Lecture 4: Overview of Plate Tectonics; Types of faults; Activity and fault Studies; Earthquake source mechanisms; Source models.

Topics

- Plate Tectonics
- Continental drift
- Faults
- Identification of Active faults
- San Andreas fault observation at Depth – (SAFOD)
- Source Mechanism
- Source models
- Requirements to be satisfied by source models
- Point source model
- Planar source model
- Case Study Comparisons of the Point and Planar Source Models

Keywords: *Faults, Plate tectonics, Sources, source models*

Topic 1

Plate Tectonics

- The Earth's outermost part (lithosphere) consists at the present geological epoch of several large and fairly stable slabs of solid and relatively rigid rock called plates. These plates evolved to their present pattern during the 200 million years that have elapsed since the breakup of the ancient super continent called Pangaea. The energy for the driving mechanisms of these drifting plates comes mainly from heat incessantly produced from the decay of radioactive elements in the rocks throughout the interior of the earth.

- The oceanic and continental crust makes up the top part of the plates. Each plate extends to a depth of 80 to 200 kilometers; a plate moves horizontally, relative to neighboring plates on softer rock immediately below. At the edge of a plate, where there is contact with adjoining plates, large deforming forces operate on the rocks, causing physical and even chemical changes in them.

- Geological evidence shows that plate geometry is not permanent but undergoing constant, gradual change. Magma is continually upwelling at the mid oceanic ridges and rising as the seafloor spreads apart. This newly emplaced rock then moves slowly across the earth's surface as new seafloor on either side of the ridge.
- In this way plates extend and move at a uniform speed of a few to 10 centimeters per year across the planet's surface, like great conveyor belts, cooling and aging

as they get farther away from the ridges. Hence mid-oceanic ridges and rises are called spreading zones.

- Millions of years after being created at a mid- ocean ridge, the crust encounters trenches along the ocean rim, where the crust then sinks, or subducts, descending back into the earth's mantle. At these places called subduction zones, the surface layers of rock plunge into the earth's interior.

- At some places plates move past each other without creating new crust or consuming old crust these are called as transform faults.

Topic 2

Continental Drift

- In 1912, a German meteorologist named Alfred Wegener presented the basic tenets of continental drift in two articles he introduced a name for the supercontinent that existed prior to the break-up that separated Africa from South America, a name that remains in use today: Pangaea (Fig 4.1).

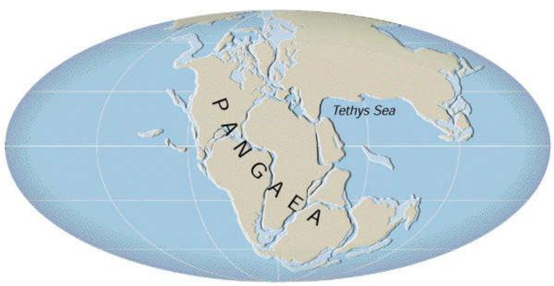


Fig 4.1: Earth 200 million years ago

- Wegener developed his idea based upon 4 different types of evidence:
    1. Fit of the Continents
    2. Fossil Evidence
    3. Rock Type and Structural Similarities
    4. Paleoclimatic Evidence

- It was the amazingly good fit of the continents that first suggested the idea of continental drift. In the 1960's, it was recognized that the fit of the continents could be even further improved by fitting the continents at the edge of the continental slope the actual extent of the continental crust. Example geographical fit of African and South America (Fig.4.2). the coal fields shared by Britain, Belgium and the Appalachian Mountains of the USA, the red sandstone band that passes through Norway, Britain, Greenland and Canada and diamond fields of South Africa and Brazil.

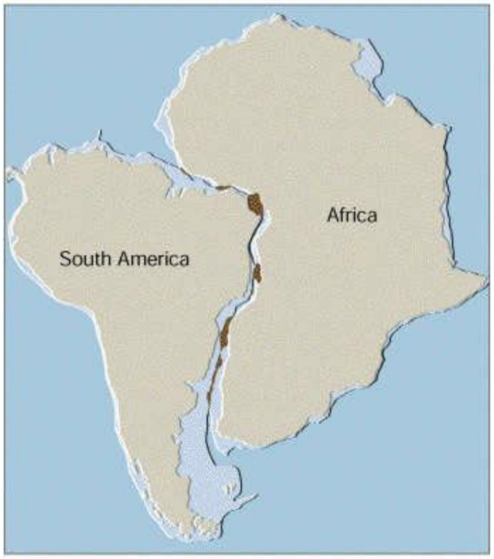


Fig 4.2: Fit of the continents

- Wegener found that identical fossils were located directly opposite on widely separated continents. This had been realized previously but the idea of "land bridges" was the most widely accepted solution. Wegener found fossils to be convincing evidence that a supercontinent had existed in the past (Fig 4.3). Example: Mesosaurus

