THE INTERIOR OF THE EARTH

Introduction:

Nebular hypothesis and the origin of solar system, which indicates that there is a differentiation (layering) in the earth.

* Sources of our knowledge about the COMPOSITION and INTERNAL STRUCTURE OF THE EARTH come from:

1. Direct methods

    1- Drilling.

    * Drilling less than 13 km on the continent.

      Drilling at deep sea on the ocean (sampling).

2. Indirect methods:

A - **Geophysics**:

a- seismic wave: are waves of force that travel through the earth or other elastic body, for example as the result of an earthquake explosion or some other process that imparts forces to the body.

b- Gravity: Measurements of the gravitational field at a series of different locations over an area of interest. The objective in exploration work is to associate variations with differences in the distribution of densities and hence rock types.

c- Magnetic anomaly: is a local variation in the Earth's magnetic field resulting from variations in the magnetic susceptibility (القابلية المغناطيسية) of the rocks. Mapping of variation over an area is valuable in detecting structures obscured by overlying material.

d-Electrical conductivity or (resistivity): is a measure of a material's ability to conduct (or resist) an electric current. When an electrical potential difference is placed across a conductor, its movable charges flow, giving rise to an electric current. The conductivity (**σ**) is defined as the ratio of the current density (**J**) to the electric field strength (E):

$$\sigma = J/E$$

B- Geochemistry

C- Lithosphere flexure.

D- Lab experiments.

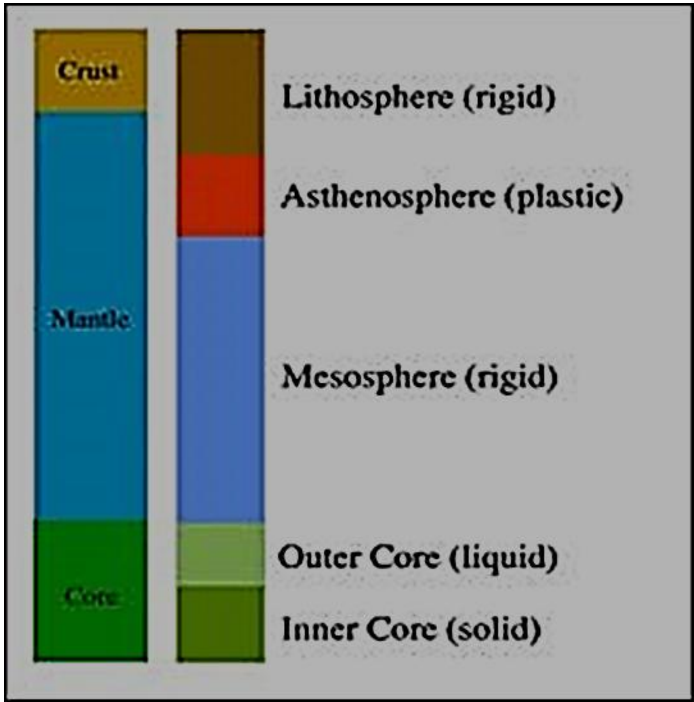
E- Meteorites (condrites and acondrites)

STRUCTURE OF THE EARTH:

Earth structure can be studied based on:

1- Seismic wave velocities: based on this criterion Earth divided into: crust, mantle, core (outer core and inner core).

2- Studying rock rheology (how rocks respond to stresses): based on this criterion, Earth divided into: lithosphere, asthenosphere, mesosphere…..



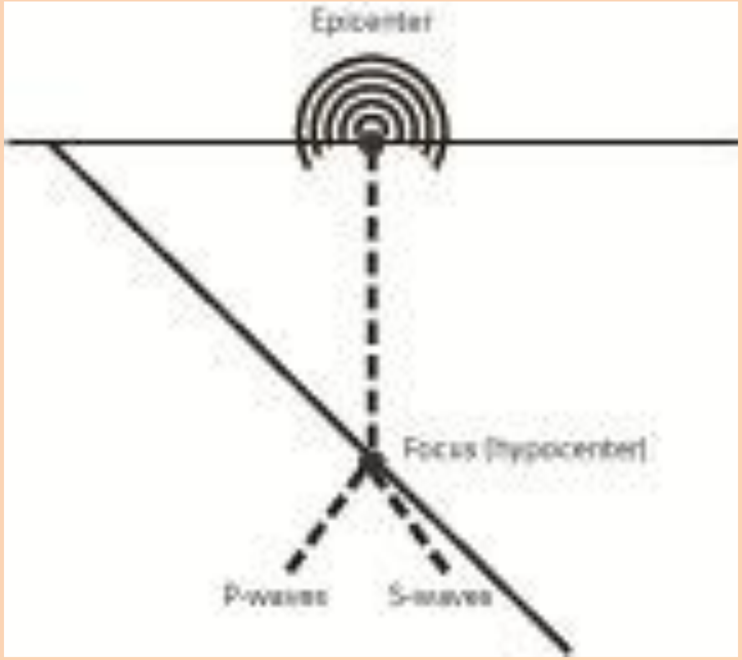
1. EARTH STRUCTURE BASED ON SEISMIC WAVES

* Here, I will introduce some knowledge about the seismic waves:

1. Earth seismology

Seismic velocity depends on:

1. Depth
2. P. and T.
3. Mineralogy
4. Chemical composition
5. Partial melting



2. Body waves (Primary and Secondary waves) and **Surface waves**

$V_p = ((K+4/3\mu)/\rho)^{1/2}$

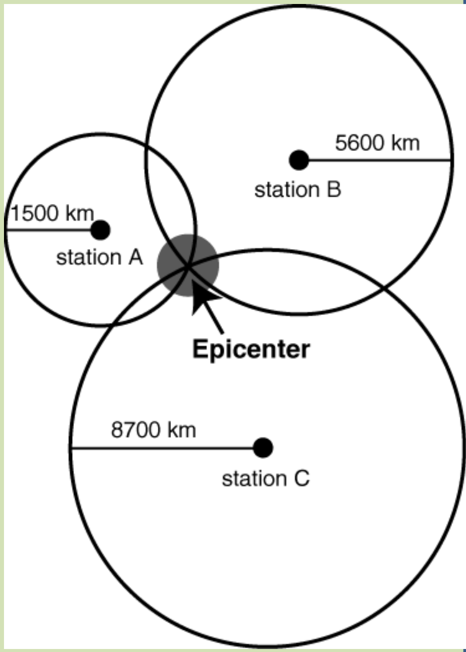
$V_s = (\mu/\rho)^{1/2}$

$V_p = 1.73\ V_s$

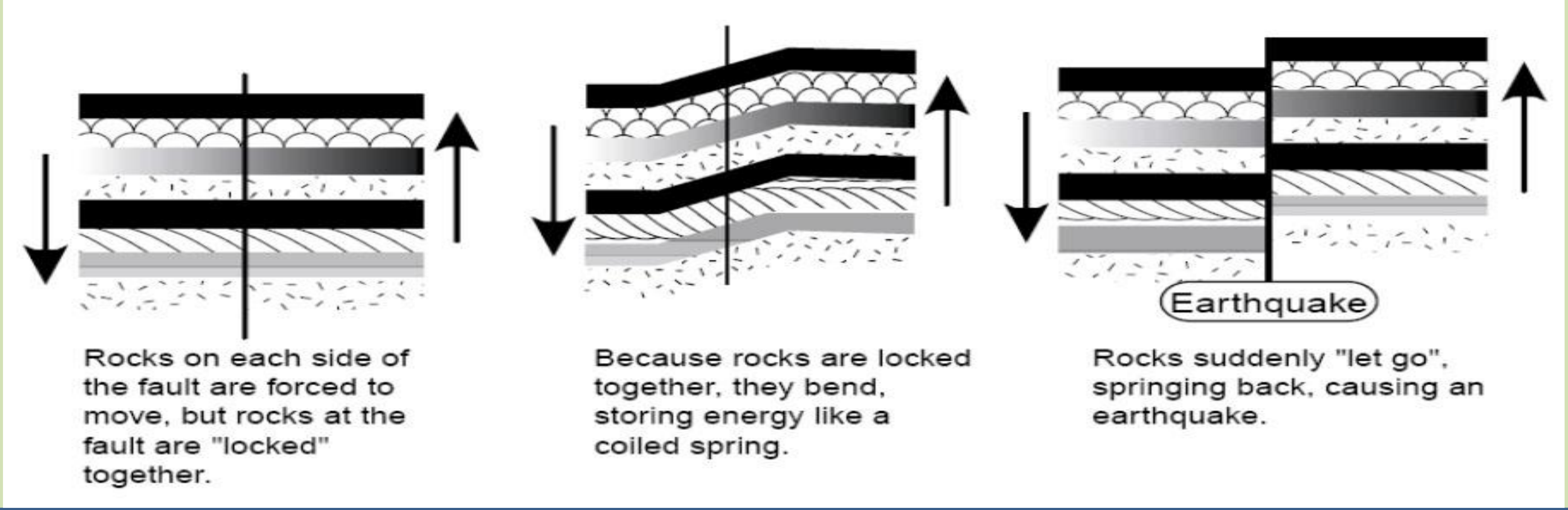
Surface waves= $0.9\ V_s$

μ= ranges from (0)for fluids and (0.5) for solids

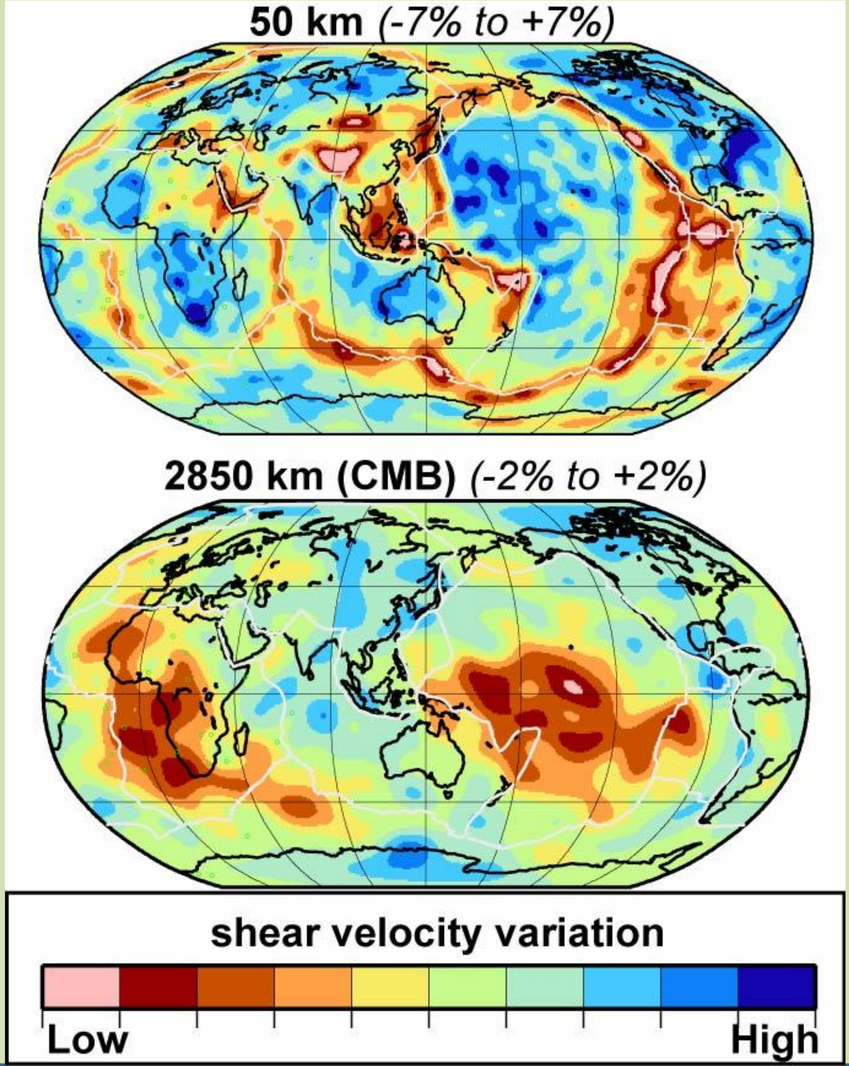
3. Earthquake location determines by (Ts-Tp) triangulation.



