Lecture 6: Theory of wave propagation; Seismic waves, body and surface waves.

Topics

- How seismic waves are produced?
- Wave and its Properties
- Wave Propagation
- Types of Seismic Waves
- Compressional or P-Waves or longitudinal waves
- S-Waves or Torsional Waves
- Love Waves
- Rayleigh Waves
- Wave Character
- Seismic Waves in the Earth
- Earthquake Record
- Chile earthquake recorded at Nana, Peru
- Earth cross section and approximate ray path for direct P- and S-waves
- PREM for Preliminary Earth Reference Model.
- Shadow Zones

Keywords: *Seismic waves, Body waves, Surface waves, wave Propagation*

Topic 1

How seismic waves are produced?

- The earth's crust is broken into seven major plates, each of which behaves for the most part as a rigid body that slides over the partially molten mantle, in which deformation occurs plastically.

- Three types of plate boundaries are defined according to their relative motion: zones of spreading, zones of relative lateral motion (transform faults), and zones of convergence, where plates collide.

- Relative plate motion at the fault interface is constrained by friction (areas of interlocking due to protrusions in the fault surfaces); strain energy accumulates in the plates, eventually overcomes any resistance, and causes slip between the two sides of the fault. This sudden slip, termed as elastic rebound, releases large amount of energy which constitutes **the Earthquake**.

- The edge of the rupture does not spread out uniformly. Progress is jerky and irregular because on the fault surface there are rough patches (often called *asperities*) and changes in fault direction and structural complexities (Fig 6.1) that act as barriers to the fault slip.

- Asperity is defined as a strong section of a fault system that is locked during the decades of stress build up in the fault system and it releases most of its energy during an earthquake. The surrounding areas, barriers, are weakly coupled; possibly drag along during an earthquake.

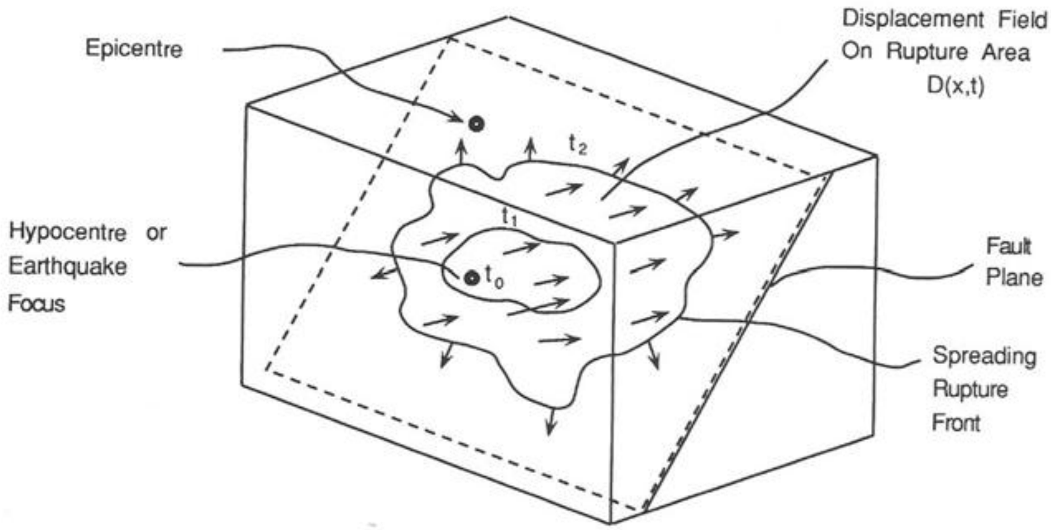

Fig 6.1: Diagram showing epicentre, focus (hypocentre), ruptures area and fault-plane

- The effective stress normal to the fault surface in asperity is believed to be relatively higher than in the barrier. Alternatively, barriers may be regions of ductile deformation in which rupture dies out. This type of barrier is known as relaxation barrier.

Topic 2

Wave and its Properties

- Waves consist of a disturbance in materials (media) that carry energy and propagate. However, the material that the wave propagates in generally does not move with the wave. The movement of the material is generally confined to particle motion of the material as the wave passes.

- After the wave has passed, the material usually looks just like it did before the wave, and, is in the same location as before the wave. (Near the source of a strong disturbance, such as a large explosion or earthquake, the wave-generated deformation can be large enough to cause permanent deformation which will be visible as cracks, fault offsets, and displacements of the ground after the disturbance have passed).

- A source of energy creates the initial disturbance (or continuously generates a disturbance) and the resulting waves propagate out from the disturbance. Because there is finite energy in a confined or short-duration disturbance, the waves generated by such a source will spread out during propagation and become smaller (attenuate) with distance away from the source or with time after the initial source, and thus, will eventually die out.

- Waves are often represented mathematically and in graphs as sine waves (or combinations of sine waves) as shown in Figure below. The vertical axis on this plot represents the temporary motion (such as displacement amplitude A) of the propagating wave at a given time or location as the wave passes.

- The horizontal axis displays time or distance and the vertical axis displays amplitude as a function of time or distance (Fig. 6.2). Amplitude can represent any type or measure of motion for any direction. Seismic wave motion is commonly displayed with a similar plot, and sometimes the wave itself looks very similar to the sine wave shown here.

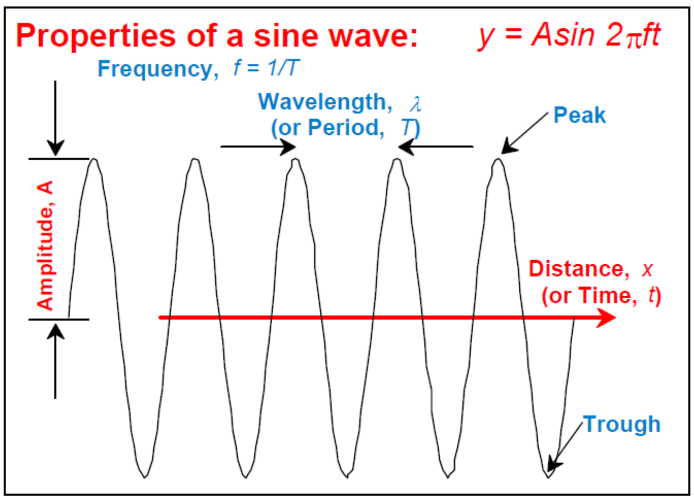

Fig 6.2: Properties of a sine wave

- Examples are water waves and a type of seismic surface waves called Rayleigh waves. Commonly, propagating waves are of relatively short duration and look similar to truncated sine waves whose amplitudes vary with time.

- Waves generated by a short duration disturbance in a small area, such as from an earthquake or a quarry blast, spread outward from the source as a single or a series of wavefronts. A good model for illustrating wave motion of this type is water waves from a pebble dropped in a still pond or pool.

- The disturbance caused by the pebble hitting the surface of the water generates waves that propagate outward in expanding, circular wavefronts. Because there is more energy from dropping a larger pebble, the resulting waves will be larger (probably of different wavelength).

- Three positions (successive times) of the expanding wavefront are shown in Fig 6.3. Particle motions for P (compressional) and S (shear) waves are also shown. Ray paths are perpendicular to the wavefronts and indicate the direction of propagation of the wave.

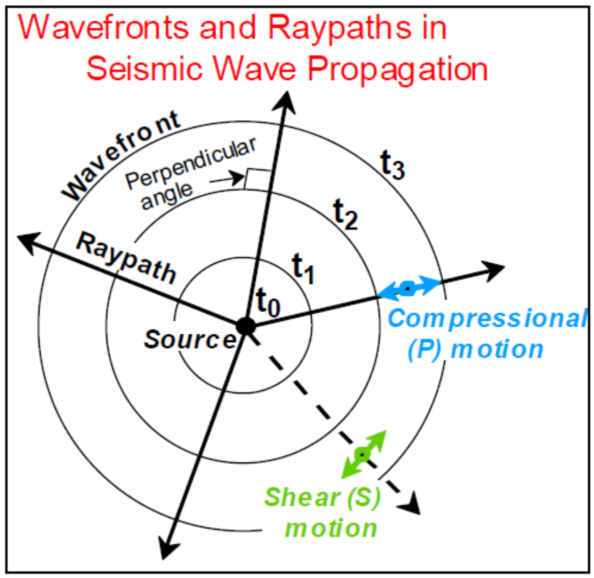

Fig 6.3: Wavefronts and ray paths for a seismic wave propagating from a source

- P waves travel faster than S waves so there will be separate wavefront representations for the P and S waves. If the physical properties of the material through which the waves are propagating are constant, the wavefronts will be circular (or spherical in three dimensions). If the physical properties vary in the model, the wavefronts will be more complex shapes.

