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INNER STRUCTURE OF THE EARTH - RELEVANCE TO EARTHQUAKES

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ABSTRACT

A study of the earth's interior structure is quite helpful in understanding the science behind the earthquake**.** At the present level of understandings, earthquakes are usually caused when rock underground suddenly breaks along a fault. This sudden release of energy causes the seismic waves that make the ground shake. When two blocks of rock or two plates are rubbing against each other, they stick a little. They don't just slide smoothly; the rocks catch on each other. The rocks are still pushing against each other, but not moving. After a while, the rocks break because of all the pressure that's built up. When the rocks break, the earthquake occurs. During the earthquake and afterward, the plates or blocks of rock start moving, and they continue to move until they get stuck again. The spot underground where the rock breaks is called the **focus** of the earthquake. The place right above the focus (on top of the ground) is called the **epicenter** of the earthquake. Movement of seismic waves from the point of focus up to the earth's surface through different layers of rocks/plates governs the magnitude and severity of the earthquake.

KEYWORDS: Earth's Layered Structure, Continental Crust, Oceanic Crust, Upper Mantle, Lower Mantle, Outer Core, Inner Core, Seismic Waves, Tectonic Plates, Fault Boundaries, Earth's Double Core

Disclaimer

Technical contents of the paper are not based on original research findings of authors. These are the extracts from published literatures available on internet websites. It is mainly a knowledge update/literature survey on earthquakes

INTRODUCTION

An earthquake is the sudden movement of the ground that releases elastic energy stored in rocks and generates seismic waves. These elastic waves radiate outward from the "source" and vibrate the ground. In an earthquake, the initial movement that causes seismic vibrations occurs when two sides of a fault suddenly slide past each other. A fault is a large fracture in rocks, across which the rocks have moved. Faults can be microscopic or hundreds-to-thousands of kilometers long and tens of kilometers deep. The width of the fault is usually much smaller, on the order of a few millimeters to meters.

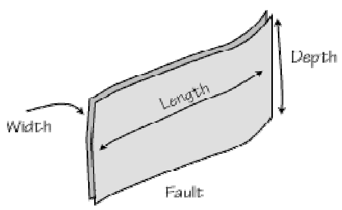

Figure 1: Schematic of a Fault

Earthquakes are the result of slow-moving processes that operate within Earth. Earth was hot when it formed, and has been cooling ever since near the surface. Earth's cooling causes the portions of Earth to move, and that movement is called earthquake.

The size of an earthquake depends on

- The area of the fault that ruptured.
- The distance that the rocks on the two sides of the fault slide past one another.

Small earthquakes rupture small faults or small sections of large faults. Fault movement during such events is quick-small quakes last only a fraction of a second and the rocks on either side of the fault don't move very far.

Large earthquakes rupture faults that are tens to thousands of kilometers long. Such ruptures can take minutes to complete, so strong shaking near the earthquakes can last several minutes and rocks across the fault can be offset tens of meters during very large earthquakes. The large earthquakes are less frequent that small ones. The temporal distribution of earthquakes by size follows a logarithmic rule.