4. Mechanism of earthquake : Elastic rebound theory.

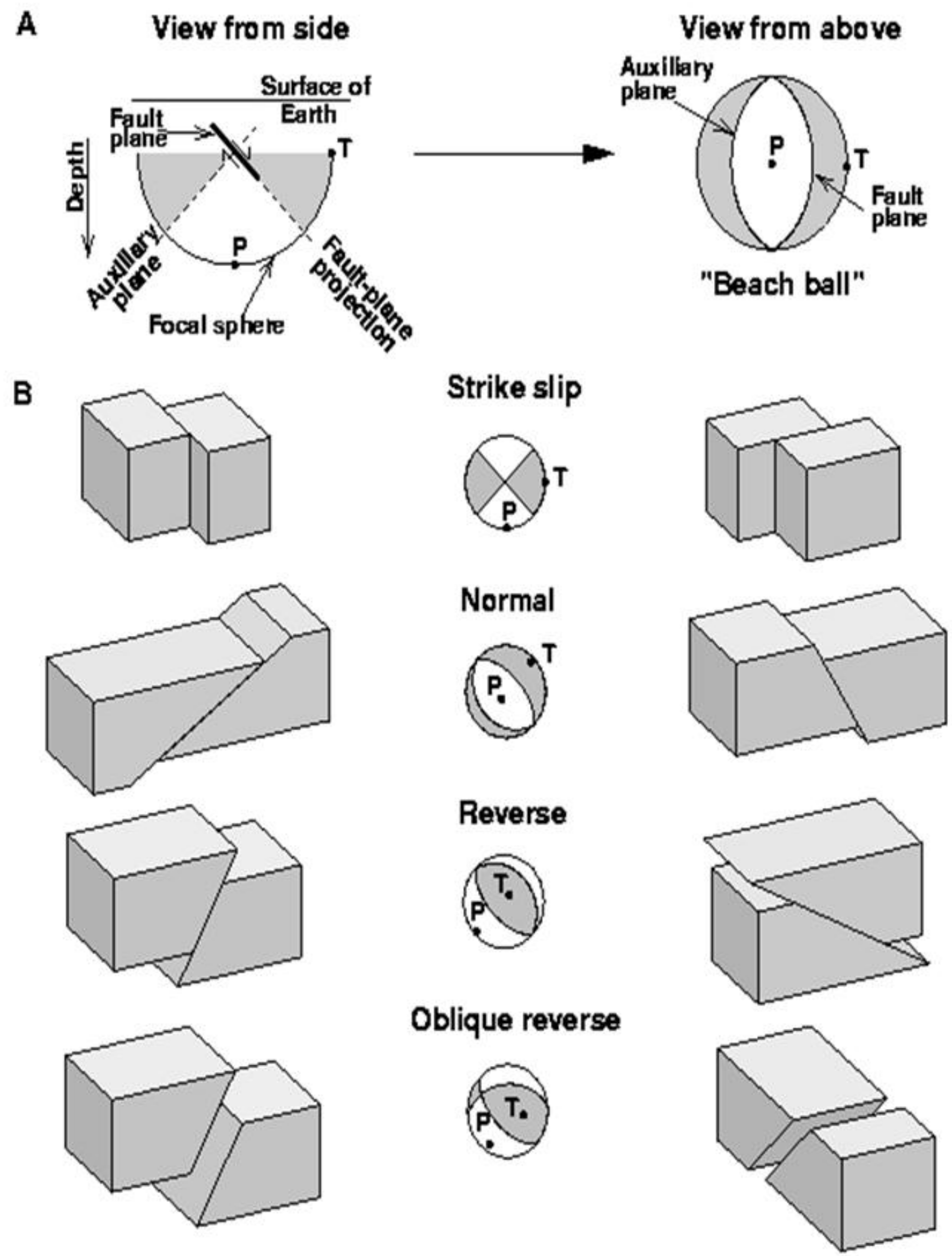


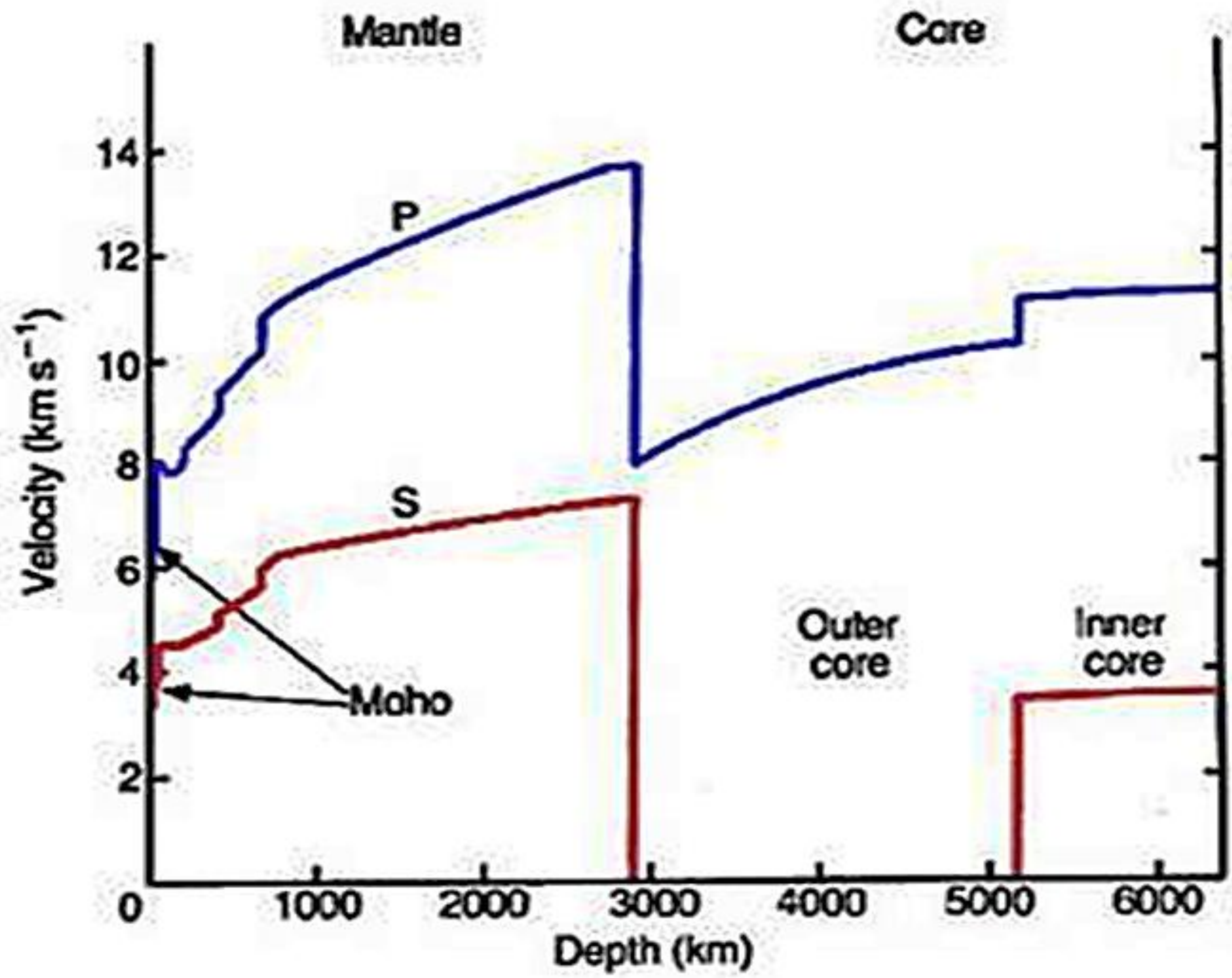
5. Seismic Tomography: is the derivation of 3-D velocity structure of the earth:



6. Focal mechanism: solution of earthquakes

Schematic diagram of a focal mechanism

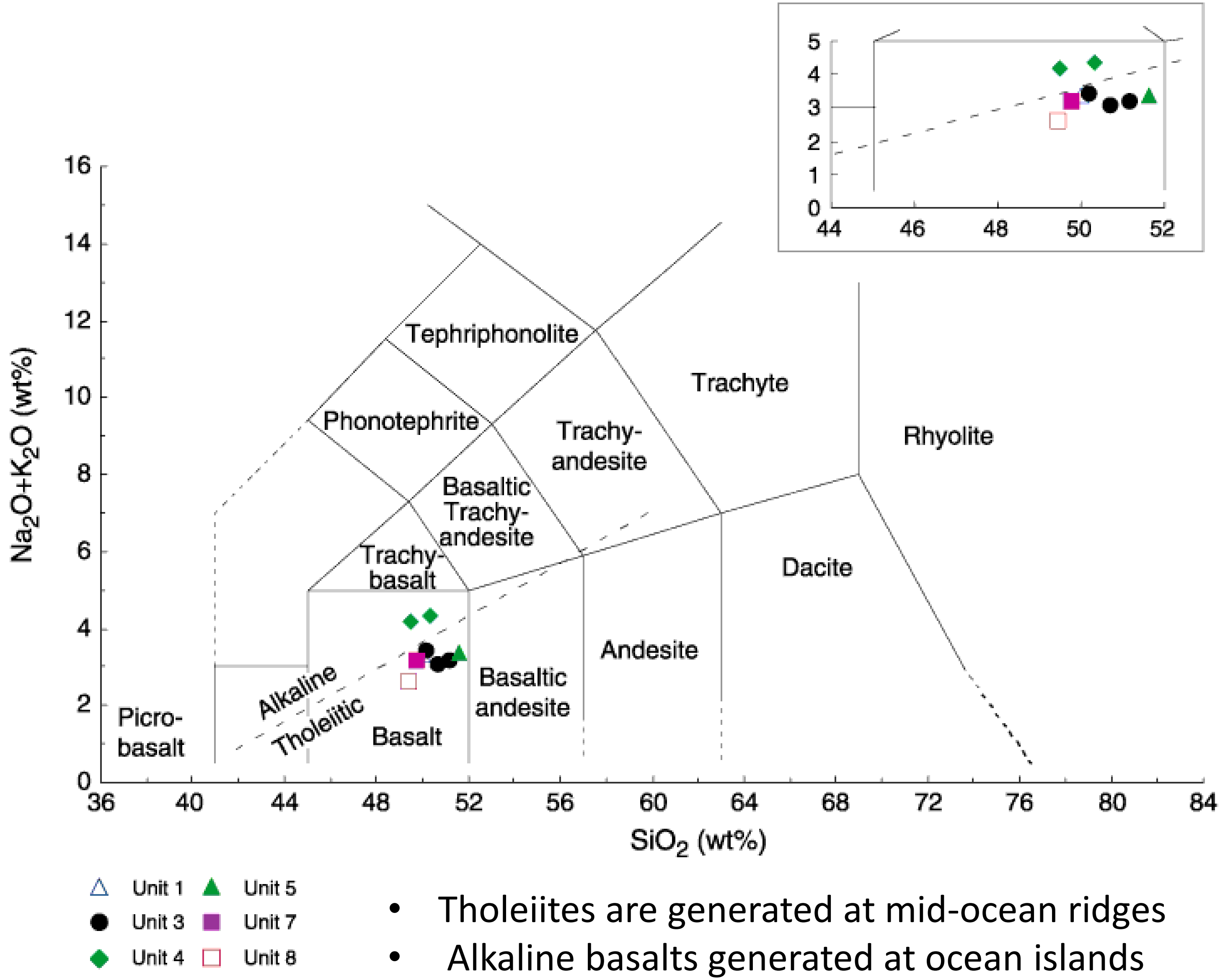



Mantle
Core
P
S
Moho
Outer core
Inner core
Velocity (km s⁻¹)
0
2
4
6
8
10
12
14
1000
2000
3000
4000
5000
6000
Depth (km)

1-Crust: It is of two types; **Continental and Oceanic**

a. Continental crust: Varies in thickness from 20 (under rift areas) to 80 km (under young mountain belts), average thickness = 40 km. **Granodioritic** in composition.

b. Oceanic crust which range in thickness from 6-10 km, average= 7 km). **Basaltic** in composition. Though almost everywhere less than 10 km thick, the oceanic crust plays a crucial role in plate tectonics. Oceanic crust is produced wherever hot mantle material comes into contact with the surface of the solid earth. In this way the oceanic crust reflects much about the composition and motion of the underlying mantle.



