Chapter 10 Plate Tectonics

Learning Objectives

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Discuss some of the early evidence for continental drift and Alfred Wegener's role in promoting this theory.
- Explain some of the other models that were used early in the 20th century to understand global geological features.
- Describe the numerous geological advances made in the middle part of the 20th century that provided the basis for understanding the mechanisms of plate tectonics and the evidence that plates have moved and lithosphere is created and destroyed.
- List the seven major plates, their extents, and their general directions of motion, and identify the types of boundaries between them.
- Describe the geological processes that take place at divergent and convergent plate boundaries, and explain the existence of transform faults.
- Explain how super-continents form and how they break apart.
- Describe the mechanisms for plate movement.

As we discovered in Chapter 1, plate tectonics is the model or theory that we use to understand how our planet works. More specifically it is a model that explains the origins of continents and oceans, folded rocks and mountain ranges, igneous and metamorphic rocks, earthquakes (Figure 10.0.1) and volcanoes, and continental drift. Plate tectonics was first proposed just over 100 years ago, but did not become an accepted part of geology until about 50 years ago. It took 50 years for this theory to be accepted for a few reasons. First, it was a true revolution in thinking about Earth, and that was difficult for many established geologists to accept. Second, there was a political gulf between the main proponent of the theory Alfred Wegener (from Germany) and the geological establishment of the day, which was mostly centred in Britain and the United States. Third, the evidence and understanding of Earth that would have supported plate tectonic theory simply didn't exist until the middle of the 20th century.

Figure 10.0.1 The San Andreas Fault at Pt. Reyes Station, California. The two parts of the fence show the offset on the fault caused by the M7.9 San Francisco earthquake in 1906. The near side of the fence is on the Pacific Plate and the far side is on the North America Plate. The relationship between tectonic plates and earthquakes was not known in Alfred Wegener's time.

Media Attributions

- Figure 10.0.1: © Steven Earle. CC BY.

10.1 Alfred Wegener: The Father of Plate Tectonics

Alfred Wegener (1880-1930) (Figure 10.1.1) earned a PhD in astronomy at the University of Berlin in 1904, but he had always been interested in geophysics and meteorology and spent most of his academic career working in meteorology. In 1911 he happened on a scientific publication that included a description of the existence of matching Permian-aged terrestrial fossils in various parts of South America, Africa, India, Antarctica, and Australia (Figure 10.1.2).

Wegener concluded that this distribution of terrestrial organisms could only exist if these continents were joined together during the Permian, and he coined the term **Pangea** ("all land") for the supercontinent that he thought included all of the present-day continents.

Figure 10.1.1 Alfred Wegener a few years before his death in 1930.

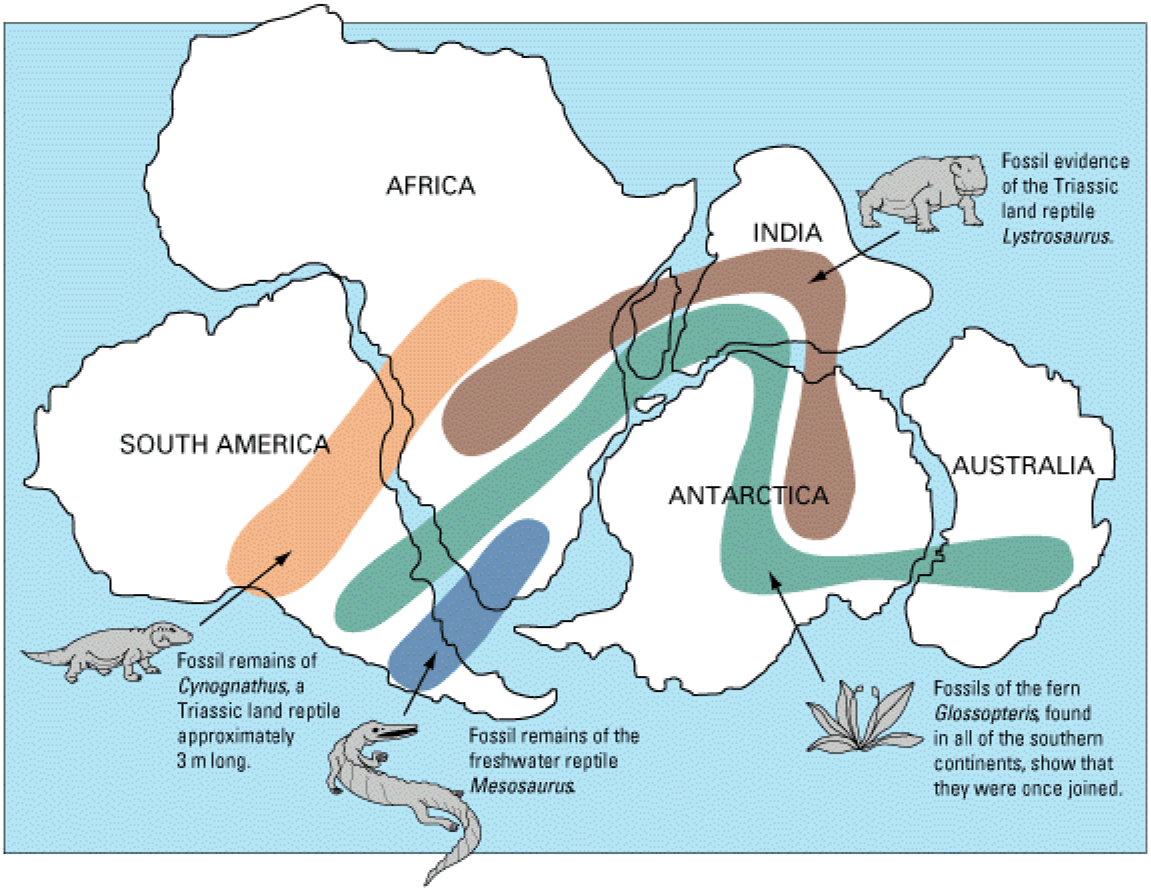


Figure 10.1.2 The distribution of several Permian terrestrial fossils that are present in various parts of continents that are now separated by oceans. [Image Description]

Wegener pursued his theory with determination—combing the libraries, consulting with colleagues, and making observations—looking for evidence to support it. He relied heavily on matching geological patterns across oceans, such as sedimentary strata in South America matching those in Africa (Figure 10.1.3), North American coalfields matching those in Europe, and the mountains of Atlantic Canada matching those of northern Britain—both in morphology and rock type.

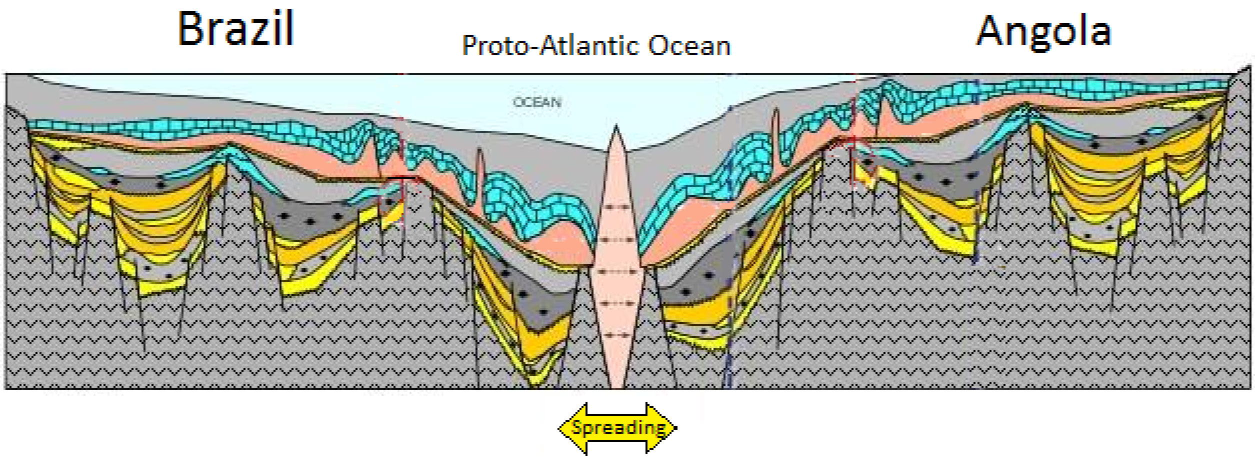


Figure 10.1.3 A cross-section showing the geological similarities between parts of Brazil (South America) on the left and Angola (Africa) on the right. The pink layer is a salt deposit, which is now known to be common in areas of continental rifting.

Wegener referred to the evidence for the Carboniferous and Permian (~300 Ma) Karoo Glaciation in South America, Africa, India, Antarctica, and Australia (Figure 10.1.4). He argued that this could only have happened if these continents were once all connected as a single supercontinent. He also cited evidence (based on his own astronomical observations) that showed that the continents were moving with respect to each other, and determined a separation rate between Greenland and Scandinavia of 11 metres per year, although he admitted that the measurements were not accurate. In fact they weren't even close—the separation rate is actually about 2.5 centimetres per year!

Figure 10.1.4 The distribution of the Carboniferous and Permian Karoo Glaciation (outlined in blue).

Wegener first published his ideas in 1912 in a short book called *Die Entstehung der Kontinente* (*The Origin of Continents*), and then in 1915 in *Die Entstehung der Kontinente und Ozeane* (*The Origin of*

Continents and Oceans). He revised this book several times up to 1929. It was translated into French, English, Spanish, and Russian in 1924.

In fact the continental fits were not perfect and the geological matchups were not always consistent, but the most serious problem of all was that Wegener could not conceive of a credible mechanism for moving the continents around. It was understood by this time that the continents were primarily composed of **sialic** material (**SIAL**: silicon and aluminum dominated, similar to "felsic"), and that the ocean floors were primarily **simatic** (**SIMA**: silicon and magnesium dominated, similar to "mafic"). Wegener proposed that the continents were like icebergs floating on the heavier SIMA crust, but the only forces that he could invoke to propel continents around were *poleflucht*, the effect of Earth's rotation pushing objects toward the equator, and the lunar and solar tidal forces, which tend to push objects toward the west. It was quickly shown that these forces were far too weak to move continents, and without any reasonable mechanism to make it work, Wegener's theory was quickly dismissed by most geologists of the day.

Alfred Wegener died in Greenland in 1930 while carrying out studies related to glaciation and climate. At the time of his death, his ideas were tentatively accepted by only a small minority of geologists, and soundly rejected by most. However, within a few decades that was all to change. For more about his extremely important contributions to Earth science, visit the NASA website to see a collection of articles on Alfred Wegener.

Image Descriptions

Figure 10.1.2 image description: Fossils found across different continents suggest that these continents were once joined as a super-continent. Fossil remains of *Cynognathus* (a terrestrial reptile) and *Mesosaurus* (a freshwater reptile) have been found in South America and Africa. Fossil evidence of the *Lystrosaurus*, a land reptile from the Triassic period, has been found in India, Africa, and Antarctica. Fossils of the fern *Glossopteris* have been found in Australia, Antarctica, India, Africa, and South America. When you position these continents so they fit together, the areas where these fossils were found line up. [Return to Figure 10.1.2]

Media Attributions

- Figure 10.1.1: "Alfred Wegener ca.1924-30." Public domain.
- Figure 10.1.2: "Snider-Pellegrini Wegener fossil map" by Osvaldocangaspadilla. Public domain.
- Figure 10.1.3: © Steven Earle. CC BY. Based on "Angola -Brazil sub-sea geology" by Cobalt International Energy can be found at U.S. Energy Information Administration: Country Analysis Brief: Angola (May 2016) [PDF].
- Figure 10.1.4: "Karoo Glaciation" © GeoPotinga. Adapted by Steven Earle. CC BY-SA.

10.2 Global Geological Models of the Early 20th Century

The untimely death of Alfred Wegener didn't solve any problems for those who opposed his ideas because they still had some inconvenient geological truths to deal with. One of those was explaining the distribution of terrestrial species across five continents that are currently separated by hundreds or thousands of kilometres of ocean water (Figure 10.1.2), and another was explaining the origin of extensive fold-belt mountains, such as the Appalachians, the Alps, the Himalayas, and the Canadian Rockies.

Before we go any further, it is important to know what was generally believed about global geology before plate tectonics. At the beginning of the 20th century, geologists had a good understanding of how most rocks were formed and understood their relative ages through interpretation of fossils, but there was considerable controversy regarding the origin of mountain chains, especially fold-belt mountains. At the end of the 19th century, one of the prevailing views on the origin of mountains was the theory of **contractionism**—the idea that since Earth is slowly cooling, it must also be shrinking. In this scenario, mountain ranges had formed like the wrinkles on a dried-up apple, and the oceans had submerged parts of former continents. While this theory helped to address the dilemma of the terrestrial fossils, it came with its own set of problems, one being that the amount of cooling couldn't produce the necessary amount of shrinking, and the other being the principle of isostasy (which had already been around for several decades), which wouldn't allow continents to sink. (See Section 9.4 for a review of the important principle of isostasy.)

Another widely held view was **permanentism**, in which it was believed that the continents and oceans have always been generally as they are today. This view incorporated a mechanism for creation of mountain chains known as the **geosyncline** theory. A geosyncline is a thick deposit of sediments and sedimentary rocks, typically situated along the edge of a continent (Figure 10.2.1).

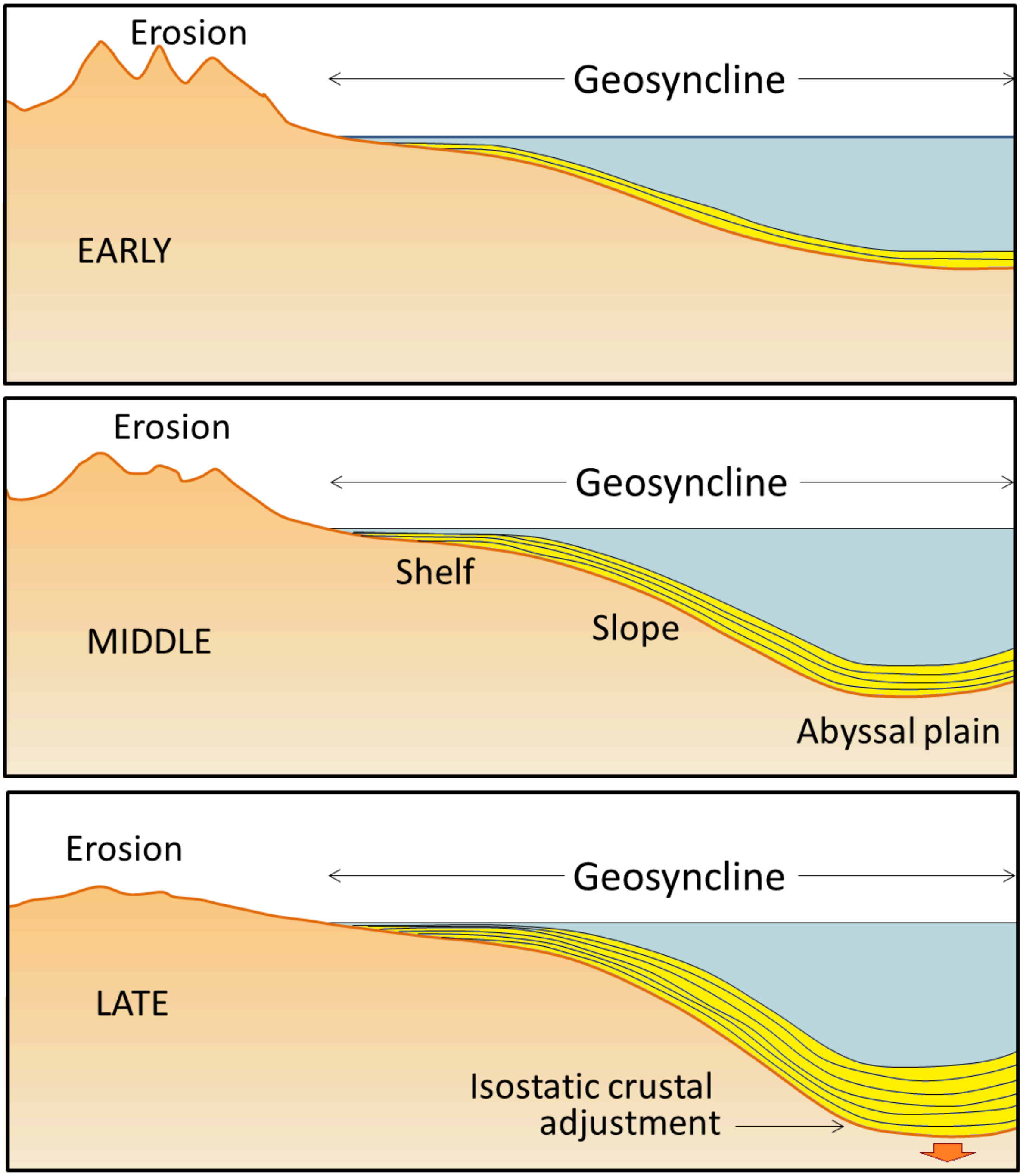


Figure 10.2.1 The development of a geosyncline along a continental margin. (Note that a geosyncline is not related to a syncline, which is a downward fold in sedimentary rocks.)

