



CHAPTER 1

Introduction to Plate Tectonics and Our Changing World

Introduction

What is Earth science? The planet that we refer to as Earth has a history that goes back billions of years. It is a continuously evolving intersection of many different integrated parts, all of which we touch upon in the study of Earth science. In this course, we will try to look at all of these parts both separately and together while trying to piece together a mosaic that all of us can understand and discuss. The subject of Earth science starts like any other endeavor in the sciences, by asking questions and following the clues that might provide the answers.

Why are there mountains in Colorado but not in Indiana? Why is an earthquake in southern California expected, yet one occurring in Florida is considered unusual? Why are there volcanoes in Hawaii but not in Kansas? In this chapter, we will begin the study of our changing world and begin to develop an understanding of the theory of plate tectonics which will help us find the answers to many of our questions about how the Earth works.

Learning Objectives

After you complete this chapter, you should be able to

- Identify the scientific disciplines that are included in Earth science
- Demonstrate knowledge of the scientific method
- Describe some of the ways in which the Earth changes
- Describe the observations that led to Wegener's hypothesis of continental drift
- Explain some of the major evidence that resulted in the theory of plate tectonics
- Identify the three types of plate boundaries and the geologic activity associated with each

Key Terms

Asthenosphere: weak, semimolten layer within the Earth that is capable of flow

Continental drift: hypothesis that states that Earth's continents were once joined as one large landmass, and the continents broke apart and drifted through the ocean to their present locations

Convergent plate boundary: where tectonic plates collide or come together

Divergent plate boundary: where tectonic plates split or move apart

Lithosphere: rigid outermost layer of the Earth

Plate tectonics: theory that states that the lithosphere is broken up into a number of slabs or plates that move about the face of the planet with respect to one another by flowing on the weak asthenosphere

Quantitative data: information for which a value or number can be assigned and statistics can be tabulated

Qualitative data: nonnumerical information such as feelings and perceptions, used more often in the health science and social science fields

Scientific theory: accepted explanation regarding the natural world

Theory: well-supported, well-tested generalization to explain a phenomenon or a set of observations

Transform plate boundary: where tectonic plates move sideways past one another

What Is Earth Science?

The study of Earth science incorporates several related disciplines. Geology, the study of Earth, includes both physical geology, which examines internal and external forces that act on our planet, and historical geology, which seeks to understand the development of Earth through time. Oceanography investigates our oceans and coastlines. The study of meteorology includes the atmosphere, weather, and climate. Astronomy examines the universe and Earth's place in it.

Earth Systems

Although the components of the Earth can be divided up in order to study them, no part of the Earth can really be considered separate from the others. The Earth operates as a dynamic, complex system with parts that change and interact with one another. Humans are part of the Earth system, both affecting our planet and being affected by it.

CASE STUDY: LA CONCHITA LANDSLIDE, 2005

A landslide or mass wasting event is a downhill movement of material under the influence of gravity. It may be triggered by natural forces such as an earthquake or a heavy rainfall event, but it may also be set in motion as a result of human activities. Removing native vegetation can de-stabilize a slope by destroying roots that help bind the soil together. Irrigation of crops can act like a heavy rain. Oversteepening the slope, often by cutting into it at or near the bottom to construct a road or buildings can also decrease slope stability.

Although the 2005 La Conchita landslide followed a heavy rain, see how many other factors you can locate in the following photograph (see **Figure 1.1**) that may have contributed to the event (Jibson, 2005, p. 6).

The various systems of our planet are interlinked so that a change in one may result in an impact on others. For example, consider a lightning strike that starts a forest fire. There is an immediate impact on the plants and animals of the forest. Once the vegetation has been burned off, the ground is exposed to the full effects of precipitation; rain washes logs and soil into the streams which become clogged with debris and mud, resulting in the water overflowing and flooding the surrounding area. The added debris and sediment in the waterways affect the aquatic life in the streams. The flood impacts the soil, animals, and plants that are in its pathway, and so on.



Figure 1.1 The 2005 La Conchita Landslide, Ventura County, California, killed 10 people and destroyed 36 homes.

Humans impact these systems in a variety of ways, such as extracting water or oil, constructing roads and buildings, diverting natural waterways and building dams, changing natural vegetation to cropland, and many other ways. Each of these actions has the potential to impact other related systems on our planet.

The Scientific Method

How do scientists learn about the natural world around them? How do scientists determine the way that the Earth works? For that matter, how do humans make sense of the complexities in the universe? The answer to each of these questions can be arrived at through the use of the scientific method. Science should be thought of as if it is an active verb: it is an activity people do or a way to think; it is the process employed to explain natural phenomena or observations. Explanations are then used to make predictions that are testable, or verifiable, so as to create a theory about complex systems.

ESTABLISHING A WORKING HYPOTHESIS

Inductive reasoning occurs when a scientist arrives at a general conclusion based on a number of specific observations.

Observation 1: There are submarine canyons off the east coast of North America

Observation 2: Fast-moving, sediment-laden currents erode canyons

Observation 3: There are fast-moving, sediment-laden currents off the east coast of North America

Conclusion (Working Hypothesis): Fast-moving, sediment laden currents will erode the submarine canyons off the coast

A scientist can predict that the currents will continue to erode the canyons. Next, the scientist can test the working hypothesis by making observations of the currents eroding submarine canyons. The form of reasoning employed in a particular situation is dependent on the situation and the available information.

