BANGLADESH METEOROLOGICAL DEPARTMENT

LOCAL TRAINING

MODULE 11: EARTHQUAKE & TSUNAMI

Project: Strengthening Meteorological Information Services and Early Warning Systems (Component-A)

Prepared By:
Grant Thornton Consulting Bangladesh Ltd

AIMS AND OBJECTIVES

- To provide delegates with an appreciation of the fundamental concepts of Earthquake.
- We will use introductory and state-of-the-art lectures on the various subjects of earthquake seismology and risk assessment, extensive practical exercises, demonstrations, workshop discussions and scientific excursions for the participants for better understating.

DELIVERY AND DESCRIPTION

This module is designed in such a way that the participants get explicit idea regarding the various terms of earthquake and concepts. Besides, we also wish that the participants will be enhance their official works. To achieve this objective, we have made the sessions based on the most important topics of Earthquake & Tsunami that are used on regular basis. We have included sufficient practical exercises to ensure that the participants not only learn how to use various tools, but they can also implement them.

KEY LEARNING OUTCOMES

By the end of the course, delegates will have a knowledge and understanding of:

- Introduction to Seismology;
- Earthquake Source Parameters;
- Types of Faults and Fault Mechanisms;
- Seismic Hazard, Vulnerability and Risk Assessment;
- Tsunami.

Disclaimer

This Module on Earthquake & Tsunami is intended solely for Bangladesh Meteorological Department (BMD) and respective stakeholders and should not be used for any other purpose or distributed to third parties or quoted or referred to in any other document without our express written consent, as the matters contained herein may be misunderstood if not placed in the proper context of our engagement.

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SESSION 1: INTRODUCTION TO SEISMOLOGY

1.1 Introduction

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.

Engineering Seismology is concerned with the solution of engineering problems connected with the Earthquakes.

Seismology is extremely important because:

- Study of earthquakes gives us important clues about the earth's interior
- Understanding earthquakes allows us to minimize the damage and loss of life

In recent years, the understanding of seismologists about the interiors of Earth has been reformed from a relatively homogeneous environment to one that is highly dynamic and chemically diverse.

This new view of Earth's interior helped in relating the events that happen deep inside the earth to what happens at its surface, like the movement of tectonic plates and earthquakes.

To understand the seismological features of the earth and to study the processes involved in seismic events, it is very much essential to know about the formation of earth and its layers.

1.2 Origin of our Universe

Big Bang model - the universe began with an explosive expansion of matter, which later became what we know as stars, planets, moons, etc. This event is thought to have occurred 10 - 15 billion years ago.

Nebular Hypothesis: Earth and the other bodies of our solar system (Sun, moons, etc.) formed from a "vast cloud of dust and gases" called a nebula.

The nebular cloud consisted of H and He, and a small percentage of the heavier elements we find in the solar system.

Within the rotating disk, the rocky material and gases began to nucleate and accrete into proto planets.

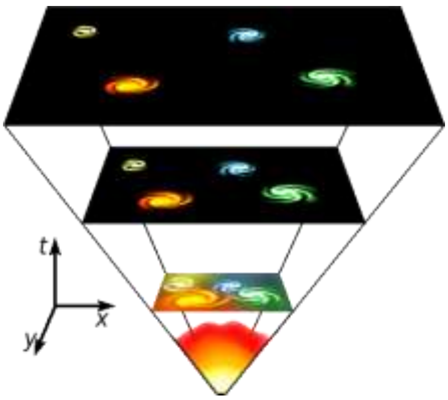


Fig: Big bang model

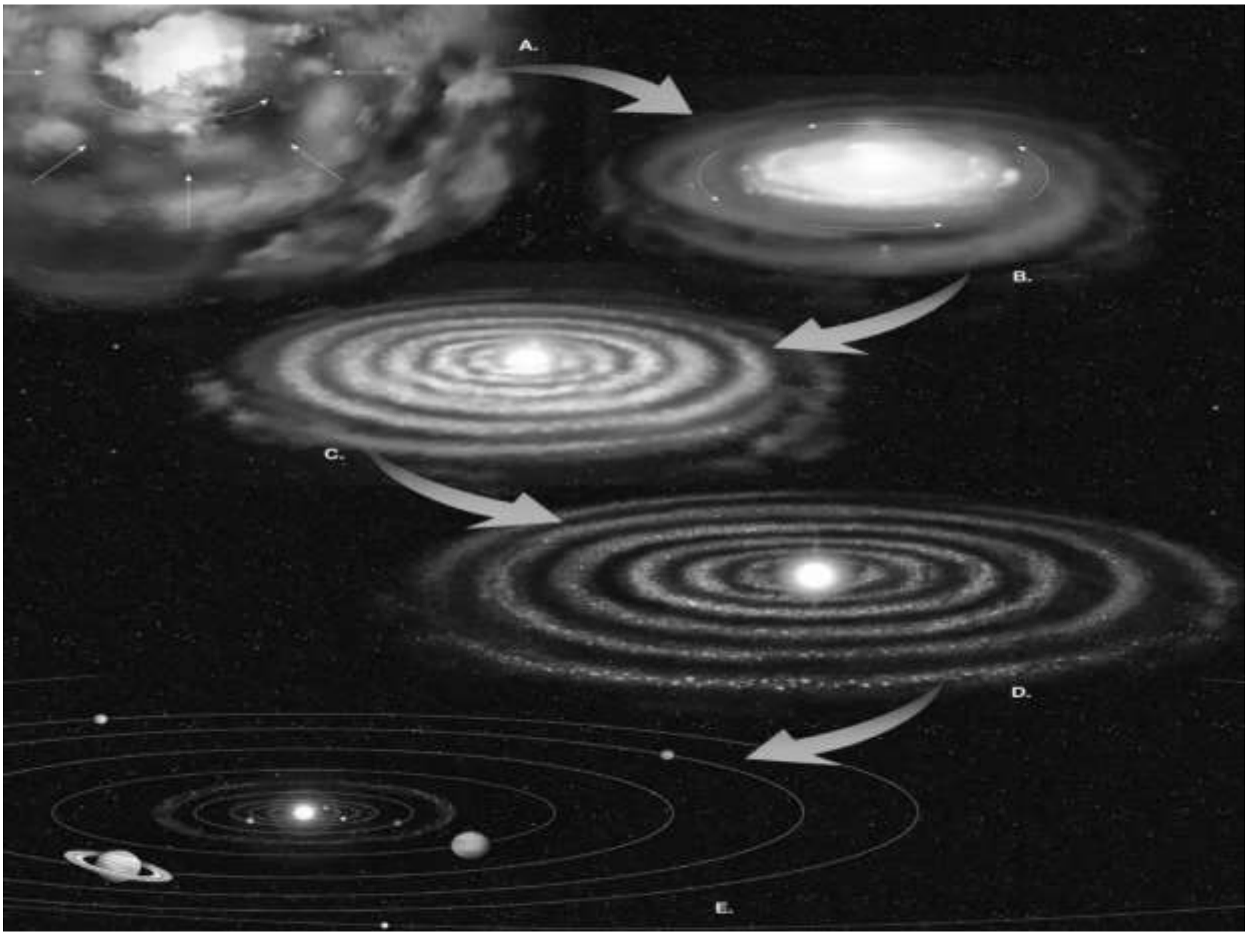


Fig: Solar Nebula

1.3 Formation of Earth's Layers

- When Earth was formed, it was extremely hot from the bombardment of space debris, radioactive decay and high internal pressures. These processes caused Earth's interior to melt.
- Molten Earth separated based on melting points and density into regions of chemical and physical differences as it cooled.
- Molten Iron & Nickel melted early and being denser, sunk to the center of the Earth. Solid Iron & Nickel formed the Inner Core. Molten Iron & Nickel formed the Outer Core. Less dense solid material formed the Mantle. The least dense rock at the surface cooled up completely as the Crust.
- Crust
    - Continental crust (approximately 5-70 km)
    - Oceanic crust (~6 km)
- Mantle
    - Upper mantle (650 km)
    - Lower mantle (2890 km)

- Core
    - Outer core: liquid (2260 km)
    - Inner core: solid (1220 km)

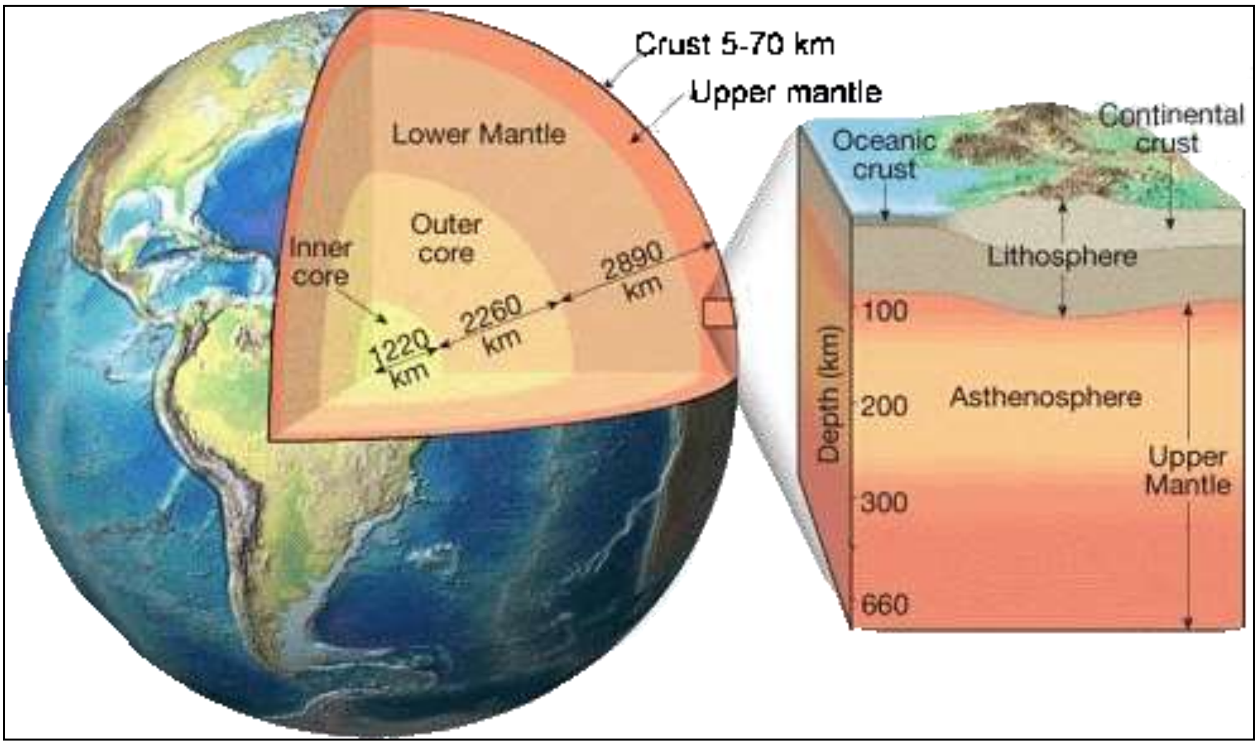


Fig: Earth's Internal Layering

1.4 Layers of the Earth

The earth is divided into four main layers: Inner core, outer core, mantle and crust. The core is composed mostly of iron (Fe) and is so hot that the outer core is molten, with about 10% sulphur (S). The inner core is under such extreme pressure that it remains solid.

Most of the Earth's mass is in the mantle, which is composed of iron (Fe), magnesium (Mg), aluminum (Al), silicon (Si), and oxygen (O) silicate compounds. At over 1000°C, the mantle is solid but can deform slowly in a plastic manner.

The crust is much thinner than any of the other layers and is composed of the least dense calcium (Ca) and sodium (Na) aluminum-silicate minerals. Being relatively cold, the crust is rocky and brittle, so it can fracture in earthquakes. Because of variations in temperature and in pressure, the materials inside the earth vary in their physical properties with depth.

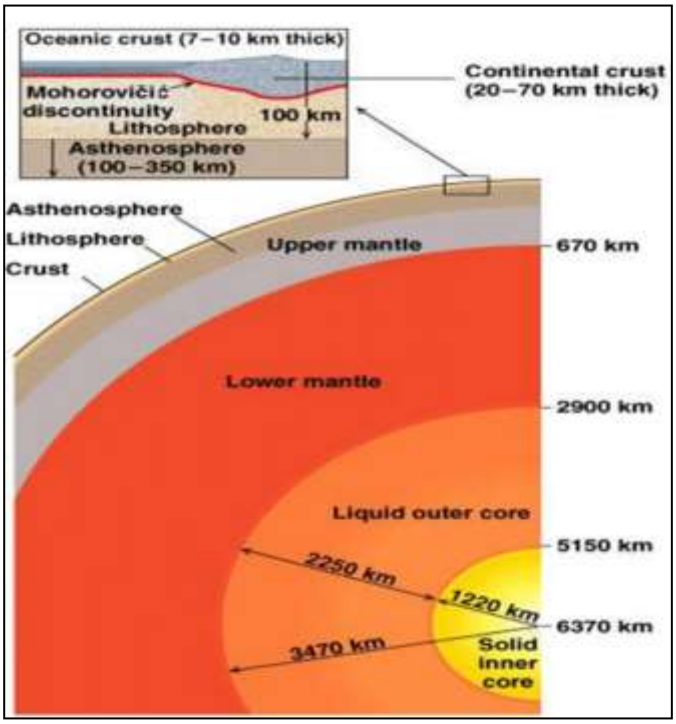
Inner Core is the central part of the iron-nickel core. It is a solid iron sphere. The reason that the iron is solid is that the pressure at the center of the earth is significantly higher than the pressure above, while the temperature is only slightly higher. While higher temperature would tend to melt materials, higher pressures tend to create solids.

Outer Core constitutes the remainder of the iron-nickel core and is liquid. It is liquid because the pressure is lower.

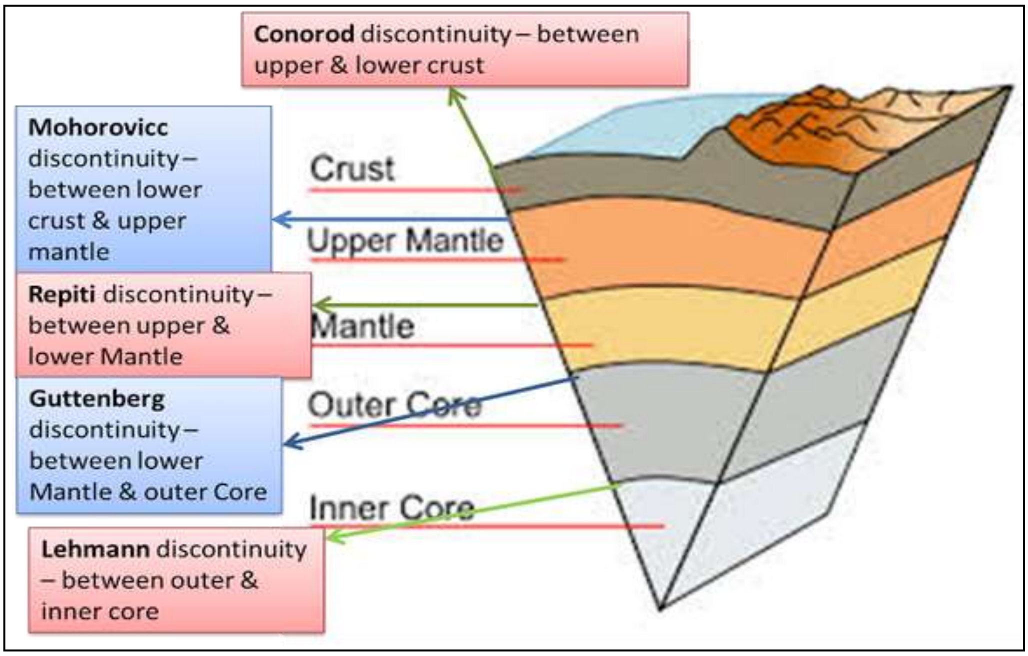
Mesosphere: The majority of the mantle from the core-mantle boundary is solid and is called the mesosphere.

Asthenosphere: Nearer to the surface of the earth the temperature is still relatively high, but the pressure is greatly reduced. This creates a situation where the mantle is partially melted. The asthenosphere is a plastic solid in that it flows over time.

Lithosphere: Above the asthenosphere, the temperature begins to drop more rapidly. This creates a layer of cool, rigid rock called the lithosphere. The lithosphere includes the uppermost part of the mantle and it also includes all of the crust. That is, the crust is the upper part of the lithosphere, and the upper mantle is the lower part of the lithosphere.



Earth has a layered structure. The boundaries between the layers are called discontinuities.



1.5 What is an earthquake?

An earthquake is the vibration of Earth produced by the rapid release of accumulated energy in elastically strained rocks

- Energy released radiates in all directions from its source, the focus
- Energy propagates in the form of seismic waves
- Sensitive instruments around the world record the event

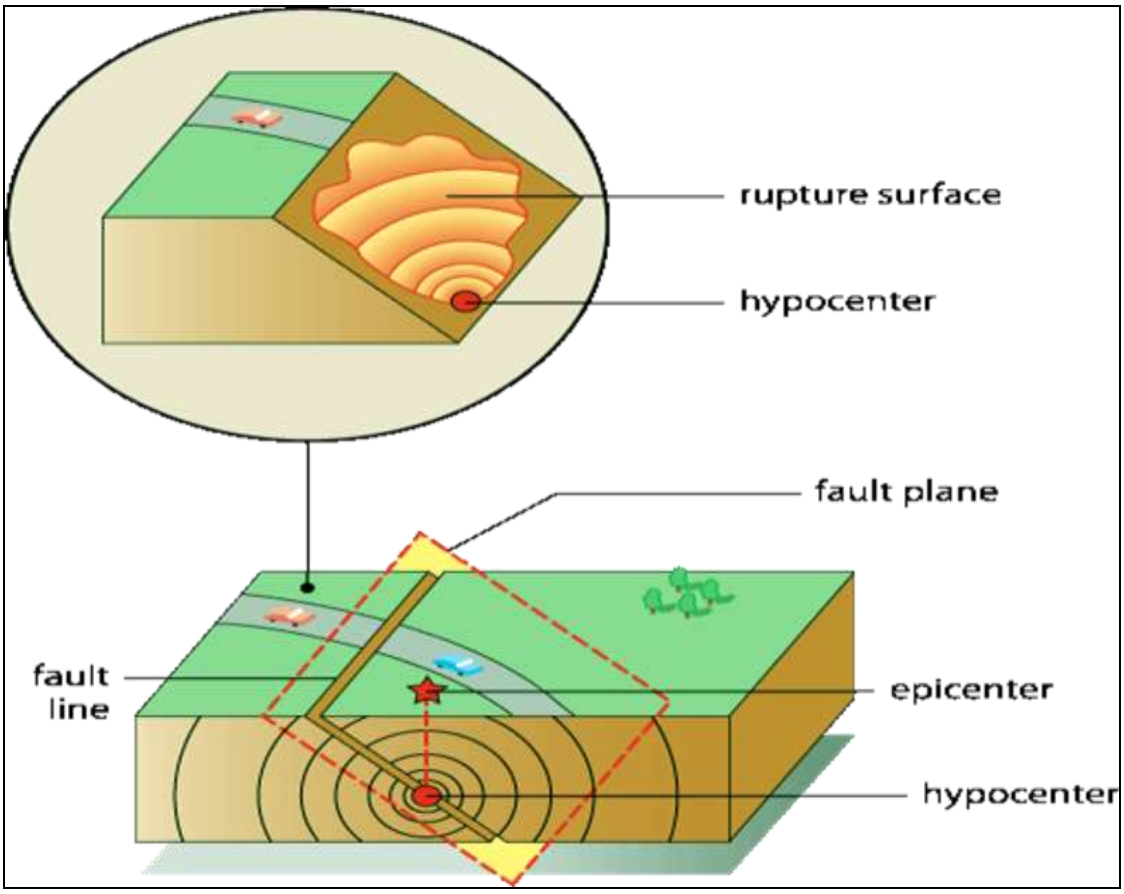
1.6 What causes an earthquake?

- Movement of Tectonic Plates

Earth is divided into sections called Tectonic plates that float on the fluid-like interior of the Earth. Earthquakes are usually caused by the sudden movement of earth plates

- Rupture of rocks along a fault

Faults are localized areas of weakness in the surface of the Earth, sometimes the plate boundary itself



1.7 Earthquake Terminology

Fault: Weakness in the rock

Fault Plane: Plane of weakness in rock

Rupture surface: The portion of the fault which slips when the earthquake occurs

Hypocenter/Focus: The place located deep within the Earth where rocks suddenly break, causing an earthquake, and from where seismic waves propagate

Epicenter: The point of the earth's surface directly above the focus of an earthquake

1.8 Earthquake Depth

Earthquakes usually occur at some depth below the ground surface. The depth can also be calculated from the seismographic records

Earthquake foci are described as:

I. Shallow: less than 70 km depth
II. Intermediate: 70 - 300 km depth
III. 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

1.9 Theory of continental drift

Theory that continents and plates move on the surface of the Earth was proposed by Alfred Wegener in 1915.

- Continental similarities and fitting of the shapes of the continents was the basis for the theory of continental drift proposed by Wegener.

- Wegener noticed that the eastern outline of South America and western outline of Africa fit like pieces of a jigsaw puzzle. He noticed similar fits among the other continents.

- Wegener theorized that a single supercontinent called Pangaea existed sometime during the late Paleozoic Era, 350 million to 225 million years ago. He maintained that the landmass broke up and that its pieces dispersed and drifted, eventually reaching their present positions.

