CHAPTER 4

PLATE TECTONICS

4. 1. INTRODUCTION

We now shift our focus from where we are on this planet, to how our islands got here. Scientific research now provides us with a well-tested explanation of the earth's land formation process.

It is an interesting and important lesson. It is also a good example of how scientific understanding develops through observations, questioning, offering of hypotheses, new discoveries, careful analysis of data, and the sharing and synthesis of different ideas.

4. 2. LAYERS OF THE EARTH AND THEIR MINERALS

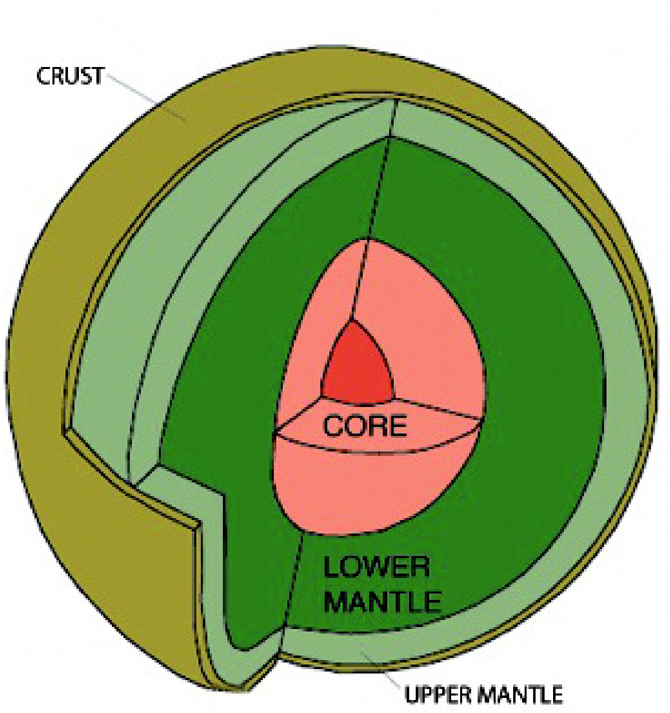
4. 2. 1. Earth Parts

Scientists divide their attention to our planet into its three existing parts. The first is the **geosphere** or the mineral rock part. The second is the **atmosphere** or the gaseous part. The third is the **hydrosphere**, composed of our earth's water—gaseous, liquid, and solid water.

These next two chapters focus on the geosphere, its parts and its dynamic events. **Geologists** are scientists who study the geosphere.

4. 2. 2. The Earth's Geospheric Layers

From the earlier work of geologists, we now know that the earth's geosphere is divided into three chemical layers: the **core**, the **mantle** and the **crust**.



Earth's Geospheric Layers

The core is known to be made mostly of iron and nickel and remains very hot, even after our earth's 4.5 billion years of cooling. The core is itself subdivided into two layers: 1) a solid inner core and, 2) a liquid outer core.

The middle layer of the earth, the mantle, is made of minerals rich in the elements iron, magnesium, silicon, and oxygen. The mantle also is composed of three layers, a lower mantle layer, an upper mantle layer, and a top-most layer called the **asthenosphere**.

The crust, where we live, is rich in the elements oxygen and silicon with lesser amounts of aluminum, iron, magnesium, calcium, potassium, and sodium. Another term for the crust is the **lithosphere**.

Volcanic eruptions and earthquakes are awe-inspiring displays of the powerful forces of nature.

The Richter Scale is used to record and compare earthquake intensities.

4. 2. 3. How Do Geologists Know about the Earth's Interior?

Much of our knowledge of the earth's interior, its chemistry and its layers comes from the interpretation of shock waves that result from **earthquakes**.

4. 3. EARTHQUAKES AND VOLCANOES

Volcanic eruptions and earthquakes are awe-inspiring displays of the powerful forces of nature. They can be extraordinarily destructive. Some societies have been devastated by them.

About 60 of the earth's 550 historically active volcanoes erupt each year. Far more volcanism takes place unobserved on the ocean floor than is observed on the earth's surface.

Earthquakes are major natural forces that have caused tremendous destruction. Historical records give us many examples of devastating earthquakes, both from here, and from all over the world.

In 1994 one of the strongest recorded earthquakes in U.S. history occurred at the Marianas Trench. It greatly affected our neighboring island of Guam.

4. 3. 1. Measuring an Earthquake's Size

The most common measure of earthquake "size" is based on the actual amount of energy released, and is called earthquake **magnitude**. It is determined by **seismic-wave** characteristics, principally stated as **amplitude** (measured as 1/2 the wavelength of the seismic wave) as recorded by **seismographs** at varying distances from the earthquake.

The concept of earthquake magnitude was introduced in 1932 by the noted **seismologist**, Charles F. Richter. The **Richter Scale**, named in his honor, is used to record and compare earthquake intensities.