EXPERIMENT/RESEARCH/DATA COLLECTION

The next stage after observation, hypothesis, and prediction is that of experiment, research, and data collection. There are two types of data, quantitative and qualitative. *Quantitative data* is information for which a value or number can be assigned and statistics can be tabulated. *Qualitative data*, used more often in the health science and social science fields, is nonnumerical information such as feelings and perceptions. Both forms of data can be used to draw conclusion about observations. Regardless of the type of research being done, the goal is to determine the validity of the predictions and hypothesis, to attempt to form a theory, and to add to the body of knowledge about the natural world. In the case presented above, the hypothesis was verified by collecting data on the location and timing of breaks in a transatlantic communications cable damaged when an earthquake triggered an underwater landslide off the east coast.

THEORIES

The term *theory* has a very specific meaning in science. Theories are not just best guesses; on the contrary, a theory is a well-supported, well-tested generalization to explain a phenomenon or a set of observations. And while theories are often subject to small modifications, once a theory has been established, it is unlikely that evidence will be found to cause wholesale changes. No new evidence has been found in the past 400 years to dispute the heliocentric theory of Earth orbiting the Sun. A *scientific theory* is not simply a theory; it is an accepted explanation regarding the natural world.

RESULTS/REPORTING

At the completion of the scientific method, the scientist will report her/his results. Science relies on peer review, particularly for positive findings. The ability to reproduce results is critical in science. If the results of an experiment cannot be confirmed in another lab, they are generally assumed to be an anomaly or false positive. Publishing results allows other trained scientists to review the method to determine that the process did indeed answer the question.

The Theory of Plate Tectonics

The theory of *plate tectonics* states that the *lithosphere*, the rigid outermost layer of the Earth (including the crust and outermost mantle), is broken into a number of slabs or plates that move about the face of the planet with respect to one another by flowing on the weak asthenosphere. It explains many of the changes that impact our dynamic planet. As will be illustrated in this course, the theory of plate tectonics explains the occurrence of volcanoes, earthquakes, mountain ranges, and even the appearance of our continents and oceans.

CONTINENTAL DRIFT

The history of plate tectonics begins in 1915 with a German scientist named Alfred Wegener. He observed that with a little tilting, the east coast of South America would fit nicely against the west coast of Africa (see **Figure 1.2**). He hypothesized that these two continents had once been joined into one large landmass, and the continents broke apart sometime in the geologic past and drifted through the ocean to their present locations. He called his new idea *continental drift* (Wegener, 1968).

In addition to the jigsaw puzzle fit of the continents, he also realized that the discovery of identical fossils on different continents needed an explanation. Did the organisms cross from one continent to another on land bridges that have since sunk beneath the waves? Did they float from one continent to another on logs? Did they cross the ocean via island stepping stones? Some of these fossils were strictly land animals, so they could not have swum from one continent to another. There was no evidence for either land bridges or island stepping stones. Therefore, Wegener hypothesized that at the time these organisms lived, the continents were joined, adding another piece of evidence to continental drift.

A third piece of evidence was the discovery of similar rocks and structures on widely separate continents. For example, the rocks, faults, and folds of the Appalachian Mountains in eastern North America match up with rocks, faults, and folds in mountain ranges in the British Isles and in Scandinavia. How else could this be explained except by the continents drifting apart (see **Figure 1.3**)?



Figure 1.2 Artist's rendering of the way South America and Africa may have fit together as a single landmass

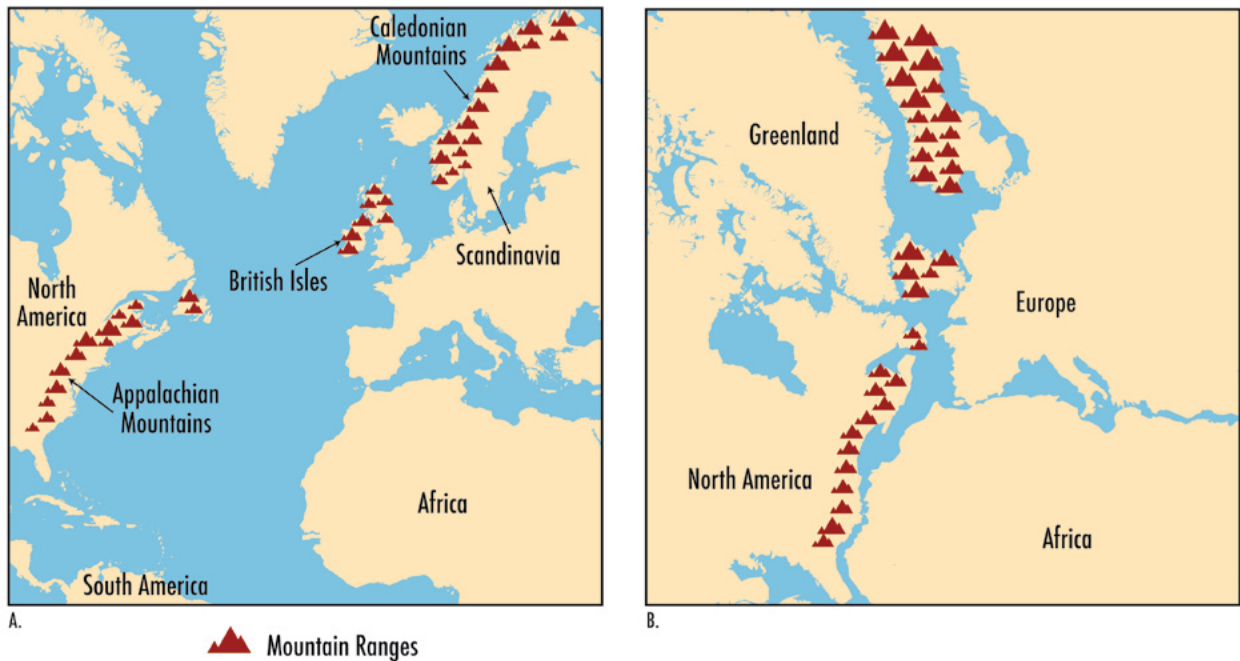


Figure 1.3 Illustration of the way the Appalachian Mountain range in North America folds into the mountain ranges in Western Europe as evidence of continental drift

