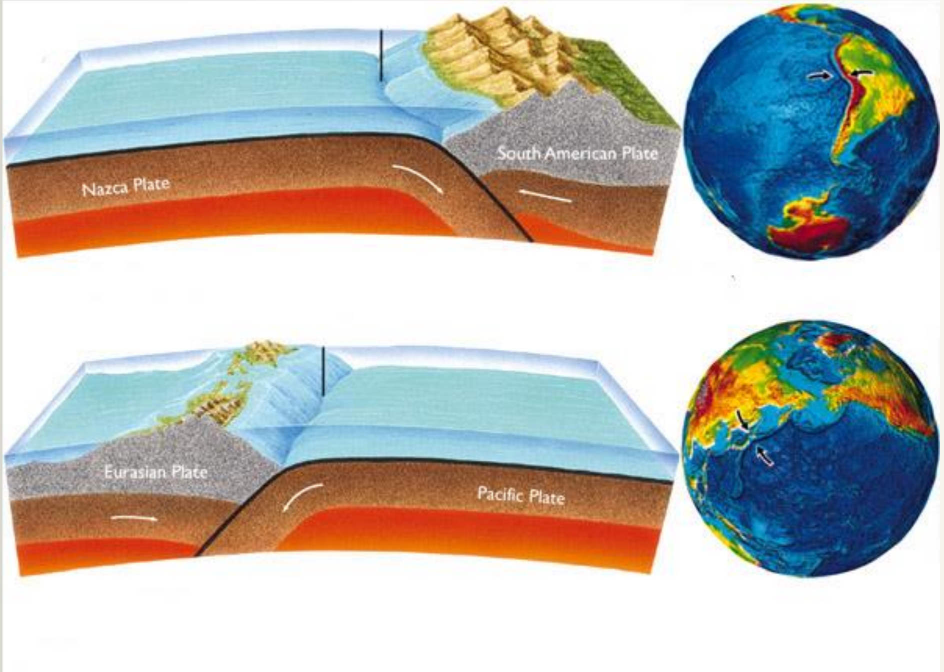


- Tectonic plates are large parts of litosphere 'floating' on the astenosphere
- Convective currents move them around with velocities of several cm/year.
- The plates interact with one another in three basic ways:

1. **They collide**
2. **They move away from each other**
3. **They slide one past another**

Interacting plates

- Collision leads to **SUBDUCTION** of one plate under another. Mountain ranges may also be formed (Himalayas, Alps...).
- It produces strong and sometimes very deep earthquakes (up to 700 km).
- Volcanoes also occur there.

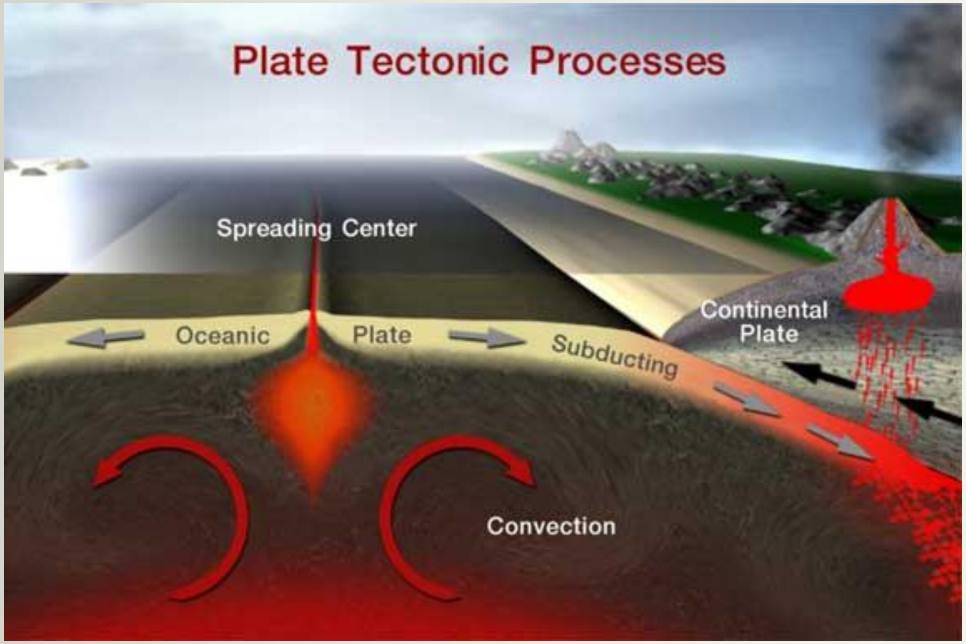


EXAMPLES: Nazca – South America

Eurasia – Pacific

Interacting plates

- Plates moving away from each other produce **RIDGES** between them (spreading centres).
- The earthquakes are generally weaker than in the case of subduction.

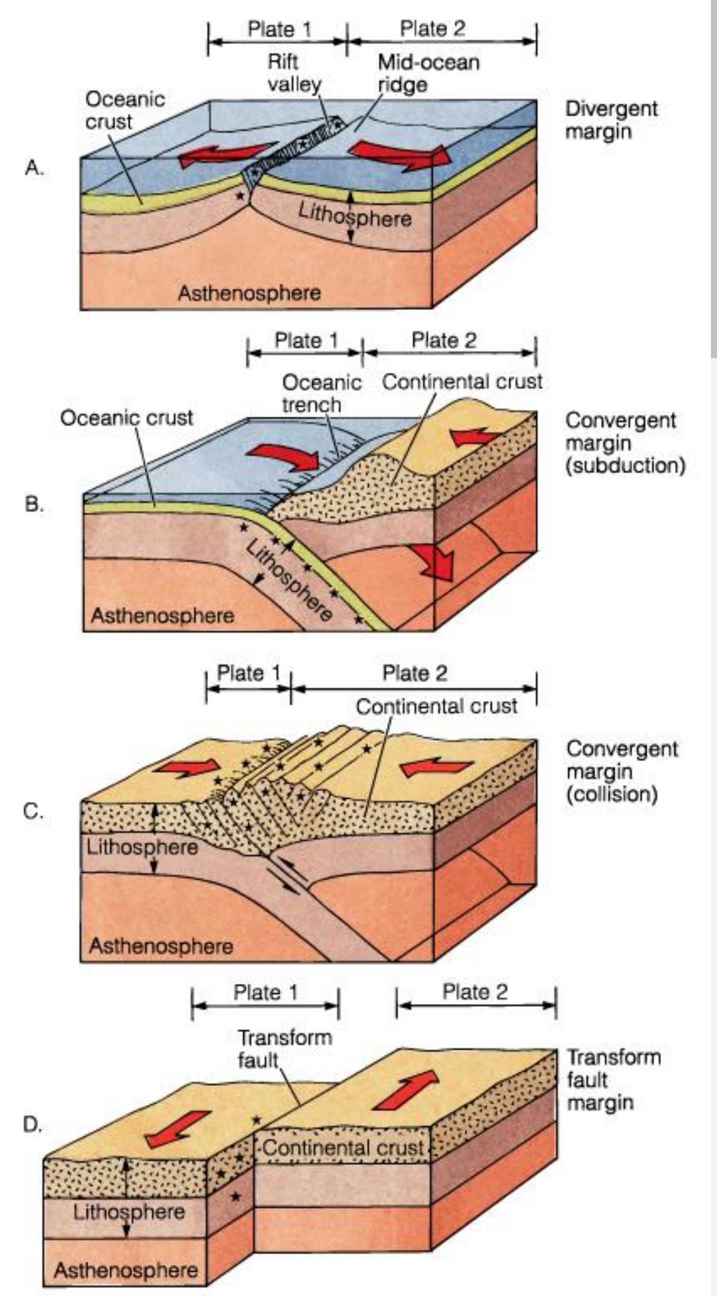


EXAMPLES: Mid-Atlantic ridge (African – South American plates, Euroasian – North American plates)

Interacting plates

- Plates moving past each other do so along the **TRANSFORM FAULTS.**
- The earthquakes may be very strong.

EXAMPLES: San Andreas Fault (Pacific – North American plate)



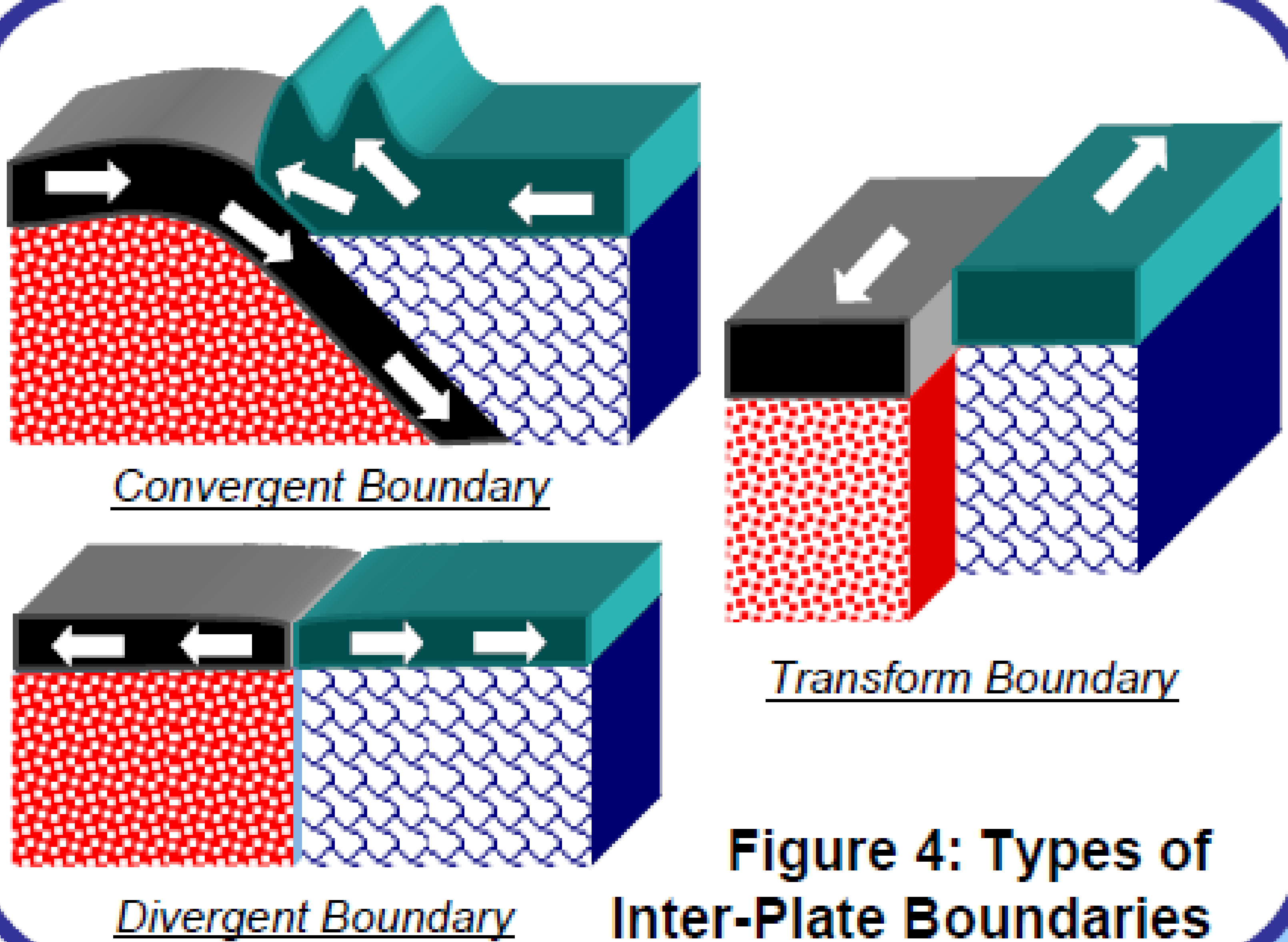


Figure 4: Types of Inter-Plate Boundaries

Earthquake

- Tectonic plates are made of elastic but brittle rocky material. And so, elastic strain energy is stored in them during the relative deformations that occur due to the gigantic tectonic plate actions taking place in the Earth.
- But, when the rocky material along the interface of the plates in the Earth's Crust reaches its strength, it fractures and a sudden movement takes place there (Figure 5)
- the interface between the plates where the movement has taken place (called the *fault) suddenly slips and releases the large elastic strain energy stored* in the rocks at the interface.
- For example the energy released during the 2001 Bhuj (India) earthquake is about 400 times (or more) that released by the *1945 Atom Bomb dropped on Hiroshima!!*

Faults

1. Dip slip fault
   a. Normal   b. Reverse
2. Strike Slip fault
3. Oblique Slip fault

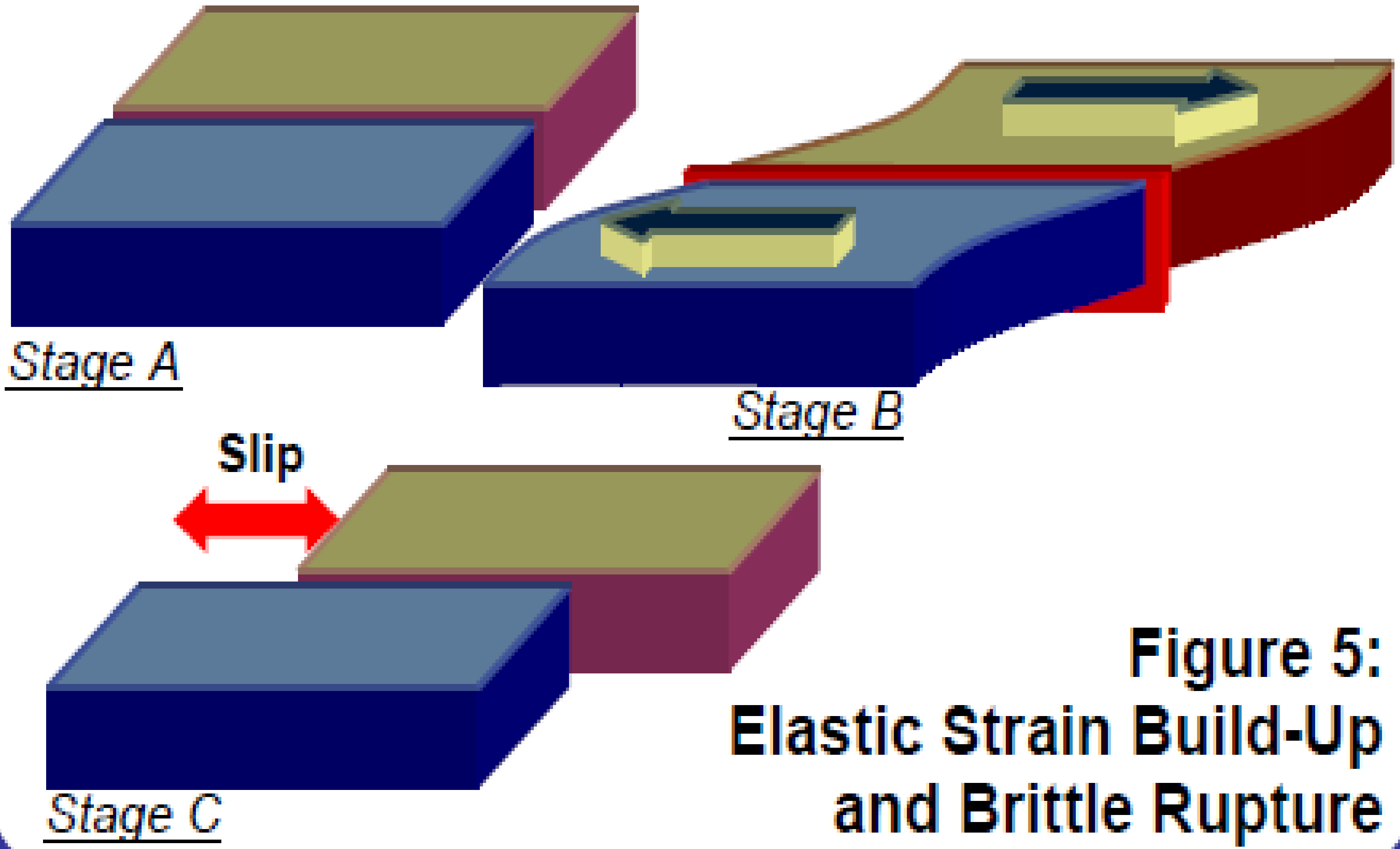
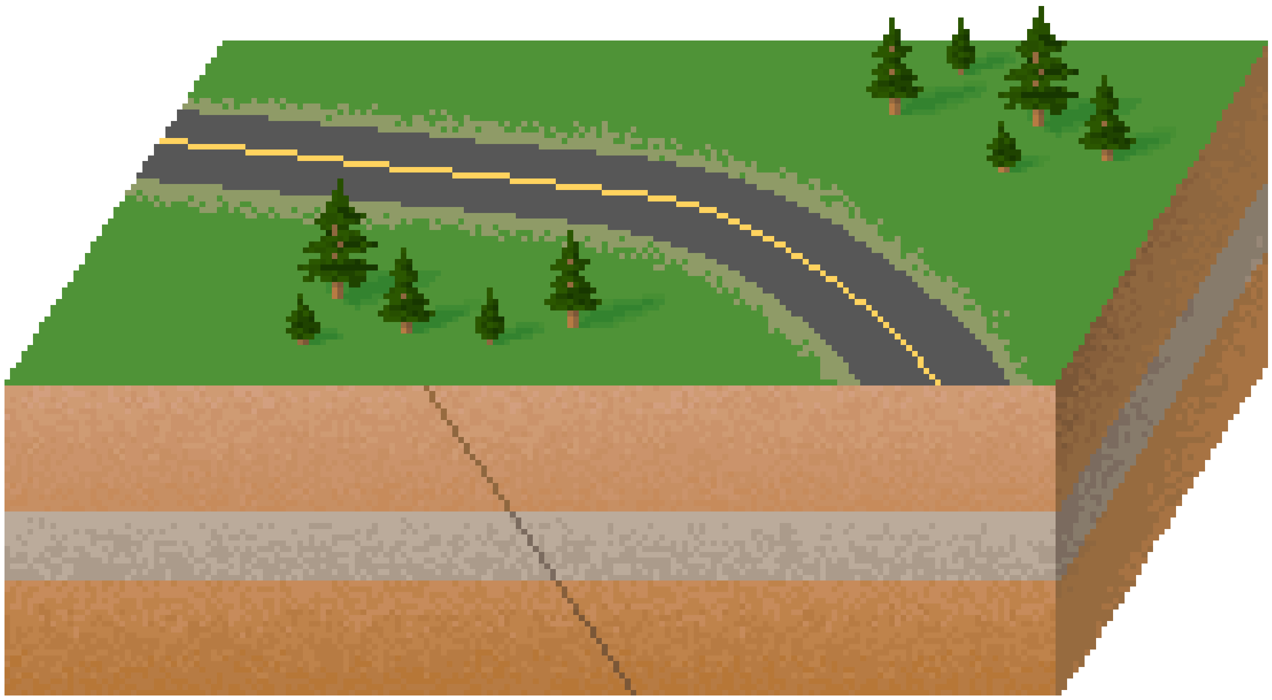
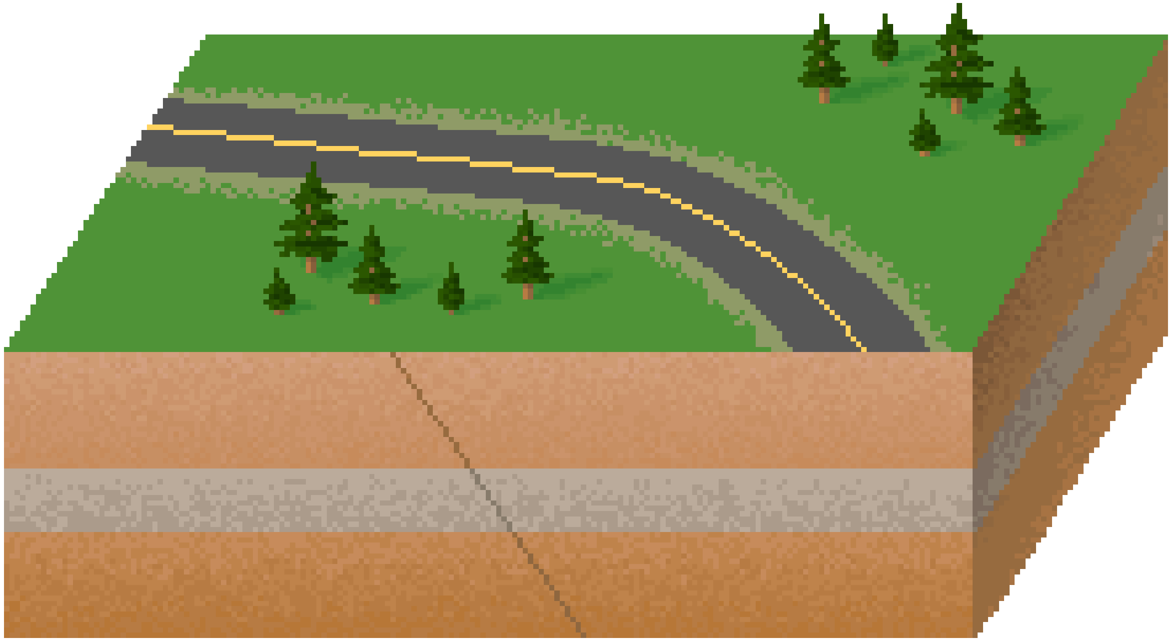