- Tholeiites are generated at mid-ocean ridges
- Alkaline basalts generated at ocean islands

The oceanic crust, excluding the overlying sediments, is <u>uniformly</u> composed of rocks having a <u>basaltic composition</u>.

It is however, found by worldwide seismic refraction experiments to consist of three layers of increasing velocity downwards.

<u>Layer 1</u> has P-wave velocities between 1.6 and 2.5 km/s.

<u>Layer 2</u> between 3.4 and 6.2 km/s; highly magnetized and believed that it cause the magnetic anomalies in the oceanic crust.

<u>Layer 3</u> between 6.4 and 7.0 km/s. These differences reflect the differing origins of each layer, and their mechanical states.

Layer 1 is on an average 0.4 km thick. It consists of unconsolidated or semiconsolidated sediments, usually thin or even not present near the mid-ocean ridges but **thickens farther away from the ridge**. Near the continental margins sediment is Terrigenous (meaning derived from the land) unlike deep sea sediments which are made of tiny shells of marine organisms, usually calcareous and siliceous oozes, or it can be made of volcanic ash and Terrigenous sediments transported by turbidity currents.

Layer 2 could be divided into three parts: layer 2A and layer 2B composed of 0.5 km thick uppermost volcanic layer of glassy to finely crystalline basalt usually in the form of pillow basalt, and layer 2C about 1.5 km thick composed of diabase dikes.

Layer 3 is formed by slow cooling of magma beneath the surface and consists of coarse grained gabbros and cumulate ultramafic rocks. It constitutes over two-thirds of oceanic crust volume with almost 5 km thickness.

*** The underlying upper mantle has velocities between 7.4 and 8.6 km/s. and in avg.=8.1 km/s.**

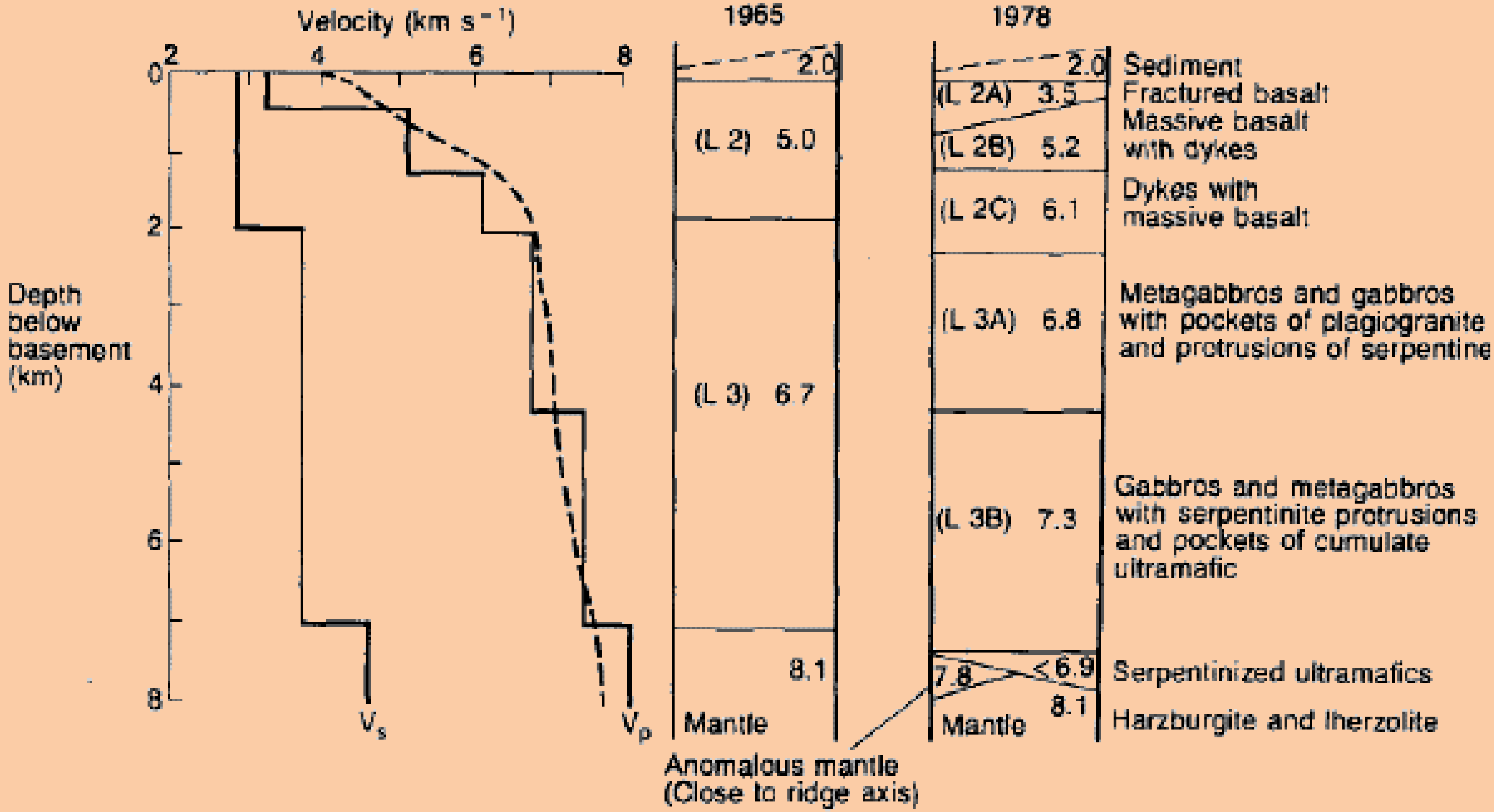
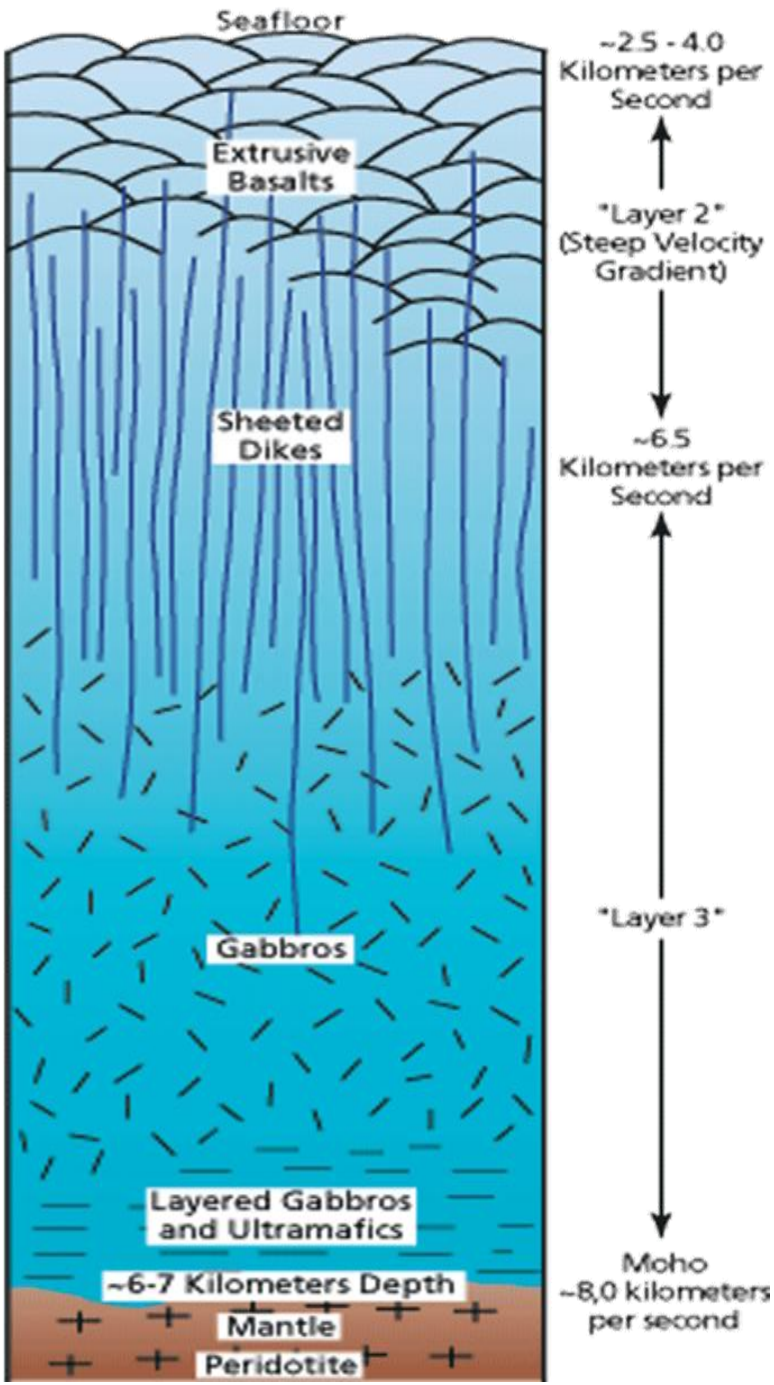
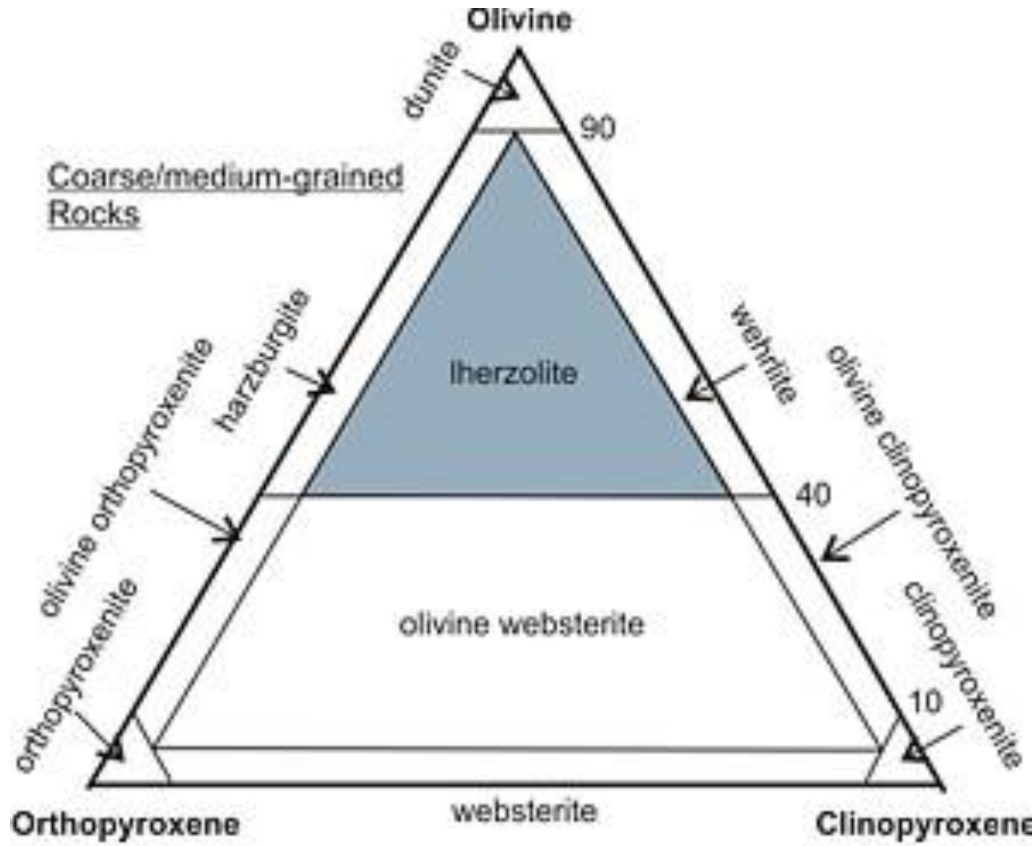


Fig. Layering of oceanic crust, numbers indicates to velocities in km/s.