Topic 3

Wave Propagation

- The fact that the waves travel at speeds which depend on the material properties (elastic moduli and density) allows us to use seismic wave observations to investigate the interior structure of the planet.

- We can look at the travel times, or the travel times and the amplitudes of waves to infer the existence of features within the planet, and this is an active area of seismological research. To understand how we see into Earth using "vibrations", we must study how waves interact with the rocks that make up Earth.

- Several types of interaction between waves and the subsurface geology (i.e. the rocks) are commonly observable on seismograms
    1. Refraction
    2. Reflection
    3. Dispersion
    4. Diffraction
    5. Attenuation

- **Refraction** - As a wave travels through Earth, the path it takes depends on the velocity (Fig 6.4). Perhaps you recall from high school a principle called Snell's law, which is the mathematical expression that allows us to determine the path a wave takes as it is transmitted from one rock layer into another. The change in direction depends on the ratio of the wave velocities of the two different rocks.

- Refraction has an important effect on waves that travel through Earth. In general, the seismic velocity in Earth increases with depth (there are some important exceptions to this trend) and refraction of waves causes the path followed by body waves to curve upward.

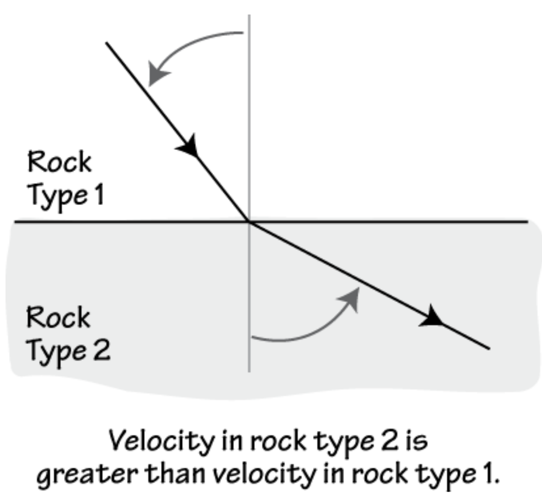

Fig 6.4: Refraction

- When waves reach a boundary between different rock types, part of the energy is transmitted across the boundary. The transmitted wave travels in a different direction which depends on the ratio of velocities of the two rock types. Part of the energy is also reflected backwards into the region with Rock Type 1.

- The overall increase in seismic wave speed with depth into Earth produces an upward curvature to rays that pass through the mantle. A notable exception is caused by the decrease in velocity from the mantle to the core. This reduction in speed bends waves backward and creates a "P-wave Shadow Zone" between about 100° and 140° distance (1° = 111.19 km).

- **Reflection** - The second wave interaction with variations in rock type is reflection (Fig.6.5). In some instances reflections from the boundary between the mantle and crust may induce strong shaking that causes damage about 100 km from an earthquake (we call that boundary the "Moho" in honor of Mohorovicic, the scientist who discovered it).

- A seismic reflection occurs when a wave impinges on a change in rock type (which usually is accompanied by a change in seismic wave speed). Part of the energy carried by the incident wave is transmitted through the material (that's the refracted wave described above) and part is reflected back into the medium that contained the incident wave.

- When a wave encounters a change in material properties (seismic velocities and or density) its energy is split into reflected and refracted waves.

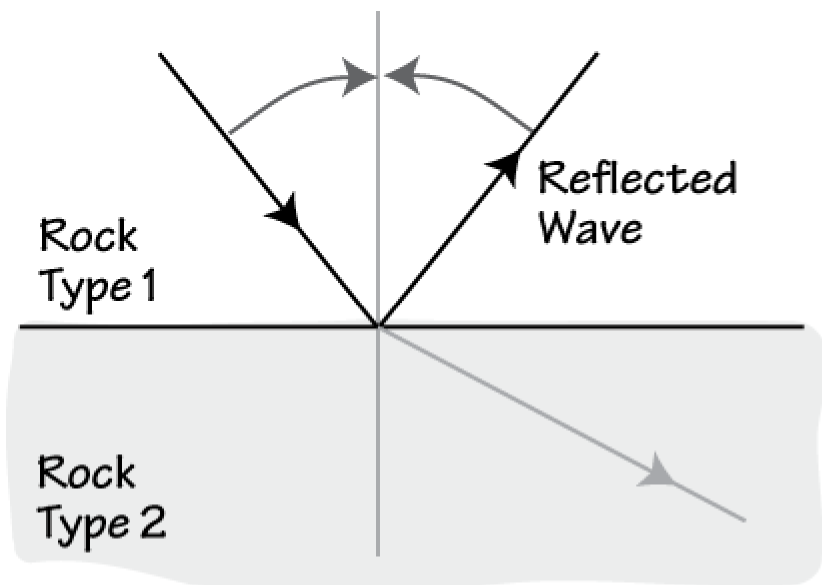

Fig 6.5: Reflection

- The magnitude of reflection depends strongly on the angle that the incidence wave makes with the boundary and the contrast in material properties across the boundary. For some angles all the energy can be returned into the medium containing the incident wave.

- **Dispersion** - The surface waves are dispersive which means that different periods travel at different velocities (Fig 6.6). The effects of dispersion become more noticeable with increasing distance because the longer travel distance spreads the energy out (it disperses the energy). Usually, the long periods arrive first since they are sensitive to the speeds deeper in Earth, and the deeper regions are generally faster.

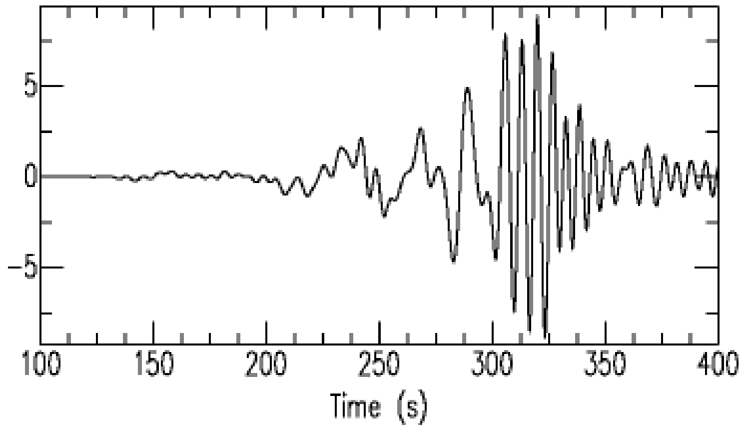

Fig 6.6: A dispersed Rayleigh wave generated by an earthquake in Alabama near the Gulf coast, and recorded in Missouri

- **Attenuation** – earthquake shaking is usually very strong on or very close to the fault, and decreases or attenuates with distance from the fault. This attenuation depends on the magnitude of the earthquake, and the geology of the region. Soft soils such as old filled-in marshes can greatly increase or amplify the ground motion.

- The effect of soil is a primary factor in the intensity of the shaking. Hence, even though shaking generally attenuates with distance from the fault, shaking can still be very strong at a large distance.

Topic 4

Types of Seismic Waves

- Two basic types of elastic waves or seismic waves are generated by an earthquake; these are body waves and surface waves (Fig 6.6). These waves cause shaking which is felt, and cause damage in various ways.

- **Body Waves** - The body waves propagate within a body of rock. The faster of these body waves is called Primary wave (P-wave) or longitudinal wave or compressional wave, and the slower one is called Secondary wave (S-wave) or shear wave or transverse wave.

- **P-wave** - The P-wave motion, same as that of sound wave in air alternately pushes (compresses) and pulls (dilates) the rock. The motion of the particles is always in the direction of propagation. The P-wave, just like sound wave, travels through both solid rock, such as granite, and liquid material, such as volcanic magma or water.

- It may be mentioned that, because of sound like nature, when P-wave emerges from deep in the Earth to the surface, a fraction of it is transmitted into atmosphere as sound waves. Such sounds, if frequency is greater than 15 cycles per second, are audible to animals or human beings. These are known as earthquake sounds.

- **S-wave** - It is known that the S-wave or the shear wave, shears the rock sideways at right angle to the direction of propagation. As shear deformation cannot be sustained in liquid, shear waves cannot propagate through liquid materials at all.

- The outer portion of Earth's core is assumed to be liquid because it does not transmit shear waves from earthquakes. The particle motion of the S-wave is perpendicular (transverse) to the propagation.

