Structure of the Earth:

- **Crust** (VP < 7.6 km/s, VS < 4.4 km/s, ρ < 3.1 g/cc) is rich in SiO_2 (60 wt. % in continental, 49% in oceanic) rocks, Al_2O_3 about 15%, CaO (6% in continent, >12% in ocean) and Fe_2O_3 (<4% in continent, >6% in ocean). Thus "**sial**" (silica-alumina).

- **Moho** (Mohorovicic discontinuity) at 5-40 km depth, separates crust from upper mantle; is a chemical boundary.

- **Upper mantle** (VP > 7.8 km/s, VS > 4.5 km/s, ρ > 3.2 g/cc) consists mixture of olivine and orthopyroxene (peridotite) or of garnet and clinopyroxene (eclogite) or a mixture of peridotite and eclogite. This is deduced from seismic velocities and rock samples (xenoliths) from kimberlite pipes (up to 200 km deep). Thus, SiO_2 < 44 %, Al_2O_3 < 2%, while MgO > 37% and FeO > 7%. Thus "**sima**" (silica-magnesia).
  - **Lithosphere** or **plate** is the upper rigid, highly viscous outer shell of the earth with thickness strongly dependent on temperature. Generally 50-100 km thick below the oceans and 75-200 km thick below continents.
  - **low velocity zone** beneath oceans, but not found under continents.
  - **asthenosphere** is zone where solidus of mantle rocks is reached (or nearly reached), thus material is more ductile and can creep easily (low viscosity). Normally associated with the low velocity zone, low viscosity zone and zone of high electrical conductivity.

- **220 km Lehmann discontinuity**: a local feature that exist under continents and island arc regions. It is probably a chemical and rheologic boundary layer – from rigid upper continental plate to more plastic lower part. This layer is variable in depth and may be a transition from anisotropic lithosphere to a more isotropic material in the lower part of the continental lithosphere. (Gu et al., GRL 28:4655, 2001)

- **420 km seismic discontinuity**: appears to be global feature, but they do vary with depth: from 360 km to 430 km (shallow near subduction zone). Is that a phase change (α-olivine to β-spinel structure and/or orthopyroxene to garnet structured majorite) or chemical boundary? Most likely phase transition, however, jump in seismic velocity is less than the jump predicted for these phase changes, so there must be other minerals that do not transform. Garnets & clinopyroxenes are candidates. The phase transformation is exothermic, and the boundary would be shallower in cold regions (subducting slab) and deeper in warm upwellings.

- **520 km seismic discontinuity?** Weak amplitude of SS reflection relative to those at 420 & 670 km. (Only SS from distance 100^o to 160^o can be used – at closer distance, it is distorted by the reflections at 420 & 670; at greater distance, the wave graze the CMB, also complicating the interpretation.) It does not reflect short period waves implying a boundary spread over at least 10km in depth. It does not reliably appear in refraction studies, suggesting that it is more of a rock density increase than a seismic velocity increase. Deuss & Woodhouse (2001, Science 294:354) finds that under mid-Pacific, South American shield & Indian shield, the "520" appears as a single reflector, whereas under the North American shield, North African shield and the Indonesian subduction zone it appears as a pair of reflections at 500 & 560 km. The 520 discontinuity appears to be 2 phrase changes with different properties depending on temperature & composition: the $\beta-\gamma$ transition in the olivine component and the garnet-perovskite transition in non-olivine component of the mantle. Other factors, such as rheology, composition & water content may also change across this 520 discontinuity. It remains to be seen why there appears to be no correlation between the 520 discontinuity and surface tectonics.

- **670 km seismic discontinuity**: appears to be global feature. Topography of the boundary may reach 20 to 30 km - tending to be deeper in regions of subducting cold material. This is consistent with the fact that the phase transformation is endothermic. Is this a phase change (spinel to perovskite structure) or chemical boundary? slab graveyard above? (Question related to whole mantle or layered mantle convection: If vigorous mixing occur by convection thru the boundary, chemical boundary is not likely to occur, and phase boundary is likely. If it is a chemical boundary, then the buoyancy force may prevent convection through the boundary, this may explain the lack of earthquakes below 670 km. On the other hand, the lack of seismicity may be due to higher creep below.) Some seismic evidence of Marianas slab penetrating into the lower mantle by a few hundred km. Some show slab under Japan deflect horizontally around 600-800 km.

- **transition zone**: zone between 420 km and 670 km depth.

- **lower mantle** : mantle below 670 km depth.

- **Deeper Mantle (900 km, 1050 or 1700 km) seismic discontinuity?**
  Some observations indicate possible boundaries near 900, 1050 and 1700km, but the extent and nature of any structure at these depths are unresolved. High temperature & pressure experiments on perovskite show that it is stable to 2300 km depth (Shim et al., 2001, Science, 293:2437). However, it cannot rule out possible phase transitions at greater depth.