- After several decades, Wegener's theory led to the revolutionary theory of plate tectonics, which could explain the observed evidence for large scale motions of the Earth's lithosphere

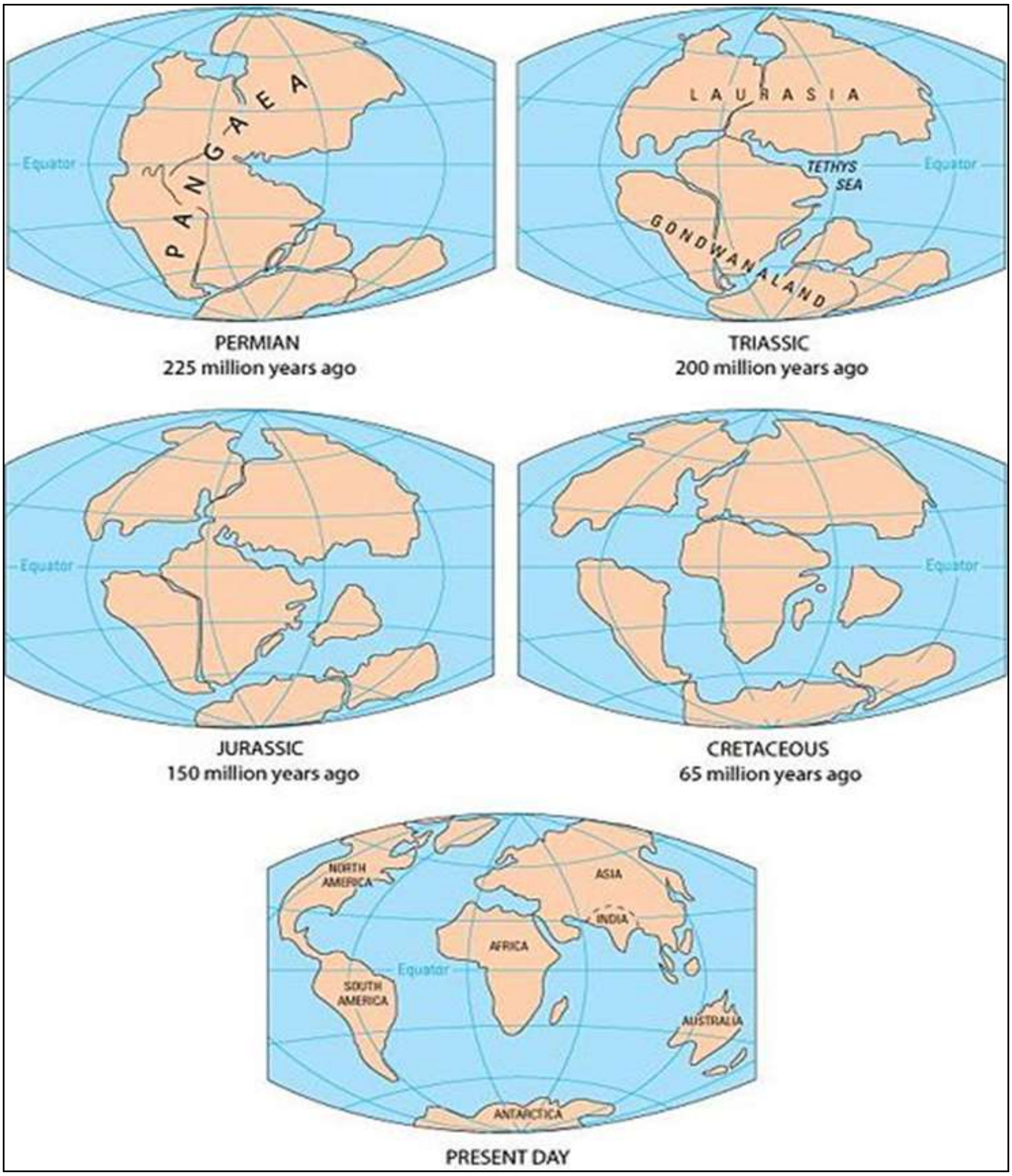
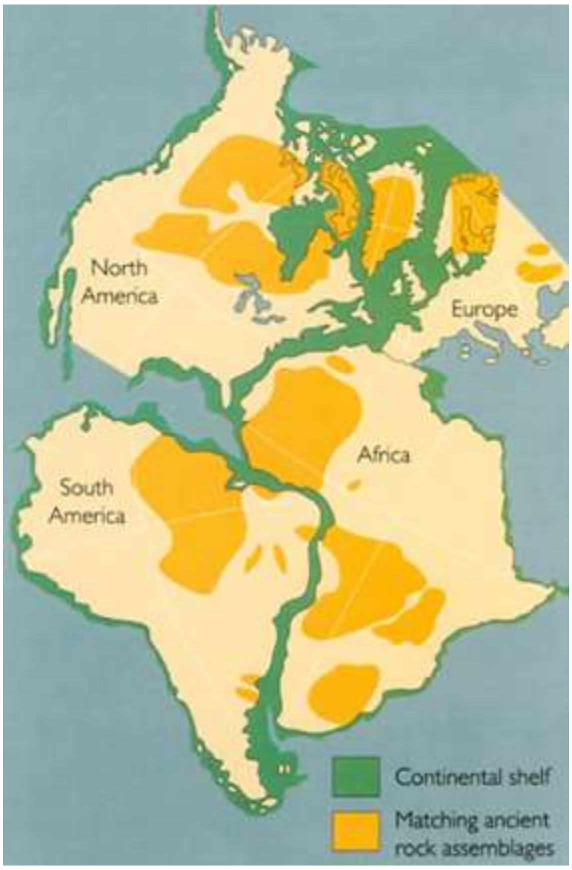
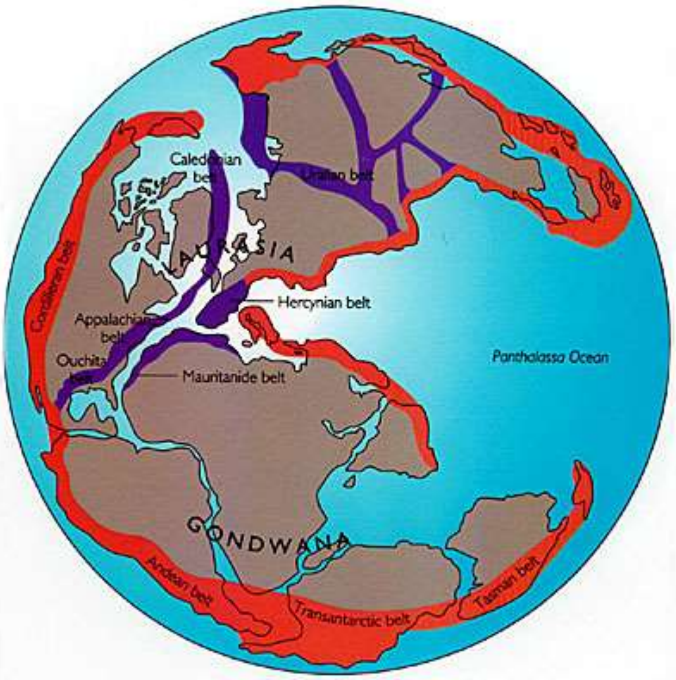


Fig: Maps by Wegener (1915), showing continental drift

Evidence for continental drift

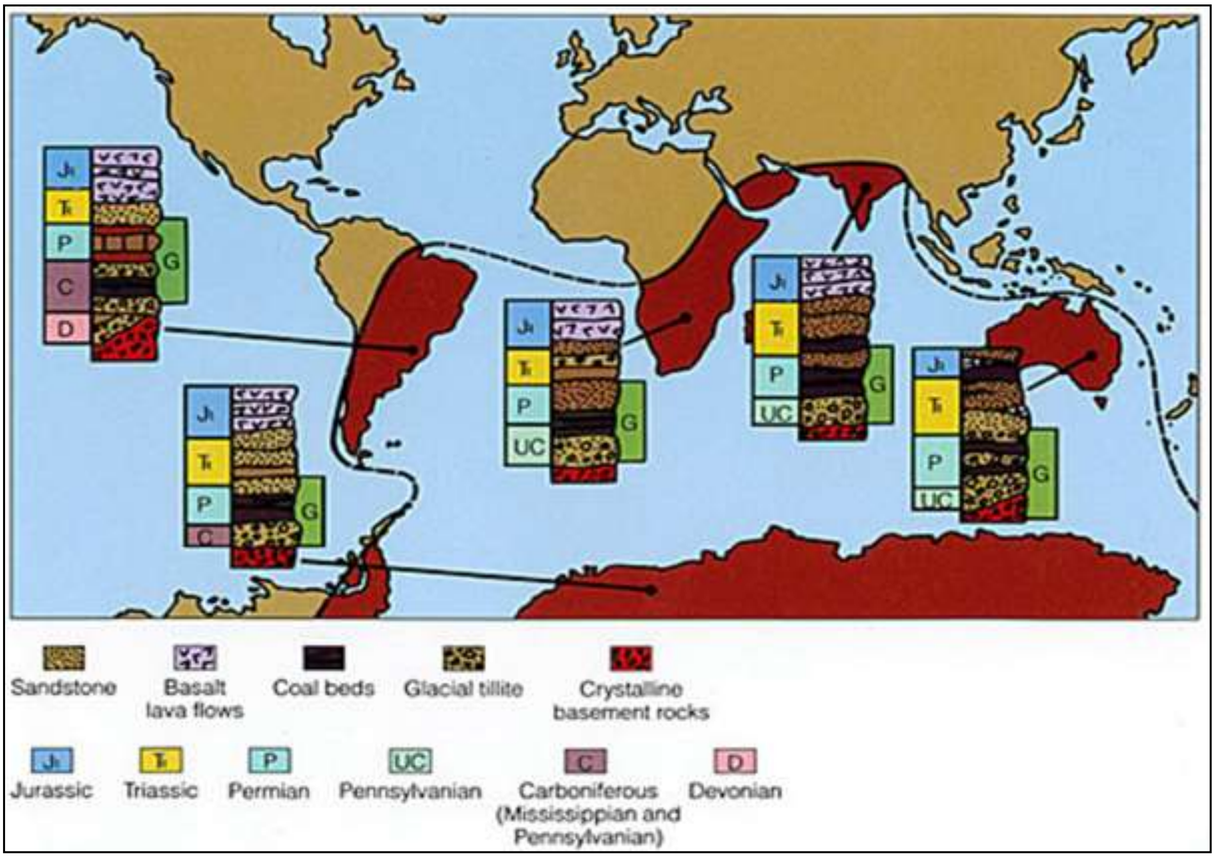
- Matching coastlines





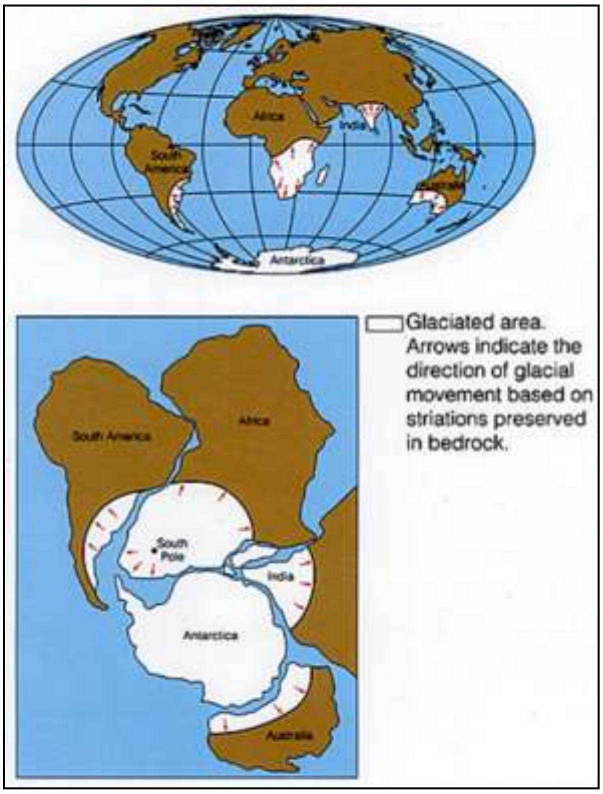
Matching mountains ranges

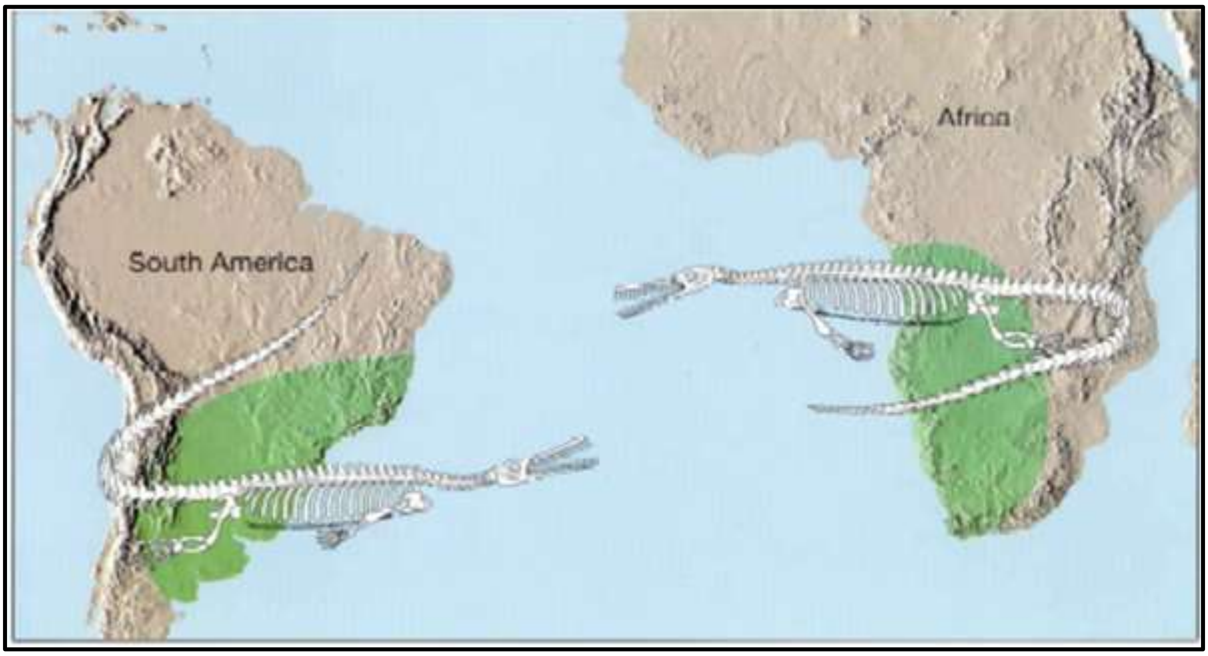
Matching rock types and rock ages



- Matching glacier deposits - Matching glacier deposits 300 million years ago

- Matching fossils - Fossils of of Mesosaurus (aquatic reptile) found on both sides of Atlantic





1.10 Earthquakes and Plate Tectonics

Earthquakes are not randomly distributed over the Earth's surface. They are observed to be concentrated in specific zones. Volcanoes and mountain ranges also found in these zones. Theory of plate tectonics which combines many of the ideas about continental drift explains the reasons for these seismological activities.

Plate tectonics tells us that the Earth's rigid outer shell (lithosphere) is broken into a mosaic of oceanic and continental plates which can slide over the plastic aesthenosphere, which is the uppermost layer of the mantle. The plates are in constant motion. Where they interact, along their margins, important geological processes take place, such as the formation of mountain belts, earthquakes, and volcanoes.

1.11 Theory of Plate tectonics

The theory of Plate tectonics was proposed in 1960s based on the theory of continental drift. This is the Unifying theory that explains the formation and deformation of the Earth's surface. According to this theory, continents are carried along on huge slabs (plates) on the Earth's outermost layer (Lithosphere).

Earth's outermost layer is divided into 12 major Tectonic Plates (~80 km deep). These plates move relative to each other a few centimetres per year.

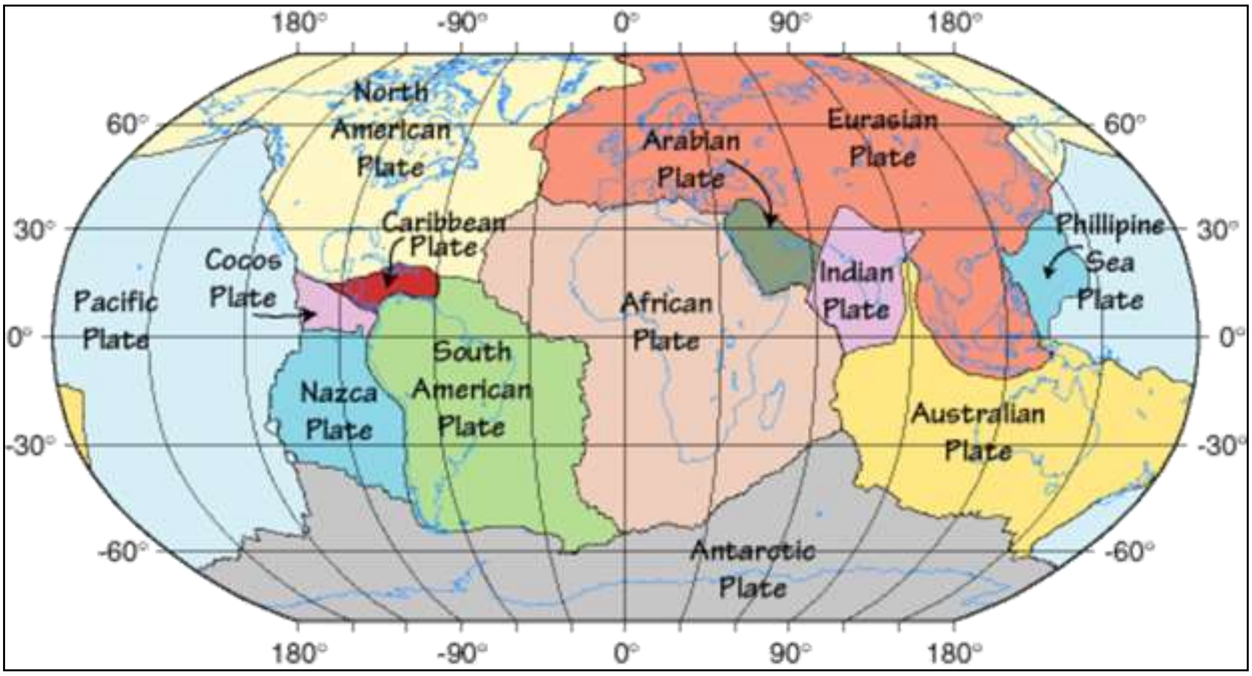


Fig: Tectonic plates of Earth

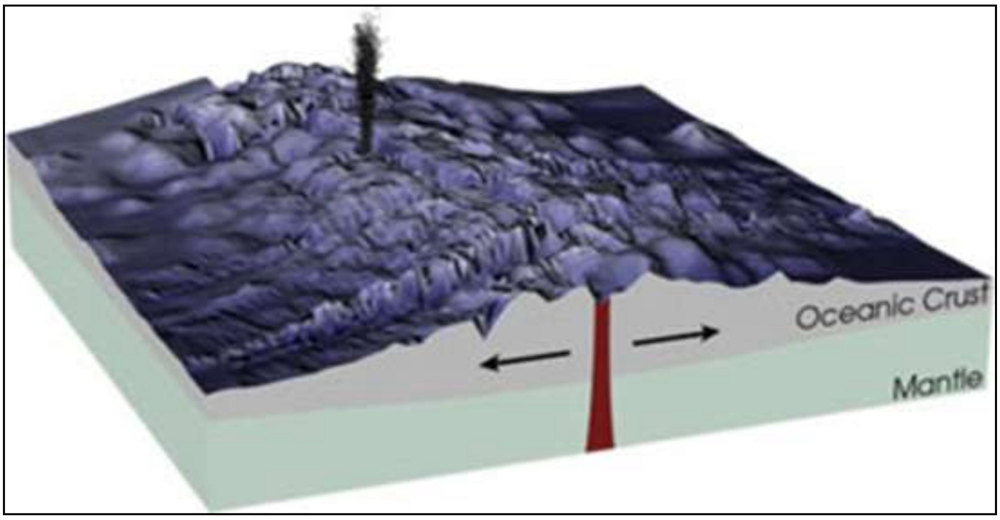
1.12 Evidence for plate tectonic movements

Wegener's theory of continental drift was not accepted initially because Wegener could not propose a mechanism which could explain the motion of continents.

Today plate tectonics and continental drift are accepted as facts because of following evidences.

- Matching coastlines of the continents
- Matching mountain ranges and rock types and age of opposite shorelines
- Matching glacier deposits and fossils of opposite shores
- Ocean floor spreading
- Geodetic measurements through satellites

1.13 Ocean floor spreading



Discovered in oceans by ships dragging magnetometers (1940s and 1950s)
Extensive mapping of magnetic stripes is carried out since then.

A series of under-water mountains called mid-ocean ridges is found throughout the world. These mountains are formed as new sea floor is created from magma that rises up from the mantle below.

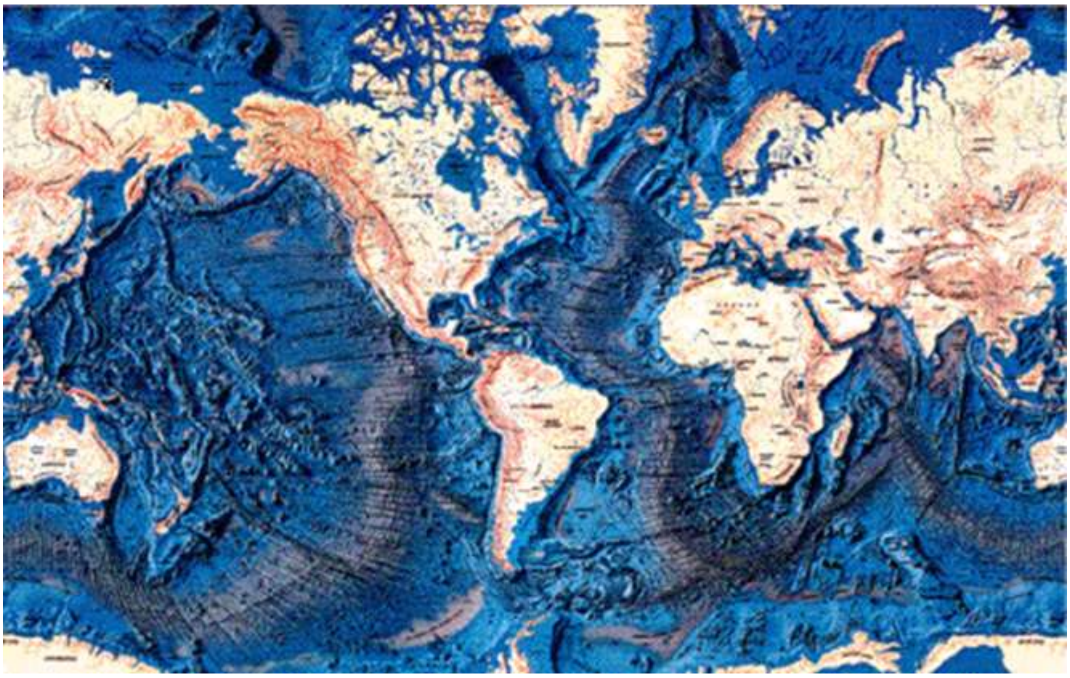
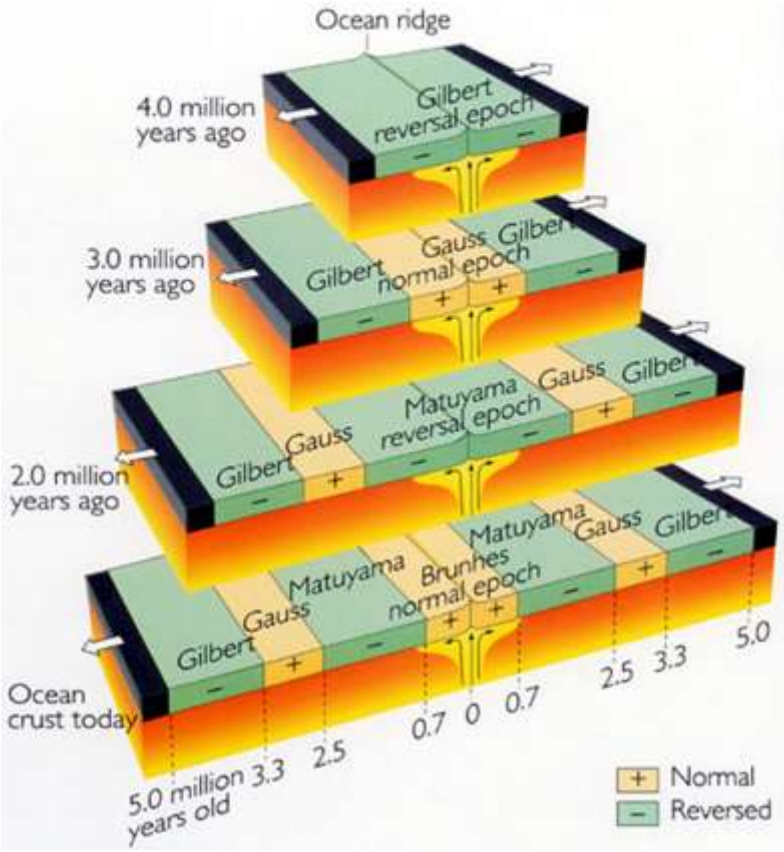


Fig: Mid oceanic Ridges

Evidence for ocean floor spreading (Paleo-magnetic reversal)

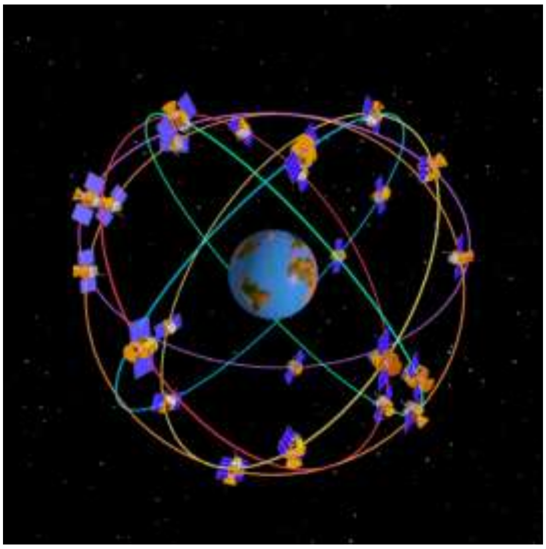
When a magnetometer is suspended across the ocean, it indicates that there are alternating zones of rock with either normal or reversed polarity. Study of these magnetic anomalies is called paleo-magnetism.



Earth's magnetic field flip-flops on average about every 250,000 years. North becomes south and south becomes north. The rocks of the sea floor record these reversals. These reversals can be seen as alternating bands on the sea floor, proving that the sea floor was spreading apart as the earth's magnetic field reversed itself over long periods of geologic time

Magnetic field of Earth reverses on semi-regular basis. Minerals act like compass needles and point towards magnetic north. "Hot" rocks record the direction of the magnetic field as they cool.

Evidence for plate tectonic movements: Geodetic measurements



The Global Positioning System (GPS) is a constellation of 24 satellites which is used for precise geodetic position measurements. Laser geodynamic satellites orbit the earth at an altitude of

3,700 miles. Laser beams are bounced from one point on thes earth, off the satellite, to a second point on the ground. Scientists can then measure the distance between the two points with great accuracy. Horizontal velocities, mostly due to motion of the Earth's tectonic plates and deformation in plate boundary zones, are recorded and maps are prepared with arrows representing the movement of plates. These systems show conclusively that the continents are still drifting at a rate of a few centimetres a year.