The Richter scale is **logarithmic**. A magnitude 6 earthquake releases approximately 30 times more energy than a magnitude 5 earthquake. In general, a magnitude 3 earthquake is about the smallest we humans can feel. Small magnitude earthquakes occur much more frequently than large ones.

For example, about 6,000 earthquakes of magnitude 4 occur each year, on average, but earthquakes of magnitude 8 occur only about once a year. In 1992 alone, 85 earthquakes worldwide exceeded magnitude 6.5 on the Richter scale, and many of them caused extensive damage. The 1994 Marianas Trench earthquake, south of Guam, measured as high as 8.3.

Even though the Richter scale has no upper or lower limits, magnitudes as great as 10.0 have not been recorded historically on earth. Such large earthquakes are not probable because rocks are not strong enough to build up the required stresses. They are likely to rupture (liquefy) at lower stress levels and allow the forces upon them to 'give way', producing a lower magnitude earthquake.

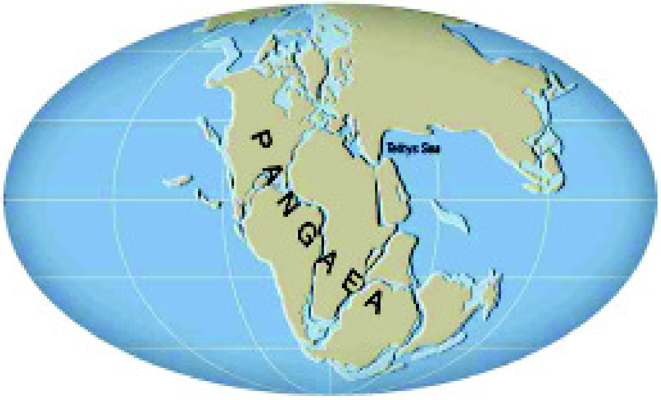
4. 4. THE CONTINENTAL DRIFT HYPOTHESIS

The best explanation of how the land features of the earth are formed is called the **Plate Tectonics Theory**. This theory divides the surface of the earth into large plates that move. The theory started with an idea that was first formally proposed by Alfred Wegener in 1912, when he published his **Continental Drift Hypothesis**.

Wegener said that about 270 million years ago all of Earth's continents formed one large continent that he called "**Pangaea**" (pan-ji-uh). This super-continent first broke into two, then these further broke up into the seven continents we know today. Ed. note: Do you know the seven continents' names, locations and shapes? If you do not, look for them on a globe or in an atlas.]

To develop his reasoning, Wegener used the fit of the continents, the distribution of fossils, and a similar sequence of rocks at numerous locations. He also used his understanding of ancient climates, and the apparent wandering of the earth's polar regions to support his idea.

Wegener believed that some force had caused the Pangaea "supercontinent" to break into smaller ones. Due to a lack of technology in his day, Wegener could not adequately explain the force that might have caused the break up and the movement of the continents.



270 million years ago all of Earth's continents formed one large continent called Pangaea.

Scientists now believe that Wegener was right in saying that continents do move, and that our current continents came from the supercontinent which we still refer to as Pangaea in his honor. In fact we now understand that there were several earlier 'supercontinents'.

Wegener thought that somehow the continents must push themselves across the earth's surface like a plow. What caused them to move was unclear but, at the time, Wegener thought that the earth's spin might be the cause. This was later proven to be inaccurate. Today, we know continents do not move themselves, but that the **crustal plates** underneath the continents move them.

Before discussing the driving force of plate movement, we need to first learn about some of the technological advances and discoveries made long after Wegener's original hypothesis.

These technologies were used to prove a slightly altered version of the continental drift hypothesis. It is this altered version that is today called the plate tectonics theory. Notice the elevation of the hypothesis to the theory level.

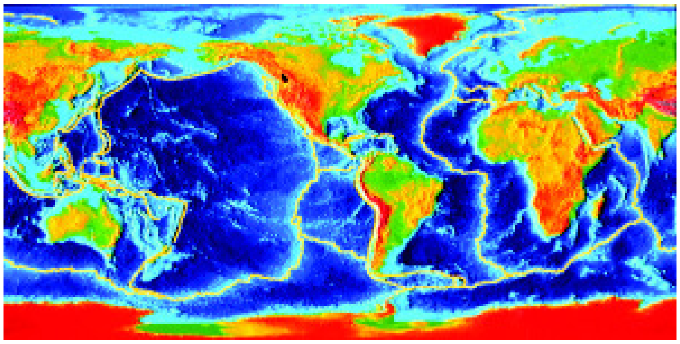
4. 5. NEW TECHNOLOGIES, OCEAN FLOOR RESEARCH, AND KEY OBSERVATIONS

4. 5. 1. Introduction

Equipment such as sonar devices, magnetometers, and side scanners, originally developed to hunt submarines, made it possible to study the ocean floor's shape. Unexpectedly, instead of a common flat seafloor, scientists found many high undersea mountains and deep trenches, along with the expected broad flat plains.

