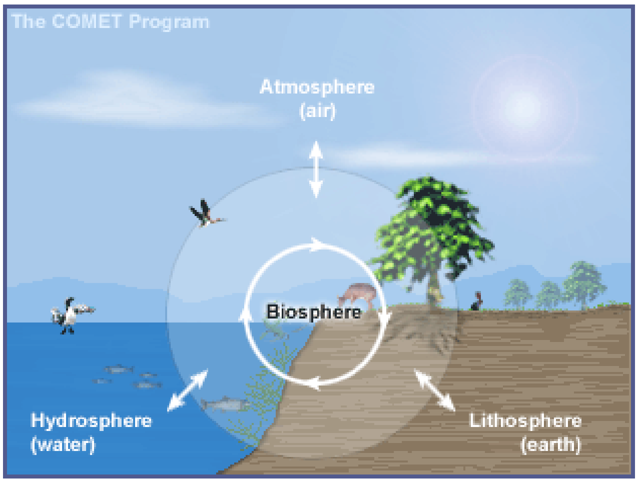
8.1.3 INSIDE THE EARTH[M31]

8.1.3.1 Spheres of Reference



In our study of our Earth, you may have noticed that we often refer to various *spheres*. To date we have encountered the atmosphere (the layer of gases surrounding the earth), the hydrosphere (the collective mass of water found over and under the surface of the earth) and the biosphere (the sum total of living organisms on the earth). As we begin our study of the geology of the earth we will be dealing with two more *spheres*—the lithosphere (from the Greek for "rocky"), the solid outermost shell of the earth, and the asthenosphere (from the Greek meaning "without strength"), a hot mobile layer of partially molten rock within the earth's upper mantle, adjacent to the lithosphere. These *spheres* are loosely related as illustrated[1].

The atmosphere and lithosphere are quite discrete, the hydrosphere exists within the lower layers of the atmosphere and the upper layers of the lithosphere, and the biosphere exists within the other three. The asthenosphere underpins the lithosphere, as we will see below.

8.1.3.2 The Structure of the Earth[2,3,4]

The size of the Earth—about 12,750 kilometers (km) in diameter—was known by the ancient Greeks. Furthermore, Isaac Newton (1642–1727) calculated, from his studies of planets and the force of gravity, that the average density of the Earth is twice that of surface rocks. He thus concluded that the Earth's interior must be composed of much denser material, but it was not until the turn of the 20th century that scientists gained any real insight into the structure of the Earth.

Our current information comes from studies of the paths and characteristics of earthquake waves travelling through the Earth, as well as from laboratory experiments on surface minerals and rocks at high pressure and temperature. Other important data on the Earth's interior come from geological observation of surface rocks and studies of the Earth's motions in the Solar System, its gravity and magnetic fields, and the flow of heat from inside the Earth.

8.1.3.2.1 Seismic Measurements[5],[6]

Seismology (from the Greek *seismos* = earthquake and *logos* = word) is the study of earthquakes and the propagation of energy waves through the Earth. Earthquakes (as well as other events and sources) produce different types of seismic waves. These waves

---

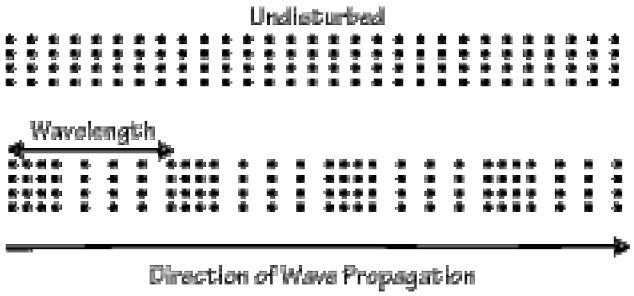
[1] http://www.ucar.edu/learn/1.htm
[2] http://pubs.usgs.gov/gip/dyamic/inside.html
[3] http://pubs.usgs.gov/gip/interior/
[4] http://www.bnsc.gov.uk/lzcontent.aspx?nid=4743
[5] http://en.wikipedia.org/wiki/Seismology
[6] http://www.visionlearning.com/library/module_viewer.php?mid=69&l=&c3

have different characteristics in different materials and thus provide a means of mapping structures deep within the Earth.

While there are several kinds of seismic waves generated by earthquakes, the two types that are relevant to a study of the Earth's interior are[7,8]:

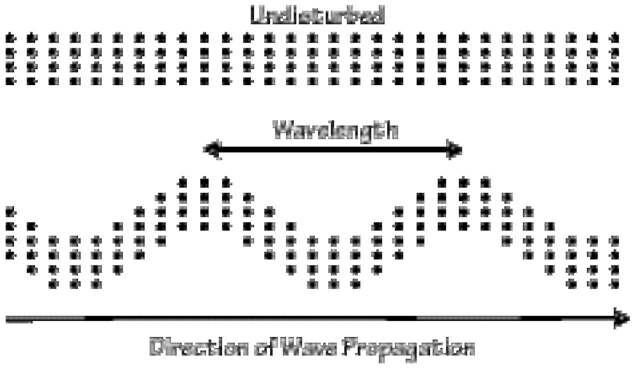
P-waves—Primary or Compressional Waves are the fastest waves, the first to be detected when an earthquake occurs. They typically travel at speeds of 1–14 km/sec, the slower speeds corresponding to P-waves travelling in water and the higher to speeds near the base of Earth's mantle.

P-waves are like sound waves—the vibration is a volume change, alternating from compression to expansion in the direction that the wave is travelling.



P-waves travel through all types of media—solid, liquid, or gas.

S-waves—Secondary or Shear waves move more slowly than P-waves, on the order of 1–8 km/sec. The lower speeds correspond to the waves in loose, unconsolidated sediment, the higher to those near the base of Earth's mantle. They are called Shear waves because they don't change the volume of the material through which they propagate, rather they shear it.



The most significant distinction between P- and S-waves in the present context, however, is that S-waves do not propagate through liquids or gases because fluids cannot transmit shear stress. Thus, S-waves can only travel through solids.

The distinction between these two waves is easy to picture with a stretched-out slinky. If you push on one end of a slinky, a compression wave passes through the slinky parallel to its length. If instead you move one end of the slinky up and down rapidly, a 'ripple' wave moves through the slinky. The compression waves are P-waves, and the ripple waves are S-waves.

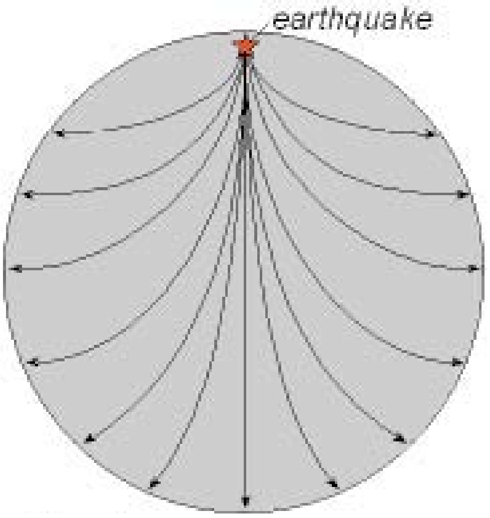
If the earth were the same composition all the way through its interior, seismic waves would radiate outward from their source (an earthquake) and behave exactly as other waves behave—taking longer to travel further and dying out in velocity and strength with distance, a process called attenuation. Given Newton's observations, if we assume

---

[7] http://www.amonline.net.au/geoscience/earth/structure.htm

[8] http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/waves_and_interior.html

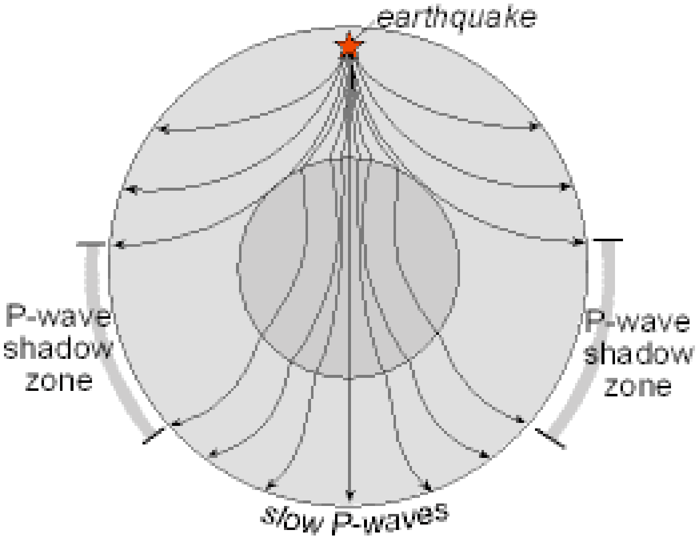
that earth's density increases evenly with depth because of the overlying pressure, wave velocity will also increase with depth and the waves will continuously refract, travelling along curved paths back towards the surface. The illustration below shows the kind of pattern we would expect to see in this case. By the early 1900s, when seismographs were installed worldwide, it quickly became clear that the earth could not possibly be so simple.



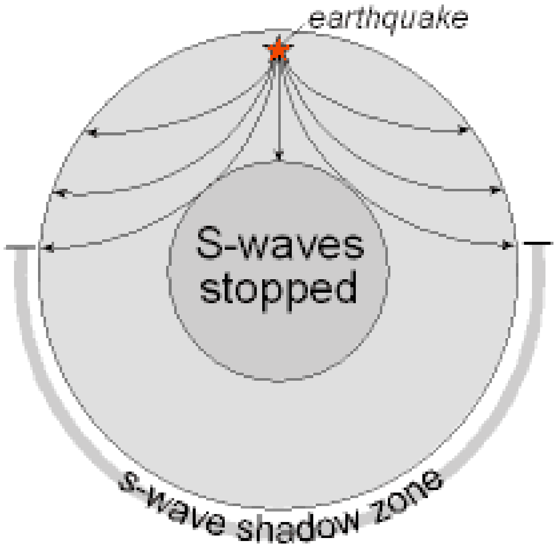
As early as 132 AD, the Chinese had built instruments to measure the ground shaking associated with earthquakes. The first modern seismographs, however, weren't built until the 1880s in Japan by British seismologists to record local earthquakes. It wasn't long before those seismologists recognized that they were also recording earthquakes occurring thousands of kilometres away.

One of the first important observations on the earth's structure was made by the Croatian seismologist Andrija Mohorovicic (1857–1936). He noticed that P-waves measured more than 200 km away from an earthquake's epicentre arrived with higher velocities than those within a 200 km radius. Although these results ran counter to the concept of attenuation, they could be explained if the waves that arrived with faster velocities travelled through a medium that allowed them to speed up. In 1909, Mohorovicic defined the first major boundary within the earth's interior—the boundary between the crust, which forms the surface of the earth, and a denser layer below, called the mantle. Seismic waves travel faster in the mantle than they do in the crust because it is composed of denser material. Thus, stations further away from the source of an earthquake received waves that had made part of their journey through the denser rocks of the mantle. The waves that reached the closer stations stayed within the crust the entire time. Although the official name of the crust-mantle boundary is the Mohorovicic discontinuity, in honour of its discoverer, it is usually called the Moho.

Another observation made by seismologists was the fact that P-waves die out about 105° away from an earthquake, then reappear about 140° away, arriving much later than expected. This region that lacks P-waves is called the P-wave shadow zone, as illustrated below.



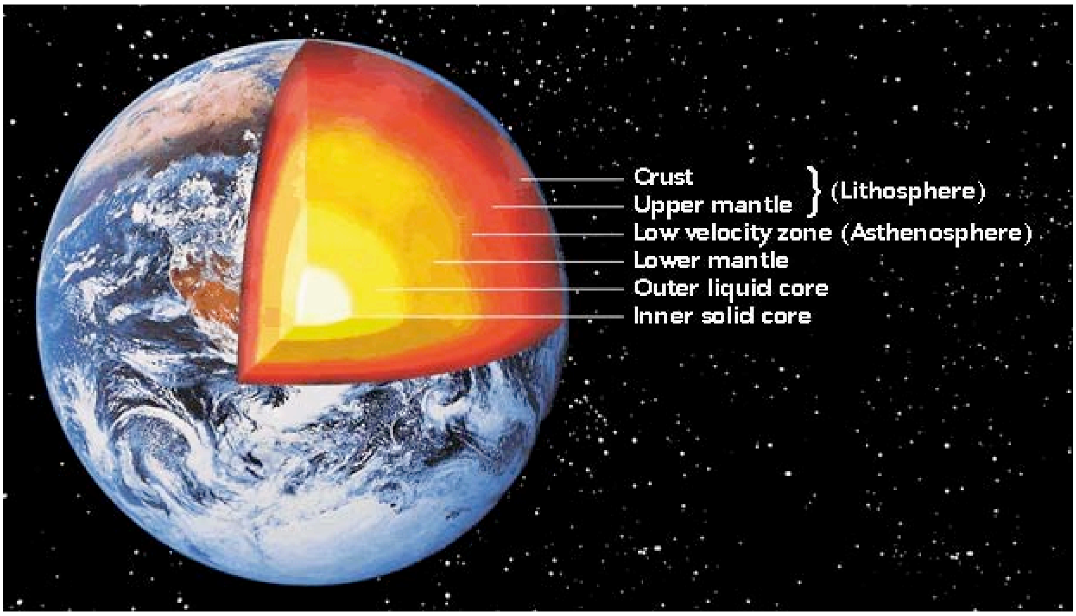
S-waves, on the other hand, die out completely around 105° from the earthquake.



Remember that S-waves are unable to travel through liquid. The S-wave shadow zone indicates that there is a liquid layer deep within the earth that stops all S-waves but not the P-waves. In the early 20th century, seismologists Richard Dixon Oldham (1858–1936), Beno Gutenberg (1889–1960) and Harold Jeffreys (1891–1989) each contributed to the determination that there was another layer inside of the earth, called its core. Gutenberg defined a sharp core-mantle boundary at a depth of 2,900 km, where P-waves were refracted and slowed and S-waves were stopped.