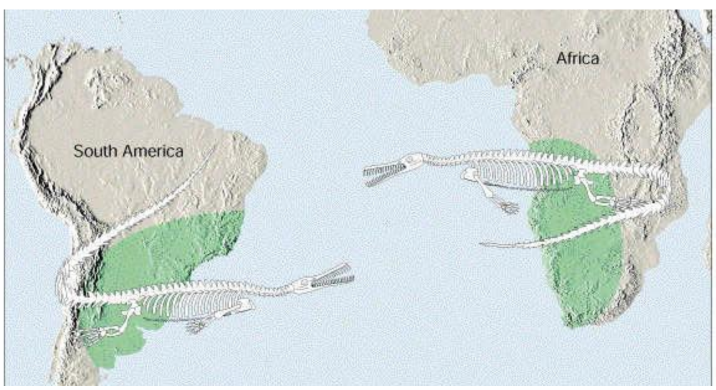


Fig 4.3: Fossil Evidence

- We find similar rock types on continents on opposite sides of the Atlantic Ocean. Similar, age, structure and rock types are found in the Appalachian Mountains (N.A.) and mountains in Scotland and Scandinavia. When the continents are reassembled, the mountain chains from a continuous belt having the same rock types, structures and rock ages (Fig.4.4).

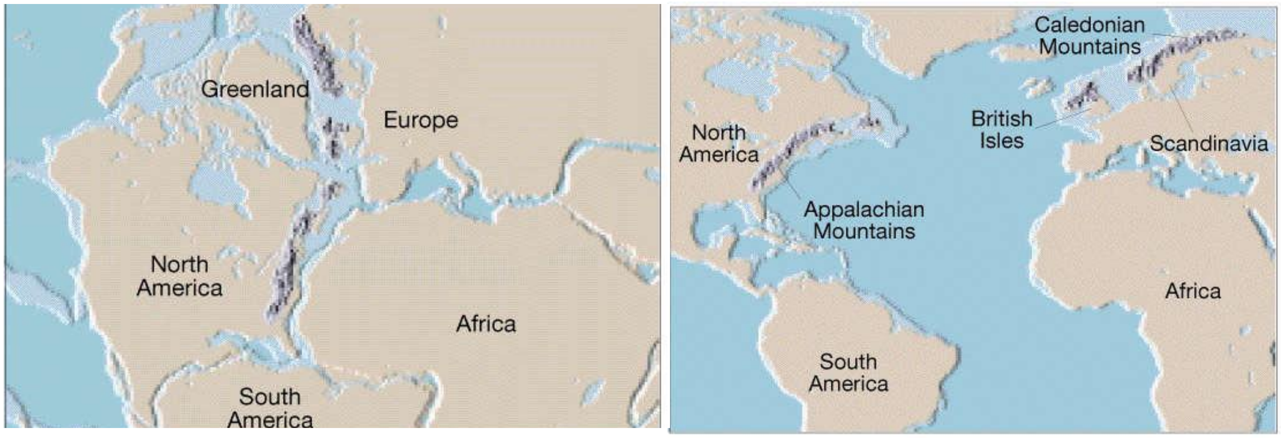


Fig 4.4: Rock Type and Structural Similarities

- Glacial till of the same age is found in southern Africa, South America, India and Australia areas that it would be very difficult to explain the occurrence of glaciations (Fig. 4.5). At the same time, large coal deposits were formed from tropical swamps in N. America and Europe. Pangaea with S. Africa centered over the South Pole could account for the conditions necessary to generate glacial ice in the southern continents. In addition, the areas with extensive coal deposits from the same time period occur in regions that would have been equatorial.