Inner Structure of the Earth

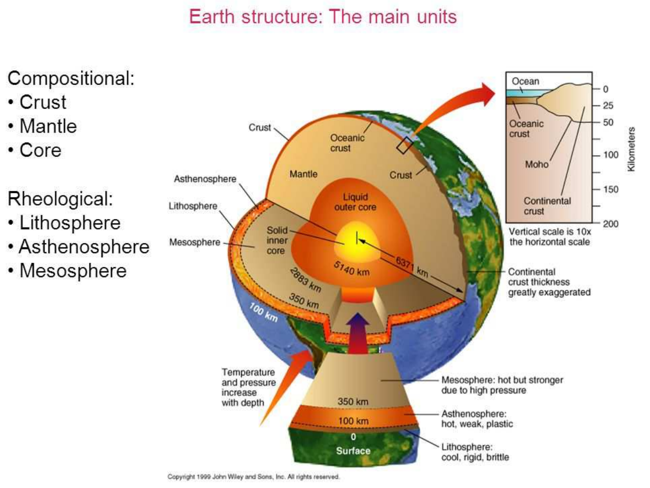

Figure 1

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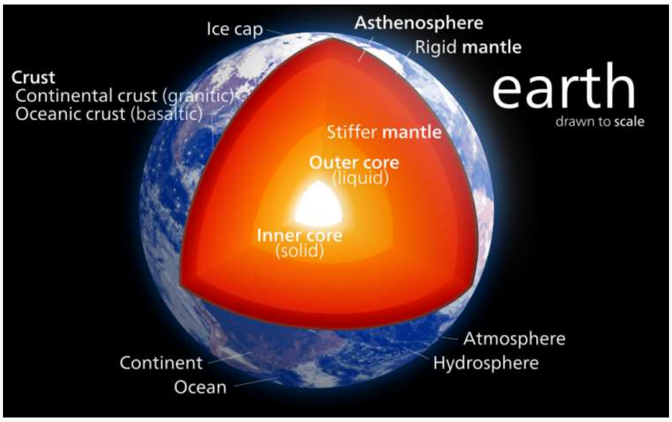

Figure 3

STRUCTURE OF THE EARTH

Earth's Interior

The interior **structure of the Earth** is layered in spherical shells. These layers can be defined by either their chemical or their rheological properties. Earth has an outer silicate solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core. Scientific understanding of the internal structure of the Earth is based on observations of topography and bathymetry, observations of rock in outcrop, samples brought to the surface from greater depths by volcanic activity, analysis of the seismic waves that pass through the Earth, measurements of the gravitational and magnetic fields of the Earth, and experiments with crystalline solids at pressures and temperatures characteristic of the Earth's deep interior.

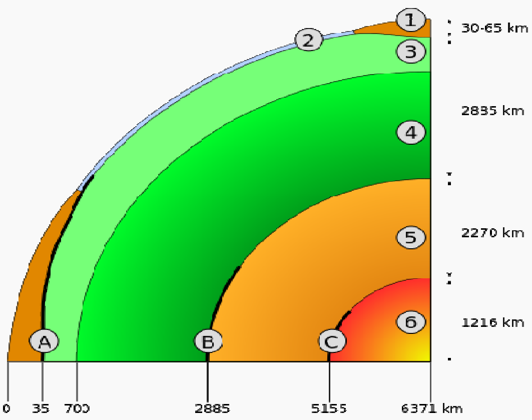

Figure 4

Schematic Representation: Inner Structure of the Earth:

- Continental crust
- Oceanic crust
- Upper mantle
- Lower mantle
- Outer core,
- Inner core

A: Mohorovičić discontinuity, B: Gutenberg discontinuity, C: Lehmann–Bullen discontinuity

The structure of Earth can be defined either by mechanical properties such as rheology or by chemical properties.

Mechanically, it can be divided into lithosphere, asthenosphere, mesospheric mantle, outer core, and the inner core. The interior of Earth is divided into 5 important layers. Chemically, Earth can be divided into the crust, upper mantle, lower mantle, outer core, and inner core. The layering of Earth has been inferred indirectly using the time of travel of refracted and reflected seismic waves created by earthquakes. The core does not allow shear waves to pass through it, while the speed of travel (seismic velocity) is different in other layers. The changes in seismic velocity between different layers causes refraction owing to Snell's law, like light bending as it passes through a prism. Likewise, reflections are caused by a large increase in seismic velocity and are similar to light reflecting from a mirror.

Core: Inner Core and Outer Core

The average density of Earth is 5,515 kg/m^3. Since the average density of surface material is only around 3,000 kg/m^3, we must conclude that denser materials exist within Earth's core. Seismic measu*rements show that the core is divided into two parts, a "solid" inner core with a radius of ~1,220* km[3] and a liquid outer core extending beyond it to a radius of ~3,400 km. The densities are between 9,900 and 12,200 kg/m^3 in the outer core and 12,600–13,000 kg/m^3 in the inner core.[4]

Mantle: Mantle (Geology)

Earth's mantle extends to a depth of 2,890 km, making it the thickest layer of Earth. The upper mantle is divided into the lithospheric mantle and the asthenosphere. The upper and lower mantles are separated by the transition zone. The lowest part of the mantle next to the core-mantle boundary is known as the D″ layer. The pressure at the bottom of the mantle is ~140 GPa (1.4 Matm). The mantle is composed of silicate rocks that are rich in iron and magnesium relative to the overlying crust. Although solid, the high temperatures within the mantle cause the silicate material to be sufficiently ductile that it can flow on very long timescales. Convection of the mantle is expressed at the surface through the motions of tectonic plates. As there is intense and increasing pressure as one travels deeper into the mantle, the lower part of the mantle flows less easily than does the upper mantle (chemical changes within the mantle may also be important). The viscosity of the mantle ranges between 10^{21} and 10^{24} Pa·s, depending on depth.[21] In comparison, the viscosity of water is approximately 10^{-3} Pa·s and that of pitch is 10^7 Pa·s.