The discovery of the evidence of glaciers in the past in places like South America, Africa, India, and Australia, all warm places that do not have glaciers today, was another point supporting Wegener's hypothesis. Huge coal deposits in places characterized by cold climates today, including places in the Northern Hemisphere and Antarctica around the South Pole, indicate tropical climates existed at those locations in the past. As we will see in a later unit in this course, coal forms in tropical swamps. How are we to explain this? The plausible solution is that the continents used to be in different locations, with some closer to the poles where they experienced glaciation, and some closer to the equator where they experienced a tropical climate (see **Figure 1.4**).

Wegener hypothesized that all the continents had been joined in the geologic past into one supercontinent that he called Pangaea (see **Figure 1.5**), which means *all land*. About 200 million years ago, Pangaea began to break up, and the continents slowly drifted to their present locations.

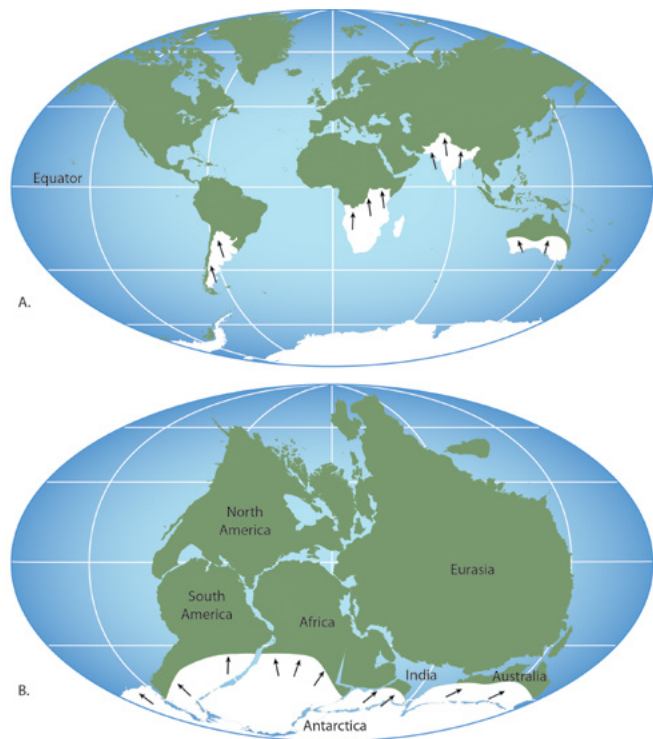


Figure 1.4 Comparison of the world map today (A) and what it might have been like millions of years ago (B), before continental drift

Unfortunately for Wegener, he could not produce a plausible mechanism for how the continents drifted. Other scientists thought he was crazy and ridiculed his ideas. In 1930, while conducting research in Greenland, Wegener died while attempting to return to base camp after taking emergency supplies by dogsled to another camp. Alfred Wegener died without seeing his hypothesis of continental drift vindicated, and the idea of continental drift essentially disappeared until the 1950s.

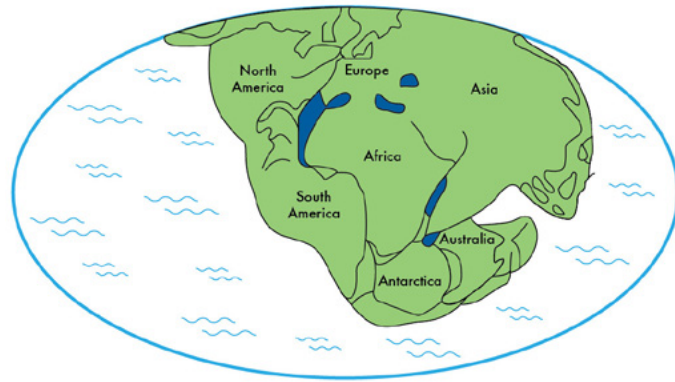


Figure 1.5 Pangaea as theorized by Wegener

NEW EVIDENCE

In the 1950s, scientists made some interesting discoveries. Igneous rocks, which include those formed in volcanic eruptions, become magnetized according to Earth's magnetic field as they cool. By studying this *fossil magnetism*, or paleomagnetism, scientists can tell where the magnetic north pole was when the rock was formed. By age dating many rocks, scientists were able to develop maps that revealed where the magnetic north pole was located at various times in the geologic past. The pole appeared to have wandered through time, ranging over the Earth's surface. However, based on knowledge of the Earth's magnetic field, it is known that the poles do not wander. So how can apparent polar wandering be explained except to think that the continents where the rocks were found had drifted to different locations over time?