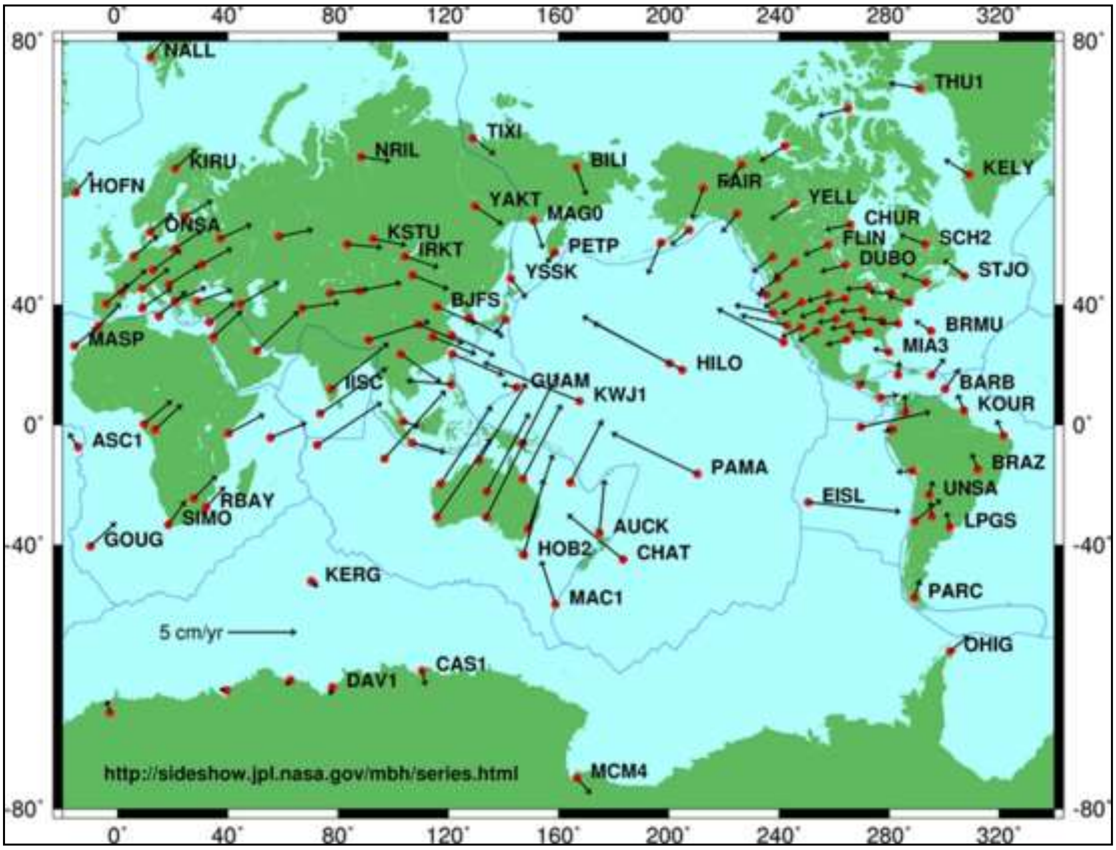


Fig: Movement of global plate boundaries

Seismic Waves

Seismic waves are waves of energy that travel through the Earth's layers, and are a result of earthquakes, volcanic eruptions, magma movement, large landslides and large man-made explosions that give out low-frequency acoustic energy. Many other natural and anthropogenic sources create low-amplitude waves commonly referred to as ambient vibrations. Seismic waves are studied by geophysicists called seismologists. Seismic wave fields are recorded by a seismometer, hydrophone (in water), or accelerometer.

When an earthquake occurs, it makes seismic waves, which cause the shaking we feel.

Seismic waves are essentially just the jiggling of the ground in response to the force put on the ground by the earthquake, similar to the way the jello in a bowl responds to a tap to the side of the bowl.

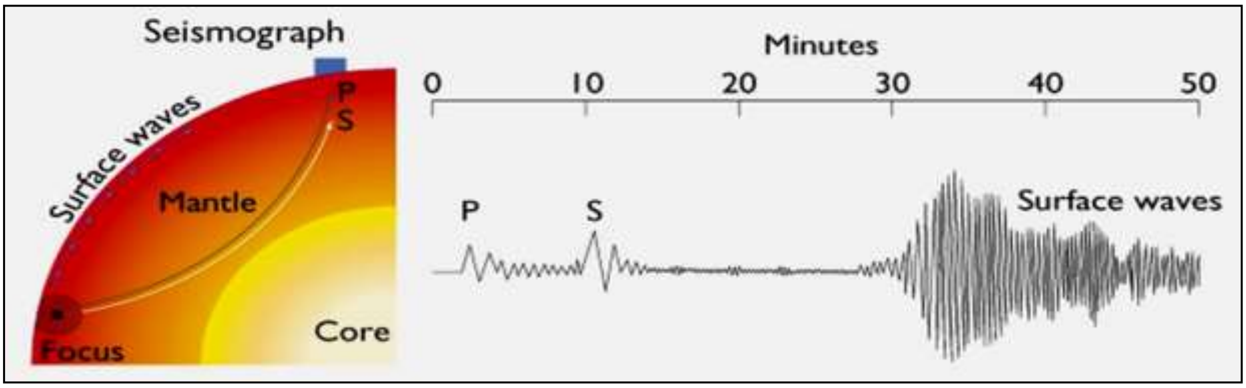


Fig: Illustrations of seismic waves

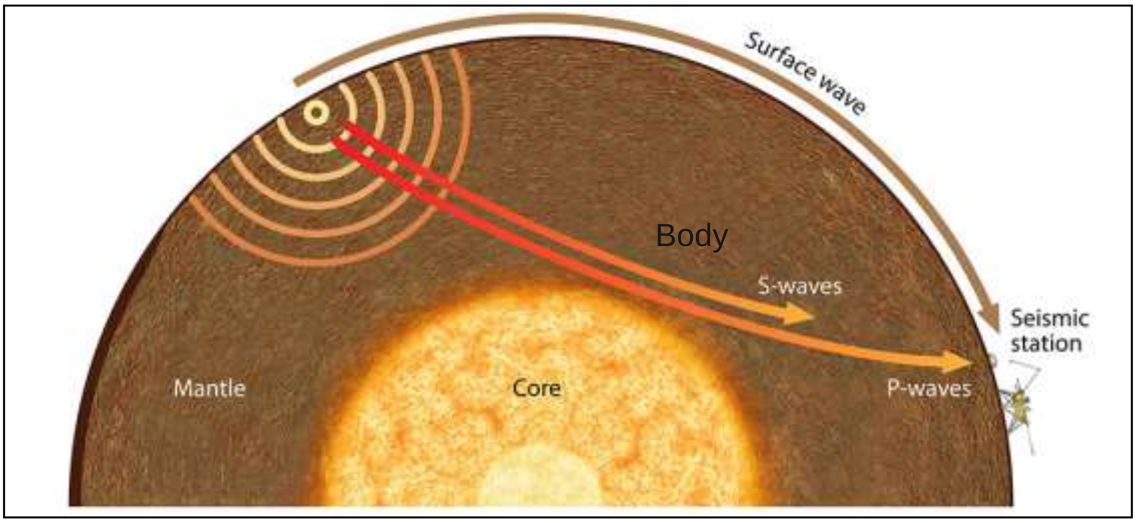
The propagation velocity of seismic waves depends on density and elasticity of the medium as well as the type of wave. Velocity tends to increase with depth through Earth's crust and mantle but drops sharply going from the mantle to the outer core.

Earthquakes create distinct types of waves with different velocities; when reaching seismic observatories, their different travel times help scientists to locate the source of the hypocenter. In geophysics the refraction or reflection of seismic waves is used for research into the structure of the Earth's interior, and man-made vibrations are often generated to investigate shallow, subsurface structures.

Types of Seismic Waves:

There are two types of seismic waves –

- Body waves
- Surface waves



Body Waves

Body waves travel through the interior of the Earth along paths controlled by the material properties in terms of density and modulus (stiffness). The density and modulus, in turn, vary according to temperature, composition, and material phase. This effect resembles the refraction of light waves.

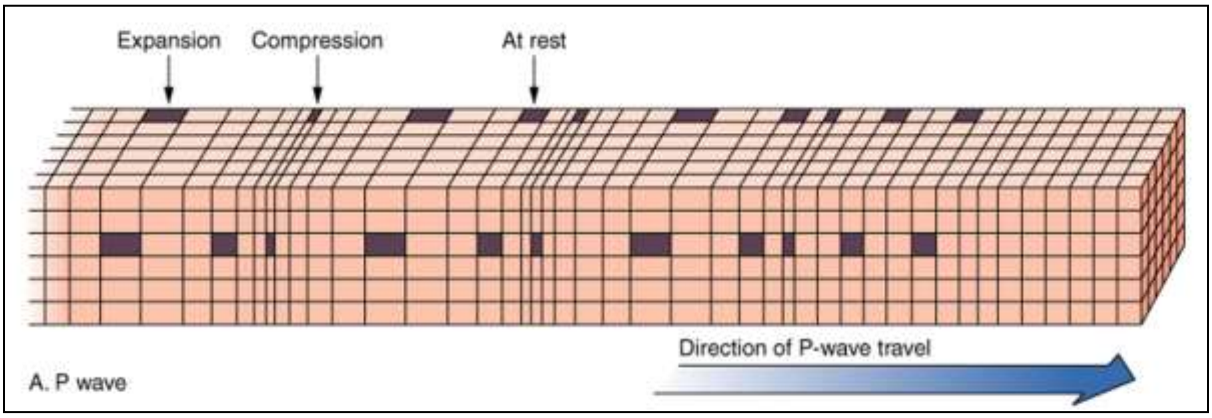
Two types of particle motion result in two types of body waves:

- Primary wave or P-wave
- Secondary wave or S-wave

Primary wave or P-wave

A P-wave is a sound (seismic) wave traveling through rock. In a P-wave, the rock particles are alternately squished together and pulled apart (called compressions and dilatations), so P waves are also called compressional waves.

These waves can travel through solids, liquids, and gases. P-waves can travel through the liquid outer core.

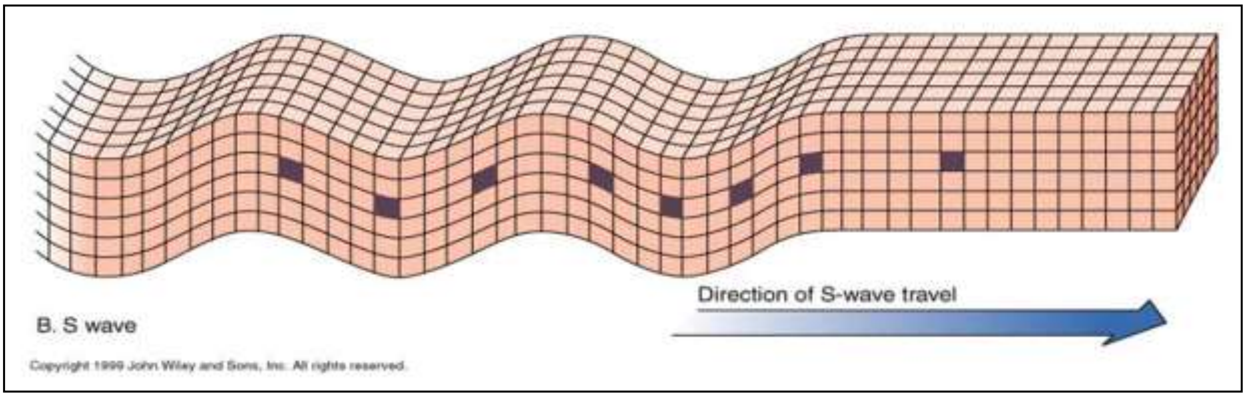


Secondary wave or S-wave

An S-wave is a different beast. In an S-wave, the rock particles slide past one another, undergoing shear -- so an S-wave is also called a shear wave.

You can make shear waves by, for example, tying a rope to a tree and shaking the free end of the rope up and down or side-to-side.

The waves themselves will travel forward, toward the tree. But the rope particles will stay in one place, sliding back and forth past each other. Shear waves cannot travel in liquids or gases -- so, for example, S-waves don't travel through the ocean or through the outer core.



Surface waves

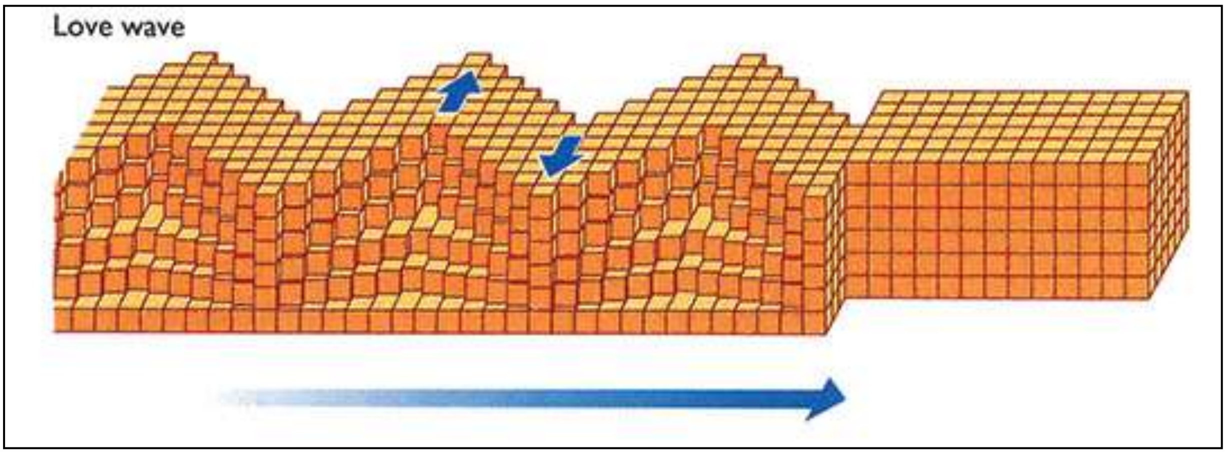
Seismic surface waves travel along the Earth's surface. They can be classified as a form of mechanical surface waves. They are called surface waves, as they diminish as they get further from the surface. They travel more slowly than seismic body waves (P and S). In large earthquakes, surface waves can have an amplitude of several centimeters.

Surface waves are called surface waves because they are trapped near the Earth's surface, rather than traveling through the ``body'' of the earth like P and S waves.

There are two major kinds of surface waves: Love waves, which are shear waves trapped near the surface, and Rayleigh waves, which have rock particle motions that are very similar to the motions of water particles in ocean waves.

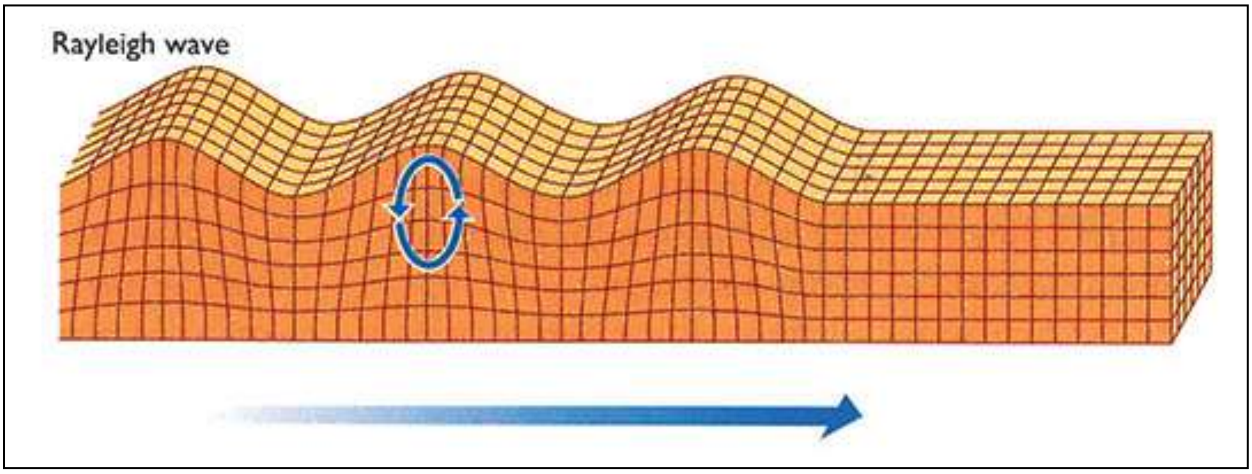
Love wave

A Love wave is a surface wave having a horizontal motion that is transverse (or perpendicular) to the direction the wave is traveling. They usually travel slightly faster than Rayleigh waves, about 90% of the S wave velocity, and have the largest amplitude.



Rayleigh waves

A Rayleigh wave is a seismic surface wave causing the ground to shake in an elliptical motion, with no transverse, or perpendicular, motion. Rayleigh wave entirely responsible for the destruction cause by an earthquake.



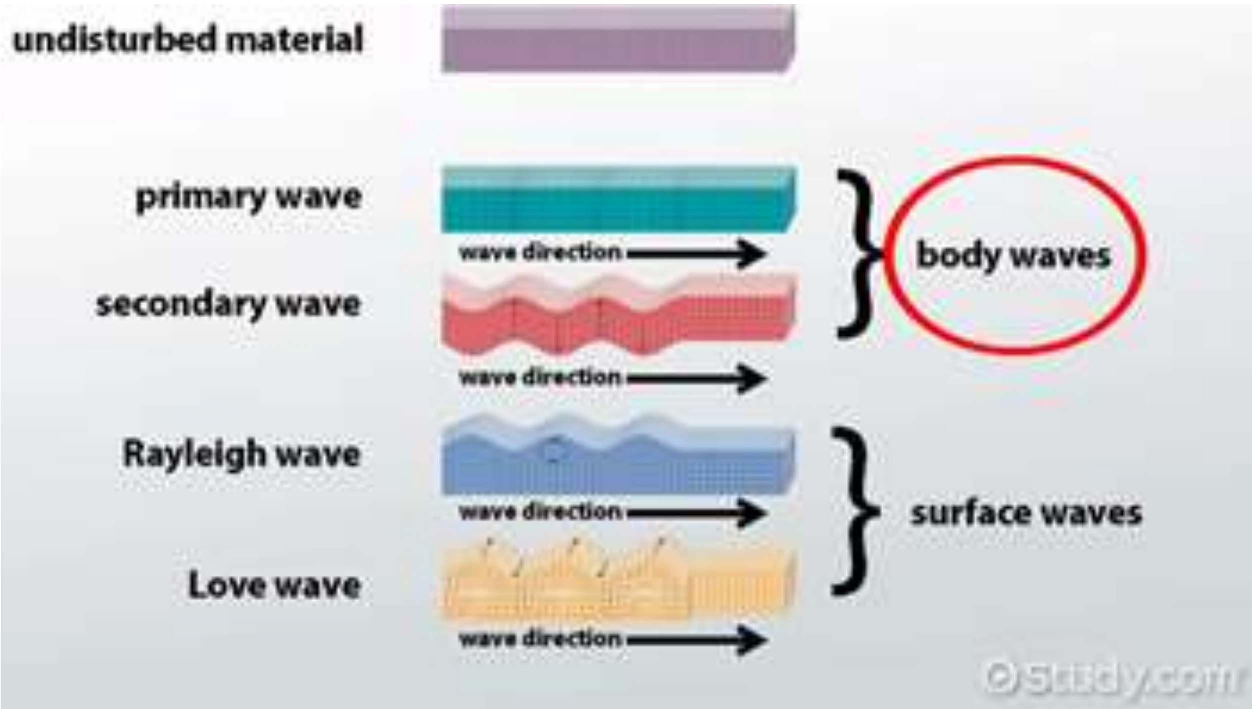


Table 2: Seismic Waves			
Type (and names)	Particle Motion	Typical Velocity	Other Characteristics
P, Compressional, Primary, Longitudinal	Alternating compressions ("pushes") and dilations ("pulls") which are directed in the same direction as the wave is propagating (along the raypath); and therefore, perpendicular to the wave front	V_P ~ 5 – 7 km/s in typical Earth's crust; >~ 8 km/s in Earth's mantle and core; 1.5 km/s in water; 0.3 km/s in air	P motion travels fastest in materials, so the P-wave is the first-arriving energy on a seismogram. Generally smaller and higher frequency than the S and Surface-waves. P waves in a liquid or gas are pressure waves, including sound waves.
S, Shear, Secondary, Transverse	Alternating transverse motions (perpendicular to the direction of propagation, and the raypath); commonly polarized such that particle motion is in vertical or horizontal planes	V_S ~ 3 – 4 km/s in typical Earth's crust; >~ 4.5 km/s in Earth's mantle; ~ 2.5-3.0 km/s in (solid) inner core	S-waves do not travel through fluids, so do not exist in Earth's outer core (inferred to be primarily liquid iron) or in air or water or molten rock (magma). S waves travel slower than P waves in a solid and, therefore, arrive after the P wave.
L, Love, Surface waves, Long waves	Transverse horizontal motion, perpendicular to the direction of propagation and generally parallel to the Earth's surface	V_L ~ 2.0 - 4.5 km/s in the Earth depending on frequency of the propagating wave	Love waves exist because of the Earth's surface. They are largest at the surface and decrease in amplitude with depth. Love waves are dispersive, that is, the wave velocity is dependent on frequency, with low frequencies normally propagating at higher

			velocity. Depth of penetration of the Love waves is also dependent on frequency, with lower frequencies penetrating to greater depth.
R, Rayleigh, Surface waves, Long waves, Ground roll	Motion is both in the direction of propagation and perpendicular (in a vertical plane), and "phased" so that the motion is generally elliptical – either prograde or retrograde	V_R ~ 2.0 - 4.5 km/s in the Earth depending on frequency of the propagating wave	Rayleigh waves are also dispersive, and the amplitudes generally decrease with depth in the Earth. Appearance and particle motion are similar to water waves.

SESSION 2: EARTHQUAKE SOURCE PARAMETERS

2.1 How Are Earthquakes Studied?

Seismologists study earthquakes by going out and looking at the damage caused by the earthquakes and by using seismographs. A seismograph is an instrument that records the shaking of the earth's surface caused by seismic waves. The term seismometer is also used to refer to the same device, and the two terms are often used inter changeably.

2.2 Seismograph

The first seismograph was invented in 132 A.D. by the Chinese astronomer and mathematician Chang Heng. He called it an "earthquake weathercock."

In 136 A.D. a Chinese scientist named Choke updated this meter and called it a "seismoscope." Columns of a viscous liquid were used in place of metal balls. The height to which the liquid was washed up the side of the vessel indicated the intensity and a line joining the points of maximum motion also denoted the direction of the tremor.

Fig: First Seismograph

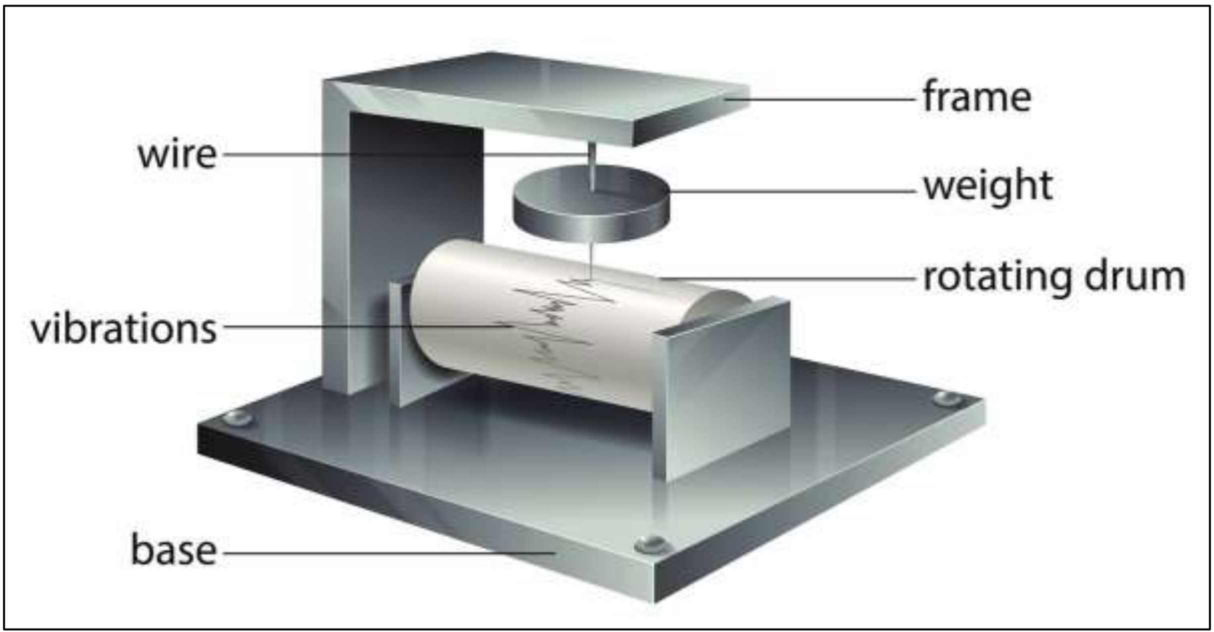


Fig: Modern Seismograph

2.3 How to Read a Seismogram?

Seismogram is the record of a seismograph either on a paper or on a magnetic tape.