Crust: Crust (Geology)

The crust ranges from 5–70 km (~3–44 miles) in depth and is the outermost layer. The thin parts are the oceanic crust, which underlie the ocean basins (5–10 km) and are composed of dense (mafic) iron magnesium silicate igneous rocks, like basalt. The thicker crust is continental crust, which is less dense and composed of (felsic) sodium potassium aluminium silicate rocks, like granite. The rocks of the crust fall into two major categories – sial and sima (Suess,1831–1914). It is estimated that sima starts about 11 km below the Conrad discontinuity (a second order discontinuity). The uppermost mantle together with the crust constitutes the lithosphere. The crust-mantle boundary occurs as two physically different events. First, there is a discontinuity in the seismic velocity, which is known as the Mohorovičić discontinuity or Moho. The cause of the Moho is thought to be a change in rock composition from rocks containing plagioclase feldspar (above) to rocks that contain no feldspars (below). Second, in oceanic crust, there is a chemical discontinuity between ultramafic cumulates and tectonized harzburgites, which has been observed from deep parts of the oceanic crust that have been obducted onto the continental crust and preserved as ophiolite sequences.

Many rocks now making up Earth's crust formed less than 100 million (1×10^8) years ago; however, the oldest known mineral grains are 4.4 billion (4.4×10^9) years old, indicating that Earth has had a solid crust for at least that long. [22]

The Structure of the Earth: Tectonic Plates

The Earth consists of four concentric layers: inner core, outer core, *mantle* and *crust*. The crust is made up of *tectonic* plates, which are in constant motion. Earthquakes and volcanoes are most likely to occur at plate boundaries.

The four distinct concentric layers are:

- **The inner core** is in the centre and is the hottest part of the Earth. It is solid and made up of iron and nickel with temperatures of up to 5,500°C. With its immense heat energy, the inner core is like the engine room of the Earth.

- **The outer core** is the layer surrounding the inner core. It is a liquid layer, also made up of iron and nickel. It is still extremely hot, with temperatures similar to the inner core.
- **The mantle** is the widest section of the Earth. It has a thickness of approximately 2,900 km. The mantle is made up of semi-molten rock called magma. In the upper parts of the mantle the rock is hard, but lower down the rock is soft and beginning to melt.
- **The crust** is the outer layer of the earth. It is a thin layer between 0-60 km thick. The crust is the solid rock layer upon which we all live.

There are two different types of crust: **continental crust**, which carries land, and **oceanic crust**, which carries water.

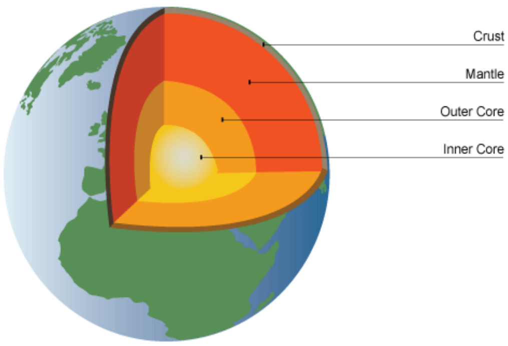

Figure 5: Four Distinct Layers of the Earth's Structure

Distribution: Tectonic Plates

The Earth's crust is broken up into pieces called plates. Heat rising and falling inside the mantle creates **convection currents** generated by radioactive decay in the core. The convection currents move the plates. Where convection currents diverge near the Earth's crust, plates move apart. Where convection currents converge, plates move towards each other. The movement of the plates, and the activity inside the Earth, is called **plate tectonics**. Plate tectonics cause earthquakes and volcanoes. The point where two plates meet is called a **plate boundary**. Earthquakes and volcanoes are most likely to occur either on or near plate boundaries.

It is to be mentioned that the Earth's plates move in different directions.

Figure 6: The map shows the world's tectonic plate and the distribution of earthquakes and volcanoes

Different Plate Boundaries

- At a **tensional**, **constructive** or **divergent boundary** the plates move apart.

- At a **compression, destructive** or **convergent** boundary the plates move towards each other.
- At a **conservative** or **transform** boundary the plates slide past each other.
- ***Tensional margins***

At a tensional or **constructive boundary** the plates are moving apart. The plates move apart due to *convection currents* inside the Earth.