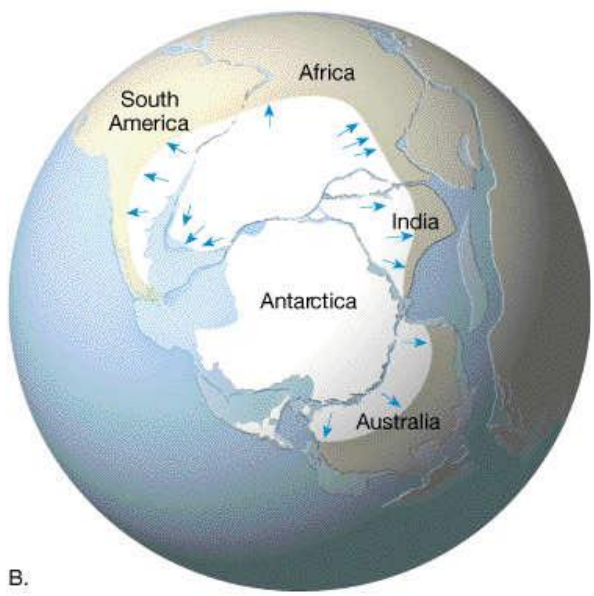


Fig 4.5: Paleoclimatic Evidence

- Fig 4.6 shows Continental drift from 200 million years ago to Today

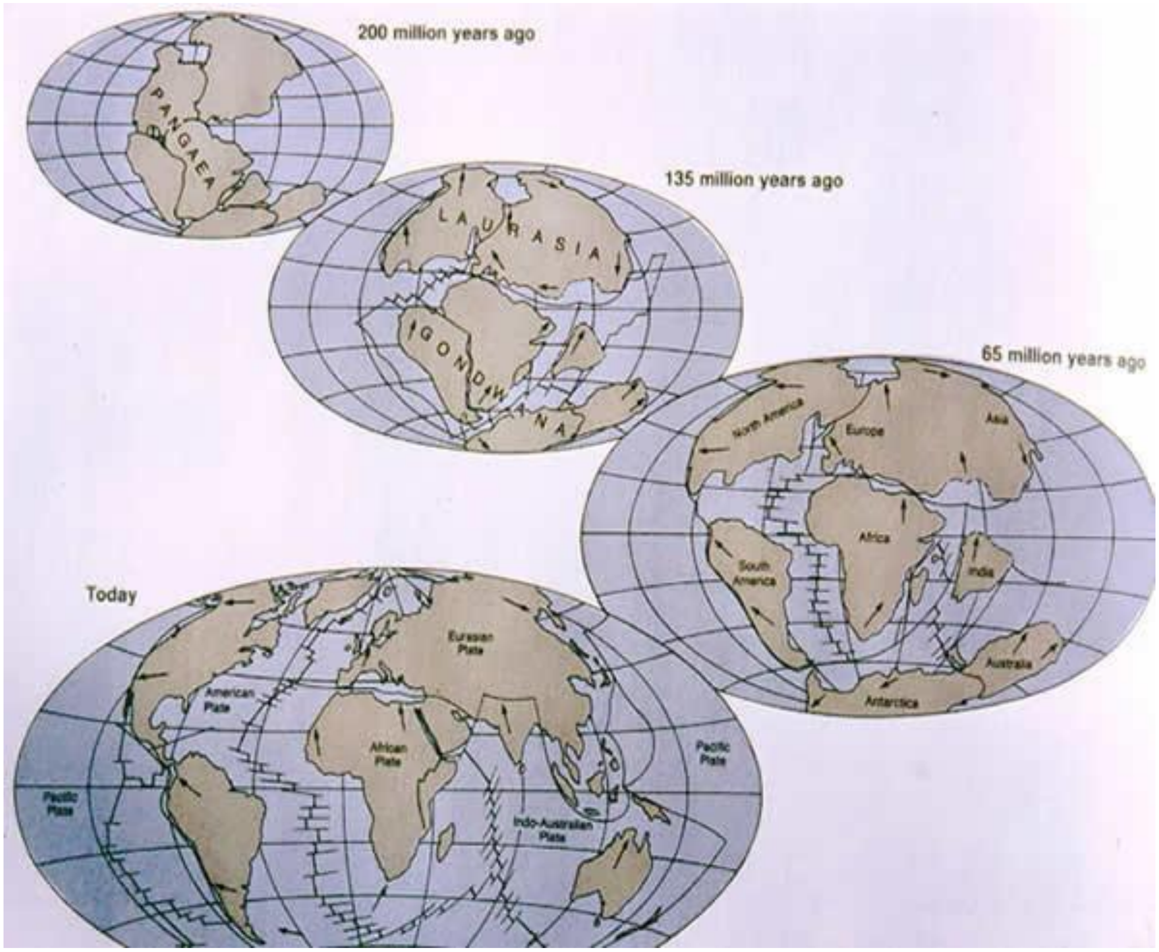


Fig 4.6: Continental Drift

Topic 3

Faults

- Faults represent pre-existing zones of weakness in the earth's curst, zones along which movement will tend to be accommodated. Or when two groundmasses move with respect to one another, elastic strain energy due to tectonic processes is stored and then released through the rupture of the interface zone. The resulting fracture in the Earth's crust is termed a 'fault'.

- Faults are classified according to their sense of motion.
  http://www.iris.edu/gifs/animations/faults.htm

1. Dip-Slip Faults

a) Normal Fault- In a normal fault, the block above the fault moves down relative to the block below the fault (Fig 4.7). This fault motion is caused by tensional forces and results in extension. [Other names: normal-slip fault, tensional fault or gravity fault]

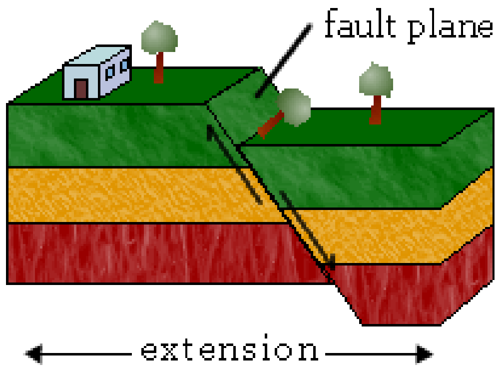


Fig 4.7: Normal fault

b) Reverse Fault - In a reverse fault, the block above the fault moves up relative to the block below the fault (Fig 4.8). This fault motion is caused by compressional forces and results in shortening. A reverse fault is called a thrust fault if the dip of the fault plane is small. [Other names: thrust fault, reverse-slip fault or compressional fault]