The most important feature discovered was the existence of a line of undersea ridges stretching all the way around the globe. We now call this the **rift system**. As discussed below, we also now refer to these rift areas both as **spreading centers** and as **divergent plate boundaries**. At these zones, much volcanism and seismic action have been noted.

Geologists also discovered a horizontal zigzag pattern or zebra-striped pattern of the orientation of seafloor magnetic rock crystals.



Tectonic boundaries

4. 5. 2. Plate Tectonics Theory Matures; Explaining the Global Rift System

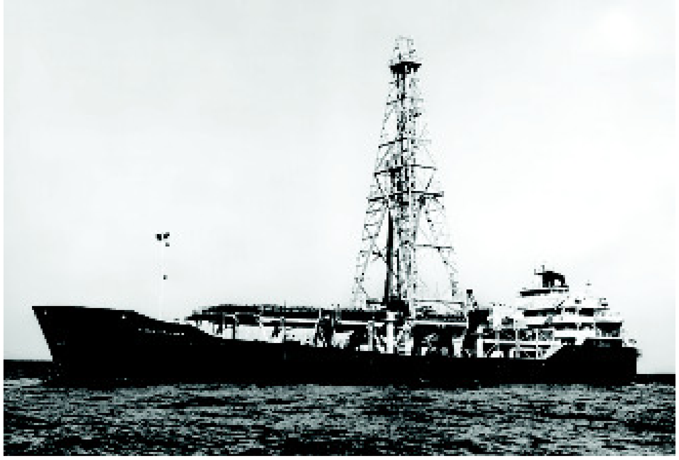
In 1962, two geologists, named Harry Hess and Robert Deitz, gave an explanation (hypothesis) for the global rift system. They showed that new ocean floor is formed at the rift of mid-ocean ridges.

The ocean floor, and the rock beneath it, are produced by magma that rises from deeper levels. The zigzags of the rock's magnetism were explained as resulting from the shifting of the earth's magnetic poles. This characteristic of seafloor rock magnetism corresponded to shifts of the earth's magnetic pole—from the North-strongest to South-strongest, then back to North-strongest.

The south orientation of seafloor magnetism occurred when magma was extruded while the magnetic pole was south of the equator. The north orientation, as it is today, occurred when the orientation was north of the equator.

At the time of this book's writing, no one yet knows why the magnetic poles do this shifting. Perhaps you will go on to study geology professionally and be the one to discover this.

The discoveries of these two geologists, along with explanations and further defining of terms given by others, helped to develop the current and comprehensive plate tectonics theory.



The Glomar Challenger was a ship specially designed for deep sea drilling.

4. 5. 3. More Discoveries, Confirmations, Definitions and Theory Synthesis

The **Glomar Challenger** was a ship specially designed for deep sea drilling. Beginning in 1965, the ship undertook a series of drillings across the floor of the earth's oceans. Again unexpectedly, analysis of its seafloor corings found that the sea's bottom was made of relatively young rocks.

These oceanic crustal rocks were of the kind called **basalt**, being formed at the undersea rift spreading-centers. By dating the rocks, geologists learned that the youngest rocks were closest to the rifts. As the corings moved away from the rift edges, the age of the rocks got older.

These findings confirmed the rift-seafloor-rock origin ideas of Deitz and Hess.

(Note the scientific process: hypothesis > prediction > experimental test > confirmation (proof).

The broad plains of rocks formed at the rifts were later called "**plates**". Since volcanic actions and earthquakes occurred at plate edges, the term "tectonics" was also applied to the changing picture of the developing earth's geography.

We call the new explanatory model of continental drift "plate tectonics". We consider it a fundamental principle of geologic science since it is the foundation of many other explanations.