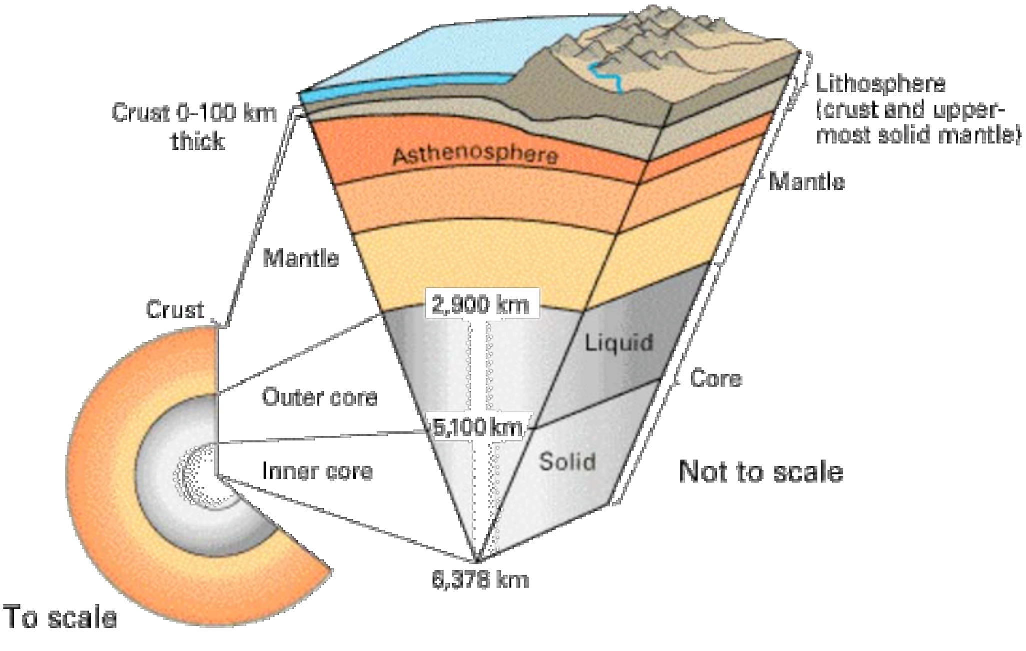
In 1936, after improvements in seismographs in the 1920s made it possible to 'see' previously undetectable seismic waves within the P-wave shadow zone, the Danish seismologist Inge Lehmann (1888–1993) determined further that the Earth must not only have a molten interior, but also a solid core at the centre. These faint waves indicated that they had been refracted again within the core when they hit the boundary between the inner and outer core.

Our picture of the interior of the earth becomes clearer as imaging techniques improve. Seismic tomography is a relatively new technique that uses seismic waves to measure very slight temperature variations throughout the mantle. Because waves move faster through cold material and slower through hot material, the images they receive help scientists 'see' the process of convection in the mantle. These and other images offer a virtual journey into the centre of the earth.

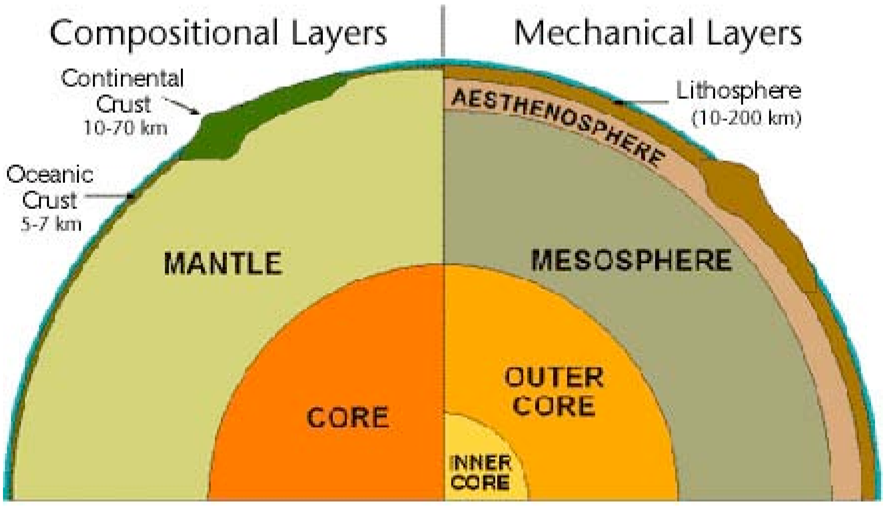


8.1.3.2.2 The Layers of the Earth

On the basis of these and other observations, geophysicists have created a cross-section of the earth.



The early seismological studies previously discussed led to definitions of compositional boundaries; for example, imagine oil floating on top of water—they are two different materials, so there is a compositional boundary between them. Later studies highlighted mechanical boundaries, which are defined on the basis of how materials act, not on their composition. Water and oil have the same mechanical properties—they are both liquids. On the other hand, water and ice have the same composition, but water is a fluid with far different mechanical properties than solid ice.



Compositional Layers

There are two major types of crust: crust that makes up the ocean floors and crust that makes up the continents. Oceanic crust is composed entirely of basalt extruded at mid-ocean ridges, resulting in a thin (~5 km), relatively dense crust (~3.0 g/cm^3). Continental crust, on the other hand, is made primarily of less dense rock such as granite (~2.7 g/cm^3). It is much thicker than oceanic crust, ranging from 15 to 70 km.

At the base of the crust is the Moho, below which is the mantle, which contains rocks made of a denser material called peridotite (~3.4 g/cm^3). The mantle, which contains more iron, magnesium, and calcium than the crust, is hotter and denser because temperature and pressure inside the Earth increase with depth. This compositional change is predicted by the behaviour of seismic waves and it is confirmed in the few samples of rocks from the mantle that we do have.

At the core-mantle boundary, composition changes again. Seismic waves suggest this material is of a very high density (10-13 g/cm^3), which can only correspond to a composition of metals rather than rock. The presence of a magnetic field around the earth is also consistent with the presence of a metallic core. Unlike the crust and the mantle, we don't have any samples of the core and can only speculate as to its composition. The current consensus, however, is that it is made up of an iron-nickel alloy with a temperature of around 4,000 kelvin.

Mechanical Layers

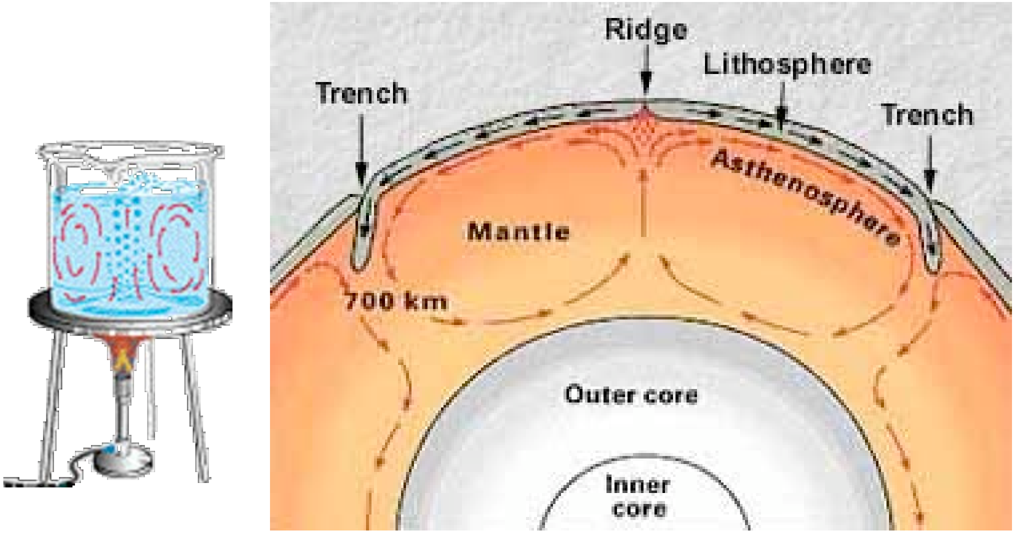
The compositional divisions of the earth were understood decades before the development of the theory of plate tectonics—the idea that the earth's surface consists of large plates that move. By the 1970s, however, geologists began to realise that the plates had to be thicker than just the crust, or they would break apart as they moved. In fact, plates consist of the crust acting together with the uppermost part of the mantle; this rigid layer is called the lithosphere and it ranges in thickness from about 10 to 200 km. Rigid lithospheric plates 'float' on a partially molten layer called the aesthenosphere that flows like a very viscous fluid, like Silly Putty. It is important to note that although the aesthenosphere can flow, it is not a liquid, and thus both P- and S- waves can travel through it. At a depth of 660 km, pressure becomes so great that the mantle can no longer flow, and this solid part of the mantle is called the mesosphere. The lithospheric mantle, aesthenosphere, and mesosphere all share the same composition (that of peridotite), but their mechanical properties are significantly different. Geologists often refer to the aesthenosphere as the jam in between two pieces of bread: the lithosphere and mesosphere.

The core is also subdivided into an inner and outer core. The outer core is liquid molten metal (and able to stop S-waves) while the inner core is solid. Because the composition of the core is different than that of the mantle, it is possible for the core to remain a liquid at much higher pressures than peridotite.

8.1.3.3 Plate Tectonics[9]

The upper part of the mantle is cooler and more rigid than the deep mantle; in many ways, it behaves like the overlying crust. Together the crust and the upper part of the mantle form a rigid layer of rock called the *lithosphere* (from *lithos,* Greek for stone). The lithosphere tends to be thinnest under the oceans and in volcanically active continental areas, such as the Western United States. Averaging at least 80 km in thickness over much of the Earth, the lithosphere has been broken up into the moving *plates* that contain the world's continents and oceans. Scientists believe that below the lithosphere is a relatively narrow, mobile zone in the mantle called the *asthenosphere* (from *asthenes,* Greek for weak). This zone is composed of hot, semi-solid material, which can soften and flow after being subjected to high temperature and pressure over geologic time.

Movement of the rigid lithospheric plates appears to be driven by convection within the mobile asthenosphere. Hot mantle material rises beneath mid-oceanic ridges, and cold, denser mantle material descends at oceanic trenches. Lateral motion of the lithospheric plates above these circular convection cells is analogous to rigid blocks riding above a rotating conveyor belt.



Convection currents in the earth's mantle appear to drive the movement of tectonic plates

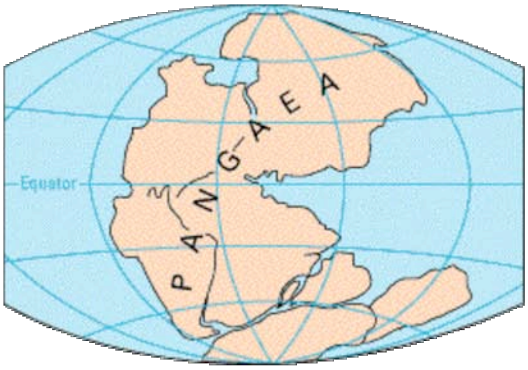
In geologic terms, a *plate* is a large, rigid slab of solid rock. The word *tectonics* comes from the Greek root "to build". Putting these two words together, we get the term *plate tectonics*, which refers to how the Earth's surface is built of plates. The *Theory of Plate Tectonics* states that the Earth's outermost layer is fragmented into a dozen or more large and small plates that are moving relative to one another as they ride atop hotter, more mobile material. Before the advent of the plate tectonic theory, however, some people already believed that the present-day continents were the fragmented pieces of preexisting larger landmasses (*supercontinents*). The diagrams below show the break-up of the supercontinent *Pangaea* (meaning "all lands" in Greek), which figured

---

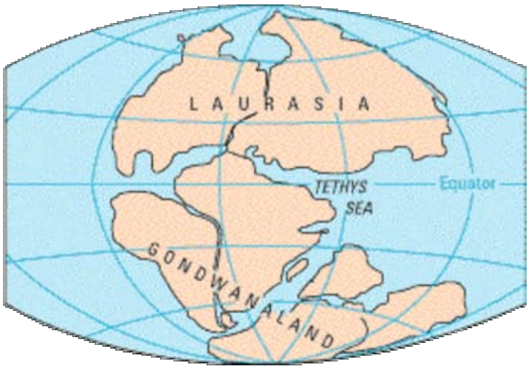
[9] http://pubs.usge.gov/gip/dynamic/historical.html#anchor9464740

prominently in the *Theory of Continental Drift*—the forerunner to the Theory of Plate Tectonics.

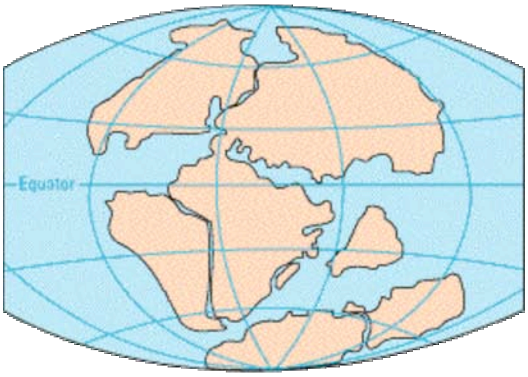
According to the continental drift theory, the supercontinent *Pangaea* began to break up about 225-200 million years ago, eventually fragmenting into the continents as we know them today.