Mapping of the sea floor, made possible by the advances in sonar technology during World War II, revealed submarine mountain ranges cut by rift valleys as well as deep trenches which are the deepest parts of the ocean basins (see **Figure 1.6**). Some of the deep ocean trenches are more than 6 miles deep. Since the most studied of the submarine mountain ranges is located approximately in the center of the Atlantic Ocean, these have become known as midocean ridges. The following cross-sectional sketch (not to scale) of the sea floor provides an idea of these features.

The Deep Sea Drilling Project, which began in the 1960s, was an international oceanic research program. The research ships were capable of lowering hollow drill pipe tens of thousands of feet to the ocean floor and drilling thousands more feet into the sea floor sediments and rocks. The drill pipe was then brought back to the ship, and the core of sediment and rock within the hollow pipe was recovered. These cores represent a history of the ocean floor over geologic time. Age dating revealed that the youngest sediment and rocks are located at the midocean ridges, and the age of the ocean

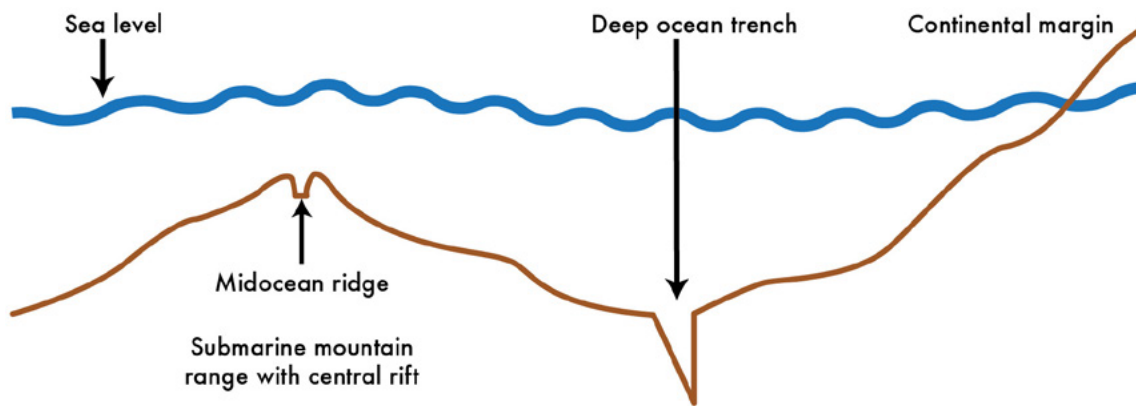


Figure 1.6 Depiction of a midocean ridge

floor increases with increasing distance away from the midocean ridges. In general, though, the ocean floor is quite young when compared to the continents. Also, the thickness of the sediment cover on the ocean floor increases as the distance away from the midocean ridges increases. The ridges themselves lack a sediment cover.

All of this new information led to a new hypothesis called sea floor spreading (Hess, 1962) which states that new oceanic crustal material is generated at the midocean ridges and carried in a conveyor belt fashion to the deep ocean trenches where it is consumed by being recycled back into the mantle, a semimolten layer within the Earth. Therefore, the reason the ocean floor is so young is that it is continually being recycled. The youngest rocks would be closest to the midocean ridge since that is where new material is generated. The older material, farther from the ridge, would have a thicker sediment cover as more time allows more sediment to accumulate. The beautiful sequence of geological recycling has been called *geopoetry*.

Sea floor spreading was confirmed with the discovery of magnetic reversals. Although this is not yet well understood, what is known is that the Earth's magnetic field actually reverses sometimes so that the North Pole becomes the South Pole and vice versa. Periods of geologic time when the magnetic field was the same as it is now are referred to as *normal* while periods of time when the magnetic field was switched are referred to as *reverse*. Mapping of the sea floor led to the discovery of rocks with both normal and reverse polarity on either side of the midocean ridges, laid out like mirror images of one another. These are now called *sea floor stripes*. Age dating of the rocks confirmed the match. As new material is added to the ocean floor at the midocean ridges, it takes on the polarity in existence at the time. Then it moves away from the ridge, conveyor belt fashion, to be replaced by more new material upwelling from deep within the Earth at the midocean ridge. When the Earth's magnetic field reverses, the new material at the ridge will take on the new polarity. Material moves away from either side of the ridge resulting in the mirror image stripes.

By 1968, Wegener's continental drift idea was tied together with the new discoveries of paleomagnetism and sea floor spreading. This new theory, which includes a driving mechanism (which Wegener's continental drift hypothesis lacked) came to be called plate tectonics. In the 1990s, with the advent of GPS (Global Positioning System) and satellite technology, the movements of the plates could be tracked. The abundance of data collected has confirmed plate tectonics, finally vindicating Wegener and his theories.