The idea of geosynclines developing into fold-belt mountains originated in the middle of the 19th century, proposed first by James Hall and later elaborated by Dwight Dana, both of whom worked extensively in the Appalachian Mountains of the eastern United States. The process of converting a geosyncline into a mountain belt was never really adequately explained, although it was widely believed that mountain belts formed when geosynclines were compressed by forces pushing from either side. The problem is that, without the lateral forces related to plate tectonics, no one was able to adequately describe what would do the pushing. The sediments that accumulate within a geosyncline are derived from erosion of the adjacent continent. Geosynclinal sediments—which eventually turn into sedimentary rocks—may be many thousands of metres thick. As they accumulate, they push down the pre-existing crustal rocks. Extensive geosynclinal deposits exist around much of the coastline of most of the continents; there is a large geosyncline along the eastern edge of North America.

Proponents of the geosyncline theory of mountain formation—and there were many well into the 1960s—also had the problem of explaining the intercontinental terrestrial fossil matchups. The simple explanation was that there were "land bridges" across the Atlantic along which animals and plants could migrate back and forth. One proponent of this idea was the American naturalist Ernest Ingersoll. Referring to evidence of past climate changes, Ingersoll contributed the following to the *Encyclopedia Americana* in 1920: "The most interesting feature of these changes, however, is that by which, now and again, the Old World was connected with the New by necks or spaces of land, known as "land-bridges"; especially as these permitted an interchange of plants and animals, giving to us many new ones from the other side of the ocean, including, finally, man himself."[1]

There are serious problems with the land-bridge theory. One is that it is completely inconsistent with isostasy, and another is that there is no evidence of the remnants of the land bridges. The Atlantic Ocean is several thousand metres deep over wide areas, and so the underwater slopes leading up to a land bridge would have to have been at least tens of kilometres wide in most places, and many times that in others. A land bridge of that size would certainly have left some trace.

Exercise 10.1 Fitting the continents together

1. http://en.wikisource.org/wiki/The_Encyclopedia_Americana_(1920)/Land-Bridges_Across_the_Oceans

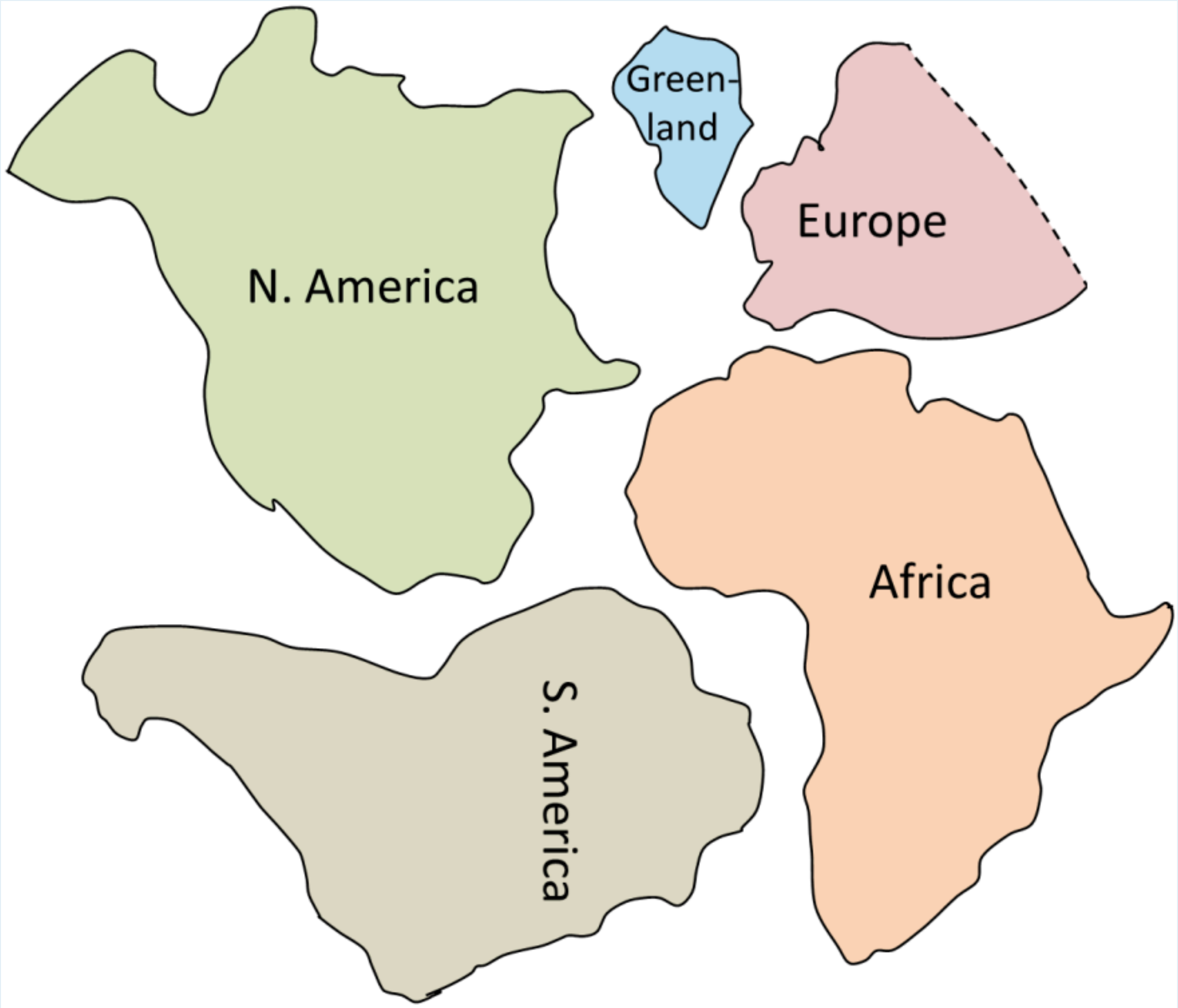


Figure 10.2.2

The main continents around the Atlantic Ocean are depicted here in the shapes that they might have had during the Mesozoic, including the extents of their continental shelves. Cut these shapes out and see how well you can fit them together in the positions that these areas occupied within Pangea. You can refer to a map of Pangea to help you make the fit.

See Appendix 3 for [Exercise 10.1 answers](#).

Media Attributions

- Figures 10.2.1, 10.2.2: © Steven Earle. CC BY.

10.3 Geological Renaissance of the Mid-20th Century

As the mineral magnetite (Fe_3O_4) crystallizes from magma, it becomes magnetized with an orientation parallel to that of Earth's magnetic field at that time. This is called **remnant magnetism**. Rocks like basalt, which cool from a high temperature and commonly have relatively high levels of magnetite (up to 1 or 2%), are particularly susceptible to being magnetized in this way, but even sediments and sedimentary rocks, as long as they have small amounts of magnetite, will take on remnant magnetism because the magnetite grains gradually become reoriented following deposition. By studying both the horizontal and vertical components of the remnant magnetism, one can tell not only the direction to magnetic north at the time of the rock's formation, but also the latitude where the rock formed relative to magnetic north.

In the early 1950s, a group of geologists from Cambridge University, including Keith Runcorn, Ted Irving,[1] and several others, started looking at the remnant magnetism of Phanerozoic British and European volcanic rocks, and collecting **paleomagnetic** data. They found that rocks of different ages sampled from generally the same area showed quite different apparent magnetic pole positions (Figure 10.3.1). They initially assumed that this meant that Earth's magnetic field had, over time, departed significantly from its present position—which is close to the rotational pole.

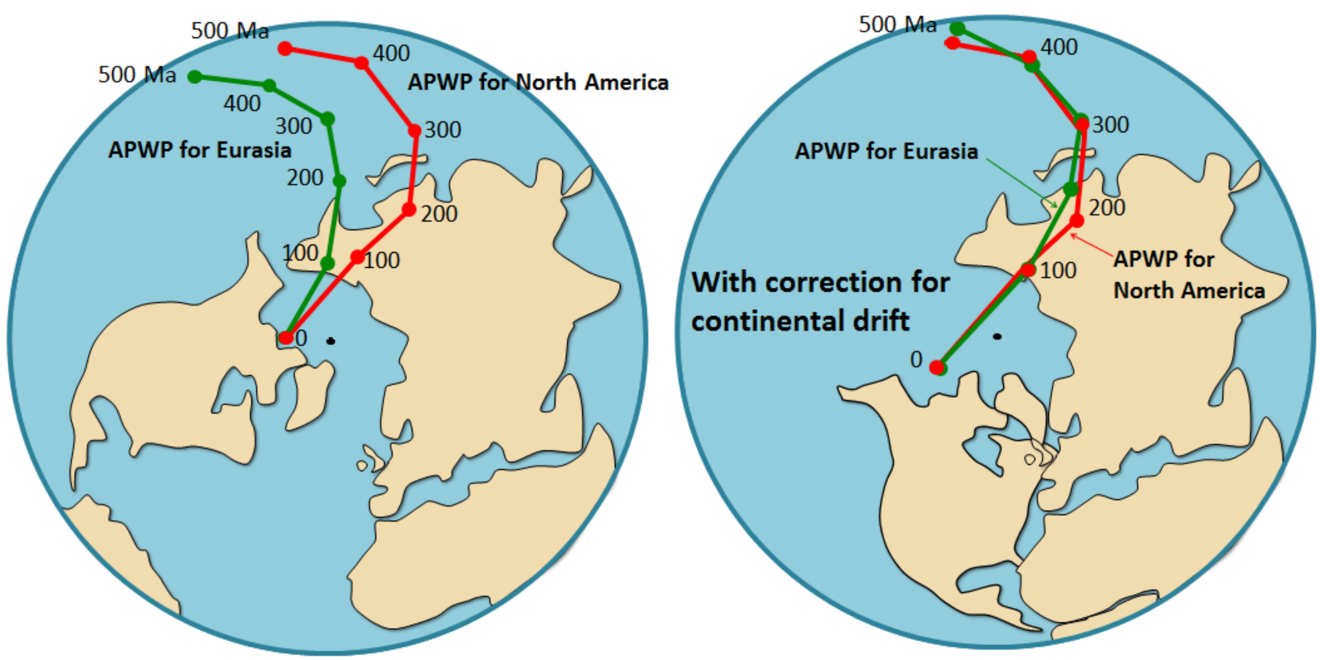


Figure 10.3.1 Apparent polar-wandering paths (APWP) for Eurasia and North America. The view is from the North Pole (black dot) looking down. The outer circle is the equator. In the diagram to the right the curve locations have been corrected taking continental drift into account.

The curve defined by the paleomagnetic data was called a **polar wandering path** because Runcorn and his students initially thought that their data represented actual movement of the magnetic poles (since

1. Ted Irving later set up a paleomagnetic lab at the Geological Survey of Canada in Sidney, B.C., and did a great deal of important work on understanding the geology of western North America.

geophysical models of the time suggested that the magnetic poles did not need to be aligned with the rotational poles). We now know that the magnetic data define movement of continents, and *not* of the magnetic poles, so we call it an *apparent* polar wandering path (APWP).

What is a polar wandering path?

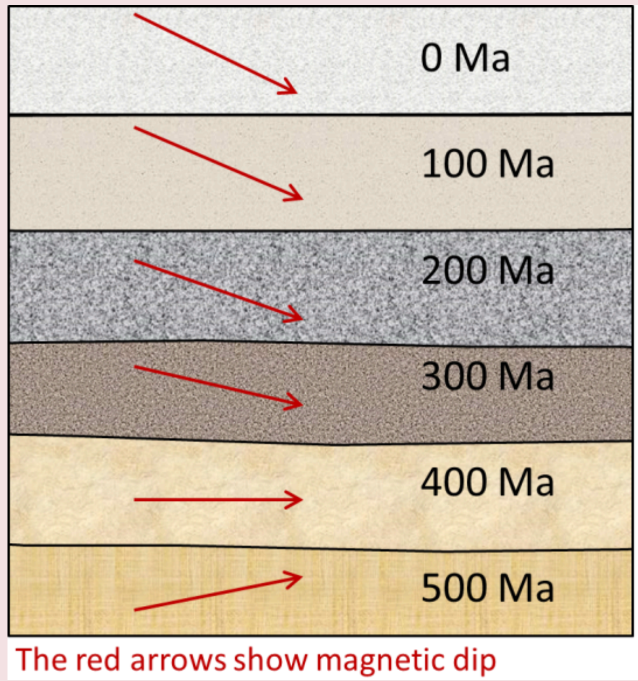


Figure 10.3.2 [Image Description]

At around 500 Ma, what we now call Europe was south of the equator, and so European rocks formed then would have acquired an upward-pointing magnetic field orientation (see Figure 9.3.2 and Figure 10.3.2). Between then and now, Europe gradually moved north, and the rocks forming at various times acquired steeper and steeper *downward-pointing* magnetic orientations.When researchers evaluated magnetic data in this way in the 1950s, they plotted where the North Pole would have appeared to be based on the magnetic data and assumed that the continent was always where it is now. That means that the 500 Ma "apparent" north pole would have been somewhere in the South Pacific, and that over the following 500 million years it would have gradually moved north.Of course we now know that the magnetic poles don't move around much (although polarity reversals do take place) and that the reason Europe had a magnetic orientation characteristic of the southern hemisphere is that it was in the southern hemisphere at 500 Ma.Runcorn and colleagues soon extended their work to North America, and this also showed *apparent* polar wandering, but the results were not consistent with those from Europe. For example, the 200 Ma pole for North America plotted somewhere in China, while the 200 Ma pole for Europe plotted in the Pacific Ocean. Since there could only have been one pole position at 200 Ma, this evidence strongly supported the idea that North America and Europe had moved relative to each other since 200 Ma. Subsequent paleomagnetic work showed that South America, Africa, India, and Australia also have unique polar wandering curves. In 1956, Runcorn changed his mind and became a proponent of continental drift.This paleomagnetic work of the 1950s was the first new evidence in favour of continental drift, and it led a number of geologists to start thinking that the idea might have some merit. Nevertheless, for a majority of geologists working on global geology at the time, this type of evidence was not sufficiently convincing to get them to change their views.

During the 20th century, our knowledge and understanding of the ocean basins and their geology increased dramatically. Before 1900, we knew virtually nothing about the bathymetry and geology of the oceans. By the end of the 1960s, we had detailed maps of the topography of the ocean floors, a clear picture of the geology of ocean floor sediments and the solid rocks underneath them, and almost as much information about the geophysical nature of ocean rocks as of continental rocks.

Up until about the 1920s, ocean depths were measured using weighted lines dropped overboard. In deep water this is a painfully slow process and the number of soundings in the deep oceans was probably fewer than 1,000. That is roughly one depth sounding for every 350,000 square kilometres of the ocean.

To put that in perspective, it would be like trying to describe the topography of British Columbia with elevation data for only a half a dozen points! The voyage of the *Challenger* in 1872 and the laying of trans-Atlantic cables had shown that there were mountains beneath the seas, but most geologists and oceanographers still believed that the oceans were essentially vast basins with flat bottoms, filled with thousands of metres of sediments.

Following development of acoustic depth sounders in the 1920s (Figure 10.3.3), the number of depth readings increased by many orders of magnitude, and by the 1930s, it had become apparent that there were major mountain chains in all of the world's oceans. During and after World War II, there was a well-organized campaign to study the oceans, and by 1959, sufficient bathymetric data had been collected to produce detailed maps of all the oceans (Figure 10.3.4).

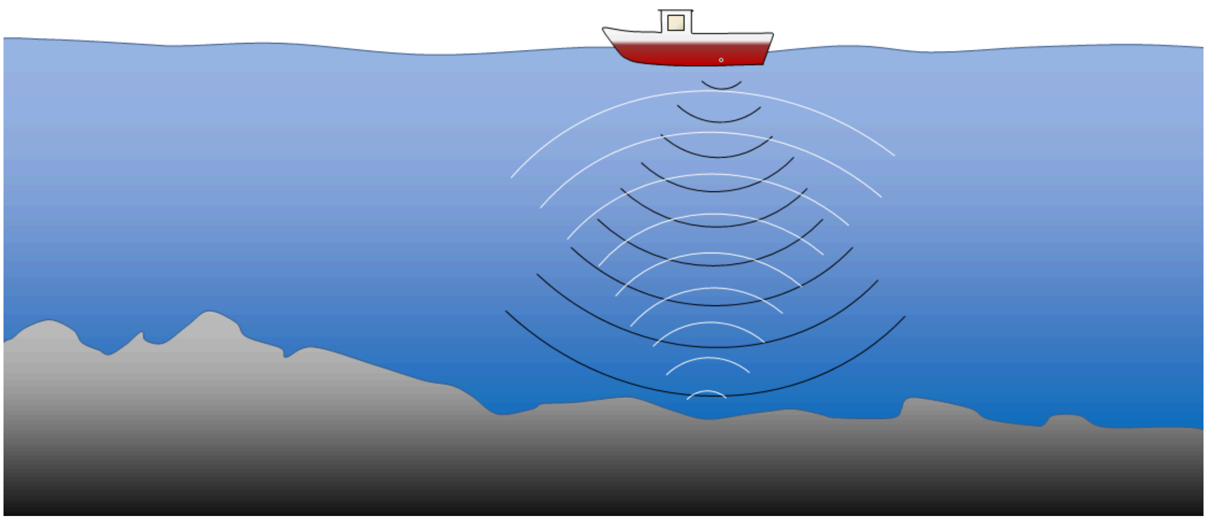


Figure 10.3.3 Depiction of a ship-borne acoustic depth sounder. The instrument emits a sound (black arcs) that bounces off the sea floor and returns to the surface (white arcs). The travel time is proportional to the water depth.