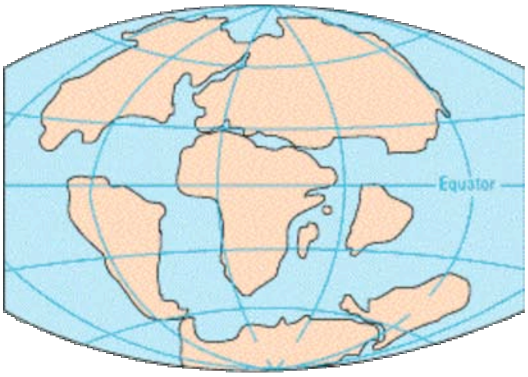
PERMIAN
225 million years ago



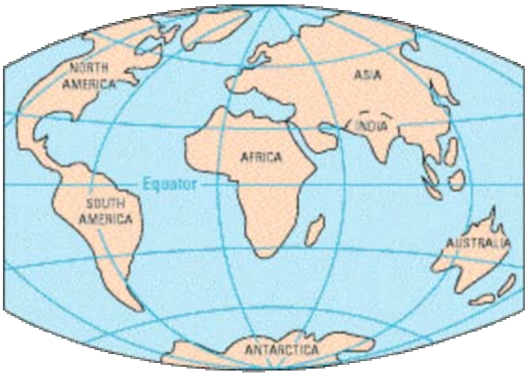
TRIASSIC
200 million years ago



JURASSIC
135 million years ago



CRETACEOUS
65 million years ago



PRESENT DAY

Plate tectonics is a relatively new scientific concept, introduced some 30 years ago, but it has revolutionised our understanding of the dynamic planet upon which we live. The theory has unified the study of the Earth by drawing together many branches of the earth sciences, from paleontology (the study of fossils) to seismology (the study of earthquakes). It has provided explanations to questions that scientists had speculated upon for centuries—such as why earthquakes and volcanic eruptions occur in very specific areas around the world, and how and why great mountain ranges like the Alps and Himalayas formed. Why is the Earth so restless? What causes the ground to shake violently, volcanoes to erupt with explosive force, and great mountain ranges to rise to incredible heights?

Scientists, philosophers, and theologians have wrestled with questions such as these for centuries. Until the 1700s, most Europeans thought that a Biblical Flood played a major role in shaping the Earth's surface. This way of thinking was known as *catastrophism,* and geology (the study of the Earth) was based on the belief that all earthly changes were sudden and caused by a series of catastrophes. However, by the mid-19th century, catastrophism gave way to *uniformitarianism,* a new way of thinking centred around the "Uniformitarian Principle" proposed in 1785 by James Hutton (1726–1797), a Scottish geologist. This principle is commonly stated as follows: *The present is the key to the past.* Those holding this viewpoint assume that the geologic forces and processes—gradual as well as catastrophic—acting on the Earth today are the same as those that have acted in the geologic past.

The belief that continents have not always been fixed in their present positions was suspected long before the 20th century; this notion was first suggested as early as 1596 by the Dutch map maker Abraham Ortelius (1527–1598) in his work *Thesaurus Geographicus*. Ortelius suggested that the Americas were "torn away from Europe and Africa . . . by earthquakes and floods" and went on to say: "The vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three [continents]." Ortelius' idea surfaced again in the 19th century. However, it was not until 1912 that the idea of moving continents was seriously considered as a full-blown scientific theory—called *Continental Drift*—introduced in two articles published by a 32-year-old German meteorologist named Alfred Lothar Wegener (1880–1930). He contended that, around 200 million years ago, the supercontinent Pangaea began to split apart. Alexander Du Toit (1878–1948), Professor of Geology at Johannesburg University and one of Wegener's staunchest supporters, proposed that Pangaea first broke into two large continental landmasses, *Laurasia* in the northern hemisphere and *Gondwanaland* in the southern hemisphere. Laurasia and Gondwanaland then continued to break apart into the various smaller continents that exist today.

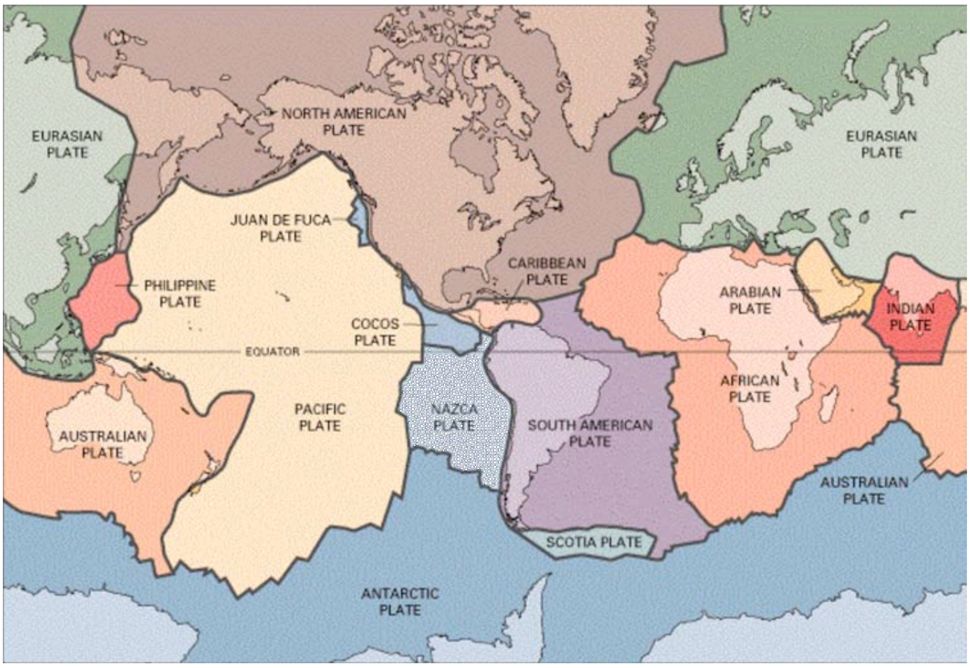
Wegener's theory was based in part on what appeared to him to be the remarkable fit of the South American and African continents, first noted by Abraham Ortelius three centuries earlier. Wegener was also intrigued by the occurrences of unusual geologic structures and of plant and animal fossils found on the matching coastlines of South America and Africa, which are now widely separated by the Atlantic Ocean. He reasoned that it was physically impossible for most of these organisms to have swum or have been transported across the vast oceans. To him, the presence of identical fossil species along the coastal parts of Africa and South America was the most compelling evidence that the two continents were once joined.

In Wegener's mind, the drifting of continents after the break-up of Pangaea explained not only the matching fossil occurrences but also the evidence of dramatic climate changes on some continents. For example, the discovery of fossils of tropical plants (in the form of coal deposits) in Antarctica led to the conclusion that this frozen land previously must have been situated closer to the equator, in a more temperate climate where lush, swampy vegetation could grow. Other mismatches of geology and climate included distinctive fossil ferns *(Glossopteris)* discovered in now-polar regions, and the occurrence of glacial deposits in present-day arid Africa, such as the Vaal River valley of South Africa.

The *Theory of Continental Drift* would become the spark that ignited a new way of viewing the Earth. But at the time Wegener introduced his theory, the scientific community firmly believed the continents and oceans to be permanent features on the Earth's surface. Not surprisingly, his proposal was not well received, even though it seemed to agree with the scientific information available at the time. A fatal weakness in Wegener's theory was that it could not satisfactorily answer the most fundamental question raised by his critics: What kind of forces could be strong enough to move such large masses of solid rock over such great distances? Wegener suggested that the continents simply plowed through the ocean floor, but Harold Jeffreys (1891–1989), a noted English geophysicist, argued correctly that it was physically impossible for a large mass of solid rock to plow through the ocean floor without breaking up.

Undaunted by rejection, Wegener devoted the rest of his life to doggedly pursuing additional evidence to defend his theory. He froze to death in 1930 during an expedition crossing the Greenland ice cap, but the controversy he spawned raged on. After his death, however, new evidence from ocean floor exploration and other studies rekindled interest in Wegener's theory, ultimately leading to the development of the *Theory of Plate Tectonics*.

Plate Tectonics has proven to be as important to the earth sciences as the discovery of the structure of the atom was to physics and chemistry and the Theory of Evolution was to the life sciences. Even though the Theory of Plate Tectonics is now widely accepted by the scientific community, aspects of the theory are still being debated today. For example, scientists debate how plate tectonics may have operated (if at all) earlier in the Earth's history and whether similar processes operate, or have ever operated, on other planets in our solar system.



Earth's tectonic plate boundaries[10]

Like many features on the Earth's surface, plates change over time. Those composed partly or entirely of oceanic lithosphere can sink under another plate, usually a lighter, mostly continental plate, and eventually disappear completely. This process is happening now off the coast of Oregon and Washington. The small Juan de Fuca Plate, a remnant of the formerly much larger oceanic Farallon Plate, will someday be entirely consumed as it continues to sink beneath the North American Plate.

---

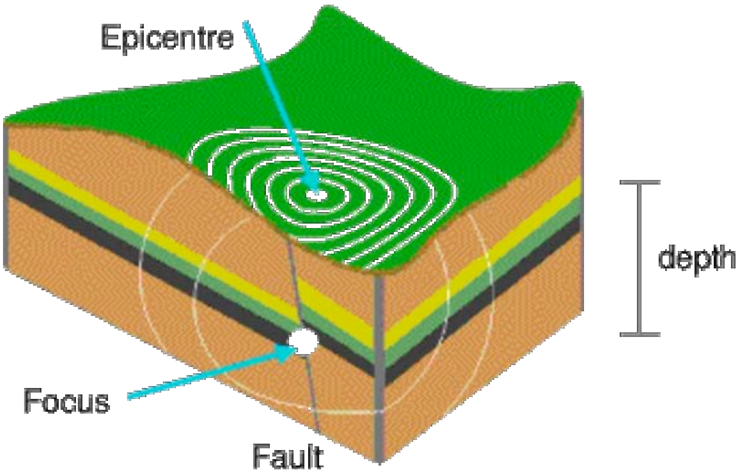
[10] http://pubs.usgs.gov/gip/dynamic/slabs.html

8.1.3.4 Earthquakes[11]

8.1.3.4.1 What are Earthquakes?

Earthquakes are the Earth's natural means of releasing stress. When the Earth's tectonic plates move against each other, the lithosphere becomes stressed. When this stress is great enough, the lithosphere breaks or shifts—rocks crack and slip past each other, creating what is known as a fault. When the break occurs, the stress is released as vast quantities of energy that move through the Earth in the form of waves.

As the initial break in the lithosphere propagates, it releases energy along the fault, so in a sense the earthquake originates from the entire fault—which may be 1,000 km long. However, it is useful to refer to one part of the fault as the place of origin of an earthquake, and this is taken as the initial break. It is called the **focus** of the earthquake. The focus may be close to the surface or many 10s of kilometres down. The point on the Earth's surface directly above the focus is called the **epicentre**.



The location of the focus and epicentre of an earthquake[12]

Some of the energy released by an earthquake is transferred to heat, but the majority is transferred as wave energy and transmitted for long distances. The shaking motion of an earthquake is the result of this sudden release of energy.

A large earthquake is frequently followed by a series of smaller earthquakes on the same fault, called aftershocks. These can continue for months after the main earthquake. They are caused by readjustment in the positions of the rocks following the main earthquake, releasing smaller, localised build-ups of energy on the fault. Sometimes the main earthquake is preceded by one or more smaller foreshocks, although these cannot be identified as foreshocks until after the main earthquake has occurred.[13]

8.1.3.4.2 Types of Earthquakes[14]

Earthquakes may occur naturally or as a result of human activities. In its most generic sense, the word earthquake is used to describe any seismic event that generates seismic waves, regardless of its origin.

---

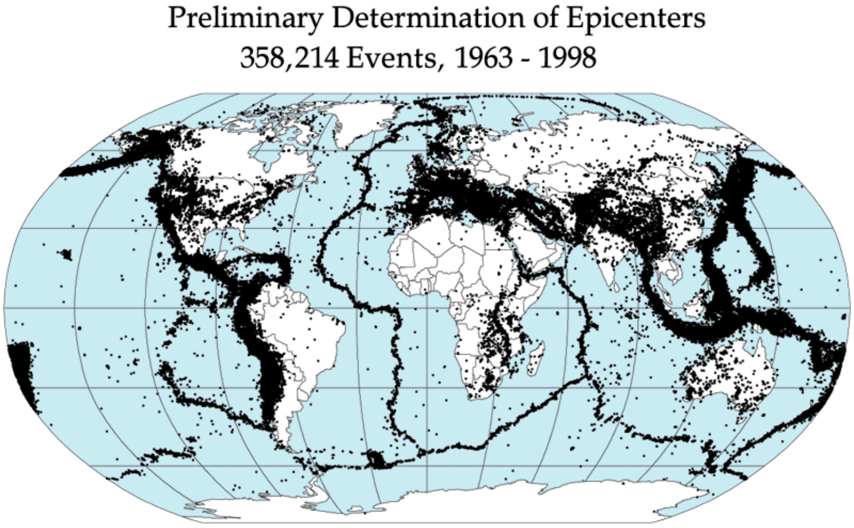
[11] http://scign.jpl.nasa.gov/learn/eq1.htm
[12] http://www.stvincent.ac.uk/Resources/EarthSci/Earth/waves.html
[13] http://openlearn.open.ac.uk/mod/resource/view.php?id=100266
[14] http://scign.jpl.nasa.gov/learn/eq2.htm

There are many different types of earthquakes. The most common are tectonic earthquakes. These occur when rocks in the earth's crust break due to geological forces created by movement of tectonic plates. Plate boundaries grind past each other, creating frictional stress. When the frictional stress exceeds a critical value, a sudden failure occurs. The boundaries of tectonic plates along which failures occur are called fault planes. When a failure at a fault plane results in a violent displacement of the Earth's crust, elastic strain energy is released and seismic waves are radiated, resulting in an earthquake.

Earthquakes may also occur in volcanic regions, as a result of the movement of magma in volcanoes. Such quakes can be an early warning of volcanic eruptions.

Smaller, collapse earthquakes can follow the collapse of underground caverns and mines, and explosion earthquakes can be generated by the detonation of nuclear and chemical devices. Earthquakes induced by explosions, however, display different seismic wave characteristics to the different kinds of natural earthquakes, making it a relatively simple task to differentiate between the two.

The illustration below plots the epicentres of all earthquakes recorded in the period 1963–1998. Note the concentration of occurrences around the boundaries of the Earth's tectonic plates, and particularly in subduction zones.



Global earthquake epicentres, 1963-1998[15]

Earthquakes happen every day around the world, but most of them go unnoticed and cause no damage.