Figure 5: Elastic Strain Build-Up and Brittle Rupture

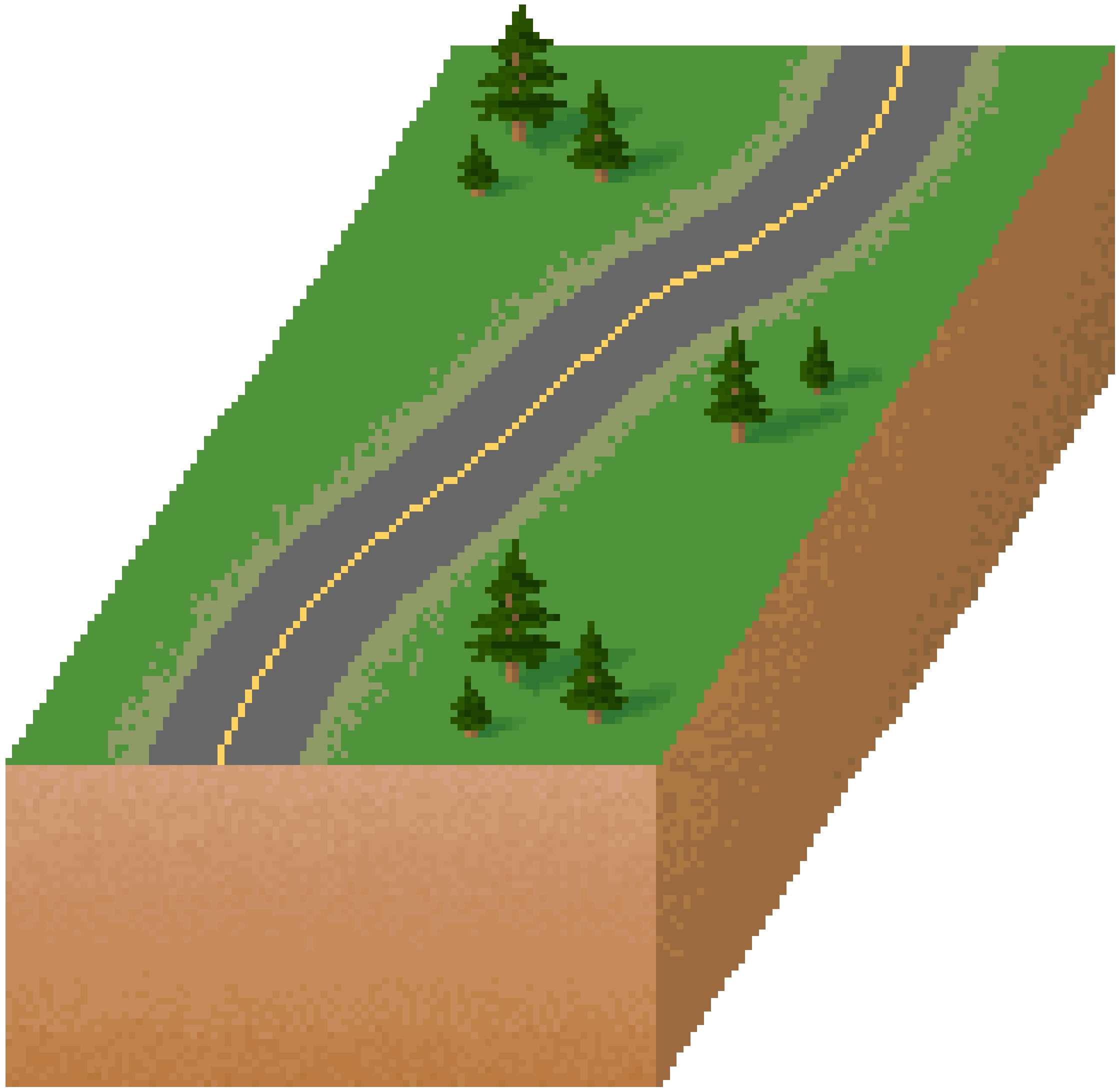
Normal slip



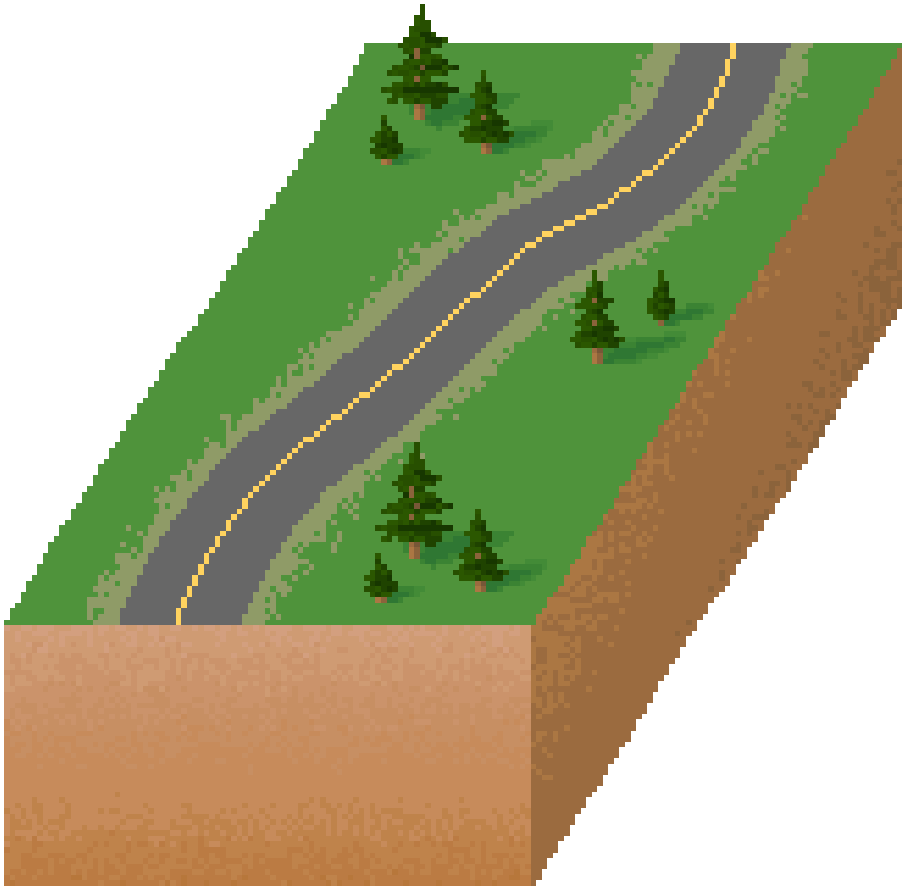
Reverse slip



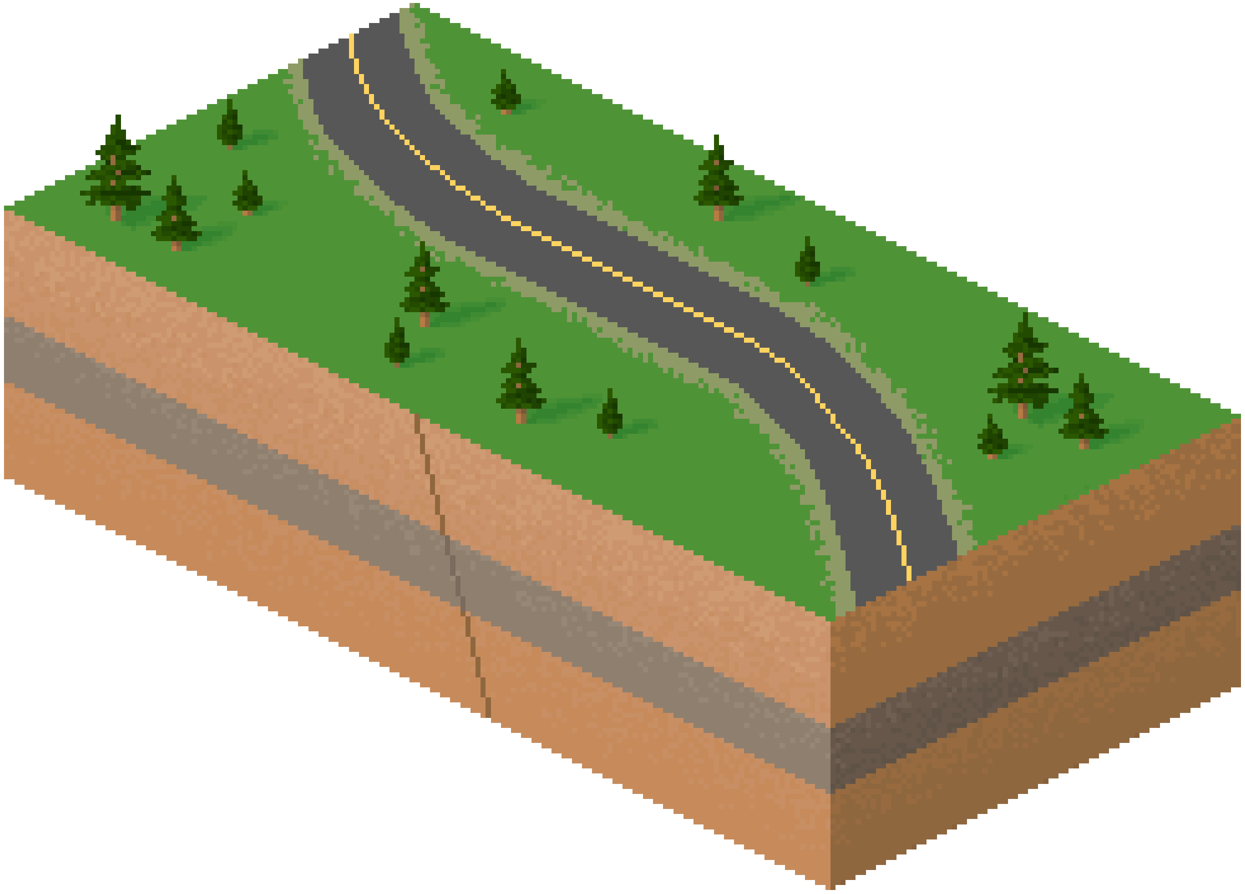
Left lateral slip



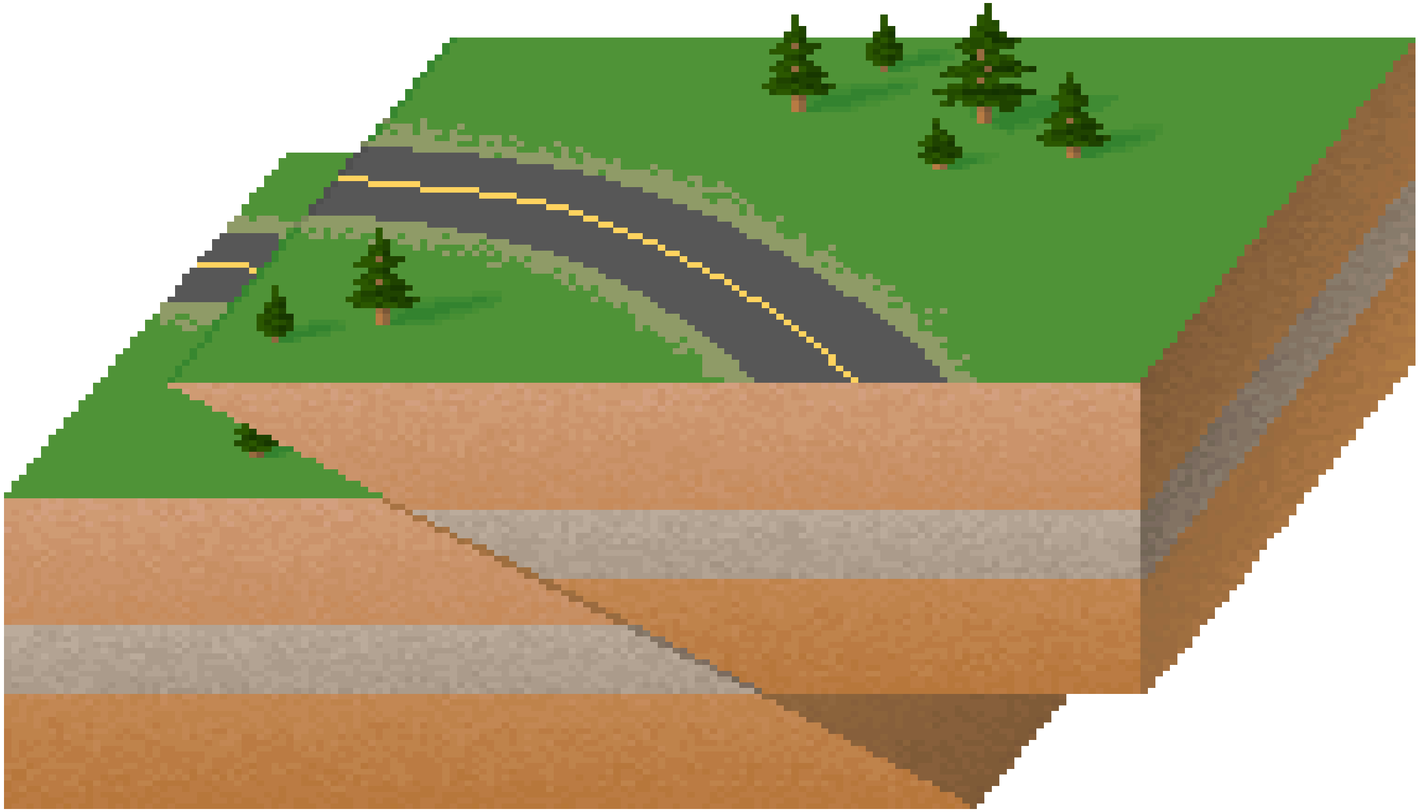
Right lateral slip



Oblique slip

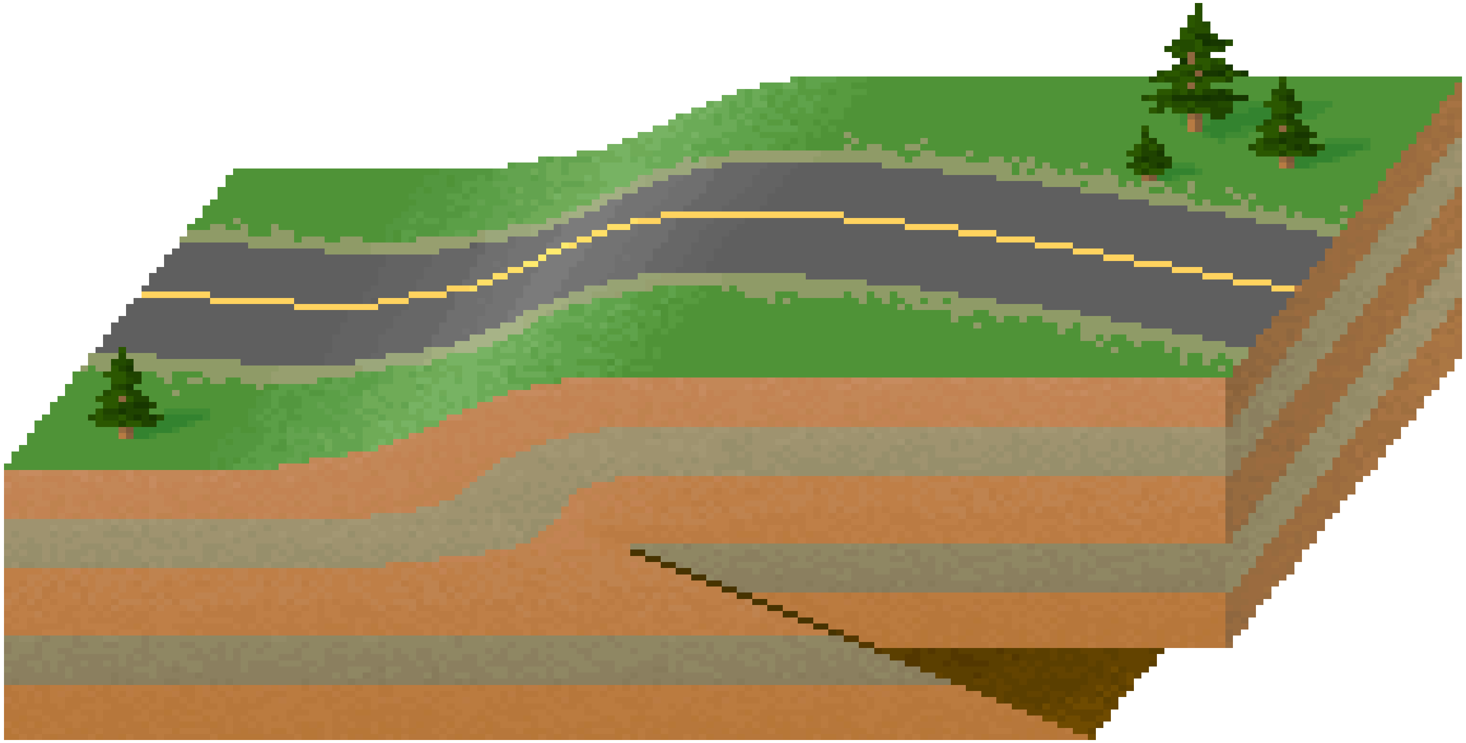


Thrust faulting



Thrust faulting

Blind Thrust



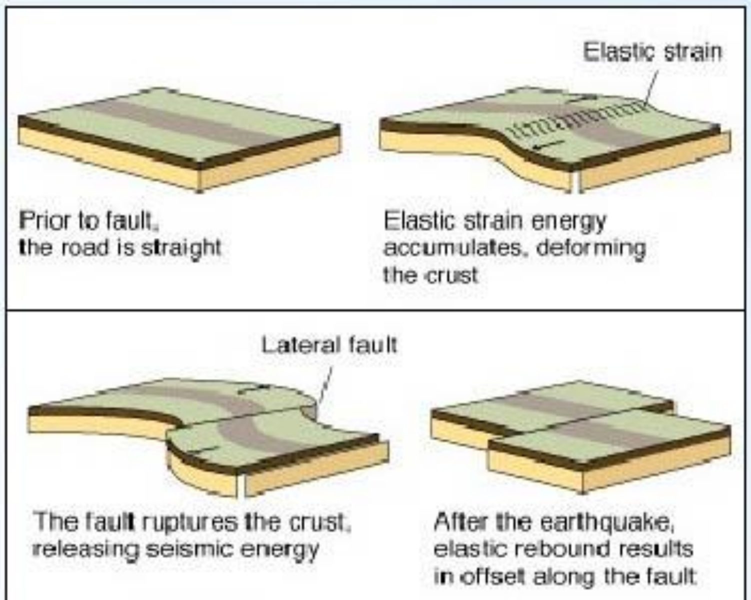
Blind thrust

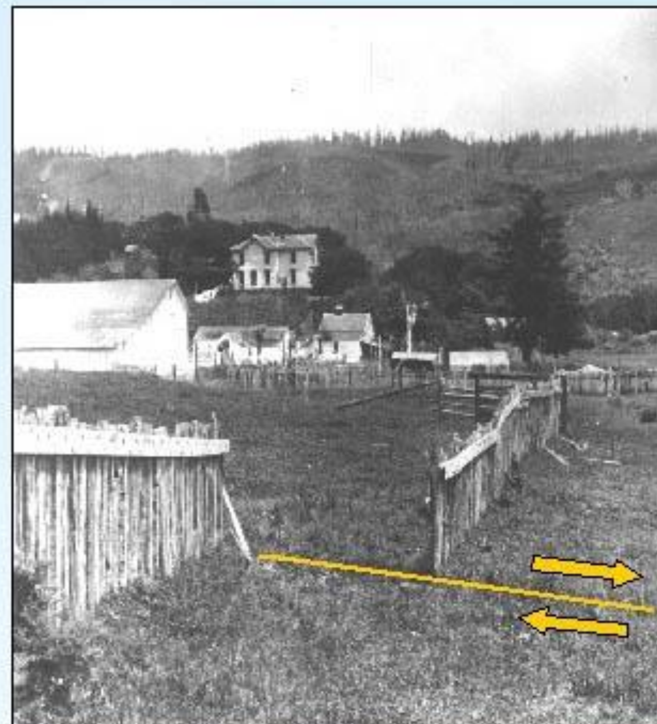
Elastic Rebound Theorey

- The sudden slip at the fault causes *the earthquake…*
- a violent shaking of the Earth during which large elastic strain energy released spreads out in the form of seismic waves that travel through the body and along the surface of the Earth.
- And, after the earthquake is over, the process of strain build-up at this modified interface between the tectonic plates starts all over again(Figure 6).
- Earth scientists know this as the *Elastic Rebound Theory. The collection of* material points at the fault over which slip occurs usually constitutes an oblong three-dimensional volume, with its long dimension often running into tens of kilometers in case of significant earthquakes.

How earthquakes occur? Elastic rebound theory

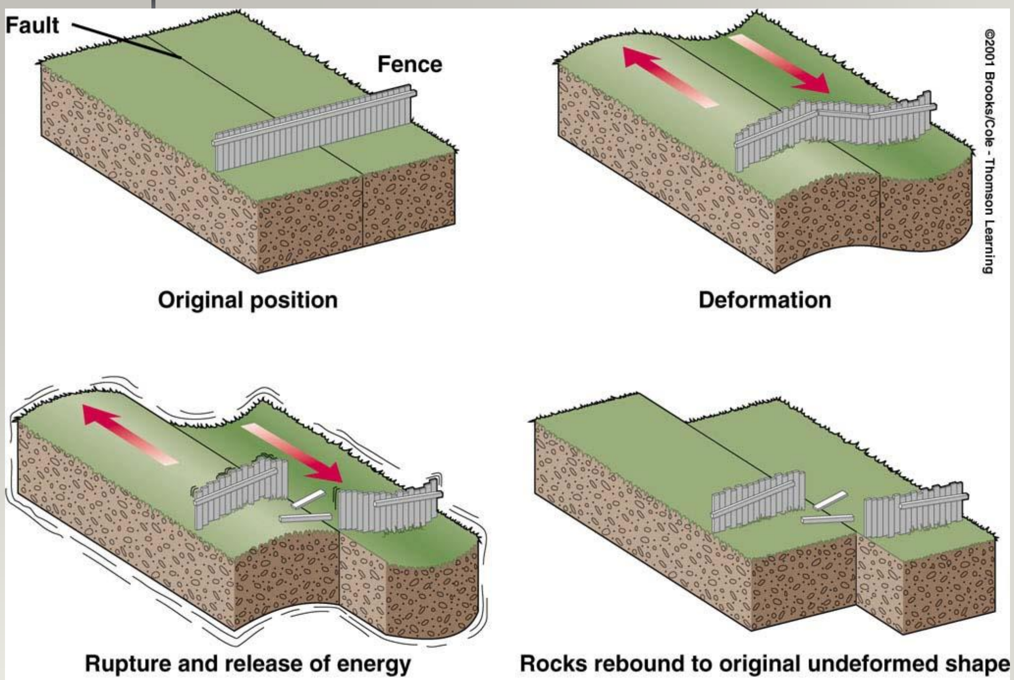
Elastic Rebound Theory Relates Faulting and Earthquakes

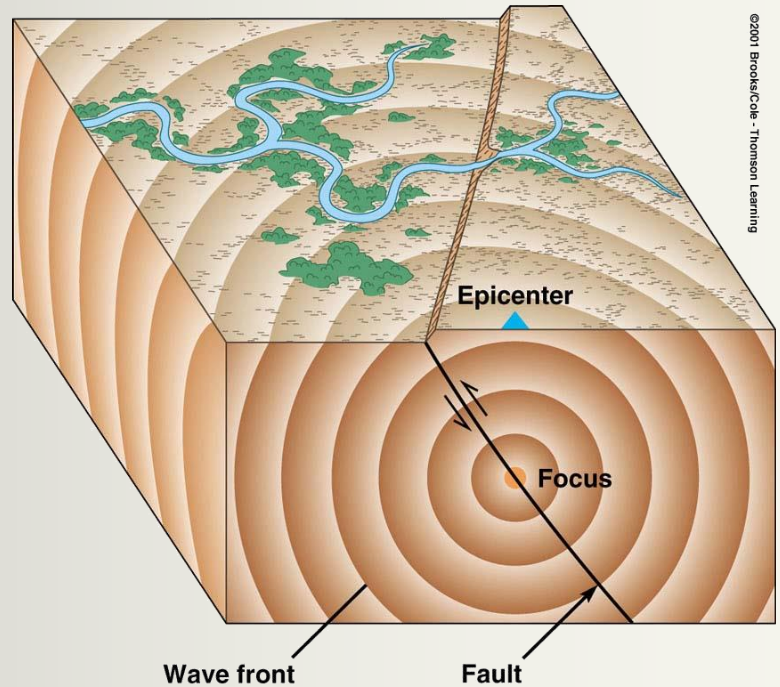




- Fence offset in 1906 quake on San Andreas Fault

How earthquakes occur? Elastic rebound theory





- **Because of friction, the blocks do not slide, but are deformed.**
- **When the stresses within rocks exceed friction, rupture occurs.**
- **Elastic energy, stored in the system, is released after rupture in waves that radiate outward from the fault.**

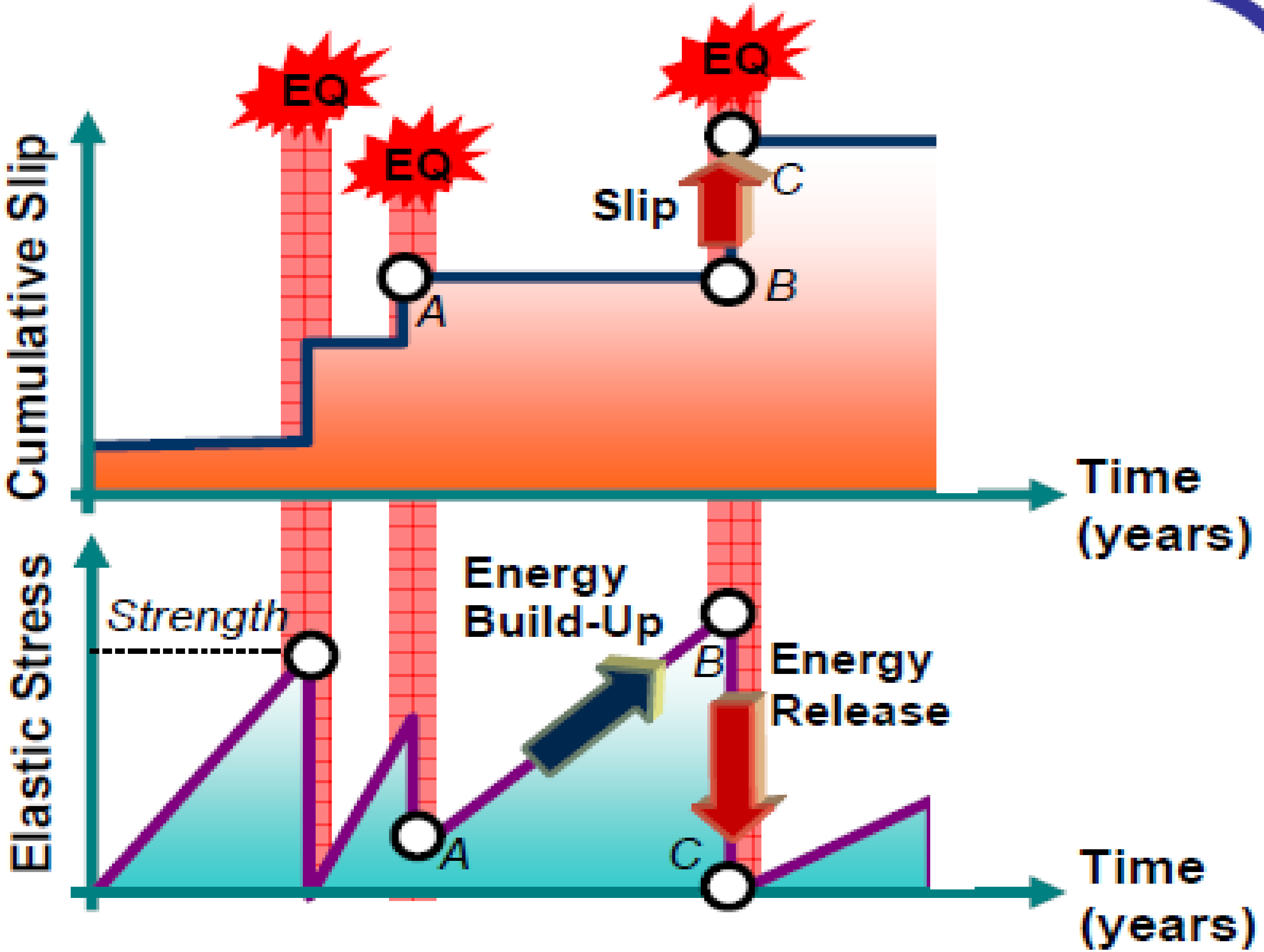
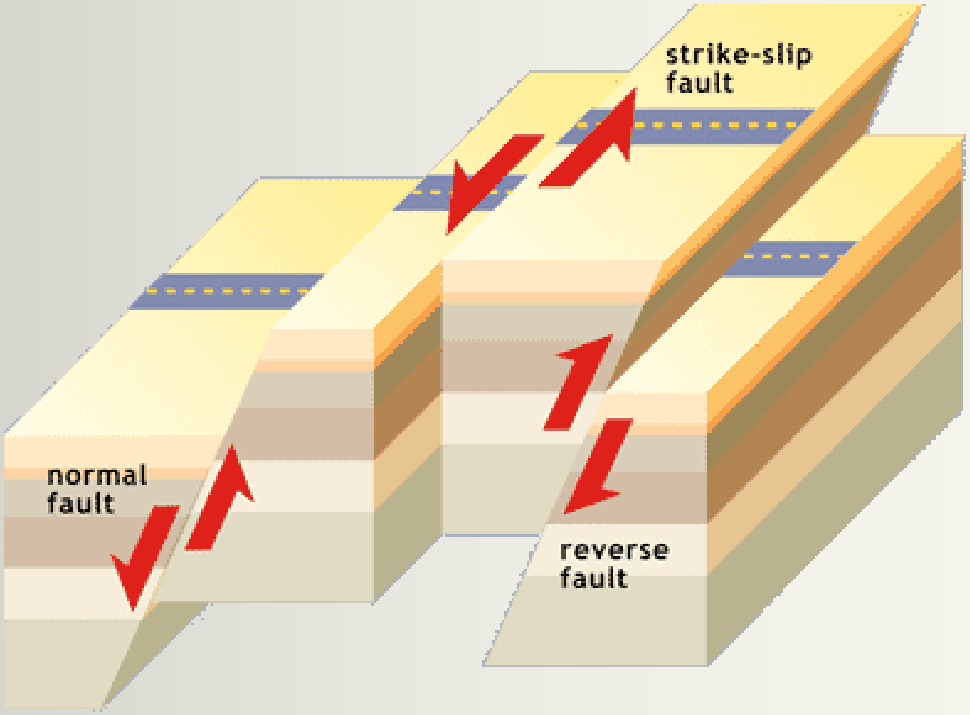


Figure 6: Elastic Rebound Theory

How earthquakes occur?