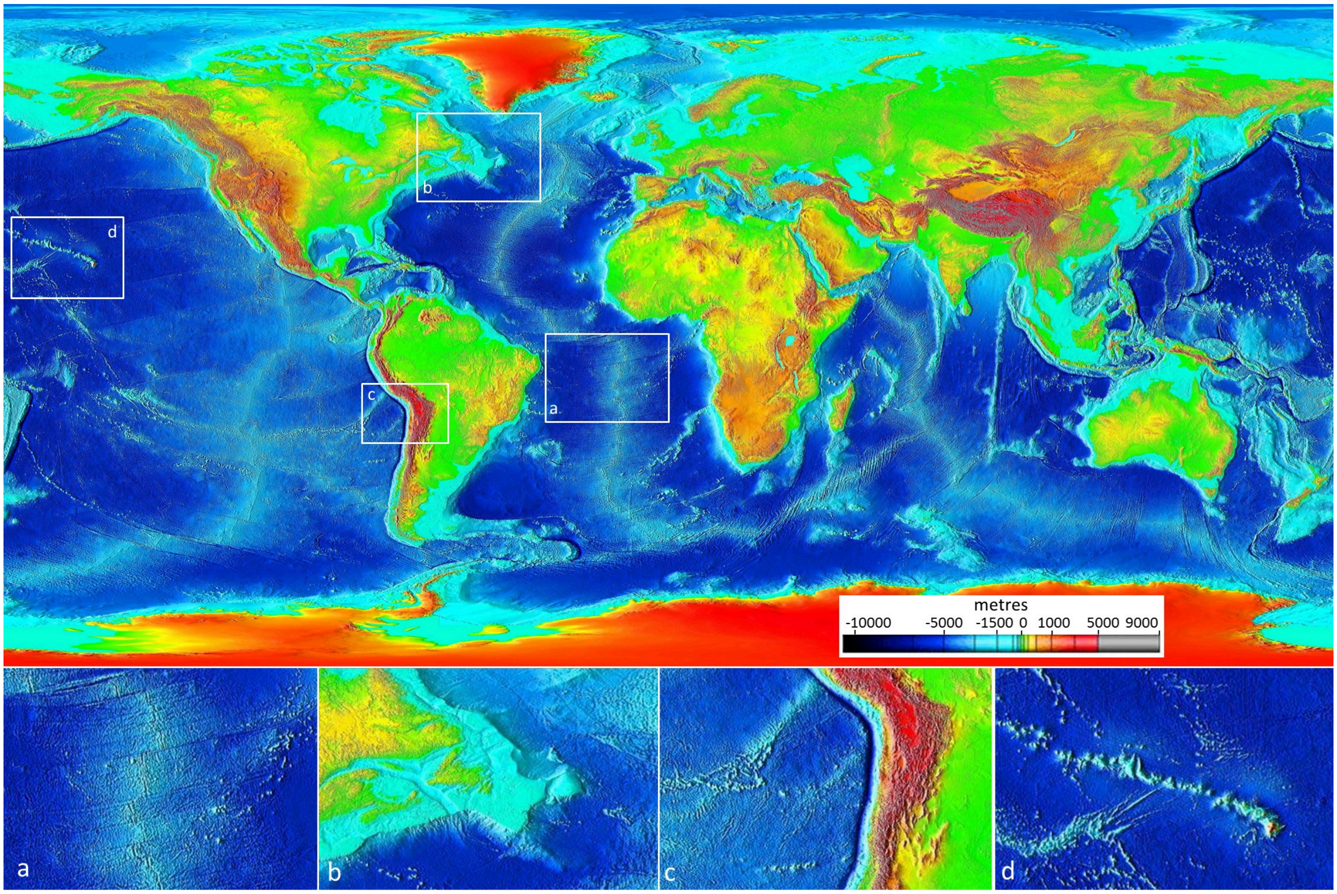


Figure 10.3.4 Ocean floor bathymetry (and continental topography). Inset (a): the mid-Atlantic ridge, (b): the Newfoundland continental shelf, (c): the Nazca trench adjacent to South America, and (d): the Hawaiian Island chain.

The important physical features of the ocean floor are:

- Extensive linear ridges (commonly in the central parts of the oceans) with water depths in the order of 2,000 to 3,000 m (Figure 10.3.4, inset a)
- Fracture zones perpendicular to the ridges (inset a)
- Deep-ocean plains at depths of 5,000 to 6,000 m (insets a and d)
- Relatively flat and shallow continental shelves with depths under 500 m (inset b)
- Deep trenches (up to 11,000 m deep), most near the continents (inset c)
- Seamounts and chains of seamounts (inset d)

Seismic reflection sounding involves transmitting high-energy sound bursts and then measuring the echos with a series of geophones towed behind a ship. The technique is related to *acoustic sounding* as described above; however, much more energy is transmitted and the sophistication of the data processing is much greater. As the technique evolved, and the amount of energy was increased, it became possible to *see through* the sea-floor sediments and map the bedrock topography and crustal thickness. Hence sediment thicknesses could be mapped, and it was soon discovered that although the sediments were up to several thousands of metres thick near the continents, they were relatively thin — or even non-existent — in the ocean ridge areas (Figure 10.3.5). The seismic studies also showed that the crust is relatively thin under the oceans (5 km to 6 km) compared to the continents (30 km to 60 km) and geologically very consistent, composed almost entirely of basalt.

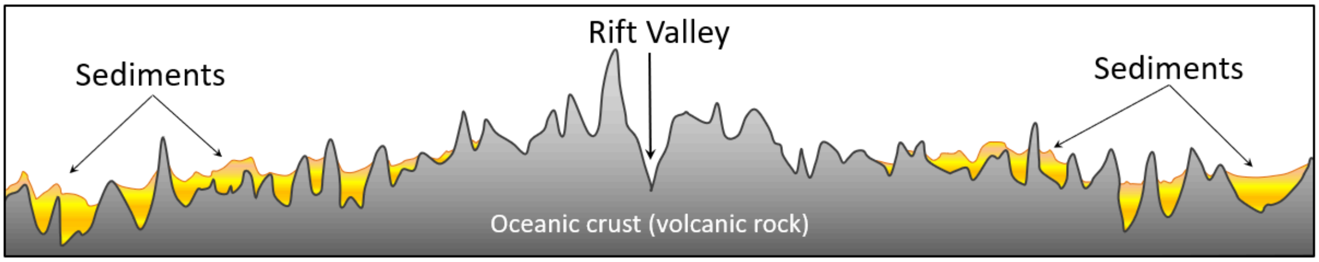


Figure 10.3.5 Topographic section at an ocean ridge based on reflection seismic data. Sediments are not thick enough to be detectable near the ridge, but get thicker on either side. The diagram represents approximately 50 km width, and has a 10x vertical exaggeration.

In the early 1950s, Edward Bullard, who spent time at the University of Toronto but is mostly associated with Cambridge University, developed a probe for measuring the flow of heat from the ocean floor. Bullard and colleagues found the rate to be higher than average along the ridges, and lower than average in the trench areas. Although Bullard was a plate-tectonics sceptic, these features were interpreted to indicate that there is convection within the mantle — the areas of high heat flow being correlated with upward convection of hot mantle material, and the areas of low heat flow being correlated with downward convection.

With developments of networks of seismographic stations in the 1950s, it became possible to plot the locations *and* depths of both major and minor earthquakes with great accuracy. It was found that there is a remarkable correspondence between earthquakes and both the mid-ocean ridges and the deep ocean trenches. In 1954 Gutenberg and Richter showed that the ocean-ridge earthquakes were all relatively shallow, and confirmed what had first been shown by Benioff in the 1930s — that earthquakes in the vicinity of ocean trenches were both shallow and deep, but that the deeper ones were situated progressively farther inland from the trenches (Figure 10.3.6).

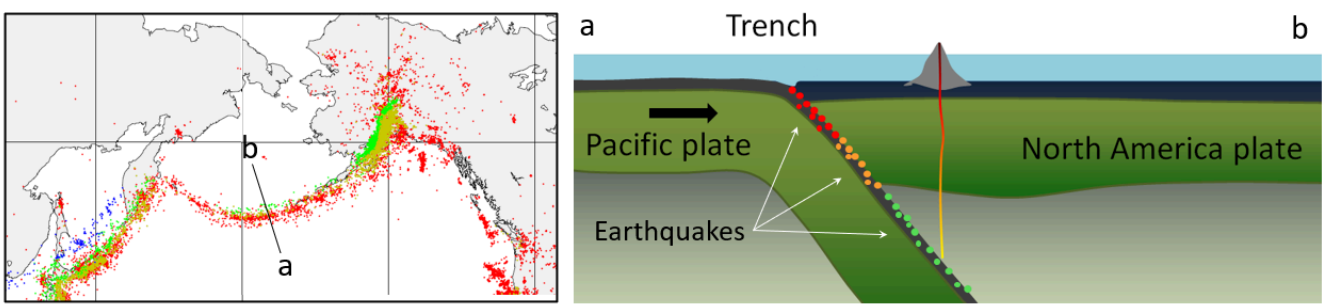


Figure 10.3.6 Cross-section through the Aleutian subduction zone with a depiction of the increasing depth of earthquakes "inshore" from the trench. [Image Description]

In the 1950s, scientists from the Scripps Oceanographic Institute in California persuaded the U.S. Coast Guard to include magnetometer readings on one of their expeditions to study ocean floor topography. The first comprehensive magnetic data set was compiled in 1958 for an area off the coast of B.C. and Washington State. This survey revealed a bewildering pattern of low and high magnetic intensity in sea-floor rocks (Figure 10.3.7). When the data were first plotted on a map in 1961, nobody understood them — not even the scientists who collected them. Although the patterns made even less sense than the stripes on a zebra, many thousands of kilometres of magnetic surveys were conducted over the next several years.

The wealth of new data from the oceans began to significantly influence geological thinking in the 1960s. In 1960, Harold Hess, a widely respected geologist from Princeton University, advanced a theory with many of the elements that we now accept as **plate tectonics**. He maintained some uncertainty about his proposal however, and in order to deflect criticism from mainstream geologists, he labelled it *geopoetry*. In fact, until 1962, Hess didn't even put his ideas in writing—except internally to the U.S. Navy (which funded his research)—but presented them mostly in lectures and seminars. Hess proposed that new sea floor was generated from mantle material at the ocean ridges, and that old sea floor was dragged down at the ocean trenches and re-incorporated into the mantle. He suggested that the process was driven by mantle convection currents, rising at the ridges and descending at the trenches (Figure 10.3.8). He also suggested that the less-dense continental crust did not descend with oceanic crust into trenches, but that colliding land masses were thrust up to form mountains. Hess's theory formed the basis for our ideas on **sea-floor spreading** and **continental drift,** but it did not deal with the concept that the crust is made up of specific **plates**. Although the Hess model was not roundly criticized, it was not widely accepted (especially in the U.S.), partly because it was not well supported by hard evidence.

Figure 10.3.7 Pattern of sea-floor magnetism off of the west coast of British Columbia and Washington.

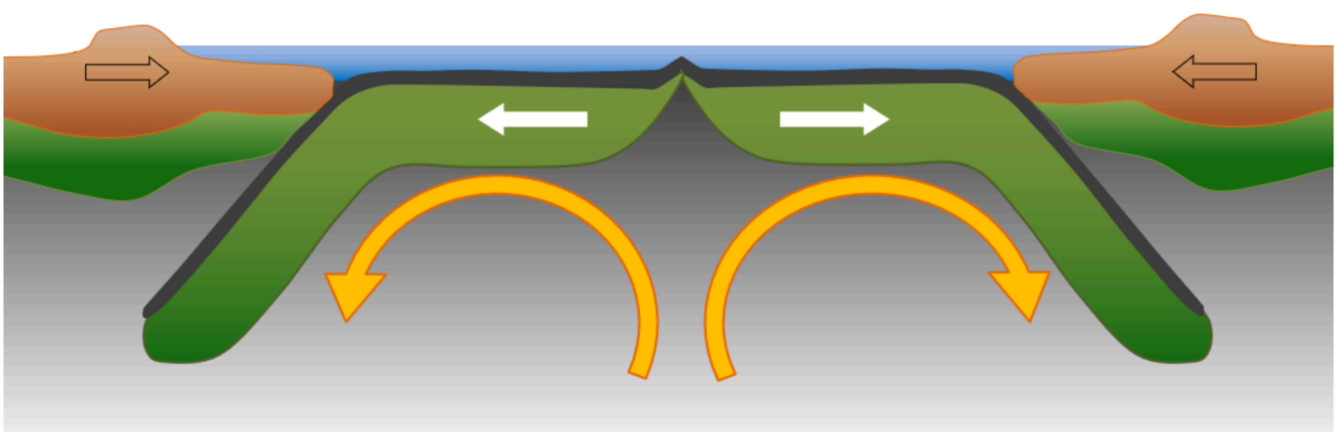


Figure 10.3.8 A representation of Harold Hess's model for sea-floor spreading and subduction.

Collection of magnetic data from the oceans continued in the early 1960s, but still nobody could explain the origin of the zebra-like patterns. Most assumed that they were related to variations in the composition of the rocks—such as variations in the amount of magnetite—as this is a common explanation for magnetic variations in rocks of the continental crust. The first real understanding of the significance of the striped anomalies was the interpretation by Fred Vine, a Cambridge graduate student. Vine was examining magnetic data from the Indian Ocean and, like others before, he noted the symmetry of the magnetic patterns with respect to the oceanic ridge.

At the same time, other researchers, led by groups in California and New Zealand, were studying the phenomenon of reversals in Earth's magnetic field. They were trying to determine when such reversals had taken place over the past several million years by analyzing the magnetic characteristics of hundreds of samples from basaltic flows. As discussed in Chapter 9, it is evident that Earth's magnetic field becomes weakened periodically and then virtually non-existent, before becoming re-established with the reverse polarity. During periods of reversed polarity, a compass would point south instead of north.

The time scale of magnetic reversals is irregular. For example, the present "normal" event, known as the Bruhnes magnetic chron, has persisted for about 780,000 years. This was preceded by a 190,000-year reversed event; a 50,000-year normal event known as Jaramillo; and then a 700,000-year reversed event (see Figure 9.3.3).

In a paper published in September 1963, Vine and his PhD supervisor Drummond Matthews proposed that the patterns associated with ridges were related to the magnetic reversals, and that oceanic crust created from cooling basalt during a *normal* event would have polarity aligned with the present magnetic field, and thus would produce a positive anomaly (a black stripe on the sea-floor magnetic map), whereas oceanic crust created during a *reversed* event would have polarity opposite to the present field and thus would produce a negative magnetic anomaly (a white stripe). The same idea had been put forward a few months earlier by Lawrence Morley, of the Geological Survey of Canada; however, his papers submitted earlier in 1963 to *Nature* and *The Journal of Geophysical Research* were rejected. Many people refer to the idea as the Vine-Matthews-Morley (VMM) hypothesis.

Vine, Matthews, and Morley were the first to show this type of correspondence between the relative widths of the stripes and the periods of the magnetic reversals. The VMM hypothesis was confirmed within a few years when magnetic data were compiled from spreading ridges around the world. It was shown that the same general magnetic patterns were present straddling each ridge, although the widths of the anomalies varied according to the spreading rates characteristic of the different ridges. It was also shown that the patterns corresponded with the chronology of Earth's magnetic field reversals. This global consistency provided strong support for the VMM hypothesis and led to rejection of the other explanations for the magnetic anomalies.

In 1963, J. Tuzo Wilson of the University of Toronto proposed the idea of a **mantle plume** or **hot spot**—a place where hot mantle material rises in a stationary and semi-permanent plume, and affects the overlying crust. He based this hypothesis partly on the distribution of the Hawaiian and Emperor Seamount island chains in the Pacific Ocean (Figure 10.3.9). The volcanic rock making up these islands gets progressively younger toward the southeast, culminating with the island of Hawaii itself, which consists of rock that is almost all younger than 1 Ma. Wilson suggested that a stationary plume of hot upwelling mantle material is the source of the Hawaiian volcanism, and that the ocean crust of the Pacific Plate is moving toward the northwest over this hot spot. Near the Midway Islands, the chain takes a pronounced change in direction, from northwest-southeast for the Hawaiian Islands and to nearly north-south for the Emperor Seamounts. This change is widely ascribed to a change in direction of the Pacific Plate moving over the stationary mantle plume, but a more plausible explanation is that the Hawaiian mantle plume has not actually been stationary throughout its history, and in fact moved at least 2,000 km south over the period between 81 and 45 Ma.[2]

2. J. A. Tarduno et al., 2003, The Emperor Seamounts: Southward Motion of the Hawaiian Hotspot Plume in Earth's Mantle, Science 301 (5636): 1064–1069.