8.1.3.4.3 Measuring Earthquakes[16]

Earthquakes can be measured in several ways. The first way is to describe the earthquake's intensity. Intensity is the measure, in terms of degrees, of damage to the Earth's surface and the effects on humans. Intensity records only observations of effects on the crust, not actual ground motion or wave amplitudes that can be recorded by instruments. While intensity helps to determine how large an area might have been effected, it is not an accurate measure for several reasons. Only the effect on an area showing the greatest direct impact tends to be reported, which may imply a greater or lesser intensity than that which actually occurred. Further, the way in which seismic waves travel varies with the type of rock through which they pass. As a result, an area

---

[15] http://denali.gsfc.nasa.gov/dtam/seismic/

[16] http://scign.jpl.nasa.gov/learn/eq8.htm

close to the focus of an earthquake that is located on loose sediment may feel nothing, while other areas at quite a distance, but located on compact, homogenous rock, may feel the effects far more.

The second type of measurement is the magnitude of the earthquake. Magnitude does not depend on population and effects to ground structures, but rather on seismic wave amplitude and the distance of the recording station from the earthquake focus. Magnitude is determined using mathematical formulae and information from seismograms. There are several scales used to record magnitudes, the best known being the Richter scale. Like most magnitude scales, the Richter scale is logarithmic—each unit in the scale represents a ten-fold change in magnitude.

Another way to measure vertical and horizontal movement of the earth is through the use of the Global Positioning System. GPS is a navigation and positioning system developed by the Department of Defence in the early 1970's. Among its many applications, scientists use GPS to monitor the movement of the Earth's crust, all over the world, between and during earthquakes. From these measurements, maps and models can be created to show how fast and in what direction the crust is moving due to both plate and fault movement.

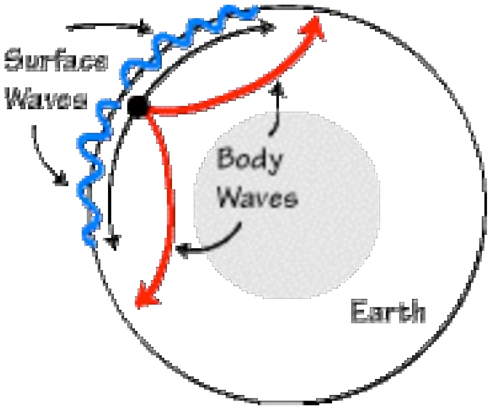
8.1.3.4.4 Seismic Waves[17]

Seismic waves propagate spherically out from the focus of an earthquake, in the same way that circular waves spread over the surface of a pond when a stone is thrown into the water. An earthquake, however, is a more complicated process than a stone splashing into water, and the seismic waves that are set up during an earthquake are more varied than those on the pond.

Seismic waves can be distinguished by a number of properties including the speed the waves travel, the direction that the waves move particles as they pass by, and where they don't propagate. The are many different seismic waves, but there are basically four types:

- Body Waves
    - P (for Prmary) or Compression Waves
    - S (for Secondary) or Transverse or Shear Waves
- Surface Waves
    - Love Waves
    - Rayleigh Waves

The first two wave types, P and S, are called body waves because they travel or propagate through the body of Earth. The latter two are called surface waves they the travel along Earth's surface and their amplitude decreases with depth into the Earth. An earthquake radiates P and S waves in all directions and the interaction of the P and S waves with the Earth's surface and shallow structures produces surface waves.



Seismic Waves: Body Waves and Surface Waves[18]

---

[17] http://scign.jpl.nasa.gov/learn/eq6.htm

[18] http://eqseis.geosc.psu.edu/~cammon/HTML/Classes/IntroQuakes/Notes/waves_and_interior.html

Seismic waves decrease in intensity the farther away from the focus of an earthquake they travel, as the energy released by the earthquake spreads throughout a larger volume of Earth. The waves also become more separated in time the further they travel because P, S, and surface waves travel at different speeds.

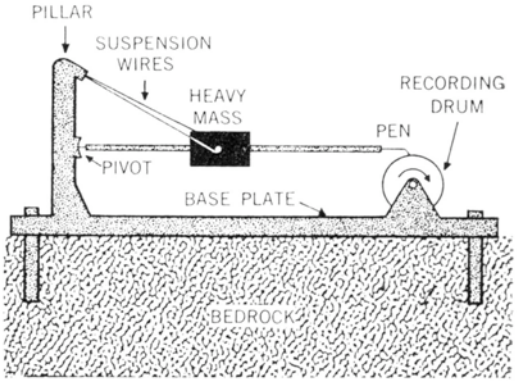
As we noted earlier, the P wave, or primary wave, is the fastest of the three waves and the first detected by seismographs. They are able to move through both liquid and solid rock. P waves, like sound waves, are compression waves, which means that they compress and expand matter as they move through it. S waves, or secondary waves, are the waves directly following the P waves. As they move, S waves shear, or cut the rock they travel through sideways at right angles to the direction of motion. S waves cannot travel through liquid because, while liquid can be compressed, it can't shear.

Both P and S waves are called body-waves because they move within the Earth's interior. Their speeds vary depending on the density and the elastic properties of the material they pass through, and they are amplified as they reach the surface.

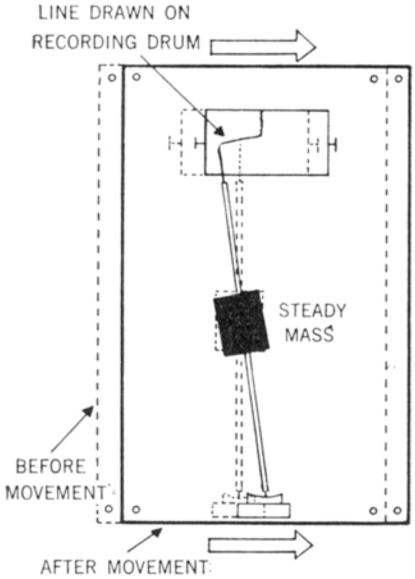
The second group of waves comprise the surface waves, which travel more slowly than the body waves. These waves move close to or on the outside surface of the ground and are the ones responsible for most of the damage caused by earthquakes. There are two main types of surface waves: Love waves and Rayleigh waves. Love waves, named after the English mathematician Augustus Love (1863–1940) who first predicted their existence, move like S-waves but only horizontally. Rayleigh waves, after the English physicist John William Strutt, Lord Rayleigh, (1842–1919) who first predicted their existence, move in a similar way to water waves in the ocean, in a vertical plane pointed in the direction of travel[19].

Detection and Recording[20]

Geologists use seismographs to record the seismic waves generated by earthquakes. Traditional instruments employed a pen on a pendulum-like arm that recorded ground movements on a revolving drum. Modern instruments, however, use electronic sensors connected directly to computers, which can provide instant access to seismic information from locations all around the globe.



Horizontal pendulum seismograph



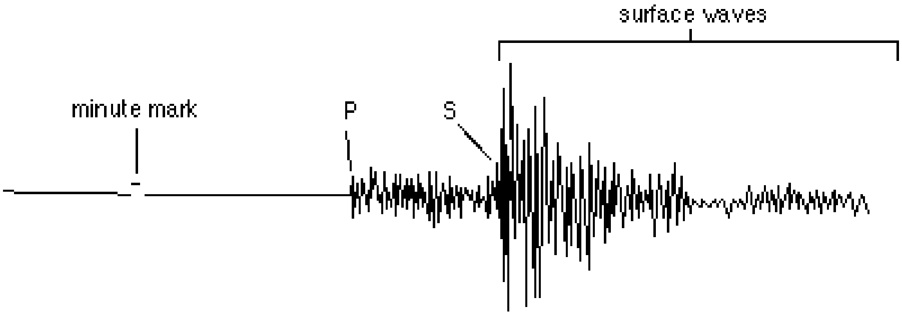
---

[19] For a demonstration of the particle motion which gives rise to each wave type, see the Featured Lesson on Seismic Waves at: http://sunshine.chpc.utah.edu

[20] http://scign.jpl.nasa.gov/learn/eq7.htm

In any case, when motion is detected a seismogram is created, recording information about the seismic waves involved—how big they were and how long they lasted. P waves are recorded first, followed by S waves and then surface waves. While surface waves are the last to reach the seismograph, they generally last the longest time.

The following is an illustration of a typical seismogram. The wiggly lines are a record of all the seismic waves that the seismograph has recorded.



Seismographic Trace[21]

Most of these waves were so small that nobody felt them. These tiny microseisms can be caused by heavy traffic near the seismograph, waves hitting a beach, the wind, and any number of other ordinary things that cause some shaking of the seismograph. There may also be some little dots or marks evenly spaced along the paper. For a traditional seismograph, there are marks for every minute that the drum of the seismograph has been turning.

So which wiggles are the earthquake? The P-wave will be the first wiggle that is bigger than the rest of the little ones (the microseisms). Because P-waves are the fastest seismic waves, they will usually be the first ones that a seismograph records. The next set of seismic waves on a seismogram will be the S-waves. These are usually bigger than the P-waves. If there are S-waves recorded on a seismogram, it probably means the earthquake happened on the other side of the planet—S-waves can't travel through the liquid layers of the earth.

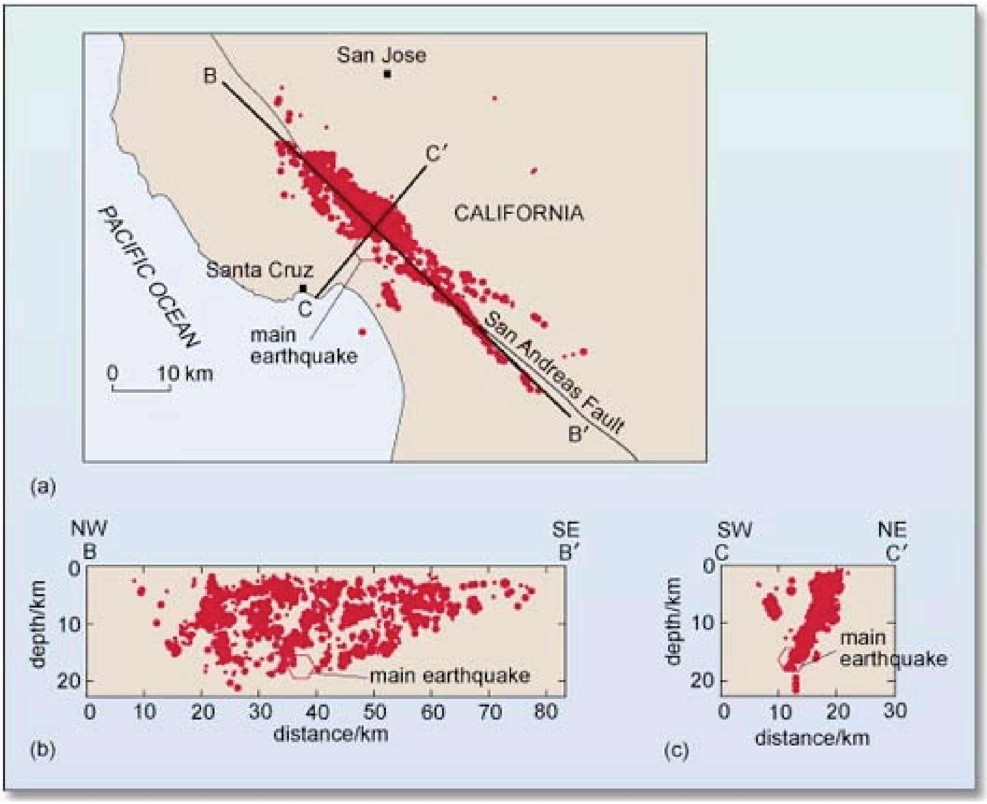
The surface waves (Love and Rayleigh waves) are the other, often larger, waves marked on the seismogram. Surface waves travel a little slower than S-waves (which are slower than P-waves) so they tend to arrive at the seismograph just after the S-waves. For shallow earthquakes (earthquakes with a focus near the surface of the earth), the surface waves may be the largest waves recorded by the seismograph. Often they are the only waves recorded a long distance from medium-sized earthquakes.

Using the information from several seismographic recordings, the epicentre and focus of the earthquake can be located using triangulation.[22]

---

[21] http://www.geo.mtu.edu/UPSeis/reading.html

[22] For an excellent on-line, animated and interactive lesson on seismogram analysis, see http://www.learninggeoscience.net/



Epicentral map (a), and cross-sections (b) and (c), showing the foci for the main earthquake and aftershocks of the Loma Prieta earthquake, California, 1989[23]

8.1.3.4.5 Richter Magnitude Scale[24]

The Richter magnitude test scale (or more correctly local magnitude M_L scale) assigns a single number to quantify the size of an earthquake. Developed in 1935 by Charles Richter (1900–1985) in collaboration with Beno Gutenberg (1889–1960), the scale was originally intended to be used only in a particular study area in California, and on seismograms recorded on a particular instrument, the Wood-Anderson torsion seismometer. Richter's motivation for creating the local magnitude scale was simply to separate the vastly larger number of smaller earthquakes from the few larger earthquakes observed in California at the time.

The inspiration for the technique was the stellar magnitude scale used in astronomy to describe the brightness of stars and other celestial objects. Richter arbitrarily chose a magnitude 0 event to be an earthquake that would show a maximum combined horizontal displacement of 1 micrometre on a seismogram recorded using a Wood-Anderson torsion seismometer 100 km from the earthquake epicentre. This choice was intended to prevent negative magnitudes from being assigned. However, the Richter scale has no upper or lower limit, and sensitive modern seismographs now routinely record quakes with negative magnitudes.

The following describes the typical effects of earthquakes of various magnitudes near the epicentre. This table should be taken with extreme caution, since intensity and thus ground effects depend not only on the magnitude, but also on the distance to the epicentre, and geological conditions (certain terrains can amplify seismic signals).