- In the figure the particle motion of the S-wave is up and down in vertical plane; it is named SV wave. However, S-wave may also oscillate in horizontal plane, which is called SH wave.

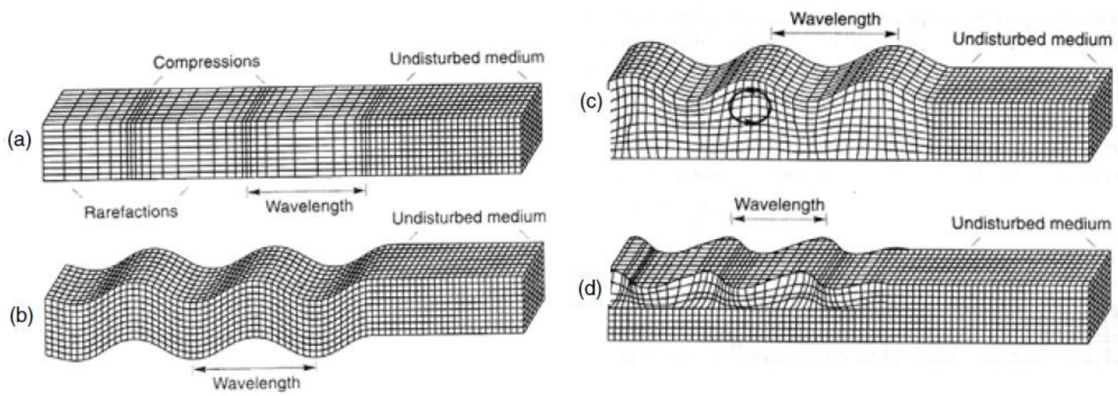

Fig 6.7: Diagram illustrating ground motion for four types of earthquake waves (a) P-wave, (b) S-wave, (c) Rayleigh wave and (d) Love wave

- **S-wave Splitting** - S-waves are also linearly polarized when propagating in homogeneous isotropic medium. In anisotropic medium they, however, split into fast and slow components. These split waves propagate with different velocity that causes time delay and related phase shift.

- The two split S-wave components superimposed to an elliptical polarization. The orientation of major axis and degree of ellipticity are controlled by fast and slow velocity directions and the degree of anisotropy. The S-wave splitting is often used to study S-wave velocity anisotropy of the Earth.

- **Surface Waves** - The second general type of earthquake wave is called surface wave, because its motion is restricted to near the ground surface. Such waves correspond to ripples of water that travel across a lake. The wave motion is located at the outside surface itself, and as the depth below this surface increases, wave displacement becomes less and less.

- Surface waves in earthquakes can be divided into two types: Love waves and Rayleigh waves. The Love waves are denoted as LQ (or G) and the Rayleigh waves as LR (or R). While Rayleigh waves exist at any free surface, Love waves require some kind of wave guide formed by velocity gradient.

- **Love Wave (LQ)** - The British mathematician A.E.H. Love demonstrated that if an SH ray strikes a reflecting horizon near surface at post critical angle, all the energy is 'trapped' within the wave guide. These waves propagate by multiple reflections between the top and bottom surfaces of the low speed layer near the surface. The waves are called Love waves, and denoted as LQ or G.

- Its motion is same as that of the S-waves that have no vertical displacement. It moves the ground from side to side in a horizontal plane parallel to Earth's surface, but at right angle to the direction of propagation so the wave motion is horizontal and transverse.

- Rayleigh Wave (LR) - Rayleigh (1885) demonstrated that the surface boundary condition can be satisfied leading the existence of a 'coupled' and 'trapped' P-SV wave traveling along the surface, such as the Earth-air interface, with a velocity lower than shear velocity, and with an amplitude decaying exponentially away from the surface. This second type of surface wave is known as Rayleigh wave.

- In general the surface waves with periods 3 to 60s are denoted R or LR. Like rolling ocean waves, the Rayleigh waves develop the particle motion both vertically and horizontally in a vertical plane pointed in the direction of wave propagation.

- Since Rayleigh waves generate from coupled P and SV waves the particle motion is always in vertical plane, and due to phase shift between P and SV the particle motion is elliptical and retrograde (counter clockwise) with respect to the direction of propagation. The amplitude of the motion decreases exponentially with depth below the surface.

Topic 5

Compression or P-Waves or longitudinal waves

http://web.ics.purdue.edu/~braile/edumod/waves/Pwave.htm

- P-waves are the first waves to arrive on a complete record of ground shaking because they travel the fastest (their name derives from this fact - P is an abbreviation for primary, first wave to arrive). They typically travel at speeds between ~1 and ~14 km/sec. The slower values correspond to a P-wave traveling in water, the higher number represents the P-wave speed near the base of Earth's mantle.

- P wave direction and particle direction is shown in Figure 6.8

- The velocity of a wave depends on the elastic properties and density of a material. If we let k represent the bulk modulus of a material, μ the shear-modulus, and ρ the density, then the P-wave velocity, which we represent by α, is defined by:

$$\alpha = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \tag{6.1}$$

- The speed of a longitudinal wave is defined as below Where v = speed in m.s-1, f = frequency in Hz and λ = wavelength in m

$$v = f.\lambda \tag{6.2}$$

- A modulus is a measure of how easy or difficulty it is to deforms a material. For example, the bulk modulus is a measure of how a material changes volume when pressure is applied and is a characteristic of a material. For example, foam rubber has a lower bulk modulus than steel.

- P-waves are sound waves, it's just that in seismology we are interested in frequencies that are lower than humans' range of hearing (the speed of sound in air is about 0.3 km/sec). The vibration caused by P waves is a volume change, alternating from compression to expansion in the direction that the wave is traveling. P-waves travel through all types of media - solid, liquid, or gas.

- The relation between compressional or P-wave velocity (Vp) and the elastic constants E (Young's modulus), (Poisson's ratio), K (bulk modulus), (rigidity modulus), (Lame's constant) and density is given as follows:

$$V_p = \left\{\frac{(\lambda + 2\mu)}{\rho}\right\}^{\frac{1}{2}} \tag{6.3}$$

- Although Lame's constants are convenient, other elastic constants are also used. From Hooke's law we can obtain the following relations:

$$\frac{\mu(3\lambda + 2\mu)}{(\lambda + \mu)} \tag{6.4}$$

$$\sigma = \frac{\lambda}{2(\lambda + \mu)} \tag{6.5}$$

$$K = \frac{3\lambda + 2\mu}{\ } \tag{6.6}$$

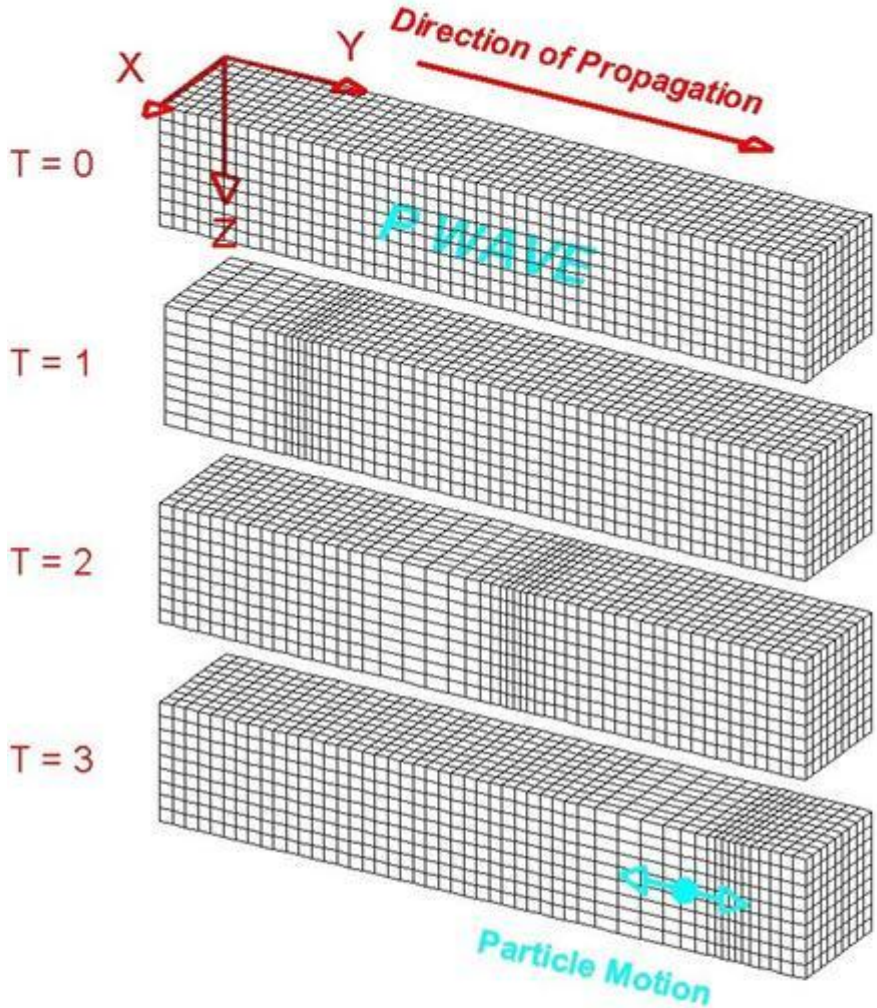

Fig 6.8: Ground is vibrated in the direction that the wave is propagating

- Thus Vp can be expressed as:

$$V_p = \left(\frac{K + \frac{4}{3}\mu}{\rho} \right)^{\frac{1}{2}} \tag{6.7}$$

$$= \left\{ \frac{E}{\rho} \left(1 + \frac{2\sigma^2}{1 - \sigma - 2\sigma^2} \right) \right\}^{\frac{1}{2}} \tag{6.8}$$

$$= \left\{ \frac{E}{\rho} \cdot \frac{1-\sigma}{(1-2\sigma)(1+\sigma)} \right\}^{\frac{1}{2}} \tag{6.9}$$

Topic 6

S-Waves or Torsional Waves

http://web.ics.purdue.edu/~braile/edumod/waves/Swave.htm

- Secondary or S waves, travel slower than P waves. They are also called "shear" waves because they don't change the volume of the material through which they propagate, they shear it. S-waves are transverse waves because they vibrate the ground in transverse or perpendicular direction to the direction that the wave is traveling.

- Even though they are slower than P-waves, the S-waves move quickly. Typical S-wave propagation speeds are on the order of 1 to 8 km/sec. The lower value corresponds to the wave speed in loose, unconsolidated sediment, the higher value is near the base of Earth's mantle.

- S wave direction with particle movement is shown in Figure 6.9

- An important distinguishing characteristic of an S-wave is its inability to propagate through a fluid or a gas because a fluids and gasses cannot transmit a shear stress and S-waves are waves that shear the material.

- In general, earthquakes generate larger shear waves than compressional waves and much of the damage close to an earthquake is the result of strong shaking caused by shear waves.

- The relation between S-wave velocity Vs, the elastic constants and density is given as:

$$Vs = \left(\frac{\mu}{\rho} \right)^{\frac{1}{2}} \tag{6.8}$$

- An alternative expression is

$$Vs = \left\{ \frac{E}{\rho} \cdot \frac{1}{2(1+\sigma)} \right\}^{\frac{1}{2}} \tag{6.9}$$

- **The velocity ratio V_P/V_S** - Either expression tells that the P-wave velocity is always greater than the S-wave velocity. The ratio is always greater than 1; first, because K and μ are always positive, second, because σ cannot be greater than 1/2 in an ideal solid. For most consolidated rock Vp/Vs ranges between 1.5 and 2.0.

$$\frac{Vp}{Vs} = \left(\frac{K}{\mu} + \frac{4}{3}\right)^{\frac{1}{2}} = \left(\frac{1-\sigma}{\frac{1}{2}-\sigma}\right)^{\frac{1}{2}} \tag{6.10}$$

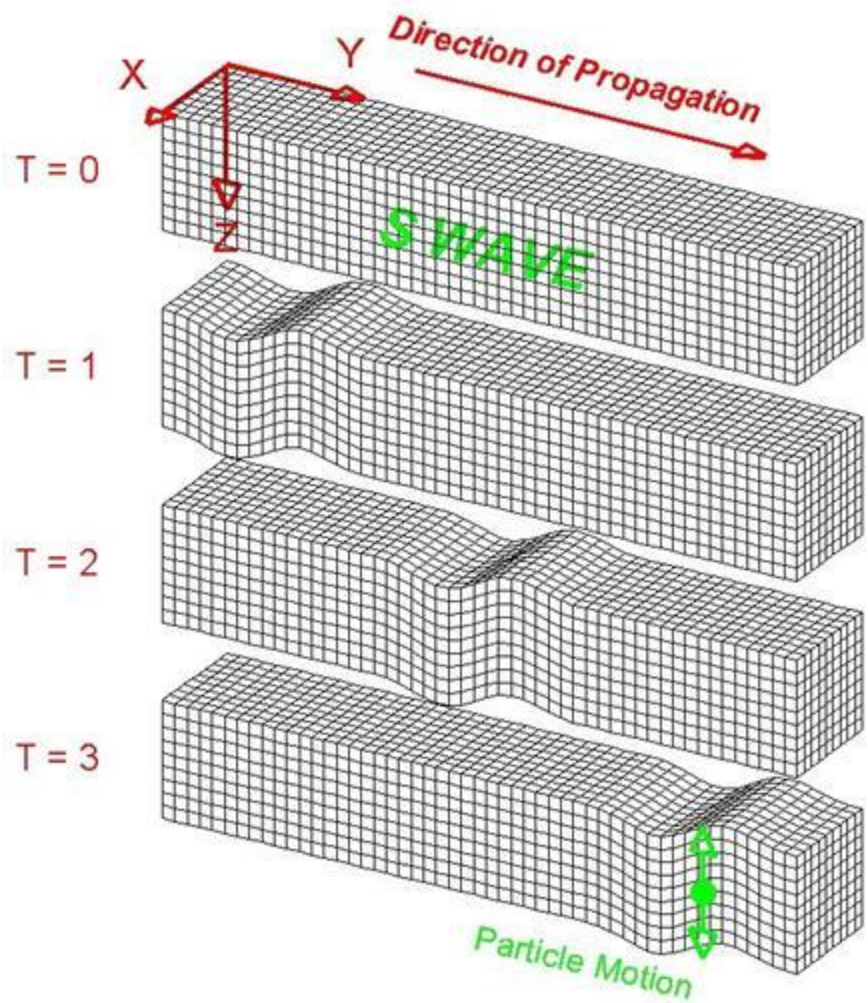

Fig 6.9: As a transverse wave passes the ground perpendicular to the direction that the wave is propagating

Topic 7

Love Waves

http://web.ics.purdue.edu/~braile/edumod/waves/Lwave.htm

- Love waves are transverse waves that vibrate the ground in the horizontal direction perpendicular to the direction that the waves are traveling (Fig 6.10). They are formed by the interaction of S waves with Earth's surface and shallow structure and are dispersive waves.

- The speed at which a dispersive wave travels depends on the wave's period. In general, earthquakes generate Love waves over a range of periods from 1000 to a fraction of a second, and each period travels at a different velocity but the typical range of velocities is between 2 and 6 km/second.

- Love waves are transverse and restricted to horizontal movement they are recorded only on seismometers that measure the horizontal ground motion.

Fig 6.10: Love Waves

- Another important characteristic of Love waves is that the amplitude of ground vibration caused by a Love wave decreases with depth - they're surface waves. Like the velocity the rate of amplitude decrease with depth also depends on the period.

- The Love wave velocity (V_L) is equal to that of shear waves in the upper layer (V_S1) for very short wave lengths, and to the velocity of shear waves in the lower layer (V_S2) for very long wave-lengths, i.e. Velocity $V_S1 < V_L < V_S2$.

- The effects of Love waves are result of the horizontal shaking, which produces damage to the foundation of structures. Love waves do not propagate through water, it affects surface water only. It causes the sides of the lakes and ocean bays to move backwards and forwards, pushing the water sideways like the sides of a vibrating tank.

Topic 8

Rayleigh Waves

http://web.ics.purdue.edu/~braile/edumod/waves/Rwave.htm

- Rayleigh waves are the slowest of all the seismic wave types and in some ways the most complicated. Like Love waves they are dispersive so the particular speed at which they travel depends on the wave period and the near-surface geologic structure, and they also decrease in amplitude with depth. Typical speeds for Rayleigh waves are on the order of 1 to 5 km/s.

- Rayleigh waves are similar to water waves in the ocean (before they "break" at the surf line). As a Rayleigh wave passes, a particle moves in an elliptical trajectory that is counterclockwise (if the wave is traveling to your right) (Fig.6.11). The amplitude of Rayleigh-wave shaking decreases with depth.