Figure 7: The Helgafjell volcano on Westman Island, Iceland

As the plates move apart (very slowly), *magma* rises from the mantle. The magma erupts to the surface of the Earth. This is also accompanied by earthquakes.

When the magma reaches the surface, it cools and solidifies to form a new crust of **igneous rock**. This process is repeated many times, over a long period of time.

Eventually the new rock builds up to form a volcano. **Constructive boundaries** tend to be found under the sea, eg the Mid Atlantic Ridge. Here, chains of underwater volcanoes have formed along the *plate boundary*. One of these volcanoes may become so large that it erupts out of the sea to form a volcanic island, e.g., Surtsey and the Westman Islands near Iceland. The animation of diagram below shows how magma pushes up between the two plates, causing a chain of volcanoes along the constructive plate boundary.

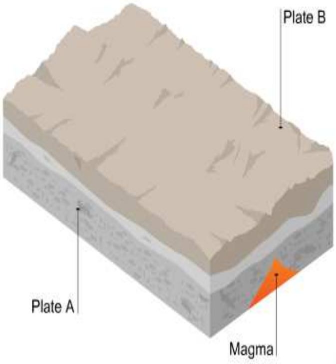

Figure 8

Compression Boundary

At a compression or **destructive boundary,** the plates are moving towards each other. This usually involves a **continental plate** and an **oceanic plate**.The oceanic plate is **denser** than the continental plate so, as they move together, the oceanic plate is forced underneath the continental plate. The point at which this happens is called the **subduction zone**. As the oceanic plate is forced below the continental plate it melts to form magma and earthquakes are triggered. The magma collects to form a *magma chamber*. This magma then rises up through cracks in the continental crust. As pressure builds up, a volcanic eruption may occur.

The animation of diagram below shows how the oceanic plate is pushed underneath the continental plate, causing mountains and possibly volcanoes to form along the destructive plate boundary.

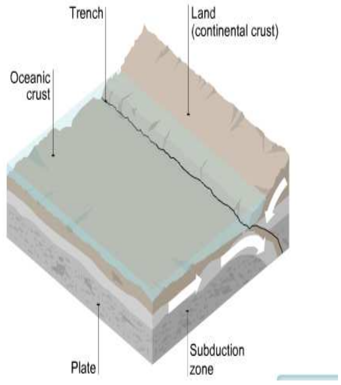

Figure 9

Figure 10: A View of the Himalayas from Gorak Shep

As the plates push together, the continental crust is squashed together and forced upwards. This is called folding. The process of folding creates ***fold mountains***. Fold mountains can also be formed where two continental plates push towards each other. This is how mountain ranges such as the **Himalayas** and the **Alps** were formed.

Earth's Interior & Plate Tectonics

(http://solarviews.com/eng/earthint.htm)

It is essential to pay attention and listen to the ring and vibration of the planet Earth in an attempt to discover its content. This is accomplished through seismology, which has become the principle method used in studying Earth's interior. Seismology on Earth deals with the study of vibrations that are produced by earthquakes. A seismograph is used to measure and record the actual movements and vibrations within the Earth and of the ground.

Scientists categorize seismic movements into four types of diagnostic waves that travel at speeds ranging from 3 to 15 kilometers (1.9 to 9.4 miles) per second. Two of the waves travel around the surface of the Earth in rolling swells. The other two, Primary (P) or compression waves and Secondary (S) or shear waves, penetrate the interior of the Earth. Primary waves compress and dilate the matter they travel through (either rock or liquid) similar to sound waves. They also have the ability to move twice as fast as S waves. Secondary waves propagate through rock but are not able to travel through liquid. Both P and S waves refract or reflect at points where layers of differing physical properties meet. They also reduce speed when moving through hotter material. These changes in direction and velocity are the means of locating discontinuities.

Figure 11: Types of seismic waves ***(Adapted from, Beatty, 1990.)***

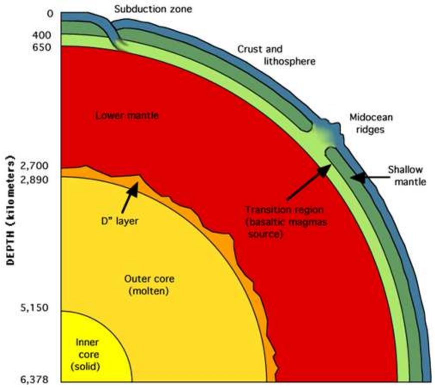

Figure 12: Image: Inner Earth's Layers

Different Layers in the Earth's Interior

Seismic discontinuities aid in distinguishing divisions of the Earth into inner core, outer core, D" layer, lower mantle, transition region, upper mantle, and crust (oceanic and continental).