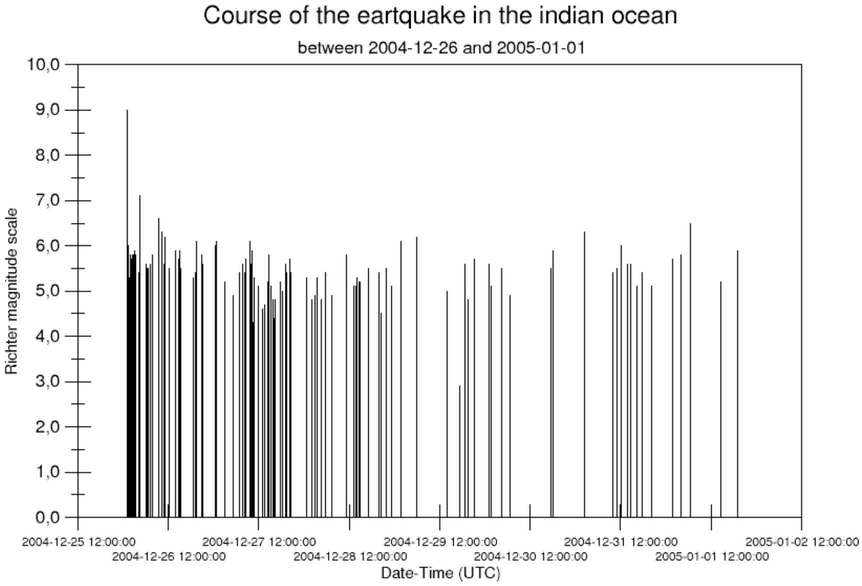
---

[23] http://openlearn.open.ac.uk/mod/resource/view.php?id=100266#FIG007_005

[24] http://en.wikipedia.org/wiki/Richter_magnitude_scale

Description	**Richter Magnitudes**	**Earthquake Effects**	**Frequency of Occurrence**
Micro	Less than 2.0	Microearthquakes, not felt.	~8,000 per day
Very minor	2.0-2.9	Generally not felt, but recorded.	~1,000 per day
Minor	3.0-3.9	Often felt, but rarely causes damage.	~49,000 per year
Light	4.0-4.9	Noticeable shaking of indoor items, rattling noises. Significant damage unlikely.	~6,200 per year
Moderate	5.0-5.9	Can cause major damage to poorly constructed buildings over small regions. At most slight damage to well-designed buildings.	800 per year
Strong	6.0-6.9	Can be destructive in areas up to about 100 miles across in populated areas.	120 per year
Major	7.0-7.9	Can cause serious damage over larger areas.	18 per year
Great	8.0-8.9	Can cause serious damage in areas several hundred miles across.	1 per year
Rarely, great	9.0 or greater	Devastating in areas several thousand miles across.	1 per 20 years

Events with magnitudes of about 4.6 or greater are strong enough to be recorded by any seismographs all over the world. Great earthquakes occur once a year, on average. The largest recorded earthquake was the Great Chilean Earthquake of May 22, 1960 that had a magnitude (M_W) of 9.5. The second largest (9.0 on the Richter scale) was the Sumatra-Andaman undersea earthquake of December 26, 2004. The earthquake triggered a series of devastating tsunami along the coast of most landmasses bordering the Indian Ocean.



Richter Magnitude Scale of the Sumatra-Andaman earthquake and Asian Tsunami[25]

Because of the limitations of the Wood-Anderson torsion seismometer used to develop the scale, the original M_L cannot be calculated for events larger than about 6.8. Many

---

[25] http://en.wikipedia.org/wiki/Image:Diagram_earthquake_english.png

investigators have proposed extensions to the local magnitude scale, the most popular being the surface wave magnitude M_S and the body wave magnitude M_B. While the use of these traditional magnitude scales persists in the mass media, they have largely been superseded by the implementation of methods for estimating the seismic moment M_O, and its associated moment magnitude scale.

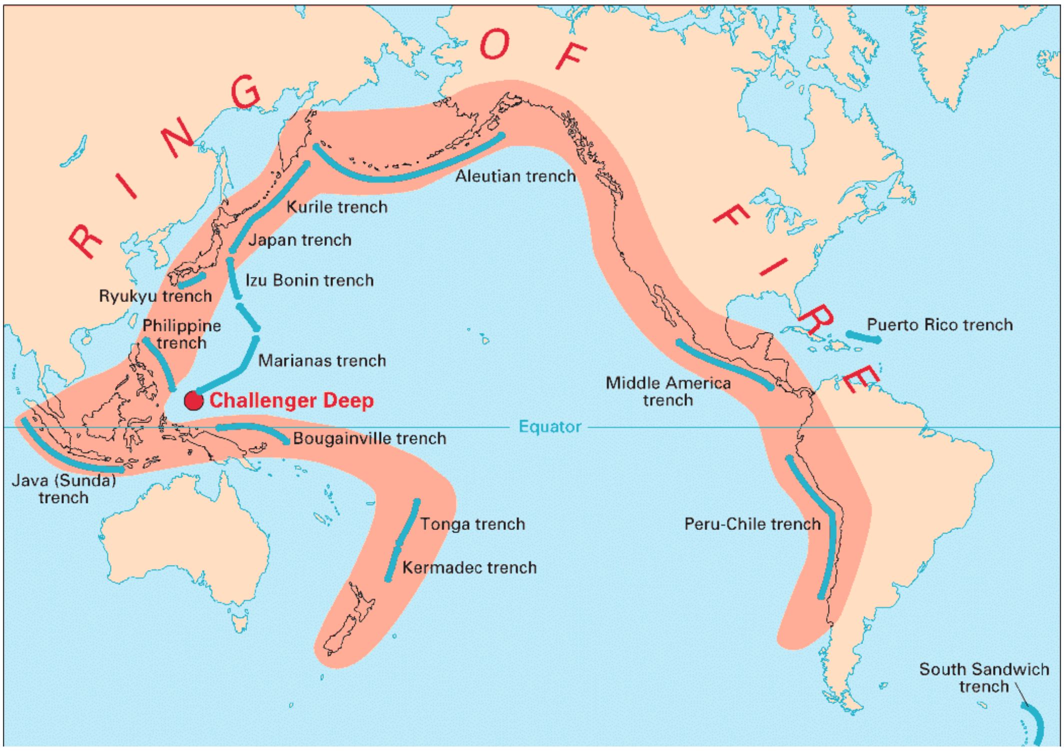
8.1.3.4.6 Size and Frequency of Occurrence

Small earthquakes occur every day all around the world, and often multiple times a day in places like California and Alaska in the U.S., Indonesia, Azores in Portugal and Japan. Large earthquakes occur less frequently, the relationship being exponential; namely, roughly ten times as many earthquakes larger than magnitude 4 occur in a particular time period than earthquakes larger than magnitude 5.

The number of seismic stations has increased from about 350 in 1931 to many thousands today. As a result, many more earthquakes are reported than in the past because of the vast improvement in instrumentation (not because the number of earthquakes has increased). The USGS estimates that, since 1900, there have been an average of 18 major earthquakes (magnitude 7.0-7.9) and one great earthquake (magnitude 8.0 or greater) per year, and that this average has been relatively stable[26]. In fact, in recent years, the number of major earthquakes per year has actually decreased.

The Pacific Ring of Fire[27]

The Pacific Ring of Fire is a zone of frequent earthquakes and volcanic eruptions encircling the basin of the Pacific Ocean. In a 40,000 km horseshoe shape, it is associated with a nearly continuous series of oceanic trenches, island arcs, and volcanic mountain ranges and/or plate movements. It is sometimes called the circum-Pacific belt or the circum-Pacific seismic belt.



The Pacific Ring of Fire[28]

---

[26] http://eaarthquake.usgs.gov/learning/faq.php?categoryID=6&faqID=110

[27] http://en.wikipedia.org/wiki/Pacific_Ring_of_Fire

[28] http://pubs.usgs.gov/publications/text/fire.html

Ninety percent of the world's earthquakes and 81% of the world's largest earthquakes occur along the Ring of Fire. The next most seismic region (5–6% of earthquakes and 17% of the world's largest earthquakes) is the Alpide belt which extends from Java to Sumatra through the Himalayas, the Mediterranean, and out into the Atlantic. The Mid-Atlantic Ridge is the third most prominent earthquake belt.

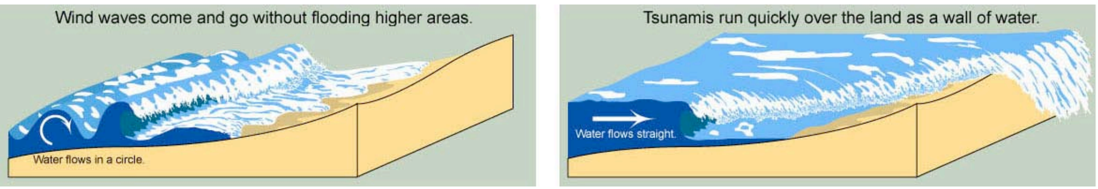
The Ring of Fire is a direct consequence of the movement of tectonic plates in the region. The eastern section of the ring is the result of the Nazca Plate and the Cocos Plate being subducted beneath the westward moving South American Plate. Further north, a portion of the Pacific Plate, along with the small Juan de Fuca Plate, is being subducted beneath the North American Plate. Along the northern rim, the northwestward moving Pacific plate is being subducted beneath the Aleutian Islands arc. To the west, the Pacific plate is being subducted along the Kamchatka-Kurile Islands arcs, down past Japan. The southern portion is more complex, with a number of smaller tectonic plates from the Mariana Islands, the Philippines, Bougainville, Tonga, and New Zealand in collision with the Pacific plate. Indonesia lies between the Ring of Fire, along the northeastern islands adjacent to and including New Guinea, and the Alpide belt, along the south and west from Sumatra, Java, Bali, Flores, and Timor.

The southern end of the Pacific Ring of Fire runs into Antarctica, which includes many large volcanoes. The makeup and structure of the volcanoes in Antarctica are quite different to those from the other places around the ring. The Antarctic Plate, encircled by several mid-ocean ridges, is almost completely surrounded by extensional zones, and there is only a small subduction zone at the tip of the Antarctic Peninsula, reaching eastward to the remote South Sandwich Islands. Mount Erebus, the best known of the Antarctic volcanoes, is the world's southernmost active volcano.

8.1.3.4.7 Tsunami[29]

A tsunami (from the Japanese *tsu*—harbour—and *nami*—wave) is a series of waves created when a body of water, such as an ocean, is rapidly displaced on a massive scale. Common throughout Japanese history, tsunami were originally described by fishermen who returned to port to find the area surrounding their harbour devastated, although they had not been aware of any wave in the open water.

A tsunami has a relatively small amplitude (wave height) offshore, and a relatively long wavelength (often hundreds of kilometres), which is why they generally pass unnoticed at sea, forming only a passing "hump" in the ocean. Tsunami have been historically referred to as tidal waves because as they approach land, they take on the characteristics of a violent, on-rushing tide rather than the sort of cresting waves that are formed by wind action upon the ocean (with which people are more familiar). Since they are not actually related to tides this term is considered misleading and its usage is discouraged.



Tsunamis are often no taller than normal wind waves, but they are much more dangerous[30]

The effects of a tsunami can range from unnoticeable to devastating.

---

[29] http://en.wikipedia.org/wiki/Tsunami

[30] http://www.ess.washington.edu/tsunami/images/tsulg.jpg

Tsunamigenic Events

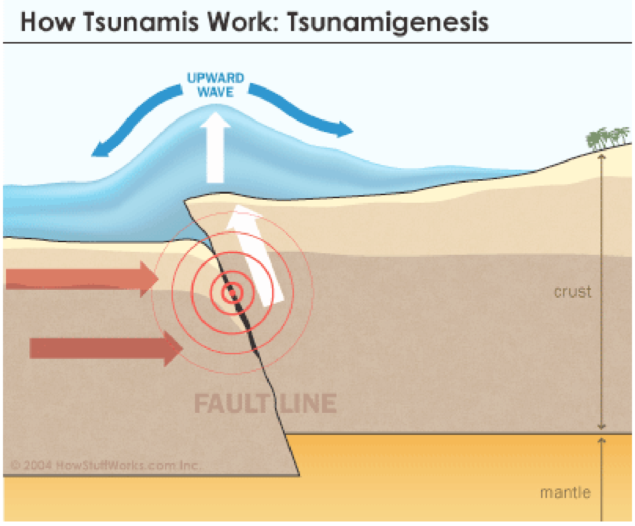
The natural occurrences capable of causing a tsunami are referred to as tsunamigenic events. In addition to earthquakes and volcanism, there are two less likely tsunamigenic events: submarine landslides and submarine volcanoes. Often, these events accompany major earthquakes, adding to the overall power of a tsunami or creating additional tsunami. They work in the same manner as an earthquake in that the extreme upward release of energy from the event affects the overlying water.

Man-made events such as underwater explosions and testing with nuclear weapons at sea also have the potential to generate a tsunami.

The Birth of a Tsunami

The most common causes of tsunamis are underwater earthquakes.

When two plates come into contact at a plate boundary, the heavier plate can slip under the lighter one in a process known as subduction. In some cases of subduction, part of the seafloor connected to the lighter plate may "snap up" suddenly due to pressure from the sinking plate. This results in an earthquake.



Formation of a Tsunami[31]

When this piece of the plate snaps up and sends tons of rock shooting upward with tremendous force, the energy of that force is transferred to the water. The energy pushes the water upward above normal sea level. This is the birth of a tsunami. The earthquake that generated the 26 December 2004 tsunami in the Indian Ocean measured 9.0–9.3[32] on the Richter scale—one of the biggest in recorded history.

Submarine landslides (which are sometimes triggered by large earthquakes) as well as collapses of volcanic edifices may also disturb the overlying water column as sediment and rocks slide downslope and are redistributed across the sea floor. Similarly, a violent submarine volcanic eruption can uplift the water column and form a tsunami.

Tsunami are surface gravity waves that are formed as the displaced water mass moves under the influence of gravity and radiates across the ocean like ripples on a pond.

Signs of an Approaching Tsunami

There is often no advance warning of an approaching tsunami. However, since earthquakes are often a cause of tsunami, an earthquake felt near a body of water may be considered an indication that a tsunami will shortly follow.