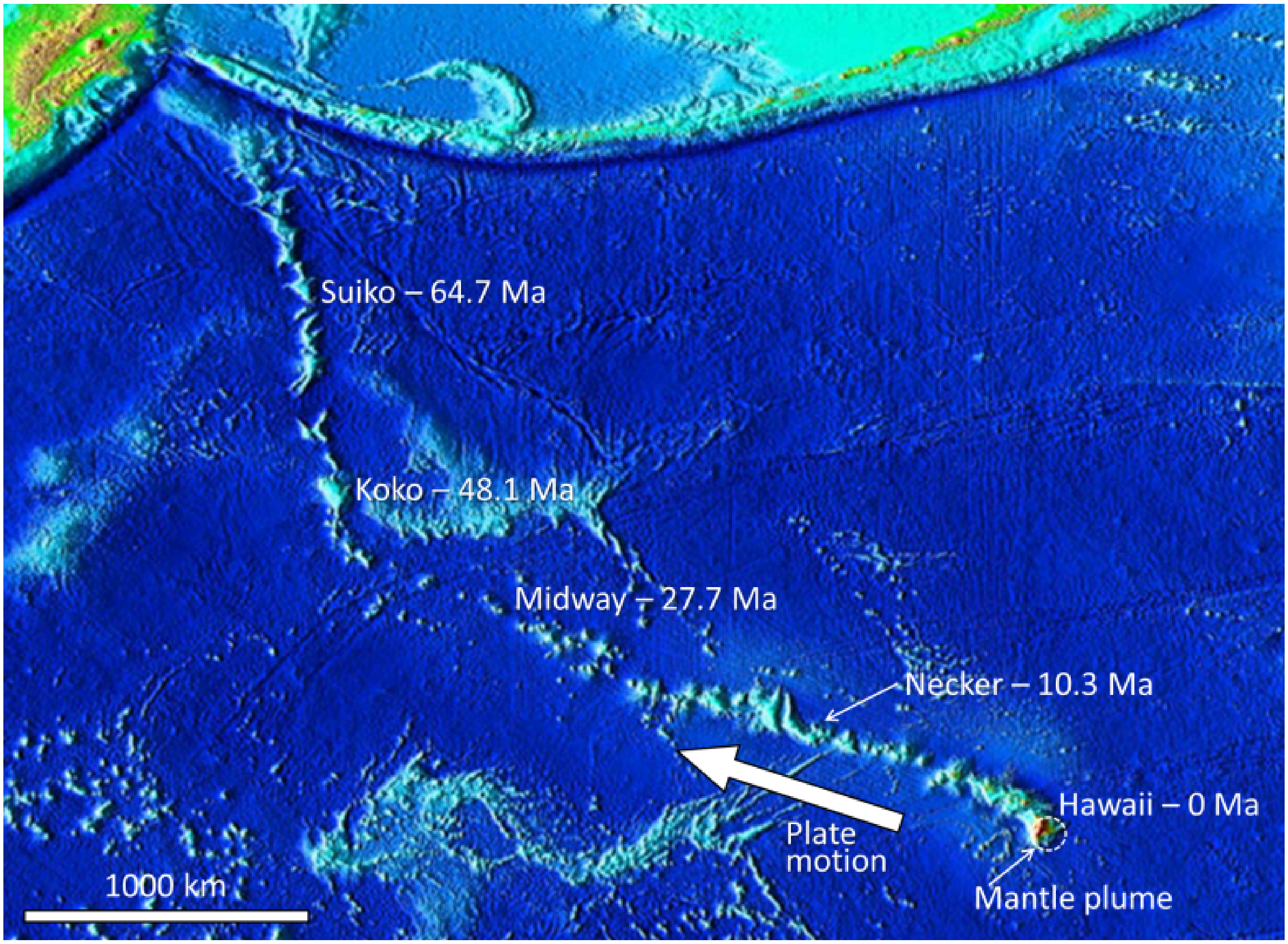


Figure 10.3.9 The ages of the Hawaiian Islands and the Emperor Seamounts in relation to the location of the Hawaiian mantle plume.

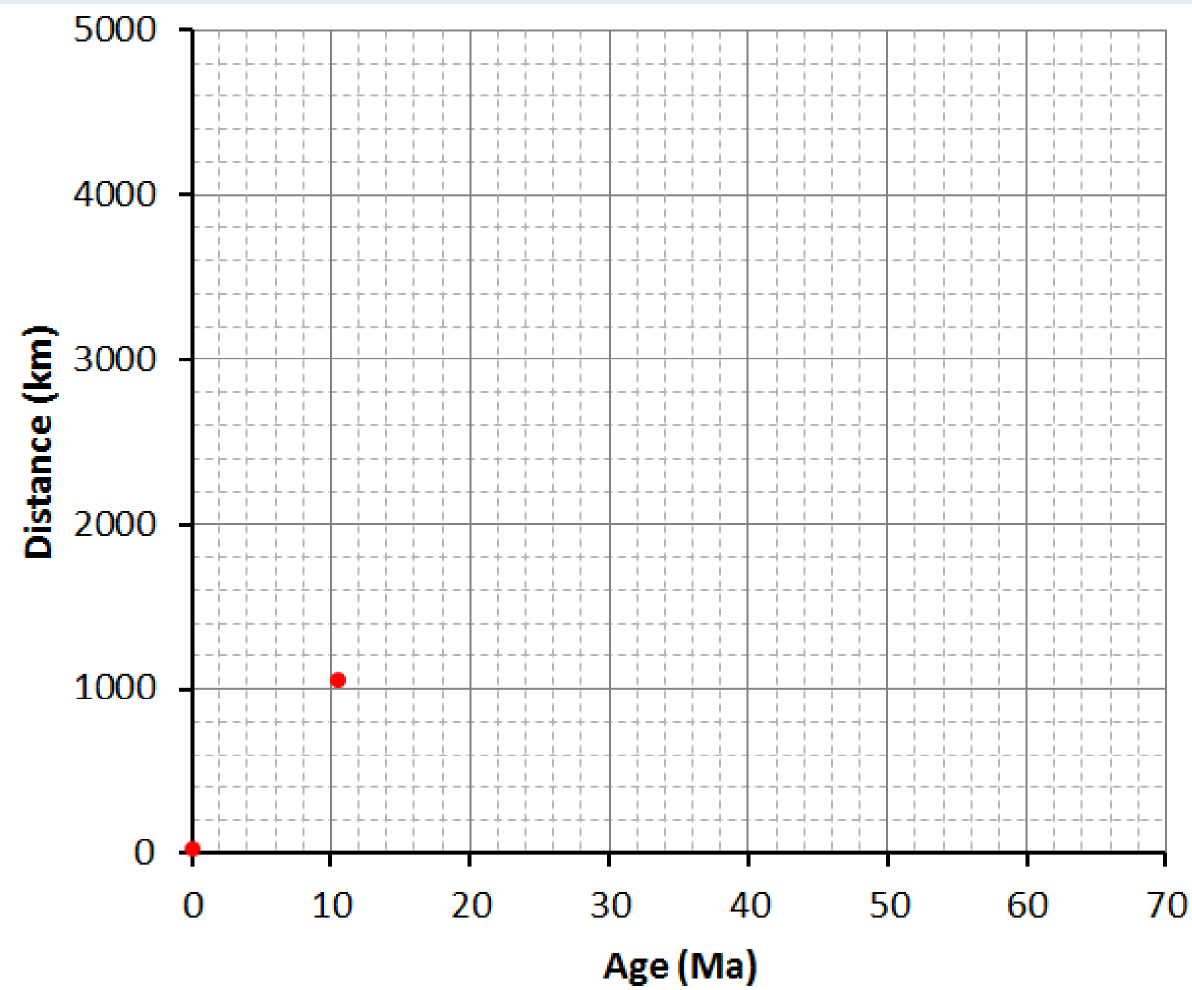
Exercise 10.2 Volcanoes and the Rate of Plate Motion

The Hawaiian and Emperor volcanoes shown in Figure 10.3.9 are listed in the table below along with their ages and their distances from the centre of the mantle plume under Hawaii (the Big Island).

Ages of Hawaiian and Emperor volcanoes and their distances from the centre of the mantle plume. Calculate their rate of movement in centimetres per year.

Island	Age	Distance	Rate
Hawaii	0 Ma	0 km	–
Necker	10.3 Ma	1,058 km	10.2 cm/y
Midway	27.7 Ma	2,432 km	
Koko	48.1 Ma	3,758 km	
Suiko	64.7 Ma	4,860 km	

Plot the data on the graph provided here, and use the numbers in the table to estimate the rates of plate motion for the Pacific Plate in cm/year. (The first two are plotted for you.)



See Appendix 3 for Exercise 10.2 answers.

There is evidence of many such mantle plumes around the world (Figure 10.3.10). Most are within the ocean basins—including places like Hawaii, Iceland, and the Galapagos Islands—but some are under continents. One example is the Yellowstone hot spot in the west-central United States, and another is the one responsible for the Anahim Volcanic Belt in central British Columbia. It is evident that mantle plumes are very long-lived phenomena, lasting for at least tens of millions of years, possibly for hundreds of millions of years in some cases.

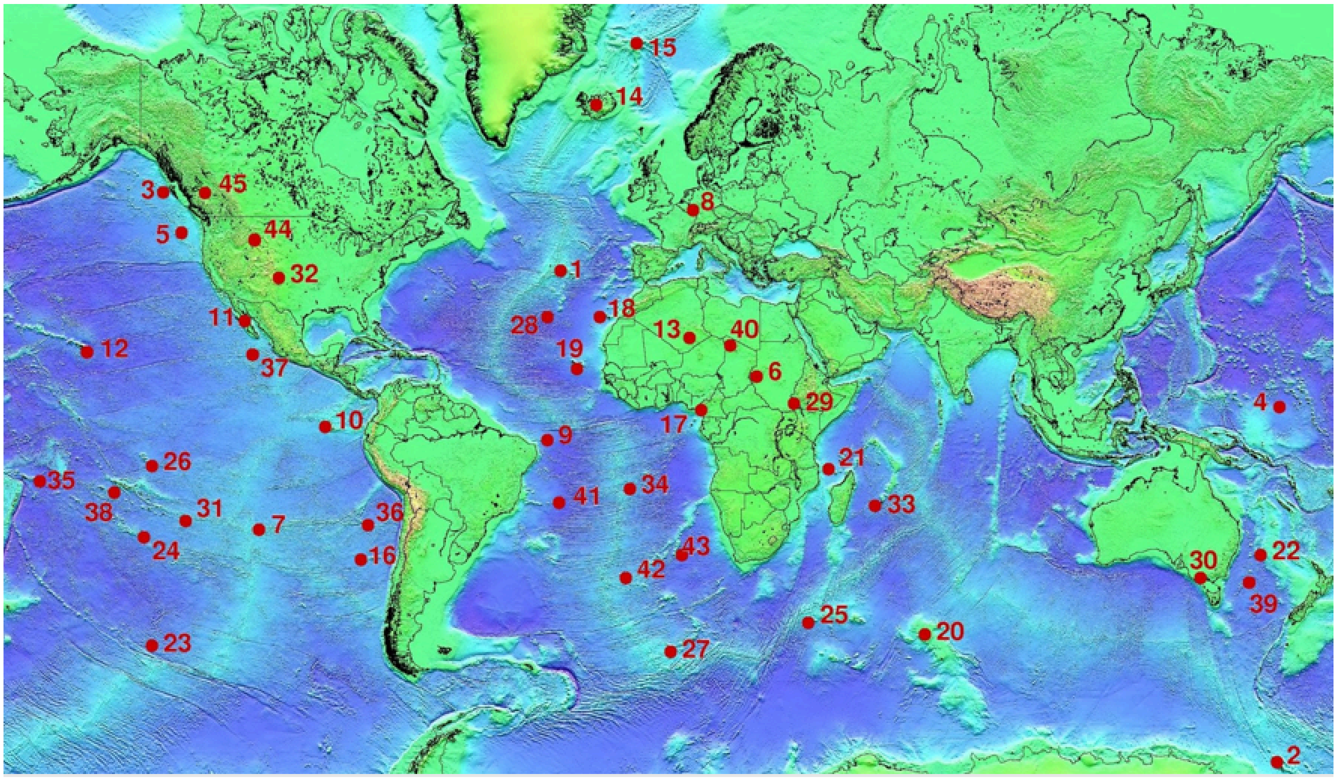


Figure 10.3.10 Mantle plume locations. Selected Mantle plumes: 1: Azores, 3: Bowie, 5: Cobb, 8: Eifel, 10: Galapagos, 12: Hawaii, 14: Iceland, 17: Cameroon, 18: Canary, 19: Cape Verde, 35: Samoa, 38: Tahiti, 42: Tristan, 44: Yellowstone, 45: Anahim

Although oceanic spreading ridges appear to be curved features on Earth's surface, in fact the ridges are composed of a series of straight-line segments, offset at intervals by faults perpendicular to the ridge (Figure 10.3.11). In a paper published in 1965, Tuzo Wilson termed these features **transform faults**. He described the nature of the motion along them, and showed why there are earthquakes only on the section of a transform fault between two adjacent ridge segments. The San Andreas Fault in California is a very long transform fault that links the southern end of the Juan de Fuca spreading ridge to the East Pacific Rise spreading ridges situated in the Gulf of California (see Figure 10.4.9). The Queen Charlotte Fault, which extends north from the northern end of the Juan de Fuca spreading ridge (near the northern end of Vancouver Island) toward Alaska, is also a transform fault.

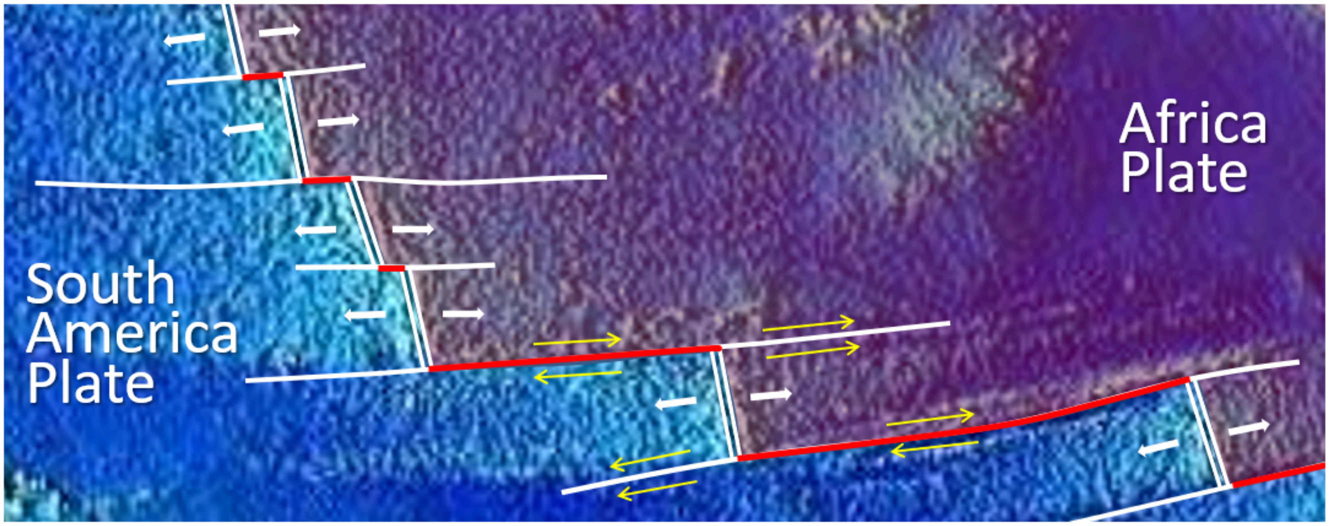


Figure 10.3.11 A part of the mid-Atlantic ridge near the equator. The double white lines are spreading ridges. The solid white lines are fracture zones. As shown by the yellow arrows, the relative motion of the plates on either side of the fracture zones can be similar (arrows pointing the same direction) or opposite (arrows pointing opposite directions). Transform faults (red lines) are in between the ridge segments, where the yellow arrows point in opposite directions.

In the same 1965 paper, Wilson introduced the idea that the crust can be divided into a series of rigid plates, and thus he is responsible for the term **plate tectonics**.

Exercise 10.3 Paper transform fault model

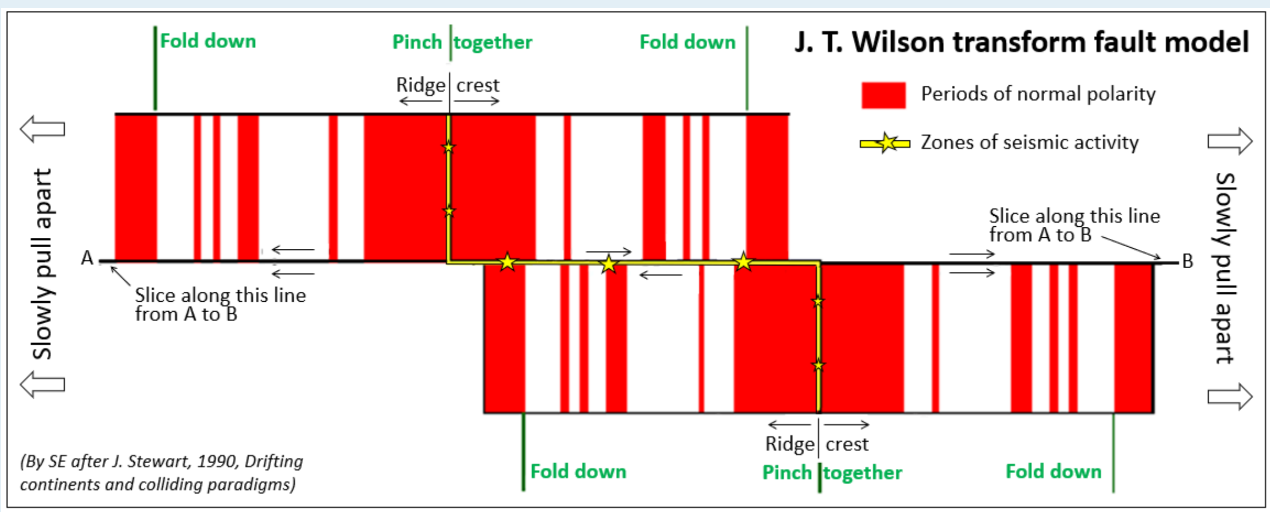


Figure 10.3.12

Tuzo Wilson used a paper model, a little bit like the one shown here, to explain transform faults to his colleagues. To use this model either print this page or download the image above and print that, then cut around the outside, and then slice along the line A-B (the fracture zone) with a sharp knife. Fold down the top half where shown, and then pinch together in the middle. Do the same with the bottom half.