- **Inner core: 1.7% of the Earth's mass; depth of 5,150-6,370 kilometers (3,219 - 3,981 miles)** The inner core is solid and unattached to the mantle, suspended in the molten outer core. It is believed to have solidified as a result of pressure-freezing which occurs to most liquids when temperature decreases or pressure increases.
- **Outer core: 30.8% of Earth's mass; depth of 2,890-5,150 kilometers (1,806 - 3,219 miles)** The outer core is a hot, electrically conducting liquid within which convective motion occurs. This conductive layer combines with Earth's rotation to create a dynamo effect that maintains a system of electrical currents known as the Earth's magnetic field. It is also responsible for the subtle jerking of Earth's rotation. This layer is not as dense as pure molten iron, which indicates the presence of lighter elements. Scientists suspect that about 10% of the layer is composed of sulfur and/or oxygen because these elements are abundant in the cosmos and dissolve readily in molten iron.
- **D" layer: 3% of Earth's mass; depth of 2,700-2,890 kilometers (1,688 - 1,806 miles)** This layer is 200 to 300 kilometers (125 to 188 miles) thick and represents about 4% of the mantle-crust mass. Although it is often identified as part of the lower mantle, seismic discontinuities suggest the D" layer might differ chemically from the lower mantle lying above it. Scientists theorize that the material either dissolved in the core, or was able to sink through the mantle but not into the core because of its density.
- **Lower mantle: 49.2% of Earth's mass; depth of 650-2,890 kilometers (406 -1,806 miles)** The lower mantle contains 72.9% of the mantle-crust mass and is probably composed mainly of silicon, magnesium, and oxygen. It probably also contains some iron, calcium, and aluminum. Scientists make these deductions by assuming the Earth has a similar abundance and proportion of cosmic elements as found in the Sun and primitive meteorites.
- **Transition region: 7.5% of Earth's mass; depth of 400-650 kilometers (250-406 miles)** The transition region

or mesosphere (for middle mantle), sometimes called the fertile layer, contains 11.1% of the mantle-crust mass and is the source of basaltic magmas. It also contains calcium, aluminum, and garnet, which is a complex aluminum-bearing silicate mineral. This layer is dense when cold because of the garnet. It is buoyant when hot because these minerals melt easily to form basalt which can then rise through the upper layers as magma.

- **Upper mantle: 10.3% of Earth's mass; depth of 10-400 kilometers (6 - 250 miles)** The upper mantle contains 15.3% of the mantle-crust mass. Fragments have been excavated for our observation by eroded mountain belts and volcanic eruptions. Olivine (Mg,Fe)2SiO4 and pyroxene (Mg,Fe)SiO3 have been the primary minerals found in this way. These and other minerals are refractory and crystalline at high temperatures; therefore, most settle out of rising magma, either forming new crustal material or never leaving the mantle. Part of the upper mantle called the asthenosphere might be partially molten.
- **Oceanic crust: 0.099% of Earth's mass; depth of 0-10 kilometers (0 - 6 miles)** The oceanic crust contains 0.147% of the mantle-crust mass. The majority of the Earth's crust was made through volcanic activity. The oceanic ridge system, a 40,000-kilometer (25,000 mile) network of volcanoes, generates new oceanic crust at the rate of 17 km^3 per year, covering the ocean floor with basalt. Hawaii and Iceland are two examples of the accumulation of basalt piles.
- **Continental crust: 0.374% of Earth's mass; depth of 0-50 kilometers (0 - 31 miles).** The continental crust contains 0.554% of the mantle-crust mass. This is the outer part of the Earth composed essentially of crystalline rocks. These are low-density buoyant minerals dominated mostly by quartz (SiO2) and feldspars (metal-poor silicates). The crust (both oceanic and continental) is the surface of the Earth; as such, it is the coldest part of our planet. Because cold rocks deform slowly, we refer to this rigid outer shell as the lithosphere (the rocky or strong layer).