When the first part of a tsunami to reach land is a trough rather than a crest of the wave, the water along the shoreline may recede dramatically, exposing areas that are normally always submerged. This can serve as an advance warning of the approach crest of the tsunami, although the warning arrives only a very short time before the crest, which typically arrives seconds to minutes later. Although in the 2004 tsunami in

---

[31] http://science.howstuffworks.com/tsunami.htm

[32] The reported magnitude varies between 9.0 and 9.3 on the Richter scale, depending on the source.

the Indian Ocean the sea receding was not reported on the African coast or any other western coasts that it hit, when the tsunami approached from the east.

8.1.3.5 Volcanoes[33,34,35]

Earthquakes and volcanoes are related, as we will see in more detail below. Earthquakes can occur without volcanoes, but volcanoes do not occur without earthquakes—volcanic activity triggers earthquakes.

We have seen that much of the interior of the earth comprises molten rock. In the upper mantle, molten rock, known as magma, comes into contact with the solid lithosphere. Because it is lighter than the solid rock around it, magma tends to rise and collect in pockets called magma chambers. Eventually some of the magma pushes through vents and fissures to the Earth's surface, forming a volcano and a volcanic eruption occurs.

Eruptions of volcanoes under the air are termed **subaerial** whereas those occurring underneath the ocean are termed **submarine**. 'Black smokers' (hydrothermal vents on the ocean floor) and mid-ocean ridges are examples of submarine volcanic activity.

Some volcanic eruptions are explosive and others are not. How explosive an eruption is depends on how viscous (runny or sticky) the magma is. If magma is thin and runny, gases can escape easily from it. When this type of magma erupts, it flows out of the volcano. When magma erupts from a volcano it becomes lava. Lava flows rarely kill people, because they move slowly enough for people to get out of their way. Lava flows, however, can cause considerable destruction to buildings in their path.

If magma is thick and sticky (viscous), gases cannot escape easily. Pressure builds up until the gases escape violently and explode. In this type of eruption, the magma blasts into the air and breaks apart into pieces called tephra. Tephra can range in size from tiny particles of ash to house-size boulders.

Most land volcanoes have the same basic structure, but volcano shape and size varies considerably. There are several elements that these different volcano types have in common:

- a **summit crater**—the mouth of the volcano, where the lava exits;
- a **magma chamber**—where the lava wells up underground;
- a **central vent**—leading from the magma chamber to the summit crater.

The biggest variation in volcano structure is the **edifice**, the structure surrounding the central vent. The edifice is built up from the volcanic material spewed out when the volcano erupts. Consequently, its composition, shape and structure are all determined by the nature of the volcanic material and the nature of the eruption. The three main types are composite volcanoes (also known as stratovolcanoes), [cinder or scoria] cone volcanoes and shield volcanoes.

8.1.3.5.1 Composite Volcanoes

These are the most familiar type of volcanoes, and generally have the most destructive history of eruptions. Their sides are composed of alternating layers of lava and ash (other volcanoes just consist of lava), and they are characterised by a fairly symmetrical mountain edifice, which curves steeply near the relatively small summit crater at the top. They are usually built by [Plinian] eruptions that launch a great deal of pyroclastic

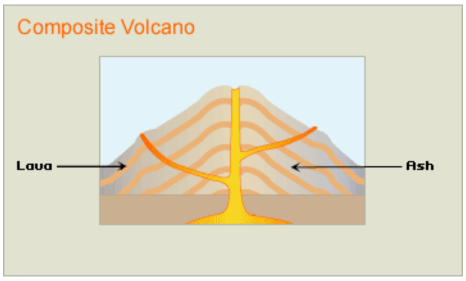
---

[33] http://www.geology.sdsu.edu/how_volcanoes_work/Volcano-tectonic.html

[34] http://www.bbc.co.uk/schools/gcsebitesize/geography/platetectonics/volcanoesrev4.shtml

[35] http://erg.usgs.gov/isb/pubs/teachers-packets/volcanoes/poster/poster.html

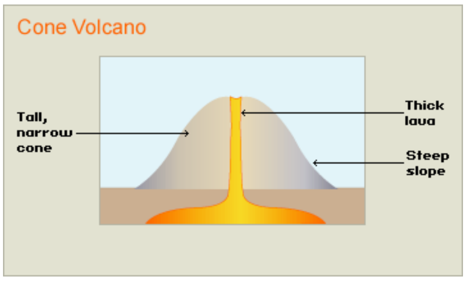
material (a mixture of hot steam, ash, rock and dust). As the lava, ash and other material spews out, it rapidly builds the edifice around the vent. Stratovolcanoes tend to have highly infrequent eruptions—hundreds of years apart—and typically form in subduction zones.



Kanaga Volcano, a Stratovolcano in Alaska, USA[36]

8.1.3.5.2 [Cinder/Scoria] Cone Volcanoes

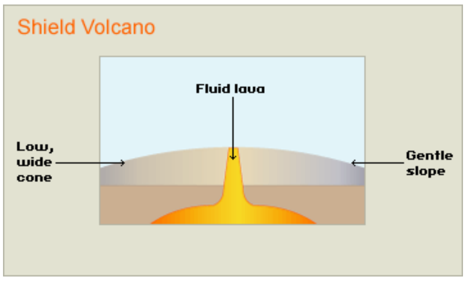
These relatively small cones are the most common volcano type. They are usually found at destructive plate boundaries and are characterised by steep slopes on both sides of the edifice, which lead up to a very wide summit crater. This edifice is composed of ashy tephra, usually spewed out by violent eruption of thick, viscous (sticky) lava. The thick lava moves relatively slowly and hardens quickly to form new rock—hence the formation of a cone shape. Unlike stratovolcanoes, many scoria cone volcanoes have only one eruption event.



Sunset Crater, a Scoria Cone volcano in Arizona, USA[37]

8.1.3.5.3 Shield Volcanoes

These wide, relatively short volcanoes occur when low-viscosity lava flows out with minimal explosiveness, such as in Hawaiian eruptions, although they are usually found at constructive boundaries. The lava disperses out over a wide surface area—sometimes hundreds of kilometres—building up a shield-shaped dome. Near the summit, the edifice gets a little steeper, giving the volcano a slightly raised centre. Many shield volcanoes erupt with great frequency (every few years or so), although these eruptions are relatively gentle.



---

[36] Photo courtesy USFWS
[37] Photo courtesy of USGS

Mauna Loa, a Shield Volcano in Hawaii, USA[38]

8.1.3.5.4 Calderas and Lava Domes

Volcanic activity can also produce other interesting structures, such as calderas and lava domes. Calderas, large crater-shaped basins, form when eruptions drain a magma chamber and the volcano edifice collapses into the empty space. These often fill up with water, creating round lakes.

The caldera at Kaguyak Volcano, in Alaska, is about 2.5 km in diameter[38]

Lava domes form when most of the gas vesicles escape during an initial eruption, and the remaining viscous lava lacks the necessary pressure to spew out and so it flows out very slowly at the summit crater. This creates a domed plug at the top of the volcano, which may continue to grow over time.

View across Spirit Lake of the Mount St Helens lava dome [39]

---

[38] Photo courtesy USGS

[39] http://vulcan.wr.usgs.gov/imgs/jpg/MSH/Images/MSH82_st_helens_spirit_lake_reflection_05-19-82_med.jpg

8.1.3.5.5 Geysers, Fumaroles and Hot Springs[40]

Geysers, fumaroles (also called *solfataras*), and hot springs are generally found in regions of young volcanic activity. Surface water percolates downward through the rocks below the Earth's surface to high-temperature regions surrounding a magma reservoir, either active or recently solidified but still hot. There the water is heated, becomes less dense, and rises back to the surface along fissures and cracks. Sometimes these features are called *dying volcanoes* because they seem to represent the last stage of volcanic activity, as the magma, at depth, cools and hardens.

Erupting geysers provide spectacular displays of underground energy suddenly unleashed, but their mechanisms are not completely understood. Large amounts of hot water are presumed to fill underground cavities. The water, upon further heating, is violently ejected when a portion of it suddenly flashes into steam. This cycle can be repeated with remarkable regularity, as for example, at Old Faithful Geyser in Yellowstone National Park, which erupts on an average of about once every 65 minutes.

Fumaroles, which emit mixtures of steam and other gases such as carbon dioxide, sulphur dioxide, hydrochloric acid, and hydrogen sulphide, are fed by conduits that pass through the water table before reaching the surface of the ground. They may occur along tiny cracks or long fissures, in chaotic clusters or fields, and on the surfaces of lava flows. Hydrogen sulfide (H_2S), one of the typical gases issuing from fumaroles, readily oxidizes to sulfuric acid and native sulfur. This accounts for the intense chemical activity and brightly colored rocks in many thermal areas.

Hot springs occur in many thermal areas where the surface of the Earth intersects the water table. The temperature and rate of discharge of hot springs depend on factors such as the rate at which water circulates through the system of underground cavities and porous rock, the amount of heat supplied at depth, and the extent of dilution of the heated water by cool ground water near the surface.

8.1.3.6 Magma[41]

The term **magma** refers to molten rock, together with any suspended mineral grains and dissolved gases. When molten rock erupts at the Earth's surface and flows from a volcano, it is called **lava**. Magma differs from lava in that magma contains **dissolved gases** whereas in lava these gases have escaped into the atmosphere.

There are actually many different types of magma, generally defined according to their silica (SiO_2) content—they vary from mafic, intermediate, to felsic as their silica content increases. Mafic (basaltic) magmas are generated directly from the mantle, either within the asthenosphere or within the overlying mantle lithosphere. Many mafic-to-intermediate (basaltic-to-andesitic) magmas appear to be derived from the melting of hydrated lithospheric mantle. More differentiated, intermediate-to-felsic magmas, on the other hand, are partly derived from the melting of continental crust by hot, mafic magmas that either pond at the crust-mantle boundary, or intrude into the overlying continents where they reside in magma chambers located at various crustal levels.

8.1.3.6.1 Partial Melting

Rocks do not melt at a specific temperature. This is because rocks are not homogeneous, but are comprised of an aggregate of different minerals. The minerals

---

[40] http://pubs.usgs.gov/gip/volc/geysers.html

[41] http://tesla.jcu.edu.au/Schools/Earth/EA1001/Igneous/1. Magmas+Melting.html

with the lowest melting point starts to melt first. For example, in a rock comprised of plagioclase + pyroxene + olivine, the pyroxene and the Na-rich (albite) component of the plagioclase will melt first, leaving an unmelted mixture of olivine and Ca-rich (anorthite) plagioclase. If the melt fraction is separated from the unmelted residue, the resulting magma and the solid residue will be of different compositions and different from that of the original source rock. This process of forming a magma of different composition to the original rock is called **magmatic differentiation by partial melting**. Furthermore, it is not heat alone that causes rocks to melt, but a combination of temperature, pressure and water content.

8.1.3.6.2 Heat

Temperatures in the Earth increase with depth, at a rate called the **geothermal gradient**. Temperatures rise rapidly from surface temperatures to around 1000°C at a depth of just over 100 km under the continents, and the rise is even greater under the oceans; i.e. the geothermal gradient is steeper under the oceans. The geothermal gradient is lower beyond 100 km and temperatures don't reach 1500° until around 500 km depth.

There are three main sources of heat within the Earth, two of which are of major importance.

- heat left over from the accretion of the planet more than 4.5 billion years ago and still emanating from the Earth's core
- heat released by the continuous decay of radioactive minerals
- The third source is frictional heat generated by fault planes and the movement of plates over the asthenosphere.

Magmas rising from greater depths are a form of extra heat and can produce melting in the rocks that they intrude. Such a situation may occur at subduction zones, where magma generated in the mantle rises to the base of the crust and penetrates into the crust.

8.1.3.6.3 Pressure

For dry melts, the temperature required to commence melting becomes higher as pressure increases. High pressure holds the atoms closer together and it takes greater heat energy in order to vibrate, weaken and break their bonds. It is for this reason that the mantle is still solid, rather than liquid. The region where mantle temperatures and pressures get closest to the melting point of mantle rocks corresponds to the region of the asthenosphere.

If the pressure is reduced, therefore, a rock may start to melt even if its temperature remains the same. Such a situation occurs at divergent margins, where pressure is reduced as the overlying crust is stretched and thinned. Mantle plumes may also undergo melting as they rise towards the surface. This is known as **decompressional melting**.

8.1.3.6.4 Water

If water is present, even in small amounts, the temperature at which a rock will melt will be considerably lowered. The dipole nature of the water molecule weakens the minerals bonds, allowing lower temperatures to vibrate and break the bonds. Consequently, hydrous minerals, that is, those that contain (OH) in their structure, melt at lower temperatures. Furthermore, whereas dry rocks require greater temperatures to melt with an increase in pressure, wet rocks become less resistant to melting at higher pressures. This is because high pressure increases the bond-breaking ability of water. An increase in pressure will also allow a greater amount of water to be dissolved in the melt, decreasing the temperature at which the onset of melting occurs.

At subduction zones, the dehydration of the subducting plate allows water to ascend into the overlying mantle and producing melting.

8.1.3.6.5 Composition of Magmas

There is a continuum of possible magma compositions, but for classification purposes, magmas can be defined on the percentage of SiO_2 that they contain.

Magmas (and rocks) that contain

- less than 45% SiO_2 are termed **ultramafic** or **ultrabasic**
- from 45% to 52% SiO_2 are termed **mafic** (from Magnesium and Iron (Fe)) or **basic**
- from 53% to 65% SiO_2 are termed **intermediate**
- more than 65% SiO_2 are termed **felsic** (from Feldspar and Silica) or **acidic**.

Three distinct magma types are most common: basaltic, andesitic, and rhyolitic. Volcanic rocks formed from these three magmas are called basalt, andesite and rhyolite, and are examples of basic, intermediate and acidic rock types respectively. These different rock types will be discussed in more detail later.

8.1.3.6.6 Viscosity

Viscosity is a measure of "stiffness" or resistance to flow, that is measured by determining the ratio of deforming stress (the amount of pressure applied) / strain (the amount of deformation) it produces.