Seafloor
~2.5 - 4.0 Kilometers per Second
Extrusive Basalts
"Layer 2" (Steep Velocity Gradient)
Sheeted Dikes
~6.5 Kilometers per Second
"Layer 3"
Gabbros
Layered Gabbros and Ultramafics
Moho ~8,0 kilometers per second
~6-7 Kilometers Depth
Mantle
Peridotite


Olivine
dunite
90
Coarse/medium-grained
Rocks
harzburgite
lherzolite
wehrlite
olivine orthopyroxenite
olivine clinopyroxenite
40
olivine websterite
clinopyroxenite
orthopyroxenite
10
websterite
Orthopyroxene
Clinopyroxene

* Remnants of complete sections of oceanic crust have been found in outcrop around the world, thrust up by past continental or island-arc collision zones.

* This oceanic crust similar to **Ophiolite** (old oceanic crust obducted over continental crust) in composition.

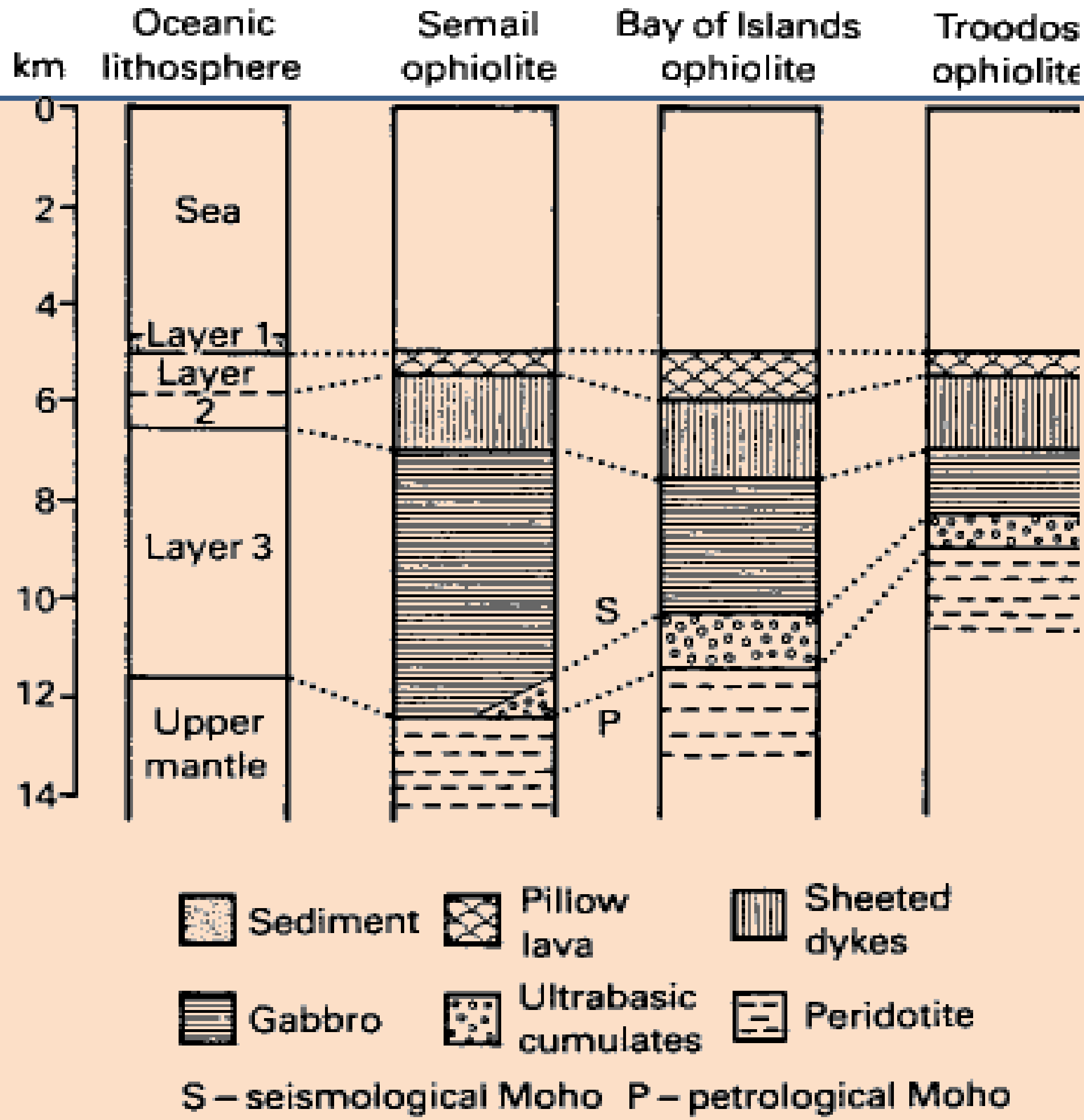
Direct sampling

Semail Ophiolite

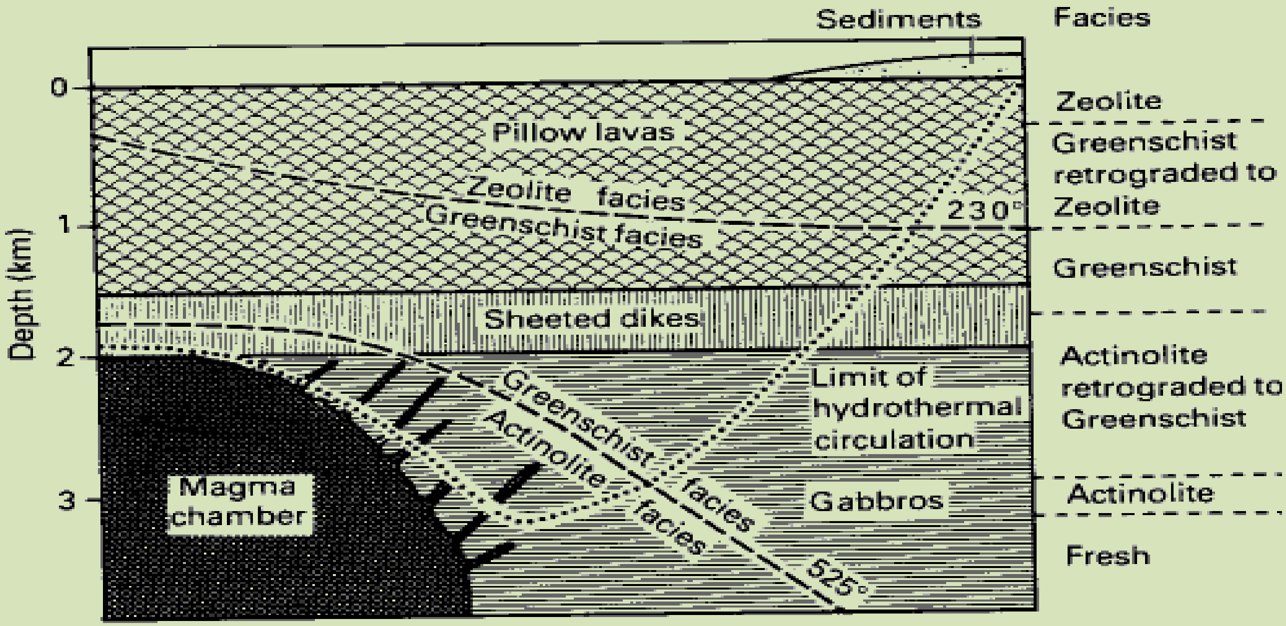
Composite section exposes:

- Radiolarian chert
- Pillow lavas
- Sheeted dikes
- Layered gabbros
- dunite
- petrologic moho
- Harzburgite (tectonized/deformed)

* The generalized *ophiolite* sections below are from Oman, Newfoundland, and Cyprus. They may be more representative of young, hot oceanic.



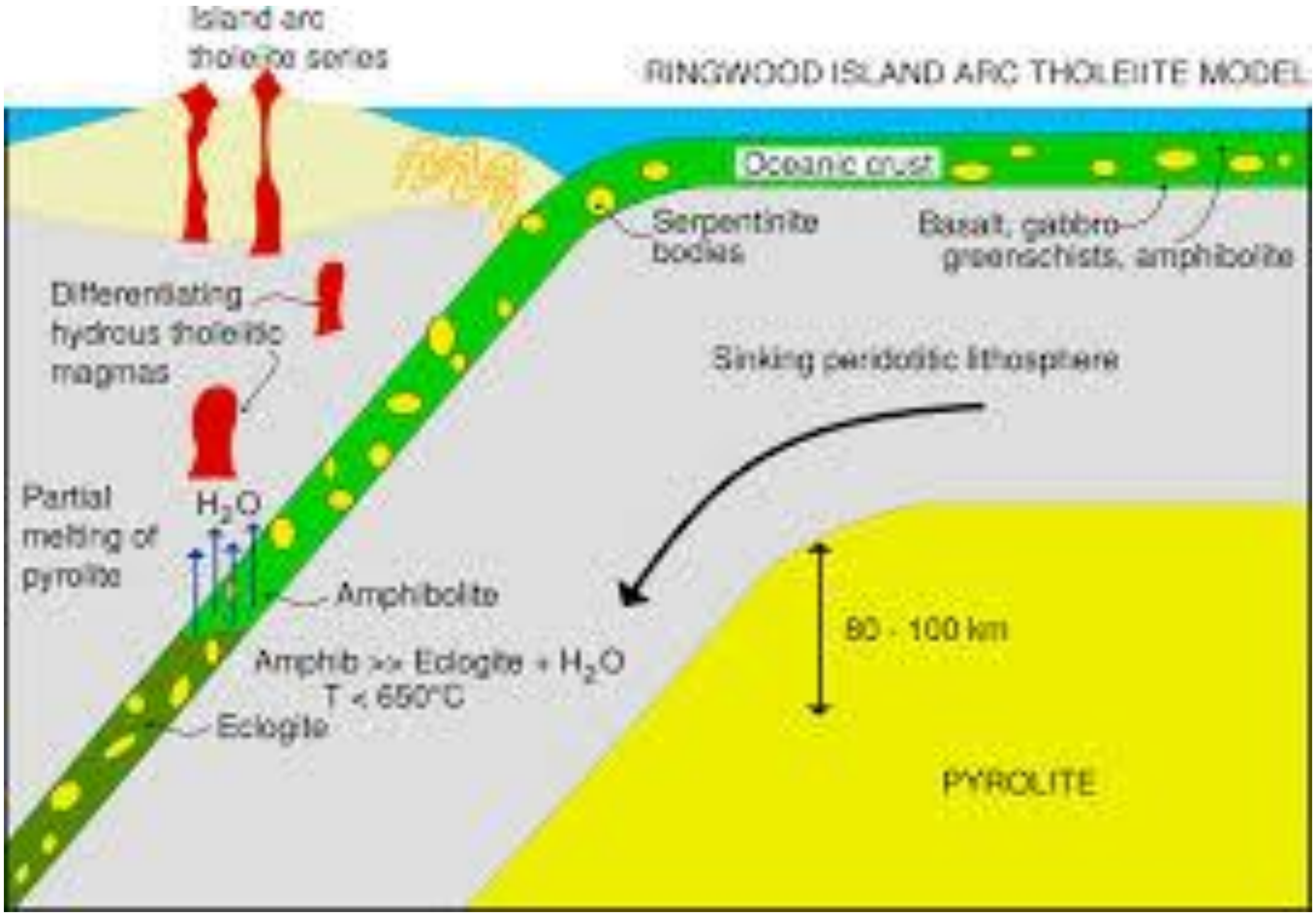
All oceanic crust is produced at spreading centers by a very specialized process. Hot mantle **pyrolite** in a thermal convection boundary layer partially melts near the surface due to the decrease in pressure. The magma cools into gabbroic intrusions below 2 km depths, while large quantities erupt at the seafloor to flow into *pillow lavas*. The top of the magma chamber is being continually intruded by dikes taking magma to the surface. Because this is occurring at a spreading center, each dike is always split by a new one, forming a vast stack of vertically-oriented dikes called a *sheeted dike complex*.