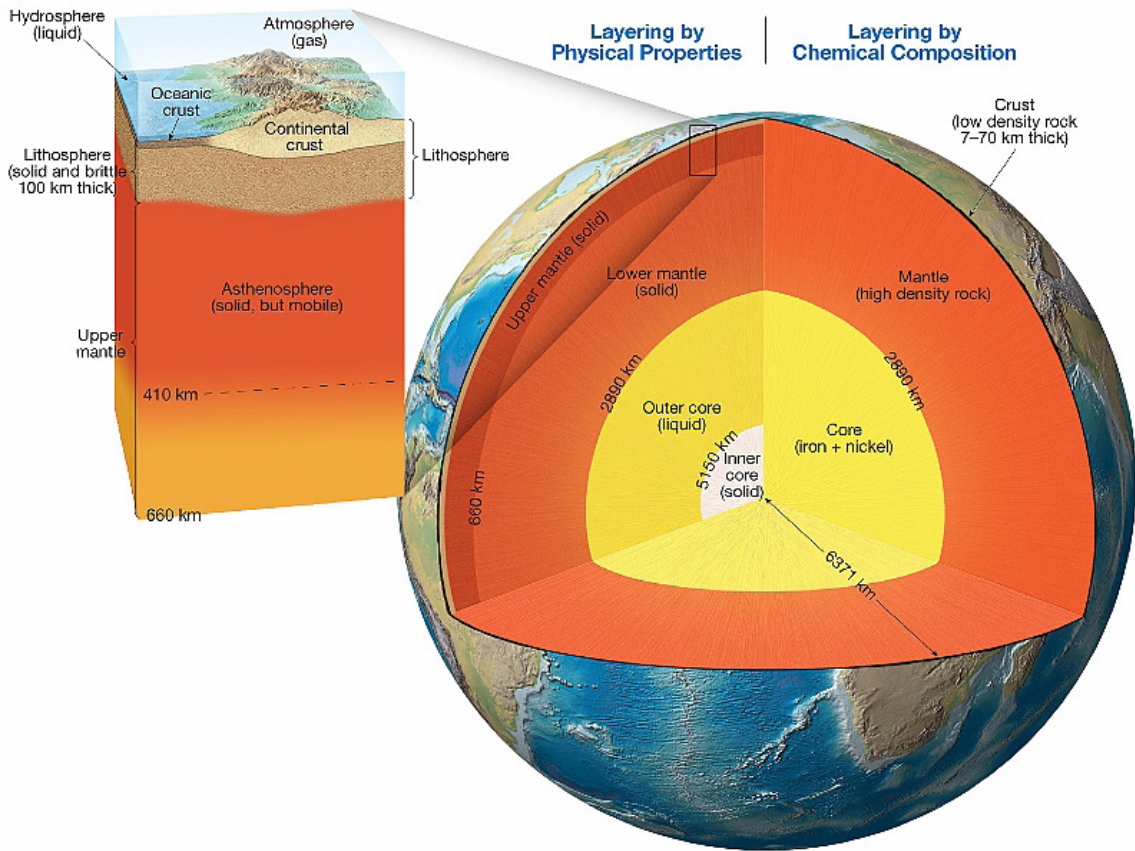
Plate Tectonics

The Earth can be divided into three major layers based on differences in composition, a result of differentiation early in Earth's history as heavier elements sank into the interior and lighter elements rose towards the surface. The outer layer, called the crust, is the thinnest. Below the crust is the thickest layer, called the mantle. At the center of the Earth is the core, composed mostly of the very heavy element iron.

The outer layers of the Earth can be divided in a different way based on differences in physical properties (see **Figure 1.7**). The Earth's crust, the outermost layer of the Earth, referred to as the lithosphere, behaves as a cool rigid shell. Below is a soft, weak, semimolten layer in the mantle which is capable of flow. Think of putty—it is a solid, but it can slowly flow. The weak layer in the mantle is called the *asthenosphere*.

The lithosphere is broken up into about 20 fragments called plates. Some plates consist of only oceanic material, but most include both continental and oceanic surface (see **Figure 1.8**). These rigid plates move about the face of the planet with respect to one another by riding on the hotter, weaker, plastic-like asthenosphere. The average rate of plate movement is only a few centimeters per year (about as fast as human fingernails grow), but over the vast expanse of geologic time, this can add up to thousands of miles of movement.

The word *tectonics* refers to building or, more specifically, mountain building in this context. Geologic activity, such as volcanoes, earthquakes, and mountain building, occurs along the edges of the plates where they interact with one another.



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Figure 1.7 Cutaway of the Earth