Viscosity increases with silica content. Like minerals, the structure of magma is dominated by SiO_4 tetrahedra groups that polymerise by sharing oxygen atoms. Unlike minerals, the polymers in magmas are irregular groupings of chains, sheets and networks. The higher the silica content, the larger the polymerised groups and the more viscous the magma. The Si-O-Si bonds have strong, rigid geometry, but if there are substantial numbers of "network modifier" cations bridging the SiO_4 groups, i.e. Si-O-cation-O-Si , the bonds are more flexible and the viscosity decreases. Basic lavas have a greater percentage of network modifier cations, such as Mg, Fe, Ca and Mn, and so are less viscous.

Basic and ultrabasic lavas are the most fluid, with flow rates measured in metres per hour or metres per day. In exceptional cases, such as on steep slopes, lava flowing at up to 16 km/h have been recorded. Acidic lavas can be tens of thousands of times more viscous than basic lavas.

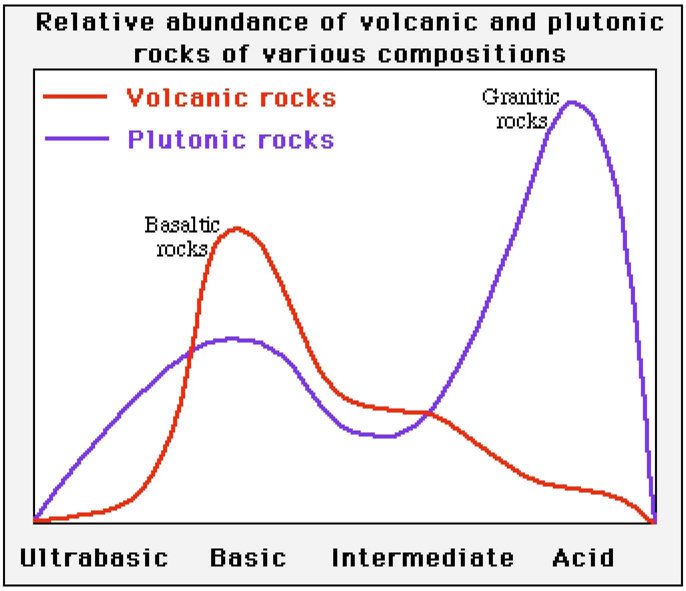
Viscosity increases as magma cools, therefore lavas tend to slow their advance further from the volcano, although local steeper slopes can increase the velocity of the flow, and the resulting vigorous flow leads to a decline in viscosity for these localised slopes. Some of the world's longest recent lava flows have been in north Queensland, notably the Undara flow, which is 160 km long, and the Toomba flow, which is 120 km long. These flows are also on very low gradients. To attain such lengths the lavas must be insulated from heat loss by some mechanism such as lava tubes.

A small amount of volatiles, particularly H_2O, in solution will lead to a significant decline in viscosity. Flows with similar compositions, therefore can have quite different surface appearances. Basaltic lavas that are hot and gas-charged are very fluid lavas that form smooth, ropy surfaces. This type of lava is known as **pahoehoe** . Basaltic lavas that are cooler and with lower volatile content have a rough, rubbly surface. This type of lava is called **aa** (from the sound that you make when you walk on it in bare feet). Some lava flows have been observed as initially being pahoehoe flows, but, as they cool and lose volatiles, they have turned into aa flows.

8.1.3.6.7 Relative Abundance of Igneous Rock Types

The density of the of the crust is around 2.7 gm/cm^3 for continental crust and 3.0 gm/cm^3 for oceanic crust, increasing slightly with depth due to pressure increase. The density of all rocks is somewhat higher for all rocks than for the melts that they produce. This leads to a natural buoyancy and a tendency for melts to rise to the surface. The rising magma follows natural weaknesses and may reach the surface where it erupts as **volcanic** extrusions. Other magmas solidify many kilometres beneath the surface, forming large **plutonic** intrusions. Erosion may later exposes these plutonic intrusions at the surface. Whether a magma solidifies under the surface or erupts and solidifies on the surface is controlled to a major extent by its chemical composition.

The following graph shows the relative abundance of rocks of various compositions that solidify under plutonic or volcanic conditions.



It can be seen that the great majority of plutonic rocks are of acid composition, whereas volcanic rocks tend to be of a basic composition. The reason for this is twofold.

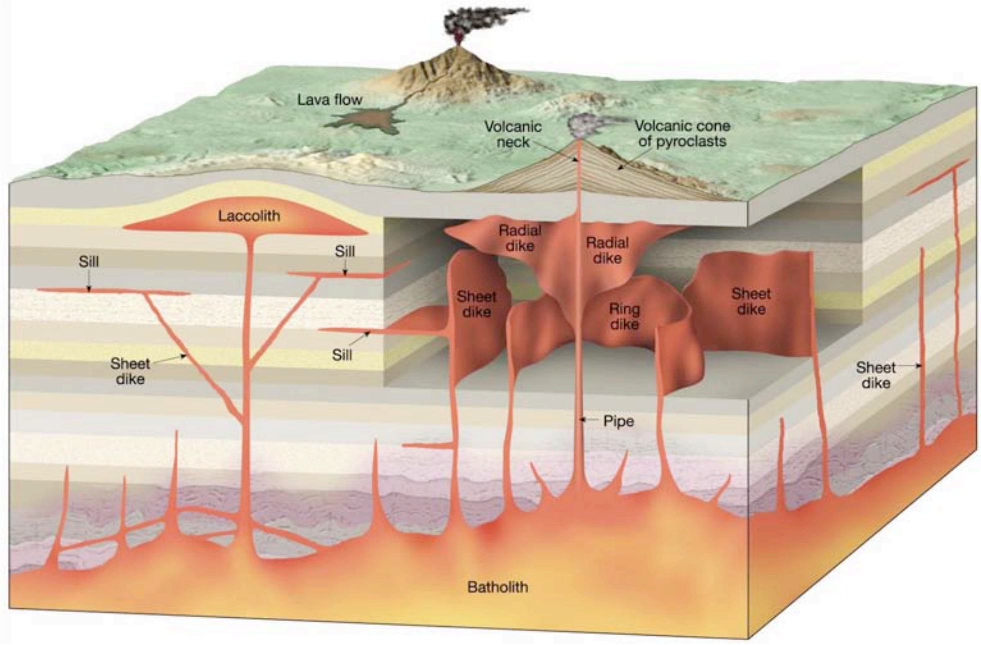
Firstly, acid magmas are highly viscous, making it difficult for them to rise quickly through fracture systems to erupt at the surface. In contrast, basic magma is relatively fluid and can rise through a fracture or conduit system without losing much heat and so can erupt onto the surface.

Secondly, acid magmas tend to crystallize over a relatively narrow temperature range. As a result, as the magma is rising slowly (because of its viscosity) and cooling, it encounters solidification temperatures and completely crystallizes while still below the surface. For basaltic (basic) magmas, crystallization occurs over a temperature range of some 200°C. Therefore, although solidification may begin, and crystals start to grow below the surface, the magma is erupted in a predominantly liquid form.

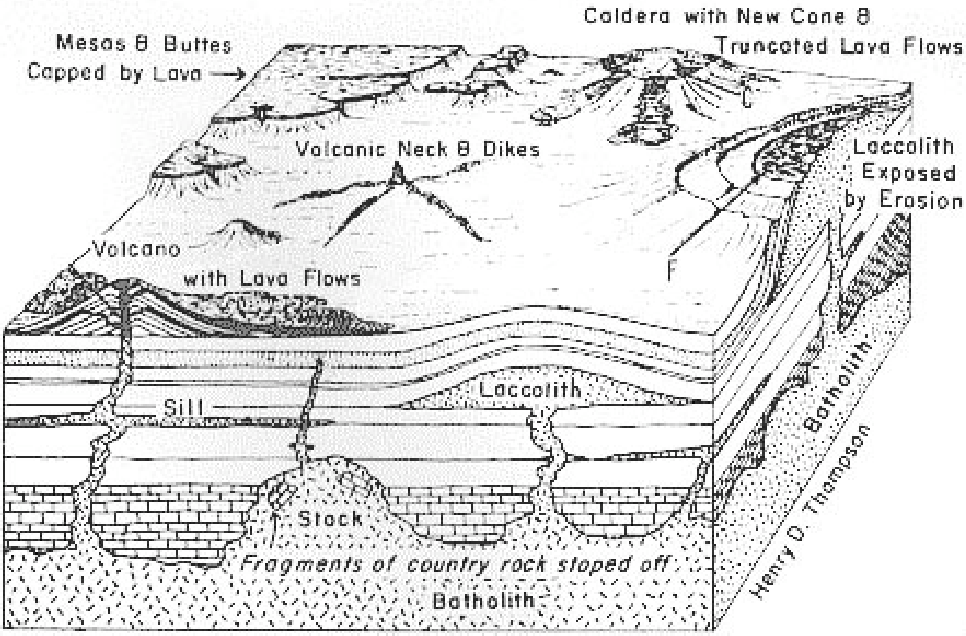
8.1.3.7 Subterranean Volcanic Features[42,43]

Igneous rocks that have cooled underground are called intrusive, because the parent magma intruded the surrounding rocks. Intrusive rocks are therefore always younger than the rocks surrounding them and can only be seen after erosion has removed the overlying rocks to expose them. Also, as intrusive rocks form underground, they cool slowly, forming rocks of medium to coarse grain size. Rocks formed in large intrusive structures are termed **plutonic**, while those that form in small intrusions are called **hypabyssal**.

8.1.3.7.1 Major (Plutonic) Intrusions



[44]



[45]

---

[42] http://tesla.jcu.edu.au/Schools/Earth/EA1001/Igneous/6.%20IgLandforms.html

[43] http://www.howstuffworks.com/volcano2.htm

[44] http://geology.wcupa.edu/hbosbysh/ess405/week_1/IgStructures-06.ppt

[45] http://www.slackpacker.com/igneous.html

Batholiths

The largest igneous intrusions are batholiths. They are defined as being over 100 km^2 in extent, but may be over 250 km wide and over 1000 km long. Batholiths are some 20 to 30 km thick, which is a sizeable proportion of the continental crust, but compared to their lateral extent, they are somewhat tabular bodies. They are typically composite, being made up of a number of distinct, but associated intrusions. Walls of batholiths are generally near vertical.

Stocks

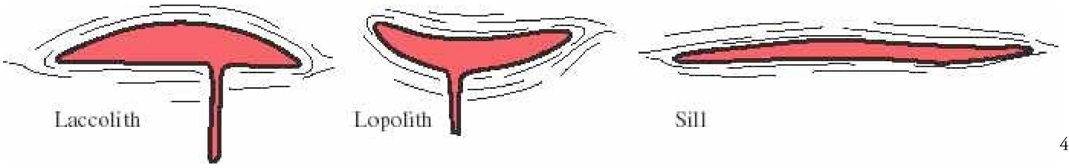
Stocks are similar to batholiths, but smaller, having an area of less than 100 km^2. They too can be composite bodies. Some stocks are just the top of a larger batholith, that only has a relatively small part of it exposed at the surface.

Laccoliths

Laccoliths intrude between parallel layers of rock at relatively shallow depths. The low pressure allows the magma to dome up the overlying rock, so the intrusion becomes a lenticular, mushroom shaped body. Laccoliths are generally formed from acidic, viscous magmas that bulge upwards rather than spreading laterally. The ratio of the thickness to the diameter of a laccolith is greater than 1:10 (otherwise the intrusion is called a sill).

Lopoliths

Lopoliths are concordant (parallel to layering) intrusions that are saucer shaped. They are formed in a similar manner to laccoliths, but are produced from dense, mafic magma that depresses the overlying strata. Many lopoliths contain layered gabbroic rocks. Some are very large with thicknesses of many kilometres. The Bushveldt lopolith in southern Africa is several hundred kilometres across and contains the richest platinum deposits known.



[46]

8.1.3.7.2 Minor (Hypabyssal) Intrusions

Dykes

Dykes are *discordant* tabular sheets that cut across the layering of the rock it intrudes and are commonly steeply inclined. In regions of crustal extension, fractures may form which are filled by magma from a deep source, or intrusive magma may promote fracturing and extension of the crust. Dykes in outcrop range from a few metres in length to many kilometres, and range from a few centimetres wide to over 100 m, although the Great Dyke of Zimbabwe is a gabbroic mass nearly 500 km long and about 8 km wide. Because dykes intrude relatively cool rocks, they frequently display a chilled margin, with grain size becoming coarser towards the centre where the rate of cooling has been slower. Dykes may occur in swarms of parallel dykes, particularly where there has been crustal extension. Veins are very thin dykes.

---

[46] http://www.geosci.usyd.edu.au/users/prey/Teaching/Granite/Granite.html#Ch6

Sills

Sills are similar to dykes, but are *concordant*—they intrude parallel to the layering of the country rock, as do laccoliths and lopoliths. Thicknesses range from metres to hundreds of metres. Because they form by lifting and separating adjacent rock layers, sills only form within a few kilometres of the surface.

Volcanic Necks / Plugs

A plug is the remainder the cylindrical feeder pipe, or conduit, of a volcano. The magma that solidified in the conduit is harder and more resistant to erosion than the pyroclastic deposits and lavas that make up the flanks of the volcano. As a result, after the volcano becomes extinct, the plug often remains standing like a spire over the landscape.

Ring Dykes

Ring dykes are large, near vertical dykes with a circular outcrop pattern. Their thickness varies from hundreds of metres to several kilometres, and the diameter can be up to 30 km. Thicker dykes contain plutonic rocks, rather than hypabyssal. They are centred around a deeper intrusion. The central section may be a block that has sunken into the underlying magma, the ring dykes representing the fracture zone around the sunken block.

Cone Sheets

Cone sheets are minor intrusions that occur as a dyke swarm with a concentric distribution. They dip towards a focus, generally several kilometres deep, at angles between 20° and 70°, but typically at around 45°.