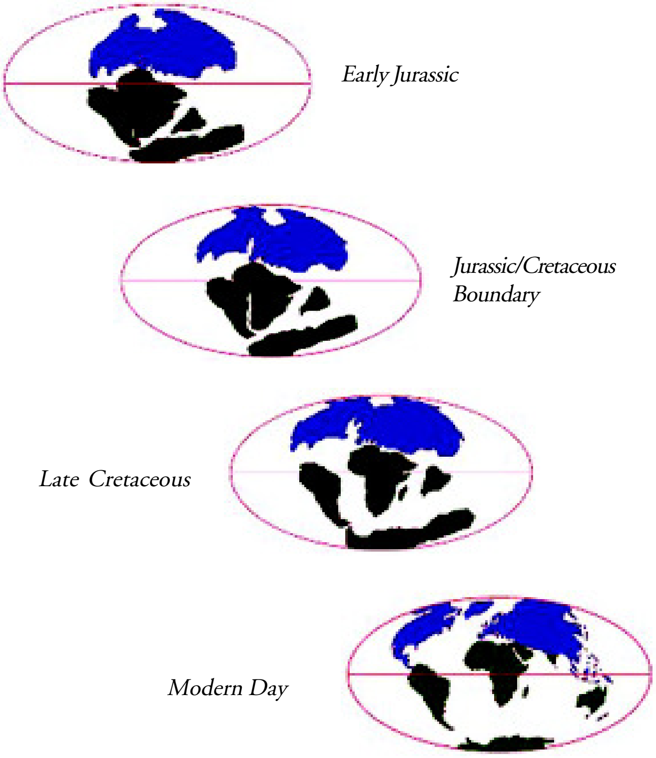
Plate tectonics explains seafloor age distribution and the spreading and plunging of plates. It also explains both undersea and dry land topography. The explanatory model details why most volcanoes and earthquakes occur at plate edges, and it illustrates the apparent "drifting" of our present day continents.

Since the mid-1960s, the plate tectonics model has been rigorously tested. Because the model has been successfully tested by numerous methods, it is now called the plate tectonics theory and is accepted by almost all geologists.

4. 6. CONTINENTAL DRIFT AND RECONSTRUCTING PREHISTORIC GEOGRAPHIES

4. 6. 1. Present Land Masses

With the plates of the crust moving across the earth's surface, it stands to reason that the land masses lying above them will move over time. Compare the maps of Pangaea from the **Early Jurassic** (200 million years before present), the **Jurassic/Cretaceous** boundary (140 million years before present), **Late Cretaceous** (70 million years before present) and the present land masses. (In our next chapter we will discuss more about geologic time and the naming of these geologic ages.)



Early Jurassic

Jurassic/Cretaceous Boundary

Late Cretaceous

Modern Day

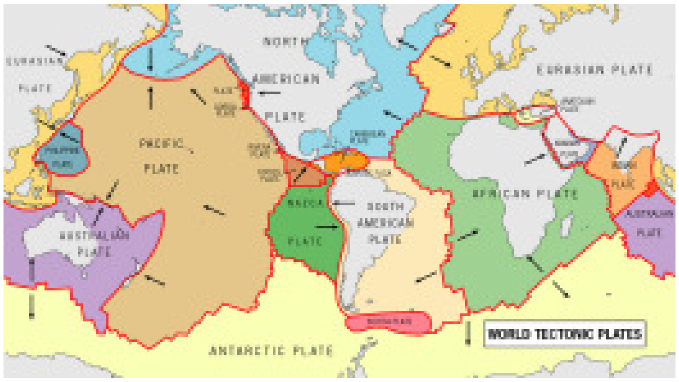
The continental progression of tectonic shifts.

In these maps, the **Gondwanaland** masses are colored black and the Laurasia land masses blue. Gondwanaland gave rise to South America, Africa, Australia, India and Madagascar. **Laurasia** gave rise to North America, Europe and Asia.

4. 6. 2. Some Points to Note from These Maps

The **lithosphere plates** move at different rates and separate at different times. Compare the distance traveled by India to the other land masses. This could be explained both by a faster rate of travel or by an earlier separation. No one yet knows.

Australia was the last land mass to separate from Antarctica. It then traveled north at about 6 centimeters per year, or just slightly faster than the speed our fingernails grow.

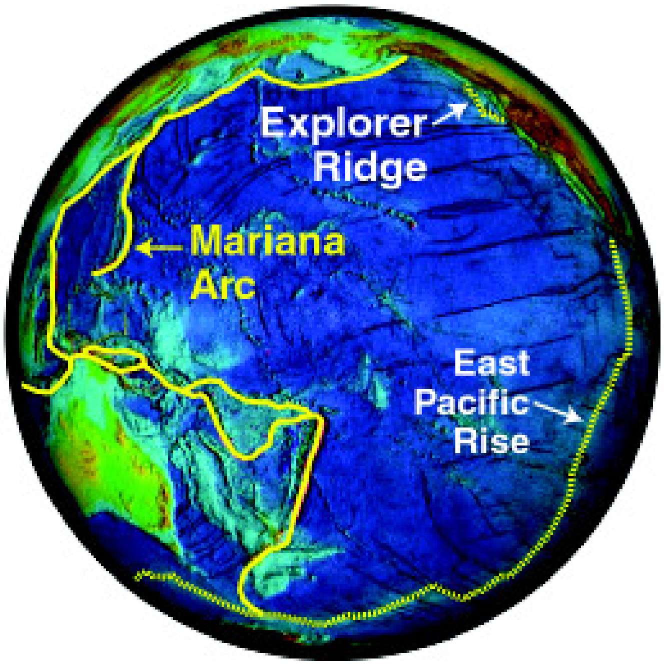


Current major tectonic plates of the world.