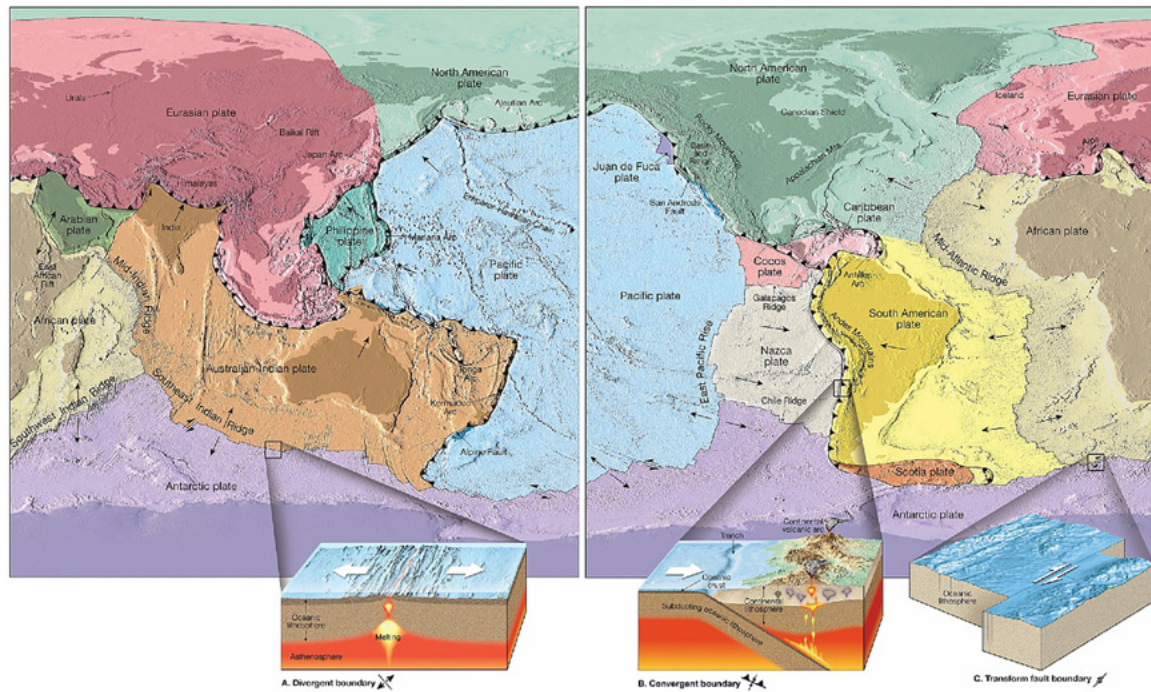
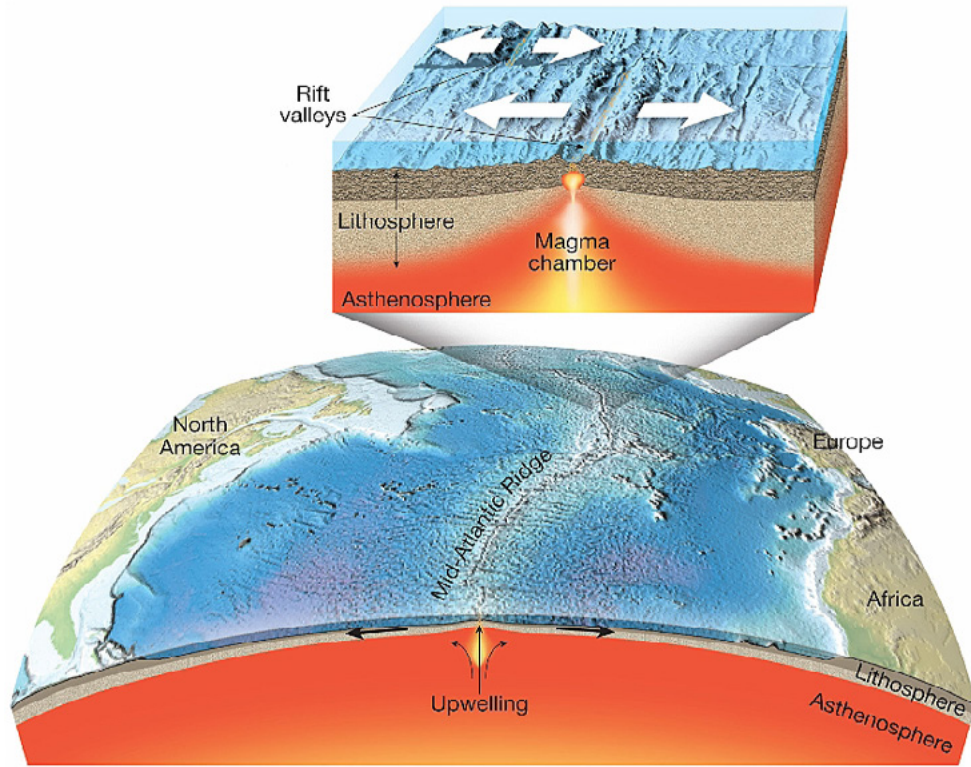
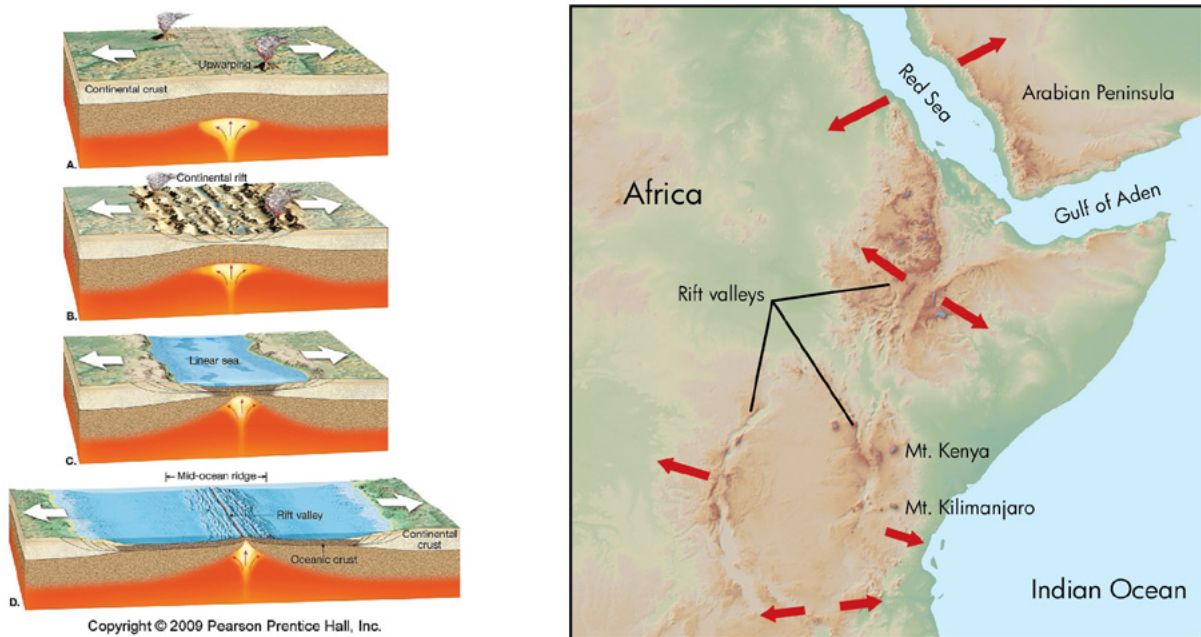