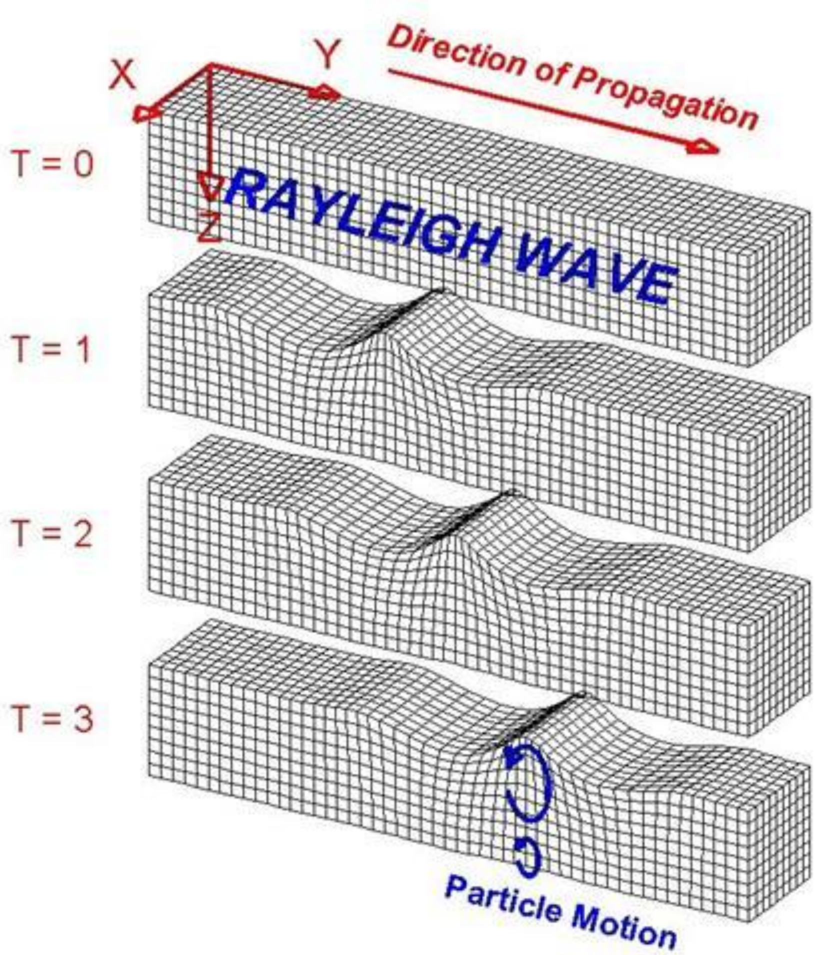

Fig 6.11: Rayleigh Waves

- The speed of Rayleigh wave (V_R) is about 0.9 times of shear wave (V_S) in the same medium; the relation is given as $V_R < 0.92\ V_S$. For short wave-lengths, V_{Rg} corresponds to 9/10 V_S of the material comprising the surface layer. For very long wave-lengths, the V_{RL} corresponds to 9/10 V_S of the substratum material since effect of the surface layer is negligible when most of the waves travel in the zone below it.

- As seen from the above equations, S-wave is slower than P-wave, and Rayleigh wave is slower than Love wave. Thus as the waves radiate outwards from an earthquake source, the different types of waves separate out from one another in a predictable pattern.

Note: ***Further reading on Theory of wave propagation- mathematical aspects of wave propagation in unbound media/semi infinite media/layer media can be obtained from standard text Book***

Topic 9

Wave Character

- The main seismic wave types are Compressional (P), Shear (S), Rayleigh (R) and Love (L) waves. P and S waves are often called body waves because they propagate outward in all directions from a source (such as an earthquake) and travel through the interior of the Earth. The P and S waves are shown propagating horizontally, parallel to the Earth's surface. Love and Rayleigh waves are surface waves and propagate approximately parallel to the Earth's surface.

- Although surface wave motion penetrates to significant depth in the Earth, these types of waves do not propagate directly through the Earth's interior. Descriptions of wave characteristics and particle motions for the four wave types are given in Table 6.1.

Table 6.1: Types of Waves, Particle motion, velocity and other characteristics

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 ray path); and therefore, perpendicular to the wavefront	V_P ~ 5-7km/s in typical Earth's crust;>~8km/s in earth's mantle and core; 1.5 km/s in water; 0.3 km/s in air	P motion wave 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, particle motion is in vertical or horizontal planes.	VS ~ 3 – 4 km/s in typical Earth's crust;	S-waves do not travel through fluids; 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.	VL ~ 2.0 - 4.4 km/s in the Earth depending on frequency,faster than the Rayleigh waves.	Decrease in amplitude with depth. Dispersive, velocity is dependent on frequency, low frequencies - propagating at higher velocity. Lower frequencies penetrating to greater depth.
R, Rayleigh, Surface waves, Long waves, Ground roll	Motion is both in the direction of propagation and perpendicular	VR ~ 2.0 - 4.2 km/s in the Earth waves.	Dispersive, amplitudes decrease with depth, Appearance likewater waves. Depth of penetration dependent on frequency, lower frequencies penetrating to greater depth

Topic 10

Seismic Waves in the Earth

- Seismic body waves (P and S waves) travel through the interior of the Earth. Because confining pressure increases with depth in the Earth, the velocity of seismic waves generally increases with depth causing raypaths of body waves to be curved (Fig 6.12).

- Because the interior structure of the Earth is complex and because there are four types of seismic waves (including dispersive surface waves), seismograms, which record ground motion from seismic waves propagating outward from an earthquake (or other) source, are often complicated and have long (several minutes or more) duration.

- An effective computer simulation that illustrates wave propagation in the Earth is the program Seismic Waves. Using this program, which shows waves propagating through the interior of the Earth in speeded-up-real-time, one can view the spreading out of wavefronts, P, S, and surface waves traveling at different velocities, wave reflection and P-to-S and S-to-P wave conversion. The program also displays actual seismograms that contain arrivals for these wave types and phases.

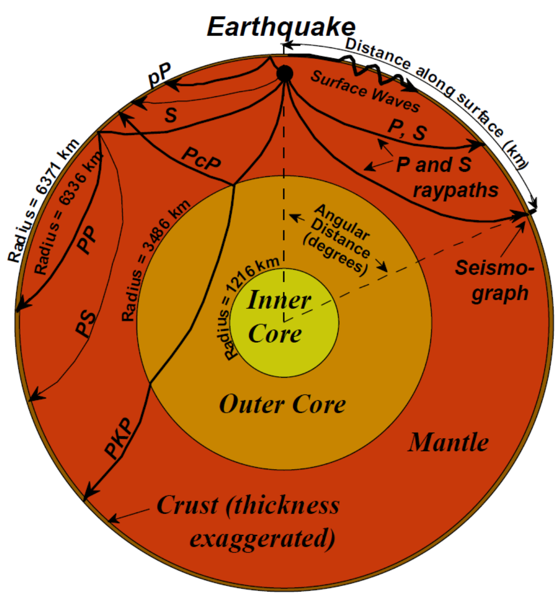

Fig 6.12: Cross section through the Earth showing important layers and representative raypaths of seismic body waves

- Direct P and S raypaths (phases), including a reflection (PP and pP), converted phase (PS), and a phase that travels through both the mantle and the core (PKP). P raypaths are shown by heavy lines. S raypaths are indicated by light lines. Surface wave propagation (Rayleigh waves and Love waves) is schematically represented by the heavy wiggly line. Surface waves propagate away from the epicenter, primarily near the surface and the amplitudes of surface wave particle motion decrease with depth.

Topic 11

Earthquake Record

- The visibility of different body wave phases depends upon their amplitude, polarization, and frequency content. Modern seismographs record all three components of ground motion over wide frequency range.

- The horizontal records are normally rotated into the radial component parallel to the azimuth to the source and the transverse component perpendicular to this azimuth.

- The Figure 6.13 shows plots the vertical, radial and transverse component records for the 1994 Northridge earthquake in southern California, recorded at station OBN in Russia, 88.5 degrees away, and identifies some of the major body wave phases. Note that the P-waves are most visible on the vertical component, with little P energy arriving on the transverse component. The time of the first discernible motion of a seismic phase is called the arrival time, and the process of making this measurement is termed picking the arrival.

- By measuring the arrival times of seismic phases at a variety of source-receiver ranges, seismologists are able to construct travel time curve for the major phases and use these to infer Earth's average radial velocity structure.