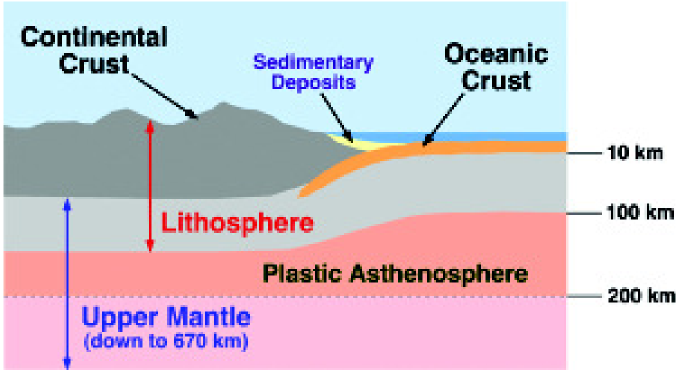
4. 7. PLATE TECTONICS, VOLCANISM AND EARTHQUAKES

4. 7. 1. Plates

The plates average about 80 kilometers thick. They are composed of the earth's relatively thin surface rind (the crust) and the topmost part of its **mantle**. The lithosphere is generally thicker under the continents than under the oceans.



The line of volcanoes that circles most of the Pacific Ocean is known as the "Ring of Fire."



The Earth's outer layer is called the lithosphere. It is made of the rigid upper mantle and the crust. The lithosphere moves on the asthenosphere, part of the mantle that flows.

The plates move very slowly on top of a flowing layer of hotter, softer mantle, the **asthenosphere**. Plate movement represents the top of a large scale circulation system. The system is driven by earth's escaping heat. The circulation extends deep into the mantle. Because heat causes the circulation, we refer to it as a **convection** system.

Where the plates grind against each other, stress builds up. This stress is relieved intermittently, causing earthquakes when the rock fractures (breaks) along planes of weakness called **faults**. Near plate boundaries, **magma** (molten rock) rises to the surface from as deep as tens of kilometers below, and erupts to form volcanoes.

The tectonic processes associated with plate movements are concentrated in the narrow boundary zones between the shifting plates. This explains why most of our restless planet's earthquakes and volcanoes are found along, or near, plate boundaries.

4. 7. 2. Locating Plate Boundaries

Earthquakes and volcanoes, evidence of unrest in the earth, help locate the edges of plates. Earthquakes are distributed in narrow, linear belts that circle the earth.

Volcanoes are also distributed along these belts. A dramatic example is the line of volcanoes that circles most of the Pacific Ocean. This belt is known as the "**Ring of Fire**" because it is the site of frequent volcanic eruptions. See more on this Ring of Fire below, in 4. 12.

The distribution of earthquakes and volcanoes coincides at most locations. The Ring of Fire is an excellent example. Geologists believe that areas of intense geologic activity, indicated by earthquakes, volcanoes, or mountain building, mark the boundaries between lithospheric plates.

The distribution of earthquakes, volcanoes, and mountain ranges define 14 large and 38 smaller plates, totalling 52 altogether. The Nazca and Juan de Fuca Plates consist of only oceanic lithosphere (sea floor crust). The Pacific Plate is mostly oceanic lithosphere, with only a small slice of continental lithosphere in southern California and Baja Mexico. Most of the other plates consist of both oceanic and continental lithospheres.

4. 8. TYPES OF CRUST AND THEIR DENSITIES

4. 8. 1. Introduction

There are two basic types of crust. As mentioned in 4. 5. 3., oceanic crust is made mostly of relatively dense rock called basalt. Continental crust is made mostly of lower density rocks, such as **andesite** and **granite**. These rock types will be discussed in more detail in our next chapter.

4. 8. 2. Asthenosphere and Lithosphere

As mentioned in 4. 2. 2., the outer layers of the earth can be further divided by their physical properties into the lithosphere and asthenosphere. The lithosphere (from the Greek, *lithos*, "stone") is the rigid outermost layer made of crust and uppermost mantle. The lithosphere is the "plate" of the plate tectonic theory.

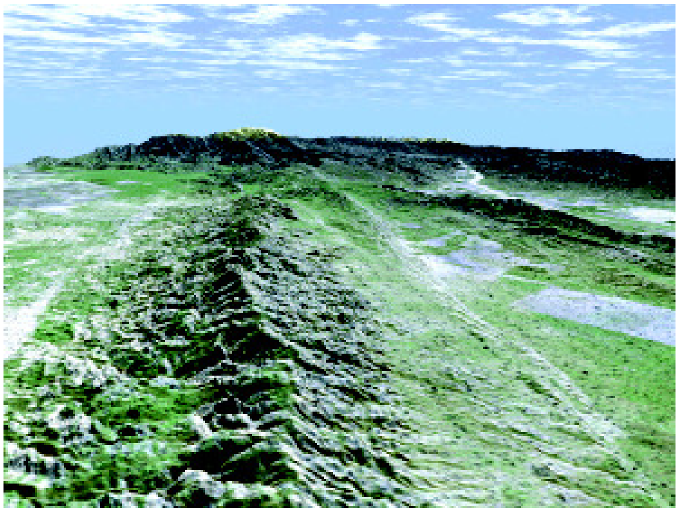
The asthenosphere (from the Greek, *asthenos*, “devoid of force”) is part of the mantle that flows. This is a characteristic called **plastic behavior**.