- Earthquakes occur at **FAULTS.**
- Fault is a weak zone separating two geological blocks.
- Tectonic forces cause the blocks to move relative one to another.



Types of Earthquakes and Faults

- Most earthquakes in the world occur along the boundaries of the tectonic plates as described above and are called *Inter-plate Earthquakes (e.g., 1897 Assam* (India) earthquake).
- A number of earthquakes also occur within the plate itself but away from the plate boundaries (*e.g., 1993 Latur (India) earthquake); these* are called *Intra-plate Earthquakes.*
- *Here, a tectonic plate* breaks in between. In both types of earthquakes, the slip generated at the fault during earthquakes is along both vertical and horizontal directions (called *Dip Slip)* and lateral directions (called *Strike Slip) (Figure 7),* with one of them dominating sometimes.

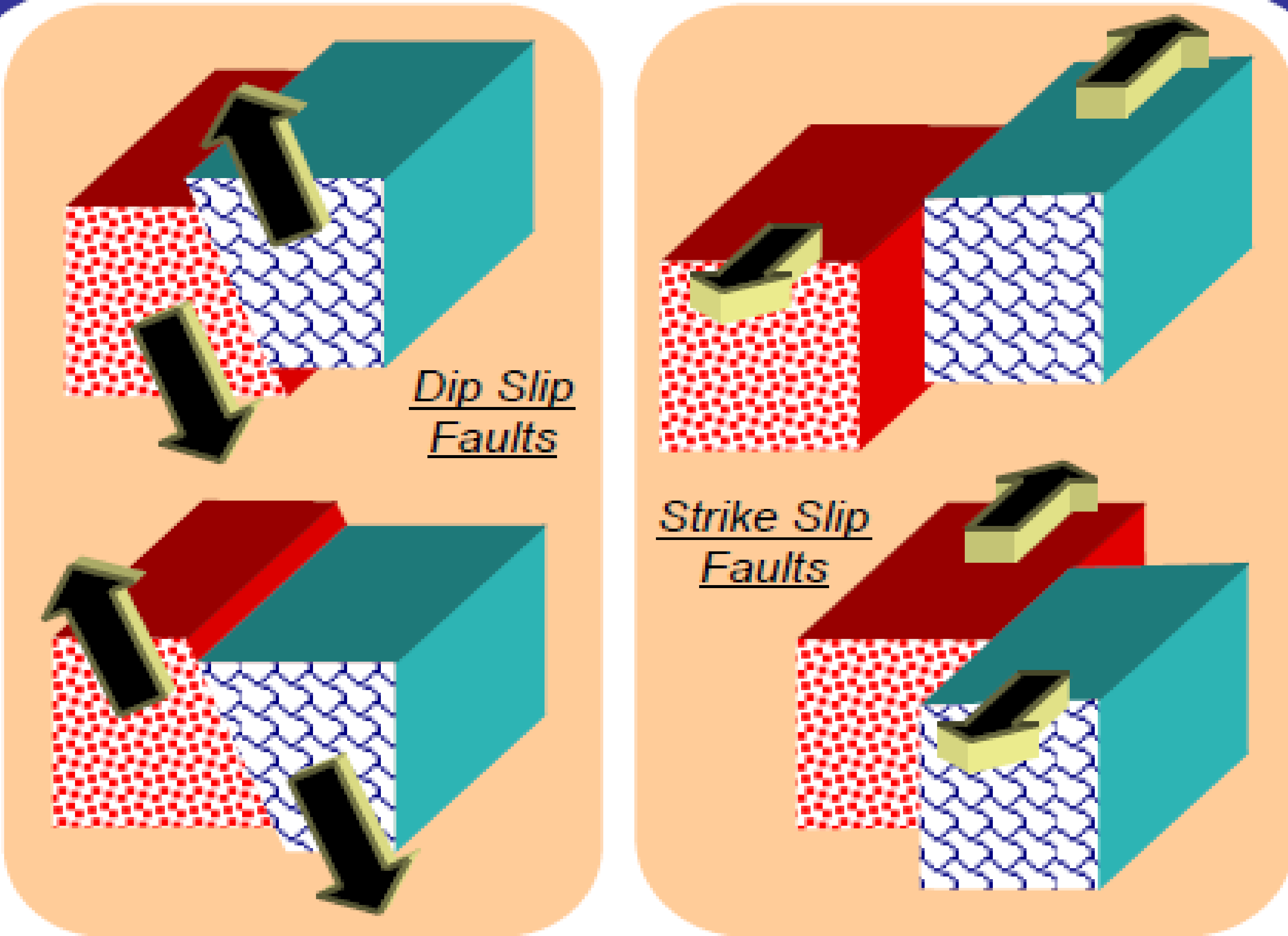
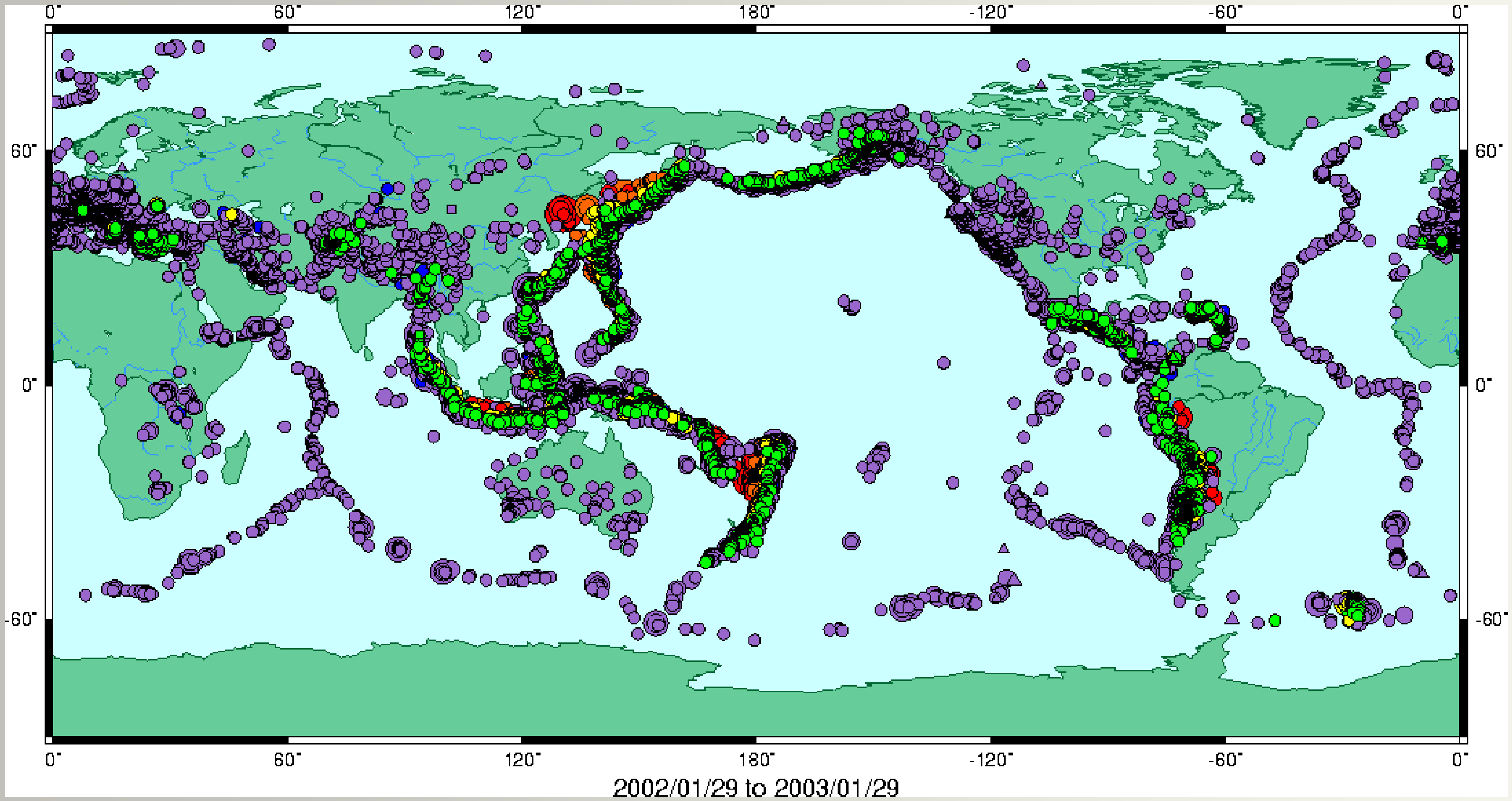
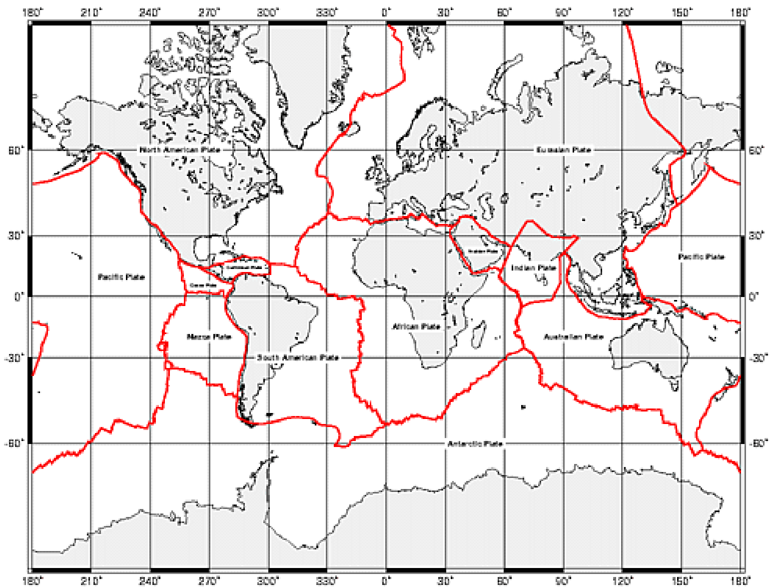


Figure 7: Type of Faults

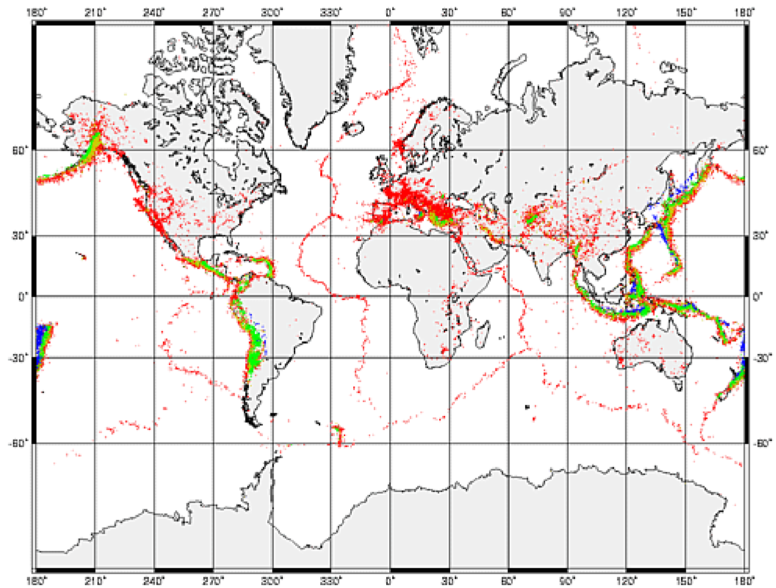
One year of seismicity

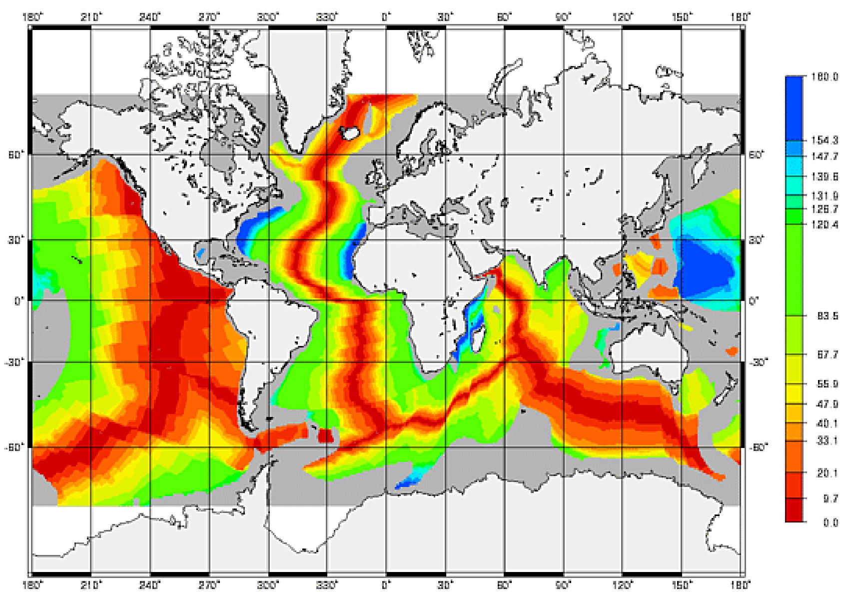


MAJOR TECTONIC PLATES

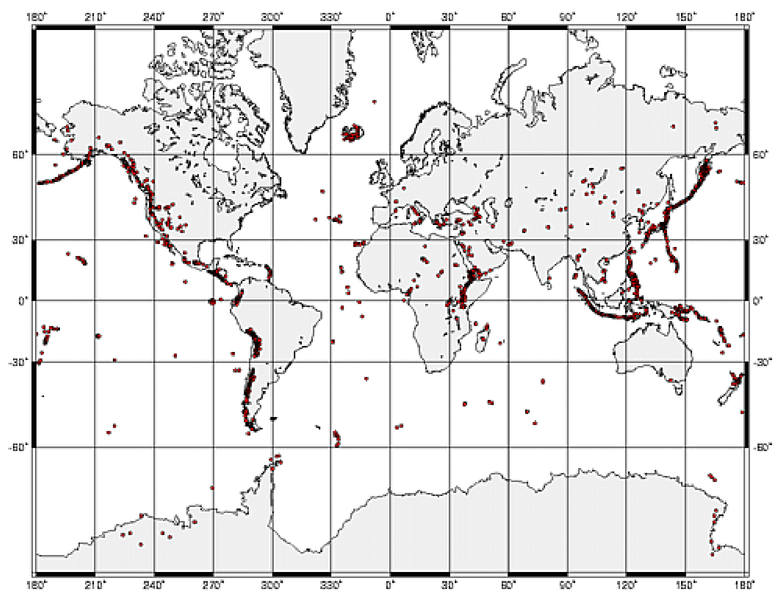


EARTHQUAKE EPICENTRES





OCEAN-BOTTOM AGE



VOLCANOES

Seismic waves

- Large strain energy released during an earthquake travels as seismic waves in all directions through the Earth's layers, reflecting and refracting at each interface.
- These waves are of two types - *body waves* and *surface waves; the latter are restricted to near the* Earth's surface (Figure 1).
- Body waves consist of *Primary Waves (P-waves) and Secondary Waves (Swaves),*
- surface waves consist of *Love waves and Rayleigh waves.*

- *Under P-waves, material particles* undergo extensional and compressional strains along direction of energy transmission,
- but under S-waves, oscillate at right angles to it (Figure 2).
- Love waves cause surface motions similar to that by S-waves, but with no vertical component.
- Rayleigh wave makes a material particle oscillate in an elliptic path in the vertical plane (with horizontal motion along direction of energy transmission).

Elastic waves – Body waves

Longitudinal waves:

- They are faster than transversal waves and thus arrive first.
- The particles oscillate in the direction of spreading of the wave.
- Compressional waves
- P-waves

Transversal waves:

- The particles oscillate in the direction perpendicular to the spreading direction.
- Shear waves – they do not propagate through solids (e.g. through the outer core).
- S-waves

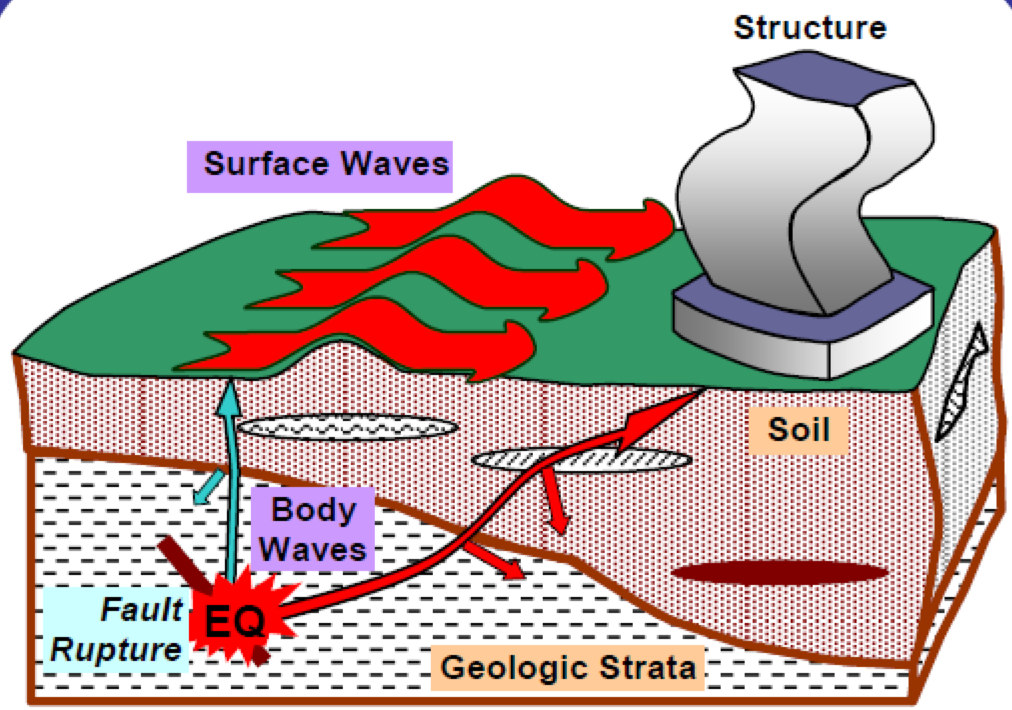
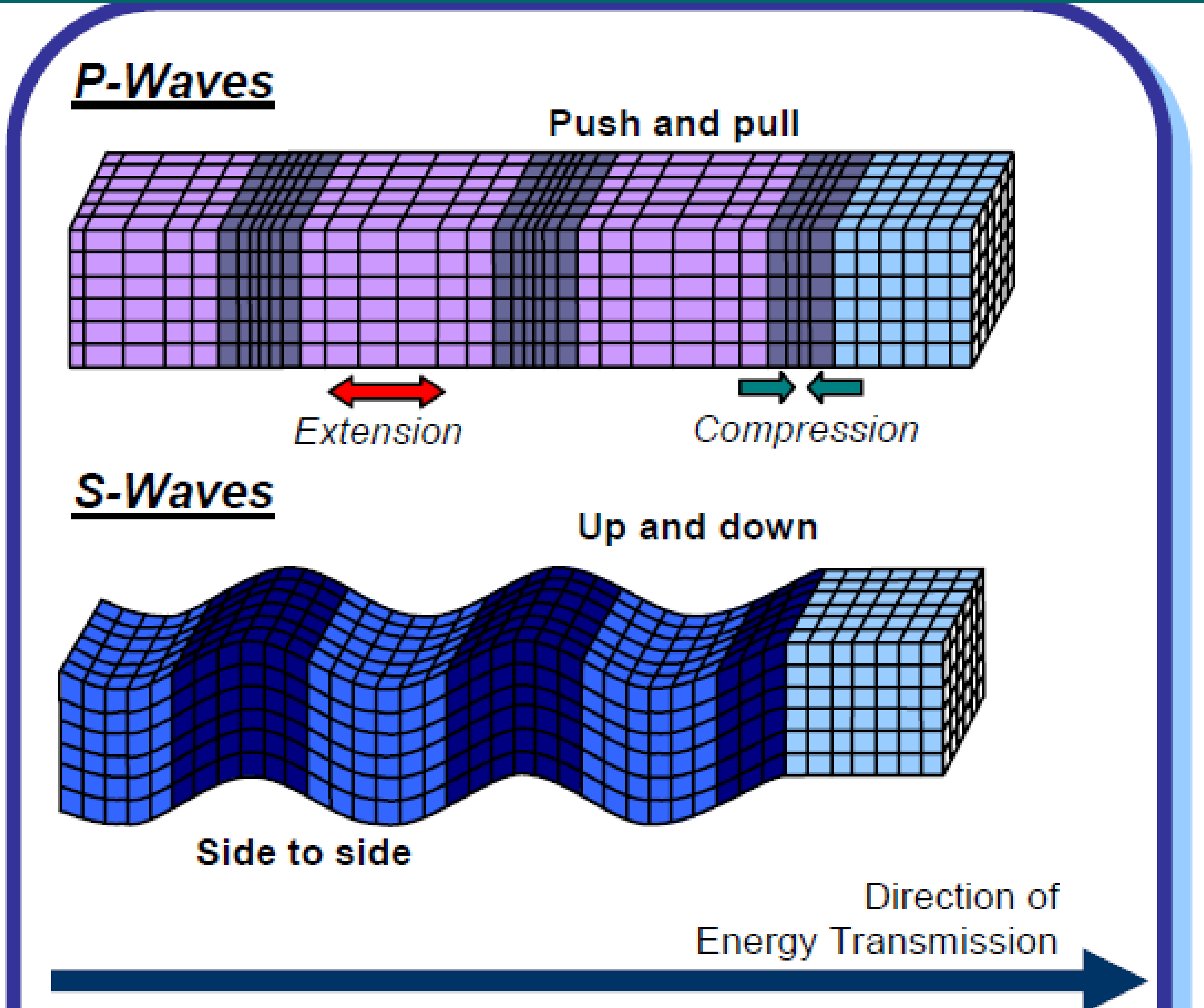
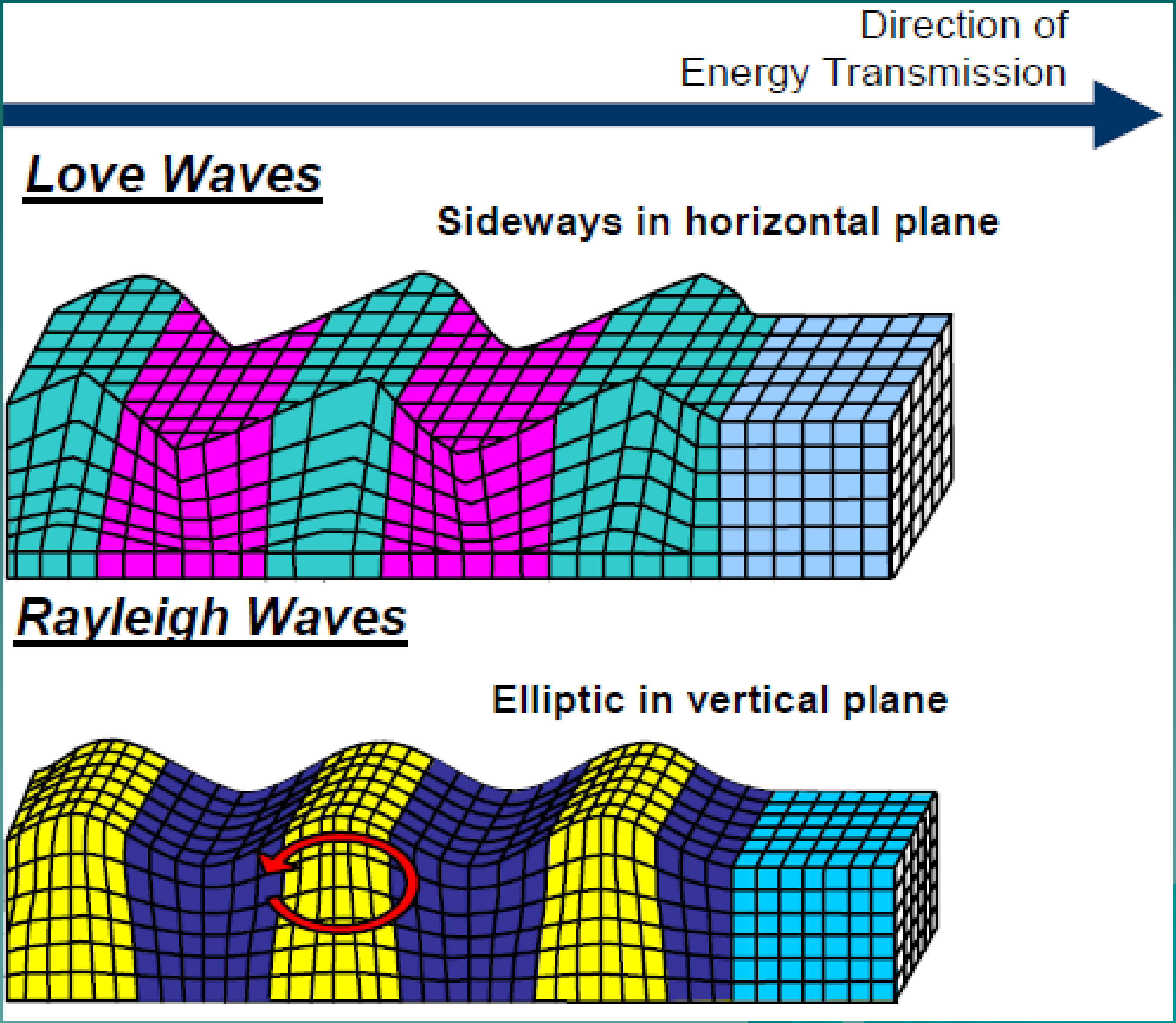