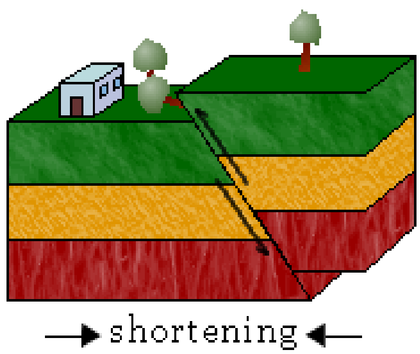


Fig 4.8: Reverse fault

2. **Strike-Slip Fault**
   In a strike-slip fault, the movement of blocks along a fault is horizontal. If the block on the far side of the fault moves to the left, as shown in Fig. 4.9, the fault is called left-lateral. If the block on the far side moves to the right, the fault is called right-lateral. The fault motion of a strike-slip fault is caused by shearing forces. [Other names: transcurrent fault, lateral fault, tear fault or wrench fault]

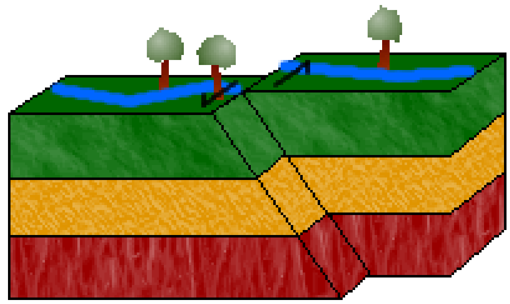


Fig 4.9: Strike-slip fault

3. Oblique-Slip Fault

Oblique-slip faulting suggests both dip-slip faulting and strike-slip faulting (Fig 4.10). It is caused by a combination of shearing and tension of compressional forces.

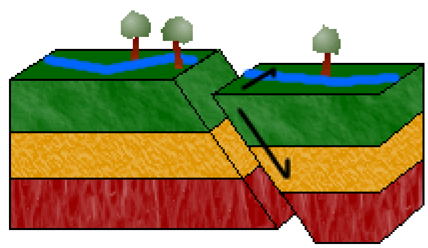


Fig 4.10: Oblique slip fault

Blind or hidden faults

When the faulting does not appear at the surface, the seismic source is termed as blind fault. Blind thrust faults are high in many seismic regions of the world. Their detection is often best accomplished by long-term mapping of micro-earthquake hypocenters in each such region.

Active and inactive faults

Inactive faults – slip no longer occurs in these faults plotted on geological maps. The last displacement to occur along a typical fault may have taken place ten of thousands or even millions of years ago. The local disruptive forces in the earth nearby may have subsided long ago, and chemical processes involving water movement may have cemented the ruptures, particularly at shallow depth.

Active faults – faults along which crustal displacements can be expected to occur. Many of these faults are in rather well-defined tectonically active regions of the Earth, such as the mid oceanic ridges and young mountain ranges.

Topic 4

Identification of active faults

- Directly observable fracture surfaces and indicators of fracturing, these include disruption of the ground surface and evidence of the movement and grinding of the two sides of the fault.
- Geologically mappable indicators. These include the juxtaposition of dissimilar materials, missing or repeated strata and the truncation of strata or structures.
- Topographic and geomorphic indicators. These include topographic scarps or triangular facets on ridges, offset streams or drainage, tilting or changes in elevation of terraces or shorelines, sag ponds (water ponded by depressions near strike-slip faults) and anomalous stream gradients.
- Secondary geologic features. These include abrupt changes in ground water levels, gradients, and chemical composition, alignment of springs or volcanic vents and the presence of hot springs.
- Lineaments on remote sensing imagery. These may be caused by topography, vegetation or tonal contrasts.
- Geophysical indicators of subsurface faulting. These include steep linear gravity or magnetic gradients, differences in seismic wave velocities, and offset of seismic reflection horizons.
- Geodetic indicators. These include fault movement appearing in geodetic surveys as tilting and changes in the distance between fixed points.

Fault activity

- Movement at or near the ground surface at least once within the past 35,000 years or movement of a recurring nature within the past 500,000 years.
- Macroseismicity instrumentally determined with records of sufficient precision to demonstrate a direct relationship with the fault.
- A structural relationship to a capable fault according to above two characteristics, such that movement on one could reasonably be expected to be accompanied by movement on the other.

Topic 5

San Andreas fault observation at Depth – (SAFOD)

- The National Science Foundation (NSF) and the USGS started in June 2004 to drill a deep hole in order to install instruments directly within the San Andreas Fault Zone. These instruments, set 2 to 3 km beneath the Earth's surface, will form a San Andreas Fault Observatory at Depth (SAFOD). This project will directly reveal, the physical and chemical processes controlling earthquake generation within a seismically active fault.

- Drilling the hole for SAFOD starts west of the San Andreas Fault through the entire fault zone until relatively undisturbed rock is reached on the east side. Fault-zone rocks and fluids will be retrieved for laboratory analyses, and geophysical measurements will be made within the active fault zone. SAFOD's long-term monitoring activities will include detailed seismological observations of small to moderate earthquakes and continuous measurements of rock deformation and other parameters during the earthquake cycle.

- SAFOD will provide direct information on the composition and mechanical properties of rocks in the fault zone, the nature of stresses responsible for earthquakes, the role of fluids in controlling faulting and earthquake recurrence, and the physics of earthquake initiation and rupture.

- PBO is a geodetic observatory designed to study the three-dimensional strain field resulting from plate boundary deformation.