*** Sea water circulates into the cooling oceanic crust to depths of 3 km, driven by the heat of the magma intrusion.**

*** This circulation release metal sulphides, water, methane, and carbon dioxide into the ocean, and entraining water and metal oxides into the crust. The circulation is shown by the metamorphism and serpentinization of the basalts and gabbros.**

*** Prominent metallic ore deposits originate at such spreading ridges.**


RINGWOOD ISLAND ARC THOLEIITE MODEL
Island arc
tholeiite series
Oceanic crust
Serpentinite
bodies
Basalt, gabbro-
greenschists, amphibolite
Differentiating
hydrous tholeiitic
magmas
Sinking peridotitic lithosphere
Partial
melting of
pyrolite
H_2O
Amphibolite
Amphib >> Eclogite + H_2O
T < 650°C
Eclogite
80 - 100 km
PYROLITE

*** P-wave velocity in continental crust:**

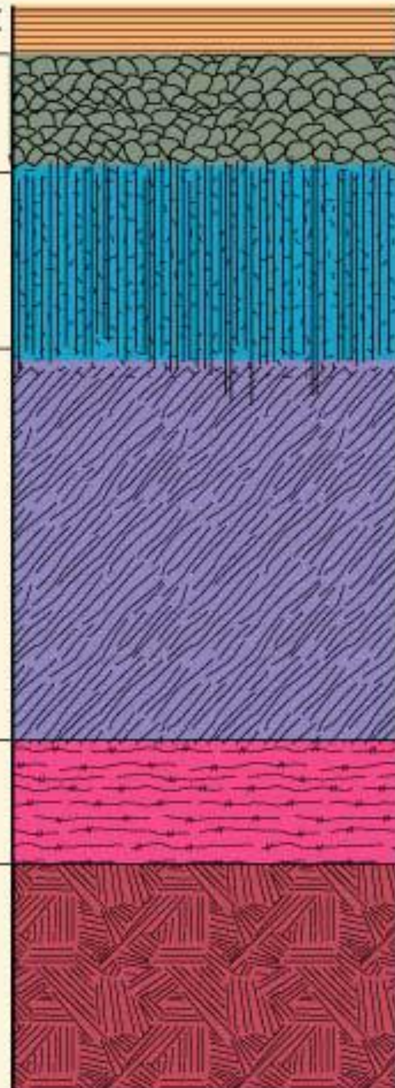
- Sediment 2-5 km/s
- Upper crust 5.6-6.3 km/s, average density = 2.7g/cm^3, mainly of **granodiorite composition (Sial)**.
- Lithostatic pressure at the base of upper crust= 6 kbar

- **Conrad discontinuity** between upper crust and lower crust.

- Lower crust 6.8 -7.2 km/s, average density = 3 g/cm^3, mainly of **basaltic** composition (Sima). Lithostatic pressure at the base of lower crust = 9 kbar.

- If lower crusts dry, its composition suggested being basaltic-amphibolites.
- P and S waves indicate that Poison's ratio about 0.3. This indicates **dry lower crust of mafic composition.**

Mohorovicic discontinuity or Moho (1909).
***** It is complex and there are regional varieties in its composition, age, and thermal history.

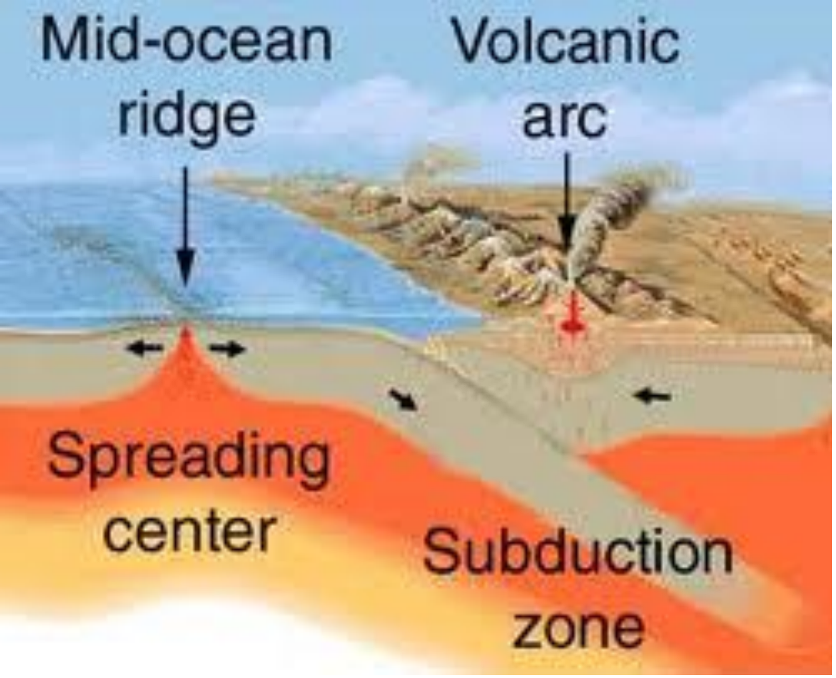


Lithology	Ocean Crustal Layers	Typical Ophiolite	Normal Ocean Crust	
		Thickness (km)		P wave vel. (km/s)
			ave.	
Deep-Sea Sediment	1	~ 0.3	0.5	1.7 -2.0
Basaltic Pillow Lavas	2A & 2B	0.5	0.5	2.0 - 5.6
Sheeted dike complex	2C	1.0 - 1.5	1.5	6.7
Gabbro	3A	2 - 5	4.7	7.1
Layered Gabbro	3B			
Layered peridotite	4	up to 7		8.1
Unlayered tectonite peridotite				

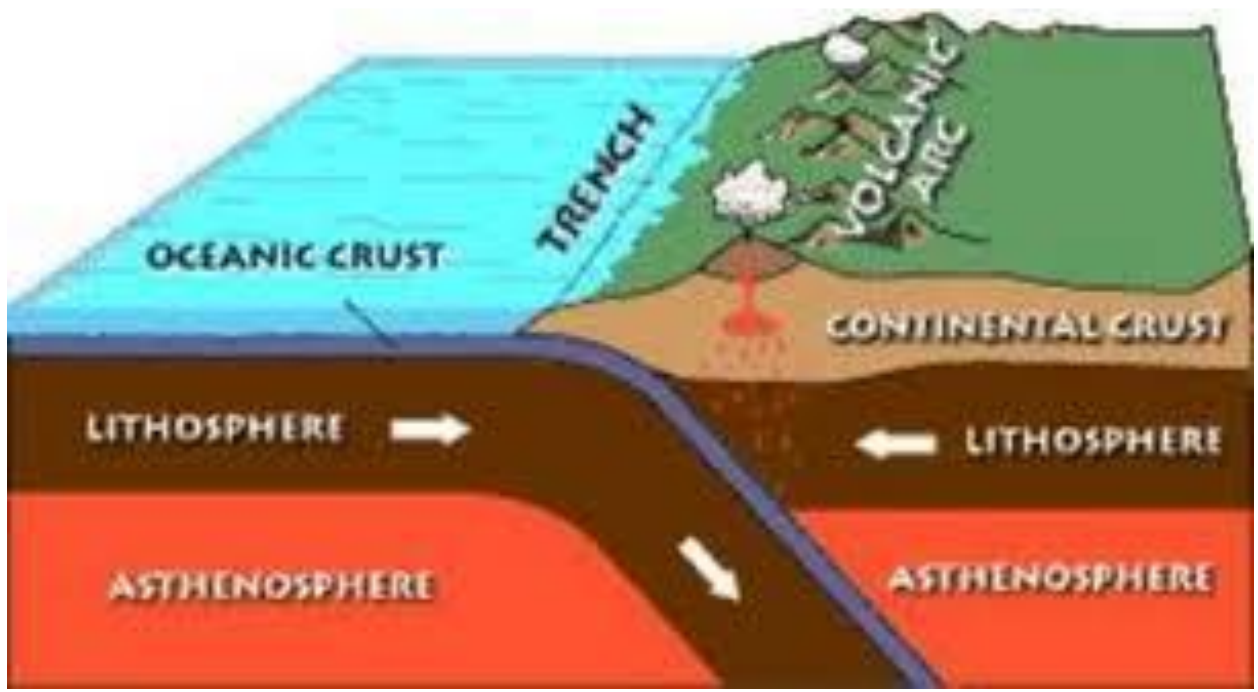
Differences between oceanic and continental crust

	Continental crust	Oceanic crust
Layering	ill defined	Well defined into 3 layers
Thickness	Avg. 35 km	Avg. 7 km
Age	Older than 3.8 billion years	Younger than 180 million years
Tectonic activity	Highly complex (folded mountain belts)	Low, except at boundaries
Igneous activity	Low, except at the boundaries	High (at mid oceanic ridges)
Heat flow	Avg. 57 mW/m2 High at rifts and low at shields and cratons	Avg. 101 mW/m2 High at mid oceanic ridges
Composition	Sial (Felsic rocks)	Sima (Mafic rocks)

The contact between OC and CC is in Continental slope.



Variation in thickness of oceanic crust near MORB (young, hot and thin) and at Trench (old, cold and thick)



2. Mantle

Seismic structure of the mantle:

Seismic tomography indicates that there are large heterogeneities in the mantle.

2- Upper mantle: 35 (average)-670 km,

Density =3.2 - 4.2 g/cm^3

P-wave velocity = 8.1 – 10.7 km/s

Pressure at its base = 270 kbar.

3- Lower mantle: 670 – 2885 km

Density = 4.3 -5.7 g/cm^3

P wave velocity =10.7 – 13.7 km/s

Pressure = 1368 kbar

- D″ layer with a thickness of 200-300 km, then Guttenberg discontinuity.

SEISMIC STRUCTURE OF THE MANTLE

1) 35-100 km deep (Part of the lithosphere)

   a. High velocity (8 km/s)

   b. Very similar to crust in behavior

2) 100-300 km low velocity zone (LVZ)

- It present under most regions of the earth except under cratons.

3) 300-400 a slow increase in seismic velocity.

4) 410-670 km deep is the transition zone

   -400 discontinuity is the upper region of the transition zone. Gradual increase in seismic velocity

   -670 discontinuity is the base of transition zone

5) 670-2885 lower mantle (Gutenberg discontinuity)

   Gradual increase in velocity. Before reaching the base of lower mantle with about 200 km, a noticeable decrease in velocity is detected (A layer called D" is encountered).

MANTLE COMPOSITION:

* **Peridotite: contains abundant olivine + <15% garnet**
* **Eclogite: contains little or no olivine +>30% garnet**

The two rocks indicate about 8 km/s.