When you're done, you should have something like the example shown on Figure 10.3.13, with two folds of paper extending underneath. Find someone else to pinch those folds with two fingers just below each ridge crest, and then gently pull apart where shown. As you do, the oceanic crust will emerge from the middle, and you'll see that the parts of the fracture zone between the ridge crests will be moving in opposite directions (this is the transform fault) while the parts of the fracture zone outside of the ridge crests will be moving in the same direction. You'll also see that the oceanic crust is being magnetized as it forms at the ridge. The magnetic patterns shown are accurate, and represent the last 2.5 Ma of geological time.

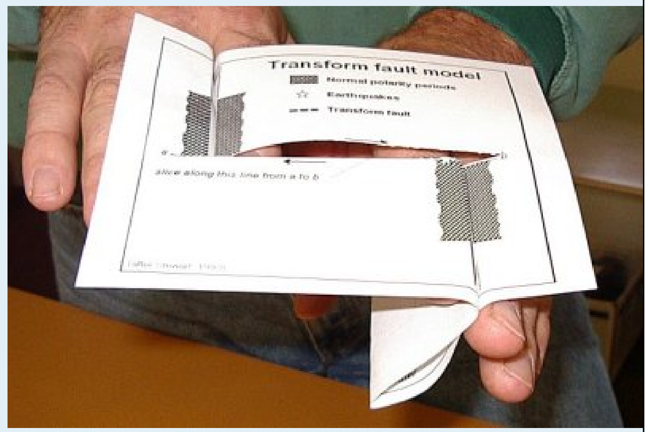


Figure 10.3.13

There are other versions of this model available here: Paper Models of Transform Faults.[3]

See Appendix 3 for Exercise 10.3 answers.

Image Descriptions

Figure 10.3.2 image description: At 500 Ma, rocks in Europe had upward-pointing magnetic orientations. At 400 Ma, the magnetic orientation leveled. From 300 Ma to the present, rocks in Europe shown an increasingly downward-pointing magnetic orientation. [Return to Figure 10.3.2]

Figure 10.3.6 image description: A cross section of the trench formed at the Aleutian subduction zone as the Pacific plate subducts under the North American plate in the middle of the Pacific Ocean. The farther away an earthquake is from this trench (on the North America plate side), the deeper it is. [Return to Figure 10.3.6]

Media Attributions

- Figures 10.3.1, 10.3.2, 10.3.3, 10.3.5, 10.3.6, 10.3.8, 10.3.11, 10.3.12, 10.3.13: © Steven Earle. CC BY.
- Figure 10.3.4: "Elevation" by NOAA. Adapted by Steven Earle. Public domain.
- Figure 10.3.7: "Juan de Fuca Ridge" by USGS. Adapted by Steven Earle. Public domain. Based on Raff, A. and Mason, R., 1961, Magnetic survey off the west coast of North America, 40˚ N to 52˚ N latitude, Geol. Soc. America Bulletin, V. 72, p. 267-270.
- Figure 10.3.9: "Hawaii Hotspot" by National Geophysical Data Center. Adapted by Steven Earle. Public domain.
- Figure 10.3.10: "Hotspots" by Ingo Wölbern. Public domain.

3. For more information see: Earle, S., 2004, *A simple paper model of a transform fault at a spreading ridge*, J. Geosc. Educ. V. 52, p. 391-2.

10.4 Plate, Plate Motions, and Plate Boundary Processes

Continental drift and sea-floor spreading became widely accepted around 1965 as more and more geologists started thinking in these terms. By the end of 1967 the Earth's surface had been mapped into a series of plates (Figure 10.4.1). The major plates are Eurasia, Pacific, India, Australia, North America, South America, Africa, and Antarctic. There are also numerous small plates (e.g., Juan de Fuca, Cocos, Nazca, Scotia, Philippine, Caribbean), and many very small plates or sub-plates. For example the Juan de Fuca Plate is actually three separate plates (Gorda, Juan de Fuca, and Explorer) that all move in the same general direction but at slightly different rates.

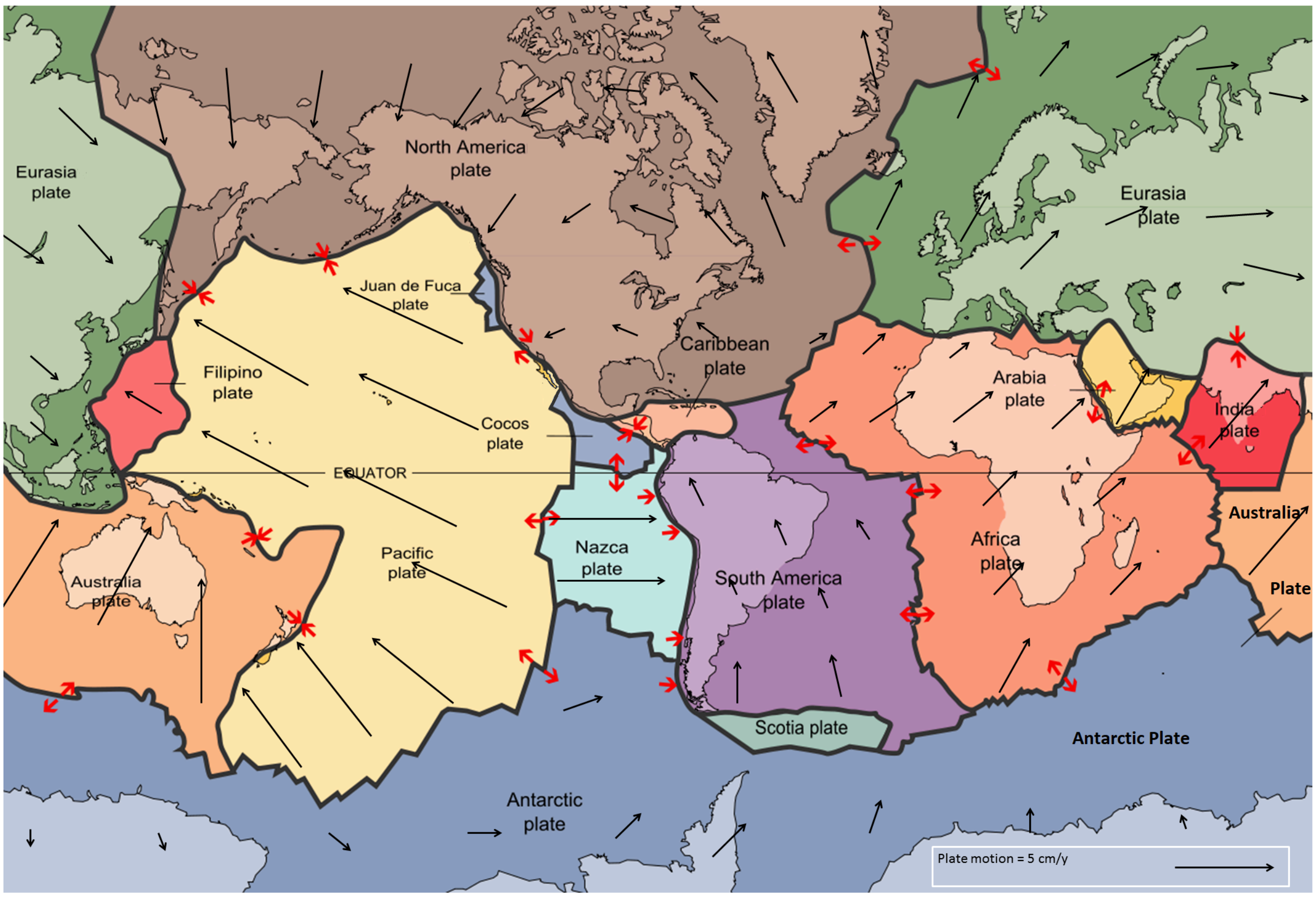


Figure 10.4.1 A map showing 15 of the Earth's tectonic plates and the approximate rates and directions of plate motions. [Image Description]

Rates of motions of the major plates range from less than 1 cm/y to over 10 cm/y. The Pacific Plate is the fastest, followed by the Australian and Nazca Plates. The North American Plate is one of the slowest, averaging around 1 cm/y in the south up to almost 4 cm/y in the north.

Plates move as rigid bodies, so it may seem surprising that the North American Plate can be moving at different rates in different places. The explanation is that plates move in a rotational manner. The North American Plate, for example, rotates counter-clockwise; the Eurasian Plate rotates clockwise.

Boundaries between the plates are of three types: **divergent** (i.e., moving apart), **convergent** (i.e., moving together), and **transform** (moving side by side). Before we talk about processes at plate boundaries, it's important to point out that there are never gaps between plates. The plates are made up of crust and the lithospheric part of the mantle (Figure 10.4.2), and even though they are moving all the time, and in different directions, there is never a significant amount of space between them. Plates are thought to move along the lithosphere-asthenosphere boundary, as the asthenosphere is the zone of partial melting. It is assumed that the relative lack of strength of the partial melting zone facilitates the sliding of the lithospheric plates.

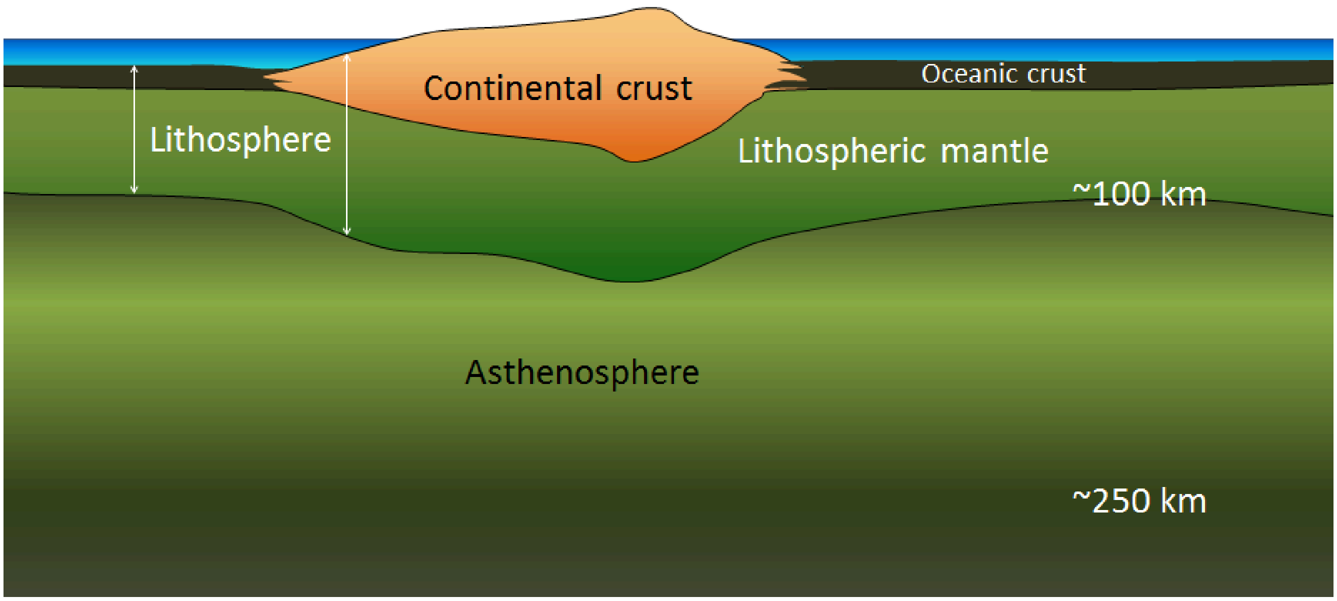


Figure 10.4.2 The crust and upper mantle. Tectonic plates consist of lithosphere, which includes the crust and the lithospheric (rigid) part of the mantle.

At spreading centres, the lithospheric mantle may be very thin because the upward convective motion of hot mantle material generates temperatures that are too high for the existence of a significant thickness of rigid lithosphere (Figure 10.3.8). The fact that the plates include both crustal material and lithospheric mantle material makes it possible for a single plate to be made up of both oceanic and continental crust. For example, the North American Plate includes most of North America, plus half of the northern Atlantic Ocean. Similarly the South American Plate extends across the western part of the southern Atlantic Ocean, while the European and African plates each include part of the eastern Atlantic Ocean. The Pacific Plate is almost entirely oceanic, but it does include the part of California west of the San Andreas Fault.

Divergent Boundaries

Divergent boundaries are spreading boundaries, where new oceanic crust is created from magma derived from partial melting of the mantle caused by decompression as hot mantle rock from depth is moved toward the surface (Figure 10.4.3). The triangular zone of partial melting near the ridge crest is approximately 60 km thick and the proportion of magma is about 10% of the rock volume, thus producing crust that is about 6 km thick. Most divergent boundaries are located at the oceanic ridges (although some are on land), and the crustal material created at a spreading boundary is always oceanic in character; in other words, it is mafic igneous rock (e.g., basalt or gabbro, rich in ferromagnesian minerals). Spreading rates vary considerably, from 2 cm/y to 6 cm/y in the Atlantic, to between 12 cm/y and 20 cm/y in the Pacific. (Note that spreading rates are typically double the velocities of the two plates moving away from a ridge.)

Some of the processes taking place in this setting include:

- Magma from the mantle pushing up to fill the voids left by divergence of the two plates
- **Pillow lavas** forming where magma is pushed out into seawater (Figure 10.4.4)
- Vertical **sheeted dykes** intruding into cracks resulting from the spreading
- Magma cooling more slowly in the lower part of the new crust and forming gabbro bodies

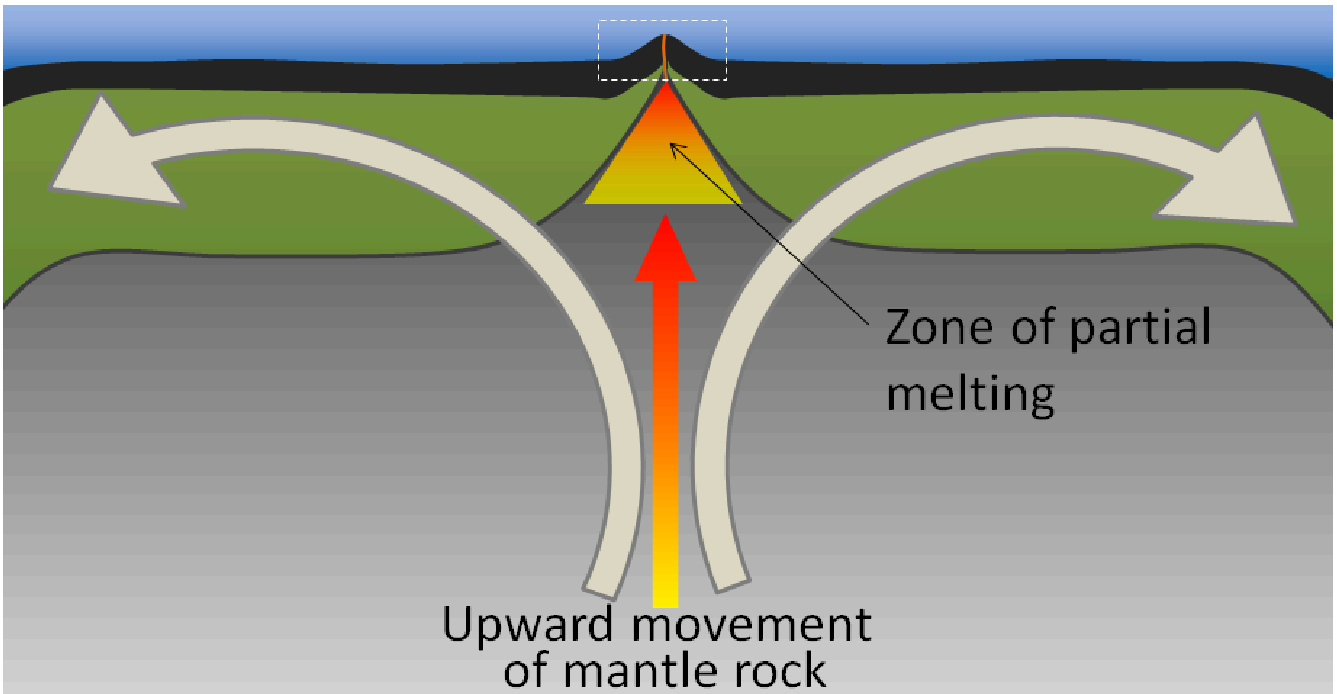


Figure 10.4.3 The general processes that take place at a divergent boundary. The area within the dashed white rectangle is shown in Figure 10.4.4.