- A 2.2-km-deep vertical pilot hole was drilled adjacent to the San Andreas Fault at Park field in the summer of 2002. The pilot project has provided both engineering and scientific data to guide the current SAFOD project to its goal of precisely drilling into the fault-zone where small, M2, earthquakes repeat on a regular schedule.

- Schematic cross section of the San Andreas Fault Zone at Park field, showing the drill hole for the San Andreas Fault Observatory at Depth (SAFOD) and the pilot hole drilled in 2002 is shown in Fig 4.11. Red dots in drill holes show sites of monitoring instruments. White dots represent area of persistent minor seismicity at depths of 2.5 to more than 10 km. The colors in the subsurface show electrical resistivity of the rocks as determined from surface surveys; the lowest-resistivity rocks (red) above the area of minor earthquakes may represent a fluid-rich zone.

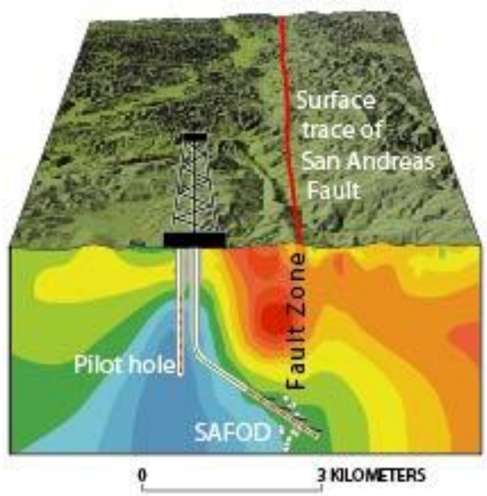


Fig 4.11: Schematic cross section of the San Andreas Fault Zone at Park field

Topic 6

Source mechanisms

- Knowledge of an earthquake's rupture process provides direct information about the style and direction of deformation of the Earth's crust in the epicentral area.

- Most earthquakes are caused by a sudden shear motion along a fault surface inside the crust. The polarities and amplitudes of the radiated seismic signals strongly depend on the direction in which the waves leave the source. This information is preserved along the travel path of the seismic waves. Seismograms recorded by several stations at locations around the epicentral area allow for the determination of the earthquake source process.

- Earthquake source mechanisms tell us the deformation style (normal, thrust, strike-slip faulting) and the orientation the fault associated with the earthquake. The P- and T-axes are the deformation axes (see picture) and correspond to the directions of maximum compression (P) and maximum extension (T).

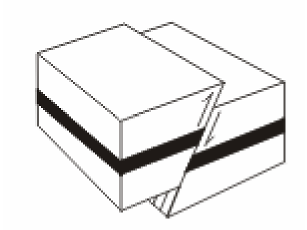
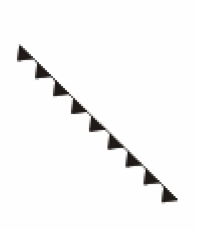
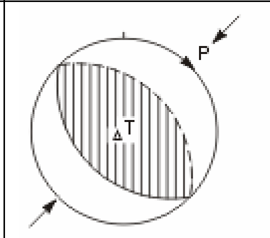
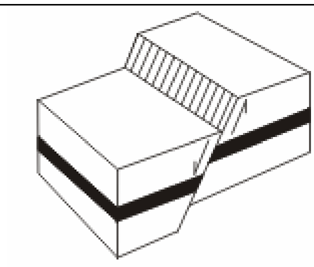
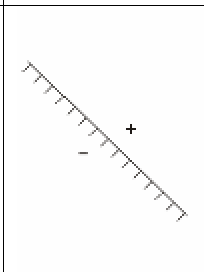
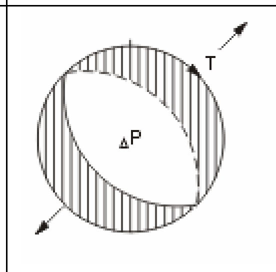
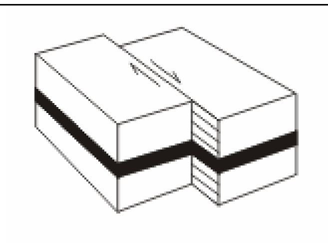
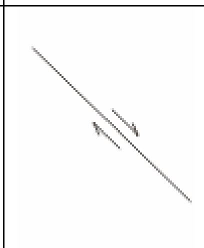
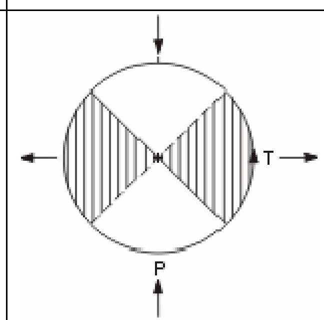
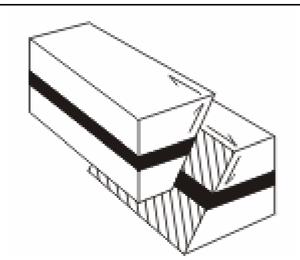
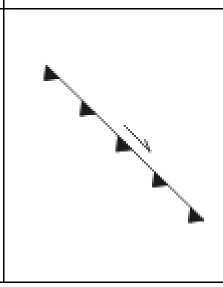
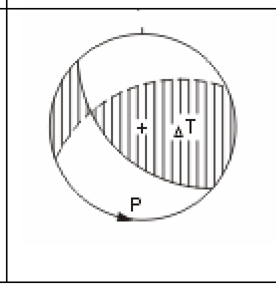
- The first motion of p-wave has long been used to determine earthquake focal mechanisms. Advantages of this approach are: only vertical component instruments are required, amplitude calibration is not needed.