Figure 1: Arrival of Seismic Waves at a Site

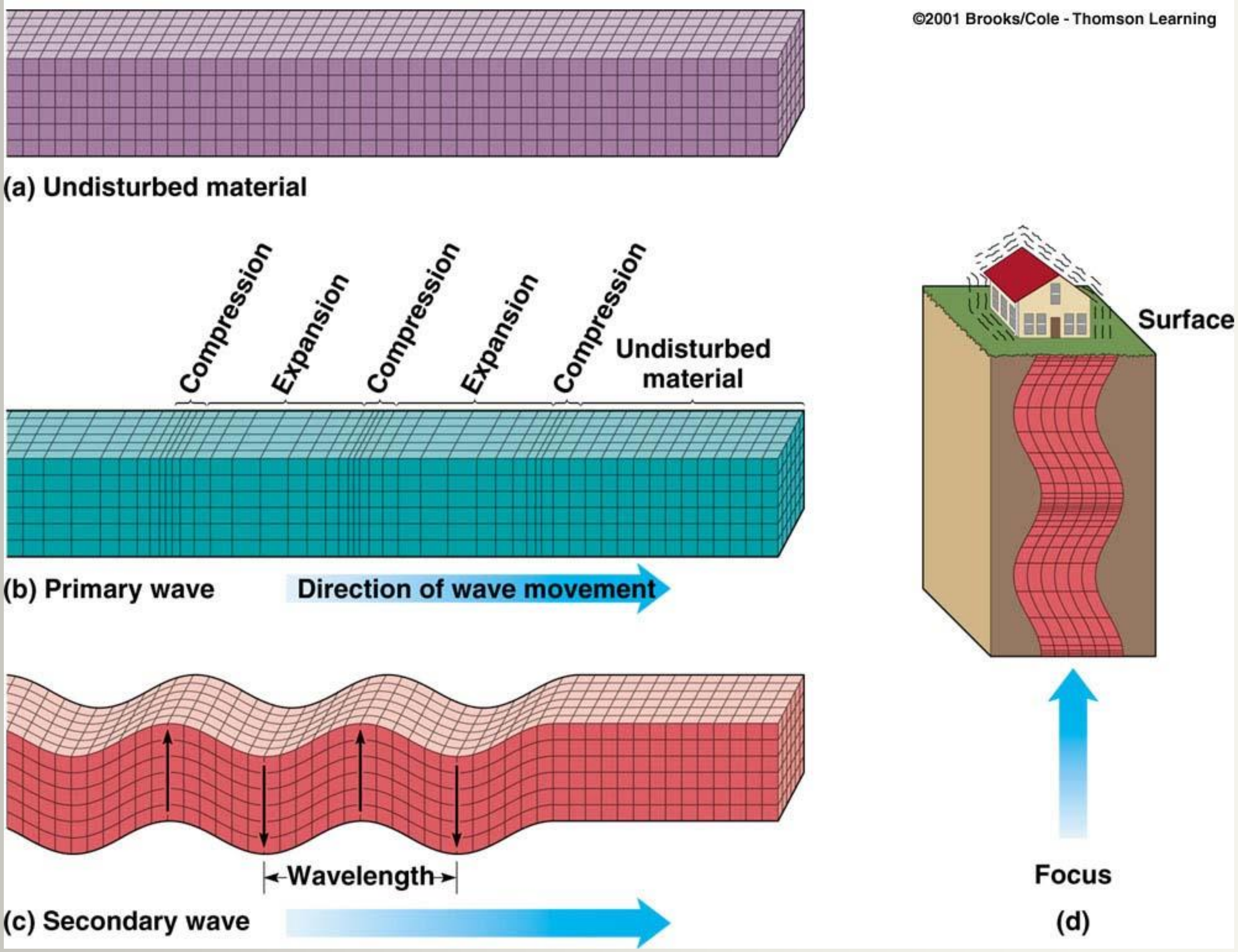

P-Waves
Push and pull
Extension
Compression
S-Waves
Up and down
Side to side
Direction of
Energy Transmission


Direction of
Energy Transmission
Love Waves
Sideways in horizontal plane
Rayleigh Waves
Elliptic in vertical plane

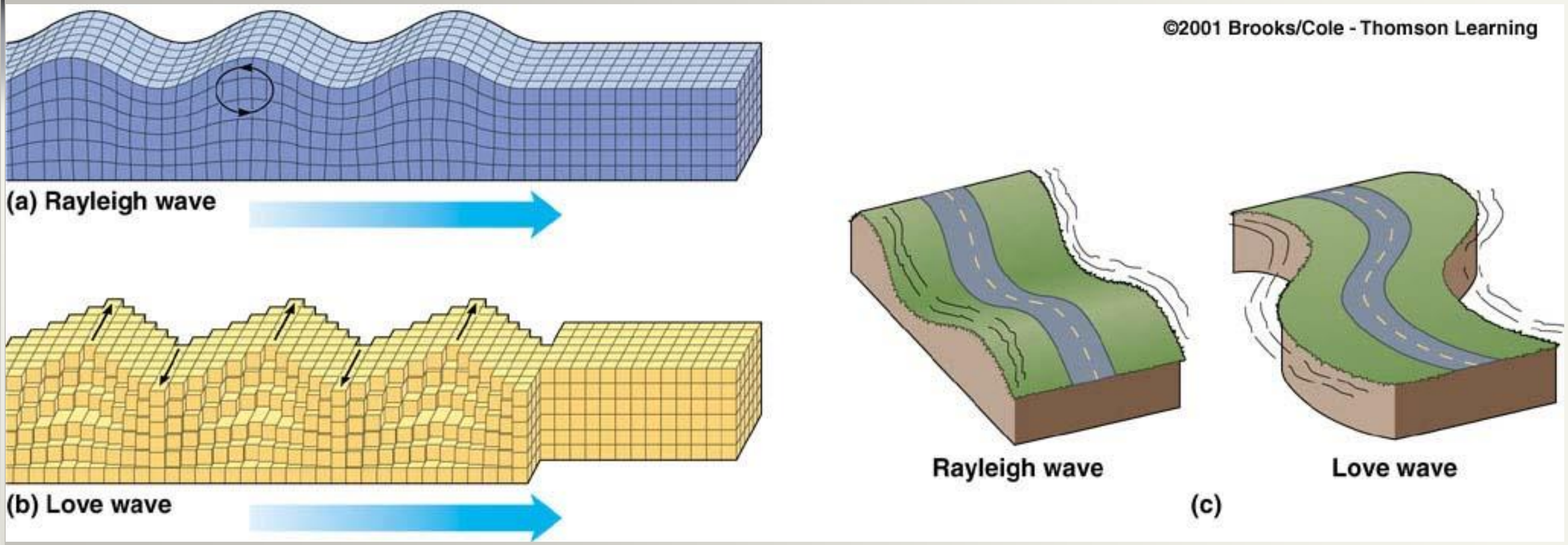
Elastic waves – Body waves

P-waves:

S-waves:



Elastic waves – Surface waves



Surface waves: Rayleigh and Love waves

- Their amplitude diminishes with the depth.
- They have large amplitudes and are **slower** than body waves.
- These are dispersive waves (large periods are faster).

Basic Terminology

- The point on the fault where slip starts is the *Focus* or *Hypocenter, and the point vertically above this on* the surface of the Earth is the *Epicenter (Figure 1).*
- *The* depth of focus from the epicenter, called as *Focal Depth*, is an important parameter in determining the damaging potential of an earthquake.
- Most of the damaging earthquakes have shallow focus with focal depths less than about 70km.
- Distance from epicenter to any point of interest is called *epicentral distance*.

- A number of smaller size earthquakes take place before and after a big earthquake (*i.e., the Main Shock).*
- Those occurring before the big one are called *Foreshocks, and the ones after are called Aftershocks.*

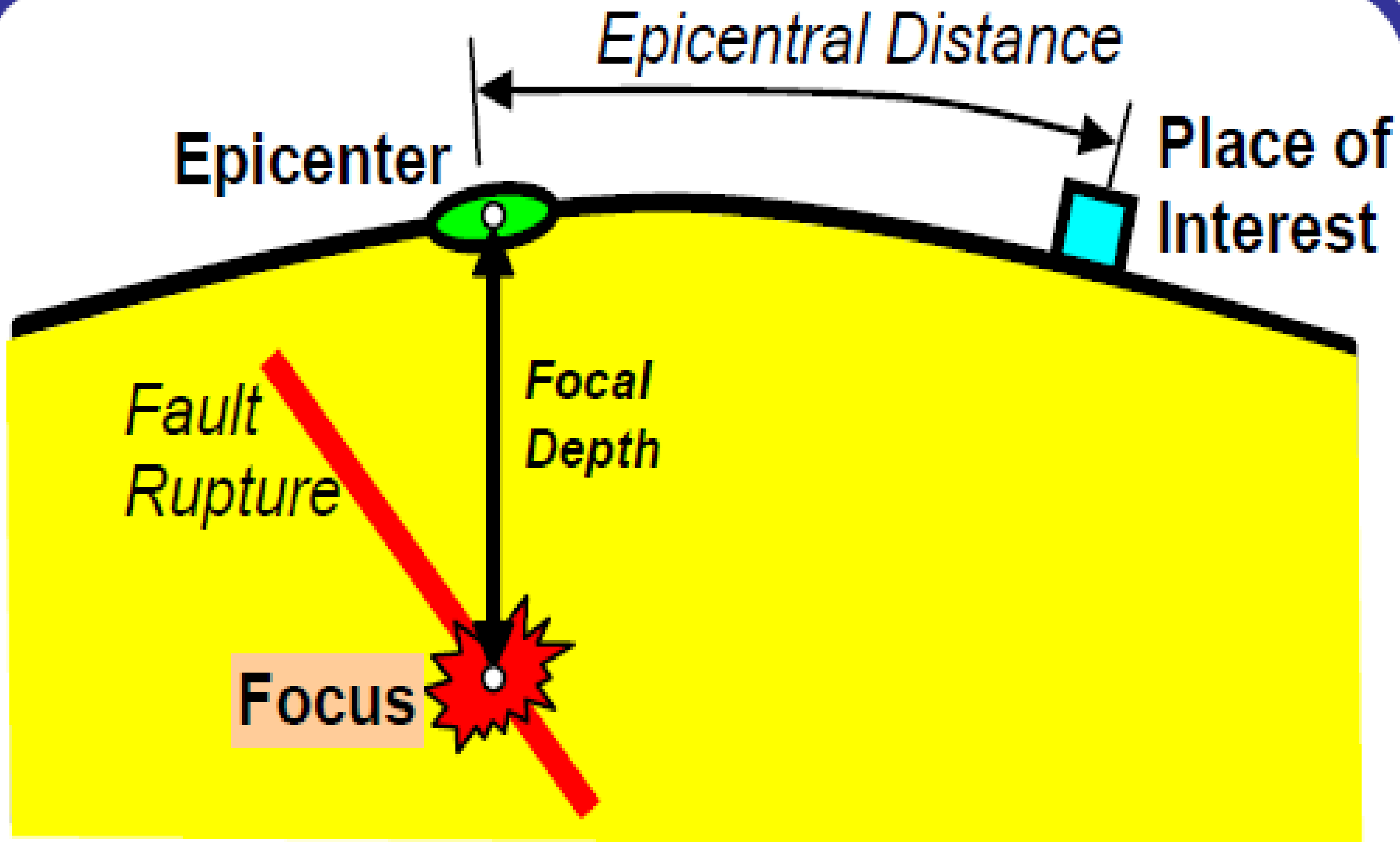


Figure 1: Basic terminology

Magnitude

- Magnitude is a *quantitative measure of the actual* size of the earthquake.
- Professor Charles Richter noticed that (a) at the same distance, seismograms (records of earthquake ground vibration) of larger earthquakes have bigger wave amplitude than those of smaller earthquakes; and (b) for a given earthquake, seismograms at farther distances have smaller wave amplitude than those at close distances.
- These prompted him to propose the now commonly used magnitude scale, the *Richter Scale.*

Magnitude

- *It is obtained from* the seismograms and accounts for the dependence of waveform amplitude on epicentral distance. This scale is also called *Local Magnitude scale.*
- *There are other* magnitude scales, like the *Body Wave Magnitude, Surface Wave Magnitude and Wave Energy Magnitude.*
- These *numerical magnitude scales have no upper and* lower limits; the magnitude of a very small earthquake can be zero or even negative.

Table 1: *Global occurrence of earthquakes*

Group	Magnitude	Annual Average Number
Great	8 and higher	1
Major	7 – 7.9	18
Strong	6 – 6.9	120
Moderate	5 – 5.9	800
Light	4 – 4.9	6,200 (estimated)
Minor	3 – 3.9	49,000 (estimated)
Very Minor	< 3.0	M2-3: ~1,000/day; M1-2: ~8,000/day

Source: http::/neic.usgs.gov/neis/eqlists/eqstats.html

Intensity

- Intensity is a *qualitative measure of the actual* shaking at a location during an earthquake, and is assigned as *Roman Capital Numerals.*
- *There are many* intensity scales. Two commonly used ones are the *Modified Mercalli Intensity (MMI) Scale and the MSK Scale.*
- *Both scales are quite similar and range from I* (least perceptive) to XII (most severe).
- The intensity scales are based on three features of shaking – perception by people and animals, performance of buildings, and changes to natural surroundings.

Basic Difference: Magnitude versus Intensity

- *Magnitude of an earthquake is a measure of its size.* For instance, one can measure the size of an earthquake by the amount of strain energy released by the fault rupture.
- This means that the magnitude of the earthquake is a *single value for a given earthquake.*
- *On* the other hand, *intensity is an indicator of the severity* of shaking generated at a given location.
- Clearly, the severity of shaking is much higher near the epicenter than farther away. Thus, during the same earthquake of a certain magnitude, different locations experience different levels of intensity.

- To elaborate this distinction, consider the analogy of an electric bulb (Figure 3).
- The illumination at a location near a *100-Watt bulb is higher than that* farther away from it. While the bulb releases *100 Watts* of energy, the intensity of light (or illumination, measured in *lumens) at a location depends on the* wattage of the bulb and its distance from the bulb.
- Here, the size of the bulb (*100-Watt) is like the* magnitude of an earthquake, and the illumination at a location like the intensity of shaking at that location.

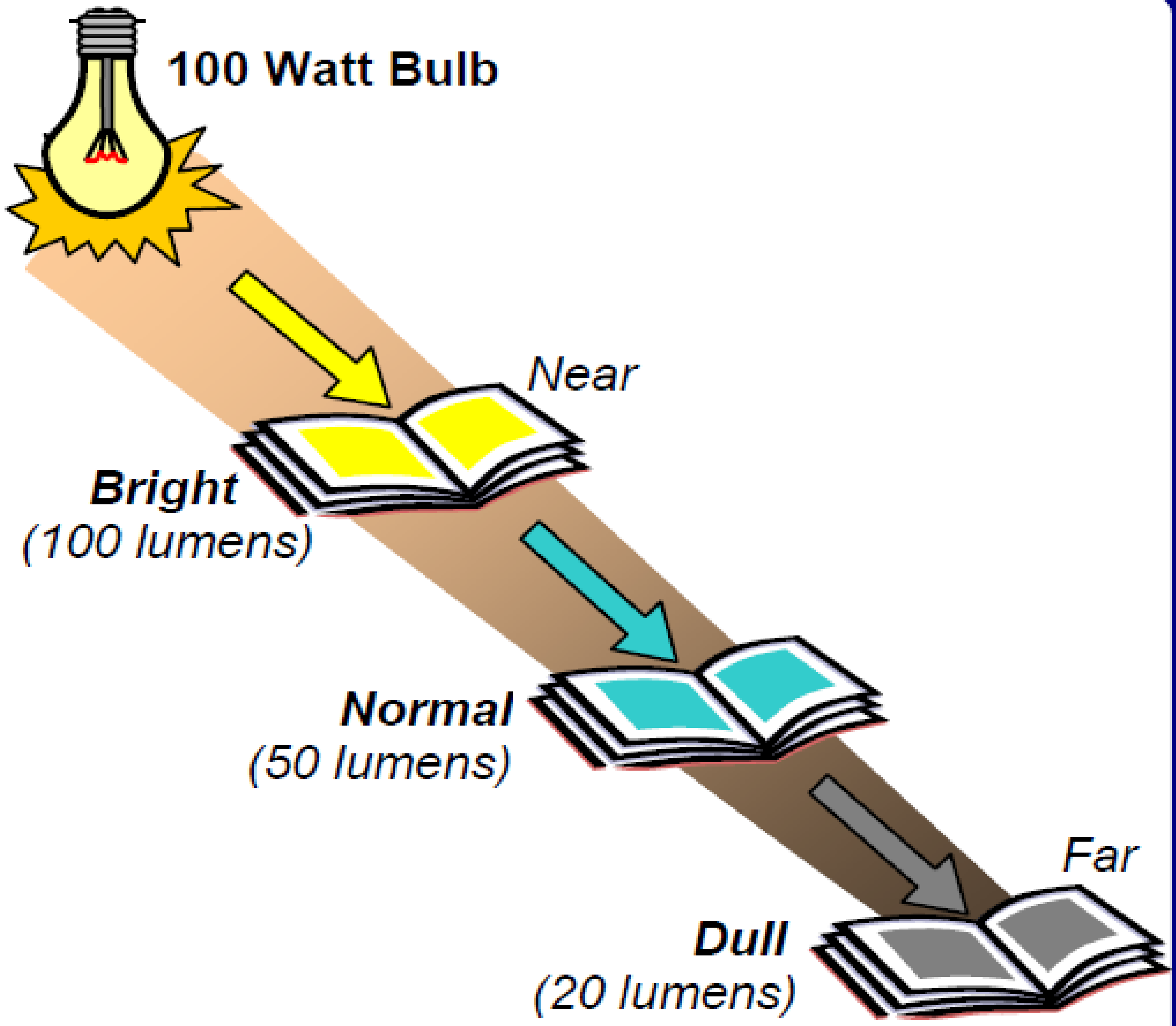


Figure 3: Reducing illumination with distance from an electric bulb

Observational Seismology Macroseismology

- MACROSEISMOLOGY deals with effects of earthquakes on humans, animals, objects and surroundings.
- The data are collected by field trips into the shaken area, and/or by questionaires sent there.
- The effects are then expressed as earthquake INTENSITY at each of the studied places.
- Intensity is graded according to **macroseismic scales** – Mercalli-Cancani-Sieberg (**MCS**), Medvedev-Sponheuer-Karnik (**MSK**), Modified Mercalli (**MM**), European Macroseismic Scale (**EMS**).
- This is a subjective method.

Observational Seismology Macroseismology

European Macroseismic Scale (EMS 98)

EMS	DEFINITION	SHORT DESCRIPTION
I	**Not felt**	Not felt, even under the most favourable circumstances.
II	**Scarcely felt**	Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.
III	**Weak**	The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	**Largely observed**	The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing.
V	**Strong**	The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few run outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Top heavy objects topple over. Doors and windows swing open or shut.

EMS	DEFINITION	SHORT DESCRIPTION
VI	**Slightly damaging**	Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings e.g. fine cracks in plaster and small pieces of plaster fall.
VII	**Damaging**	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.
VIII	**Heavily damaging**	Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse.
IX	**Destructive**	Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely.
X	**Very destructive**	Many ordinary buildings collapse.
XI	**Devastating**	Most ordinary buildings collapse.
XII	**Completely devastating**	Practically all structures above and below ground are heavily damaged or destroyed.

Measuring Instruments

- The instrument that measures earthquake shaking, a *seismograph, has three components – the sensor, the recorder and the timer.*
- *The principle on which it works* is simple and is explicitly reflected in the early seismograph (Figure 3) – a pen attached at the tip of an oscillating simple pendulum (a mass hung by a string from a support) marks on a chart paper that is held on a drum rotating at a constant speed.
- A magnet around the string provides required damping to control the amplitude of oscillations.
- The pendulum mass, string, magnet and support together constitute the *sensor; the* drum, pen and chart paper constitute the *recorder; and* the motor that rotates the drum at constant speed forms the *timer.*

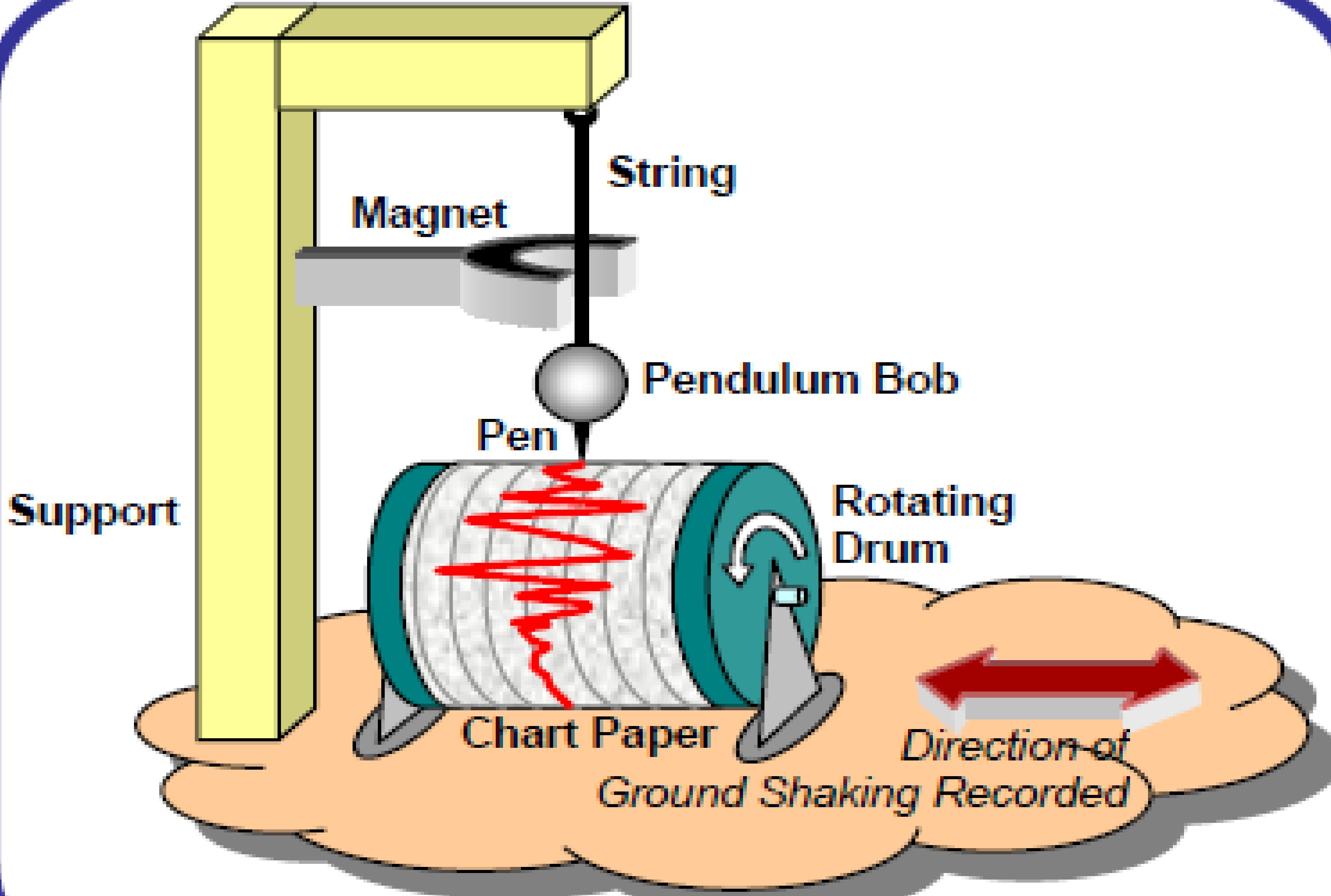
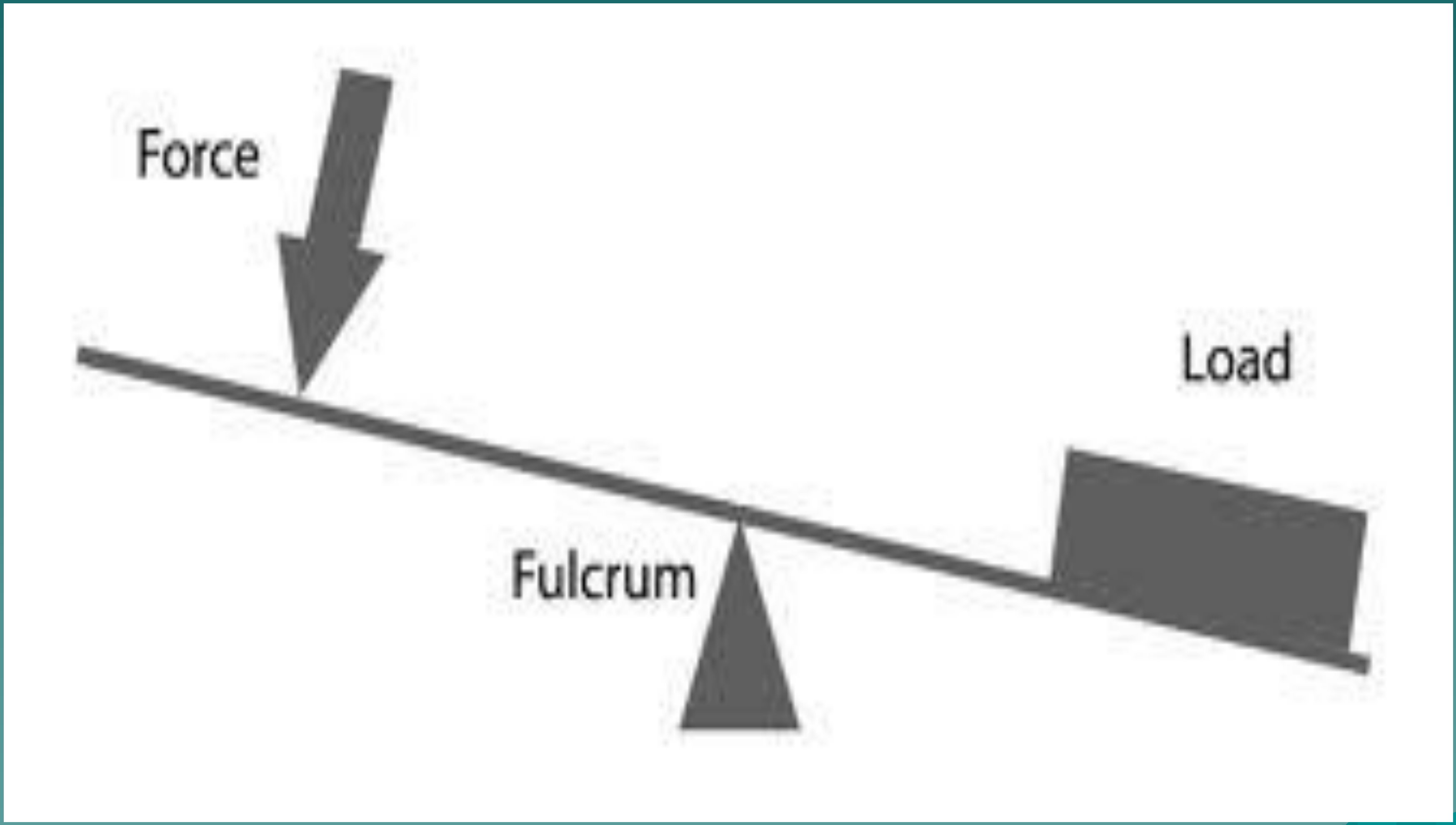