Topic 12

Chile earthquake recorded at Nana, Peru

- Seismograms recorded by a 3-component seismograph at Nana, Peru for an earthquake located near the coast of central Chile on September 3, 1998. The three seismograms record motion in the horizontal (east-west and north-south) and the vertical (Z) directions. P, S, Rayleigh and Love waves are identified on the record.

- The S wave arrives significantly after the P-wave because S-wave velocity in rocks is lower than P wave velocity. Additional arrivals between the P and the S wave are P and S waves that have traveled more complicated paths from the earthquake location to the seismograph.

- The surface waves arrive after the S waves because surface wave velocities in rocks are lower than the shear wave velocity. The surface waves extend over a long time interval because surface wave propagation is dispersive (the velocity of propagation is dependent on the frequency of the wave). This dispersive character can easily be seen in the Rayleigh wave on the vertical component seismogram in that the earliest Rayleigh wave energy has a longer period than the later arriving waves.

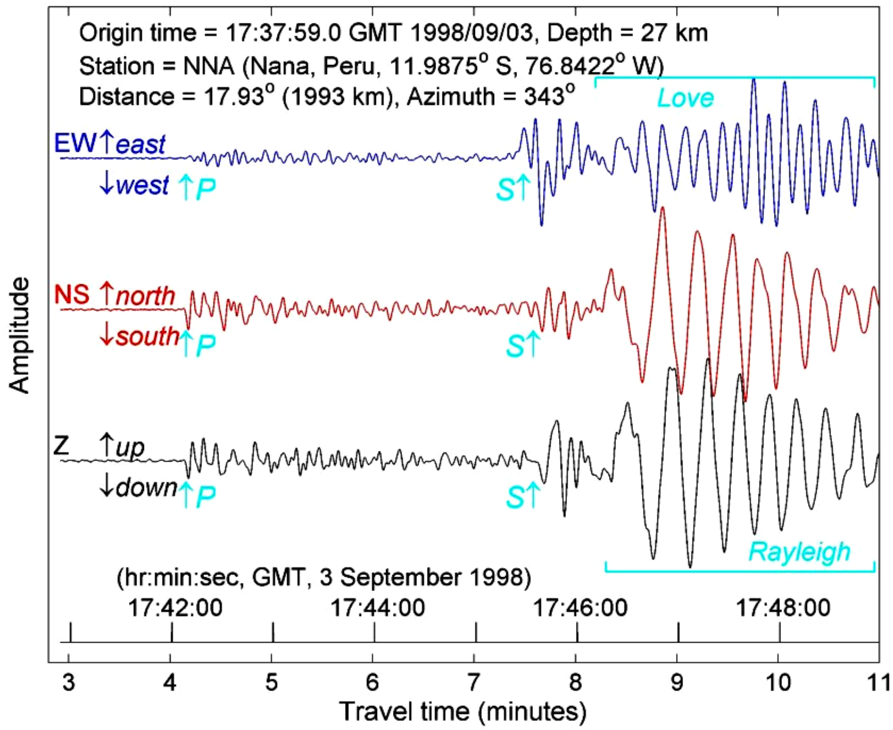

Fig 6.13 Earthquake Magnitude 6.5, near coast of central Chile, 29.2934°S, 71.5471°W

Topic 13

Earth cross section and approximate ray path for direct P- and S-waves

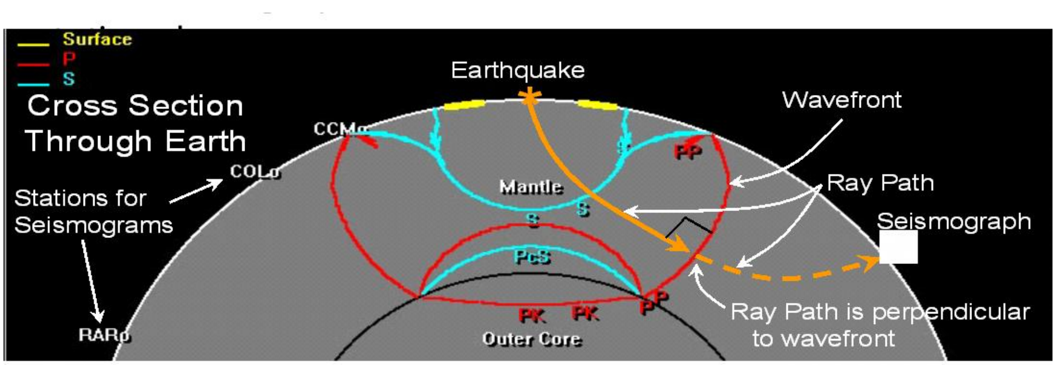

Fig 6.14: Partial screen views of the Seismic Waves computer program.

- Fig 6.14: shows seismic wave fronts traveling through the Earth's interior five minutes after the earthquake.
- Three and four letter labels on the Earth's surface show relative locations of seismograph stations that recorded seismic waves corresponding to the wave front representations in the Seismic Waves program.

- Here the main layers are the mantle, the fluid outer core, and the solid inner core. P- and S-wave legs in the mantle and core are labeled as follows:
    1. P : P-wave in the mantle
    2. K : P-wave in the outer core
    3. I : P-wave in the inner core
    4. S : S-wave in the mantle
    5. J : S-wave in the inner core
    6. c : reflection of the core-mantle boundary (CMB)
    7. i : reflection of the inner core boundary (ICB)

- For P- and S-waves in the whole earth, the above abbreviations apply and stand for successive segments of the ray path from source to receiver. Some examples of these ray paths and their names are shown in the Figure 6.15.

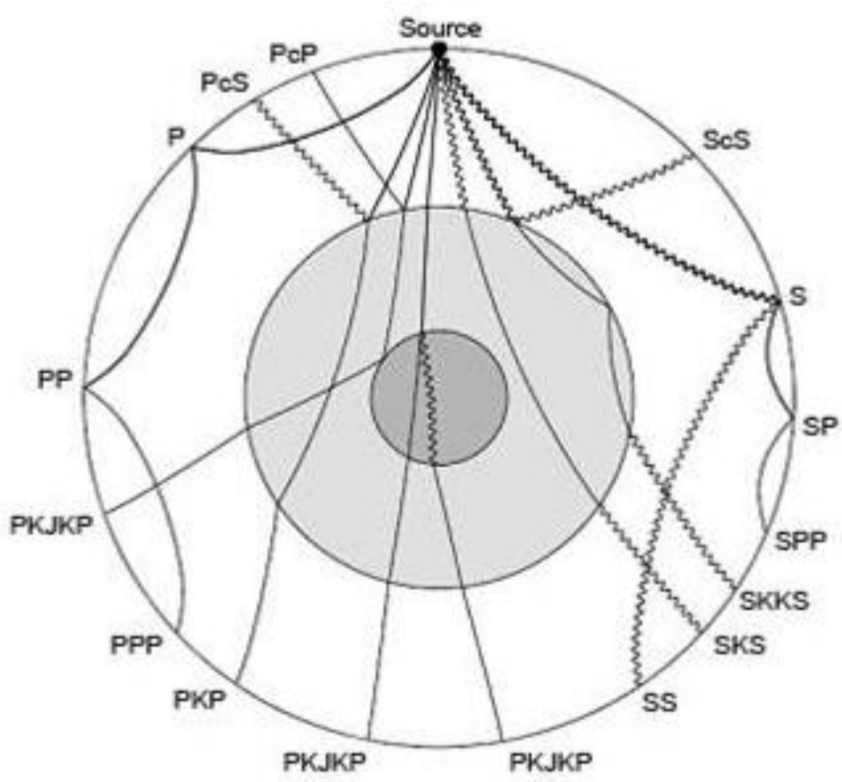

Fig 6.15: Global seismic ray paths and phase names, computed for the PREM velocity model

- Notice that surface multiple phases are denoted by PP, PPP, SS, SP, and so on. For deep focus earthquakes, the up going branch in surface reactions is denoted by a lowercase p or s.

- These are termed depth phases, and the time separation between a direct arrival and a depth phase is one of the best ways to constrain the depth of distant earthquakes. P-to-S conversions can also occur at the CMB; this provides for phases such as PcS and SKS.

- Ray paths for the core phase PKP are complicated by the Earth's spherical geometry, leading to several triplications in the travel time curve for this phase. Often the inner-core P phase PKIKP is labeled as the df branch of PKP. Because of the sharp drop in P velocity at the CMB, PKP does not turn in the outer third of the outer core. However, S-to-P converted phases, such as SKS and SKKS, can be used to sample this region.