- The sense of first p motion (i.e. up or down) can be easily noted from the seismogram at the same time the arrival time is picked, the initial motion of the p-wave determines whether the ray left the source in a compressional (upward first motion at a surface receiver) or dilatational quadrant (downward first motion)

- The results are plotted on what is termed as focal sphere, an imaginary sphere surrounding the source that shows the take off angle so the rays. The focal sphere is used as a means of displaying focal mechanisms. The lower hemisphere is plotted and the compressional quadrants are shaded to produce the traditional "beach ball" image (Table 4.1).

- Normal and reverse faulting may be distinguished in beach ball plots by noting if the center of the plot is white or black. If it is white in the middle with black edges, then it represents a normal fault and a probable region of extension. Whereas black in the center with white edges indicates a reverse or thrust fault and a likely compressional regime.

Table 4.1: Types of faults and their earthquake mechanism

Fault name	Fault Types	Cartographic Depiction	Earthquake Source Mechanism
Thrust Fault			
Normal Fault			
Strike-Slip Fault			
Oblique Thrust (combination of Thrust and Strike-slip Faulting)			

Topic 7

Source models

- The elastic rebound theory proposed by Reid in 1911 constitutes the essential foundation of the earthquake source process used in the modeling of strong ground motion.

- Sudden fault rupture that results from the accumulation of strains in the crust is the cause of the radiation of seismic waves and consequently of ground motion. The development and propagation of the dislocation front on the fault surface, and the time for completion of the slip, are essential for an explanation of the ground motion.

- Seismic moment, various stress parameters, rupture velocity, and slip-time functions are considered as the main parameters necessary for description of the source and for the simulation of ground motion.

Topic 8

Requirements to be satisfied by source models

- Source models should offer conceptual clarity and physical insight.
- They should be simple in physical description and in application, permitting an analysis with a hand calculator or a spreadsheet.
- They should have sufficient scope of application (for different shapes, soil profiles, ground properties).
- They should also offer acceptable accuracy, as demonstrated by comparing the results of the simplified models with those of rigorous methods.
- They should be adequate to explain the main physical phenomena involved, and have direct use in engineering practice for everyday design.
- They need to be useable for checking the results of more sophisticated analysis.
- Finally there should be a potential generalization of the concept with clear links to the rigorous methods.

Topic 9

Point source model

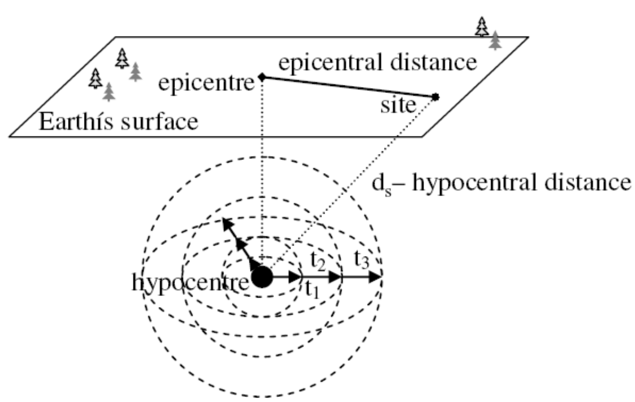


Fig 4.12 Point source model with spheres of wave's front propagation from the hypocenter in time t_1-t_3

- An earthquake source is usually a tectonic fault Forecasting of dynamic fault rupture propagation is rather complex and therefore simplified point models are used (Fig. 4.12).

- The simplest of these is the point source model. Longitudinal seismic waves travel faster than the transversal waves and therefore there will be a time lag Δtw between their arrivals. The time lag is estimated form the ground motion record. Let ds represent the straight-line (slant) distance from the earthquake hypocenter and a recording site on the earth's surface.

- If vt and vl denote the velocities of propagation of the transversal and longitudinal waves respectively, then the transversal waves take a time $dslv^{-1}$ to arrive. Hence by measuring the difference Δtw between these arrival times, and inverting the relationship, one arrives at:

$$ds = \frac{\Delta tw}{1/vt - 1/vl} \qquad (4.1)$$

- For the typical range of longitudinal wave velocity of 6-7 km/s at depths greater than 1 km the corresponding typical range of the transversal wave velocity is 3.5-4 km/s. longitudinal and transversal wave velocities are coupled by a factor called Poisson's ration. The ration range for rock at depths greater than 1 km is from 0.24 to 0.26.