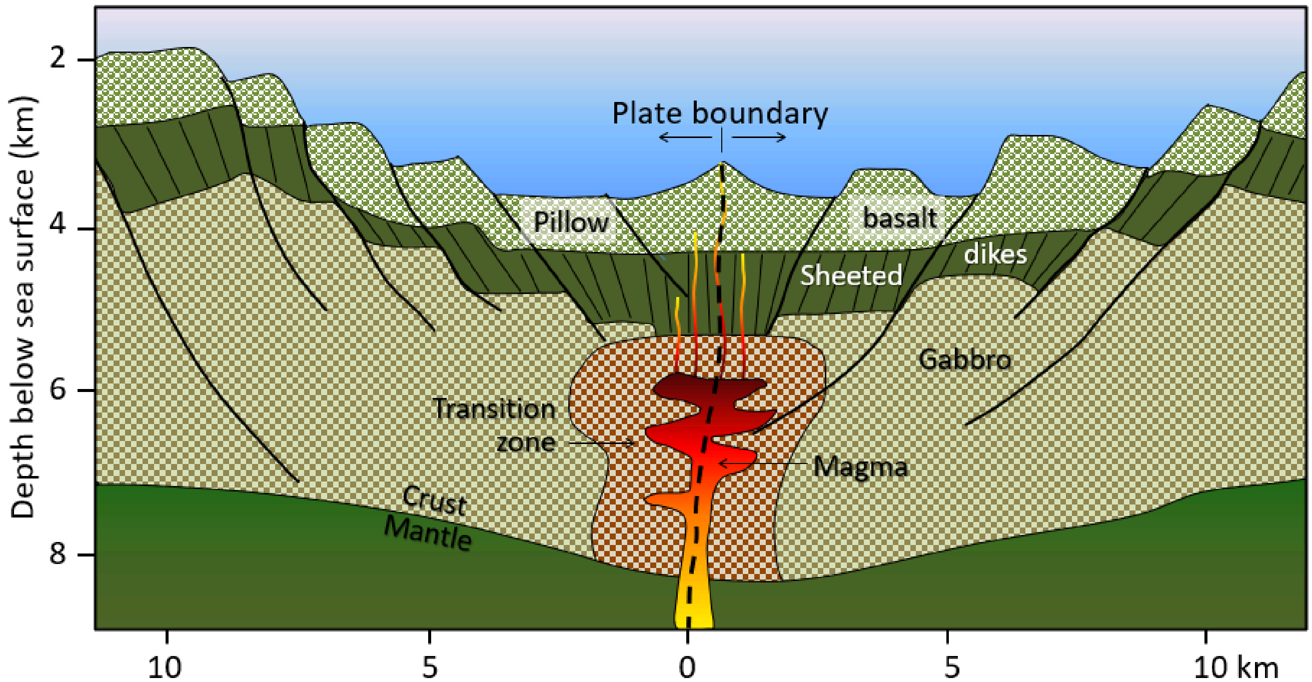


Figure 10.4.4 Depiction of the processes and materials formed at a divergent boundary.

Spreading is hypothesized to start within a continental area with up-warping or doming related to an underlying mantle plume or series of mantle plumes. The buoyancy of the mantle plume material creates a dome within the crust, causing it to fracture in a radial pattern, with three arms spaced at approximately 120° (Figure 10.4.5). When a series of mantle plumes exists beneath a large continent, the resulting rifts may align and lead to the formation of a rift valley (such as the present-day Great Rift Valley in eastern Africa). It is suggested that this type of valley eventually develops into a linear sea (such as the present-day Red Sea), and finally into an ocean (such as the Atlantic). It is likely that as many as 20 mantle plumes, many of which still exist, were responsible for the initiation of the rifting of Pangea along what is now the mid-Atlantic ridge (see Figure 10.3.10).

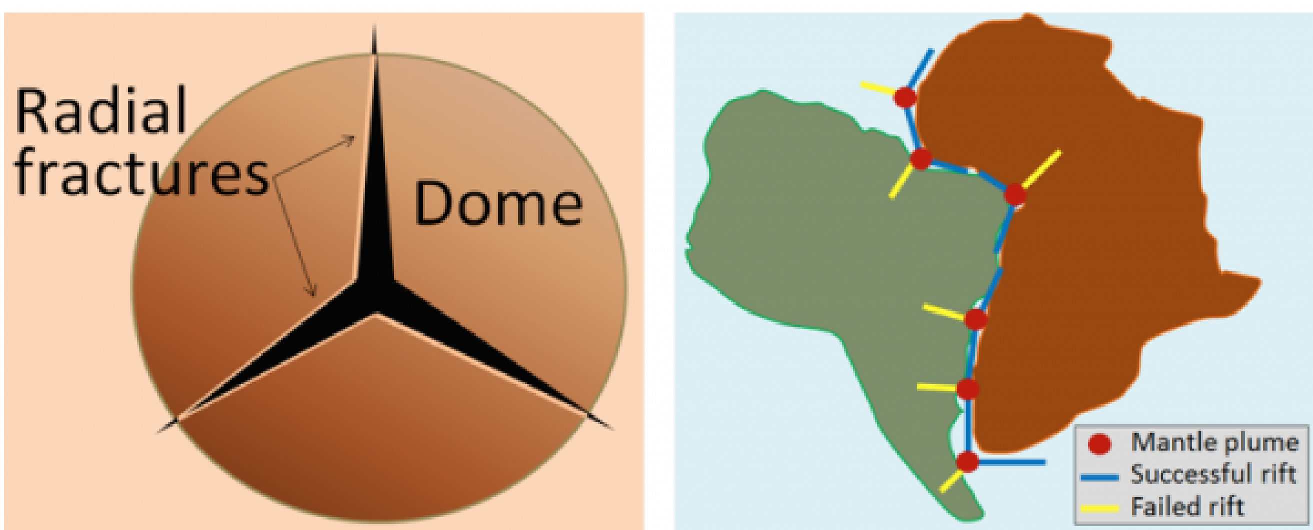


Figure 10.4.5 Depiction of the process of dome and three-part rift formation (left) and of continental rifting between the African and South American parts of Pangea at around 200 Ma (right).

Convergent Boundaries

Convergent boundaries, where two plates are moving toward each other, are of three types, depending on whether oceanic or continental crust is present on either side of the boundary. The types are ocean-ocean, ocean-continent, and continent-continent.

At an ocean-ocean convergent boundary, one of the plates (oceanic crust and lithospheric mantle) is pushed, or subducted**,** under the other. Often it is the older and colder plate that is denser and subducts beneath the younger and hotter plate. There is commonly an ocean trench along the boundary. The subducted lithosphere descends into the hot mantle at a relatively shallow angle close to the subduction zone, but at steeper angles farther down (up to about 45°). As discussed in the context of subduction-related volcanism in Chapter 4, the significant volume of water within the subducting material is released as the subducting crust is heated. Most of this water is present within the sheet silicate mineral serpentine which is derived from alteration of pyroxene and olivine near the spreading ridge shortly after the rock's formation. It is released when the oceanic crust is heats and then rises and mixes with the overlying mantle. The addition of water to the hot mantle lowers the rocks's melting point and leads to the formation of magma (flux melting) (Figure 10.4.6). The magma, which is lighter than the surrounding mantle material, rises through the mantle and the overlying oceanic crust to the ocean floor where it creates a chain of volcanic islands known as an island arc. A mature island arc develops into a chain of relatively large islands (such as Japan or Indonesia) as more and more volcanic material is extruded and sedimentary rocks accumulate around the islands.

As described above in the context of Benioff zones (Figure 10.3.6), earthquakes take place close to the boundary between the subducting crust and the overriding crust. The largest earthquakes occur near the surface where the subducting plate is still cold and strong.

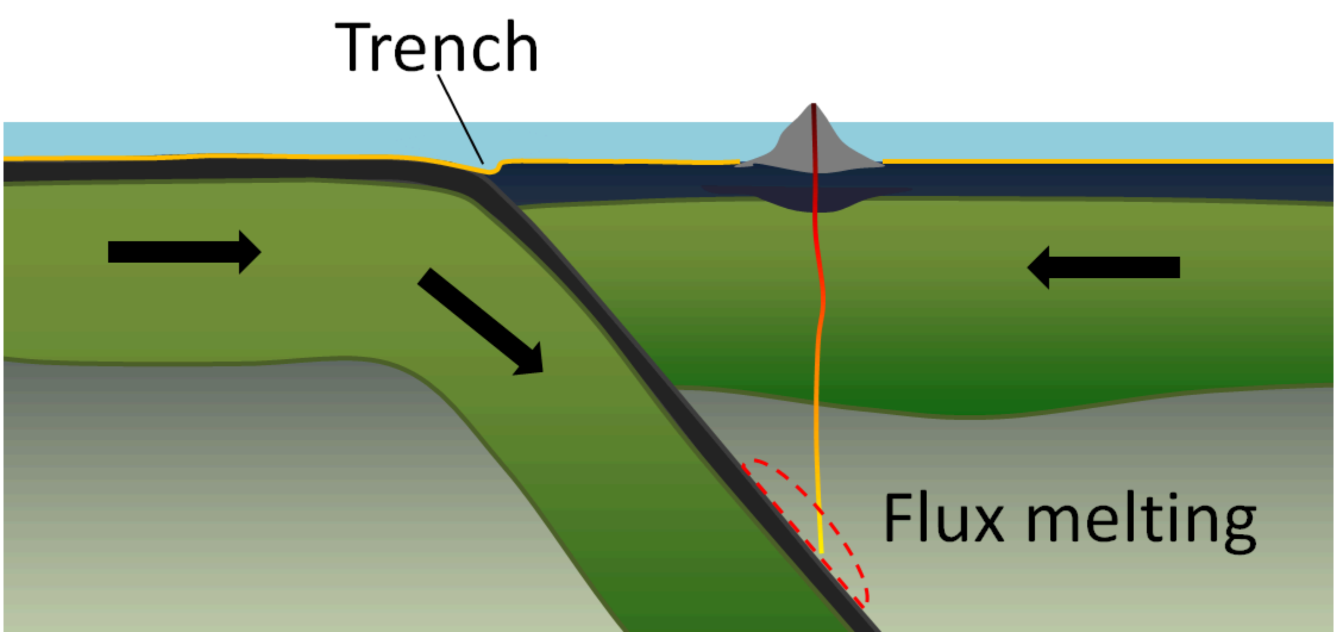


Figure 10.4.6 Configuration and processes of an ocean-ocean convergent boundary.

Examples of ocean-ocean convergent zones are subduction of the Pacific Plate beneath the North America Plate south of Alaska (Aleutian Islands) and beneath the Philippine Plate west of the Philippines, subduction of the India Plate beneath the Eurasian Plate south of Indonesia, and subduction of the Atlantic Plate beneath the Caribbean Plate (see Figure 10.4.1).

At an ocean-continent convergent boundary, the oceanic plate is pushed under the continental plate in the same manner as at an ocean-ocean boundary. Sediment that has accumulated on the **continental slope** is thrust up into an accretionary wedge, and compression leads to thrusting within the continental plate (Figure 10.4.7). The mafic magma produced adjacent to the subduction zone rises to the base of the continental crust and leads to partial melting of the crustal rock. The resulting magma ascends through the crust, producing a mountain chain with many volcanoes.

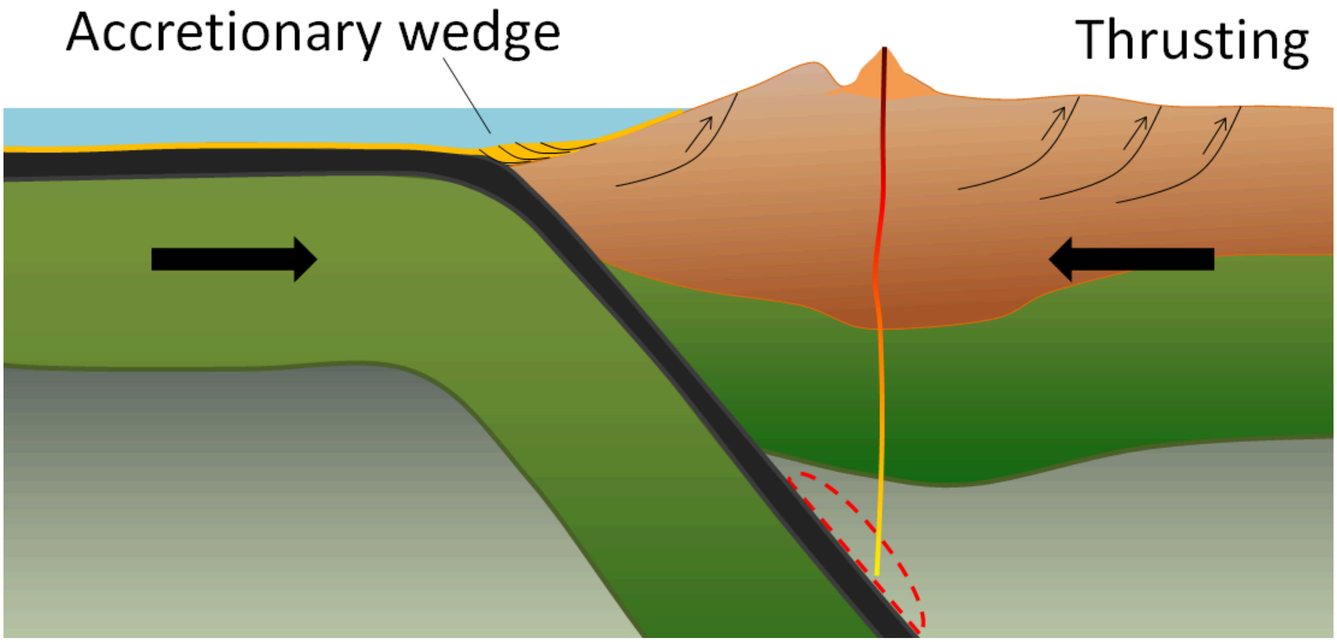


Figure 10.4.7 Configuration and processes of an ocean-continent convergent boundary.

Examples of ocean-continent convergent boundaries are subduction of the Nazca Plate under South America (which has created the Andes Range) and subduction of the Juan de Fuca Plate under North America (creating the mountains Garibaldi, Baker, St. Helens, Rainier, Hood, and Shasta, collectively known as the Cascade Range).

A continent-continent collision occurs when a continent or large island that has been moved along with subducting oceanic crust collides with another continent (Figure 10.4.8). The colliding continental material will not be subducted because it is too light (i.e., because it is composed largely of light continental rocks [SIAL]), but the root of the oceanic plate will eventually break off and sink into the mantle. There is tremendous deformation of the pre-existing continental rocks, and creation of mountains from that rock, from any sediments that had accumulated along the shores (i.e., within geosynclines) of both continental masses, and commonly also from some ocean crust and upper mantle material.

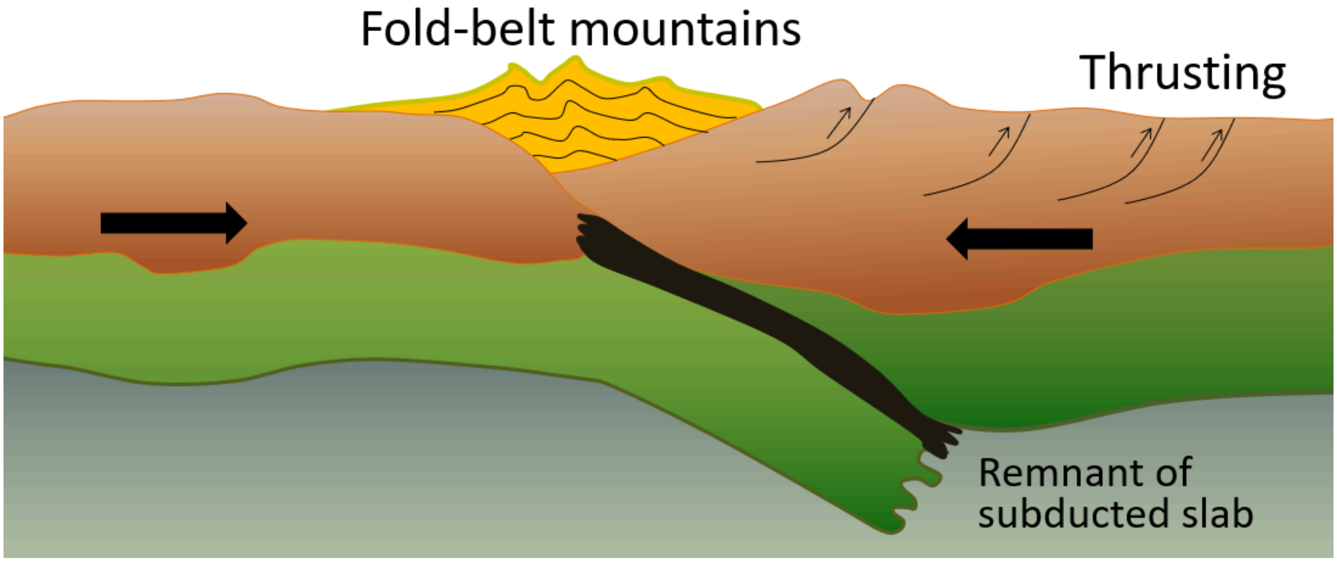


Figure 10.4.8 Configuration and processes of a continent-continent convergent boundary.

Examples of continent-continent convergent boundaries are the collision of the India Plate with the Eurasian Plate, creating the Himalaya Mountains, and the collision of the African Plate with the Eurasian Plate, creating the series of ranges extending from the Alps in Europe to the Zagros Mountains in Iran. The Rocky Mountains in B.C. and Alberta are also a result of continent-continent collisions.