Figure 1.8 Plates including both continental and oceanic surface



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Figure 1.9 Upwelling of molten material



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Figure 1.10 An example of continental divergence, the East Africa Rift

PLATE BOUNDARIES

The plates interact with one another at three different types of plate boundaries. Plate rifting occurs when two plates move apart from each other at a **divergent plate boundary**. As the plates move apart, molten material wells up from deep within the Earth, cools and solidifies as new rock, and adds to the edges of the plates. The upwelling of molten material most commonly occurs at the midocean ridges (see **Figure 1.9**). The oceanic crust is thinner than continental crust, so rifting or pull-apart is easier in the ocean than on a continent. The new crust is hot and buoyant, so it stands high, resulting in the submarine mountain range at the rift zone. As it moves away from the rift zone, it cools, contracts, and subsides to lower elevations.

Although most divergent boundaries are seen in the ocean, the East Africa Rift is an example of continental divergence (see **Figure 1.10**). If divergence continues here, the Indian Ocean could flood the rift valley and cut East Africa off from the mainland, creating a new, smaller plate.

The rifting at divergent boundaries frequently triggers earthquakes, and the upwelling of molten material may result in volcanoes. Mount Kilimanjaro (see **Figure 1.11**) in the East African Rift is an example of a volcano at a divergent boundary.

New crust is generated or created at divergent boundaries, but the Earth is not expanding. Therefore, crust must also be consumed or destroyed somewhere. Crust is consumed and destroyed in the deep ocean trenches at **convergent plate boundaries** where two plates come together. Oceanic crust is thinner than continental crust but is also denser; therefore, where oceanic crust converges with continental crust, the oceanic crust will be consumed at the deep ocean trench. The process is called subduction, and a deep ocean trench where subduction is occurring is referred to as a subduction zone. The deeper a plate travels into the Earth, the hotter it gets until eventually the descending slab becomes molten and is reabsorbed or destroyed.

Residue of the melting plate may rise through the crust to create a chain of volcanoes along the edge of the subduction zone. Examples include the Andes Mountains in South America, the Cascade Mountains in the Pacific Northwest of North America, and the Aleutian Islands which extend westward from Alaska in the northern Pacific Ocean.



Figure 1.11 Mount Kilimanjaro, Tanzania

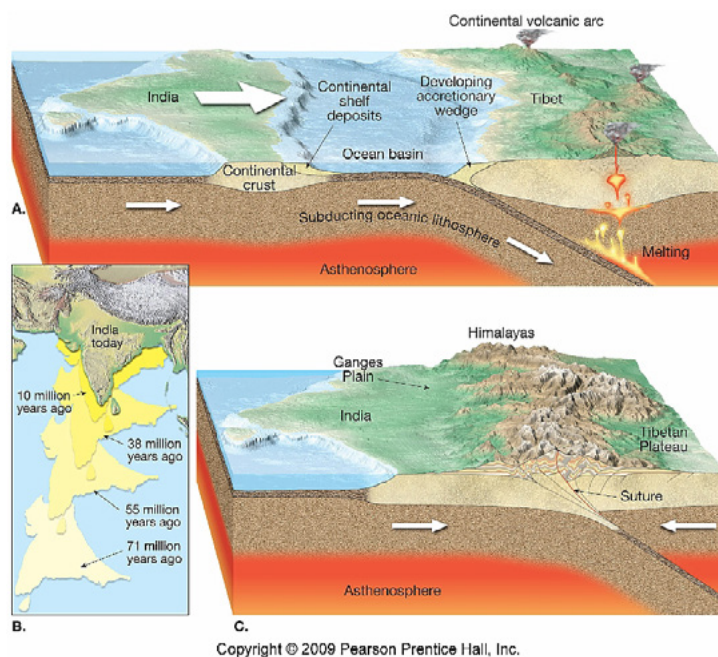


Figure 1.12 Plate convergence over time

One exception to subduction at a convergent boundary is where two continents collide. Since the densities are the same, neither one will be subducted, and the end result is the building of a great mountain range at the boundary as the two plates smash into each other and crumple up against one another. The Appalachian Mountains in eastern North America were formed in this way a long time ago when North America, Europe, and Africa all collided, and the Himalaya Mountains in Asia are still rising as the subcontinent of India collides with the Eurasian plate (see **Figure 1.12**).

Plate convergence can result in earthquakes, volcanic activity, and mountains. Mount Rainier is one of the active volcanoes in the Cascade Range which is at the edge of an oceanic-continental plate convergence. Mt. Everest in the Himalayas, the highest mountain peak in the world, rose because of continental-continental plate convergence. Mount Cleveland is one of the most active volcanoes in the Aleutian chain, and it is the result of oceanic-oceanic plate convergence.