When you look at a seismogram, there will be wiggly lines all across it. These are all the seismic waves that the seismograph has recorded. Most of these waves were so small that nobody felt them. These tiny microseisms can be caused by heavy traffic near the seismograph, waves hitting a beach, the wind, and any number of other ordinary things that cause some shaking of the seismograph. There may also be some little dots or marks evenly spaced along the paper. These are marks for every minute that the drum of the seismograph has been turning. How far apart these minute marks are will depend on what kind of seismograph you have.

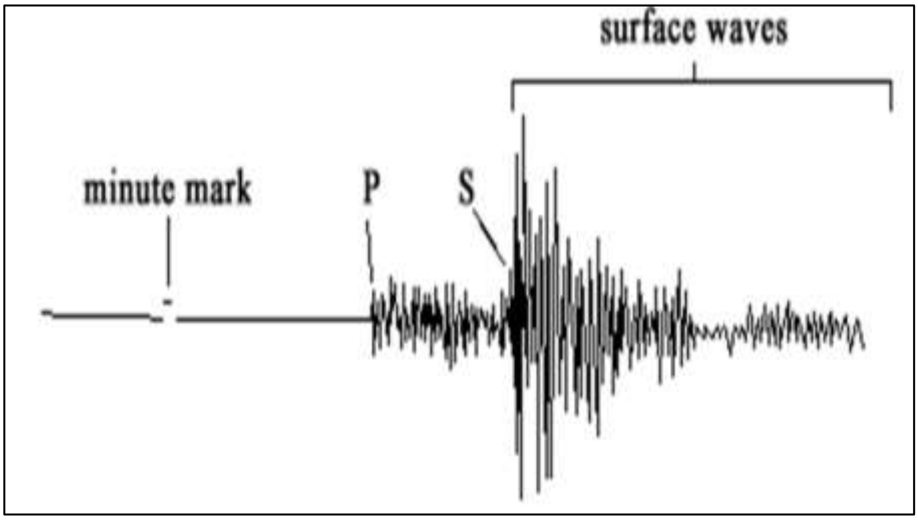


Fig: Seismogram (not seismograph)

Characteristics of Different seismic waves

- The P-waves will be the first wiggle that is bigger than the rest of the little ones.
- S-waves are usually bigger than the P-waves. If there aren't any S-waves marked on seismogram, it probably means the earthquake happened on the other side of the planet.
- The surface waves (Love- and Rayleigh- waves) are, often larger, waves marked on the seismogram. Surface waves travel a little slower than S-waves, so they tend to arrive at the seismograph just after the S-waves. Surface waves may be the only waves recorded a long distance from medium-sized earthquakes.

The parameters regularly determined during an Earthquake include-

- Magnitude
- Intensity
- Location
- Depth

2.4 Magnitude

Magnitude is a measurement of the energy released by an earthquake. Earthquake magnitude scales in general do not directly represent any physical parameters of the source. Magnitude scales can be used to represent relative size of earthquakes.

- Simplicity of magnitude scales allows us to process large number of events in a very short time.
- Providing the public with quick information on the *size of an earthquake.*
- Fundamental data to be included in earthquake catalogs, which are the basis for a variety of scientific research projects.

The magnitude scales currently used for measuring relative sizes of earthquakes are based on empirical formulas, which give results that depend on the *wave types* and *frequency band used.*

Magnitude is a logarithmic measure of the size of an earthquake or explosion based on instrumental measurements. The magnitude concept was first proposed by Richter (1935). Magnitudes are derived from ground motion amplitudes and periods or from signal duration measured from instrumental records. There is no a priori scale limitation to magnitudes as exist for macro seismic intensity scales. Magnitudes are often misleadingly referred to in the press as "... according to the open-ended RICHTER scale...". In fact, the maximum size of tectonic earthquakes is limited by nature, i.e., by the maximum size of a brittle fracture in a finite and heterogeneous lithospheric plate. The largest moment magnitude, Mw, observed so far was that of the Chile earthquake in 1960 (Mw~ 9.5; Kanamori 1977). On the other hand, the magnitude scale is open at the lower end. Nowadays, highly sensitive instrumentation close to the sources may record events with magnitude smaller than zero. According to Richter ś original definition these magnitude values become negative. With empirical energy-magnitude-relationships the seismic energy, ES radiated by the seismic source as seismic waves can be estimated. Common relationships are those given by Gutenberg and Richter (1954, 1956) between ES and the surface-wave magnitude MS and the body-wave magnitude mB: log ES = 11.8 + 1.5 Ms and log ES = 5.8 + 2.4 mB, respectively (when ES is given in erg; 1 erg = 10-7 Joule). According to the first relationship, a change of M by two units corresponds to a change in ES by a factor of 1000. Based on the analysis of digital recordings, there exist also direct procedures to estimate ES (e.g., Purcaru and Berckhemer, 1978; Seidl and Berckhemer, 1982; Boatwright and Choy, 1986; Kanamori et al., 1993; Choy and Boatwright, 1995) and to define an "energy magnitude" Me. Since most of the seismic energy is concentrated in the higher frequency part around the corner frequency of the spectrum, Me is a more suitable measure of the earthquakes' potential for damage. In contrast, the seismic moment (see below) is related to the final static displacement after an earthquake and consequently, the moment magnitude, Mw, is more closely related to the tectonic effects of an earthquake.

Another quantitative measure of the size and strength of a seismic shear source is the scalar seismic moment M_0:

$$M_0 = \mu D A$$

with μ - rigidity or shear modulus of the medium, D - average final displacement after the rupture, A - the surface area of the rupture. M_0 is a measure of the irreversible inelastic deformation in the rupture area. This inelastic strain is described in (1) by the product D A. On the basis of reasonable average assumptions about μ and the stress drop Δσ (i.e., withΔσ/μ = constant) Kanamori (1977) derives the relationship ES = 5×10 -5 M0 (in J). More information about the deformation in the source is described by the seismic moment tensor. Its determination is now standard in the routine analysis of strong earthquakes by means of waveform inversion of long-period digital records.

Richter's (1935) local magnitude, ML, (or Richter scale)

- The first earthquake-magnitude scale was the Richter scale, devised by Charles F. Richter, a seismologist at the California Institute of Technology.
- The Richter scale is based on the amplitude of seismic waves–the stronger the earthquake, the stronger the seismic vibrations it causes. The Richter magnitude of an earthquake is expressed as a decimal number, such as 6.7.
- The most important thing to remember about Richter magnitude is that it is a logarithmic scale, meaning that an increase of one in magnitude corresponds to a factor of ten increase in the amplitude of ground motion. For example, a magnitude 6.7 earthquake causes shaking 10 times greater in amplitude than a magnitude 5.7 earthquake and 100 times greater than a magnitude 4.7 earthquake.

Figure 4.6-1: Example of the determination of the Richter scale.

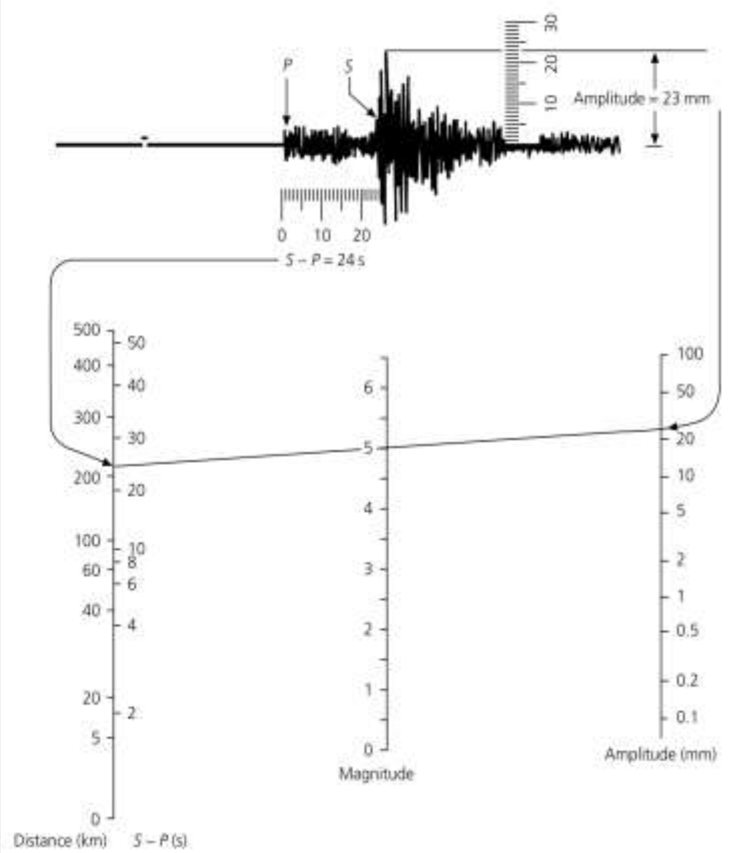


Fig: Graphical procedure of determining Richter magnitude

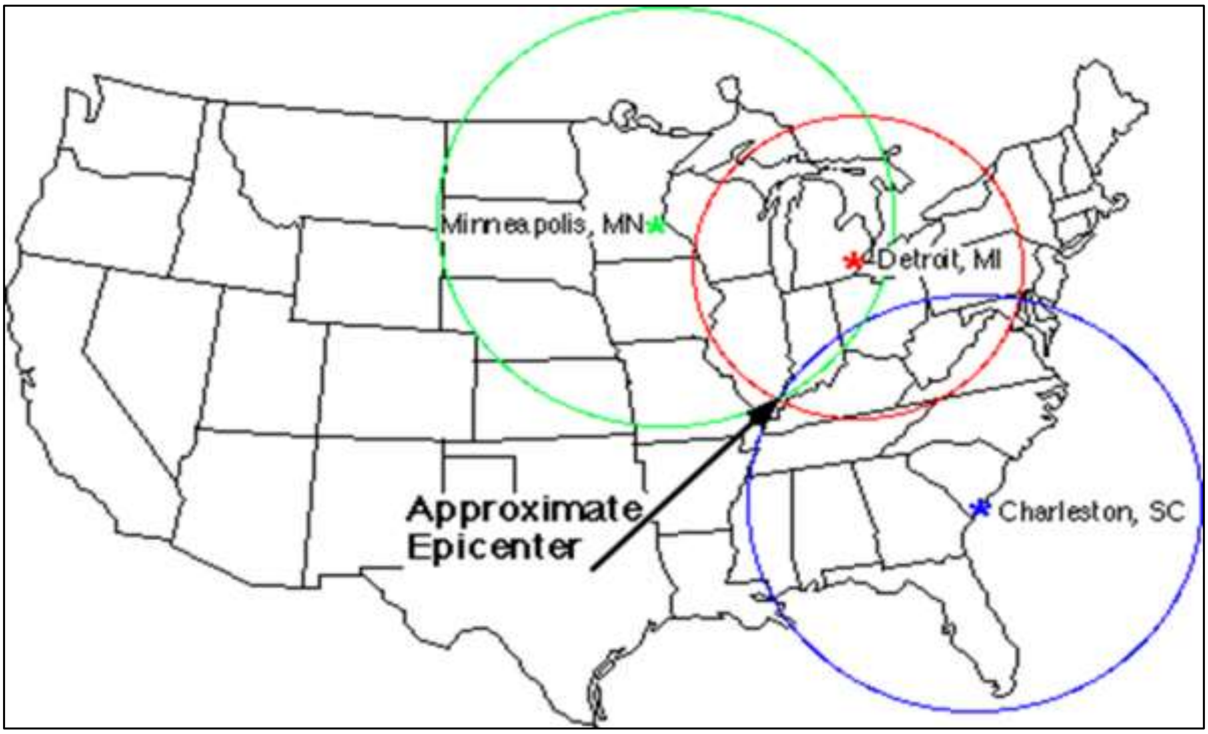
- Measure the distance between the first P wave and the first S wave. In this case, the first P and S waves are 24 seconds apart.

- Find the point for 24 seconds on the left side of the chart below and mark that point. According to the chart, this earthquake's epicenter was 215 kilometers away.

- Measure the amplitude of the strongest wave. The amplitude is the height (on paper) of the strongest wave. On this seismogram, the amplitude is 23 millimeters. Find 23 millimeters on the right side of the chart and mark that point.

- Place a ruler (or straight edge) on the chart between the points you marked for the distance to the epicenter and the amplitude. The point where your ruler crosses the middle line on the chart marks the magnitude (strength) of the earthquake. This earthquake had a magnitude of 5.0.

2.5 Finding the Epicentre or Location



- Check the scale on your map. It should look something like a piece of a ruler. All maps are different. On your map, one centimeter could be equal to 100 kilometres or something like that.

- Figure out how long the distance to the epicentre (in centimetres) is on your map. For example, say your map has a scale where one centimetre is equal to 100 kilometres. If the epicentre of the earthquake is 215 kilometres away, that equals 2.15 centimetres on the map.

- Using your compass, draw a circle with a radius equal to the number you came up with in Step #2 (the radius is the distance from the centre of a circle to its edge). The centre of the circle will be the location of your seismograph. The epicentre of the earthquake is somewhere on the edge of that circle.

2.6 Earthquake Intensity

Earthquake intensity is defined as the strength of seismic shaking at a given location. Whereas an earthquake has just a single magnitude, it will have many different intensities at different locations.

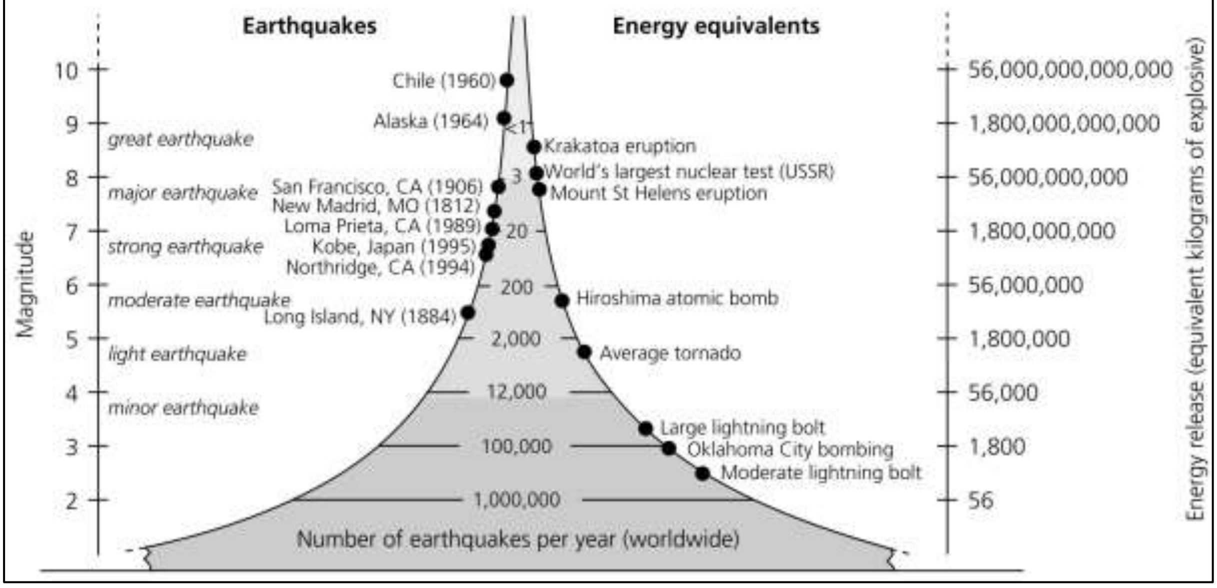
In general, areas closest to the epicenter experience the highest intensities, and shaking diminishes in strength farther away. This phenomenon is the result of seismic-wave attenuation, which is the reduction in wave amplitude and wave energy as they travel away from their source.

In order to study the patterns of earthquake intensity during different earthquakes, a system has been devised to assign specific numbers to different levels of shaking. The Mercalli scale was developed in 1902 and modified in the 1930s. The Mercalli scale assigns a numerical value, from Roman numeral I to XII, to the intensity of seismic shaking at any one particular location.

I. Instrumental	Generally not felt by people unless in favorable conditions.
II. Weak	Felt only by a couple people that are sensitive, especially on the upper floors of buildings. Delicately suspended objects (including chandeliers) may swing slightly.
III. Slight	Felt quite noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration similar to the passing of a truck. Duration can be estimated. Indoor objects (including chandeliers) may shake.
IV. Moderate	Felt indoors by many to all people, and outdoors by few people. Some awakened. Dishes, windows, and doors disturbed, and walls make cracking sounds. Chandeliers and indoor objects shake noticeably. The sensation is more like a heavy truck striking building. Standing automobiles rock noticeably. Dishes and windows rattle alarmingly. Damage none.
V. Rather Strong	Felt inside by most or all, and outside. Dishes and windows may break and bells will ring. Vibrations are more like a large train passing close to a house. Possible slight damage to buildings. Liquids may spill out of glasses or open containers. None to a few people are frightened and run outdoors.
VI. Strong	Felt by everyone, outside or inside; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight to moderate to poorly designed buildings, all others receive none to slight damage.
VII. Very Strong	Difficult to stand. Furniture broken. Damage light in building of good design and construction; slight to moderate in ordinarily built structures; considerable damage in poorly built or badly designed structures; some chimneys broken or heavily damaged. Noticed by people driving automobiles.
VIII. Destructive	Damage slight in structures of good design, considerable in normal buildings with a possible partial collapse. Damage great in poorly built structures. Brick buildings easily receive moderate to extremely heavy damage. Possible fall of chimneys, factory stacks, columns, monuments, walls, etc. Heavy furniture moved.
IX. Violent	General panic. Damage slight to moderate (possibly heavy) in well-designed structures. Well-designed structures thrown out of plumb. Damage moderate to great in substantial buildings, with a possible partial collapse. Some buildings may be shifted off foundations. Walls can fall down or collapse.
X. Intense	Many well-built structures destroyed, collapsed, or moderately to severely damaged. Most other structures destroyed, possibly shifted off foundation. Large landslides.
XI. Extreme	Few, if any structures remain standing. Numerous landslides, cracks and deformation of the ground.
XII. Catastrophic	Total destruction – everything is destroyed. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock move position. Landscape altered, or leveled by several meters. Even the routes of rivers can be changed.

Fig: Modified Mercalli intensity scale

Figure 1.2-2: Comparison of frequency, magnitude, and energy release.



2.7 Geology of Earthquake Source Region

Introduction

- It is generally accepted that crustal earthquakes are caused by sudden displacements on faults, and many earthquakes of M>6 are accompanied by faulting at the earth's surface.

- However, faulting at the surface may not be representative of fault conditions at 10-20 km depth where crustal earthquake nucleate.

- High pressure and temperature cause rocks to respond far differently in the earthquake source region than they do at the surface.

- Most earth materials at the surface are too weak to store enough elastic strain energy to produce a damaging earthquake, and the displacement and rupture length at the surface may be considerably less than they are at nucleation depth.

Understanding what happens at the nucleation site of a large earthquake is complicated by the fact that we are as yet unable to sample rocks directly at earthquake nucleation depths.

Although dip drilling projects by several countries may resolve the sampling problem in the next decade or two. We are limited now to-

1) interpretations based on seismograms of earthquakes and dip seismic reflection profiles,
2) study of ancient mid-crustal rocks that have been uplifted and eroded so that they may be studied directly
3) experimental deformation of rocks in the laboratory under mid- crustal pressure and temperatures, and
4) theoretical modelling.

What can we infer from the distribution of earthquakes in the earth's crust?

- In continents, earthquakes occur in the upper crust, with the deepest earthquakes in the oldest crust.

- In ocean basins, the deepest earthquakes occur in the oldest lithosphere (excluding those in subduction zones).

- Because the oldest crust is the coldest in continents and ocean basins alike, the depth of earthquakes appears to be limited by temperature.

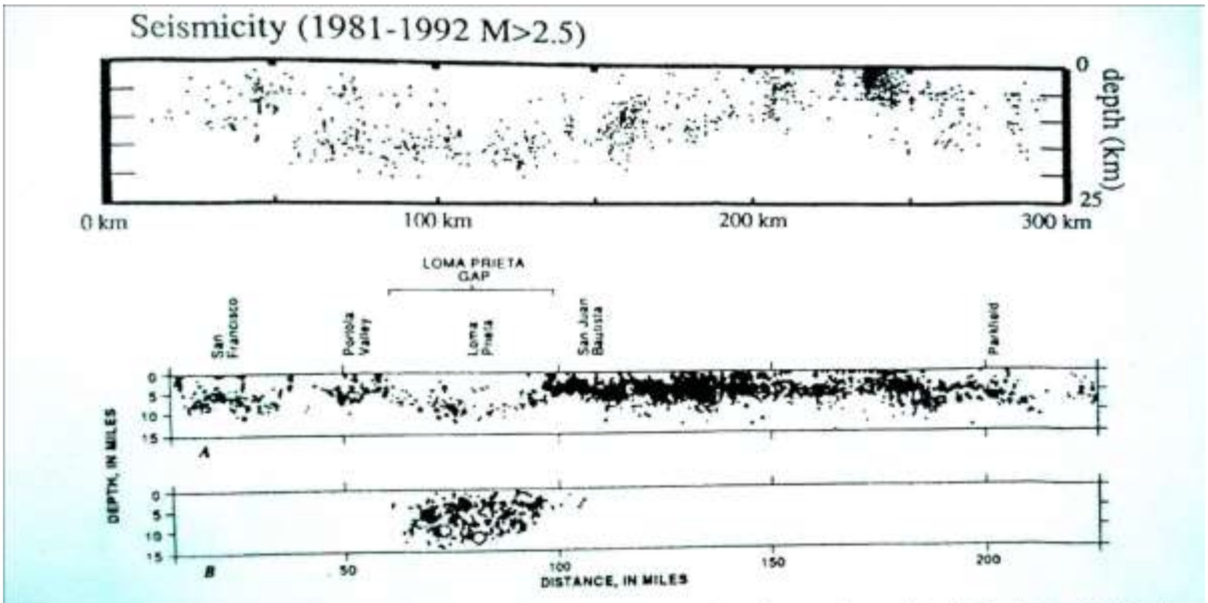


Figure 3–1. Depth distribution of earthquakes parallel to strike of two major strike-slip faults in California. Top diagram shows earthquakes on the San Jacinto fault from 1981 to 1992. Northwest is to left. Bottom diagram shows (a) a 20-year record of earthquakes on central San Andreas fault prior to the October 17, 1989 Loma Prieta earthquake; and (b) aftershocks of the Loma Prieta earthquake. Northwest is to left. San Jacinto seismicity cross section from Peterson and Wesnousky (1994). San Andreas cross sections from U.S. Geological Survey Staff (1990).

- The sharp cutoff of earthquakes with depth is most apparent along fault zones characterized by high seismicity and monitored by extensive, high quality seismic networks.

- Fig. 3-1 shows long term seismicity parallel to strike of San Jacinto and central San Andreas faults of California.

- The base of earthquakes along the San Jacinto fault rises to the southeast, reflecting the higher geothermal gradient near the Salton Sea

- The base of the earthquakes along the San Andreas fault rises and falls, suggesting control by rock-type in the fault zone in addition to temperature.

- The shallowest levels tend to have fewer earthquakes than deeper levels; note the San Jacinto fault between 10 and 40 km south and 80 and 150 km south of point A.

- The shallow aseismic layer between 80 and 130 km may be a seismic gap analogous to the gap filled by the Loma Prieta earthquake, as shown in the fig. 3-1b.

- The shallowest level of San Andreas fault have relatively low seismicity near San Francisco, San Juan Bautista, and Parkfield.

Seismic site effects are related to the amplification of seismic waves in superficial geological layers. The surface ground motion may be strongly amplified if the geological conditions are unfavorable (e.g. sediments). Therefore, the study of local site effects is an important part of the assessment of strong ground motions, seismic hazard and engineering seismology in general. Damage due to an earthquake may thus be aggravated as in the case of the 1985 Mexico City earthquake.