Topic 14

PREM for Preliminary Earth Reference Model

- The main regions of Earth and important boundaries are labeled. This model was developed in the early 1980's and is called PREM for Preliminary Earth Reference Model. The diagram is a plot of the P- and S-wave velocities and the density as a function of depth into Earth. The top of the Earth is located at 0 km depth; the center of the planet is at 6371 km.

- Figure 6.16 shows Velocity and density variations within Earth based on seismic observations

- First note that in several large regions such as in the lower mantle, the outer core, and inner core, the velocity smoothly increases with depth. The increase is a result of the effects of pressure on the seismic wave speed. Although temperature also increases with depth, the pressure increase resulting from the weight of the rocks above has a greater impact and the speed increases smoothly in these regions of uniform composition.

- The shallow part of the mantle is different; it contains several important well-established and relatively abrupt velocity changes. In fact, we often divide the mantle into two regions, upper and lower, based on the level of velocity heterogeneity.

- The region from near 400 to 1000 km depth is called the transition zone and strongly affects body waves that "turn" at this depth and arrive about 20°-30° distant from a shallow earthquake. In this depth range the minerals that make up

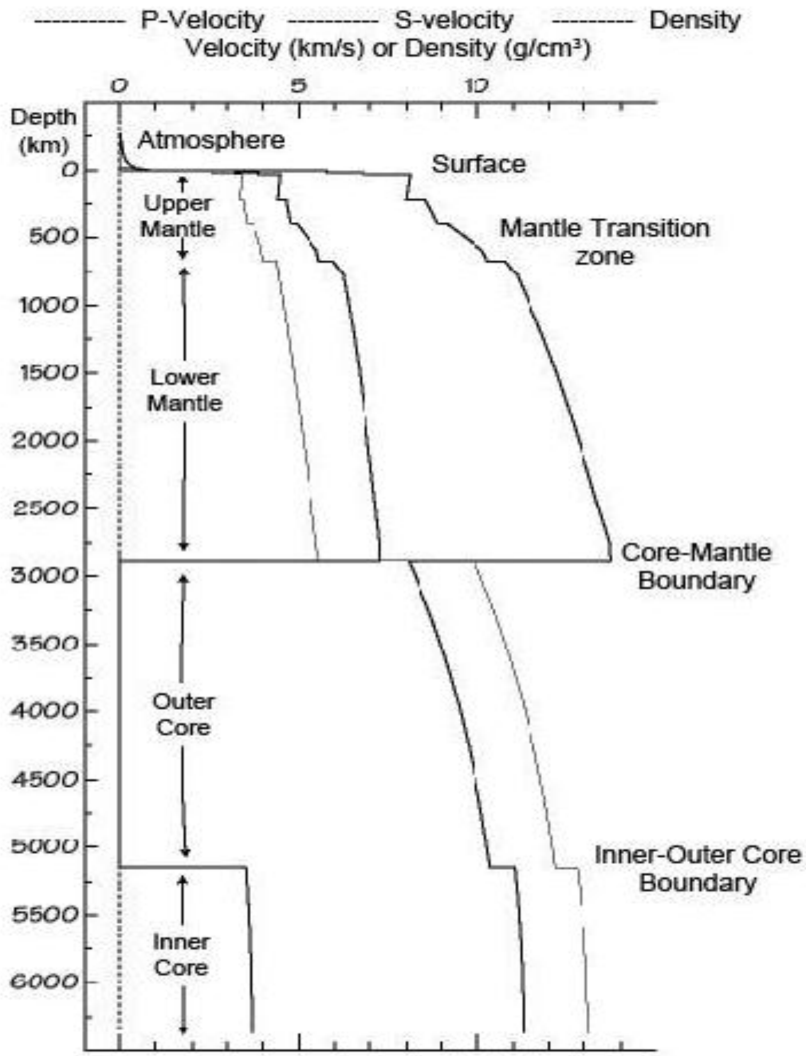

Fig 6.16: Velocity and density variations within Earth based on seismic observations

the mantle silicate rocks are transformed by the increasing pressure. The atoms in these rocks rearrange themselves into compact structures that are stable at the high pressures and the result of the rearrangement is an increase in density and elastic moduli, producing an overall increase in wave speed.

- The PREM model is a useful reference for understanding the main features of Earth. More recent efforts have focused on estimating the lateral variations in wave speed within the shells that make up the reference model. The basic idea is to use observed delayed (or early) arrival times (delayed with respect to the reference model) to locate regions of relatively fast and relatively slow seismic wave speed.

- In the two decades tomography has been applied to Earth studies on many scales, from looking at small regions of Earth's crust that may contain petroleum, to imaging the entire planet. On a global scale, we might expect that the shallow parts of the mantle would correlate with the major structural features we can observe at the surface - the plate boundaries.

- Figures 6.17 and 6.18 shows map of the variations in seismic shear-wave speed with respect to the value in PREM at 100 km and 2880 km depth

- In regions where material is rising from the mantle, it should be warmer, and the velocity should be lower, in regions that are old and cold, such as beneath many of the old parts of continents, we would expect to see faster regions (assuming that temperature is the only difference). The actual variations are influenced by both temperature and composition variations, but they agree well with the ideas of plate tectonics, particularly at the divergent boundaries or oceanic spreading ridges.

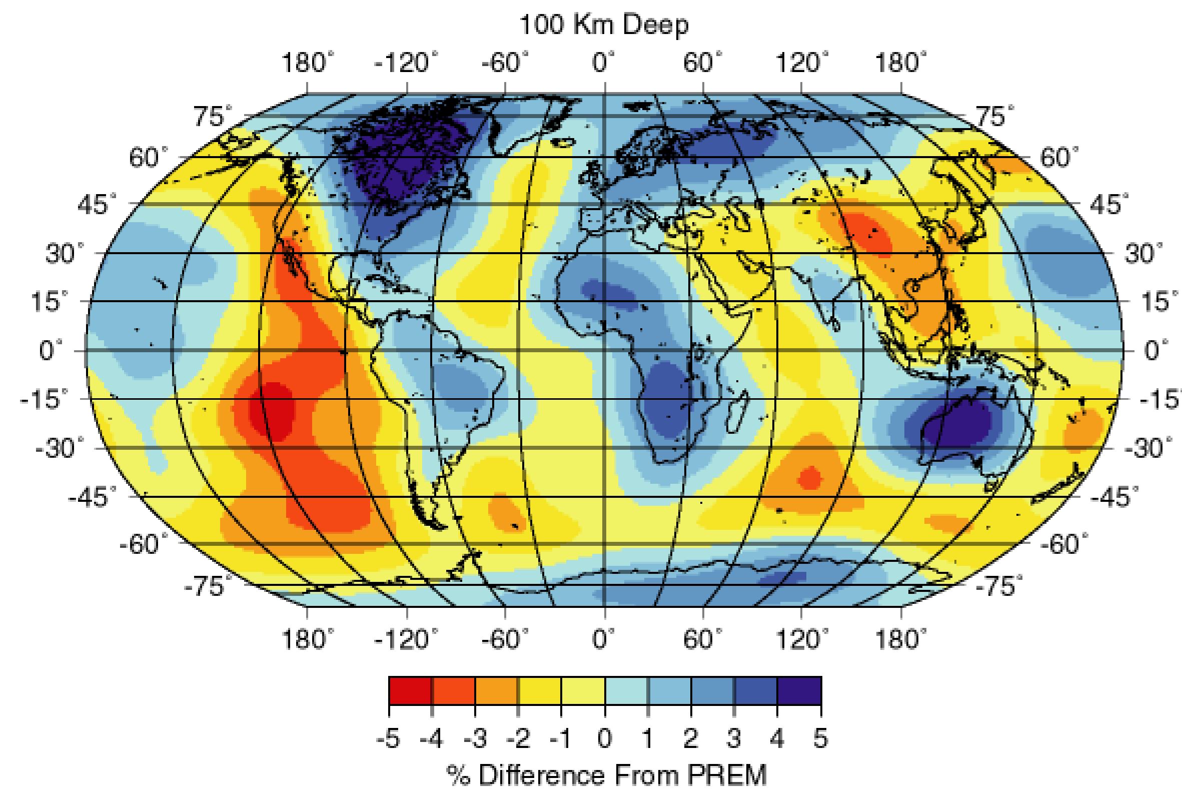

Fig 6.17: Map of the variations in seismic shear-wave speed with respect to the value in PREM at 100 km depth

- The warm colors (red, orange, and yellow) show regions with slower than normal speeds; the darker regions are faster than normal. Note the correlation with plate boundaries and surface heat flow.