The third type of plate boundary is called a **transform plate boundary**. A transform plate boundary accommodates the motion of two plates that are sliding or grinding past each other, with crust being neither created nor destroyed. Geologic activity also occurs at transform plate boundaries where tectonic plates move sideways past one another. Probably the most famous transform plate boundary is the San Andreas Fault in southern California. The fault illustrates the Pacific Plate's motion as it slowly grinds northwest past the North American Plate that is moving slowly towards the southeast. Some of the earthquakes that have resulted from this movement are quite famous, including the 1906 San Francisco quake and the 1989 Loma Prieta quake. New Zealand's Alpine Fault, also a transform fault, is along the boundary between the Australian and Pacific Plates. Many other transform boundaries are found in the oceans connecting segments of the midocean ridges or of subduction zones. Although earthquakes are common at transform boundaries, volcanic activity is not. Most large-scale geologic activity occurs at plate boundaries, and plate interiors are relatively quiet, though there are exceptions.

Driving Mechanism for Plate Tectonics

Alfred Wegener could not explain how the continents drifted, and therefore other scientists refused to accept his ideas on continental drift. Although abundant evidence for plate tectonics currently exists, there remains uncertainty about the driving mechanisms behind plate movement. And yet, regardless of

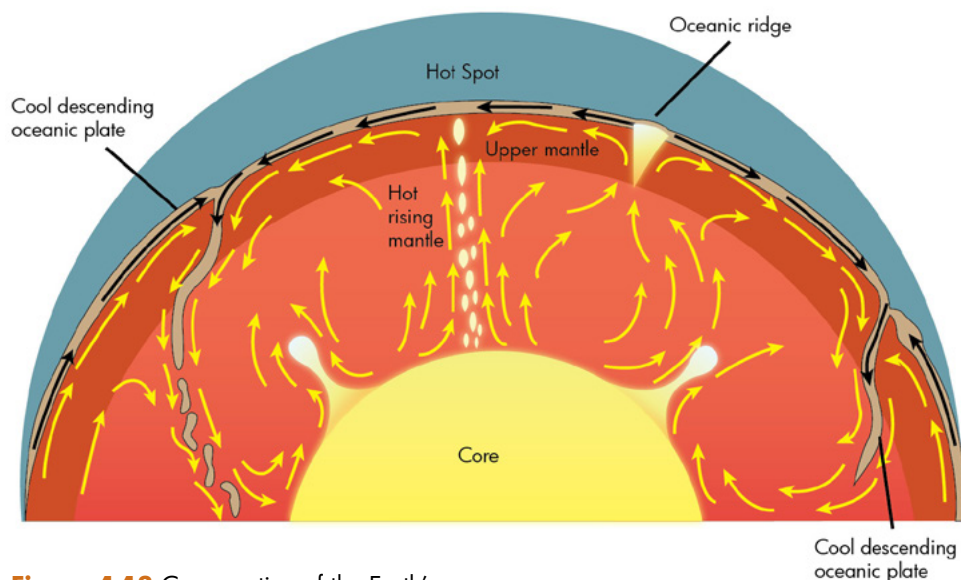


Figure 1.13 Cross section of the Earth's core

the theory proposed to explain plate tectonics and plate movement, it is highly likely that the unequal distribution of heat within the Earth's interior generates a form of thermal convection that influences plate movement.

If it were possible to travel deep within the Earth, you would find that the temperature increases the deeper you traveled, as a result of the geothermal gradient. Furthermore, it is well-documented that heat rises. An accurate thermometer will show you that it is warmer up by the ceiling than down close to the floor. Thus, as the temperature deep within the Earth heats up the mantle, this hot, semimolten material slowly rises. And as it rises closer to the Earth's surface, it begins to cool and eventually subsides or sinks to be replaced by hotter material rising up from the depths.

The circulation of the semimolten material within the Earth is called convection. A likely explanation for the movement of the plates is that *plate divergence* occurs where two convection cells move away from each other to sink back into the Earth. Whereas, *plate convergence* occurs where two convection cells come together. A cross section of the Earth (see **Figure 1.13**) reveals the convection cells in the mantle created by the heat generated in the core. The crust is not shown as it is such a thin layer at the surface.

Keep in mind that this is a fairly simplistic explanation as the flow in the semimolten mantle is significantly more complicated than described. Plate motion may actually be the result of a combination of mechanisms, some of which scientists may not even be aware of yet. However, while it is clear that thermal convection does play a role in plate tectonics, what that role is, and its extent, is still, as yet, unknown.

Summary

The Earth is a complex, dynamic planet with many interacting parts. A change in one may cause a domino-like effect resulting in many other changes. Earth science seeks to understand our planet's many changing systems through its interdisciplinary studies of geology, oceanography, meteorology, and astronomy. The scientific method uses observations to make predictions that can be tested to aid understanding of the natural world. A scientific theory is a well-tested, well-supported, and accepted explanation.

Alfred Wegener is credited with the theory of continental drift. Wegener proposed the idea that all the continents were once joined together into one large landmass, Pangaea, which split apart with the separate continents drifting to their current locations. Additional evidence ultimately resulted in the theory of plate tectonics, a comprehensive model of Earth that states that the outermost layer of the Earth is broken up into a number of large slabs called plates that move about the face of the planet with respect to one another. Where the plates interact at plate boundaries, there are earthquakes, volcanoes, mountain building, and other geologic processes occurring. Plates move apart from one another at divergent plate boundaries, and new material wells up from depth to be added to the edges of the spreading plates. Plates come together at convergent plate boundaries where one plate may be subducted beneath another resulting in the destruction or recycling of material back into the Earth's mantle. These processes balance each other so that the size of the Earth is constant. At the third type of plate boundary (transform), plates slide past one another with neither creation nor destruction of material occurring.

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