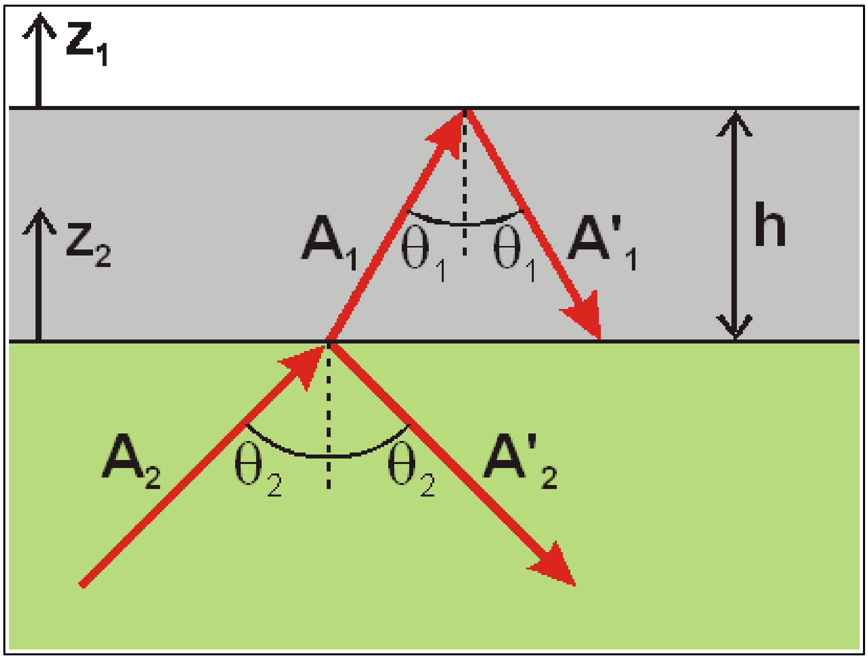


Fig1: Seismic site effects / wave amplification in a horizontal layer (SH-waves): various wavefields.

When propagating, the seismic waves are reflected and refracted at the interface between the various geological layers (**Fig.1**).

The example of **Figure 1** depicts the seismic wave amplification in horizontal geological layers. We consider a homogeneous elastic half-space (in green) over which an elastic alluvial layer of constant thickness h is located (in gray). A shear wave (SH) of amplitude A_2 reaches the interface between the half-space and the alluvial layer with an incidence θ_2. It thus generates:

- a reflected wave in the half-space with amplitude A_2' and incidence θ_2
- a refracted wave in the superficial layer with amplitude A_1 and incidence θ_1

The refracted wave originates a reflected wave when reaching the free surface; its amplitude and incidence are denoted A_1' and θ_1 respectively. This latter wave will be reflected and refracted several times at the base and the top of the surficial layer. If the layer is softer than the half-space, the surface motion amplitude can be larger than A_2 thus leading to the *amplification of seismic waves* or *seismic site effects*. When the geological interfaces are not horizontal, it also possible to study seismic site effects by considering the *basin effects* due to the complex geometry of the alluvial filling[2] For small inclinations of the subsurface layers and/or low impedance contrasts, the assumption of horizontal layering (i.e. the 1D assumption) can still be used to predict site response.[3]

Example: site effects in Mexico City (1985)

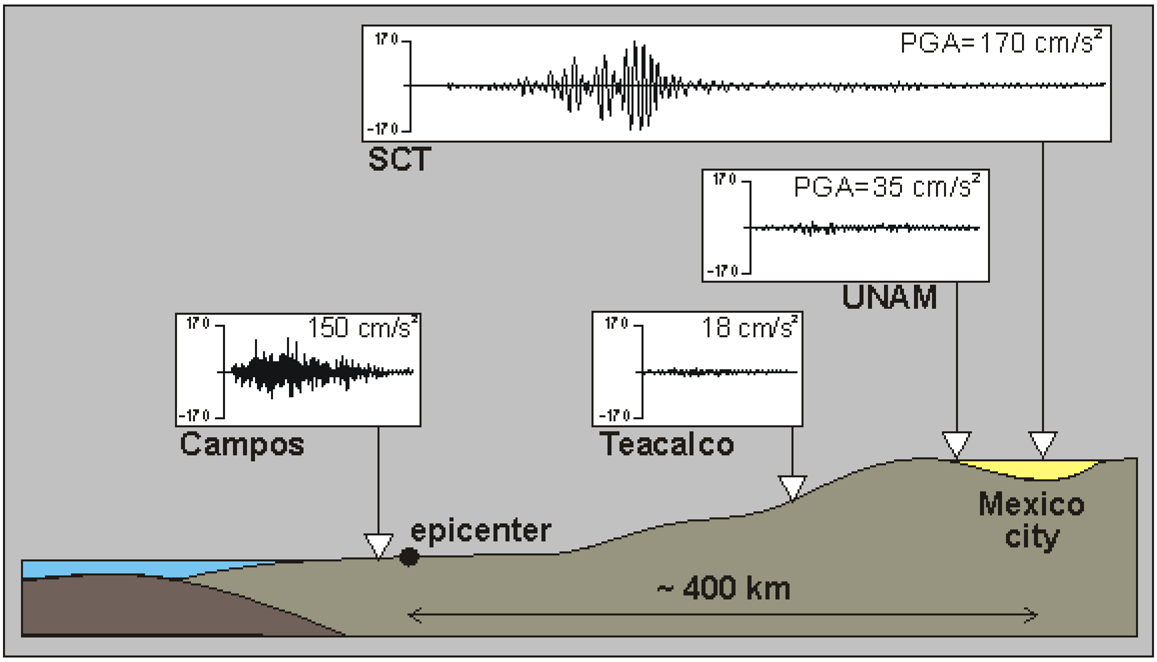


Fig: Site effects in Mexico City: recordings from the 1985 earthquake

Seismic site effects have been first evidenced during the 1985 Mexico City earthquake. The earthquake epicenter was located along the Pacific Coast (several hundred kilometers from Mexico-City), the seismic shaking was however extremely strong leading to very large damages.

Figure above displays the recordings performed at different distances from the epicenter during the earthquake sequence. The acceleration amplitude measured at different distances changes drastically:

- Campos station: this station is located very close to the epicenter and recorded a maximum acceleration of 150 cm/s2.

- Teacalco station: this station is located at more than 200 km from the epicenter and recorded a much lower acceleration (about 18 cm/s2). This amplitude decay is due to the wave attenuation during the propagation process: geometrical attenuation due to the expansion of the wavefront and material (or intrinsic) attenuation due to the energy dissipation within the medium (e.g. grains friction),
- UNAM station: this station is located at more than 300 km from the epicenter and recorded a maximum acceleration of 35 cm/s2, larger than that recorded at the Teacalco station,
- SCT station: this station is located in Mexico City at approximately 400 km from the epicenter and recorded a very strong maximum acceleration (about 170 cm/s2).

We may notice that the acceleration amplitude strongly decreases first and then increases when the seismic waves reach the alluvial deposit on which Mexico City has been founded.

2.8 Earthquake Prediction and Difficulties

Earthquake prediction is a branch of the science of seismology concerned with the specification of the time, location, and magnitude of future earthquakes within stated confidence limits. Of particular importance is the prediction of hazardous earthquakes that are likely to cause damage to infrastructure or loss of life.

Earthquake prediction is sometimes distinguished from earthquake forecasting, which some authorities consider to be the probabilistic assessment of general earthquake hazard, including the frequency and magnitude of damaging earthquakes, in a given area over periods of years or decades. It can be further distinguished from real-time earthquake warning systems, which, upon detection of a severe earthquake, can provide a few seconds of warning to neighboring regions.

To be useful, earthquake predictions must be precise, timely, and reliable. A prediction must be precise enough to warrant the cost of increased precautions, including the disruption of ordinary activities and commerce, and timely enough that preparations can be made. Predictions must also be reliable, as false alarms and canceled alarms are economically costly and undermine confidence in, and thereby the effectiveness of, any kind of warning.

With over 13,000 earthquakes around the world each year having a Richter magnitude of 4.0 or greater, trivial success in earthquake prediction is easily obtained using sufficiently broad parameters of time, location, or magnitude. However, such trivial "successful predictions" are not useful. Useful prediction of large (damaging) earthquakes in a timely manner is generally notable for its absence, the few claims of success being controversial. Extensive searches have reported many possible earthquake precursors, but "none have been found to be reliable.

In the 1970s, scientists were optimistic that a practical method for predicting earthquakes would soon be found, but by the 1990s continuing failure led many to question whether it was even possible. While some scientists still hold that, given enough resources, prediction might be possible, many others now maintain that earthquake prediction is inherently impossible.

Earthquake Prediction Methods

Earthquake prediction is an immature science in that it cannot predict from first principles the location, date, and magnitude of an earthquake. Research in this area therefore seeks to empirically derive a reliable basis for predictions in either distinct precursors, or some kind of trend or pattern.

- Precursors

An earthquake precursor is an anomalous phenomenon that might give effective warning of an impending earthquake. Reports of these – though generally recognized as such only after the event – number in the thousands, some dating back to antiquity. There have been around 400 reports of possible precursors in scientific literature, of roughly twenty different types. None have been found to be reliable.

In the early 1990, produced a "Preliminary List of Significant Precursors". 40 nominations were made, of which five were selected as possible significant precursors, with two of those based on a single observation each.

After a critical review of the scientific literature the International Commission on Earthquake Forecasting for Civil Protection (ICEF) concluded in 2011 there was "considerable room for methodological improvements in this type of research. In particular, many cases of reported precursors are contradictory, lack a measure of amplitude, or are generally unsuitable for a rigorous statistical evaluation.

- Animal Behavior
- Changes in Vp/Vs
- Radon emissions
- Electro-magnetic variations
- Trends (Elastic rebound, Characteristic Earthquakes, Seismic gaps, Seismicity patterns)

2.9 Animal Behaviour

For centuries there have been occasional anecdotal accounts of anomalous animal behavior preceding and associated with the occurrence of earthquakes. In cases where animals display unusual behavior some tens of seconds prior to a quake, it has been suggested they are responding to the P-wave. These travel through the ground about twice as fast as the S-waves that do the serious shaking. They predict not the earthquake itself — that has already happened — but only the imminent arrival of the more destructive S-waves.

It has also been suggested that unusual behavior hours or even days beforehand could be triggered by foreshock activity at magnitudes that most people don't notice. A study that attempted to control for these kinds of factors found an increase in unusual animal behavior (possibly triggered by foreshocks) in one case, but not in four other cases of seemingly similar earthquakes.

Changes in Vp/Vs

Vp is the symbol for the velocity of a seismic "P" (primary or pressure) wave passing through rock, while Vs is the symbol for the velocity of the "S" (secondary or shear) wave. Small-scale laboratory experiments have shown that the ratio of these two velocities – represented as Vp/Vs – changes when rock is near the point of fracturing. In the 1970s it was considered a likely breakthrough when Russian seismologists reported observing such changes in the region of a subsequent earthquake. This effect, as well as other possible precursors, has been attributed to dilatancy, where rock stressed to near its breaking point expands (dilates) slightly.

Study of this phenomena near Blue Mountain Lake in New York State led to a successful prediction in 1973. However, additional successes there have not followed, and it has been suggested that the prediction was only a fluke. A Vp/Vs anomaly was the basis of a 1976 prediction of a M 5.5 to 6.5 earthquake near Los Angeles, which failed to occur. Other studies relying on quarry blasts (more precise, and repeatable) found no such variations.

Radon Emissions

Most rock contains small amounts of gases that can be isotopically distinguished from the normal atmospheric gases. There are reports of spikes in the concentrations of such gases prior to a major earthquake; this has been attributed to release due to pre-seismic stress or fracturing of the rock. One of these gases is radon, produced by radioactive decay of the trace amounts of uranium present in most rock.

Radon is attractive as a potential earthquake predictor because being radioactive it is easily detected, and its short half-life (3.8 days) makes it sensitive to short-term fluctuations. A 2009 review found 125 reports of changes in radon emissions prior to 86 earthquakes since 1966. But as the ICEF found in its review, the earthquakes with which these changes are supposedly linked were up to a thousand kilometers away, months later, and at all magnitudes. In some cases, the anomalies were observed at a distant site, but not at closer sites. The ICEF found "no significant correlation". Another review concluded that in some cases changes in radon levels preceded an earthquake, but a correlation is not yet firmly established.

Electro-magnetic variations

Various attempts have been made to identify possible pre-seismic indications in electrical, electric-resistive, or magnetic phenomena. The most touted, and most criticized, is the VAN method of professors P. Varotsos, K. Alexopoulos and K. Nomicos – "VAN" – of the National and Capodistrian University of Athens. In a 1981 paper they claimed that by measuring geoelectric voltages – what they called "seismic electric signals" (SES) – they could predict earthquakes of magnitude larger than 2.8 within all of Greece up to 7 hours beforehand. Later the claim changed to being able to predict earthquakes larger than magnitude 5, within 100 km of the epicentral location, within 0.7 units of magnitude, and in a 2-hour to 11-day time window. Subsequent papers claimed a series of successful predictions. Despite these claims, the VAN group generated intense public criticism in the 1980s by issuing telegram warnings, a large number of which were false alarms.

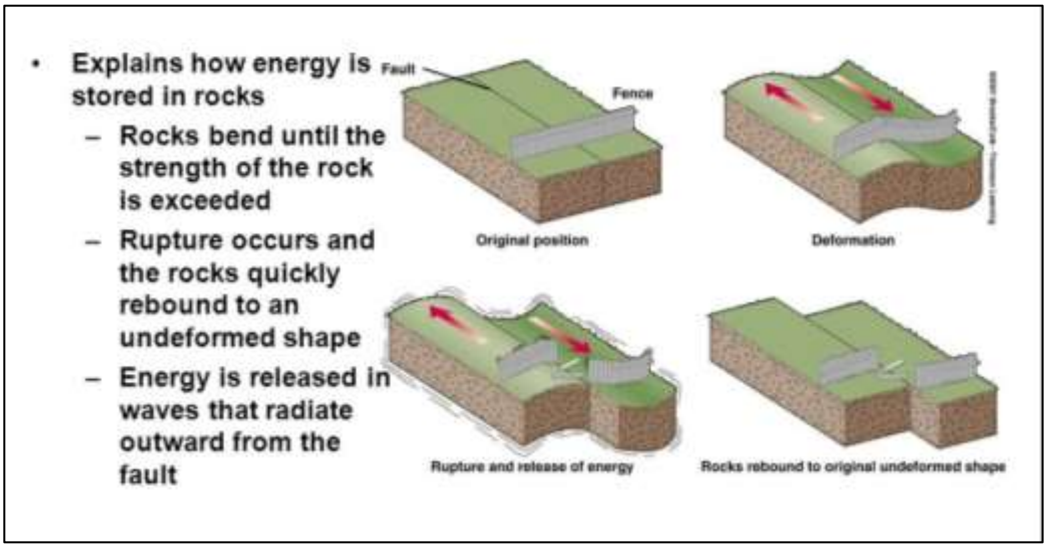
<u>Objections have been raised that the physics of the claimed process is not possible</u>. For example, none of the earthquakes which VAN claimed were preceded by SES generated SES themselves, as would have been expected. Further, an analysis of the wave propagation properties of SES in the Earth's crust showed that it would have been impossible for signals with the amplitude reported by VAN to have been generated by small earthquakes and transmitted over the several hundred kilometers distances from the epicenter to the monitoring station.

Trends

Instead of watching for anomalous phenomena that might be precursory signs of an impending earthquake, other approaches to predicting earthquakes look for trends or patterns that lead to an earthquake. As these trends may be complex and involve many variables, advanced statistical techniques are often needed to understand them, therefore these are sometimes called statistical methods. These approaches also tend to be more probabilistic, and to have larger time periods, and so merge into earthquake forecasting.

- Elastic rebound

Even the stiffest of rock is not perfectly rigid. Given a large enough force (such as between two immense tectonic plates moving past each other) the earth's crust will bend or deform. What happens next is described by the elastic rebound theory of Reid (1910): eventually the deformation (strain) becomes great enough that something breaks, usually at an existing fault. Slippage along the break (an earthquake) allows the rock on each side to rebound to a less deformed state, but now offset, and thereby accommodating inter-plate motion. In the process energy is released in various forms, including seismic waves. The cycle of tectonic force being accumulated in elastic deformation and released in a sudden rebound is then repeated. As the displacement from a single earthquake ranges from less than a meter to around 10 meters (for an M 8 quake), the demonstrated existence of large strike-slip displacements of hundreds of miles shows the existence of a long running earthquake cycle.



- Characteristic Earthquakes

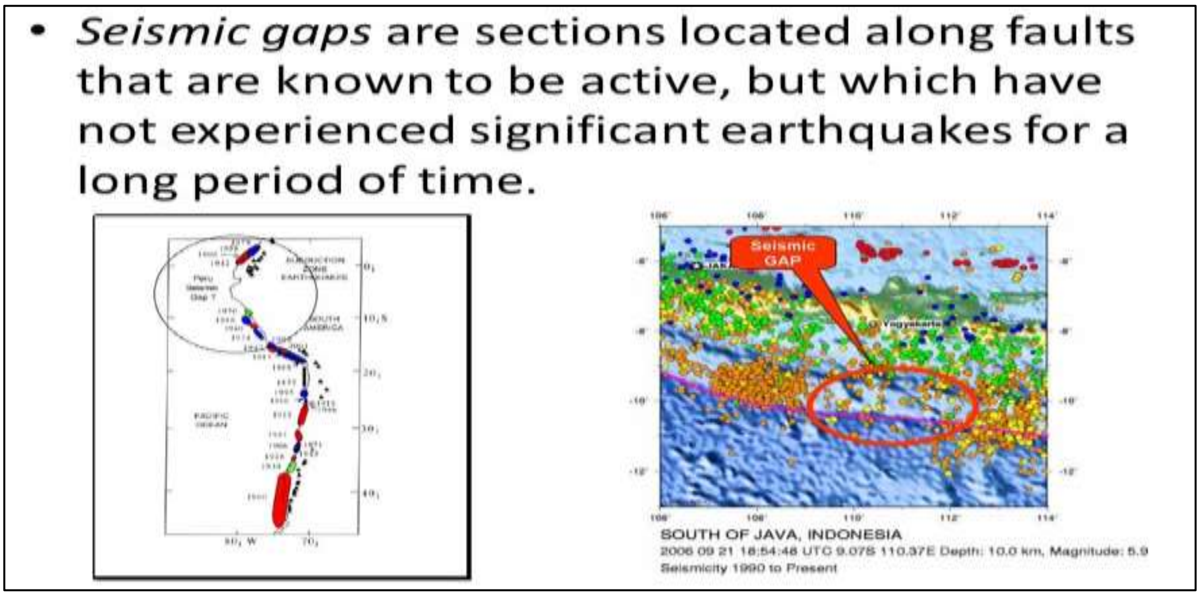
The most studied earthquake faults (such as the San Andreas fault) appear to have distinct segments. The characteristic earthquake model postulates that earthquakes are generally constrained within these segments. As the lengths and other characteristics of the segments are fixed, earthquakes that rupture the entire fault should have similar characteristics. These include the maximum magnitude (which is limited by the length of the rupture), and the amount of accumulated strain needed to rupture the fault segment.

In that the strain accumulates steadily, it seems a fair inference that seismic activity on a given segment should be dominated by earthquakes of similar characteristics that recur at somewhat regular intervals. For a given fault segment, identifying these characteristic earthquakes and timing their recurrence rate (or conversely return period) should therefore inform us when to expect the next rupture; this is the approach generally used in forecasting seismic hazard.

- Seismic gaps

At the contact where two tectonic plates slip past each other every section must eventually slip, as (in the long-term) none get left behind. But they do not all slip at the same time; different sections will be at different stages in the cycle of strain (deformation) accumulation and sudden rebound. In the seismic gap model the "next big quake" should be expected not in the segments where recent seismicity has relieved the strain, but in the intervening gaps where the unrelieved strain is the greatest. This model has an intuitive appeal; it is used in long-term forecasting and was the basis of a series of circum-Pacific (Pacific Rim) forecasts in 1979 and 1989–1991.

It has been asked: "How could such an obvious, intuitive model not be true? "Possibly because some underlying assumptions are not correct. A close examination suggests that "there may be no information in seismic gaps about the time of occurrence or the magnitude of the next large event in the region"; statistical tests of the circum-Pacific forecasts shows that the seismic gap model "did not forecast large earthquakes well". Another study concluded that a long quiet period did not increase earthquake potential.



➢ Seismicity patterns

Various empirically derived algorithms have been developed for predicting earthquakes. Probably the most widely known is the M8 family of algorithms (including the RTP method) developed under the leadership of Vladimir Keilis-Borok. M8 issues a "Time of Increased Probability" (TIP) alarms for a large earthquake of a specified magnitude upon observing certain patterns of smaller earthquakes. TIPs generally cover large areas (up to a thousand kilometers across) for up to five years. Such large parameters have made M8 controversial, as it is hard to determine whether any hits that happened were skillfully predicted, or only the result of chance.

M8 gained considerable attention when the 2003 San Simeon and Hokkaido earthquakes occurred within a TIP. But a widely publicized TIP for an M 6.4 quake in Southern California in

2004 was not fulfilled, nor two other lesser known TIPs. A deep study of the RTP method in 2008 found that out of some twenty alarms only two could be considered hits (and one of those had a 60% chance of happening anyway).

The problem of earthquake prediction

There is, on average, about one Richter magnitude (M) of 8 or larger earthquake somewhere in the world each year, and there are 15 or so "major" M ≥ 7 quakes per year, another 134 "large" quakes above M 6, and about 1300 quakes in the "moderate" range, from M 5 to M 5.9 ("felt by all, many frightened), and M 4 to M 4.9 range – "small" ‒13,000 quakes annually. Quakes less than M 4 – noticeable to only a few persons, – number over a million each year.

To be meaningful, an earthquake prediction must be properly qualified. This includes unambiguous specification of time, location, and magnitude. These should be stated either as ranges ("windows", error bounds), or with a weighting function, or with some definitive inclusion rule provided. To show that a prediction is not post-selected ("cherry-picked") from a number of generally unsuccessful and unrevealed predictions, it must be published in a manner that reveals all attempts at prediction, failures as well as successes.

Significance

A prediction or a set of predictions might be deemed significant if they have been shown to be successful beyond chance. Therefore, methods of statistical hypothesis testing are used to determine the probability that an earthquake such as is predicted would happen anyway (the null hypothesis). The predictions are then evaluated by testing whether they correlate with actual earthquakes better than the null hypothesis.

For some types of studies, it is reasonable to compare observations against a null hypothesis of random occurrence. Can the observed distribution of earthquakes be distinguished from random? In many instances, however, earthquake occurrence is clearly not random, with clustering in both space and time. In southern California it has been estimated that about 6% of M≥3.0 earthquakes are "followed by an earthquake of larger magnitude within 5 days and 10 km. It has been estimated that in central Italy 9.5% of M≥3.0 earthquakes are followed by a larger event within 30 km and 48 hours. While such statistics are not satisfactory for purposes of prediction (in giving ten to twenty false alarms for each successful prediction) they will skew the results of any analysis.

Consequences

As the purpose of short-term prediction is to enable emergency measures to reduce death and destruction, failure to give warning of a major earthquake, that does occur, or at least an adequate evaluation of the hazard, can result in legal liability, or even political purging. But warning of an earthquake that does not occur also incurs a cost: not only the cost of the emergency measures themselves, but of major civil and economic disruption. So, for example, if anomalous data are recorded in Japan, the Prime Minister, acting in response to a recommendation by an Earthquake Assessment Committee could issue the alarm, which would shut down all expressways, bullet trains, schools, factories, etc., all coming with economic cost. False alarms, including alarms that are cancelled, also undermine the credibility, and thereby the effectiveness, of future warnings.

Option:	If Quake:	If No Quake:
Alarm	**Great losses, mitigated by** preparations (cost of alarm incidental).	**False alarm:** cost of alarm, panic and economic disruption. Multiple instances?
The Bar Lowering the bar..	reduces odds of losses	but increases the cost of false alarms.
No Alarm	**Great losses, worsened by** being caught off–guard.	**Normal:** no losses, no disruption, no cost of alarm.

SESSION 3: TYPES OF FAULTS AND FAULT MECHANISMS

3.1 Where Do Earthquakes Happen?

Earthquakes occur all the time all over the world, both along plate edges and along faults.

Along Plate Edges:

Most earthquakes occur along the edge of the oceanic and continental plates. The earth's crust (the outer layer of the planet) is made up of several pieces, called plates. The plates under the oceans are called oceanic plates and the rest are continental plates. The plates are moved around by the motion of a deeper part of the earth (the mantle) that lies underneath the crust. These plates are always bumping into each other, pulling away from each other, or past each other. The plates usually move at about the same speed that your fingernails grow. Earthquakes usually occur where two plates are running into each other or sliding past each other.

Along Faults:

Earthquakes can also occur far from the edges of plates, along faults. Faults are cracks in the earth where sections of a plate (or two plates) are moving in different directions. Faults are caused by all that bumping and sliding the plates do. They are more common near the edges of the plates.