Figure 3: Schematic of ***Early Seismograph***

- One such instrument is required in each of the two orthogonal horizontal directions. Of course, for measuring vertical oscillations, the *string pendulum* (Figure 3) is replaced with a *spring pendulum* oscillating about a fulcrum.
- Some instruments do not have a timer device (*i.e., the drum holding the chart* paper does not rotate). Such instruments provide only the maximum extent (or scope) of motion during the earthquake; for this reason they are called *seismoscopes.*


Force
Load
Fulcrum

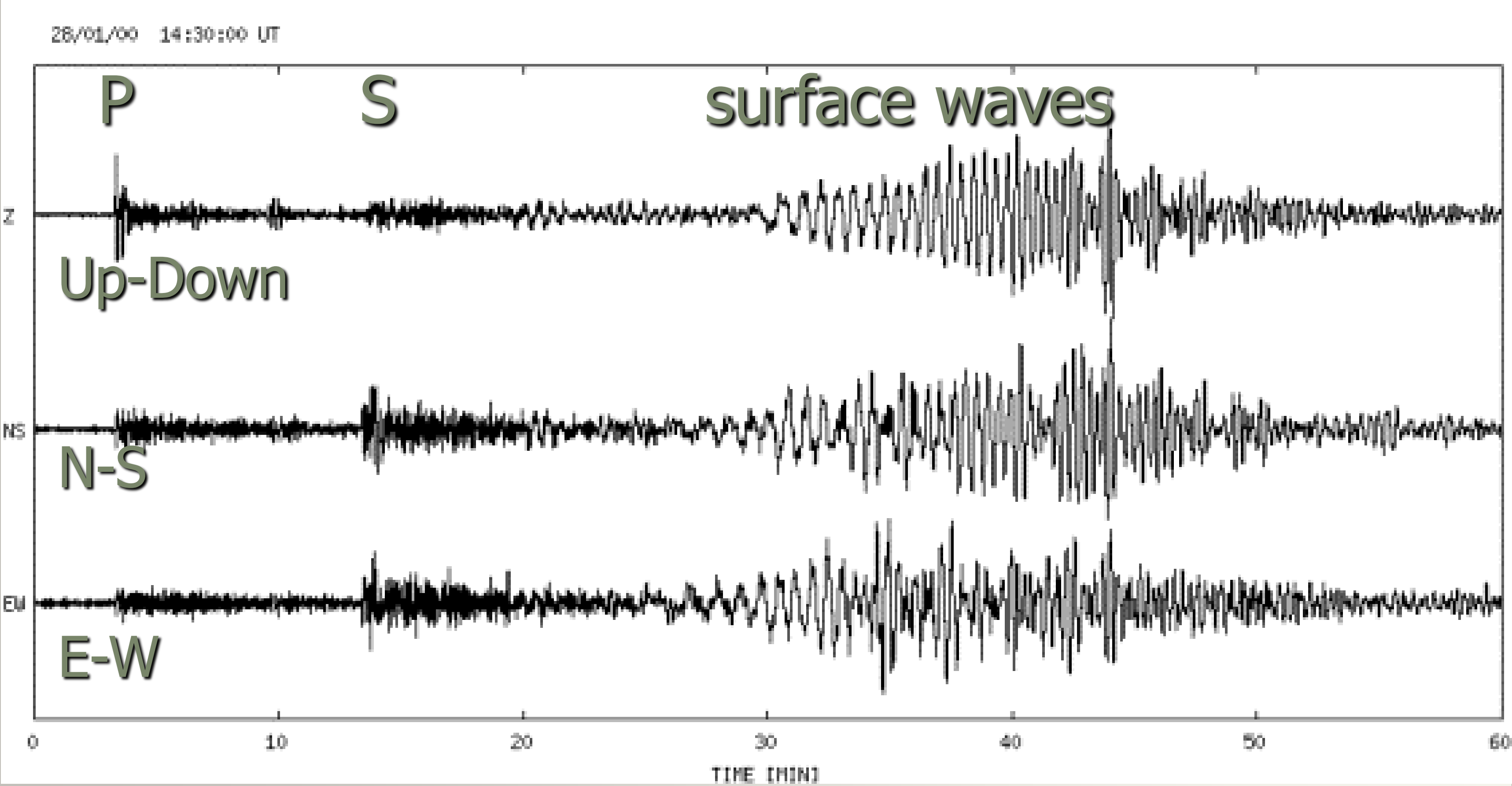
- The analog instruments have evolved over time, but today, *digital instruments using modern computer* technology are more commonly used.
- The digital instrument records the ground motion on the memory of the microprocessor that is in-built in the instrument.

Seismogram

Earthquake in Japan

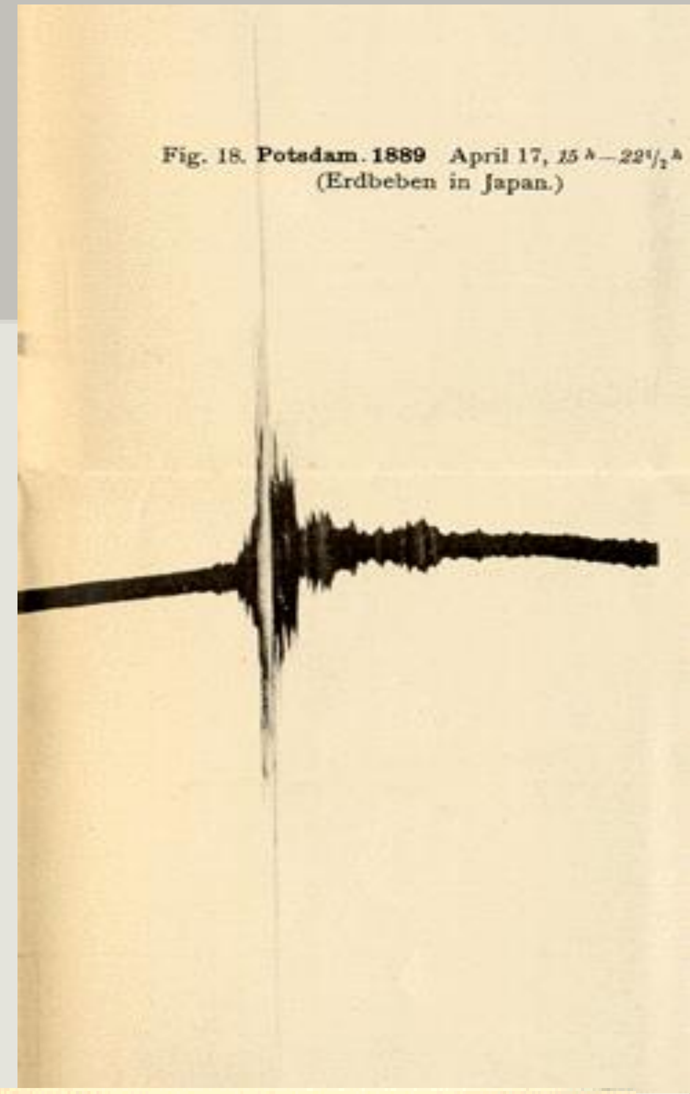
Station in Germany

Magnitude 6.5

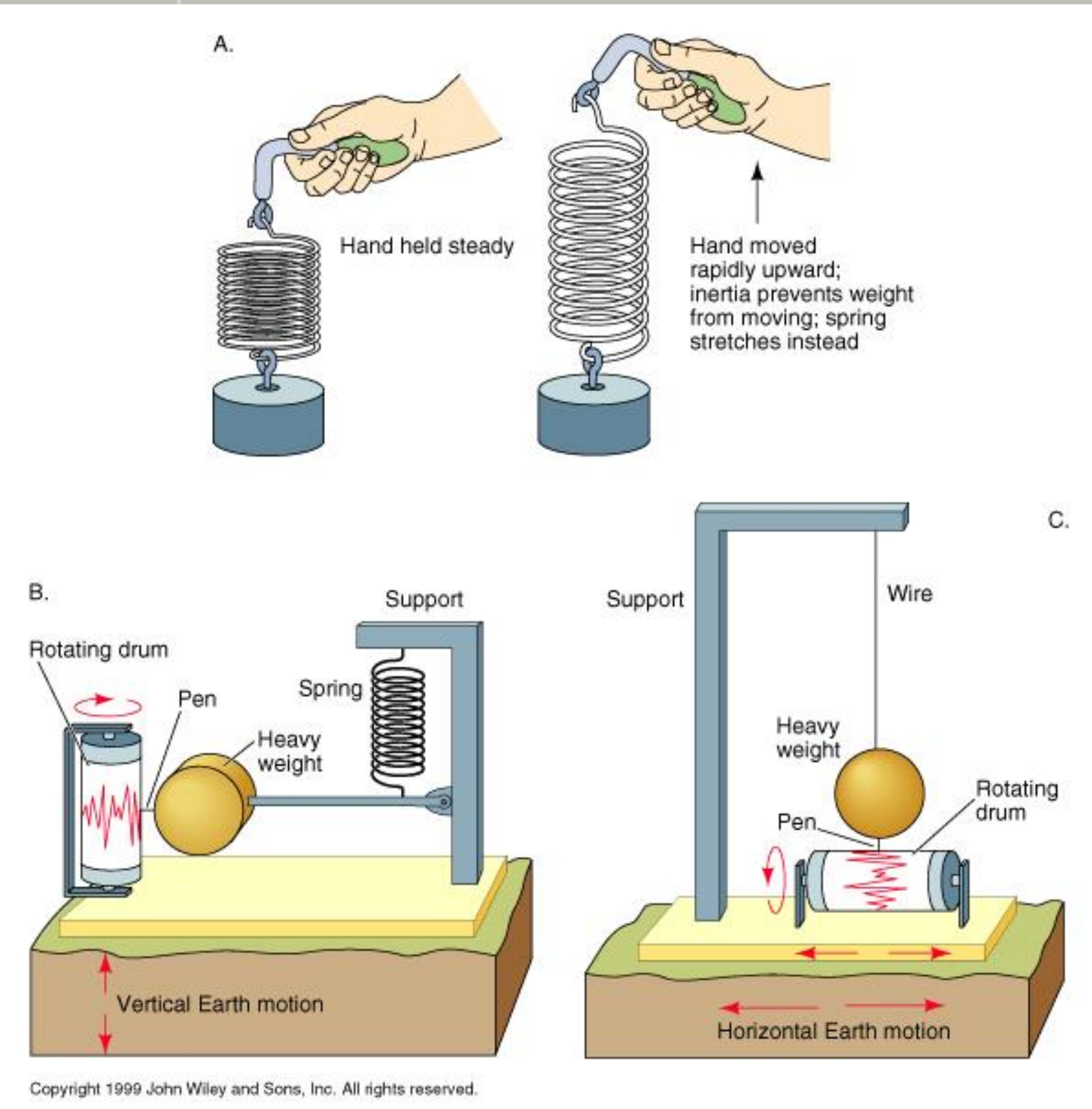


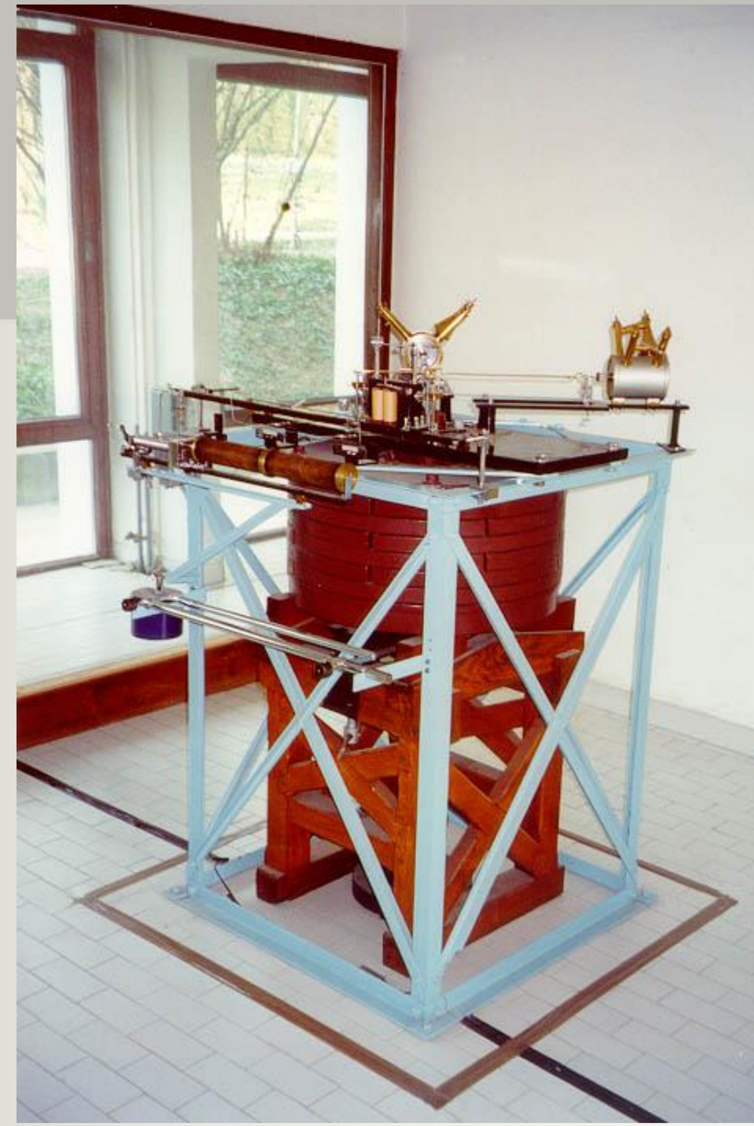
Seismographs

- Seismographs are devices that record ground motion during earthquakes.
- The first seismographs were constructed at the very end of the 19th century in Italy and Germany.



Seismographs





Horizontal 1000 kg Wiechert seismograph in Zagreb (built in 1909)

Seismographs

- Modern digital broadband seismographs are capable of recording almost the whole seismological spectrum (50 Hz – 300 s).
- Their resolution of 24 bits (high dynamic range) allows for precise recording of small quakes, as well as unsaturated registration of the largest ones.

Strong Ground motions

- Vibrations induced in the Earth's crust often induce in the ground, actual movements (accelerations) which are generally of short duration, rarely exceeding 1 minute.
- Ground motions are caused by seismic waves generated by release of strain energy at the focus.
- These waves travel with different velocities, amplitudes and levels of energy. Thus, the amplitudes and directions of these ground motions randomly vary with time. That is why earthquake loading is called randomly varying load

Strong Ground motions

- In general, severity of ground shaking increases as magnitude increases and decreases as distance from the hypocenter increases, That is large earthquakes at great distances can produce weak motions that may not damage structures

Characteristics of Strong Ground Motions

- The ground motion can be represented in terms of displacement, velocity and acceleration as shown in below figure.
- A graph plotted between acceleration of ground and time is called accelerogram.
- The nature of accelerograms may vary depending on energy released at focus, type of fault, geology along the fault plane, and local soil.
- The ground velocity and displacement can be obtained by direct integration of an accelerogram.
- Accelerograms having important information about ground motion, peak amplitude, duration of strong motion such as frequency and energy content

Characteristics of Strong Ground Motions

- Peak Ground Acceleration (PGA) is the maximum acceleration which is experienced by particle on the ground

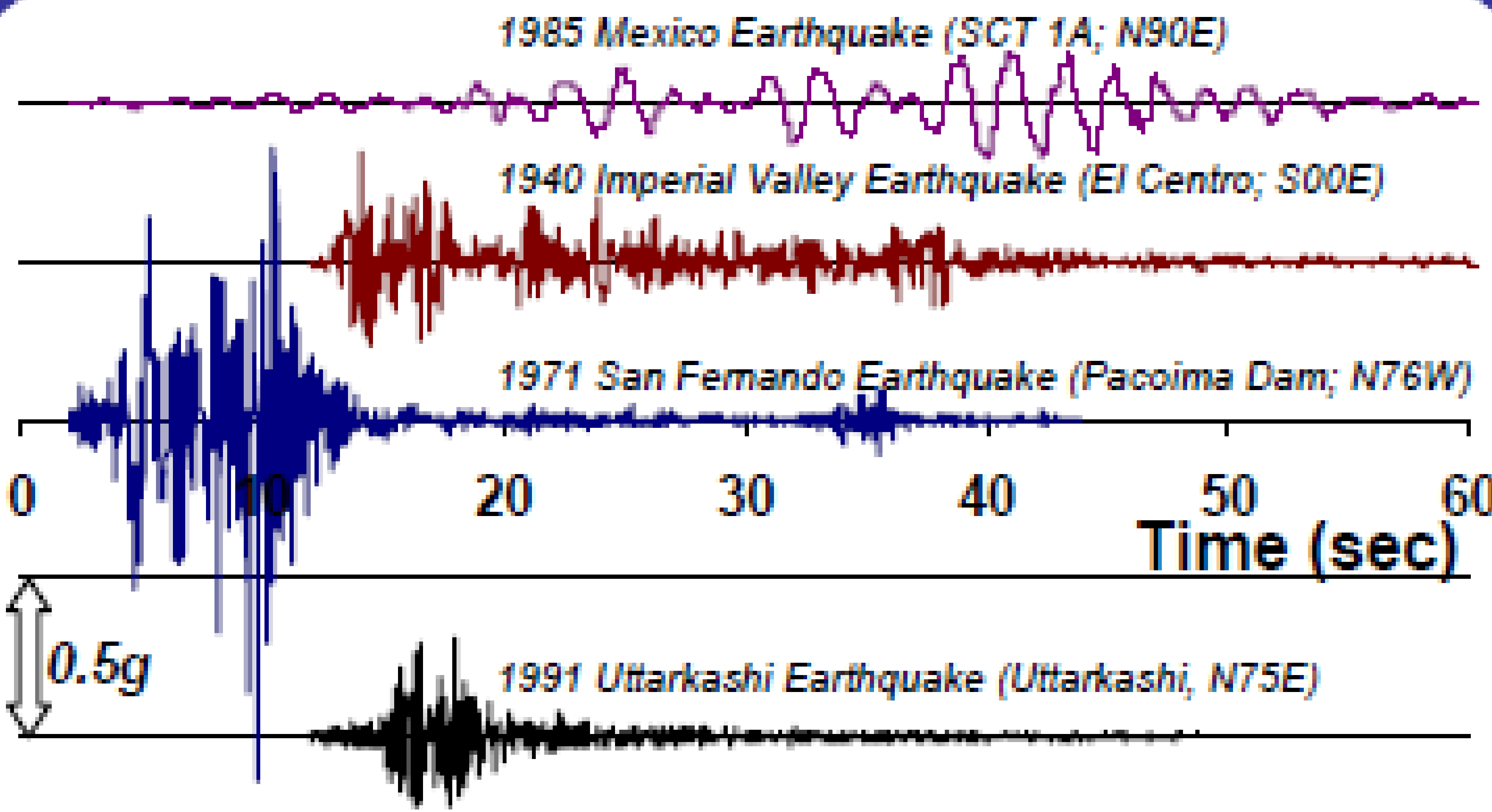
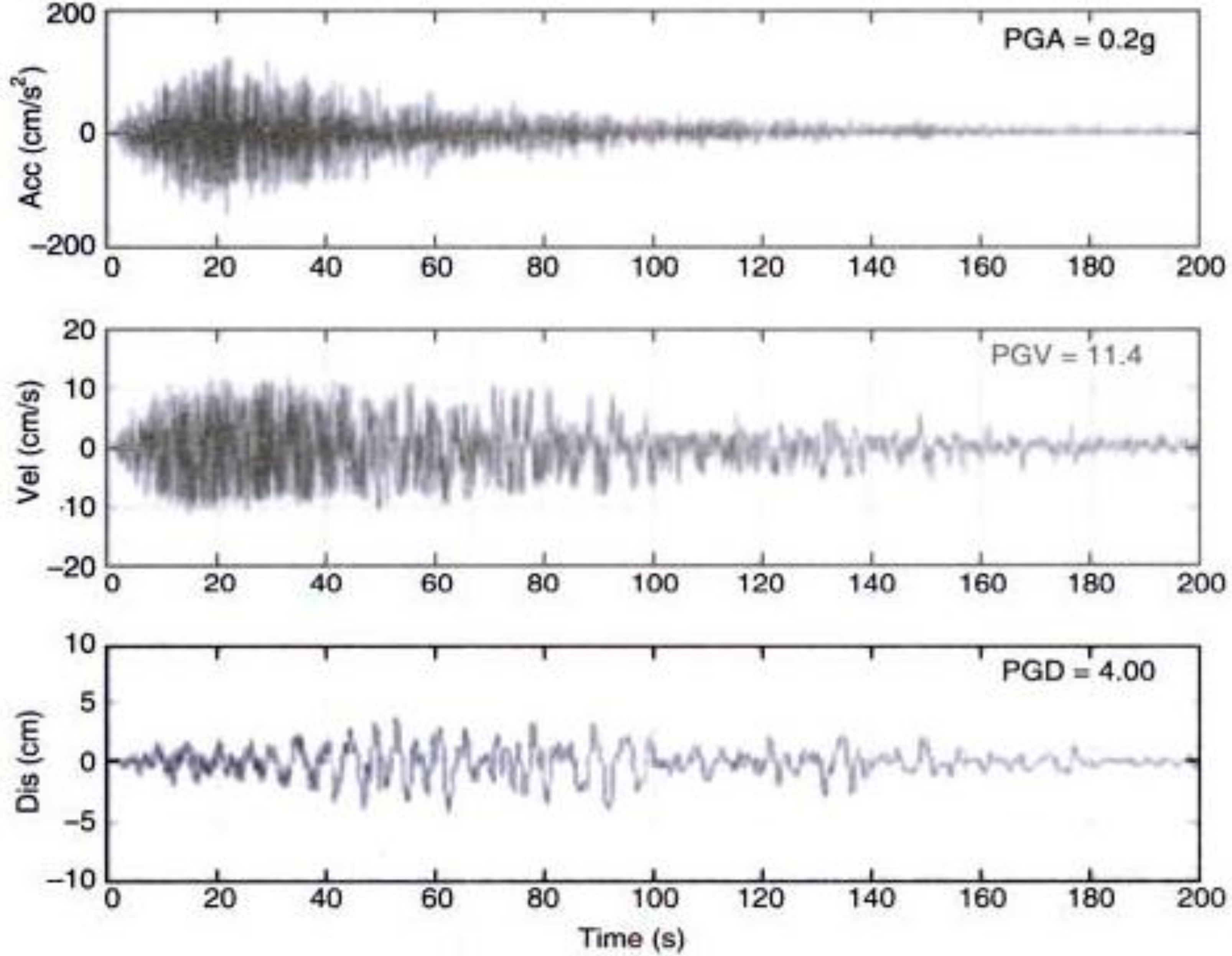


Figure 4::
Some typical recorded accelerograms



PGA = 0.2g
Acc (cm/s²)
200
0
−200
PGV = 11.4
Vel (cm/s)
20
10
0
-10
−20
PGD = 4.00
Dis (cm)
10
5
0
−5
−10
0
20
40
60
80
100
120
140
160
180
200
Time (s)

Factors Influencing Ground Motion

- Magnitude of Earthquake: Higher the magnitude, large is the peak ground acceleration and duration
- Epicentral distance: PGA decreases as the epicentral distance increases
- Local soil condition: Soil layers overlaying the bed rock at a given place, change the characteristics of the waves in terms of amplitude, frequency and duration by the time they reach the surface. This is called soil amplification.