4. 8. 3. Flow of the Asthenosphere

It might seem strange that a solid material can flow. A good example of a solid that flows, or has plastic behavior, is the movement of toothpaste in a tube. Toothpaste, a somewhat ‘semi-solid’, flows from a tube when the tube is squeezed. The asthenosphere flows as well. Riding along on top of this semi-solid asthenosphere is the ‘fully solid’ lithosphere. The flow of the asthenosphere is part of mantle convection, which plays an important role in moving the lithosphere’s plates.

4. 9. WHAT CAUSES PLATES TO MOVE?

Some geologists believe that the downward gravitational force of the steeply dipping plate is enough to pull a plate away from a mid-ocean ridge, essentially providing a driving force for plate tectonics. Other geologists believe that the plates are pushed away from the mid-ocean ridge by forces generated at the ridge. Still, most geologists would agree that both forces are important.



The San Andreas Fault is a clear example of plates moving side by side.

Convection currents move the ocean floor from a rift zone to an ocean trench. The movement is in the asthenosphere and the overlying lithosphere rides along. A counter-convection activity occurs at the ocean trench, where dense basalt moves back into the mantle.

Gravity becomes greater here due to the extra mass. The pushing of more plate material adds more gravity, which causes a high level of heat as the new material plunges inwards.

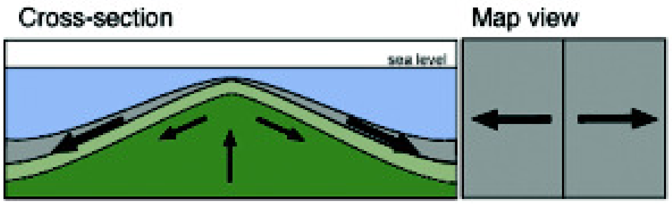
The convection currents also help move the continents, as if on a conveyor belt. Convection is the force that Wegener was looking for earlier to best explain the movement of the continents.

4. 10. PLATE BOUNDARIES—TYPES AND ACTIONS

4. 10. 1 Introduction

Three things can happen when the crustal plates meet. When the plates move side by side in opposite directions, they form a **transform plate boundary** and large fault zones. For example, two plates that move side by side cause the San Andreas Fault in California.

Next, two plates can move away from each other and form a **divergent plate boundary**. This kind of motion causes a rift zone, where there is much volcanic activity. An example of plates moving away from each other is the Mid-Atlantic Ridge.

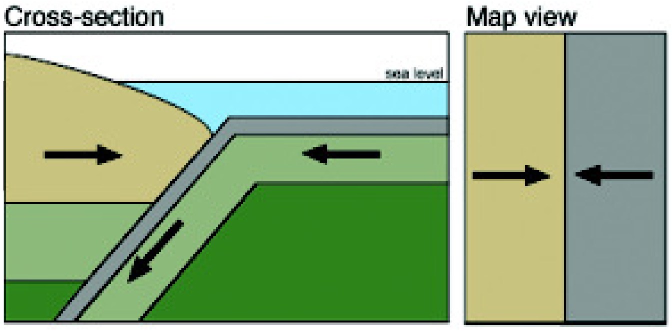


Where two plates move away from each other, they form a divergent plate boundary.

The last kind of movement that happens is when two plates collide with each other and form a **convergent plate boundary**. This type of movement usually forms a **subduction zone**, a place where an oceanic plate meets another plate and is ‘subducted’ below it. The most classic example of this, (taught in geology classes throughout the world,) is our very own Pacific plate’s subduction which we will soon discuss in 4. 12.

4. 10. 2. Divergent Plate Boundaries

The process of adjacent plates moving away from each other is best seen at the oceanic spreading ridges. These submarine features are impressive mountain ranges. Some of these mountain ranges have two parallel crests that are separated and are marked by a central trough, or **rift valley**, where two plates are separating.



Most convergent plate boundaries are called subduction zones because one of the plates moves down, or is subducted, beneath the other.

New ocean floor is produced along the spreading ridges as magma from the earth’s mantle rises to form new oceanic crust. This adds about 15-20 cubic kilometers of new oceanic crust each year. About an equal volume of old crust is lost each year at convergent plate boundaries, so that the overall size of the earth stays the same. An estimated three-quarters of all the **lava** erupted on earth each year pours out along the oceanic spreading ridges.