- The velocities deeper in the Earth have also been imaged. Figure 6.18 shows the variations at 2,880 km depth, in the mantle just above the core-mantle boundary. The color scale is the same but note how the lower-mantle velocity variations are more subdued than those in the more heterogeneous upper mantle. Also, note that the correlation with surface tectonics is gone, as you would expect for a complex convective system such as Earth's mantle.

- The warm colors (red, orange, and yellow) show regions with slower than normal speeds; the darker regions are faster than normal. Note the correlation with plate boundaries and surface heat flow. These variations are actually quite small, on the order of a few percent, so the basic idea of Earth being a spherically stratified planet is well founded. In the crust, the variations are larger and can reach tens of percent. The crust is the material extracted from the mantle over the last 4.5 billion years.

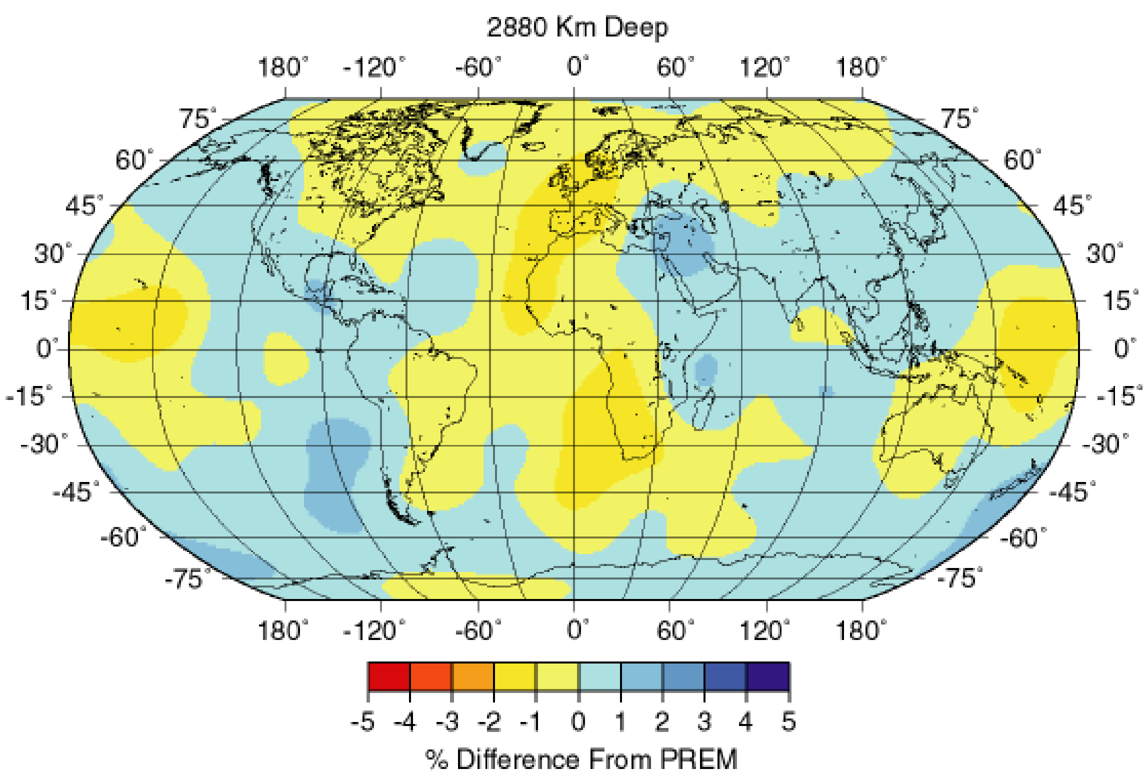

Fig 6.18: Map of the variations in seismic shear-wave speed with respect to the value in PREM at 2,880 km depth, just above the core mantle boundary

Topic 15

Shadow Zones

- A shadow zone is an area in which an S-Wave (secondary seismic wave) is not detected due to it not being able to pass through the outer core of the earth due to it being liquid. When an earthquake occurs, seismographs near the epicenter, out to about 90 ° distances, are able to record both Primary and Secondary waves, but those at a greater distance no longer detect the S-wave. This is because shear waves cannot pass through liquids. This was how Oldham proved that the Earth had a liquid outer core. The Moon has been proven by seismic testing to have a solid core, because it conducts shear waves.

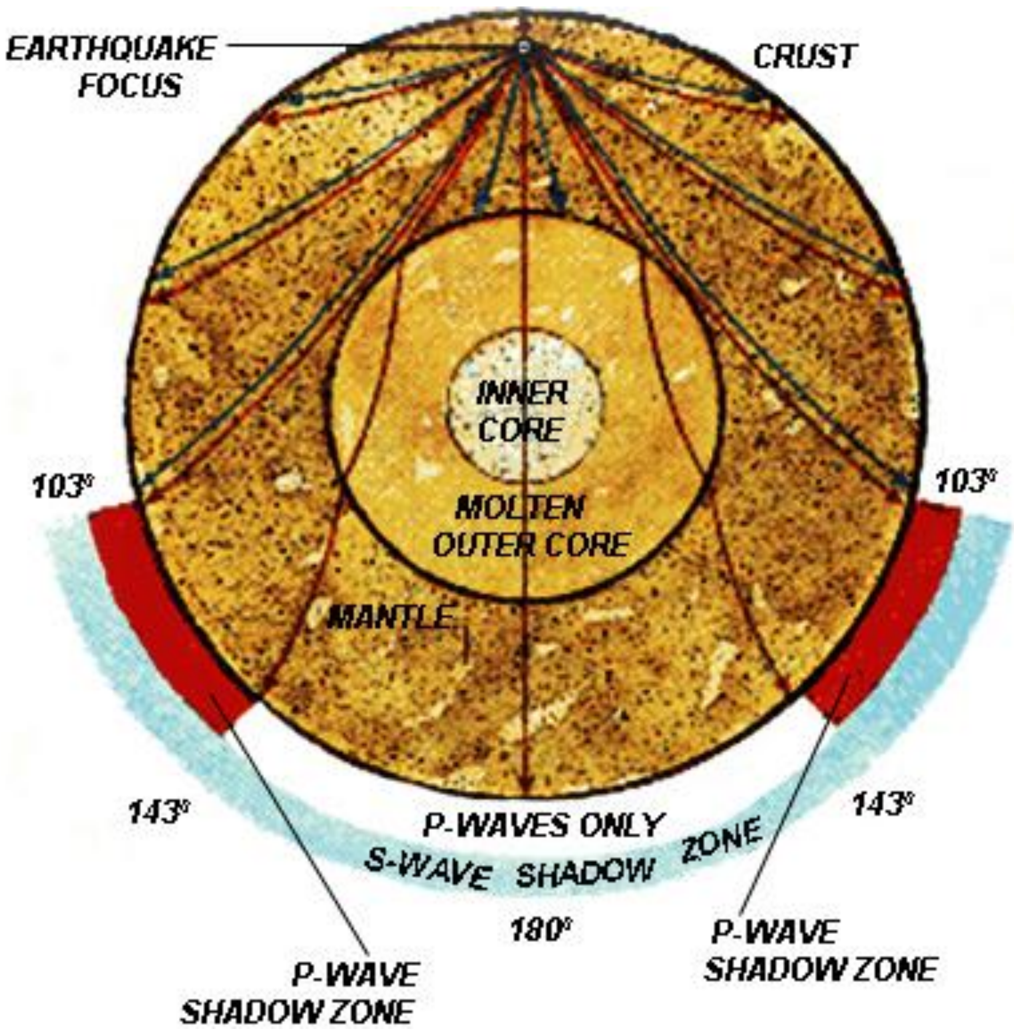

Fig 6.19: A cross-section of the earth, with earthquake wave paths defined and their shadow-zones highlighted

- Figure 6.19 shows shadow zones for different types of waves

- The S-wave shadow zone occurs between 105 degrees and 180 degrees latitude (with the point of origin as zero and due south of origin as 180 degrees).

- P-Waves (primary seismic waves) also have a shadow zone as they are refracted downwards on entering the Earth's core as the liquid outer core lowers their speed. This shadow zone occurs between 104 and 140 degrees.

End of Lecture 6 in Theory of wave propagation; Seismic waves, body and surface waves.