- Studies indicate Peridotite, because

1. The velocity of P-wave is anisotropic, and this characterizes peridotite not eclogite.
2. Peridotite present in ophiolite and xenoliths.
3. A peridotitic composition is also indicated by estimates of Poisson's ratio from P and S velocities.
4. The density of Eclogite is too high to explain the Moho topography of isostatically compensated crustal structures.

It is necessary to distinguish between:

* Depleted mantle and undepleted mantle

Depleted mantle → partial melting→ basaltic composition

*** Experiments indicated that the composition of mantle mainly Pyrolite.**
Pyrolite: 3 parts dunite + 1 part basalt fully depleted mantle
- Basalt corresponds to partial melt.

*** Depending on Temperature, Pressure and water vapor pressure, the normal form of pyrolite existing up to 70 km deep and it is pyroxene pyrolite, which transforms into garnet pyrolite at depths of 70-350km.**

*** Chemical composition of the mantle (average):**

CaO		**FeO (wustite)**	
Al_2O_3	**5-10%**	**MgO (periclase)**	**90%**
Na_2O		**SiO_2 (Stishovite)**	

*** Only six oxides comprises > 98% of the mantle**

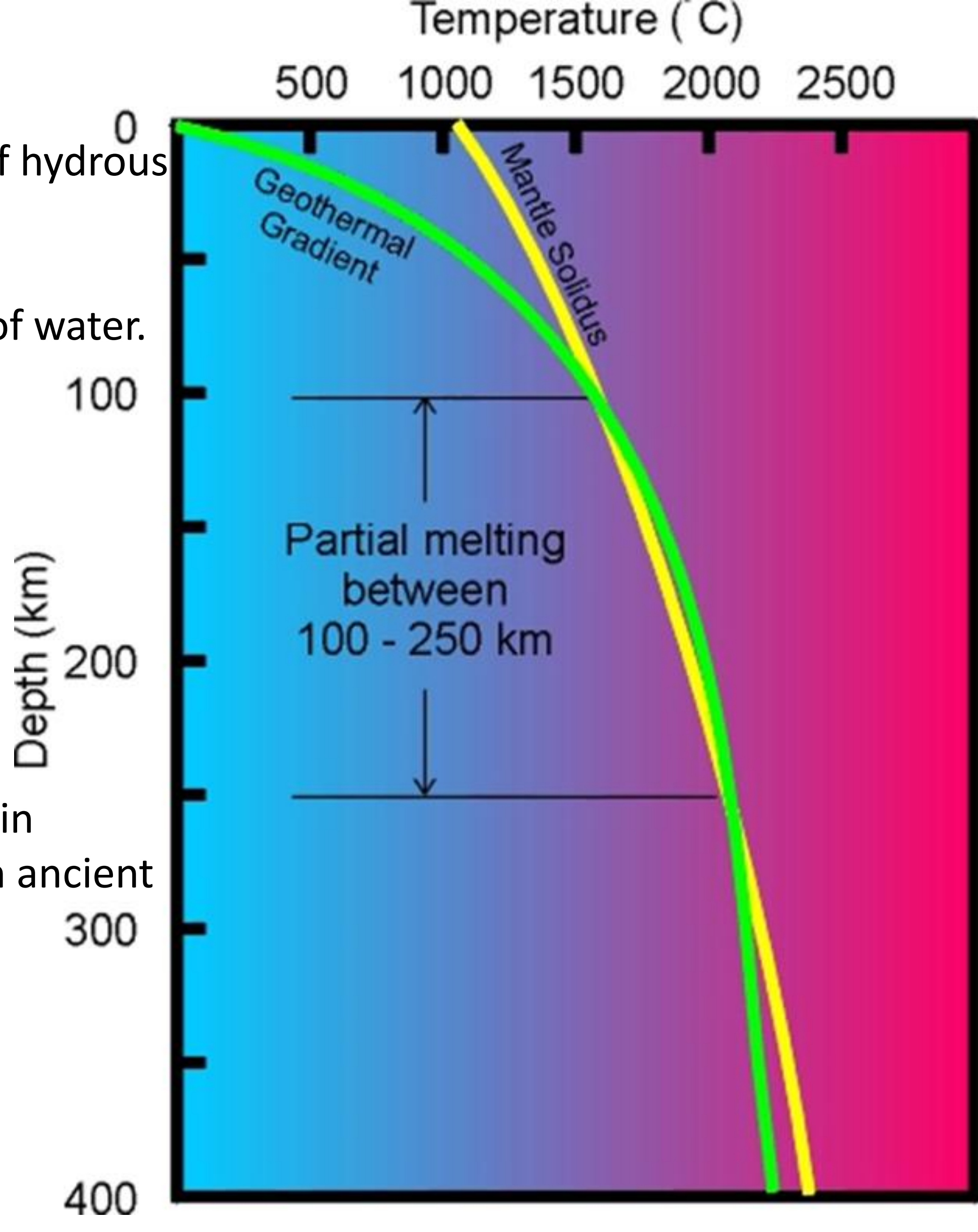
THE MANTLE LOW VELOCITY ZONE (LVZ)

- High electrical conductivity.
-High seismic attenuation (It is more clear in S-waves than P-waves).
- In general, low seismic velocities happened due to because

1) Anomalously high temperature
2) Has mineralogical phase change
3) A composition change
4) Partial melting.

 * It found that 100-250 km, the mantle material is molten. Why?

- the answer: is the breakdown of hydrous mantle phases.
- LVZ base at (250 or 300) km is determining by the availability of water.



- It is believed that 1% molten.
- Universally present for S-waves, and may be absent for P-waves in some regions especially beneath ancient shield areas.

The mantle low velocity zone is of major importance to plate tectonics as it represents a low viscosity layer along which relative movements of the lithosphere and asthenosphere can be accommodated.

MANTLE TRANSITION ZONE (T. Z.)

It is bounded by 410 and 660 km deep discontinuities in the Earth. They are not sharp but over a wide range of depth. Seismic velocity increases rapidly in stepwise.

The cause of discontinuities is <u>phase change not compositional</u> (not change in Mineralogy). Change from Olivine (Forsterite) (Mg_2SiO_4) to perovskite structure (MgSiO$_3$).

Mineral stabilities:

(at 410 km and 1600º C) Olivine (0.89 Mg +0.11 Fe) SiO_4 → distorted form of spinel structure (β-phase). The atoms more closely packed. At this level 57% of the mantle is of olivine.
Another contribution comes from phase change of Pyroxene into garnet (350-400) km.
***** This is the reason of discontinuity.**

2. At (500-600) km (specifically speaking at 520 km) distorted form of spinel structure (β-phase) → spinel structure.

3. At 660 km spinel breaks down <u>to perovskite structure ($MgSiO_3$)</u> and periclase (MgO) and the density increses by 11%. Also at this depth pyrope garnet ($Mg_3Al_2(SiO_4)_3$→ ilmenite structure ($FeTiO_3$) and at 800 km → perovskite ($MgSiO_3$).
**** This causes the lower discontinuity.**

Table 2.4 *Phase transformations of olivine that are thought to define the upper mantle transition zone (after Helffrich & Wood, 2001).*

Depth	***Pressure***	
410 km	13–14 GPa	$(Mg,Fe)_2SiO_4 = (Mg,Fe)_2SiO_4$ Olivine Wadsleyite (β-spinel structure)
520 km	18 GPa	$(Mg,Fe)_2SiO_4 = (Mg,Fe)_2SiO_4$ Wadsleyite Ringwoodite (γ-spinel structure)
660 km	23 GPa	$(Mg,Fe)_2SiO_4 = (Mg,Fe)SiO_3 + (Mg,Fe)O$ Ringwoodite Perovskite Magnesiowüstite

LOWER MANTLE

- Homogenous in mineralogy (Perovskite structure).
- Both Vp and Vs increase progressively
- Has the D'' layer (the lowest 200-300 km of the mantle in molten phase). The seismic velocities decrease due to anomalously high temperature. The iron of the core reacts with the silicates of the mantle to produce metallic alloys and non-metallic silicates (from perovskite), and this produces very heterogeneous layer.
- It is worth to say that mantle plumes originate at this layer.

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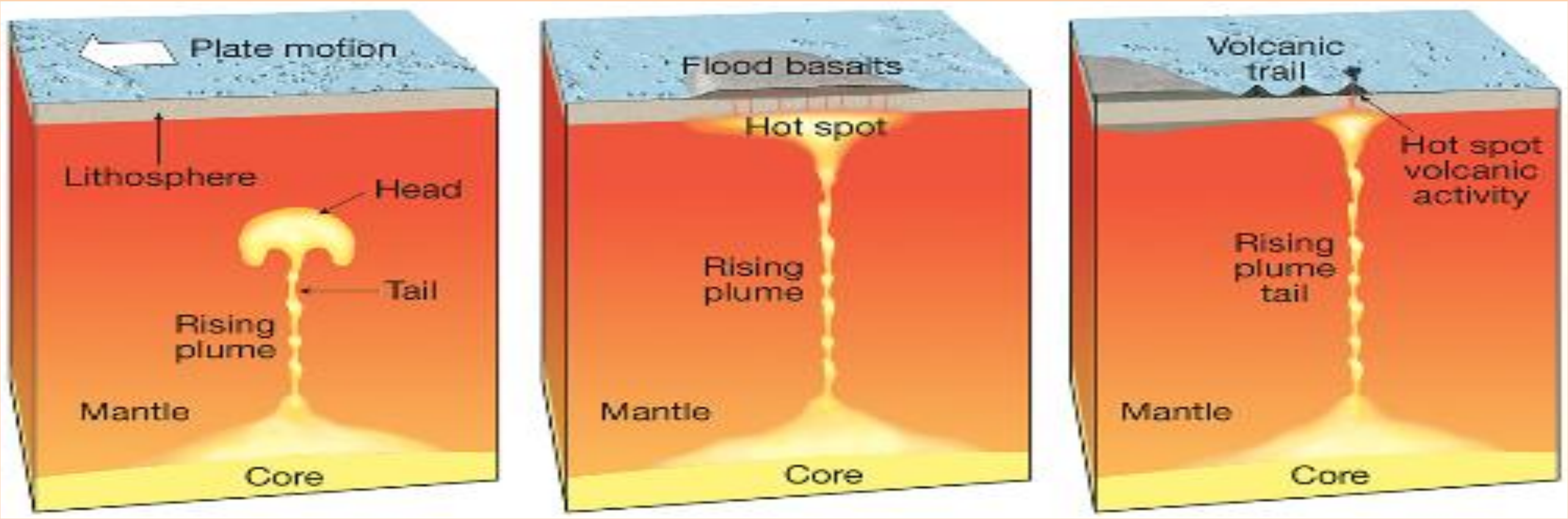
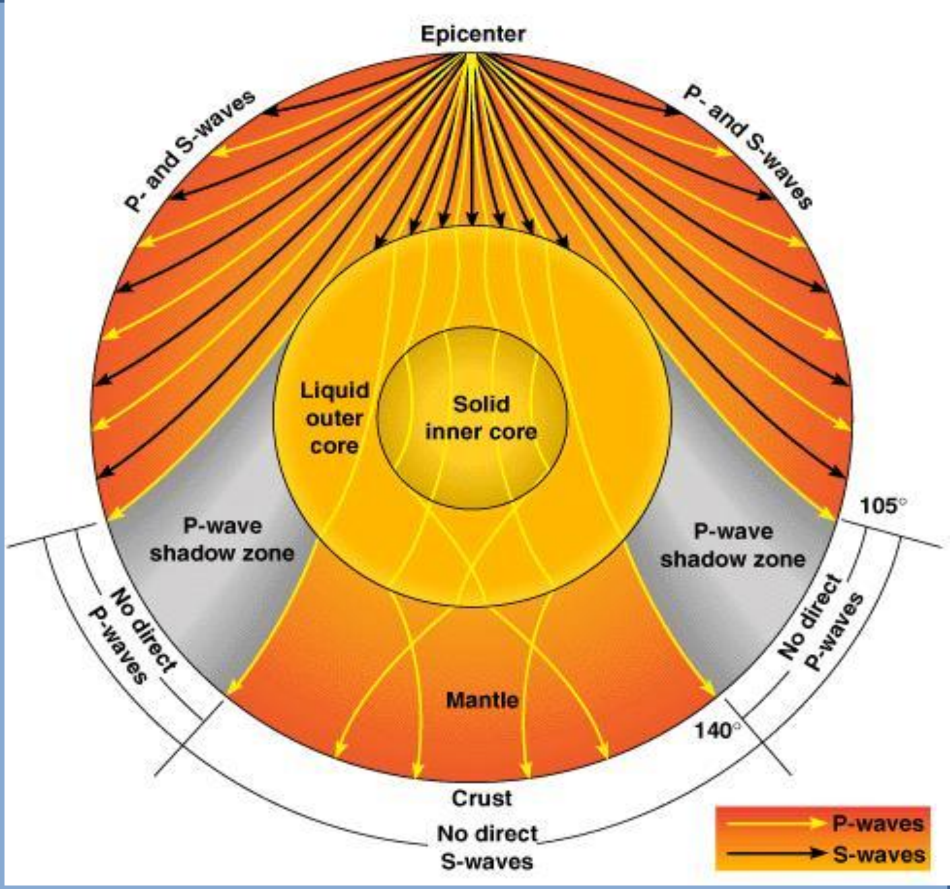
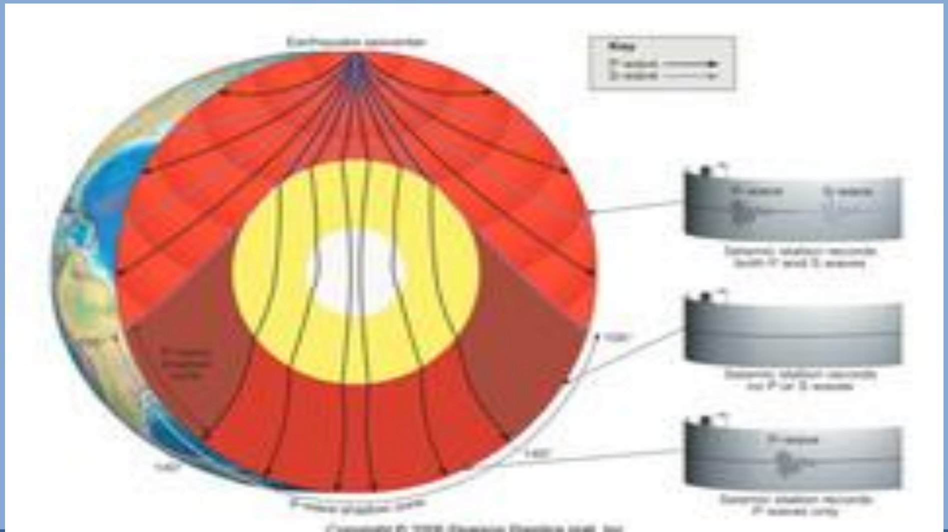