- The wave propagation through earth's interior causes mainly elastic deformations because material damping is small and amounts to less than 1% of the energy transmitted by waves.
- The point source model assumes that the wave front propagates from the source as concentric spheres. In this case, the ground motion at a hypocentral distance ds will be inversely proportional to the square root of the energy density, i.e.

$$\sqrt{\frac{E_d}{E_o}} \sim \sqrt{\frac{1}{e^{k_d . d_s} .4.\Pi.d_s^2}} \qquad (4.2)$$

- E_o is the total energy released at the earthquake source, E_d is the energy density at a hypocentral distance ds, k_d is an average material damping coefficient (about 0.001 – 0.01). e^{kd} is the effect of material damping, $4\Pi d_s^2$ is the effect of radiation damping on seismic energy dissipating with distance ds to the source.

- The above equation is valid for distances from the source where the body seismic waves dominate the ground motion at the surface. At distances greater than a few tens of kilometers from the source, where the surface seismic waves appear at the surface and predominate the ground motion, the radiation damping may be proportional to $ds^{-0.5}$, because the circumference of the surface wave propagation front is πds.

Topic 10

Planar source model

- The planar model fits better the recorded peak ground accelerations than the point source model. Planar tectonic fault radiates the energy as a wave train uniformly in all directions in a medium with an average material damping coefficient k_d.

- Planar model requires knowledge of the fault plane size and location as well as of the attitude and thickness of the non-seismogenic zone, information that has to be assumed by the engineer a priori. For known faults the use of the planar source model is not much complicated than the use of the point source model.

- To model a planar fault a four-gauss-point integration scheme is used. The locations of four integration points on a fault plane and distances to the site are shown in Fig 4.13.

- The point source model equation is replaced by

$$\sqrt{\frac{E_d}{E_t}} \sim \sqrt{L_f . W_f \sum_{i=1}^{4} \frac{1}{e^{k_d . d_i} .4.\Pi.d_i^2}} \qquad (4.3)$$

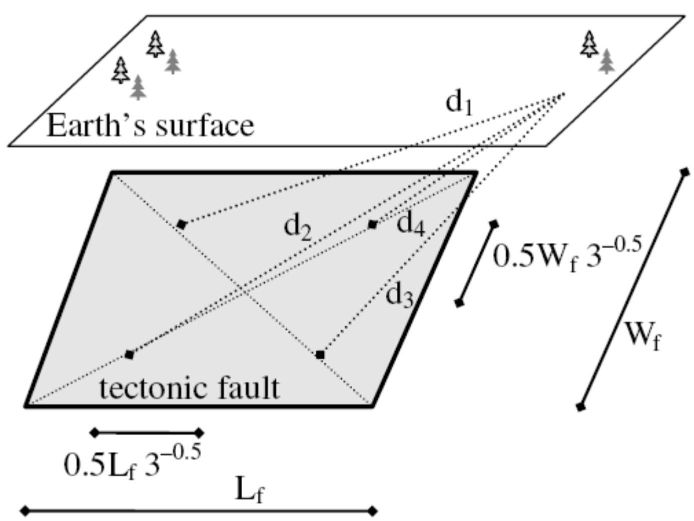


Fig 4.13: The location of four Gauss integration points on a fault plane and slant distances $d_{1\text{-}4}$ to the side

- $E_t = E_o(L_f W_f)^{-1}$ is the total energy released at the earthquake source per unit area of the source, L_f is tectonic fault length, W_f is tectonic fault width. The equation is valid for distances up to source-to-site distance of a few tens of kilometers, where the body seismic waves dominate the ground motion at the surface.

- At greater distances where surface waves dominate the ground motion at the surface the equation is replaced by

$$\sqrt{\frac{E_d}{E_t}} \sim \sqrt{L_f.W_f \sum_{i=1}^{4} \frac{1}{e^{k_d.d_i}.2.\Pi.d_i}} \qquad (4.4)$$

Topic 12

Case Study Comparisons of the Point and Planar Source Models

- For each earthquake listed in Table 4.2 above, horizontal ground accelerations were measured at a number of different recording stations, at various distances from the earthquake source.
- Table 4.2: Basic earthquake source data in the example

No	Earthquake	Date	Time	Magnitude M_w[#]	Causative fault type[*]
1	Tabas- Iran	16 September 1978	15:35:57	7.35	Oblique
2	Montenegro	15 April 1979	06:19:41	7.0	Thrust
3	Campano Lucano-Italy	23 November 1980	18:34:52	6.93	Normal

- Ratios between the peak horizontal accelerations at two recording stations can therefore be calculated. If the most remote recording station is used as reference, then the ratio for this station itself is one.

- From the above Fig 4.14 it follows that there is a good agreement between predicted peak acceleration ratios based on the planar source model and the best fit of ratios (shown by thick dashed line) calculated from recorded peak accelerations using the fault distances as well as between predicted peak acceleration ratios based on the point source model and the best fit of ratios (shown by thick dotted line) calculated from recorded peak accelerations using the epicentral distances.