Types of Earthquake

- According to plate boundaries

  1.Interplate 2.Intraplate (with in boundary)

- According to its depth of focus

  1.Shallow focus :depth less than 70km, 80% of world earthquake

  2.Intermediate focus : 70 – 300 km

  3.Deep focus: Greater than 300km

- According to the origin of the earthquake

1.Tectonic 2.Volcanic 3.Submarine (Tsunami's2)

- Based on Magnitude (M)

1.Micro M<3.0 2.Intermediate 3<M<4

3.Moderate 5<M<5.9 4.Strong 6<M<6.9

5.Major 7<M<7.9 6.Great M>8.0

Tsunami

Tsunami

- A **tsunami** is a series of water waves caused by the displacement of a large volume of a body of water, generally an ocean or a large lake. Earthquakes, volcanic eruptions and other underwater explosions landslides, glacier calvings, meteorite impacts and other disturbances above or below water all have the potential to generate a tsunami

Tsunami

- Tsunami is a japanese word with the English translation, “Harbour wave”
- Tsu means harbour and nami means wave
- It can be generated when the sea floor abruptly deforms and vertically displaces the overlaying water
- Tectonic earthquakes are a particular kind of earthquakes that are associated with the earth’s crustal deformation, when these earthquakes occurs beneath the sea, the water above the deformed area is displaced from its equilibrium position.

Tsunami

- Waves are formed as the displaced water mass , which acts under the influence of gravity, attempts to regain its equilibrium. When large areas of the sea floor elevate or subside , a Tsunami can be created
- Tsunami can move hundreds of miles per hour in the open ocean and smash into land with waves as high as 100 feet or more

Seismic zoning map of India

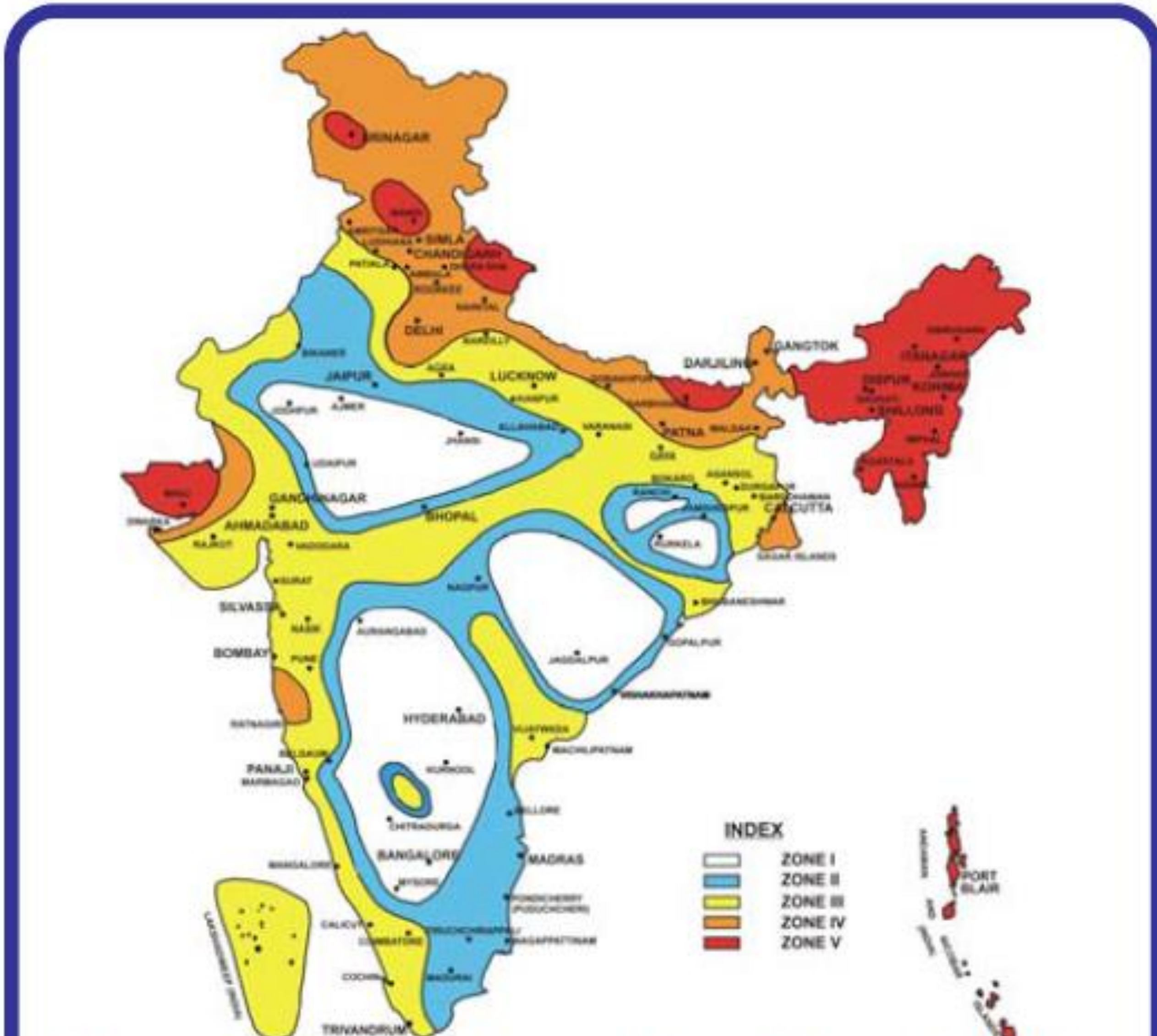


Figure 3: Indian Seismic Zone Map of 1970

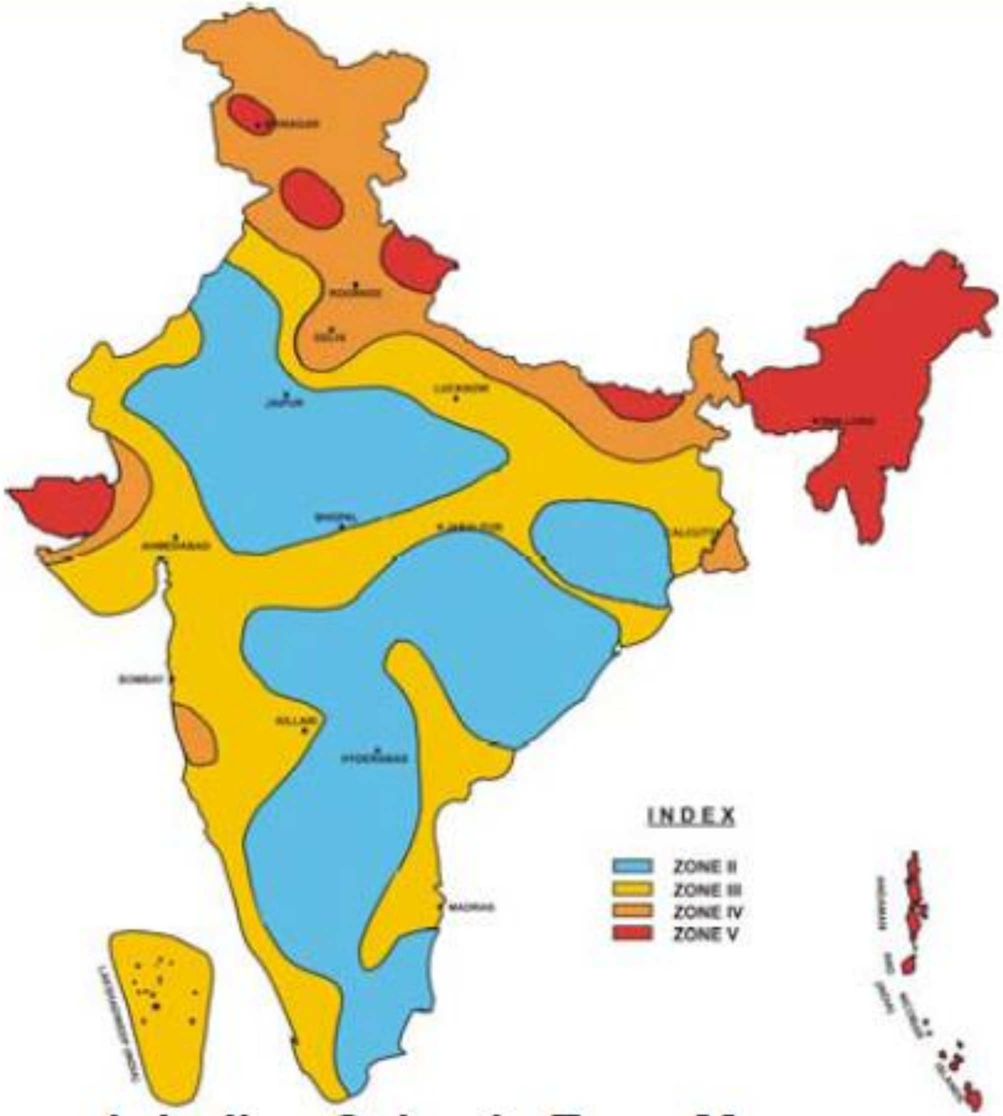
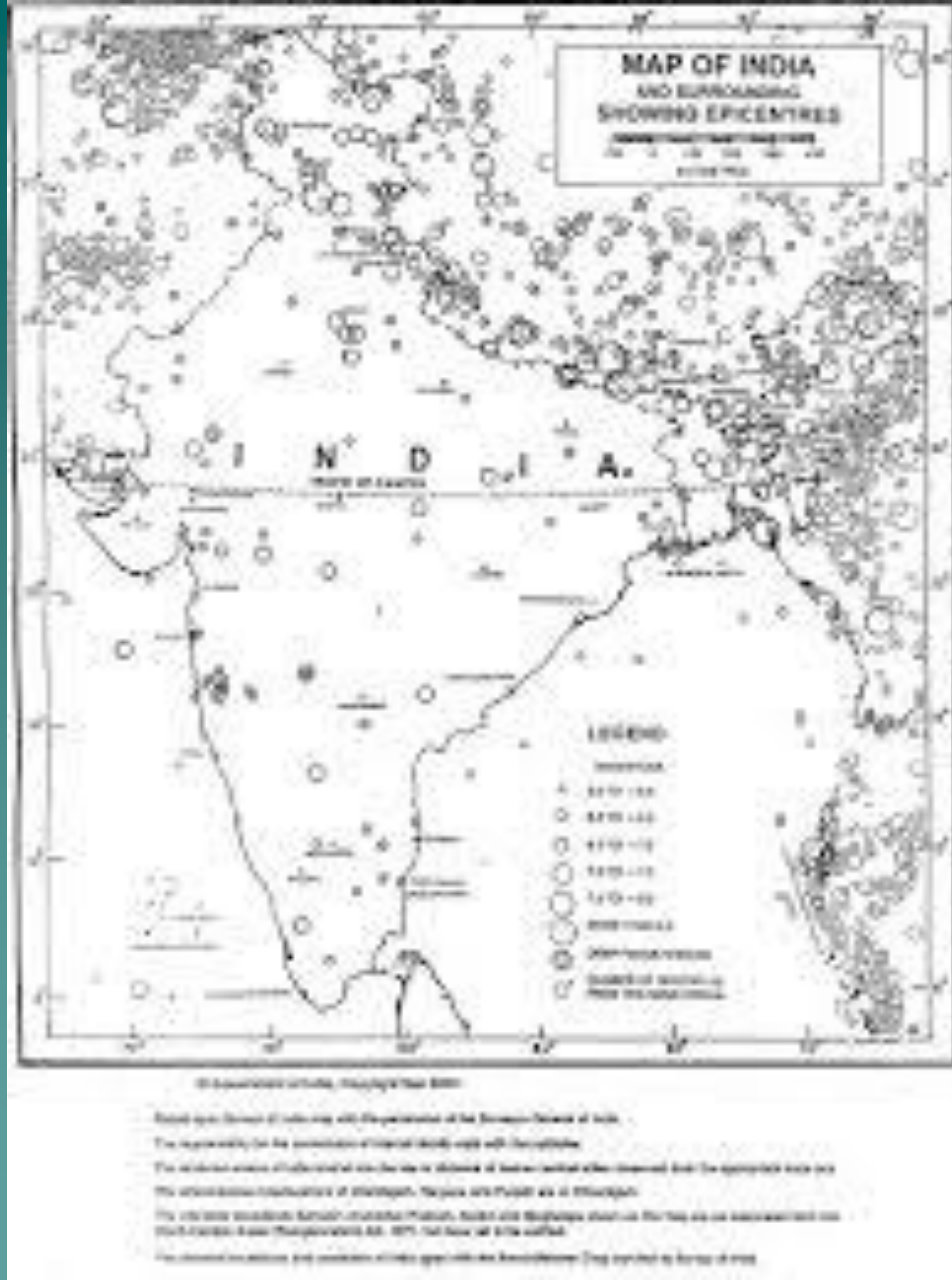


Figure 4: Indian Seismic Zone Map as per IS:1893 (Part 1)-2002


MAP OF INDIA
AND SURROUNDING
SHOWING EPICENTRES
INDIA
LEGEND

- The varying geology at different locations in the country implies that the likelihood of damaging earthquakes taking place at different locations is different.
- Thus, a seismic zone map is required to identify these regions. Based on the levels of intensities sustained during damaging past earthquakes, the 1970 version of the zone map subdivided India into five zones – I, II, III, IV and V (Figure 3).
- The maximum Modified Mercalli (MM) intensity of seismic shaking expected in these zones were *V or less, VI, VII, VIII,* and *IX and higher, respectively.*
- *Parts of Himalayan* boundary in the north and northeast, and the Kachchh area in the west were classified as zone V.

- The seismic zone maps are revised from time to time as more understanding is gained on the geology, the seismotectonics and the seismic activity in the country.
- The Indian Standards provided the first seismic zone map in 1962, which was later revised in 1967 and again in 1970.
- The map has been revised again in 2002 (Figure 4), and it now has only four seismic zones – II, III, IV and V. The areas falling in seismic zone I in the 1970 version of the map are merged with those of seismic zone II.
- Also, the seismic zone map in the peninsular region has been modified.

- Madras now comes in seismic zone III as against in zone II in the 1970 version of the map.
- This 2002 seismic zone map is not the final word on the seismic hazard of the country, and hence there can be no sense of complacency in this regard.
- The national Seismic Zone Map presents a largescale view of the seismic zones in the country.
- Local variations in soil type and geology cannot be represented at that scale. Therefore, for important projects, such as a major dam or nuclear power plant, the seismic hazard is evaluated specifically for that site.
- Also, for the purposes of urban planning, metropolitan areas are microzoned. Seismic microzonation accounts for local variations in geology, local soil profile, *etc,*.

Past Earthquakes in India

Date	Event	Time	Magnitude	Max. Intensity	Deaths
16 June 1819	Cutch	11:00	8.3	IX	1,500
12 June 1897	Assam	16:25	8.7	XII	1,500
8 Feb. 1900	Coimbatore	03:11	6.0	VII	Nil
4 Apr. 1905	Kangra	06:10	8.0	X	19,000
15 Jan. 1934	Bihar-Nepal	14:13	8.3	X	11,000
15 Aug. 1950	Assam	19:39	8.6	X	1,530
21 Jul. 1956	Anjar	21:02	6.1	IX	115
10 Dec. 1967	Koyna	04:30	6.5	VIII	200
23 Mar. 1970	Bharuch	20:56	5.2	VII	30
21 Aug. 1988	Bihar-Nepal	04:39	6.6	IX	1,004
20 Oct. 1991	Uttarkashi	02:53	6.4	IX	768
30 Sep. 1993	Killari (Latur)	03:53	6.2	VIII	7,928
22 May 1997	Jabalpur	04:22	6.0	VIII	38
29 Mar. 1999	Chamoli	00:35	6.6	VIII	63
26 Jan. 2001	Bhuj	08:46	7.7	X	13,805

Some Recent Indian Earthquakes

- Koyna – 1967
- Bihar – Nepal – 1988
- Uttarkashi – 1991
- Killari(Latur) – 1993
- Jabalpur – 1997
- Bhuj – 2001
- Sumatra – 2004
- Sikkim - 2006

Koyna

- **1967 Koynanagar Earthquake** occurred in and around Koynanagar town in Maharashtra, India. On 11 December the 6.5 magnitude earthquake hit near the site of Koyna dam.
- The earthquake claimed at least 180 - 200 human lives and injured over 1500 people.
- The earthquake also damaged more than 80% of the houses in Koyana Nagar Township.However it didn't cause any major damage to the dam except some cracks which were repaired afterwards.
- There have been several earthquakes of smaller magnitude there since 1967.

- The deadly earthquake had caused a 10-15 cm fissure in the ground which spread over a length of 25 km.
- This earthquake led to the revision of Indian seismic zone map wherein the area around Koyna was changed from Zone I to Zone IV

Bihar – Nepal – 1988

- **1988 Nepal earthquake** occurred in Nepal near the Indian border and affected much of northern Bihar.
- The magnitude 6.8 earthquake shook the region on August 21, killing about 1000-1500 persons (282 in India and 900 in Nepal) and injuring more than 16,000.
- The earthquake struck in two installments of 10 seconds and 15 seconds each and left cracks in 50,000 buildings, including Raj Bhavan and the old Secretariat Building inPatna, Bihar.

Uttarkashi – 1991

- On October 20, 1991, at 2.53 a.m. local time, an earthquake occurred in the Garhwal Himalayas in northern India of magnitude 6.6.
- The earthquake caused strong ground shaking in the district of Uttarkashi, Tehri, and Chamoli in the state of Uttar Pradesh.
- Official information indicates that population of about 307,000 in 1,294 villages were effected; 768 persons died while 5,066 were injured.
- In addition the earthquake claimed 3,096 head of livestock. As many as 42,400 houses were damaged

Killari(Latur) – 1993

- A magnitude of 6.4 was felt on Sep 30, 1993 at Killari in Latur district killing about 81000 persons

Jabalpur – 1997

- The Jabalpur earthquake of May 22, 1997, in the state of Madhya Pradesh in central India, is an important event for India from the point of view of seismic preparedness and expertise in repair of seismically damaged structures.
- This is the first time that an M6 earthquake has occurred this close to a major city in India, Jabalpur having a population of about 1.2 million people.
- This means that for the first time, it was possible to observe the seismic response of modern Indian building types which are prevalent all over the country and are unique to India

Bhuj – 2001

- The powerful earthquake that struck the Kutch area in Gujarat at 8:46 am on 26 January 2001 has been the most damaging earthquake in the last five decades in India.
- The M7.9 quake caused a large loss of life and property. Over 18,600 persons are reported to be dead and over 167,000 injured; the number of deaths is expected to rise with more information coming in.
- The estimated economic loss due to this quake is placed at around Rs.22,000 Crores (~US$5 billions)

Sumatra – 2004

- The two largest earthquakes of the past 40 years ruptured a 1600-kilometer-long portion of the fault boundary between the Indo-Australian and southeastern Eurasian plates on 26 December 2004 [seismic moment magnitude (M_w) = 9.1 to 9.3] and 28 March 2005 (M_w = 8.6).
- The first event generated a tsunami that caused more than 283,000 deaths. Fault slip of up to 15 meters occurred near Banda Aceh, Sumatra, but to the north, along the Nicobar and Andaman Islands, rapid slip was much smaller.
- Tsunami and geodetic observations indicate that additional slow slip occurred in the north over a time scale of 50 minutes or longer.

Sikkim - 2006

- The moderate 5.7 magnitude earthquake occurred in the state of Sikkim (India) on February 14, 2006 at 06:25:23 a.m. local time.
- The shaking was felt in the North-Eastern states of India and in the neighbouring countries. However, shaking-related damage was reported only from the East and South districts of Sikkim.
- Most of the structural damage was observed in and around the state capital Gangtok with the maximum intensity of shaking as VII on MSK scale.
- The earthquake caused damage to heritage structures as well as modern buildings.

Learning from past Earthquakes

RC framed structures

- Avoid soft storey ground floors often the column are damaged by the cyclic displacements between the moving soil and the upper part of the building.
- Avoid soft storey upper floors
- Avoid short columns. These attract large shear and fail
- Avoid open ground floor and discontinuous column
- Adopt proper detailing as per IS 13920-1993
- Provide suitable foundation based on the soil condition
- Adopt seismic resistant design for the buildings which are located in the zone of seismicity

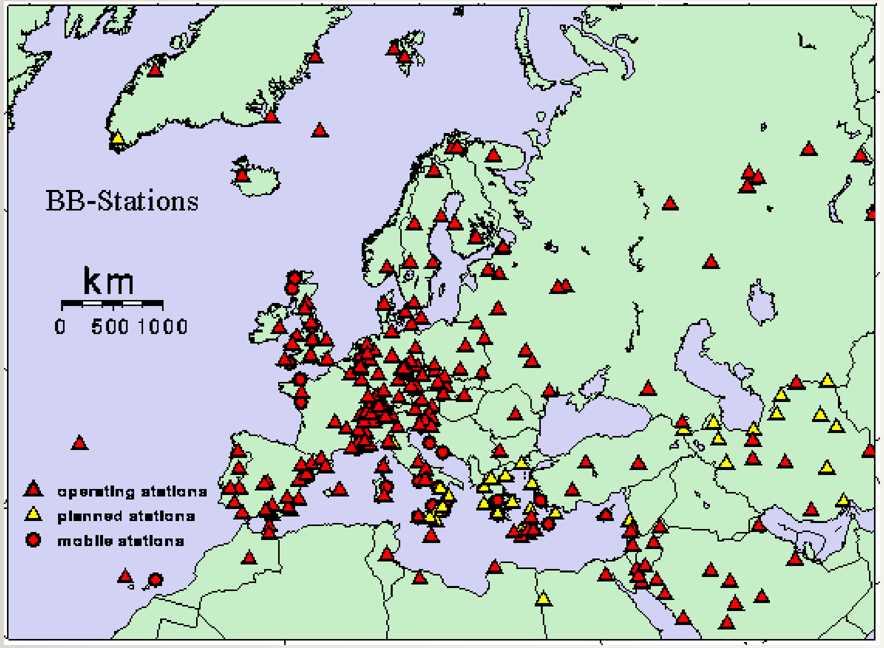
Learning from past Earthquakes

Masonry structures

- Poor wall connections at corners often lead to failure of wall
- Infill walls with large openings cause pier effect leading to extensive damage
- Disproportionate wall openings
- Rigid roof slab, excessive load and improper distribution can lead to roof failure

Observational Seismology

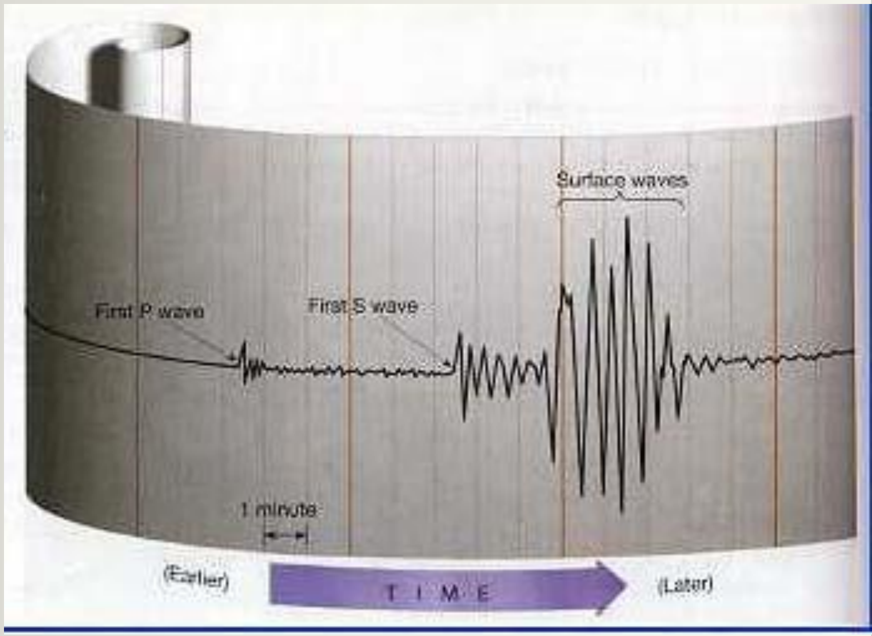
- We are now equipped to start recording and locating earthquakes. For that we need a seismic network of as many stations as possible.
- Minimal number of stations needed to locate the position of an earthquake epicentre is three.



Broad-band seismological stations in Europe

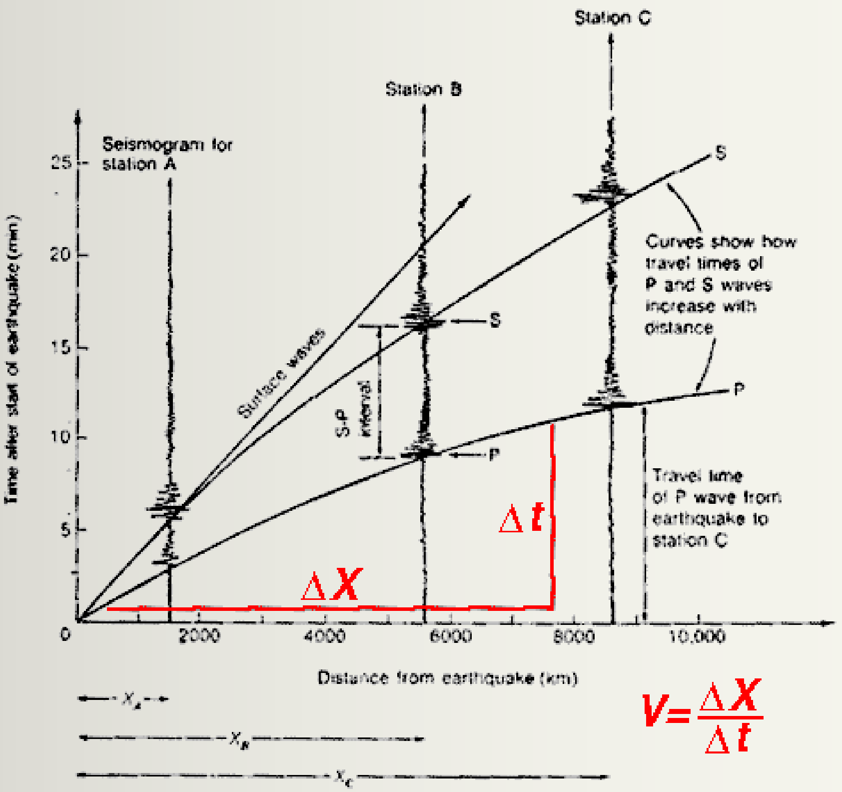
Observational Seismology
Locating Earthquakes

- To locate an earthquake we need precise readings of the times when P- and S-waves arrive at a number of seismic stations.
- Accurate absolute timing (with a precission of 0.01 s) is essential in seismology!