8.1.3.7.3 Weathered Landforms[47]

Igneous rocks, whether intrusive or extrusive, in layers or in masses, form distinctive components of local geology, which can contribute to landscape development via differential erosion. Igneous rocks contribute to local geology in 3 ways:

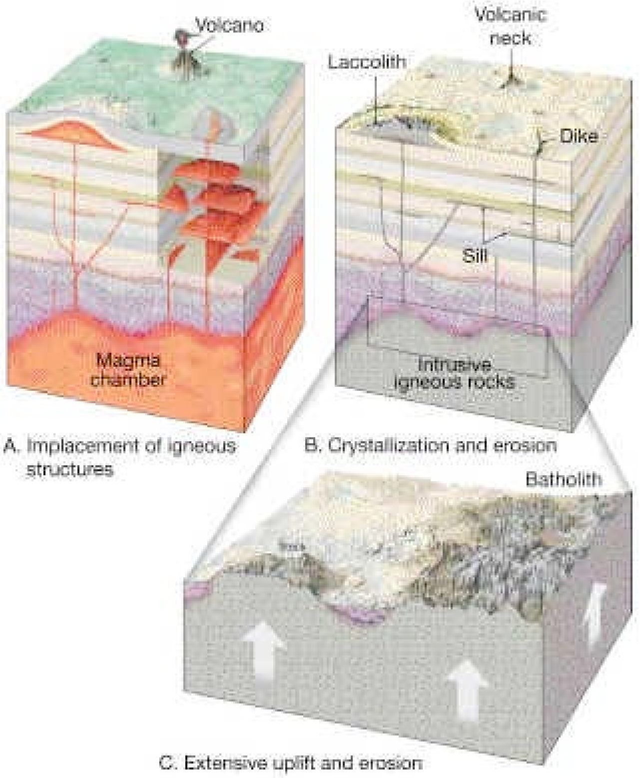
1. Plutons;
2. Flood Basalts;
3. Pyroclastic Flow Deposits

---

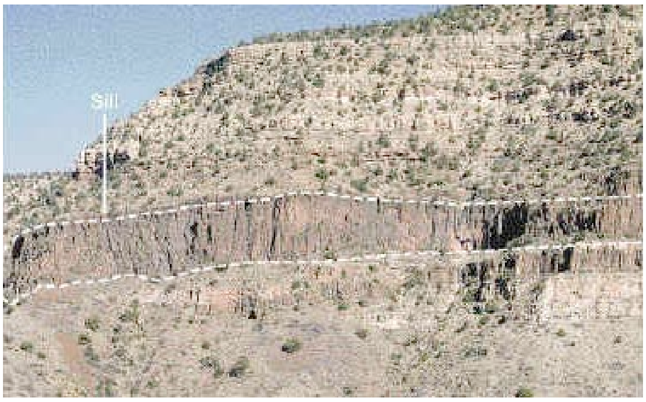
[47] http://courses.unt.edu/hwilliams/GEOG_3350/examreviews/volcanic_structures.htm

Plutons

Most igneous rocks are intrusive—created below the surface forming masses of rock collectively known as plutons. These contribute to geomorphology when they are exposed at the surface after the overlying rocks are worn away. Most igneous rock, such as granite, is usually of relatively high resistance—therefore many exposed plutons form high relief features due to differential erosion. Batholiths are usually exposed as mountain ranges, while exposed laccoliths may also form resistant uplands.



Sills, formed as horizontal intrusions between layers of pre-existing rock, can be exposed in eroded cliff faces.



Salt River Canyon, AZ, USA. The dark, essentially horizontal band is a sill of basaltic composition tha intruded into horizontal layers of sedimentary rock.

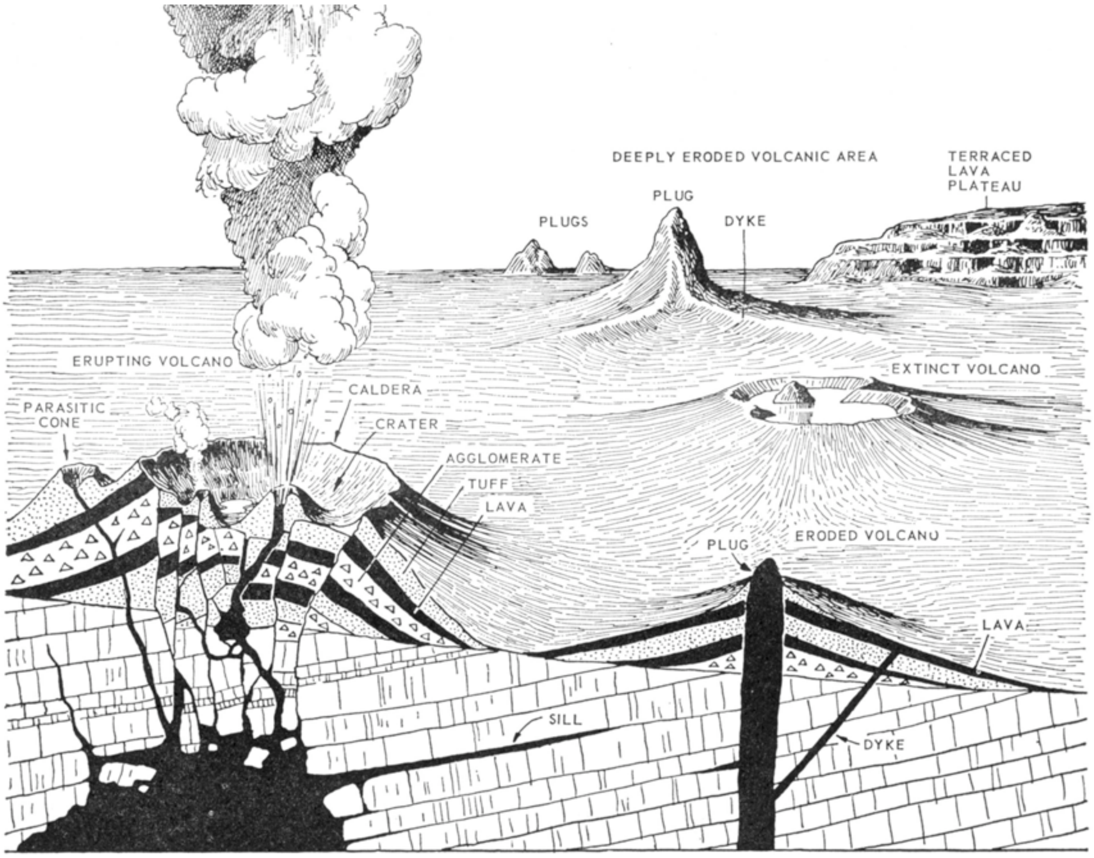
Flood Basalts

Lava flows on the surface tend, for the most part, to be basalt, because it is fluid and capable of flowing over large areas, especially if erupted from a long fissure rather than a single vent. Repeated eruptions of basaltic lava form flood basalts, which can build up to great thickness and cover very large areas, such as the Columbia Plateau of the Pacific Northwest in North America. Flood basalts can erode like horizontal strata, forming canyons with "stepped" sides.

Pyroclastic Flow Deposits

Pyroclastic (ash, dust, rocks) flows can form thick deposits over large areas. A wide range of rocks is included, from compacted, welded ash (tuff), which can be easily eroded, to more resistant volcanic debris flow conglomerates.

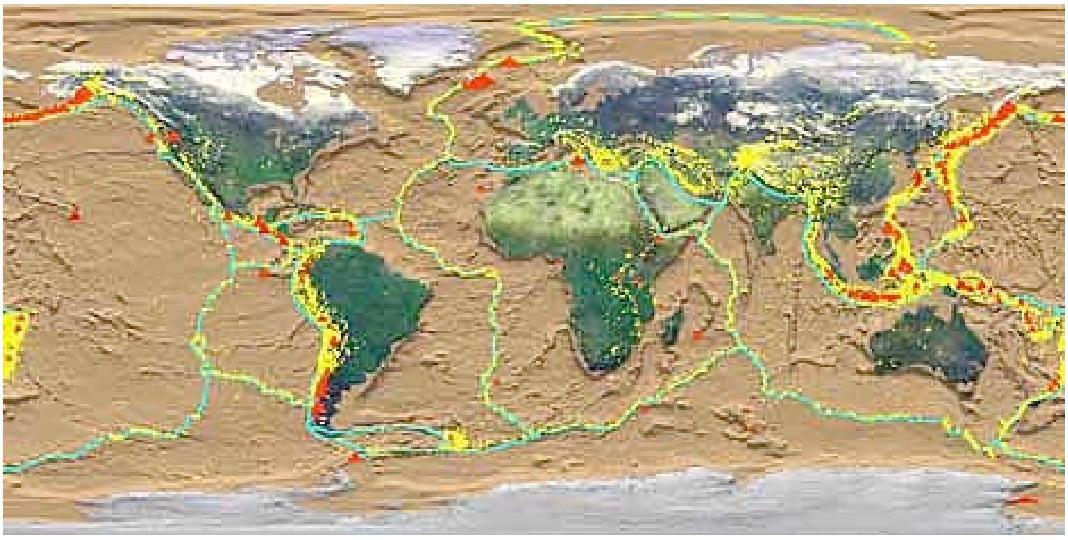
If pyroclastics are mixed with water (*e.g.* melting ice/snow), **lahars** (volcanic debris flows) can form. Lahars caused much of the destruction in the eruption of Mt. St. Helens (May 18th, 1980). All types of pyroclastic flow can fill in pre-existing valleys or form layers, which then become part of the geology and contribute to differential erosion.



Volcanic landforms

8.1.3.8 Distribution of Active Volcanoes and Seismic Activity

There are more than 500 *active* volcanoes in the world, about as many *dormant* volcanoes, and many volcanoes that have been deemed *extinct*. As illustrated in the map below, most of these are located along the margins of adjacent tectonic plates.



World map showing plate boundaries (blue lines), the distribution of recent earthquakes (yellow dots) and active volcanoes (red triangles)[48]

Determinations of activity are largely based on subjective interpretation or somewhat arbitrary standards. The traditional criterion for this determination is the date of the last eruption. If the last eruption fell within historic times—the period people have been recording history—the volcano was deemed active. If the last eruption occurred before historic times but within 10,000 years, the volcano was considered dormant because it likely had the potential to erupt again. Volcanoes that had not erupted in more than 10,000 years were considered extinct, because it seemed unlikely they would erupt again.

8.1.3.8.1 Volcanism at Plate Tectonic Boundaries

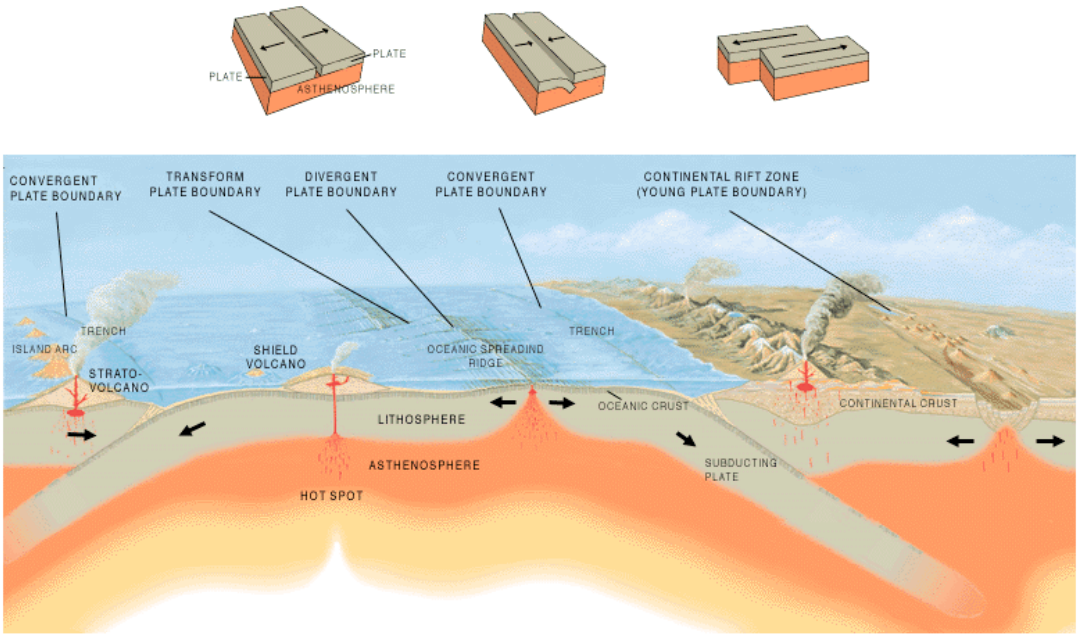
Volcanism is typically widespread along tectonic c plate boundaries, driven by the ascent of molten rock (magma) from deep beneath the surface. Plate boundaries mark the sites where two plates are either moving away from one another, moving toward one another, or sliding past one another. Adjacent plates are delineated by three types of boundaries defined by this relative motion:

- Divergent plate boundaries—Plates diverge from one another at the site of thermally buoyant mid-oceanic ridges. Oceanic crust is created at divergent plate boundaries.
- Convergent plate boundaries—Plates converge on one another at the site of deep oceanic trenches. Oceanic crust is destroyed at convergent plate boundaries.
- Transform plate boundaries—Plates slide past one another.

Although volcanism is abundant at divergent and convergent plate boundaries, there is a distinct lack of significant volcanism associated with transform plate boundaries. Spreading centre volcanism occurs at divergent plate margins, and subduction zone volcanism occurs at convergent plate margins.

---

[48] Courtesy of NASA



Tectonic Plate Movements[49]

Further, while volcanism in the interior of plates is less common, these intra-plate regions can also generate voluminous eruptive products, as is the case in the Hawaiian islands.

References

Earth: An Introduction to Physical Geography (8th Edition)
Tarbuck, E.J. and Lutgens, F.K. ISBN 0-13-114865-6 (Prentice Hall 2005)
See also http://www.prenhall.com/tarbuck for additional on-line resources

Essentials of Geology (9th Edition)
Lutgens, F.K. and Tarbuck, E.J. ISBN 0-13-149749-9 (Prentice Hall 2006)

Australian Museum Online
(http://www.amonline.net.au/geoscience/earth/index.htm)

U.S. Geological Survey
(http://www.usgs.gov)

---

[49] http://en.wikipedia.org/wiki/Image:Tectonic_plate_boundaries.png