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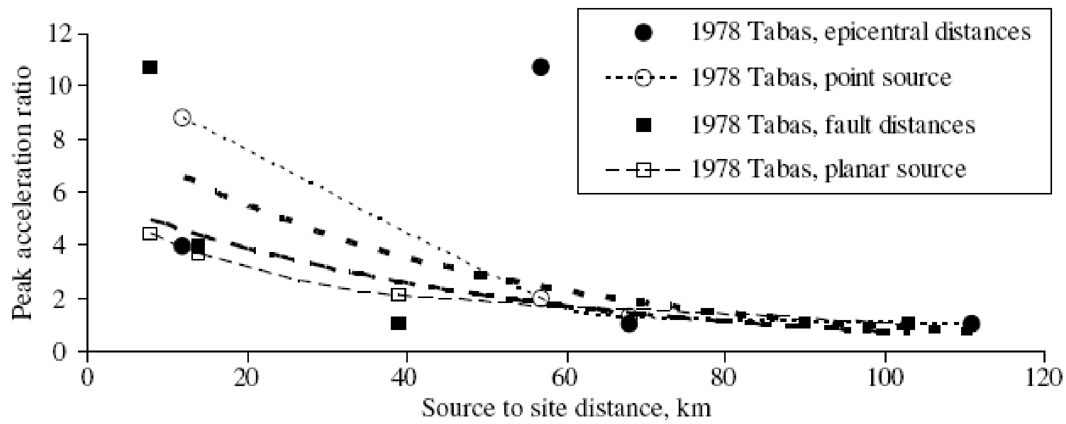
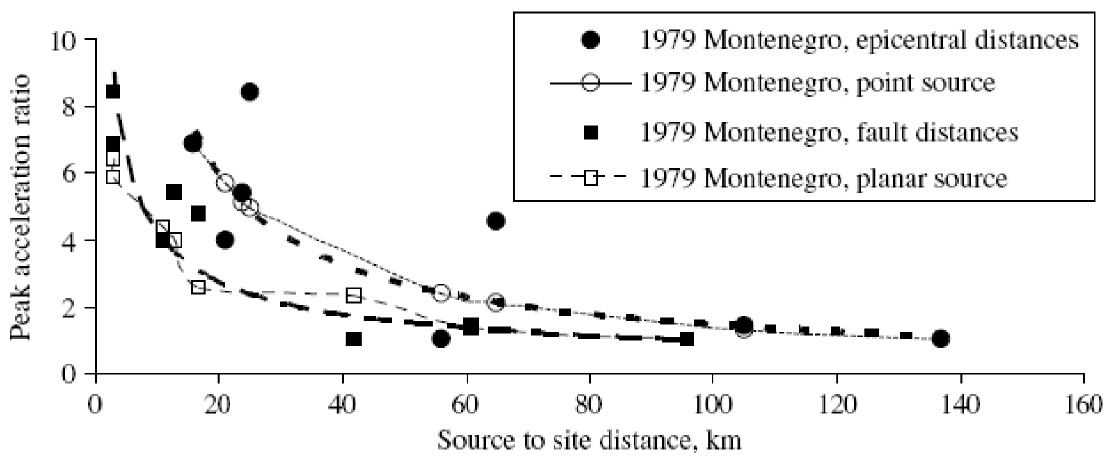


(a)



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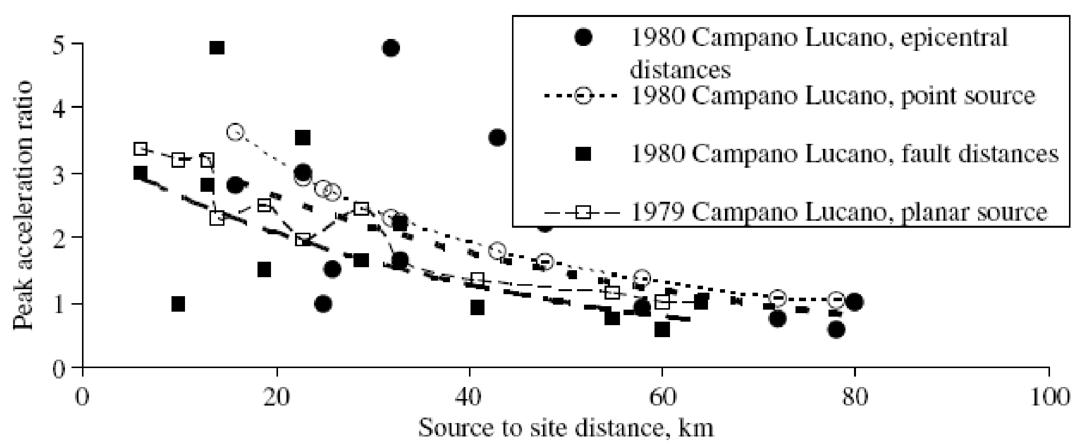

(c)

Fig 4.14 (a, b, c): Peak acceleration ratios versus source to site distances of the three earthquakes

- It is possible to notice a number of outliers, i.e. values that are significantly different from the best fit, at the site-to-source distances greater than about 20 km particularly when the epicentral distances are considered. This suggests that the use of epicentral distances is not always appropriate when considering attenuation of peak accelerations associated with radiation damping.

End of Lecture 4 in Overview of Plate Tectonics; Types of faults; Activity and fault Studies; Earthquake source mechanisms; Source models.