The Lithosphere and Plate Tectonics

Oceanic Lithosphere

The rigid, outermost layer of the Earth comprising the crust and upper mantle is called the lithosphere. New oceanic lithosphere forms through volcanism in the form of fissures at mid-ocean ridges which are cracks that encircle the globe. Heat escapes the interior as this new lithosphere emerges from below. It gradually cools, contracts and moves away from the ridge, traveling across the seafloor to subduction zones in a process called seafloor spreading. In time, older lithosphere will thicken and eventually become more dense than the mantle below, causing it to descend (subduct) back into the Earth at a steep angle, cooling the interior. Subduction is the main method of cooling the mantle below 100 kilometers (62.5 miles). If the lithosphere is young and thus hotter at a subduction zone, it will be forced back into the interior at a lesser angle.

Continental Lithosphere

The continental lithosphere is about 150 kilometers (93 miles) thick with a low-density crust and upper-mantle that are permanently buoyant. Continents drift laterally along the convecting system of the mantle away from hot mantle zones toward cooler ones, a process known as continental drift. Most of the continents are now sitting on or moving toward cooler parts of the mantle, with the exception of Africa. Africa was once the core of Pangaea, a supercontinent that eventually broke into todays continents. Several hundred million years prior to the formation of Pangaea, the southern continents - Africa, South America, Australia, Antarctica, and India - were assembled together in what is called Gondwana.

Plate Tectonics

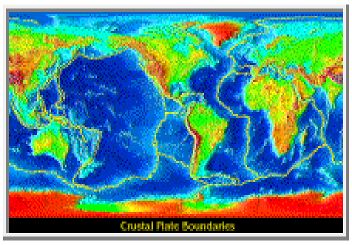

Figure 13: Crustal Plate Boundaries *(Courtesy NGDC)*

Plate tectonics involves the formation, lateral movement, interaction, and destruction of the lithosphere plates. Much of Earth's internal heat is relieved through this process and many of Earth's large structural and topographic features are consequently formed. Continental rift valleys and vast plateaus of basalt are created at plate break up when magma ascends from the mantle to the ocean floor, forming new crust and separating mid ocean ridges. Plates collide and are destroyed as they descend at subduction zones to produce deep ocean trenches, strings of volcanoes, extensive transformed faults, broad linear rises, and folded mountain belts. Earth's lithosphere presently is divided into eight large plates with about two dozen smaller ones that are drifting above the mantle at the rate of 5 to 10 centimeters (2 to 4 inches) per year. The eight large plates are the African, Antarctic, Eurasian, Indian-Australian, Nazca, North American, Pacific, and South American plates. A few of the smaller plates are the Anatolian, Arabian, Caribbean, Cocos, Philippine, and Somali plates.

Inner-core and Outer-core

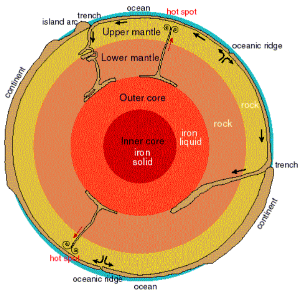

Figure 14

Inner Core

The earth's inner core is the earth's innermost part and according to seismological studies, it is primarily a solid ball with a radius of about 1220 kilometers.

Outer Core

This is a liquid layer about 2,300 km (1,400 mi)[1] thick and composed of iron and nickel that lies above Earth's solid inner core and below its mantle. Its outer boundary lies 2,890 km (1,800 mi) beneath Earth's surface. The transition between the inner core and outer core is located approximately 5,150 km (3,200 mi) beneath the Earth's surface.

Third Rock from the Sun - Restless Earth

(http://ase.tufts.edu/cosmos/print_images.asp?id=4)

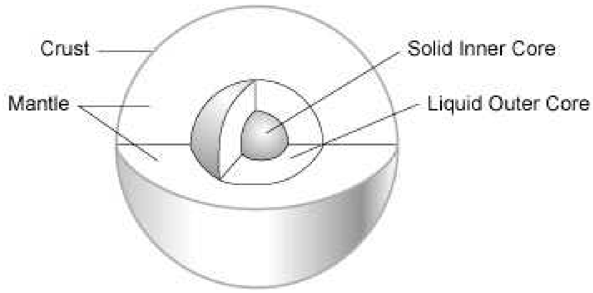

Figure 15

A relatively thin, rocky crust covers a thick silicate mantle. They overlie a liquid outer core, composed mainly of molten iron, and an inner core of solid iron. These nested layers have been inferred from seismic waves that travel through the Earth, changing velocity and direction at the layer boundaries as shown below in (Figs. A, B).