❖ Types of Faults: Three types of faults

1. <u>Normal faults</u> are the cracks where one block of rock is sliding downward and away from another block of rock. These faults usually occur in areas where a plate is very slowly splitting apart or where two plates are pulling away from each other. A normal fault is defined by the hanging wall moving down relative to the footwall, which is moving up.
2. <u>Reverse faults</u> are cracks formed where one plate is pushing into another plate. They also occur where a plate is folding up because it's being compressed by another plate pushing against it. At these faults, one block of rock is sliding underneath another block, or one block is being pushed up over the other. A reverse fault is defined by the hanging wall moving up relative to the footwall, which is moving down.
3. <u>Strike-slip faults</u> are the cracks between two plates that are sliding past each other. You can find these kinds of faults in California. The San Andreas fault is a strike-slip fault. It's the most famous California fault and has caused a lot of powerful earthquakes.

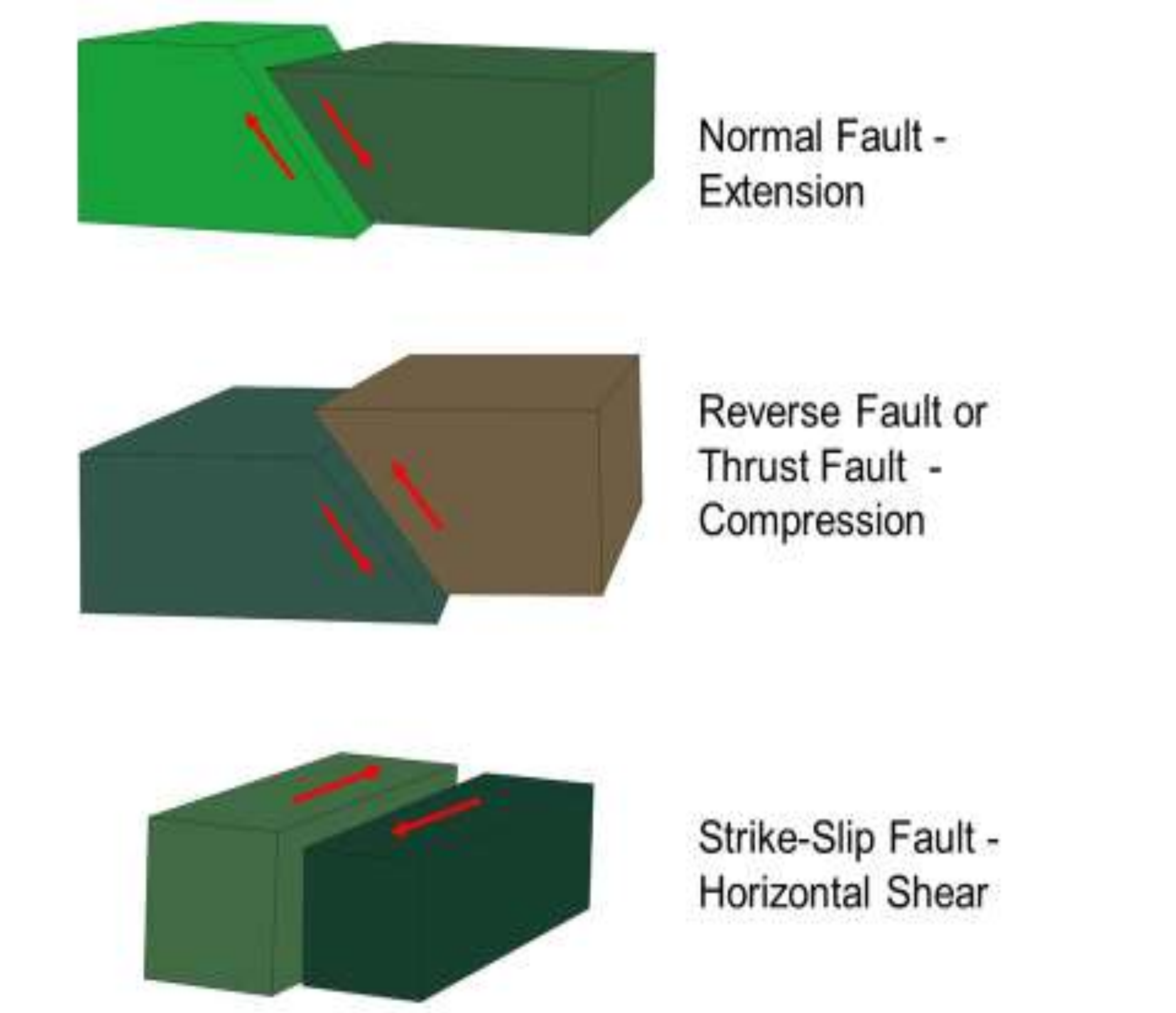
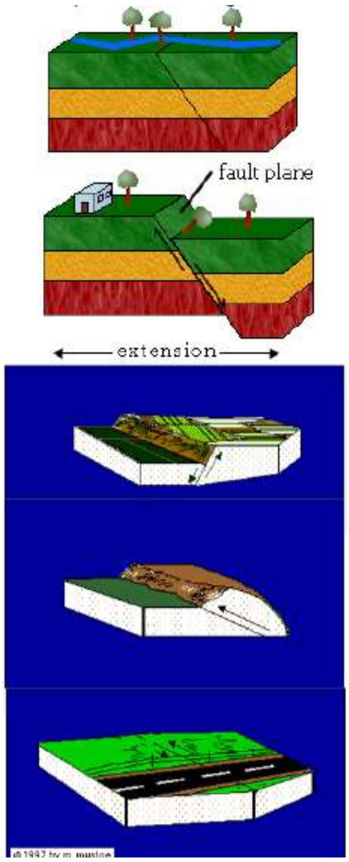


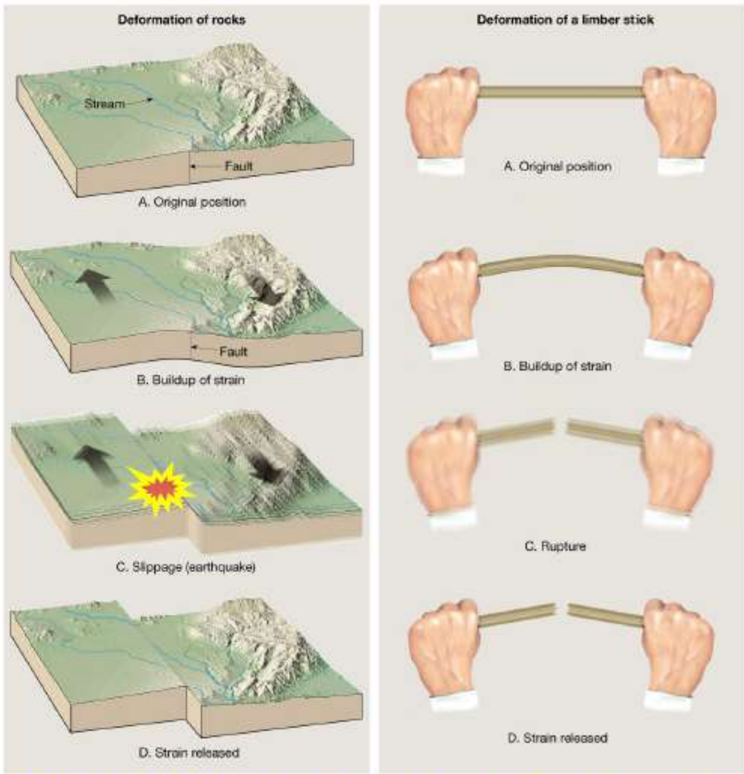
Fig: Different types of Fault

3.2 Fault Mechanisms

A sudden motion or trembling in the Earth caused by the abrupt release of slowly accumulated strain is called earthquake.

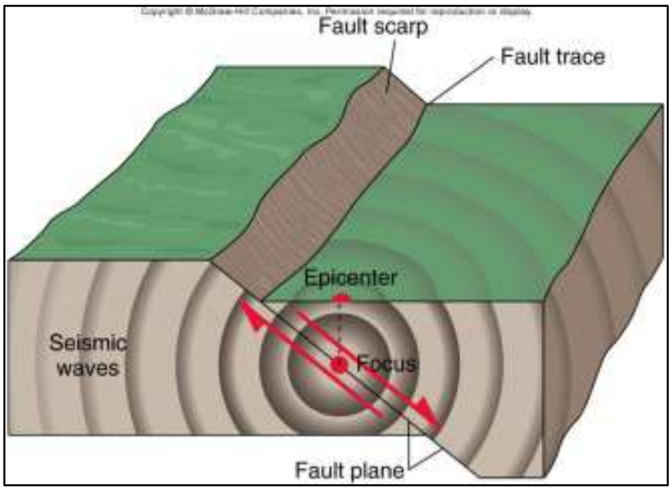
- Occurs when stress exceeds rock strength
- This movement results in a fault (which is a break in rocks along which movement occurs)
- Seismic waves travel outward in concentric circles from the origin (focus)
- The place on the surface of the earth directly above the focus is known as the epicentre

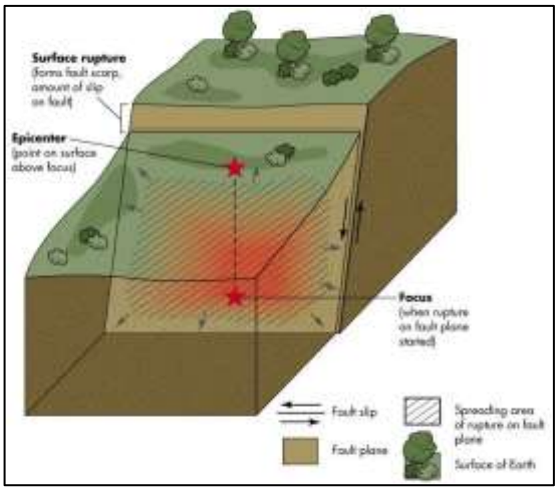




"Elastic Rebound" Theory of Earthquakes

The initial rupture point of an earthquake, where strain energy is first converted to elastic wave energy





The point within the Earth which is the center of an earthquake is Focus of an earthquake.
The point on the Earth's surface that is directly above the focus of an earthquake is Epicenter.

3.3 Seismotectonics in and around Bangladesh

Seismicity of a region expresses the proneness of earthquakes to the region. The proneness of a region to earthquake occurrences in future is studied based on the occurrences of past earthquakes.

A region, which experiences a large number of earthquakes of higher magnitude, is thought to have a higher seismicity in comparison to the one with low frequency and small magnitude earthquakes.

An accounting and analysis of temporal and spatial distribution of all earthquakes is a pre-requisite for assessing the seismic status of any region.

The epicentre and magnitude range of earthquakes of different regions can be plotted on the maps and their relative concentration can be taken as one of the measures of seismicity.

Varying seismicity of a region can be delineated with the help of the tectonic history of that region.

Various geophysical parameters such as resistivity, magnetic and gravity etc. also reflect seismic status of a region. All these factors, may individual or collectively, be used to represent the seismicity of various regions.

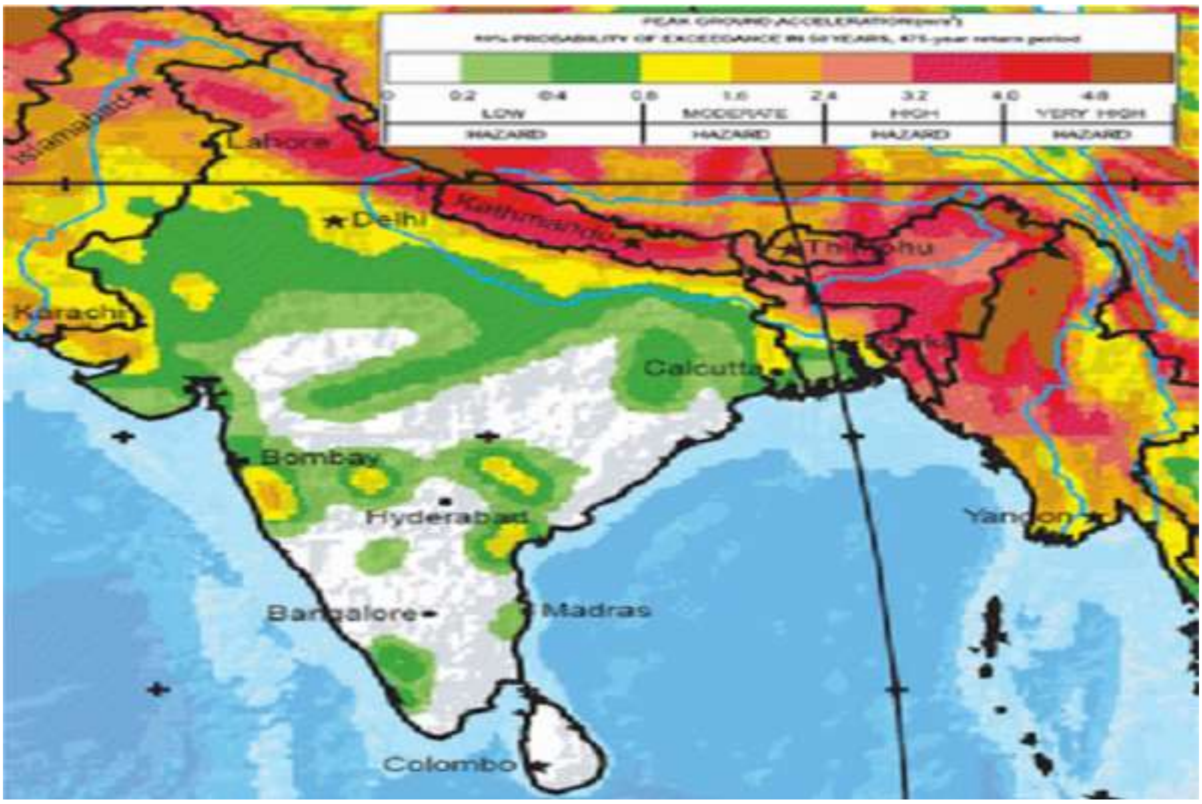


Fig: Seismic Hazard Map of India, the Himalaya and Bangladesh

Bangladesh is surrounded by the regions of high seismicity which include the Himalayan Arc and Shillong Plateau in the north, the Burmese Arc and Arakan Yoma Anticlinorium in the east and complex Naga-Disang-Jaflong thrust zones in the northeast.

Historical records show that Bangladesh has been shaken by seven large earthquakes ($M \geq 7$) during the last 150 years whose epicenters were located in India and Bangladesh.

Seismotectonics of Bangladesh and surroundings

The Bengal Basin covers an extensive area of northeastern part of the Indian plate, which includes Bangladesh and parts of the adjacent Indian states of west Bengal, Tripura and Assam.

Bangladesh is located at the head of the Bay of Bengal and occupies most of the Bengal Basin (about three fourth). This Bengal Basin is bordered to the west by the Precambrian Indian shield, to the east by the Cenozoic Indo- Burma- ranges and to the north – east by the Precambrian shillong Plateau.

The Ganges, Brahmaputra and Meghna rivers have formed this large delta by transporting huge sediments. The tectonic processes have played an important role in the development of these delta systems.

The Bengal Basin is situated at the triple junction of the Tibetian, Indian and Burmese Continental plates and it formed after the separation of the Indian plate from the Southern continent of Gondowana (Carry & Moore, 1974). The separation started during the late Cretaceous and initially marine sediments were deposited within the Basin floor. (Miogeosynclinal wedge). During the Eocene time the Indian plate collided with the Burmese plate, which cause the deposition of sediment eroded from the uplifted Indo-Burman hill range. The Indian plate then further collided with the Tibetian and Burmese plates during Miocene times, causing a huge sediment influx into the basin from South of the Himalayas and western part of the Indo-Burman hill range.

During the Pliocene a large-scale movement along the Dauki fault caused upliftment of the Shillong plateau and the subsidence of the Garo-Rajmahal gap. This tectonic activity resulted in the formation of the North-South trending Tripura-Chittagong folded belt.

The tectonic framework of Bangladesh can be divided into two main elements: the Indian platform comprising the north western part and the Bengal foredeep representing the thick sedimentary column forming geosynclinals area in the south east. These two elements are separated by a flexure zone named as "Calcutta-Mymenshing hinge zone". Further the Bengal foredeep is divided into two parts the folded flank in the east and platform flanks on the west which is demarcated by "Barisal high". The platform flanks include Sylhet trough, Faridpur trough, Hatiya trough and the Madhupur high structures. The deepest part of Bengal Basin is the Patuakhali trough.

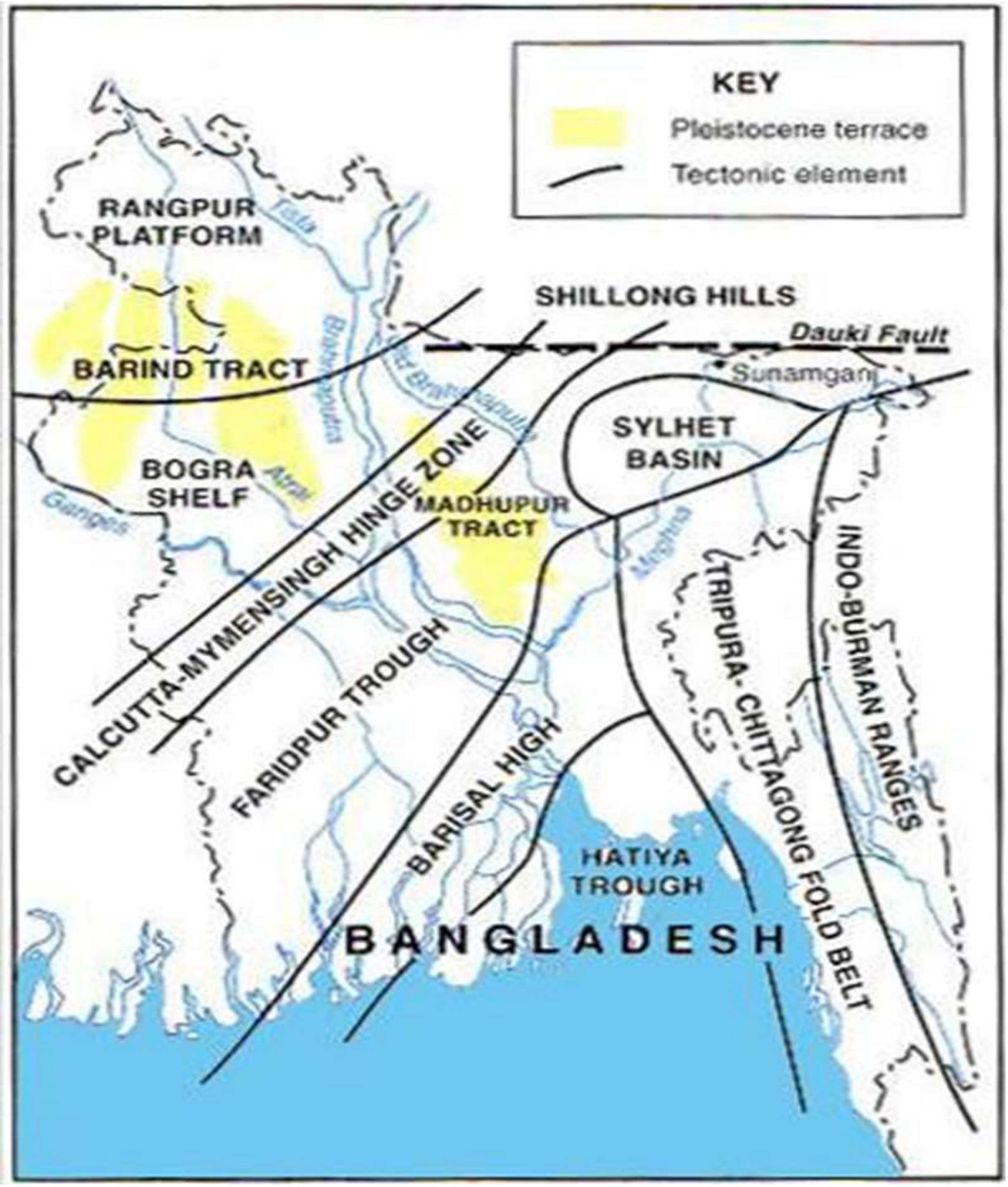


Fig: Tectonic framework of Bangladesh

Bangladesh is surrounded by the regions of high seismicity which include the Himalayan Arc and Shillong Plateau in the north, the Burmese Arc, Arakan Yoma Anticlinorium in the east and complex Naga-Disang-Jaflong thrust zones in the northeast. Northern and Eastern Bangladesh and adjoining regions lie in one of the most seismically active zones in the world. Historical records show that Bangladesh has been shaken by seven large earthquakes (M≥7) during the last 150 years whose epicenters were located in India and Bangladesh.

The 1897 Great Indian Earthquake (M =8.7) had its epicenter at around 250 km from Dhaka. From the reported damage, Sabri (2002) estimated that the intensity in Dhaka for this earthquake generated to be around VIII. According to Bolt (1987), Bangladesh can be affected by earthquake generated in four tectonic zones, namely the Assam fault zone in the north, Tripura fault zone to the east, Sub-Dauki fault zone in the north-east and the Bogra fault zone in the west. Dhaka located in the central region of Bangladesh, could be affected by any of these sources.

Date	Name of Earthquake	Magnitude (Richter)	Intiensity at Dhaka (EMS)	Epicentral Distance from Dhaka (km)
10 January,1869	Cachar Earthquake	7.5	V	250
14 July,1885	Bengal Earthquake	7.0	VII	170
12 June, 1897	Great Indian Earthquake	8.7	VIII+	230
8 July 1918	Srimongal Earthquake	7.6	VI	150
2 July 1930	Dhubri Earthquake	7.1	V+	250
15 January,1934	Bihar-Nepal Earthquake	8.3	IV	510
15 August, 1950	Assam Earthquake	8.6	IV	780

Table: List of Historical Earthquakes Affecting Bangladesh (Choudhury, 2005)

Earthquake History of Bangladesh and Surroundings

There are many historical earthquakes had occurred in and around Bangladesh.

Among these 1762 Bengal-Arakan, 1885 Manikganj, 1918 Srimongal and Great Indian Earthquakes were prominent. They had 7.5, 7.0, 7.6 and 8.7 magnitudes respectively. Some of these historical earthquakes epicenter with magnitudes are shown in figure below. These entire earthquakes left great effect of destructions in Bangladesh.

Date	Name of Earthquake	Magnitude (Richter)	Epicenter, Lat-Long, Focal depth
22 Nov, 1997	Chittagong earthquake	6.0	Unknown
22 Jul, 1999	Maheshkhali earthquake	5.2	Moheshkhali island, Chittagong
19 Dec, 2001	Dhaka eartquake	4.5	1.5 km SE of kamarkanda,Dhaka /23.632 N,90.376E, 10 km
20 Jun, 2002	Rajshahi earthquake	5.1 (IMD)	NE of Rajshahi/25.868N,88.874 E/ 37.7 km
26 Jul, 2003	Barkal earthquake	5.6 (NEIC)	Barkal,Rangamati/22.8N, 92.331E/ 2.6 km, Chittagong
26 Dec, 2004	Sumatra earthquake	9.3 (NEIC)	Indian territory near Bangladesh
7 Nov, 2007	Roninpara earthquake	5.2 (GS-NEIC)	2km WSW of Rroninpara
5Jul, 2008	Rajshahi earthquake	4.1 (DUEO)	WNW of Rajshahi/24.400 N,88.500 E/29.4 km
27 Jul, 2008	Mymensingh-Gajipur earthquake	5.1 (DUEO)	ENE of Mymensign/24.773 N,90.480 E/ 5.2 km
20 Sep, 2008	Mirjapur-Tangail earthquake	4.4 (DUEO)	Mirzapur 9 km WSW of Dhaka /24.100 N,90.100 E/ 20 km
11 Aug, 2009	Andaman earthquake	7.8	980 0f SSE of Dhaka
18 Sep	Sikim earthquake	6.8	495 km NW of Dhaka

Table: List of recent large earthquake in and around of Bangladesh

There are many historical earthquakes had occurred in and around Bangladesh. Among these 1762 Bengal-Arakan, 1885 Manikganj, 1918 Srimongal and 1897 Great Indian Earthquakes were prominent. They had 7.5, 7.0, 7.6 and 8.7 magnitudes respectively. Some of these historical earthquakes epicenter with magnitudes are shown in figure below. These entire earthquakes left great effect of destructions in Bangladesh.