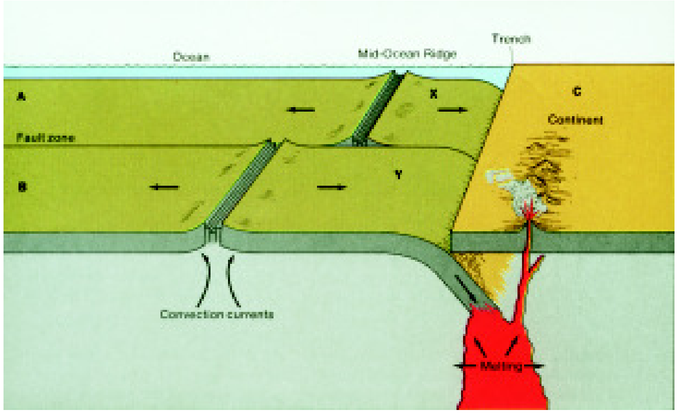
The Mid-Atlantic ridge divergent plate boundary is an area defined by zones of active volcanoes marking the spreading boundary between the North American and Eurasian plates and the South American and African plates.

Almost all of the world’s divergent plate boundaries, and the abundant volcanism along them, lie beneath the oceans. An exception is Iceland, a remote island nation located in the North Atlantic Ocean. Here the mid-ocean ridge is exposed on land. With its many volcanoes and snow-capped mountain peaks, Iceland is truly “The Land of Fire and Ice”.

Earthquake activity along the oceanic spreading ridges is neither as strong, nor as deep, as at convergent plate boundary zones. The reason for this is that the younger, hotter lithosphere is very thin and weak, and stresses cannot build up enough to cause large earthquakes.

4. 10. 3. Convergent Plate Boundaries

As mentioned, most convergent plate boundaries are called subduction zones because one of the plates moves down, or is **subducted**, beneath the other. Often a deep trench forms on the ocean floor where the subducting plate begins its decent. Over three-quarters of the world’s earthquakes take place at convergent plate boundaries.



As the subducted lithosphere moves deeper into the hot mantle, its fluids are “sweated out” and rise triggering partial melting with the overlying mantle.

As the subducted lithosphere moves deeper into the hot mantle, its fluids are “sweated out” and rise, triggering partial melting of the overlying mantle. The new magma is less dense than the surrounding rock and ascends buoyantly; some of it erupts on the earth’s surface to form a line of volcanoes.

Such volcanoes typically are steep-sided cones called **stratovolcanoes** that erupt explosively. Nearly four-fifths of the earth’s historically active volcanoes are found near convergent plate boundaries.

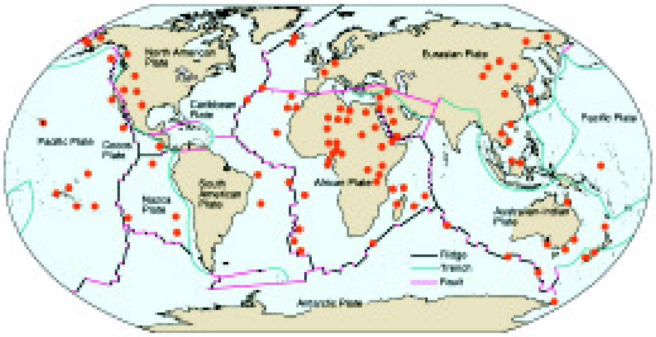
Convergent and divergent plate boundaries are natural complements. New crust is formed at the spreading ridges and is then rafted away to either side of the ridges.

Old parts of the lithosphere, generally far away from the spreading ridges, are eventually consumed by subduction in a natural “recycling” process; consequently no oceanic crust is older than about 200 million years.

As the subducting plate sinks deeper into the hot mantle, it softens to a state incapable of producing earthquakes by brittle fracture. It ultimately loses its identity altogether and merges into the deeper mobile mantle that convectively flows back toward the spreading ridges.

4. 10. 4. Transform Plate Boundaries

Plates slide horizontally past one another along transform boundaries; a well-known example is the San Andreas Fault, California. In places, the friction between the plates is so great that tremendous rock stresses can build up before being intermittently relieved by sometimes very powerful earthquakes. For example, in 1906, in San Francisco, California, a very destructive earthquake occurred along the San Andreas Fault.



Oceanic fracture zones produce the step-like plate margins so prominent on world volcanic-earthquake epicenter maps.

Many transform faults lie near to, but horizontally offsetting, the divergent plate boundaries. These transform faults are sometimes perpendicular to, and sometimes parallel to, the divergent plate boundaries. The oceanic fracture zones formed in this way produce the step-like plate margins so prominent on world volcanic-earthquake epicenter maps.