THE CORE

-Begins from Gutenberg discontinuity (at 2891 km) which is compositional discontinuity. It comprises outer core (2891-5150 km) and inner core (5150-6371 km deep) with a radius of 3480 km.





THE OUTER CORE:

- Outer core: 2891-5150 km

  Density = 9.71 – 12.2 g/cm^3

  P wave velocity = 8.1 – 10.3 km/s

  Pressure = 1400 -3300 kbar

- Doesn't transmit S-wave, so it is believed that it is like fluid.
- The convection motions in this part are responsible for the generation of The Earth magnetic Field. It is originated by the circulation of good electrical conductor in this region.
- A fluid state is also indicated by the response of the Earth to the gravitational attraction of the Sun and Moon.

** Shock waves proved that the major constituents of both inner and outer core must comprise elements of an atomic number > 23 (Iron, Nickel, Vanadium or Cobalt). But Iron (Fe) is the only mineral presents in sufficient amount in the solar system. Also the studies on solar system Ni presents in about 4%.

So, outer core have a mixture of Fe-Ni with this composition is 8-15 % denser than expected for outer core. So, It believes to contains small quantities of lighter elements (Silicon, Sulphur, Oxygen and Potassium).
Inge Lehmann (Swedish 1934) or Bullen Discontiuty 1940

THE INNER CORE

- Inner core: 5150-6371 Km
  Density: 15 g/cm^3
  P wave velocity = 11.2 km/s
  Pressure in the center of the earth = 3600 kbar

- Has a seismic velocity and density consistent with a composition of pure iron.

Inner core is Solid and the discontinuity is sharp without transition zone.

It is solid for several reasons:

Certain oscillations of the Earth produced by Large Earthquakes can only be explained by a solid inner core.

* Transverses of S-waves.

The amplitude of a phase reflected off the inner core suggests that it must has a finite rigidity and thus be solid.

EARH STRUCTURE BASED ON RHEOLOGY: HOW PLATE RESPONDS TO STRESS.

EARTH DIVIDES INTO:

1. Lithosphere (thickness): ~60-80 (under ocean), while 100-150 km (under continents), Average thickness = 100 km (brittle).

-Lithosphere = crust + upper most mantle,

- it has flexural rigidity. Flexural rigidity: the resistance of material to bending under loading. In case of unloading, it respond elastically.

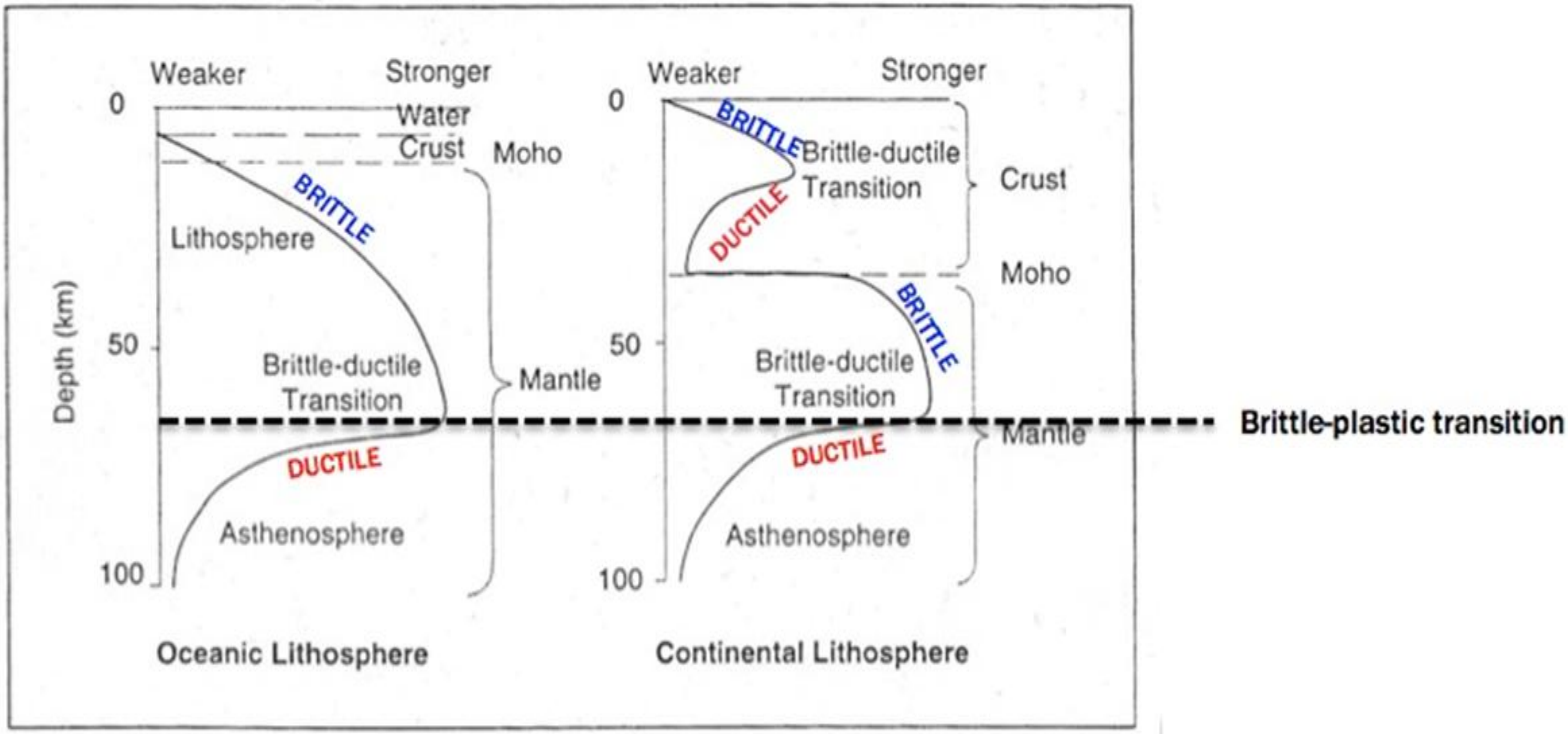
- Lithosphere have flexural rigidity (especially under craton which are the most rigid because it's cold and old).

- Heat transfer through lithosphere from down by conduction or advection

- Depend on many studies the lithosphere and upper mantle are composed of ultramafic rock in which olivine is the major constituent .

- **Continental lithosphere behaves as sandwich, that is very weak at the Moho, and have two transitions to ductile behavior. (at about 15 km and at about 50 km). So, at collision zones, the crust splitted and thrusted.**

- Oceanic lithosphere behaves as a unit at more strengthen at 30 km.



Weaker
Stronger
0
Water
Crust
Moho
BRITTLE
Lithosphere
Depth (km)
50
Brittle-ductile
Transition
Mantle
DUCTILE
Asthenosphere
100
Oceanic Lithosphere
Weaker
Stronger
0
BRITTLE
Brittle-ductile
Transition
Crust
DUCTILE
Moho
BRITTLE
50
Brittle-ductile
Transition
Mantle
DUCTILE
Asthenosphere
100
Continental Lithosphere
Brittle-plastic transition

2. Asthenosphere: extends from base of lithosphere (100 km) until 660 km. It includes Low velocity zone (LVZ).

-In average, LVZ extends from 100 to 250 km, density = 3.64 g/cm^3, P wave velocity = 8.1-9 km/s, weak layer deformed by creep (ductile deformation).

- It is absent beneath shields.