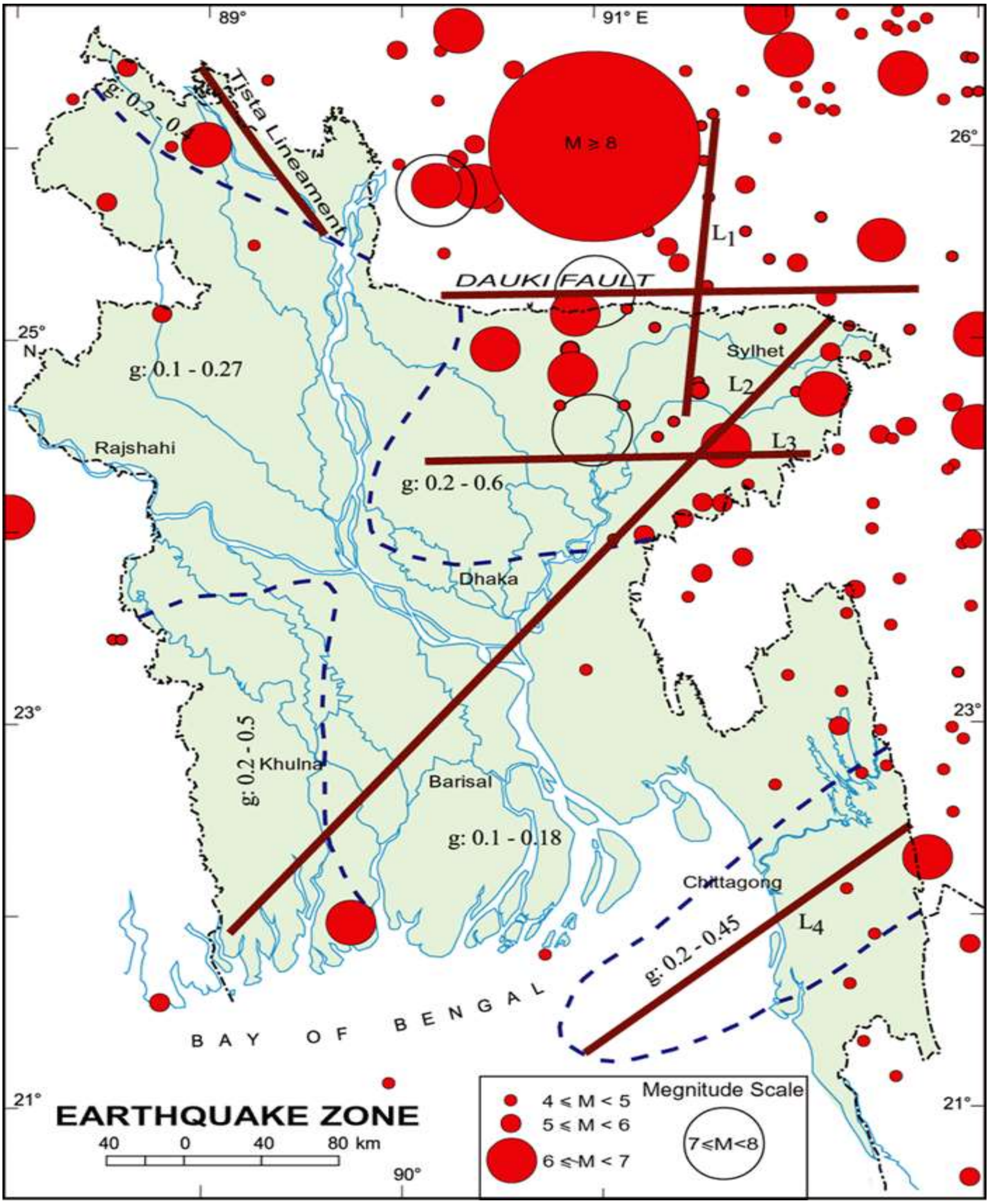


Figure: Location of earthquake epicenters and tectonic elements in and closes vicinity of Bangladesh

3.4 Seismic Zoning of Bangladesh

In 1979 Geological Survey of Bangladesh (GSB) through an inter-ministerial national committee prepared a Seismic Zoning Map of Bangladesh and Outline of Code for Earthquake Resistant Design of Structures based on historical earthquakes. In that study Bangladesh is divided into three seismic zones, such as Zone I, Zone II and Zone III based on seismic co-efficient of each zone (Figure 9).

In Zone I, Zone II and Zone III the basic seismic co-efficients are 0.08, 0.05 and 0.04 respectively. Where Zone I is the most and Zone III is the least vulnerable to seismic risk.

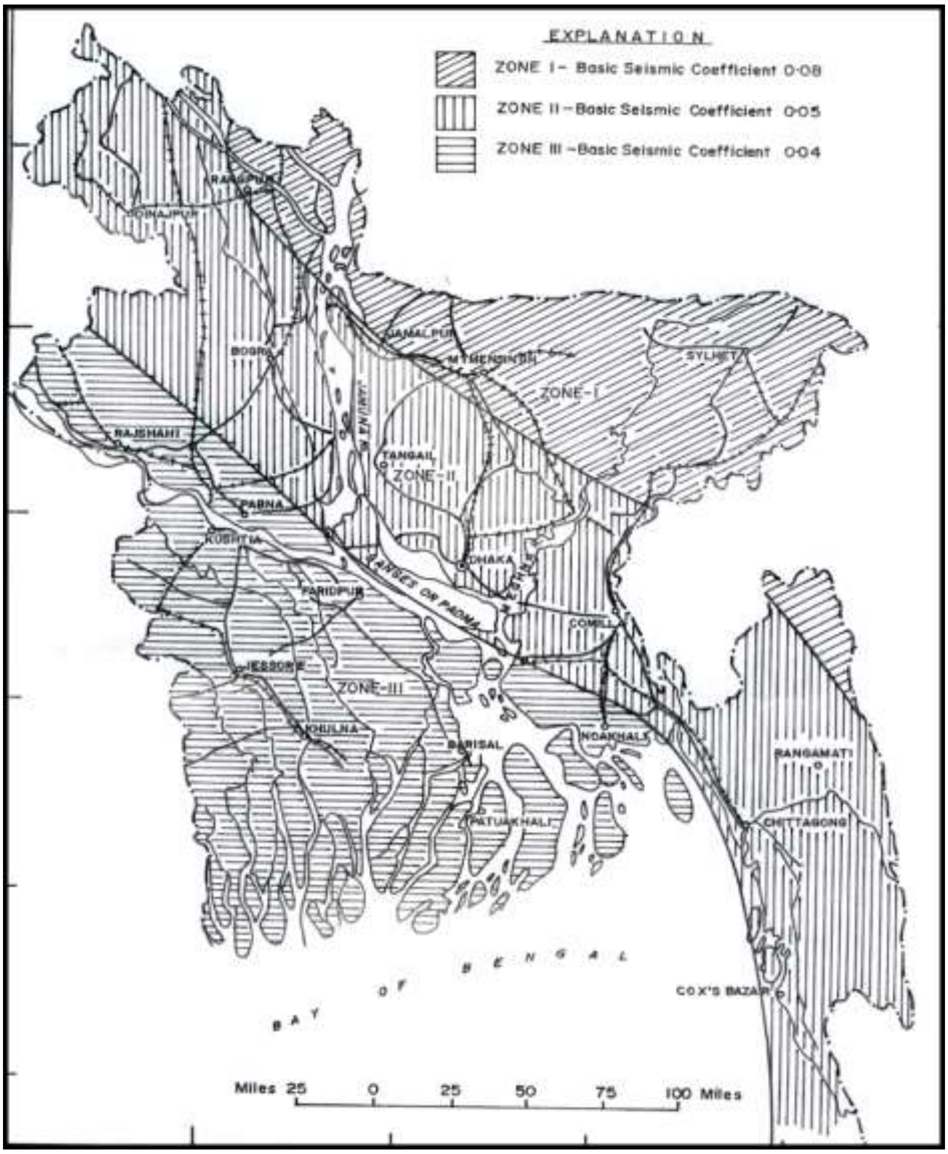


Fig: Seismic Zoning map of Bangladesh (1979)

Later on, a revised seismic zoning map is prepared in 1993. This map is included in Bangladesh National Building Code (BNBC, 1993). In BNBC map Bangladesh is also divided into three zones based on maximum ground acceleration. The zones are Zone I, Zone II and Zone III where the values are 0.075g, 0.15g and 0.25g respectively.

The Zone I which is the seismically least active zone includes Rajshahi, Pabna, Koshtia, Faridpur, Jessore, Khulna, Barisal, Noakhali, Patuakhali. Dinajpur, Panchagarh, Thakurgaon, Nilphamari, Bogra, Tangail, Dhaka, Munshigonj, Comilla, Rangamati, Chittagong, Cox's Bazar, are included in Zone II. Sylhet, Mymensingh, Jamalpur, Netrokona, Kishoreganj, Kurigram, Lalmonirhat are included in Zone III which is the most seismically active zone

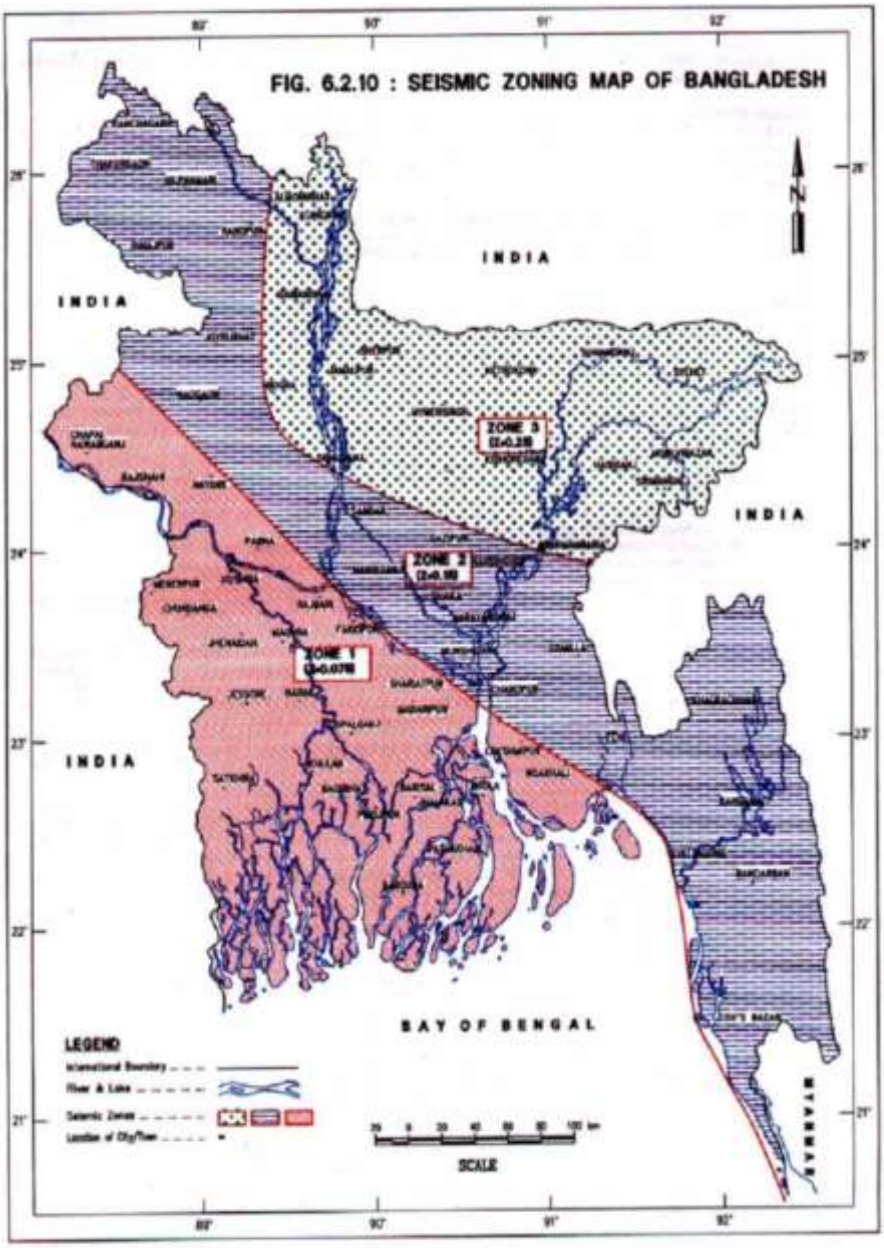


Fig: Seismic Zoning map of Bangladesh (1993)

SESSION 4: SEISMIC HAZARD, VULNERABILITY AND RISK ASSESSMENT

4.1 Introduction

Seismic Hazard is the probability of occurrence of a specified level of ground shaking in a specified period of time. But a more general definition includes anything associated with an earthquake that may affect the normal activities of people, i.e. surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, and tsunamis.

Vulnerability is the degree of damage caused by various levels of loading. The vulnerability may be calculated in a probabilistic or deterministic way for a single structure or groups of structures.

Seismic Risk is expressed in terms of economic costs, loss of lives or environmental damage per unit of time.

$$\text{risk} = \text{hazard} \otimes \text{vulnerability} \otimes \text{cost}$$

4.2 Vulnerability

Vulnerability can be defined as the damage degree of a structural element exposed to seismic risk, or of a combination of such elements under the action of an earthquake with given characteristics. Vulnerability measures the probability relative to economic and social criteria for achieving or exceeding a given damage value, for a given site and assuming a given exposure period.

Factors influencing vulnerability depend on the structural failure mode as a result of a seismic action that leads to loss of functionality or onsets the successive collapse of structural members. Structures can fail as a result of efforts exceeding strength capacity or by loss of stability. Failures may have a brittle or ductile characteristic.

Worldwide the seismic vulnerability concept is recognized and used widely both in research and in practical application. Given the multitude of factors, that need to be taken into account when assessing the seismic vulnerability, and accounting for their variability, performing an accurate deterministic vulnerability analysis is nearly impossible. An alternative method implies the use of probabilistic methods to assess the structural behaviour, structural vulnerability being represented by a distribution (probabilistic or statistics) of the damages induced by an earthquake. According to the United Nations' Office for the Coordination of Humanitarian Affairs (OCHA) a disaster is defined as a "serious disruption of the functioning of society, causing widespread human, material or environmental losses which exceed the ability of affected society to cope using only its own resources".

To better understand the previously presented definition OCHA presents also the following formula:

$$\text{Disaster} = \text{Vulnerability} \times \text{Risk factors}.$$

To assess the vulnerability of damaged structure one needs to quantify the damage state prior to the seismic event. This involves uncertainties that need to be accounted using probabilistic means.

One of the major drawbacks in performing a vulnerability analysis is represented by the lack of statistical data related to a seismic event, especially those describing the prior and posterior damage state. When analytical and computational tools are used, the existence of statistic databases will help overcome the multitude of obstacles involved by such an analysis. This is due to the existing theories depicting material's constitutive laws and behaviour under loading. Using probabilistic methods to describe the structural behaviour, the vulnerability can be represented by a distribution (statistic or probabilistic) of the damages induced by the earthquake.

From the prediction point of view the vulnerability represents a damage degree distribution class that is function of a parameter, generally one that describes the seismic intensity. During the design phase, when computing the vulnerability for a class of structures only one major seismic event is considered for a given interval, T. For the same class of structures, when computing the risk, one accounts for several successive seismic actions, for the same time period, T.

The Seismic Risk Concept

The seismic risk concept is associated with the probability that a given event, based on a decision will produce other effects than those anticipated. The risk is directly linked with factors and hypothesis that have unfavourable characteristics. As new risk related data become available, the level of understanding in this field is enhanced and also new assessment methodologies are developed.

Seismic risk analyses are bounded by the deterministic predictions regarding seismic events. Such predictions are used to compute the vulnerability of structural elements subjected to seismic loading and to assess the consequences of earthquake induced damages. This is due to the fact that the seismic risk is strongly connected to the building's structural performances. History shows that due to lack of knowledge, ignorance, etc., wrong decisions had catastrophic effects and resulted in significant material damages and loss of human life.

4.3 Seismic Hazard

The hazard reflects the occurrence probability of a potentially destructive event within a well-defined area and during a given time (floods, earthquakes, explosions, etc.). A hazard anticipation measure is given by the probability associated with a certain event to exceed a given value and might be determined using probability distribution functions.

The mathematical models used in hazard prognosis are based on statistical methods and use a large number of events recorded during a very large period of time. Strictly speaking the seismic hazard is independent with respect to the existing volume of data, being a fundamental natural characteristic. The accuracy of its approximated value can be improved by the use of a larger number of recordings and also by the choice of adequate mathematical models, especially probability distribution functions.

A high value of the hazard does not automatically involve a high level of risk, this being conditioned by a low value of the vulnerability. The seismic risk (SR) is defined by the damage degree associated with event, i, that has an occurrence probability, Hi:

$$(SR)_i = V \times H_i$$

Nowadays there are two distinct approaches when assessing the seismic induced hazard: the deterministic method and the probabilistic one.

<u>The deterministic method</u> – based on a particular seismic event of a given intensity, on a specific site and used to evaluate ground displacements at the given site. This method depicts the worst-case scenario but fails to provide any information regarding the event's occurrence. This leads to the method's inability to estimate the probability of a seismic event occurring during the structure's lifespan at the given site.

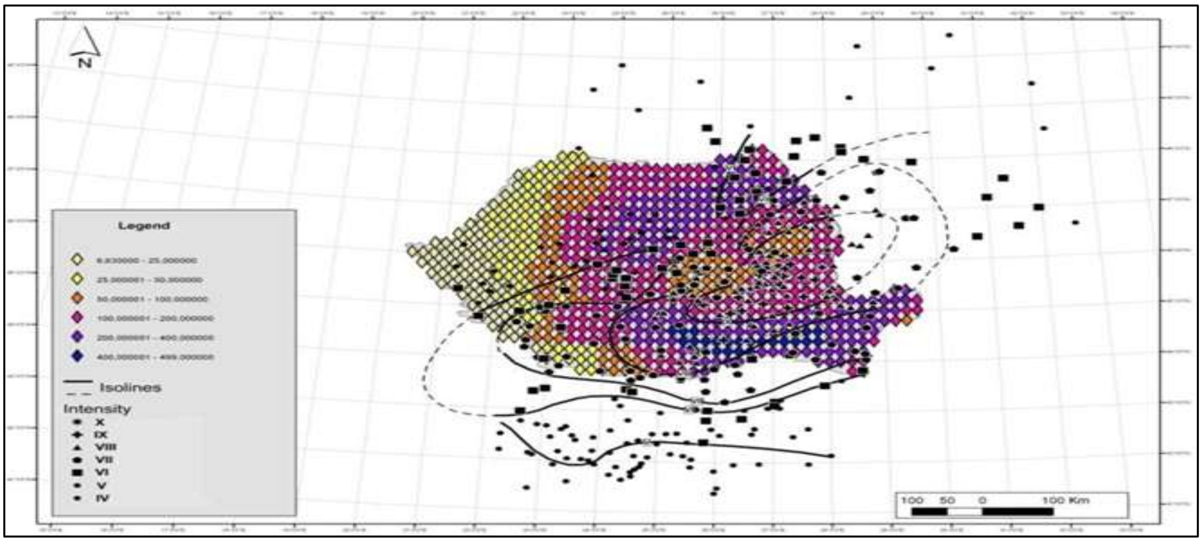


Fig: Seismic hazard determined using the strongest recorded earthquake with magnitude Mw = 7.7 (10th November 1940, Ardeleanu, 2010).

<u>The probabilistic method</u> was proposed, and subsequently accepted worldwide, by Cornell, (1968). Today it is the most commonly used method.

In this case, instead of a seismic event given for every source, a probabilistic distribution is used. For every source an earthquake with a maximum intensity is chosen in order to represent the superior boundary for all other seismic events that are to be considered in the analysis. Comparing the two methods, it can be noticed that the deterministic approach is an intuitive one, based on choosing a well-defined event and using it subsequently as a model.

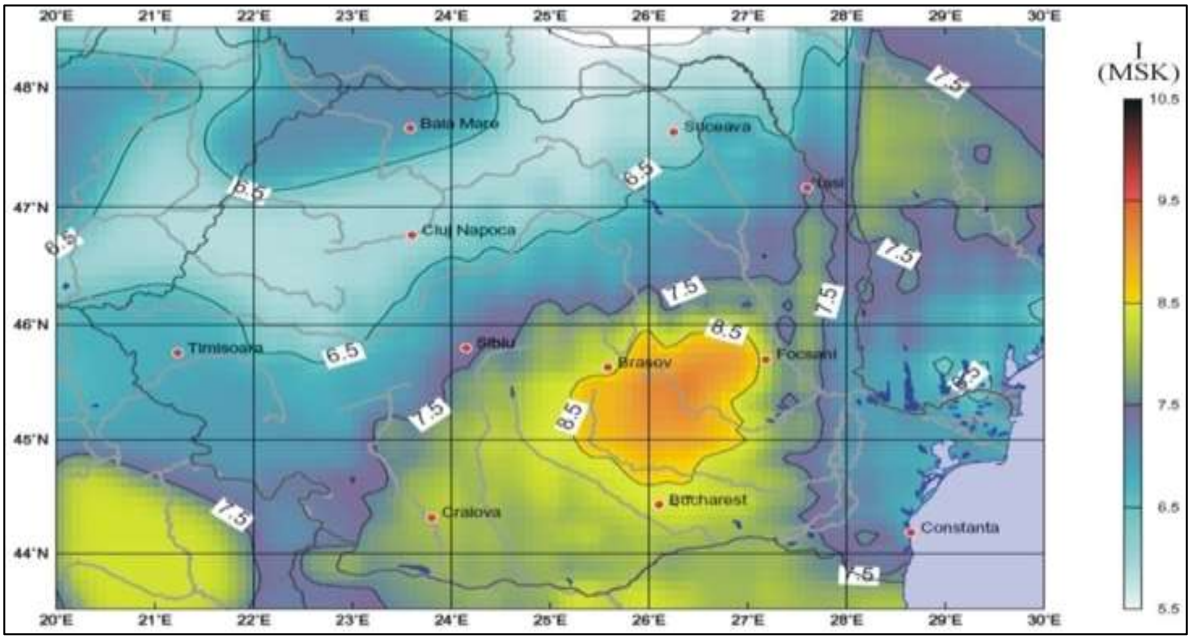


Fig: Probabilistic seismic hazard computed in terms of microseismic intensity (MSK scale), resulted by considering all seismic zones, with a return period of 475 years (Ardeleanu, 2010).

The hazard includes effects of all earthquakes that are more or less likely to occur at a given site and can use more attenuation models – each with its specific uncertainties. Hazard analysis can include events with different characteristics.

Both methodologies play a significant role in seismic risk and hazard analyses and are designed to support decision making processes as well as criteria selection to initiate structural retrofitting. In Romania, the highest level of seismic hazard can be found on the curvature area of the Oriental Carpathians. This area generates intermediate depth earthquake that can affect large parts of Central Europe.

The hazard is different from the potential natural phenomena that might lead to economic losses and/or human life casualties. It is quantified by the probability that certain parameters that define a phenomenon exceed a certain value at a given time or during a given time interval. The hazard is the cause of negative effects and not the consequences of the phenomena itself: damage, loss of human life, etc. It can be said that the hazard has as a consequence the fact that losses are quantified through the risk notion.

The risk expresses the probability of economic or human life losses occurrence, and it is quantified by the probability that, within a given time interval, the negative effects exceed a given level. Seismic hazard analyses try to estimate the parameters of ground movement at a given site.

4.4 Microzonation and Urban Resilience

Microzonation is a technique that aims planned land use to reduce potential disaster hazard for a region. To provide planned and healthy land using via planning, microzonation is used to create economically, socially and politically compatible and useable zones by researching geological, geophysical and geotechnical conditions against earthquake hazard.

Microzonation is one of the most accepted tolls in seismic hazard assessment and risk evaluation and it is defined as the zonation with respect to ground motion characteristics taking into account source and site conditions. Topics such as ground amplification, ground motion level, liquefaction, slope stability, water floods and surface faulting are examined during seismic microzonation studies.

Microzonation studies have generally made in three phases:

First Phase – General Zoning: This phase includes compilation of fundamentals obtain from historical sources, formerly prepared reports and various databases and interpreting them all. In this phase zoning studies are done between the scales of 1/1.000.000 to 1/50.000.

Second Phase – Detailed Zoning: In this phase satellite imageries, field studies, geotechnical investigations are added to the first phase of the study and a detailed zoning is made. In this phase zoning studies are done between the scales of 1/100.000 to 1/10.000.

Third Phase – More Detailed Zoning: If potential risk is too high more detailed studies should be done to provide a high detailed zoning. These are the zoning studies that require more detailed, field-basic, specific and their costs are high. In this phase zoning studies are done between the scales of 1/25.000 to 1/5.000.

Damages of earthquake basically depends on three groups of factors: earthquake source and path characteristics, local geological and geotechnical site conditions, structural design, construction features and building materials. The most important factor for reduction of disaster risk is developing a planning approach that considers all of these conditions. As an applied research seismic microzonation frequently needs to be revised. Seismic microzonation is the first step of disaster risk reduction and needs an interdisciplinary approach that includes geology, seismology and geotechnical engineering.

The main point for seismic microzonation that aims to minimize the loss in man-made environment is the transition of selected microzonation parameters for land use and planning. Therefore, both selected microzonation parameters and maps can be understood and interpreted by planners and public officers as well as geologists. Various zones should be separated as a guide to determine population density, building density and structural features for urban planners. Transitions between these zones are not so clear.