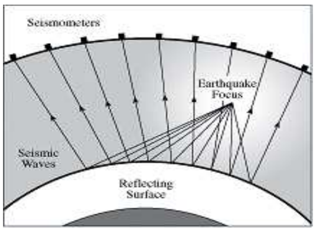

Figure 16: A

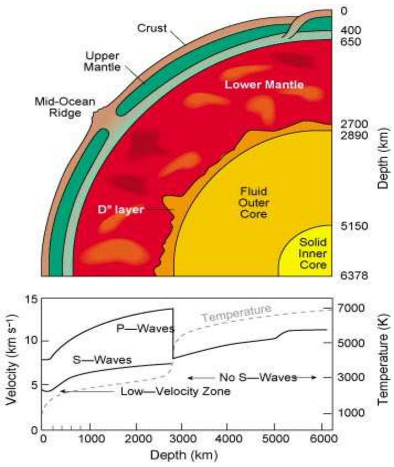

Figure 17: B

Layered Structure of the Earth

The Earth's internal structure is determined by the varying velocity of earthquake waves. There are two types of waves that travel through the Earth. They are known as the compression P, or push and pull, waves and the shear S, or shake, waves. The P waves move almost twice as fast as the S waves, and the P waves pass through the fluid outer core which the S waves cannot do. The boundary between the mantle and core is marked be a precipitous drop in the velocity of the P waves at a depth of about 2.9 million meters. The S waves do not propagate beyond this boundary. The liquid outer core is separated from the solid inner core at a radius of 1.22 thousand meters where the P waves increase in velocity.

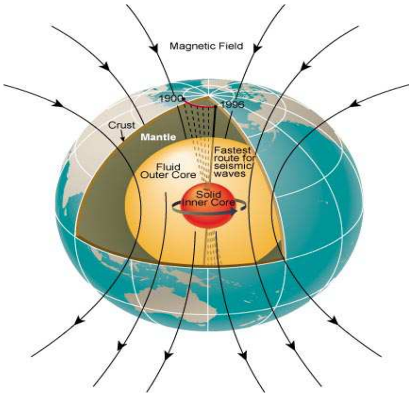

Figure 18: Image: The Earth's Double Core

The mantle and part of the crust have been cut away here to show the relative sizes of the Earth's fluid and solid cores. The outer fluid core is about 55 percent of the radius of the Earth, and the inner solid core is slightly smaller than the Moon. The Earth's magnetic field is thought to be generated and sustained by moving currents in the planet's electrically-conducting, fluid outer core, which is composed of molten iron. Geophysicists have discovered that the route of the rapid polar (north-south) waves through the Earth's interior is gradually shifting eastward because the inner core is rotating slightly faster than the rest of the planet. The fast rotation of the inner solid core may help explain how Earth's magnetic field reverses polarity (Courtesy of Paul Richards, Lamont-Doherty Earth Observatory.)

Hot Zone

http://www.pbs.org/wnet/savageearth/animations/hellscrust/main.html

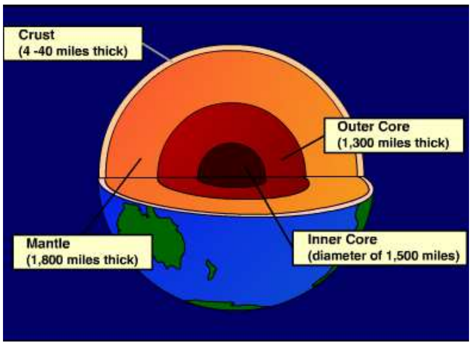

Figure 19: Image: The Hot Zone

The outermost layer of the Earth is the crust. In the oceans, it is about 4 miles thick. On the thickest continents, it extends some 40 miles into the Earth.Below the crust is the mantle, a layer of weaker, hotter rock some 1,800 miles thick.Beneath the mantle lies the outer core, a sea of liquid iron about 1,300 miles thick. Finally, at the center of the Earth is the solid iron core, a sphere some 1,500 miles across. This illustration shows the surface of the Earth and the upper part of its interior, and the forces that produce the violent activity we see on the surface. (It does not represent a picture of any real geographical area, but is meant to illustrate a number of different geological processes.)Shown at left is a collision zone where continental plates collide, as they do, for example, in the Asian subcontinent.At either edge of the ocean (blue) are subduction zones, where the edges of the heavier oceanic plate are slowly sinking below continental plates.Subduction at the oceanic plate's edges very gradually pulls the plate apart in the middle, forming what is called a "spreading center" or "mid-ocean ridge," shown at middle.