- **It has not flexural rigidity.**

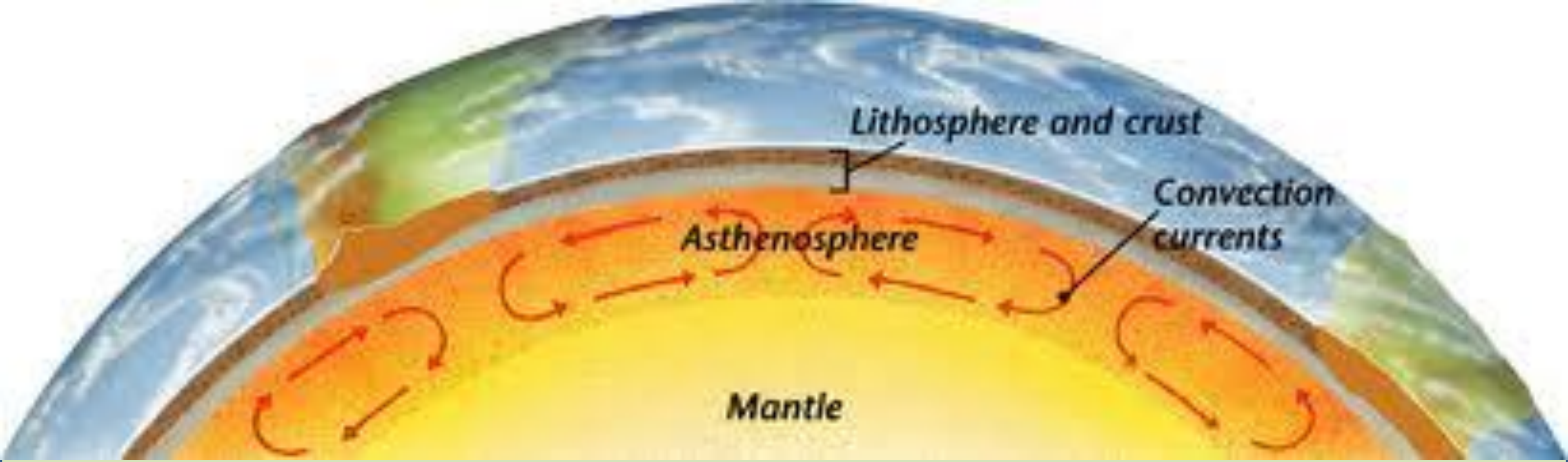
- **LVZ is at the base of lithosphere, with relatively has low viscosity upon which plates are slide with very little friction.**

- Transition zone = 410- 660 km

- At 410 olivine breaks down to sphinel

- At 660 sphinel transform into (perovskit+magesiowestite)

- Heat transfer in asthenosphere by **convection**



- The boundary between lithosphere and asthenosphere is the iso-therm 1280° C.

- The boundary is thermal, so it is variable (under MORB or continents). While between crust and mantle is compositional.

3. Mesosphere:

-D”: 200- 300 km thick, characterizes by very steep temperature gradient.

4. Outer core: fluid.

5. Inner core: Solid.

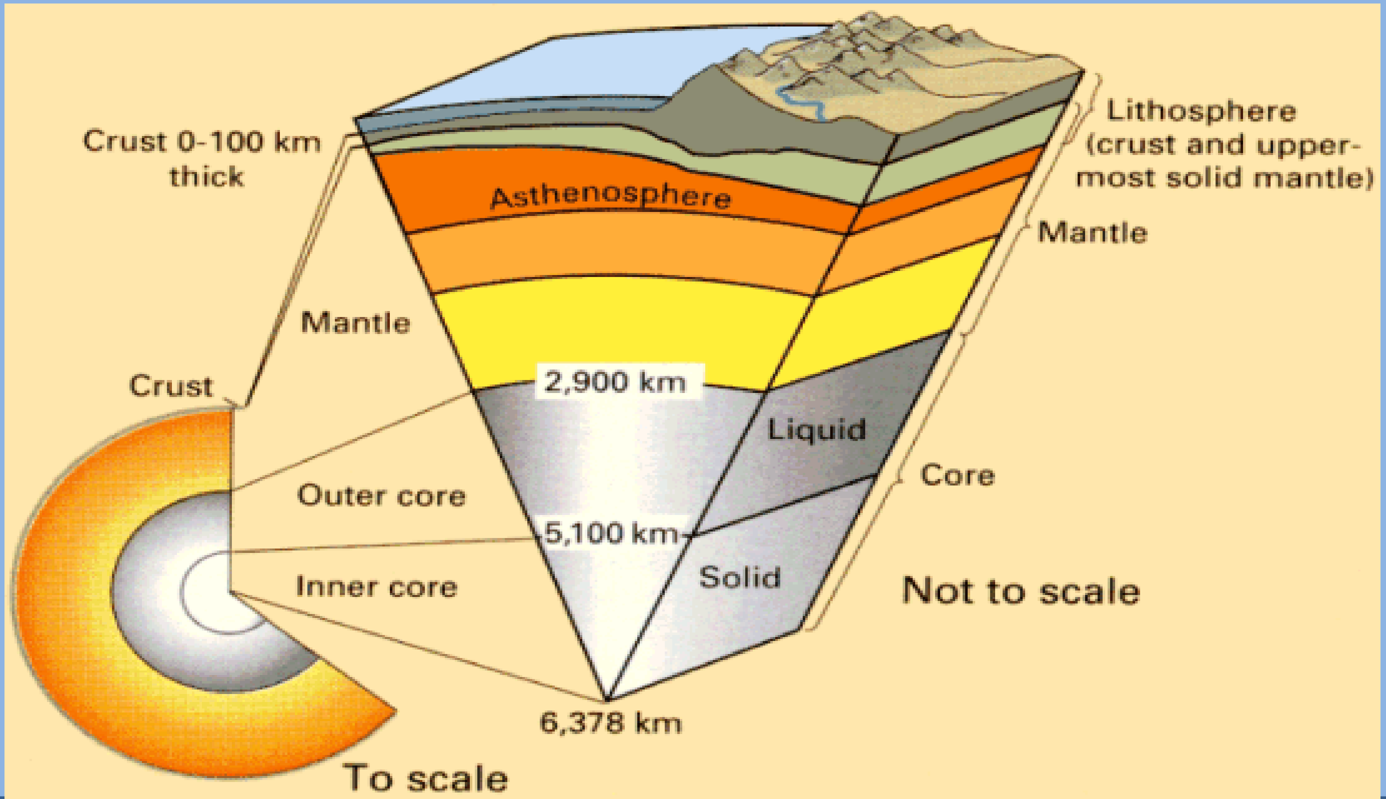
TABLE 1.2

Most Common Chemical Elements in the Earth

Whole Earth		Crust	
Element	**Weight Percent**	**Element**	**Weight Percent**
Iron	32.4	Oxygen	46.6
Oxygen	29.9	Silicon	27.7
Silicon	15.5	Aluminum	8.1
Magnesium	14.5	Iron	5.0
Sulfur	2.1	Calcium	3.6
Nickel	2.0	Sodium	2.8
Calcium	1.6	Potassium	2.6
Aluminum	1.3	Magnesium	2.1
(All others, total)	.7	(All others, total)	1.5

(Compositions cited are averages of several independent estimates.)

- Seismic data (mass and moment) of inertia shows that the mean atomic weight of the Earth = 27.
- At the mantle and crust silicates 22.4%
- About 90% of the earth is made of 4 elements. They are: Fe 30% Si (15%), Mg (15%), O_2 (30%), and
- About 10% made of S (2.5%), Ni (2%), Ca (1%), Al (1%), Na (0.5%) and other elements



ISOSTASY

The response of the outer shell of the Earth to the imposition and removal of large loads (i.e. mountain belts).

* For such features to exist on earth surface, we need compensating mechanism to avoid the large stresses.

* This is proven through the work in the Andes and Himalaya mountains. These mountains are found compensating due to the existence of negative mass anomaly beneath the mountains (-ve Bouger anomaly).

* From gravity data, it is clear that the mountains compensated at depth with density contrasts.

ISOSTASY

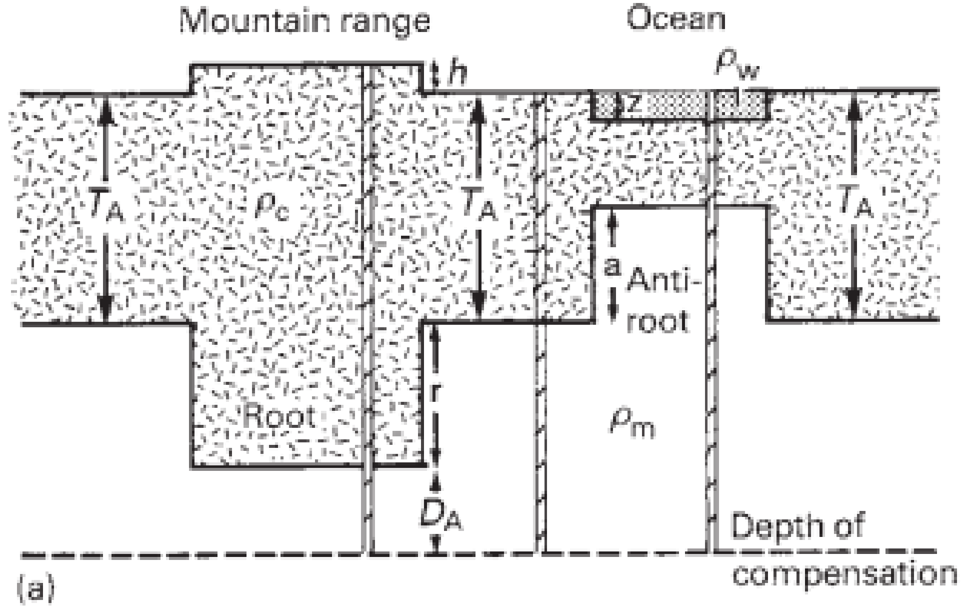
- Beneath a certain depth, known as depth of compensation, the pressures generated by all overlying materials are every where equal.

This is the weight of vertical columns of unit cross-section although variable, are identical at the depth of compensation, if the region is in isotactic equilibrium.

*** Airy's Hypothesis:**

- Mountain ranges underlain by a thick root (r).

$$r = h\rho_c/(\rho_m - \rho_c)$$



$$r = \frac{h\rho_c}{(\rho_m - \rho_c)}$$

$$a = \frac{z(\rho_c - \rho_w)}{(\rho_m - \rho_c)}$$

- Oceans underlain by antiroot (thin outer layer).
- The base of the outer shell is an exaggerated mirror image of the surface topography.

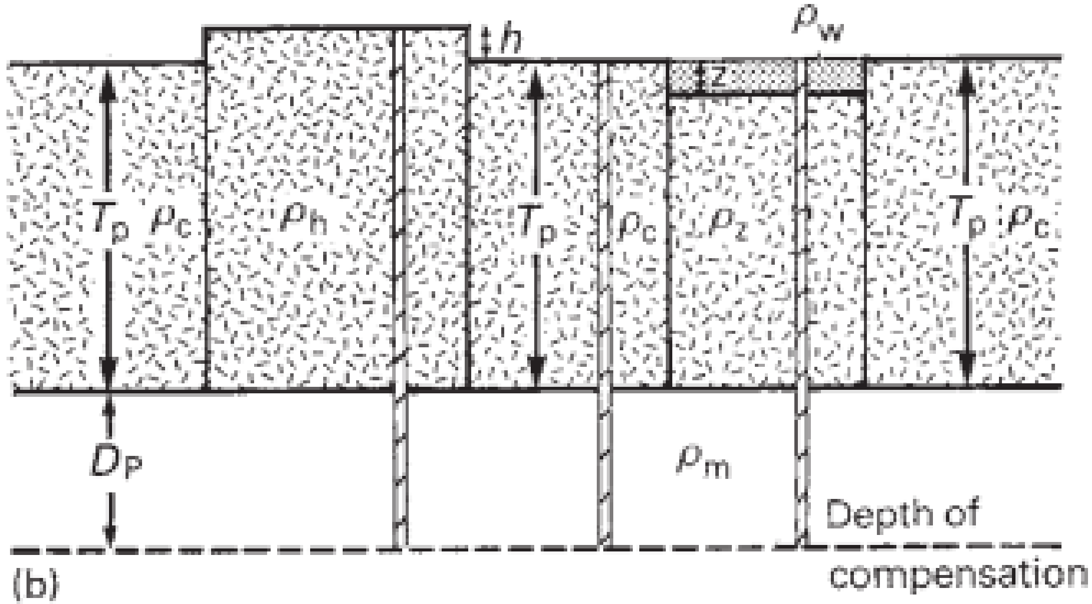
* Pratt's hypothesis:

- Constant depth but density varies according to the surface topography.

- Mountains are underlain by low density materials (ρ_h),

$$\rho_h = T_p \, \rho_c / (T_p + h)$$

Oceans are underlain by high density materials.



$$\rho_h = \frac{T_p \rho_c}{(T_p + h)}$$

$$\rho_z = \frac{(T_p \rho_c - z\rho_w)}{(T_p - z)}$$