Microzonation studies are interdisciplinary studies that provide a base for planning activities with determining the disaster risk in both settlement areas and developing areas. In addition, they are used for giving suitable decisions for land using and zoning, determining strategic goals, aims and priorities for urban renewal and mitigation planning.
These studies can be defined as the studies that determine the disaster hazard and disaster risk in local scales. The role of geological and geotechnical survey in microzonation is crucial to describe, control and obviate the hazards for planning urban infrastructure and hazardous energy fields. Especially educational buildings, hospitals, public buildings and infrastructure facilities such as substations, communication centers and gas pipelines network must be planned in consideration of the suitability analysis for settlement area which is made as a result of microzonation studies.

Settlement Suitability Analysis

Suitability analysis for settlement area are the final maps which are created after the evaluating all of the raw data maps (geology, slope, underground water maps, etc.), semiproduct maps (local soil classes, etc.) and final hazard maps (soil enlargement, liquefaction) prepared by the studies. Beside this engineering comments are added to these maps. With settlement suitability analysis area is divided into four groups: Suitable Areas (UA), Precautionary Areas (ÖA), Areas Requiring Detailed Geotechnical Surveys (AJE) and Unsuitable Areas (UOA).

Suitable Areas (UA): Areas that have no potential for natural disaster hazard except earthquake hazard, no engineering problems that can affect suitability to settlement. In other words, the areas where are ready for settlement without taking any precautions within the study area.

Precautionary Areas (ÖA); Areas within the study area that have been specified as hazardous area in terms of earthquake, mass movement and high slope, water flood, avalanche, engineering problems and other hazards. These areas should be divided into sub-sections according to the type of problems and their precautions. The areas specified as precautionary area does not refer to the area forbidden to be used for construction purposes. However, it implies that certain measures must be taken before and/or during building construction.

Areas Requiring Detailed Geotechnical Surveys (AJE); These are the areas where the detailed geotechnical investigations (drilling, laboratory experiments, hazard analysis, etc.) are required in terms of providing more efficient statements for determining the suitability of the areas for settlements. The issues that should be studied in the geotechnical investigations to be conducted afterwards must be highlighted in reports.

Unsuitable Areas (UOA); Areas where should not to be opened to settlement because of taking measures have not been considered suitable because of natural disaster hazards in project area, geological problems and related laws.

Suitability analysis for settlement area are made to provide a base for planning activities. Therefore, the determined area groups and necessary preventive actions which are determined under the guidance of microzonation studies should be noted on plans and in planning.

Example: Microzonation of Istanbul, Turkey

% Distribution	European Side	Asian Side
Suitable Areas(UA)	39.64	39.14
Precautionary Areas (ÖA)	58.94	60.30
Unsuitable Areas(UOA)	1.42	0.56

Table: suitability distributions of Istanbul microzonation field

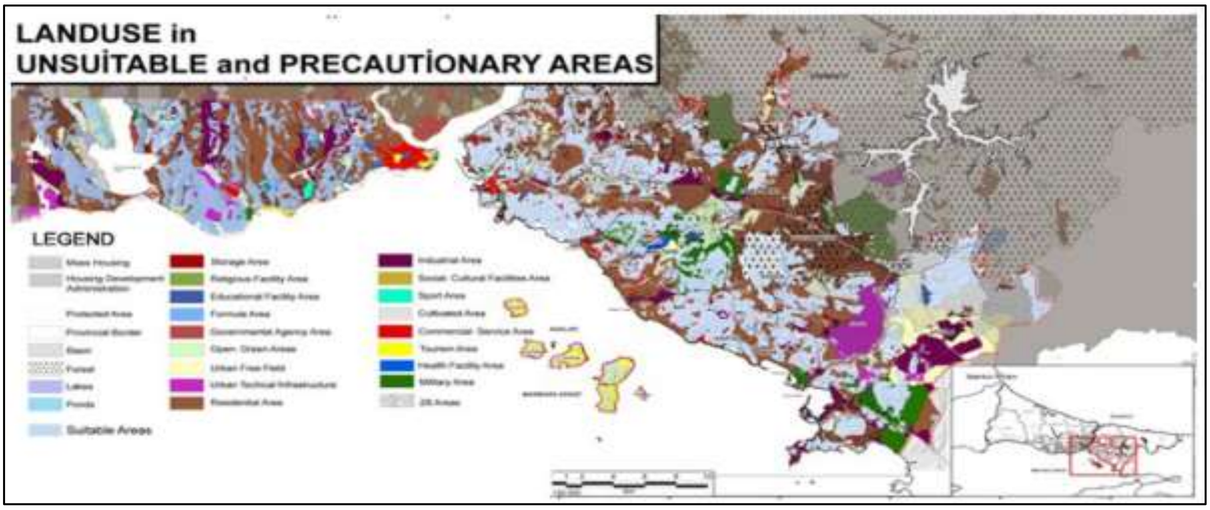


Fig: Landuse in unsuitable and precautionary areas

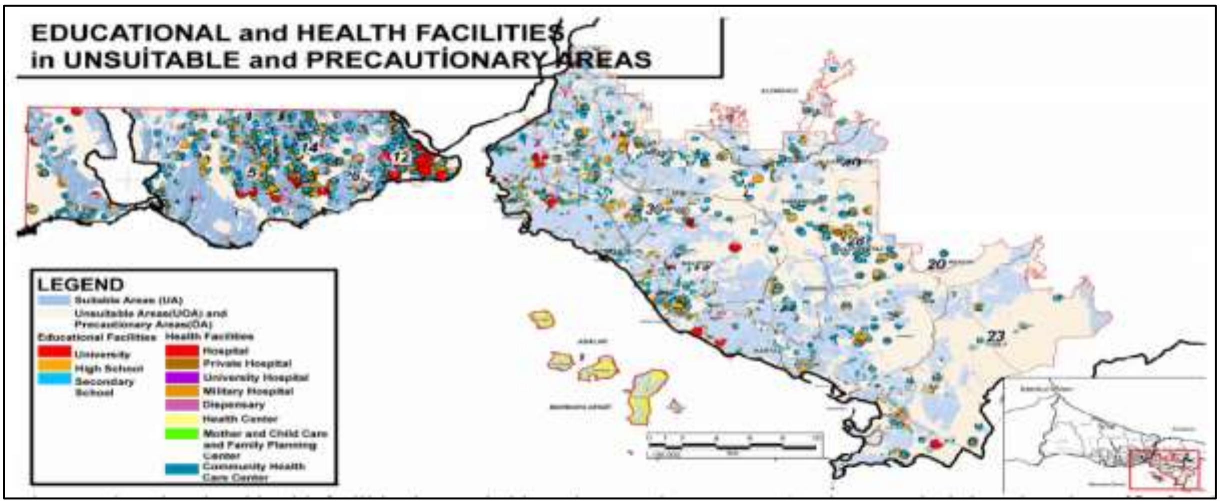


Fig: Educational and health facilities in unsuitable and precautionary areas

4.5 Risk Sensitive Land Use Planning

Increasing urbanization resulting in poorly planned settlements is becoming a major driver of disaster risks. Rapid and uncontrolled urbanization is increasing the exposure of populations and infrastructure to potential hazards. Building a city's resilience to disasters should be on top of government's agenda since the loss of life, destruction of property, and disruption of essential services has huge socio-economic, and even political, implications. Development Agencies, Private Sectors and Non-Government Organizations (NGOs) are increasingly aware that there are ways to improve the resilience of populations and cities towards disasters. The UN Office for Disaster Risk Reduction (ISDR) has also released relevant guidelines and policy tools in order to help national and sub-national governments meet the objectives of HFA. One of its main goals is to encourage pro-active risk reduction. Behind the goal of shifting from reactive disaster management to pro-active disaster risk management is the overall goal to strengthen the resilience of people, communities, and institutions to disasters. The impact of natural and man-made hazards can be reduced through adequate planning and incorporating specific DRR measures in land use planning and urban development processes, thus minimizing the human, economic and environmental damage. By increasing the resilience of communities, DRR also improves the ability of people and infrastructure to recover from disasters.

Risk Sensitive Land Use Planning

Risk-sensitivity integrates two new considerations into the conventional approach to land use planning (disaster risk reduction parameters). Hazard, vulnerability, risk, and capacity parameters together with disaster/emergency management requirements are identified, collected, and integrated with traditional land use planning information (e.g., socioeconomic profiles, demographics, and transport networks), and integration through formal government activities. Measures are taken to ensure understanding, acceptance, and support for the plan; to improve the competency and knowledge about risk-sensitive land use planning among planners and other professionals; and to raise the awareness and support of all stakeholders. Land use planning involves an interactive and continuous process to regulate the use and development of land, allowing feedback between government planners and other stakeholders. Land use management provides the regulatory and non-regulatory tools that enable the government to establish its mandate on land use (Earthquakes and Megacities Initiative, 2008). However, the present study emphasizes on earthquake hazard for preparing risk sensitive land use planning as the detailed area plan of RAJUK (2010-2015) incorporates hazards like flood, fire etc. excluding earthquake. As stated above, Dhaka being located on floodplain is highly vulnerable to earthquake hazards like amplification and liquefaction.

Risk Sensitive Land Use Planning

SESSION 5: TSUNAMI

5.1 Introduction

Tsunami is a Japanese word, meaning 'harbour waves. The term was introduced by the fishermen who on return to the port (after fishing) found the area surrounding the harbor devastated by sea waves (Figure 1), a scenario which they had not encountered during voyage through the open sea/ocean. The apparent paradox is because of the fact that the offshore Tsunami waves in the open sea have very small amplitudes (several metres) compared to the extremely large wavelengths (often hundreds of kilometre long). It is because of that the wave passes unnoticed forming only a fleeting bulge over the mid-sea/ocean.

The Tsunami waves which appear quite innocuous in open sea move with high velocity. Using the mathematical formula illustrated in Figure 2, we find that for ocean depth of 5 km, the wave velocity would be about 220 m/sec, i.e. approximately 800 km/hr, which is comparable to the speed of a jet-propelled aircraft.

Figure 1. Devastation of the southeastern coastal areas of the Bay of Bengal during 26 December 2004 Tsunami (Photo: AFP. From wave page of www.smh.com.au).

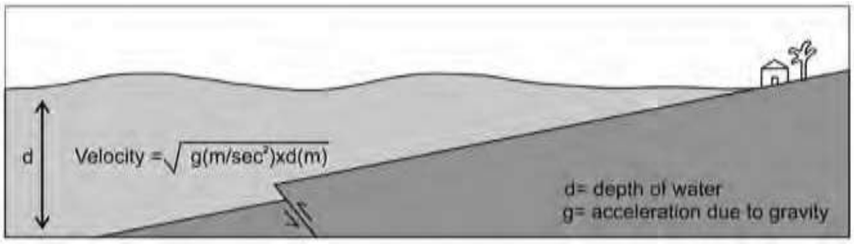


Figure 2. Cartoon diagram illustrating the mathematical relationship between depth-velocity relationship of Tsunami wave.

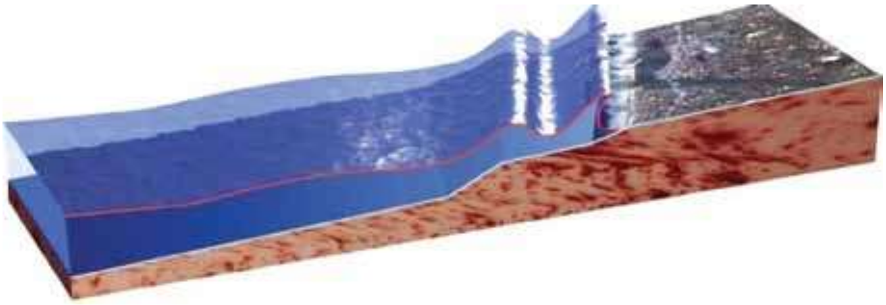


Figure 3. An artist's impression of buildup of Tsunami as the waves approach the shoreline. (Courtesy: Wikipedia).

Figure 4. Tsunami waves after reaching the shelf sea region undergo manifold amplification and looks like monstrous hydra heads. (Courtesy: Dr. Viacheslav K. Gusiakov, ICMMG, Siberian Division, Russian Academy of Sciences).

Dynamics of tsunami are essentially governed by the shallow water equations. The wavelength of a Tsunami wave (which is the product of velocity and time) is about 200 km having a period of 15-30 minutes in the open sea. In open sea thickness of water column could be as much as 3 to 4 km. As tsunami leaves the deep water of the open sea and arrives at the shallow waters near the coast, it undergoes a transformation, mainly due to a significant change in the water column thickness. Near the coast due to decrease in the water column thickness, the velocity of tsunami waves drops. However, the total energy and the period of the wave remains the same. Due to such a combination of energy and wavelength, more water is forced between the wave crests causing the height of the wave to increase. Because of this, the tsunami waves which are imperceptible in deep water undergo manifold increase in wave heights, as they reach the coast (Figure 3).

A little before hitting the land, this slow-moving wave is overridden by successive waves from the rear, and the composite wave after attaining a great height (at times over 70 m) and lashes the coastline like monstrous hydra-heads.

5.2 Causes of tsunami generation

Confusion prevails over the processes of Tsunami generation. Tsunamis are traditionally described as tidal waves. This is because, on approaching the land, the Tsunami waves take on the characteristics of violent onrushing tide rather than the sort of familiar cresting waves formed by wind action upon the ocean. The essential prerequisite for triggering a Tsunami is the sudden displacement of sea/ocean water on a massive scale. Tsunami is generated as the disturbed water level attempts to attain equilibrium. The disturbed ocean water moving under the influence of gravity radiates across the sea/ocean similar to ripples in a pond. Because there is very little energy loss during the propagation of the Tsunami waves over the ocean water, the harbour waves, which finally strike the coastal areas assume awesome ferocity. The process of Tsunami generation sets off with abrupt dislodgement of blocks of ocean floor rocks due to faulting with a strong vertical component of displacement. Two different situations are possible. Faulting can lift a part of the ocean floor vertically upward which in turn would push up the column of water above it creating a local bulge over the normal sea level (Figure 5A). On the other hand, if faulting causes down-sagging of the ocean floor relative to the adjacent part, a local depression in the sea water level is created causing ebbing tide. Such a situation may develop in Subduction Zones where the heavier Oceanic Lithosphere slides down below the lighter continental Crust (Figure 5B). In such a case, water is withdrawn from the coastal areas, resulting in a “draw-down “situation, a feature witnessed during 26 December 2004, Indian Ocean Tsunami (Figure 6).

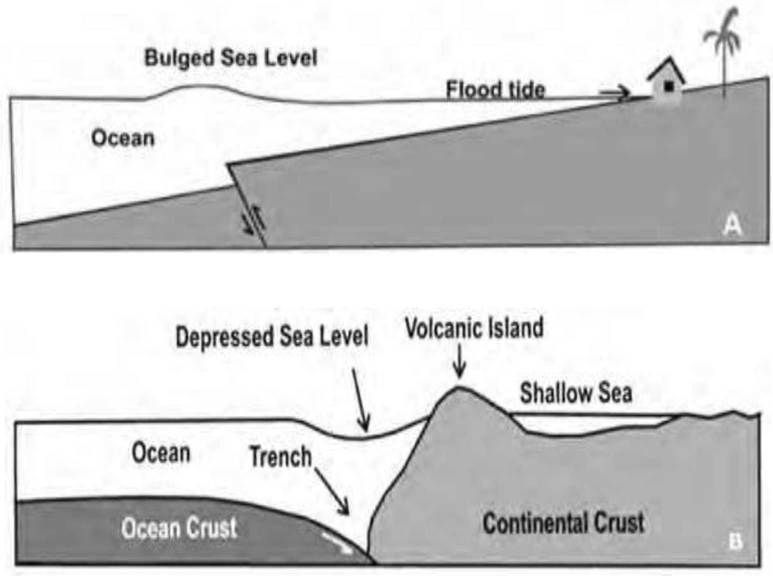


Figure 5 (A) Schematic diagram showing development of local bulge over the sea level because of uplifting of a block of Ocean Crust. This causes flood tide in coastal region. (B)

Where fault causes down-sagging of a block as in Subduction Zone, a local depression in the sea level is created.

Figure 6. Draw-down situation recorded at Tiruchendur on 26 December 2004, because of sudden receding of sea water (Photo credit: Geological Survey of India, Newsletter).

The Circum-Pacific belt is the most Tsunami-prone stretch in the world today which is characterised by the presence of deep Trenches over the Subduction Zones associated with an inclined zone of seismicity (Benioff Zones) .Because of the down-sagging movement at regular intervals, a space is created virtually coinciding with the zone of Trenches. This in turn creates a sudden depression in the water column above the zone, leading to imbalance. The process that follows in attaining the equilibrium leads to generation of Tsunami waves. The tectonic situation of the 2004-Indian Ocean Tsunami is comparable to those that develop along the Circum-Pacific belt. The similarity is perceptible with regard to the source and nature of tsunami generation, due to massive down-sagging of the Indian Ocean Crust along the Java Trench.

Sudden displacement of huge mass of water (enough to cause a Tsunami) could also be due to processes other than faulting. These include:

- Volcanic eruptions near sea or underwater. The most horrifying example recorded in history was the eruption of Krakatao in Indonesia on 26-27 August 1883.
- Large meteorite impacts on ocean water (no known instance is recorded in human history). However, presence of some 'erratic' deposits along the Gulf coast of Mexico and the United States was presumed to have resulted during the apparent impact of a meteorite about 65 million years ago near the tip of the Yucatan Peninsula of Mexico
- Underwater testing of nuclear bombs (Nuclear testing by the United States in the Marshall Islands in the 1940s and 1950s generated Tsunamis).
- Massive landslides generated Tsunamis. The most famous example of a landslide induced Tsunami occurred at Lituya Bay in Alaska (USA) on 9 July 1958, producing a giant water wave that reached 524 metres up the local mountains. However, there was virtually no effect outside the bay region (Figure 7).

Besides these, a Tsunami could generate, if a landslide drops a huge mass of rock debris or an avalanche pours in huge chunks of ice mixed with rubbles of rocks and soils into sea or ocean. The Tsunamis generated by such processes generally have a localised influence. The waves generated usually dissipate quickly, and rarely affect the coastlines distant from the source because of the small area of the affected sea.

Figure 7. A landslide induced Tsunami affecting the Lituya Bay in Alaska (USA) on 9 July 1958. It produced giant water waves that reached 524 metres up the local mountains. The non-forested areas of land lining (white) of the shore of the bay mark the approximate extent of the D.J. Miller, United States Geological Survey).

5.3 Tsunami-earthquake link

All the Tsunamis in the Circum-Pacific belt are invariably associated with earthquakes. So intimate is the association that these 'harbour waves' are conventionally described as 'earthquake generated Tsunami' or 'seismic sea waves' (Roy, 2008). Impressed by the close Tsunami-earthquake link, some enthusiastic earth scientists have even attributed the circum-Pacific earthquakes as 'Tsunamigenic'.

Without refuting the Tsunami-earthquake link, the usage appears misleading because scientifically speaking both earthquake and Tsunami are manifestations of sudden dislodgement of rock masses during faulting, and the association does not bear any cause-and effect relationship (Roy, 2008). Earthquakes are vibrations in the Crust caused by moving energy waves released during the breaking (faulting) of 'strained rocks. 'Elastic Rebound Theory' aptly explained how the energy released during disruption (or faulting) of strained rocks radiated from the source of origin as elastic waves along the San Andreas Fault (Reid, 1906). It would be wrong to say that the earthquake waves can provide energy for generating a Tsunami. A point to remember is that no Tsunami was generated during severe earthquakes along the San Andreas Fault, a considerable part of which runs through the ocean floor. The reason is that the movement along the fault causing earthquake was of translational or strike-slip type and did not displace water in any significant way. And the fact is that unless there is massive displacement of water, no Tsunami would generate even though the faulting might cause a high- intensity earthquake.

In the ill-famed 'Troika of Catastrophe' that marked the 1 November 1755, Lisbon event, an earthquake-induced massive landslide into the Atlantic water generated a mega- Tsunami that destroyed many settlements all along the coastlines. But, even in that case, it cannot be said that the Tsunami waves were generated directly by the earthquake. Earthquake can definitely be the cause of a type of 'enhanced' waves called 'Seiche' (also a Japanese term, pronounced 'saash'). The ground motion during an earthquake shakes the water back and forward at regular intervals setting off Seiche waves, which may at times and places be quite destructive. Such a Phenomenon, similar to Seiche waves, occurred in the southern Bengal coastal corridor on 26 December 2004.

5.4 Tsunami prediction and possible mitigation

We cannot prevent generation of a Tsunami, nor is it possible to make a precise prediction about it. There are, however, some warning signs of an impending tsunami. Mention has been made about the draw-down effect along beaches as an advance signature of incoming Tsunami waves (Fig.4). This happens when the displacement of water is linked with sudden down-sagging of the ocean floor (as it normally happens in case of Subduction related faulting). Under such a situation, there will be an unusual incidence of ebbing tide in the coastal regions; and the sea in such situations will recede from the coast, before the tsunami wave's arrival. If the continental slope is shallow, this recession can exceed many hundreds of metres. The time, for the return of water in form of giant 'harbour waves' might not be sufficient for the people to get prepared to face the impending disaster. Only those who have prior knowledge of tsunami resultant changes in the ocean wave dynamics saved themselves and others by rushing to elevated zones of the area. Others perished due to lack of sufficient time to run for safety.

One of the early warnings of an incoming Tsunami is sounded by the nearby animals, which have the ability to sense danger and flee to higher ground before the water arrives. This was first recorded in the event of Lisbon earthquake-Tsunami on 1 November 1755, in Europe. The phenomenon was also noted in Sri Lanka during the recent Indian Ocean Tsunami. It is said that animals may have the ability to sense subsonic seismic waves from an earthquake minutes or hours before a tsunami strikes the shore. Some other views about the animal behaviour have also been expressed suggesting that certain large animals especially the elephants are able to sniff out danger. This instinct force them to flee in the direction opposite to the approaching roars of Tsunami waves.

In regions of high risk, the 'Tsunami Warning Systems' are being used to detect approaching Tsunami to warn the general population before the wave reaches land. Since 1995, National

Oceanic and Atmospheric Administration (NOAA) began developing the "Deep-Ocean Assessment and Reporting of Tsunamis (DART)" system. (Tsunami Information: www.ess.washington.edu/tsunami). Several stations have been deployed in the Pacific Ocean, which have 'pressure recorder' for detecting the passage of a Tsunami. The basic assumption is that the pressure of the water column is related to the height of the sea-surface. Any sudden change in the depth of the water column is indicated by a corresponding change in the water pressure. This in turn is an indication that a Tsunami is developing. The information is immediately sent to the 'Pacific Tsunami Warning Center' (PTWC) for dissemination to all concerned. The DART system rings out early warnings to all the Pacific coastal countries. We should however remember that the DART information from the Pacific would not be effective for the Indian Ocean region, because the Tsunamis developing in the Pacific would have no free passage to the Indian Ocean. Considering this, there is now an Indian Tsunami monitoring System working in the Indian Ocean.

Tsunami is an exotic word for us without having any equivalent phrase in Indian languages, unlike the earthquake and the volcano (Shetye, 2005). This clearly implies that the Tsunami is not a regular visitor in the Indian coastal regions. Truly speaking, there is no information about any dreadful appearance of Tsunami 'monster' in the region in the known history barring one that had lashed the northern coastal belts of the Arabian Sea on 19 June 1945.

The memory of the 2004 Indian Ocean Tsunami is so fresh in our mind that it is not possible to disbelieve that the 'waves' that devastated the region were anything other than a dreadful Tsunami. Even if it is assumed that 1737 Calcutta event was a Tsunami of a scale comparable with the most recent one, there is hardly any reason to be panicky. Tsunami of 2004 magnitude may not happen in the near future, as this tsunami was triggered by a very high magnitude earthquake that destabilised large chunks of the crust. Japan has implemented an extensive programme of building Tsunami walls of up to 4.5 metres high in front of populated coastal areas. In some other parts of the world, floodgates and channels have been constructed to redirect the water from incoming tsunami. Without questioning the effectiveness of such Tsunami walls, it may be said that such a measure is economically unviable for the poor maritime countries in south Asia and Africa.

One useful suggestion, which might partly mitigate the effects of Tsunami is to plant trees like coconut, palms, and mangroves to cover the shoreline. The effectiveness of such a measure has been witnessed during the recent Indian Ocean Tsunami when some coastal areas covered by trees have escaped virtually unharmed, because much of the Tsunami energy was worn out considerably in the tree-covered belts (Figure 8).

Figure 8. Thick Growth of Mangrove Along Southern Part of Sundarban Seem To Have Helped In Protecting The Hinterland From The Fury Of December 26, 2004 Tsunami