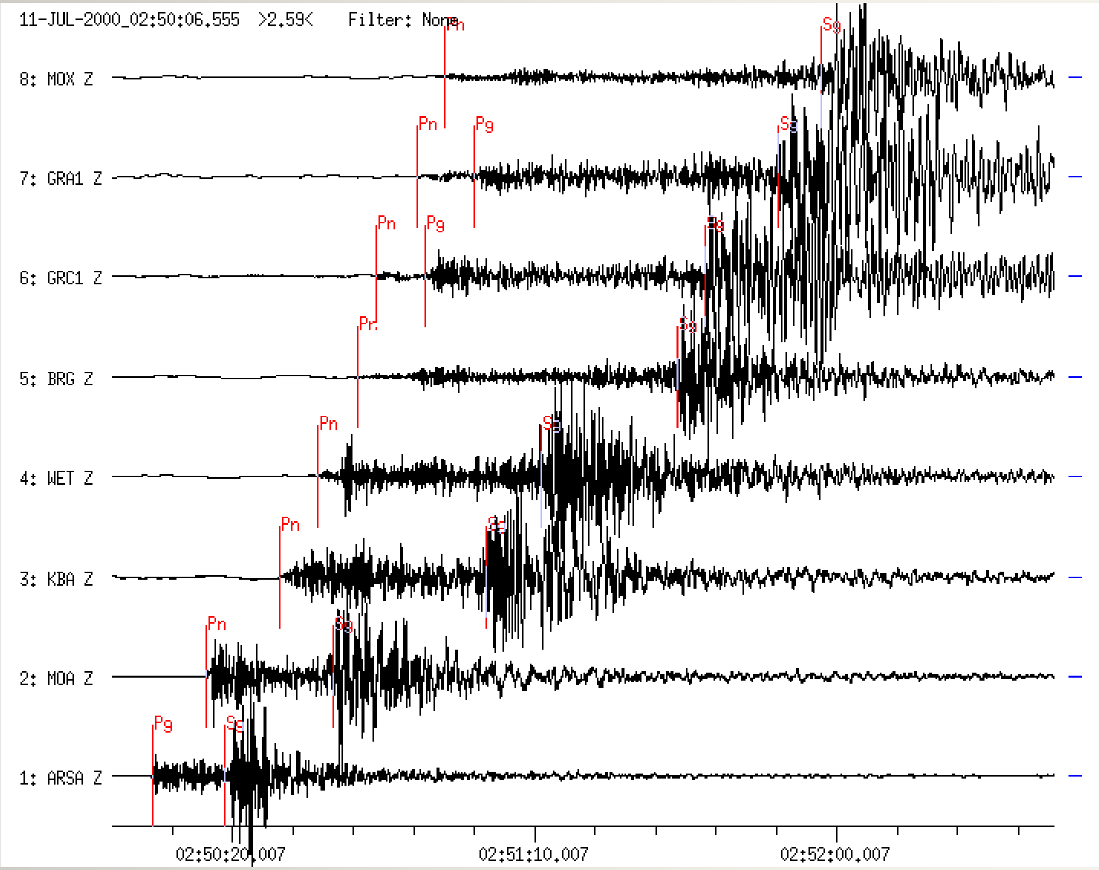
Observational Seismology
Locating Earthquakes

- Knowing the difference in arrival times of the two waves, and knowing their velocity, we may calculate the distance of the epicentre.
- This is done using the travel-time curves which show how long does it take for P- and S-waves to reach some epicentral distance.



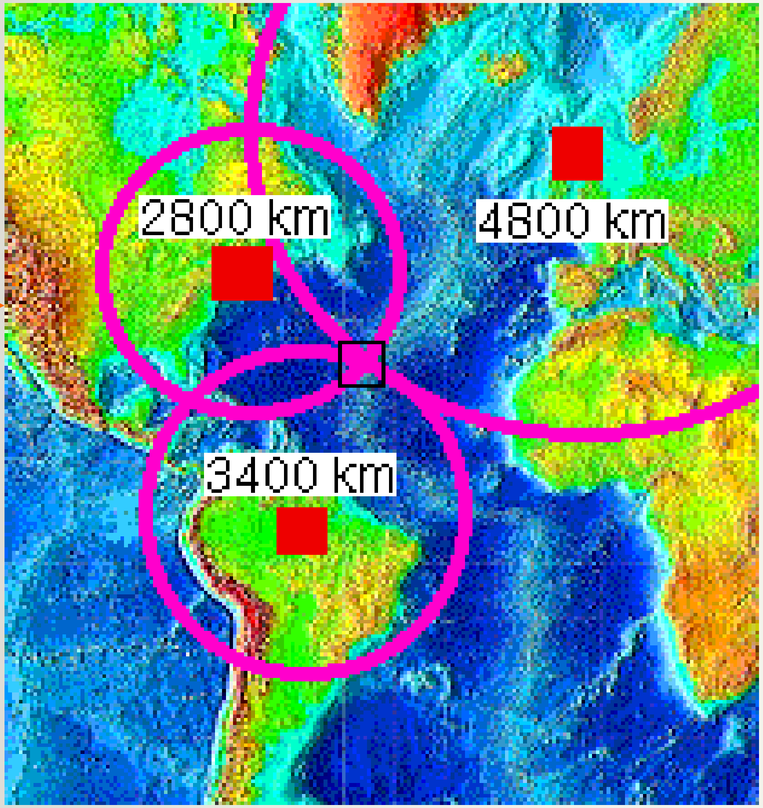
Observational Seismology
Locating Earthquakes

Another example of picking arrival times



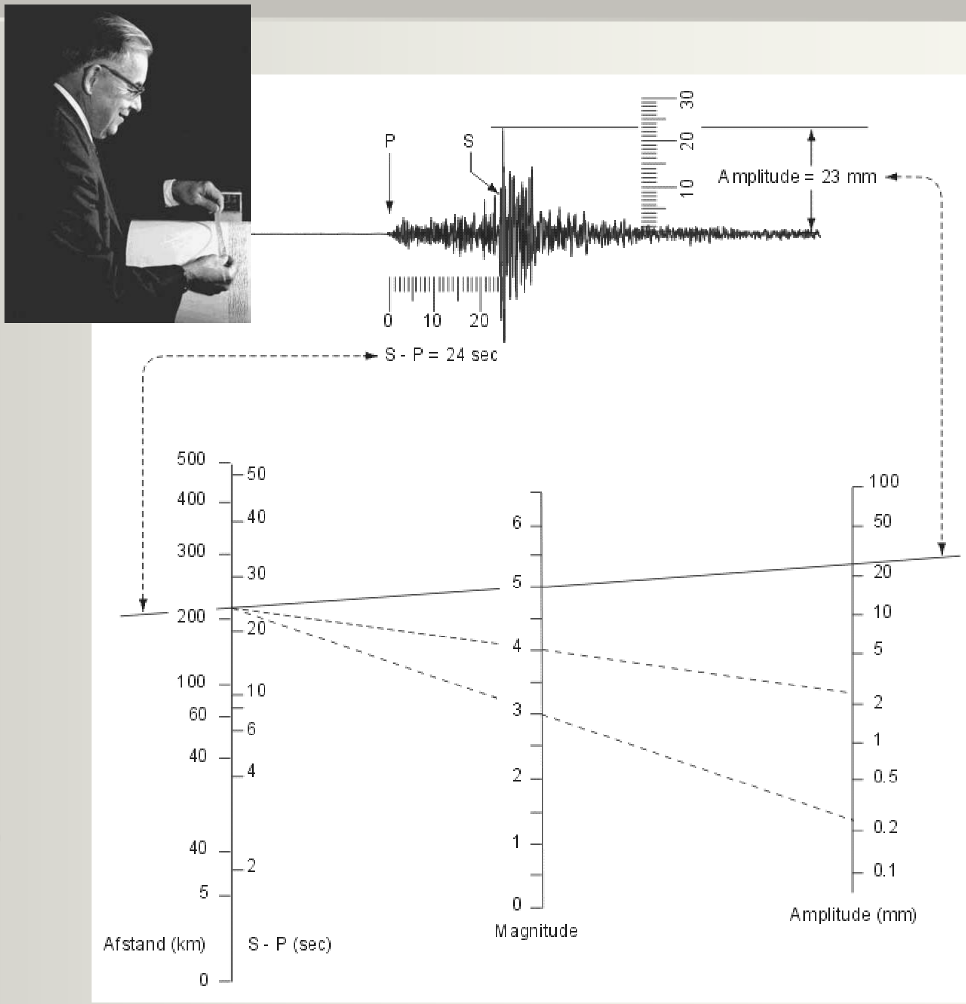
Observational Seismology
Locating Earthquakes

- After we know the distance of epicentre from at least three stations we may find the epicentre like this
- There are more sofisticated methods of locating positions of earthquake foci. This is a classic example of an *inverse problem.*



Observational Seismology Magnitude determination

- Besides the position of the epicentre and the depth of focus, the earthquake magnitude is another defining element of each earthquake.
- Magnitude (defined by **Charles Richter** in 1935) is proportional to the amount of energy released from the focus.
- Magnitude is calculated from the amplitudes of ground motion as measured from the seismograms. You also need to know the epicentral distance to take attenuation into account.



Observational Seismology
Magnitude determination

Formula:

$M = \log(A) + c_1 \log(D) + c_2$

where A is amplitude of ground motion, D is epicentral distance, and c_1, c_2 are constants.

- There are many types of magnitude in seismological practice, depending which waves are used to measure the amplitude: M_L, m_b, M_c, M_s, M_w, ...
- Increase of 1 magnitude unit means ~32 times more released seismic energy!

Observational Seismology
Some statistics

Magnitude	Effects	Number per year
less than 2	Not felt by humans. Recorded by instruments only.	Numerous
2	Felt only by the most sensitive. Suspended objects swing	>1 000 000
3	Felt by some people. Vibration like a passing heavy vehicle	100 000
4	Felt by most people. Hanging objects swing. Dishes and windows rattle and may break	12 000
5	Felt by all; people frightened. Chimneys topple; furniture moves	1 400
6	Panic. Buildings may suffer substantial damage	160
7-8	Widespread panic. Few buildings remain standing. Large landslides; fissures in ground	20
8-9	Complete devastation. Ground waves	~2

Observational Seismology
Some statistics

Equivalent Magnitude	Event	Energy (tons TNT)
2.0	Large quary blast	1
2.5	Moderate lightning bolt	5
3.5	Large ligtning bolt	75
4.5	Average tornado	5 100
6.0	Hiroshima atomic bomb	20 000
7.0	Largest nuclear test	32 000 000
7.7	Mt. Saint Helens eruption	100 000 000
8.5	Krakatoa eruption	1 000 000 000
9.5	Chilean earthquake 1960	32 000 000 000

Observational Seismology
Some statistics

10 LARGEST EARTHQUAKES IN THE WORLD SINCE 1900

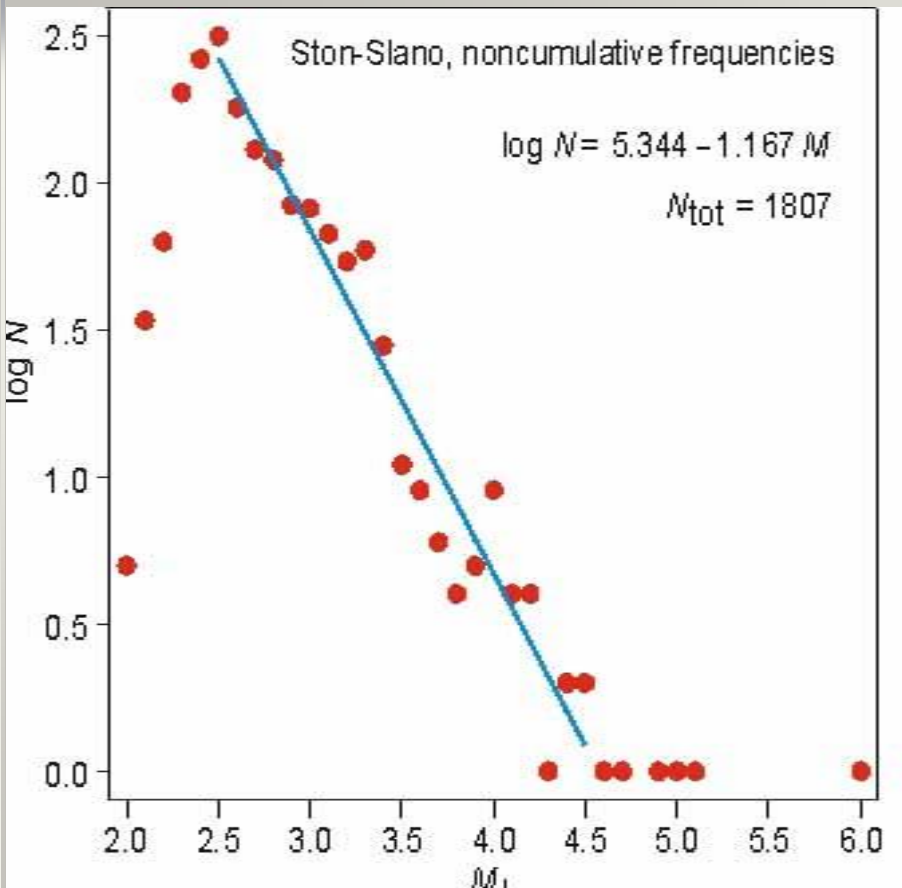
	Location	Date	Magnitude	Deaths
1.	Chile	22 May 1960	9.5	>5000
2.	Alaska	28 March 1964	9.2	131
3.	Russia	4 November 1952	9.0	0
4.	Ecuador	31 January 1906	8.8	>1000
5.	Alaska	9 March 1957	8.8	0
6.	Kuril Islands	6 November 1958	8.7	0
7.	Alaska	4 February 1965	8.7	0
8.	India	15 August 1950	8.6	1530
9.	Chile	11 November 1922	8.6	>100
10.	Indonesia	1 February 1938	8.5	0

Observational Seismology
Some statistics

10 WORLD EARTHQUAKES CAUSING THE LARGEST NUMBER OF FATALITIES

	Location	Date	Deaths	Magnitude
1.	Shaanxi, China	23 January 1556	830,000	8.0
2.	Antioch, Syria	13 December 0115	260,000	7.5
3.	Tangshan, China	27 July 1976	255,000	7.9
4.	Azerbaijan	25 September 1139	230,000	7.0
5.	Shanxi, China	17 September 1303	200,000	8.0
6.	Ningxia, China	16 December 1920	200,000	8.6
7.	Qumis, Iran	22 December 0856	200,000	7.9
8.	Kanto, Japan	1 September 1923	143,000	8.3
9.	Aleppo, Syria	15 October 1138	130,000	7.5
10.	Messina, Italy	28 December 1908	80,000	7.5

Observational Seismology
Some statistics



- **Gutenberg-Richter frequency-magnitude relation:**

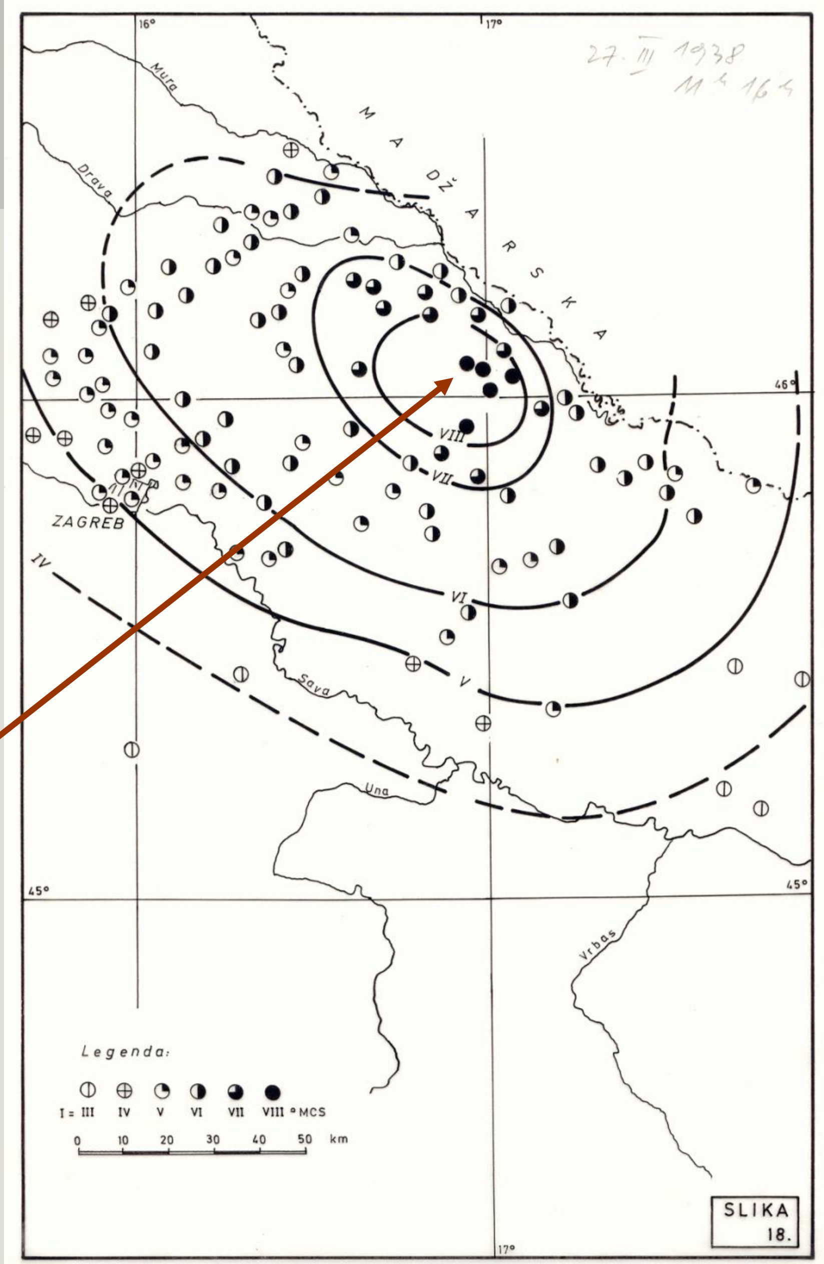
  $\log N = a - bM$

- b is approximately constant, $b = 1$ world-wide → there are ~10 more times M=5 than M=6 earthquakes
- **This shows selfsimilarity and fractal nature of earthquakes.**

Observational Seismology

Macroseismology

- Results of macroseismic surveys are presented on **isoseismal maps.**
- **Isoseismals** are curves connecting the places with same intensities.
- DO NOT CONFUSE INTENSITY AND MAGNITUDE!
- Just approximately, **epicentral intensity** is: $I_0 = M + 2$
- One earthquake has just one magnitude, but many intensities!



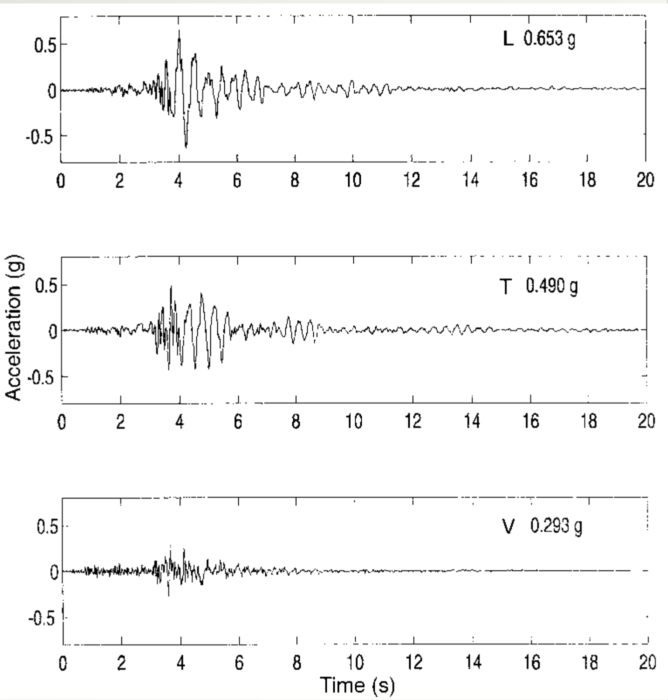
Engineering Seismology

- Earthquakes are the only natural disasters that are mostly *harmless* to humans! The only danger comes from buildings designed *not to withstand* the largest possible earthquakes in the area.
- **Engineering seismology** provides civil engineers parameters they need in order to construct seismically safe and sound structures.
- **Engineering seismology** is a bridge between *seismology* and *earthquake engineering.*

Izmit, Turkey, 1999

Engineering Seismology

Most common input parameters are:
- maximal expected horizontal ground acceleration (PGA)
- maximal expected horizontal ground velocity (PGV)
- maximal expected horizontal ground displacement (PGD)
- response spectra (SA)
- maximal expected intensity (Imax)
- duration of significant shaking
- dominant period of shaking.



Accelerogram of the Ston-Slano (Croatia, M = 6.0, 1996) event

- Engineering seismologists mostly use records of ground acceleration obtained by strong-motion accelerographs.

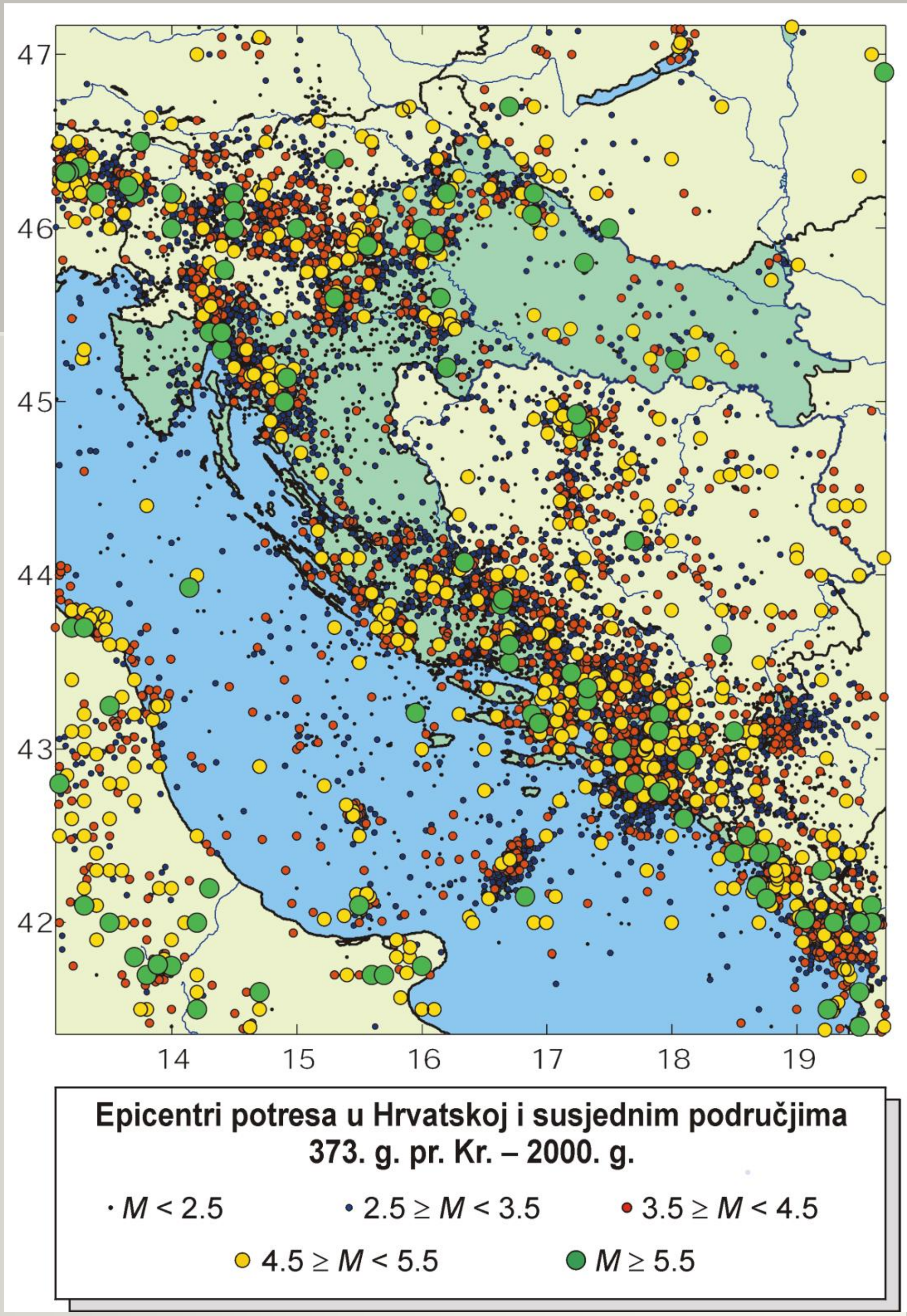
Engineering Seismology

In order to estimate the parameters, seismologists need:

- Complete earthquake catalogues that extend well into the past,
- Information on the soil structure and properties at the construction site, as well as on the path between epicentre and the site,
- Records of strong earthquakes and small events from near-by epicentral regions,
- Results of geological surveys ...

Engineering Seismology

Complete and homogeneous earthquake catalogues are of paramount importance in seismic hazard studies.