Transform boundaries exist where one plate slides past another without production or destruction of crustal material. As explained above, most transform faults connect segments of mid-ocean ridges and are thus ocean-ocean plate boundaries (Figure 10.3.11). Some transform faults connect continental parts of plates. An example is the San Andreas Fault, which extends from the southern end of the Juan de Fuca Ridge to the northern end of the East Pacific Rise (ridge) in the Gulf of California (Figures 10.28 and 10.29). The part of California west of the San Andreas Fault and all of Baja California are on the Pacific Plate. Transform faults do not just connect divergent boundaries. For example, the Queen Charlotte Fault connects the north end of the Juan de Fuca Ridge, starting at the north end of Vancouver Island, to the Aleutian subduction zone.

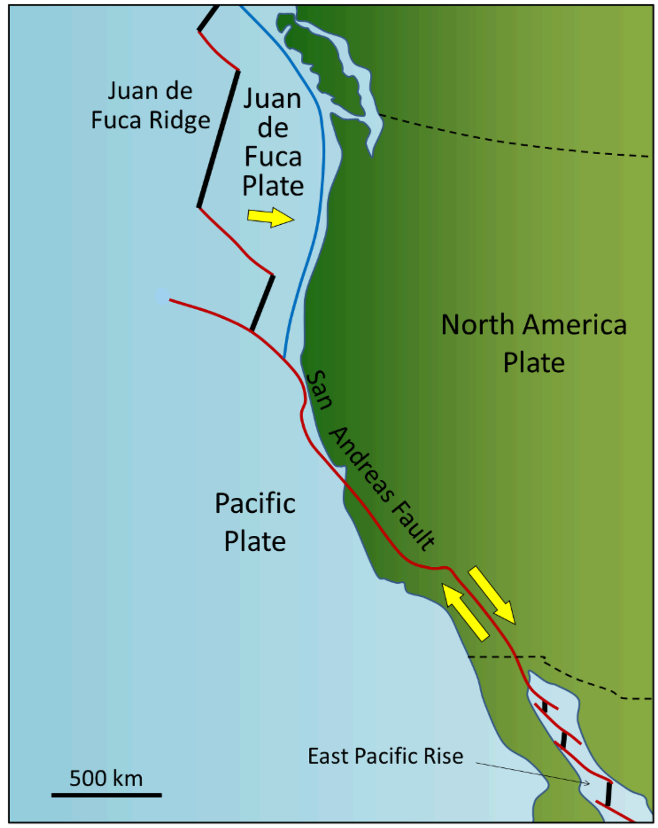


Figure 10.4.9 The San Andreas Fault extends from the north end of the East Pacific Rise in the Gulf of California to the southern end of the Juan de Fuca Ridge. All of the red lines on this map are transform faults.

Figure 10.4.10 The San Andreas Fault at Parkfield in central California. The person with the orange shirt is standing on the Pacific Plate and the person at the far side of the bridge is on the North American Plate. The bridge is designed to accommodate motion on the fault by sliding on its foundation.

Exercise 10.4 A different type of transform fault

This map shows the Juan de Fuca (JDF) and Explorer Plates off the coast of Vancouver Island. We know that the JDF Plate is moving toward the North American Plate at around 4 centimetres per year to 5 centimetres per year. We think that the Explorer Plate is also moving east, but we don't know the rate, and there is evidence that it is slower than the JDF Plate.

The boundary between the two plates is the Nootka Fault, which is the location of frequent small-to-medium earthquakes (roughly up to magnitude 5), as depicted by the red stars. Explain why the Nootka Fault is a transform fault, and show the *relative* sense of motion along the fault with two small arrows.

See Appendix 3 for Exercise 10.4 answers.

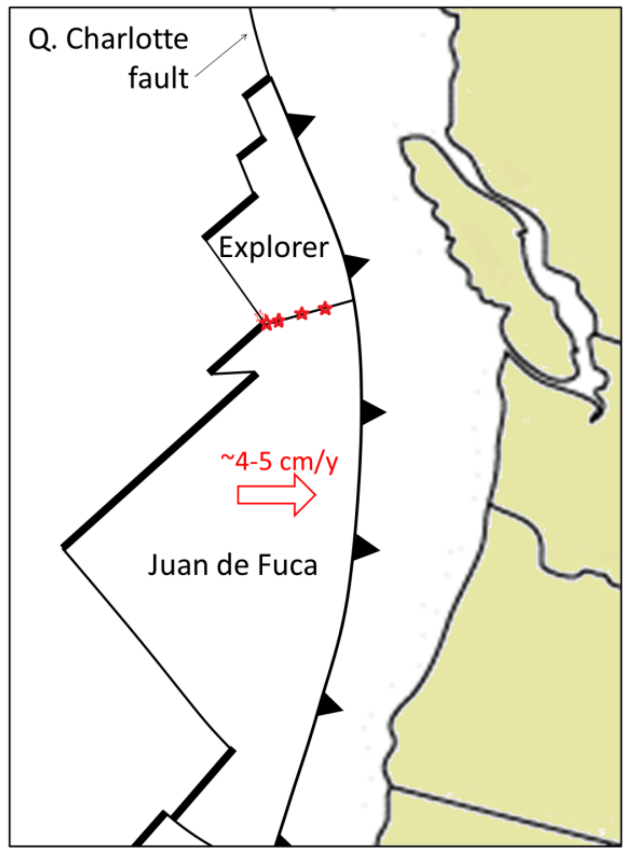


Figure 10.4.11

As originally described by Wegener in 1915, the present continents were once all part of a supercontinent, which he termed **Pangea** (meaning *all land*). More recent studies of continental matchups and the magnetic ages of ocean-floor rocks have enabled us to reconstruct the history of the break-up of Pangea.

Pangea began to rift apart along a line between Africa and Asia and between North America and South America at around 200 Ma. During the same period, the Atlantic Ocean began to open up between northern Africa and North America, and India broke away from Antarctica. Between 200 and 150 Ma, rifting started between South America and Africa and between North America and Europe, and India moved north toward Asia. By 80 Ma, Africa had separated from South America, most of Europe had separated from North America, and India had separated from Antarctica. By 50 Ma, Australia had separated from Antarctic, and shortly after that, India collided with Asia. To see the timing of these processes for yourself, go to time lapse of Continental Movements.

Within the past few million years, rifting has taken place in the Gulf of Aden and the Red Sea, and also within the Gulf of California. Incipient rifting has begun along the Great Rift Valley of eastern Africa, extending from Ethiopia and Djibouti on the Gulf of Aden (Red Sea) all the way south to Malawi.

Over the next 50 million years, it is likely that there will be full development of the east African rift and creation of new ocean floor. Eventually Africa will split apart. There will also be continued northerly movement of Australia and Indonesia. The western part of California (including Los Angeles and part of San Francisco) will split away from the rest of North America, and eventually sail right by the west coast of Vancouver Island, en route to Alaska. Because the oceanic crust formed by spreading on the mid-Atlantic ridge is not currently being subducted (except in the Caribbean), the Atlantic Ocean is slowly getting bigger, and the Pacific Ocean is getting smaller. If this continues without changing for another couple hundred million years, we will be back to where we started, with one supercontinent.

Pangea, which existed from about 350 to 200 Ma, was not the first supercontinent. It was preceded by Pannotia (600 to 540 Ma), by Rodinia (1,100 to 750 Ma), and by others before that.

In 1966, Tuzo Wilson proposed that there has been a continuous series of cycles of continental rifting and collision; that is, break-up of supercontinents, drifting, collision, and formation of other supercontinents. At present, North and South America, Europe, and Africa are moving with their respective portions of the Atlantic Ocean. The eastern margins of North and South America and the western margins of Europe and Africa are called **passive margins** because there is no subduction taking place along them.

This situation may not continue for too much longer, however. As the Atlantic Ocean floor gets weighed down around its margins by great thickness of continental sediments (i.e., geosynclines), it will be pushed farther and farther into the mantle, and eventually the oceanic lithosphere may break away from the continental lithosphere (Figure 10.4.12). A subduction zone will develop, and the oceanic plate will begin to descend under the continent. Once this happens, the continents will no longer continue to move apart because the spreading at the mid-Atlantic ridge will be taken up by subduction. If spreading along the mid-Atlantic ridge continues to be slower than spreading within the Pacific Ocean, the Atlantic Ocean will start to close up, and eventually (in a 100 million years or more) North and South America will collide with Europe and Africa.

There is strong evidence around the margins of the Atlantic Ocean that this process has taken place before. The roots of ancient mountain belts, which are present along the eastern margin of North America, the western margin of Europe, and the northwestern margin of Africa, show that these land masses once collided with each other to form a mountain chain, possibly as big as the Himalayas. The apparent line of collision runs between Norway and Sweden, between Scotland and England, through Ireland, through Newfoundland, and the Maritimes, through the northeastern and eastern states, and across the northern end of Florida. When rifting of Pangea started at approximately 200 Ma, the fissuring was along a different line from the line of the earlier collision. This is why some of the mountain chains formed during the earlier collision can be traced from Europe to North America and from Europe to Africa.

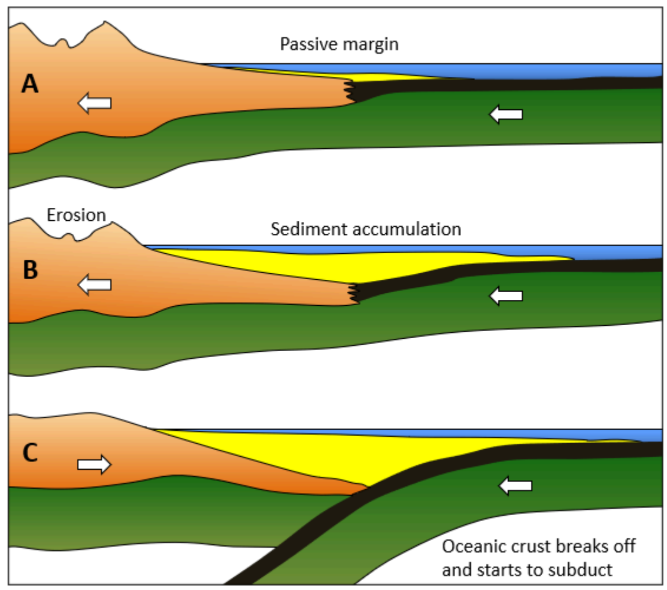


Figure 10.4.12 Development of a subduction zone at a passive margin. Times A, B, and C are separated by tens of millions of years. Once the oceanic crust breaks off and starts to subduct the continental crust (North America in this case) will no longer be pushed to the west and will likely start to move east because the rate of spreading in the Pacific basin is faster than that in the Atlantic basin.

That the Atlantic Ocean rift may have occurred in approximately the same place during two separate events several hundred million years apart is probably no coincidence. The series of hot spots that has been identified in the Atlantic Ocean may also have existed for several hundred million years, and thus may have contributed to rifting in roughly the same place on at least two separate occasions (Figure 10.3.13).

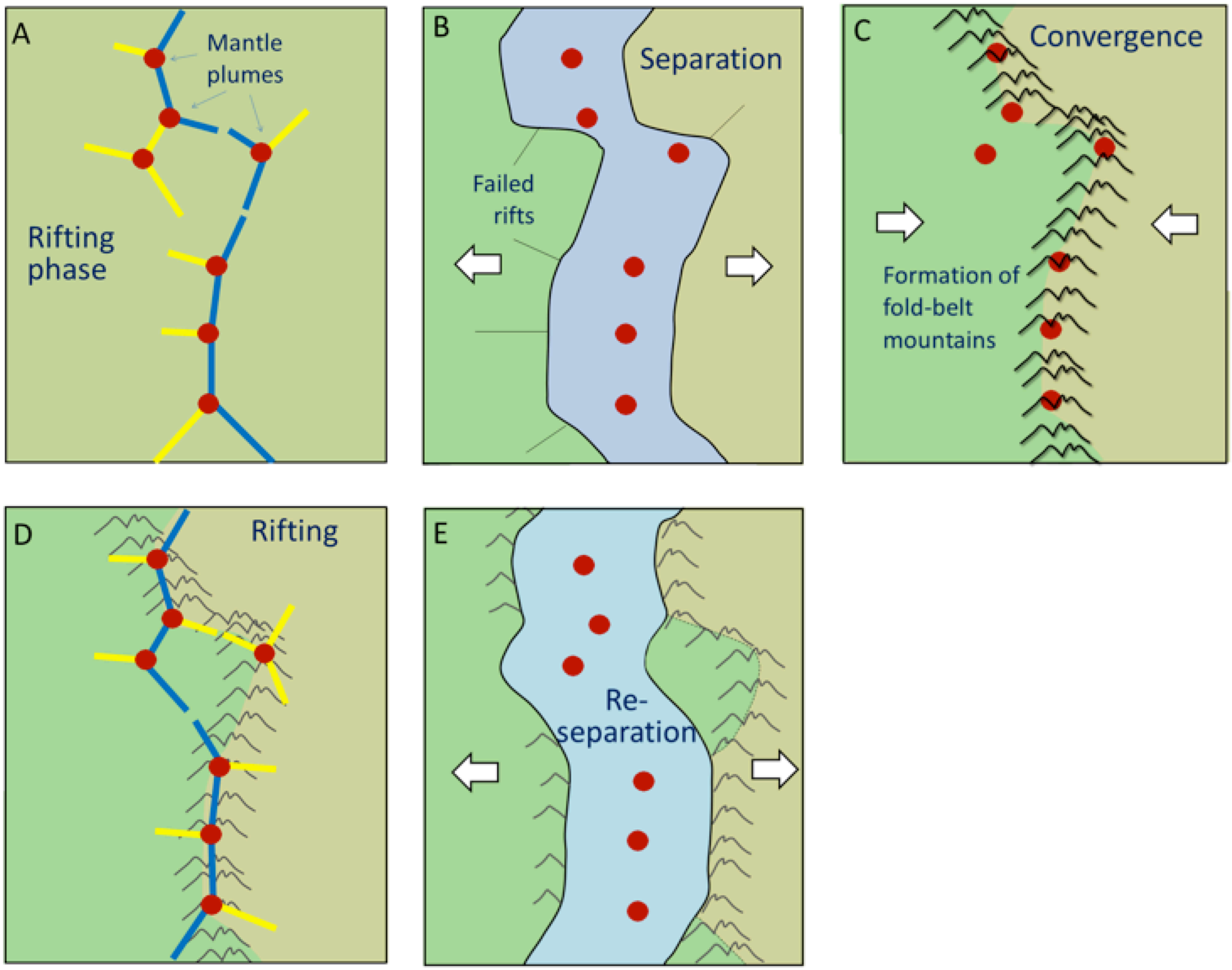


Figure 10.4.13 A scenario for the Wilson cycle. (A) The cycle starts with continental rifting above a series of mantle plumes. (B) The continents separate, and then (C) re-converge some time later, forming a fold-belt mountain chain. (D) Eventually rifting is repeated, possibly because of the same set of mantle plumes, but this time the rift is in a different place.

Exercise 10.5 Getting to know the plates and their boundaries

This map shows the boundaries between the major plates. Without referring to the plate map in Figure 10.4.1, or any other resources, write in the names of as many of the plates as you can. Start with the major plates, and then work on the smaller ones. Don't worry if you can't name them all.

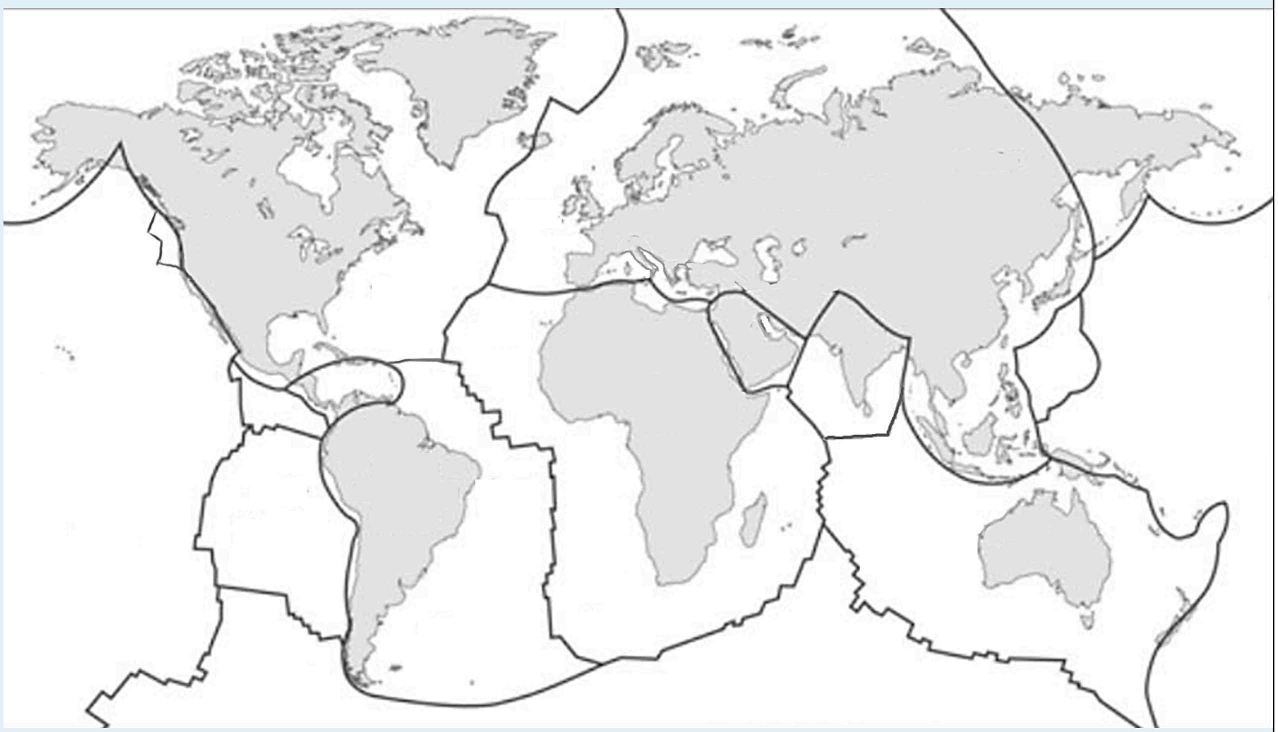


Figure 10.4.14

Once you've named most of the plates, draw arrows to show the general plate motions. Finally, using a highlighter or coloured pencil, label as many of the boundaries as you can as divergent, convergent, or transform.