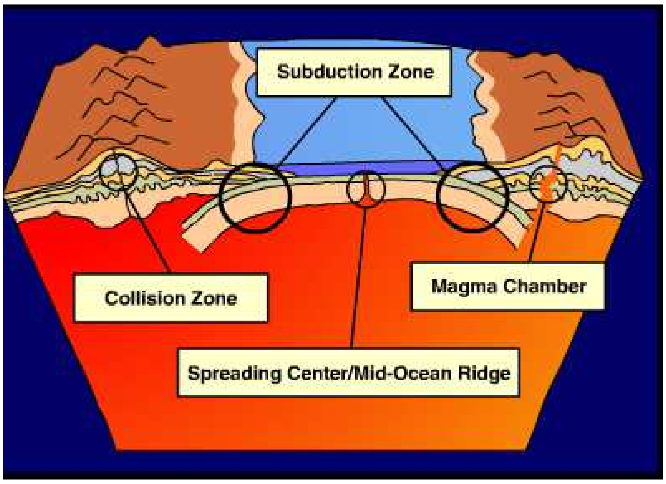

Figure 20

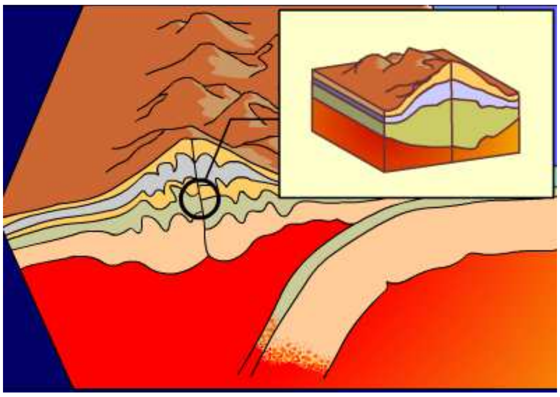

Figure 21

Where continental plates collide, they crunch together and form mountains and cause earth quake.

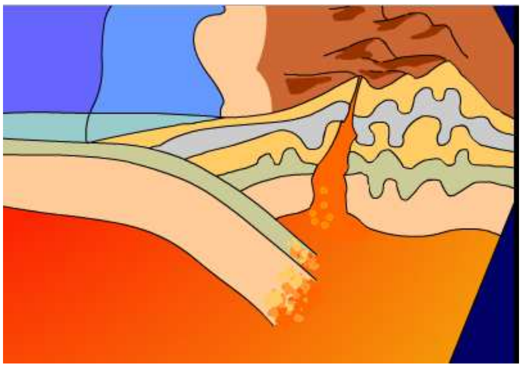

Figure 22

When the edge of a cold, rocky oceanic plate sinks in to the mantle under a continental plate, it is heated and deformed and becomes part of the mantle. Large earthquakes often occur in these areas. Volcanoes also form within the continental plate when melting occurs in the mantle above the sub -ducting oceanic plate, feeding "magma chambers" within the crust. The magma can find its way to the surface as volcanoes.

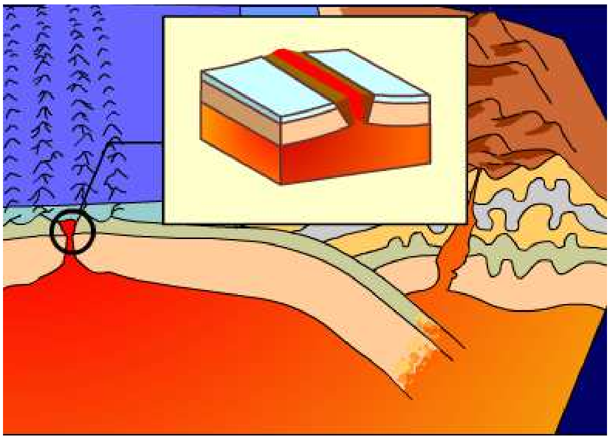

Figure 23

As its edges sub duct in different directions, the oceanic plate is pulled apart, in the middle, forming a "spreading center" or "mid ocean ridge". Magma percolates up in the middle and cools to form new crust (which gradually sinks to the sides forming a ridge). The birth of new crust is accompanied by earth quakes. (Not shown: Volcanic Island like Surtsey and Heimaey, off the coast of Iceland and featured in HELL'S CRUST, may also form)

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