4. 11. HOTSPOTS

An interesting case of tectonic evidence comes from the Hawaiian Island chain. Some active volcanoes, such as those making up the islands of Hawaii, are located nearly 3,000 kilometers from the nearest plate boundary.

The tallest island, Hawaii, is still an active volcano. From it, a line of inactive volcanic islands, first high, then smaller, then atolls and finally seamounts, stretch off to the northwest. The line ends at an undersea trench off the coast of Russia.

The tallest island, Hawaii, is still an active volcano.

All the islands and seamounts are on the Pacific Plate. Each rides along on top of it at a very slow rate. Along the way, each high island steadily erodes, eventually going all the way down to sea level.

All of the Hawaiian islands will eventually ride the plate down into the trench. Each island was originally formed in just the same way and in pretty much the same place as the island of Hawaii is forming today.

Active volcanoes on Hawaii, like Kilauea and Mauna Loa and the nearby offshore submarine volcano called “Loihi”, presently forming in the sea just to the southeast of Hawaii, currently lie above the Hawaiian **hotspot**.

In many thousands of years, Loihi may grow above sea level to become the next island in the Hawaiian chain. Geologists refer to this area as a hotspot. It is believed that a plume in the mantle continuously rises there spawning the volcanism that is developing the islands.

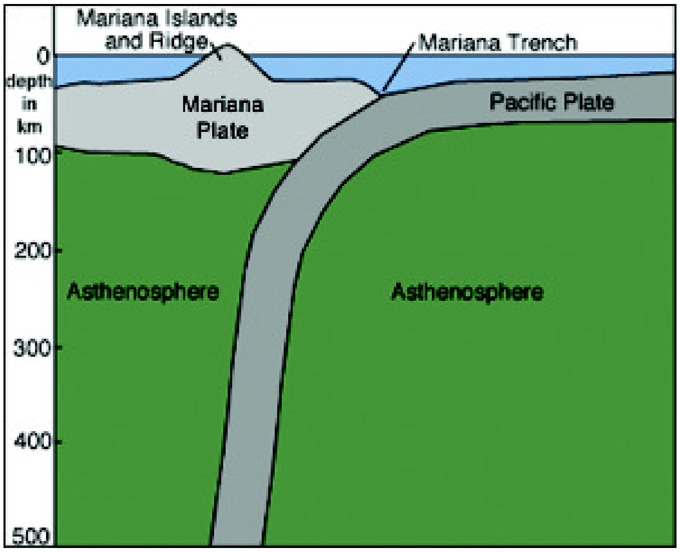
4. 12. THE MARIANA ISLANDS, THE ANDESITE LINE, AND THE PACIFIC RING OF FIRE

As we have noted, the Mariana Trench is an example of a subduction zone. Here the Pacific Plate meets the small Mariana Plate, lying adjacent to the larger Philippine Plate. For a subduction zone to form, something must push the crustal plate.

A rift zone in the eastern Pacific, called the East Pacific Rise, is pushing the Pacific Plate into the Mariana Plate. The Pacific Plate is moving away from the Nazca Plate at the East Pacific Rise and new crust is being formed there.

As the new crust forms, it forces the Pacific Plate to travel west, under the Mariana Plate. It also forces the Nazca Plate to travel east into the continent of South America, thus forming the Andes Mountains.

At a subduction zone, one of the plates must go under the other plate. Usually it is the heavier or the faster moving of the two plates that goes underneath the other. As one plate moves under the other, they form a trench.



The Marianas Trench is an example of a subduction zone.

The friction of the two plates rubbing against each other also causes earthquakes and forms molten rock. This molten rock, called magma, is forced back up to the surface. It forms volcanoes on the upper plate. As the subduction zone slowly moves, volcanic activity starts in new areas.

Trench-island arc systems are formed in the Western Pacific at the subduction zones where the large Pacific Plate is forced under the numerous smaller plates along the Western Pacific coastlines.

In the Mariana Islands, any volcanic activity is in the northern island arc chain and west of the southern island arc chain. It is unlikely that volcanoes will become active on any of the islands that make up the southern group: Farallon de Medinilla, Saipan, Tinian, Aguiguan, Rota, and Guam.

Besides being located at a subduction zone, the Mariana Islands are also located on an **andesite line**. An andesite line is the boundary between a plate that contains continental crust and a plate that contains oceanic crust. The real location of the andesite line is the trenches at the edge of continental plate. To find this line, we must examine rock types.

On one side of the line, the andesite rock is lighter in color and weighs less than the basalt rock that is on the other side. The andesite line is where geologists find about 80 percent of the volcanoes on earth, and where most earthquakes occur.

Scientists give a special name to the andesite line in the Pacific Region: “The Ring of Fire”. The Ring of Fire is a chain of volcanoes that surrounds the rim of the Pacific Ocean.