See Appendix 3 for Exercise 10.5 answers.

Image descriptions

Figure 10.4.1 image description: Descriptions of 15 different plates and their movements.

Plate name	**Description of plate**	**Bordering plates (ordered from longest border to shortest)**	**Description of movement**
Africa plate	This plate includes all of Africa and the surrounding ocean, including the eastern Atlantic Ocean, the surrounding Antarctic Ocean, and the western Indian ocean.	South America plate, Antarctic plate, Eurasia plate, North America plate, Arabia plate, India plate, Australia plate	This plate is moving north east towards the Arabia and Eurasia plates.
Antarctic plate.	This plate makes up all of Antarctica and much of the surrounding ocean.	Pacific plate, Australia plate, Africa plate, Scotia plate, Nazca plate, South America plate.	The part of the plate around the South America plate is moving northwards and a little east. The part of the plate around the Australia plate is moving southwards.
Arabia plate	This plate includes all of Saudi Arabia, and much of the Levant (up to Iraq and Syria).	Eurasia plate, Africa plate, India plate	This plate is moving north east towards the Eurasia plate.
Australia plate	This plate includes Australia and much of the surrounding ocean. New Guinea and the northern parts of New Zealand are part of the Australia plate. The ocean area along southern Asia up to the India plate is also a part of the Australia plate.	Antarctic plate, Pacfic plate, Eurasia plate, India Plate, Africa plate.	This plate is moving north east towards the Eurasia plate and the Pacific plate.
Caribbean plate	This plate is small. It includes the central Caribbean countries and runs along the northern edge of South America.	North America plate, South America plate, Cocos plate.	N/A
Cocos plate	This plate is small. It runs along the west coast of Mexico and western Caribbean countries.	Nazca plate, Pacific plate, North America plate, Caribbean plate.	This plate is moving north east towards the Caribbean and North America plates.
Eurasia plate	This plate includes the northeastern part of the Atlantic ocean, all of Europe, all of Russia (except its most eastern part), and down through southeast Asia, including China and Indonesia.	North America plate, Africa plate, Australia plate, Arabia plate, India plate, Filipino plate.	This plate is rotating in a clockwise direction towards the Pacific plate.
Filipino plate	This plate includes the islands that make up the Philipines and north to include parts of southern Japan.	Eurasia plate, Pacific plate.	This plate is moving north west towards the Eurasia plate.
India plate	This plate includes India and the surrounding India Ocean.	Australia plate, Eurasia plate, Africa plate, Arabia plate.	This plate is moving north north east towards the Eurasia plate.

Plate name	**Description of plate**	**Bordering plates (ordered from longest border to shortest)**	**Description of movement**
Juan de Fuca plate	This plate is small. It runs along the north western coast of the United States and the southern British Columbia coast.	Pacific plate, North America plate.	N/A
Nazca plate	This plate is in the Pacific Ocean between the Pacific plate and the South America plate.	South America plate, Pacific plate, Antarctic plate, Cocos plate	This plate is moving directly east towards the South America plate.
North America Plate	This plate includes all of North America, Greenland, the eastern most part of Russia, northern Japan, and the northwestern part of the Atlantic ocean.	Eurasia plate, Pacific plate, Africa plate, Caribbean plate, South America plate, Cocos plate, Juan de Fuca plate	This plate is rotating counter clockwise in towards the Pacific plate.
Pacific plate	This plate makes up most of the Pacific Ocean.	North America plate, Australia plate, Antarctic plate, Nazca plate, Filipino plate, Cocos plate, Juan de Fuca plate	This plate is moving northwest towards the Australia, Filipino, and Eurasia plates.
Scotia plate	This plate is small. It runs from the tip of South America eastwards to form a barrier between the Antarctic plate and the South America plate.	Antarctic plate, South America plate.	N/A
South America plate	This plate starts at the western edge of South America and stretches east into the southwestern parst of the Atlantic Ocean.	Africa plate, Nazca plate, Scotia plate, Caribbean plate, Antarctic plate, North America plate	This plate moves north and slightly west towards the Caribbean plate and the North America plate.

[Return to Figure 10.4.1]

Media Attributions

- Figure 10.4.1: "Plates tect2 en" by the USGS. Adapted by Steven Earle. Public domain.
- Figures 10.4.2, 10.4.3, 10.4.5, 10.4.6, 10.4.7, 10.4.8, 10.4.9, 10.4.10, 10.4.11, 10.4.12, 10.4.13, 10.4.14: © Steven Earle. CC BY.
- Figure 10.4.4: © Steven Earle. CC BY. Based on Keary and Vine, 1996, Global Tectonics (2ed), Blackwell Science Ltd., Oxford.

10.5 Mechanisms for Plate Motion

It has been often repeated in this text and elsewhere that convection of the mantle is critical to plate tectonics, and while this is almost certainly so, other forces likely play a significant role. One side in the argument holds that the plates are only moved by the traction caused by mantle convection. The other side holds that traction plays only a minor role and that two other forces, ridge-push and slab-pull, are more important (Figure 10.5.1). Some argue that the real answer lies somewhere in between.

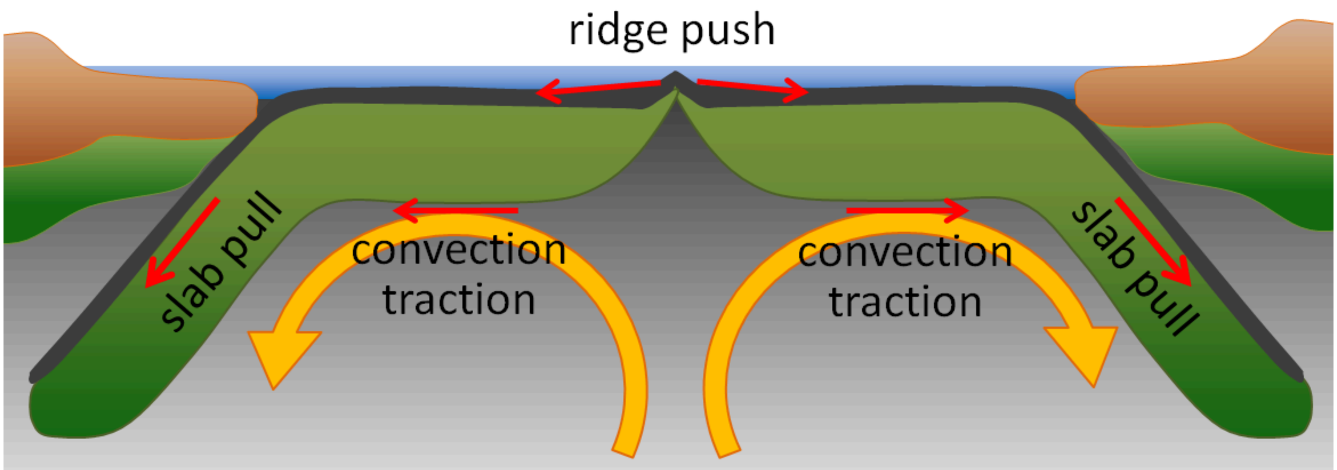


Figure 10.5.1 Models for plate motion mechanisms. [Image Description]

Kearey and Vine (1996)[1] have listed some compelling arguments in favour of the **ridge-push/slab-pull** model, as follows: (a) plates that are attached to subducting slabs (e.g., Pacific, Australian, and Nazca Plates) move the fastest, and plates that are not (e.g., North American, South American, Eurasian, and African Plates) move significantly slower; (b) in order for the traction model to apply, the mantle would have to be moving about five times faster than the plates are moving (because the coupling between the partially liquid asthenosphere and the plates is not strong), and such high rates of convection are not supported by geophysical models; and (c) although large plates have potential for much higher convection traction, plate velocity is not related to plate area.

In the ridge-push/slab-pull model, which is the one that has been adopted by most geologists working on plate-tectonic problems, the lithosphere is the upper surface of the convection cells, as is illustrated in Figure 10.5.2.

1. Kearey and Vine , 1996, Global Tectonics (2ed), Blackwell Science Ltd., Oxford

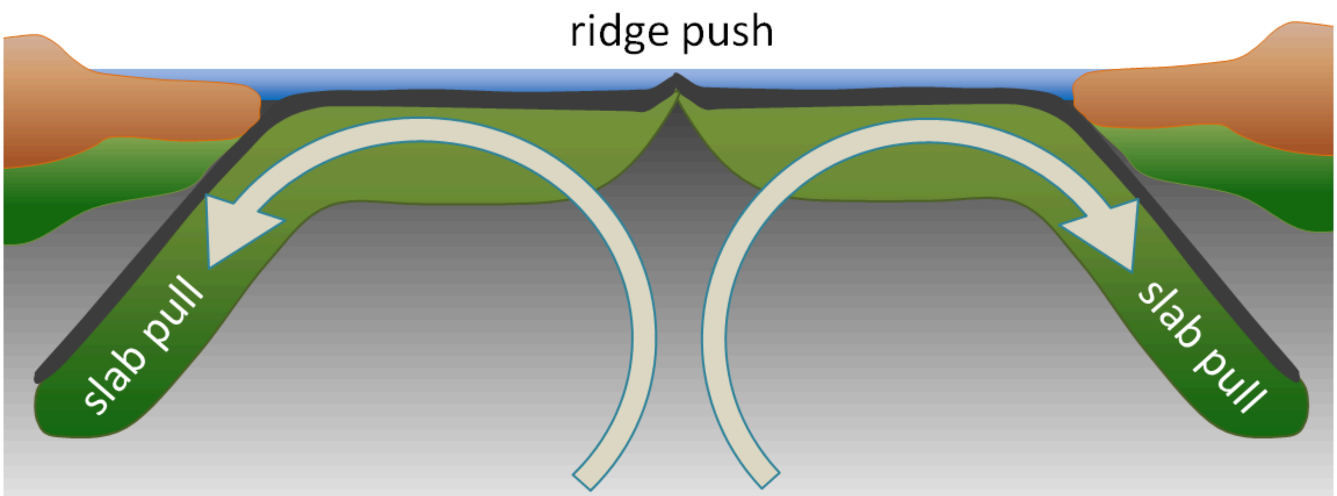


Figure 10.5.2 The ridge-push/slab-pull model for plate motion, in which the lithosphere is the upper surface of the convective systems.

Although ridge-push/slab-pull is the widely favoured mechanism for plate motion, it's important not to underestimate the role of mantle convection. Without convection, there would be no ridges to push from because upward convection brings hot buoyant rock to surface. Furthermore, many plates, including our own North American Plate, move along nicely—albeit slowly—without any slab-pull happening.

Image Descriptions

Figure 10.5.1 image description: In this model, there are three forces working to move the plates. Ridge-push forces cause two plates to pull apart on the surface. Slab-pull forces pull the plates down. This movement of out and down is also encouraged by convection traction, or clockwise and counterclockwise currents that are present beneath the plates. [Return to Figure 10.5.1]

Media Attributions

Summary

The topics covered in this chapter can be summarized as follows:

Section	Summary
10.1 Alfred Wegener: The Father of Plate Tectonics	The evidence for continental drift in the early 20th century included the matching of continental shapes on either side of the Atlantic and the geological and fossil matchups between continents that are now thousands of kilometres apart.
10.2 Global Geological Models of the Early 20th Century	The established theories of global geology were permanentism and contractionism, but neither of these theories was able to explain some of the evidence that supported the idea of continental drift.
10.3 Geological Renaissance of the Mid-20th Century	Giant strides were made in understanding Earth during the middle decades of the 20th century, including discovering magnetic evidence of continental drift, mapping the topography of the ocean floor, describing the depth relationships of earthquakes along ocean trenches, measuring heat flow differences in various parts of the ocean floor, and mapping magnetic reversals on the sea floor. By the mid-1960s, the fundamentals of the theory of plate tectonics were in place.
10.4 Plate, Plate Motions, and Plate Boundary Processes	Earth's lithosphere is made up of over 20 plates that are moving in different directions at rates of between 1 cm/y and 10 cm/y. The three types of plate boundaries are divergent (plates moving apart and new crust forming), convergent (plates moving together and one being subducted), and transform (plates moving side by side). Divergent boundaries form where existing plates are rifted apart, and it is hypothesized that this is caused by a series of mantle plumes. Subduction zones are assumed to form where accumulation of sediment at a passive margin leads to separation of oceanic and continental lithosphere. Supercontinents form and break up through these processes.
10.5 Mechanisms for Plate Motion	It is widely believed that ridge-push and slab-pull are the main mechanisms for plate motion, as opposed to traction by mantle convection. Mantle convection is a key factor for producing the conditions necessary for ridge-push and slab-pull.

Questions for Review

1. List some of the evidence used by Wegener to support his idea of moving continents.
2. What was the primary technical weakness with Wegener's continental drift theory?

3. How were mountains thought to be formed (a) by contractionists and (b) by permanentists?
4. How were the trans-Atlantic paleontological matchups explained in the late 19th century?
5. In the context of isostasy, what would prevent an area of continental crust from becoming part of an ocean?
6. How did we learn about the topography of the sea floor in the early part of the 20th century?
7. How does the temperature profile of the crust and the mantle indicate that part of the mantle must be convecting?
8. What evidence from paleomagnetic studies provided support for continental drift?
9. Which parts of the oceans are the deepest?
10. Why is there less sediment in the ocean ridge areas than in other parts of the sea floor?
11. How were the oceanic heat-flow data related to mantle convection?
12. Describe the spatial and depth distribution of earthquakes at ocean ridges and ocean trenches.
13. In the model for ocean basins developed by Harold Hess, what took place at oceanic ridges and what took place at oceanic trenches?
14. What aspect of plate tectonics was not included in the Hess theory?
15. Figure 10.36 shows the pattern of sea-floor magnetic anomalies in the area of a spreading ridge. Draw in the likely location of the ridge.
16. What is a mantle plume and what is its expected lifespan?
17. Describe the nature of movement at an ocean ridge transform fault (a) between the ridge segments, and (b) outside the ridge segments.
18. How is it possible for a plate to include both oceanic and continental crust?
19. What is the likely relationship between mantle plumes and the development of a continental rift?
20. Why does subduction not take place at a continent-continent convergent zone?

Figure A

21. Divergent, convergent, and transform boundaries are shown in different colours on Fiugre 10.37. Which colours are the divergent boundaries, which are the convergent boundaries, and which are the transform boundaries?

22. Name the plates on this map and show their approximate motion directions.
23. Show the sense of motion on either side of the plate boundary to the west of Haida Gwaii (Queen Charlotte Islands).
24. Where are Earth's most recent sites of continental rifting and creation of new ocean floor?
25. What is likely to happen to western California over the next 50 million years?
26. What geological situation might eventually lead to the generation of a subduction zone at a passive ocean-continent boundary such as the eastern coast of North America?

Answers to Review Questions can be found in Appendix 2.

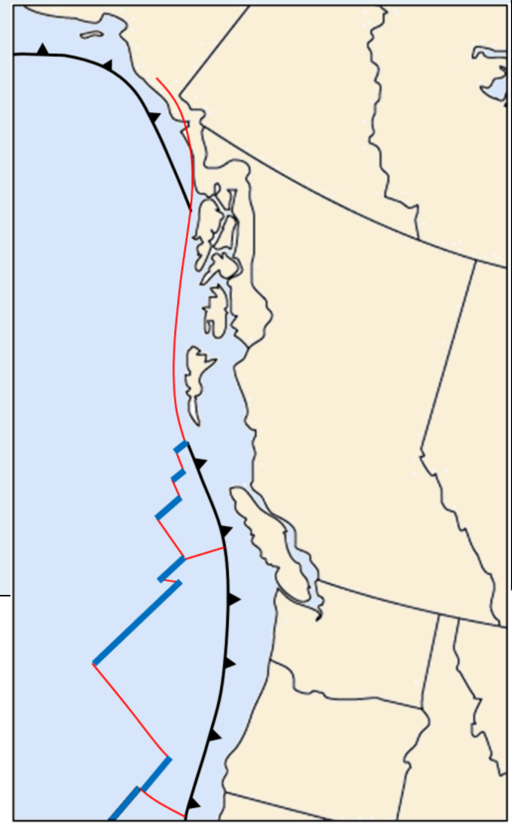


Figure B [Image Description]

Image Descriptions

Figure B image description: A black line with triangles pointing towards the coast stretches from the Oregon and Washington state up just past Vancouver Island to the southern tip of Haida Gwaii. This line also appears along the Alaskan coast and stretches part way down the Alaskan Pan-Handle. A thin red line stretches from the Alaskan Pan-Handle down just past the southern tip of Haida Gwaii. From that point, it alternates from being a thin red to a thick blue line to form uneven angles zig zagging south past Oregon state. [Return to Figure B]

Media Attributions

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