Seismicity of Croatia after the Croatian Earthquake Catalogue that lists over 15.000 events

Engineering Seismology

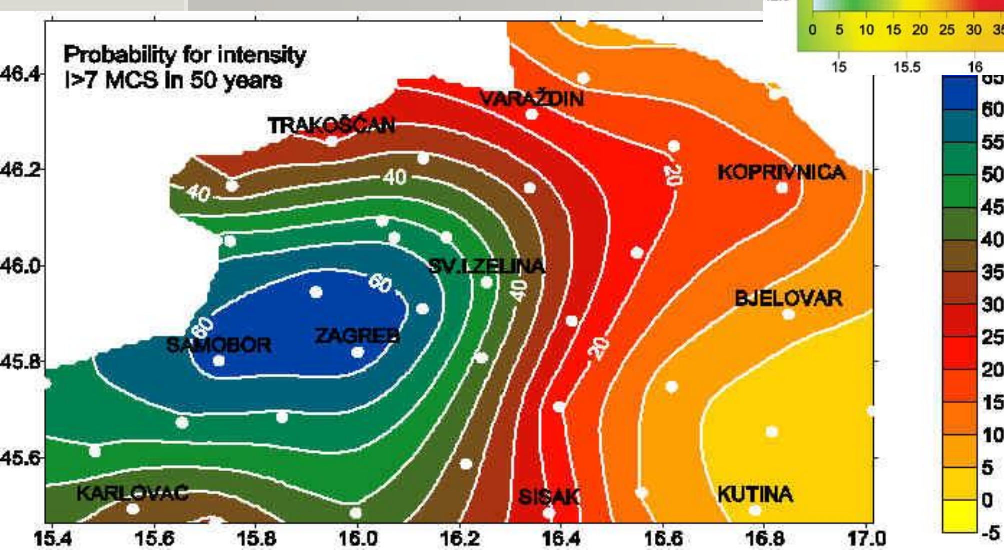
- In estimating the parameters you may use:

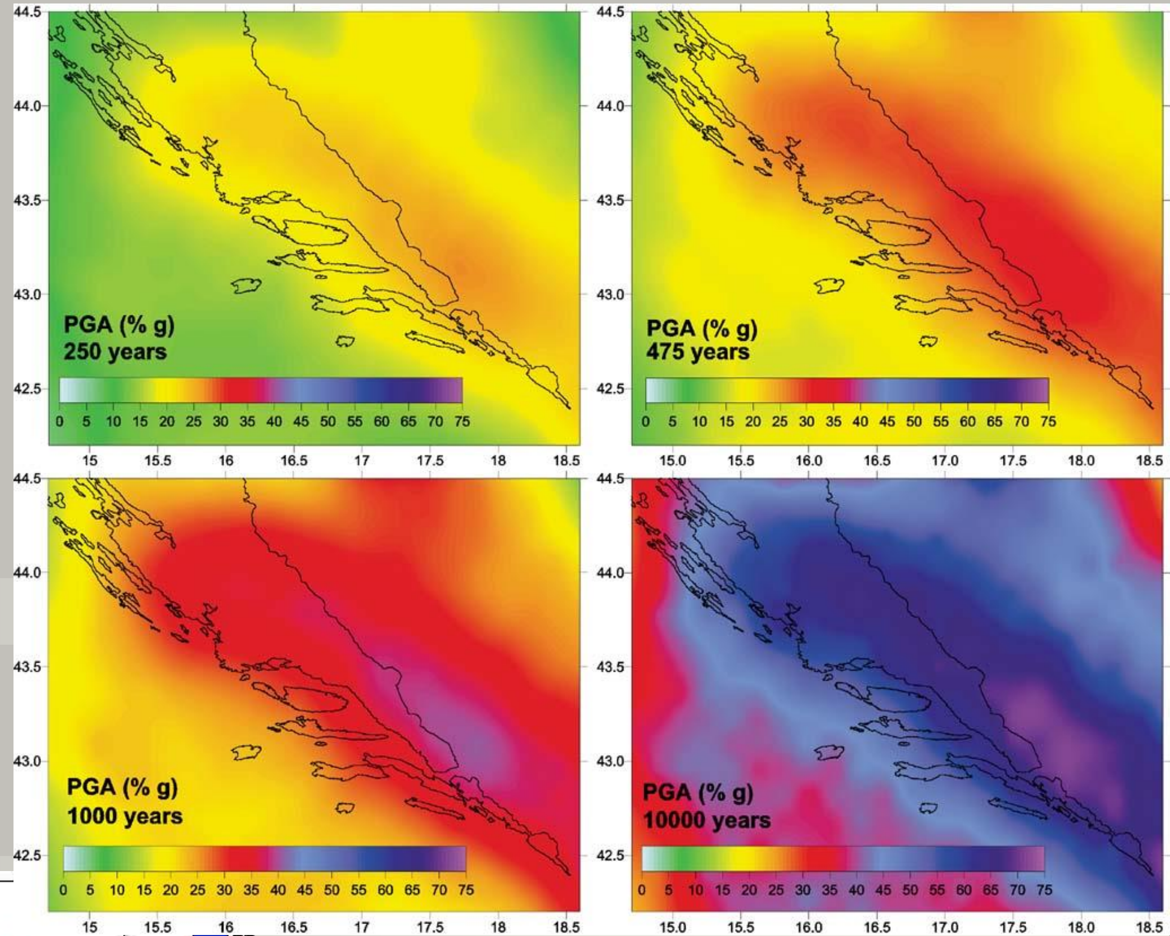
1. **PROBABILISTIC APPROACH** –use statistical methods to assess probability of exceeding a predefined level of ground motion in some time period (earthquake return period), based on earthquake history and geological data.
2. **DETERMINISTIC APPROACH** – use a predefined earthquake and *calculate* its effects and parameters of seismic forces on the construction site. This is very difficult to do because the site is in the near-field (close to the fault) and most of the approximations you normally use are not valid.
3. A combination of the two

Engineering Seismology

Examples of probabilistic hazard assessment in Croatia

Probability of exceeding intensity VII °MSK in any 50 years (Zagreb area)

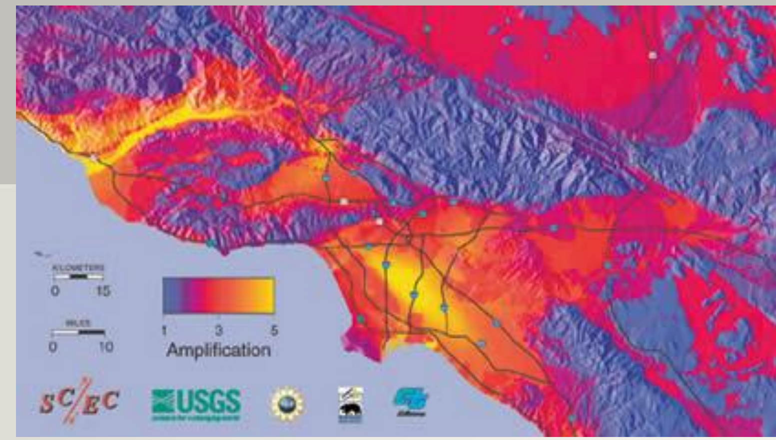


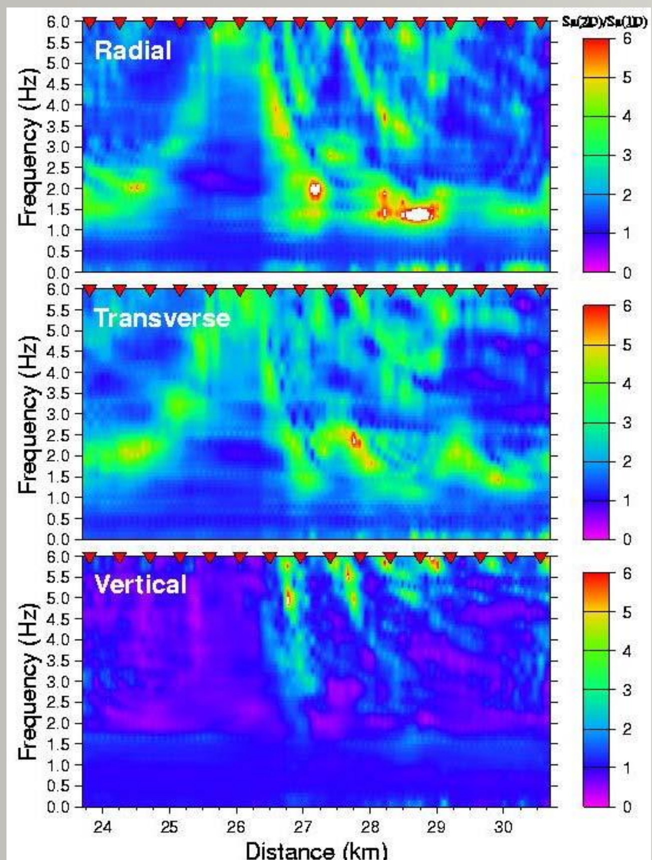


Earthquake hazard in Southern Croatia (Dalmatia) in terms of PGA for 4 return periods

Engineering Seismology

Soil amplification



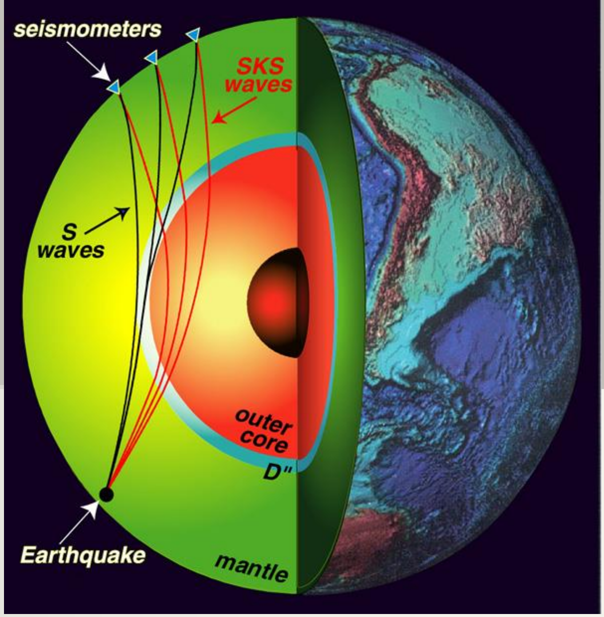


Spectral amplification along a profile in Thessaloniki , Greece

Amplification of seismic waves in shallow soil deposits may cause extensive damage even far away from the epicentre. It depends on:

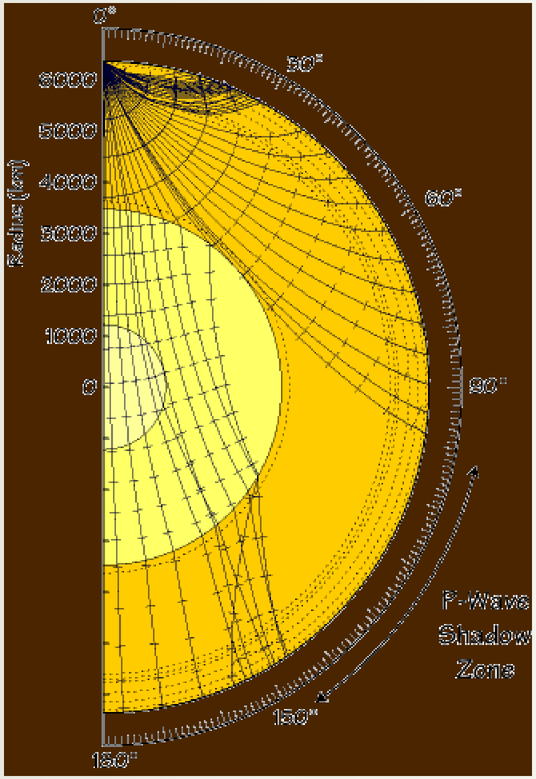
- Thickness of soil above the base rock,
- Density and elastic properties of soil,
- Frequency of shaking,
- The strength of earthquake...

‘Physical’ Seismology

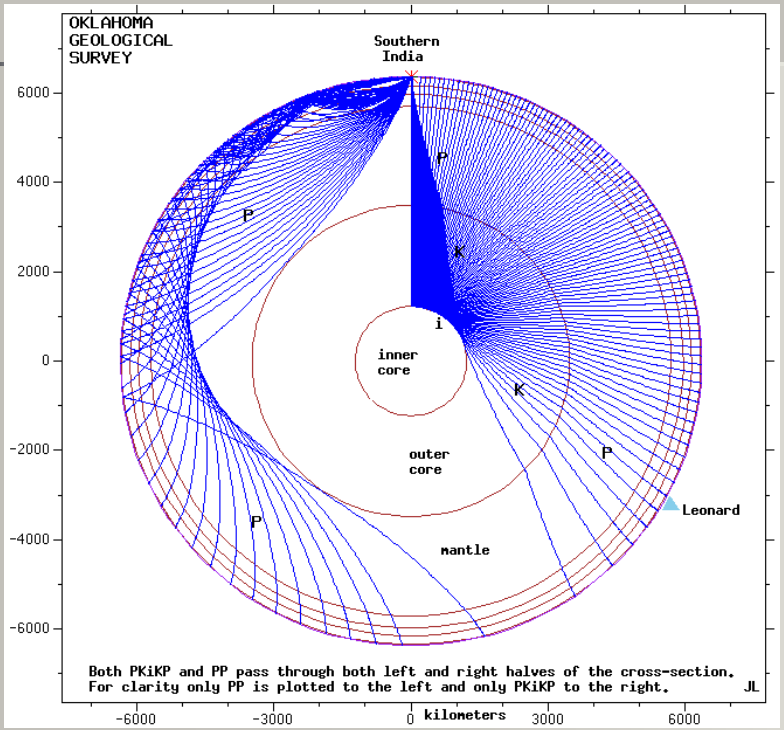


- Our knowledge about the structure of the Earth deeper than several km was gained almost exclusively using seismological methods.

- Seismologists use seismic rays to look into the interior of the Earth in the same way doctors use X-rays.



'Physical' Seismology



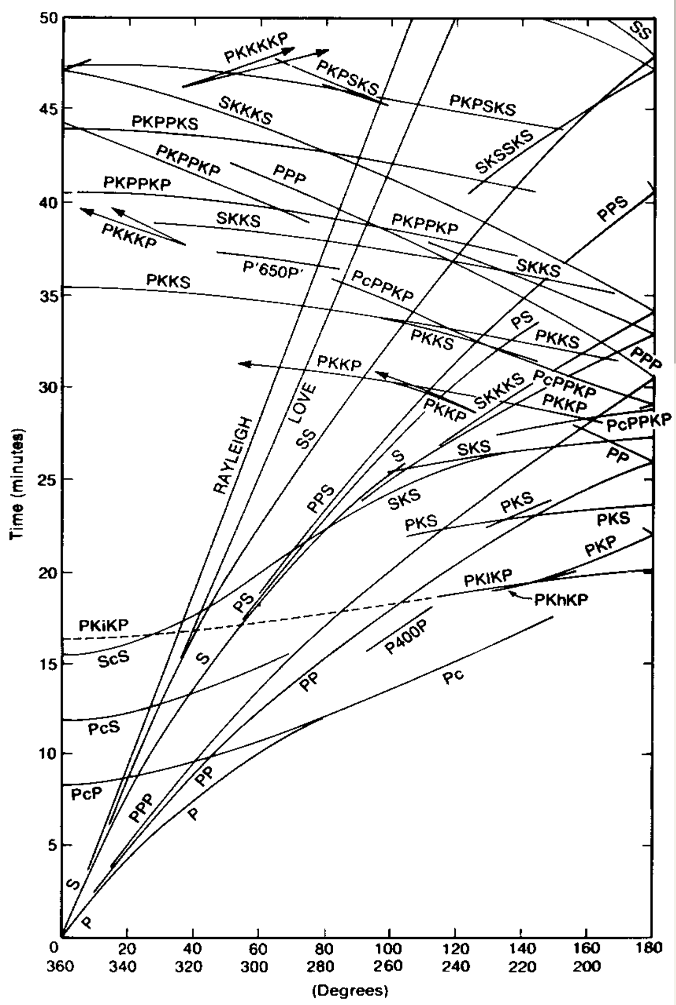


Figure 1.1.2a Travel-time curves for earthquake phases (Bolt, 1976).

Seismic waves get reflected, refracted and converted on many discontinuities within the earth thus forming numerous seismic phases. The rays also bend because the velocity of elsastic waves changes with depth.

‘Physical’ Seismology
Forward problem:

- Given the distribution of velocity, density and attenuation coefficient with depth, and positions of all discontinuities, calculate travel times and amplitudes of some seismic phase (e.g. pP or SKS).

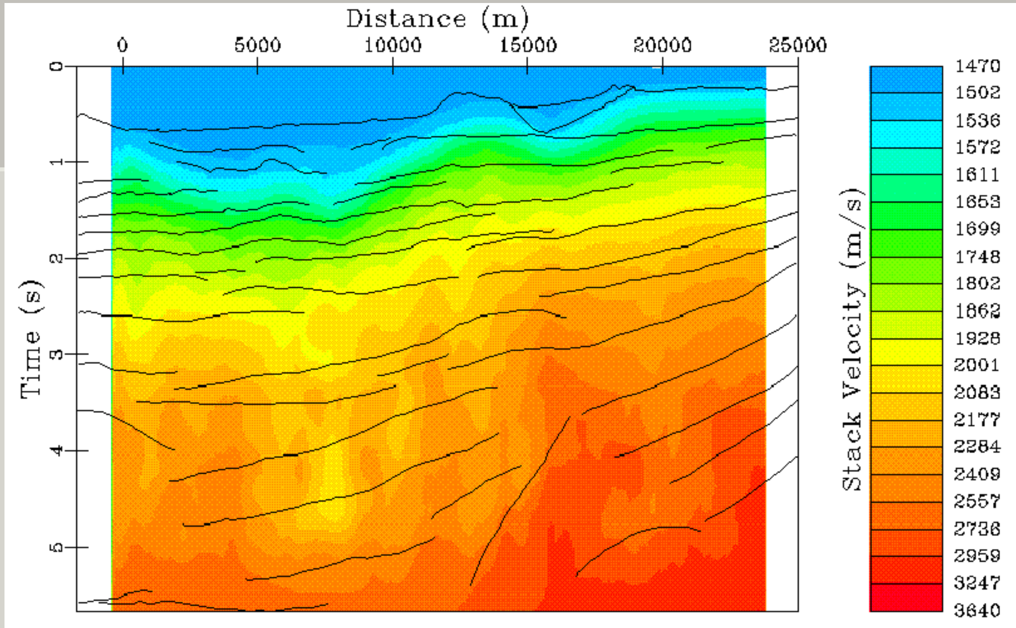
This is relatively easy and always gives unique solution.

‘Physical’ Seismology Inverse problem:

- Given the arrival times and amplitudes of several seismic phases on a number of stations, compute distribution of velocity, density and attenuation coefficient with depth, and positions of all discontinuities.

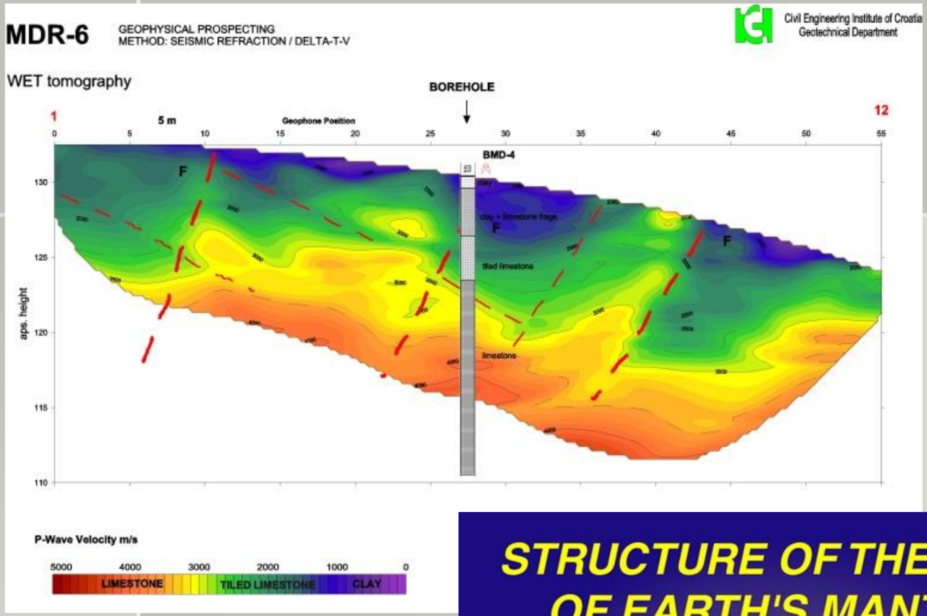
This is very difficult and often does not give a unique solution. Instead, a range of solutions is offered, each with its own probability of being correct. The solution is better the more data we have.

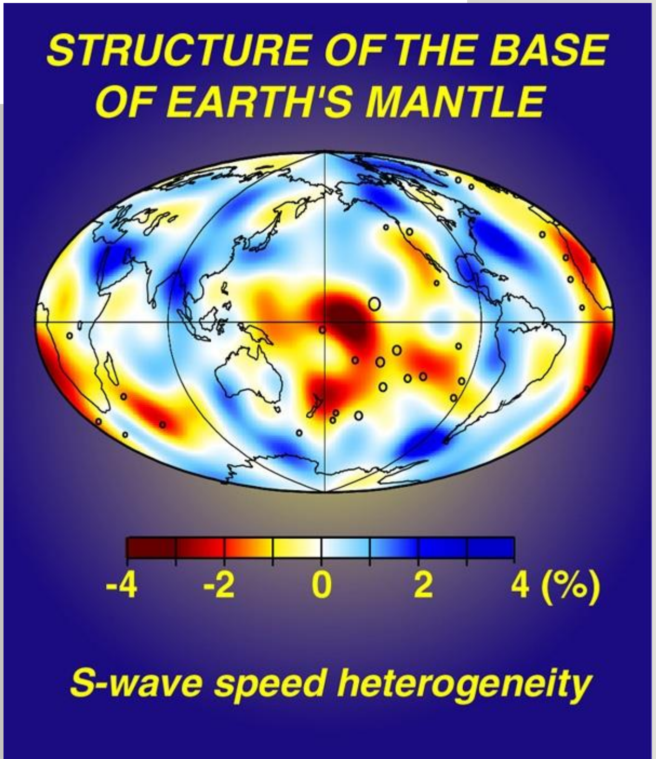
Inverse problems: Tomography

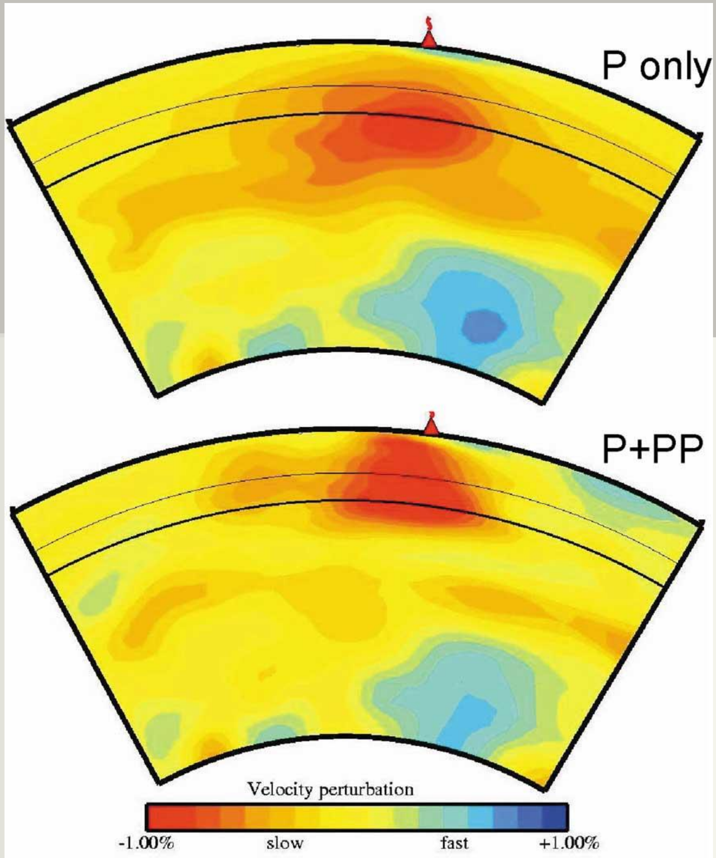


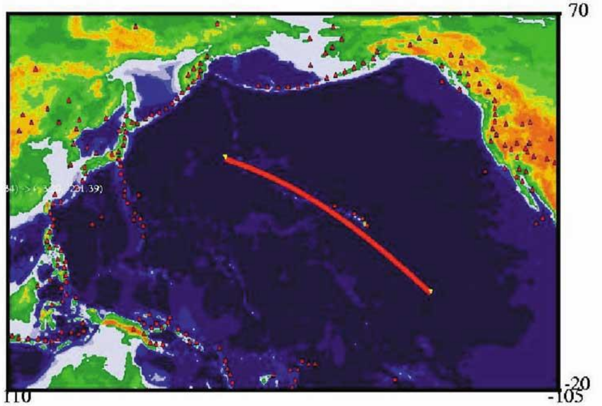
Seismic tomography gives us 3-D or 2-D images of shallow and deep structures in the Earth. They may be obtanied using earthquake data, or explosions (controlled source seismology). These methods are also widely used in explorational geophysics in prospecting for oil and ore deposits.

Tomography


MDR-6
GEOPHYSICAL PROSPECTING
METHOD: SEISMIC REFRACTION / DELTA-T-V
Civil Engineering Institute of Croatia
Geotechnical Department
WET tomography
BOREHOLE
Geophone Position
BMD-4
aps. height
P-Wave Velocity m/s
5000 4000 3000 2000 1000 0
LIMESTONE
TILED LIMESTONE
CLAY


STRUCTURE OF THE BASE OF EARTH'S MANTLE
-4 -2 0 2 4 (%)
S-wave speed heterogeneity


P only
P+PP
Velocity perturbation
-1.00%
slow
fast
+1.00%


70
-20
110
-105

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