- **D'' layer** at the bottom 250 km of the mantle. Lateral P-wave variation is ±2% and ±3% for S-wave. How thick is it? What is its topography ? Is this a thermal boundary layer (hot, low velocity and density)? origin of low density thermal plumes? slab graveyard (higher density)? Does the velocity decrease with depth (due to heating)? or does it increase with depth (due to chemical boundary)?
- In the lowermost few tens of km of the mantle within the D”, **ultralow-velocity zones** have been detected and interpreted as evidence for partial melt.
- Existence of triplication at 72º to 95º indicates there may be abrupt velocity increase in D"- existence of the **Core-Rigidity Zone**. Using ScP waveforms, Rost & Revenaugh (2001, Science 294:1911) show that a rigid zone exists beneath the Tonga-Fiji region. The zone is thin (0.12-0.18 km), and likely to be a zone of molten iron mixed with solid mantle material, but it can be topographic highs of the CMB filled by light core sediments. The existence of this layer have important implications on nutation of the earth’s rotation, convection of the outer core, and may control frequency of geomagnetic field reversals.

- **core-mantle boundary**

-low velocity outer core (P shadow zone between 103º to 143º)

-delayed P arrivals but S is absent for Δ=142º to 180º.

-P velocity in outer core is 8-10 km/s compared with 13 km/s in lower mantle.

-S velocity drop from 7.3 km/s in the lower mantle to zero at the CMB (Free oscillation, SKS amplitude would be smaller if S to P conversion is across a solid-solid boundary). Thus, outer core is fluid.

- separates the silicate mantle from the Fe fluid core

-PKP with shallow penetration into the outer core come out at A with epicentral distance of 188º. With decreasing angle of incidence, the epicentral distance of PKP decreases from 188º to 143º, i.e. at B, then it increases to again to 170º. The cusp of the T-Δ curve at B is a geometrical effect of the total ray path. The rays which penetrate the inner core emerges at 110º (Δ) and with further decreasing angle of incidence, emerges at the anticenter at E.

-From Reflection Seismology: strong reflected phase such as PcP, ScS and PnKP demonstrates that the Core-Mantel Boundary (CMB) is a sharp discontinuity over less than 2 km.

-Reflection seismology and Free Oscillation data give the mean depth of the CMB at 2886 km (radius of the outer core is 3485±3km)

-due to Earth rotation, the CMB is flattened at about 1/390 or equatorial radius minus polar radius is 12 km.

-Undulations or bumps on the CMB (effect transfer of angular momentum between core and mantle through topographic coupling, geomagnetic field generation etc.) and the existence of thermal anomalies at the bottom of the mantle (with important implications on mantle convection) or seismic anisotropy is hot topic in research today.

-density increases across the CMB (from 10 to 12 gm/cc), compatible with constraint placed by the Moment of Inertia deduced from the Earth's rotational motion.

-PKP phase bottoms around 1000 km below the CMB, to determine the velocity below, SKS and SKKS are used (no low-velocity zone is seen by these converted waves since S-vel at the base of the mantle is slightly lower than the P-vel in the fluid core; they bottom at about 100 km above the inner core boundary). Important question: does the depth dependence of K and ρ follow the Adams-Williamson equation? (i.e. is the core stably stratified?)

-Is there a thick transition zone just above the inner core boundary (ICB)? Gutenberg (1959) thought that the transition zone is 150 km thick because he thought a precursor to the PKIKP phase exist between 125º and 143º. Bolt (1962, 1964) thought that it is 400 km thick and give rise to the GH branch. Later these are identified as scattered PKKP rays - thus, no need to introduce a transition zone.

-seismic attenuation in the outer core is negligible.

- solid inner core -

-Lehmann found weak P arrivals in the shadow zone from Δ=110º to 142º. This cannot be diffracted rays from the core-mantle boundary, but must be due to a strong increase of P velocity within the core. This indicates the existence of an inner core. The sharp bending of rays at an inner boundary results in the brance DE in the T-Δ curve.

-PKiKP which is reflected at ICB, shows that the inner-outer core boundary is sharp (transition over 1-2 km at most). The radius of the inner core is about 1227 km.

-Radius of the core is about 1217 km (5154 km depth).

-No topography has been detected on the ICB

-P wave velocity increase by about 0.6km/s from the bottom of the outer core to the inner core, and reaches 11.3 km/s near the centre of the Earth.

-Inner core is solid (existence of certain overtones of spheroidal free oscillation; SKJKP with S velocity of 3.5 km/s in the inner core; amplitude of PKiKP indicate nonzero rigidity in the inner core).

-attenuation strongly increases in the inner core

-seismic waves traversing the inner core on paths parallel to the spin axis travel (1s) faster than waves in the equatorial plane, indicating the existence of inner core anisotropy. This axial symmetry may result from convective flow in the inner core that induces an alignment in weakly anisotropic crystals of solid iron. Recent work shows that this fast (spin) axis moves eastwards tracing a 10º circular path around the north pole. (Waves travelled along the N-S path differ by 0.3s from the 1960s to 1990s). This indicates that the inner core is rotating faster than the mantle (in 100 years, core rotate about 90º more).

-density increases sharply but only slightly across the inner-outer core boundary.