University of Basrah

College of Science

Department of Geology

Geotectonics

Wathiq Ghazi Abdulnaby

wathiq.abdulnaby@uobasrah.edu.iq

2019

Contents

1. Introduction

James Hutton (1726–1797) published his book “Theory of the Earth with Proofs and Illustrations,” in 1785. Since the publication of this book, there has been a group of scientists who recognize themselves as geologists. These new geologists defined the geometry of structures in mountain ranges, learned how to make geologic maps, discovered the processes involved in the formation of rocks, and speculated on the origins of specific structures and on mountain ranges in general.

Ideas about the origin of mountains have evolved gradually. At first, mountain ranges were thought to be a consequence of a vertical push from below, perhaps associated with intrusion of molten rock along preexisting zones of weakness, and folds and faults in strata were attributed to gravity sliding down the flanks of these uplifts. Subsequently, the significance of horizontal forces was emphasized, and geologists speculated that mountain ranges and their component structures reflected the contraction of the Earth that resulted from progressive cooling. In this model, the shrinking of the Earth led to wrinkling of the surface.

One of the more notable discoveries (about 1850) was the recognition by James Hall (1811–1898) that Paleozoic strata in the Appalachian Mountains of North America were much thicker than correlative strata in the interior of the continent. This discovery led to the development of the geosyncline theory, a model in which deep sedimentary basins, called geosynclines, evolved into mountain ranges.

Contraction theory and geosynclinal theory, or various combinations of the two, were widely accepted until the 1960s, when the views of Alfred Wegener (1880–1930), Arthur Holmes (1898–1965), and Harry Hess (1906–1969) led to the formulation of a very different model. Building on the work of Alfred Wegener’s continental drift theory and Arthur Holmes’s mantle convection model, Harry Hess proposed the revolutionary idea of a mobile seafloor (seafloor spreading hypothesis) that lead to the formulation of plate tectonic theory. In this theory, the Earth consists of several, rigid plates that change in space and time. The interaction between these plates offers a unifying explanation for the occurrence of mountain ranges, ocean basins, earthquakes, volcanoes, and other previously disparate geologic phenomena.

2. Dynamic Earth and Geotectonics

Why is Earth a dynamic planet?

Earth is a dynamic planet that has continuously changed during its 4.6-billion-year existence. The size, shape, and geographic distribution of continents and ocean basins have changed through time, the composition of the atmosphere has evolved, and life forms existing today differ from those that lived during the past. Mountains and hills have been worn away by erosion, and the forces of wind, water, and ice have sculpted a diversity of landscapes. Volcanic eruptions and earthquakes reveal an active interior, and folded and fractured rocks are testimony to the tremendous power of Earth's internal forces.

What are geotectonic theories?

Geotectonic theories are comprehensive set of ideas that explain the development of regional geologic features, such as the distinction between oceans and continents, the origin of mountain belts, and the distribution of earthquakes, volcanoes, and rock types.

The geotectonic theories are (1) contraction theory, (2) geosyncline theory, (3) continental drift theory, (4) seafloor-spreading theory, and (5) plate tectonic theory.

What are hypothesis and theory?

Recall that a "hypothesis" is simply a reasonable idea that has the potential to explain observations. A "theory" is an idea that has been rigorously tested and has not yet failed to explain relevant observations. Nevertheless, a theory could someday be proven wrong.

3. Contraction and Geosyncline Theories

Prior to the proposal of plate tectonics theory, most geologists had a "fixist" view of the Earth, in which continents were fixed in position through geologic time. In this context, geologists viewed mountain building to be a consequence predominantly of vertical motions. Pre–plate tectonics ideas to explain mountain building included: (1) The contracting Earth hypothesis, which stated that mountains formed when the Earth cooled, shrank, and wrinkled, much like a baked apple removed from the oven; (2) The geosyncline hypothesis, which stated that mountain belts formed out of the deep, elongate sedimentary basins (known as “geosynclines”) that formed along the margins of continents. According to this hypothesis, mountain building happened when the floor of a geosyncline sank deep enough for sediment to melt; the resulting magma rose and in the process deformed and metamorphosed surrounding rock. Both ideas have been thoroughly discredited.

In pre–plate tectonic literature, a passive-margin sedimentary wedge was referred to as a “geosyncline.” Geosynclines, in turn, were subdivided into a “miogeosyncline,” which consisting of shallower-water facies of the continental shelf, and a “eugeosyncline,” consisting of deep-water facies of the slope and rise (Figure 1).

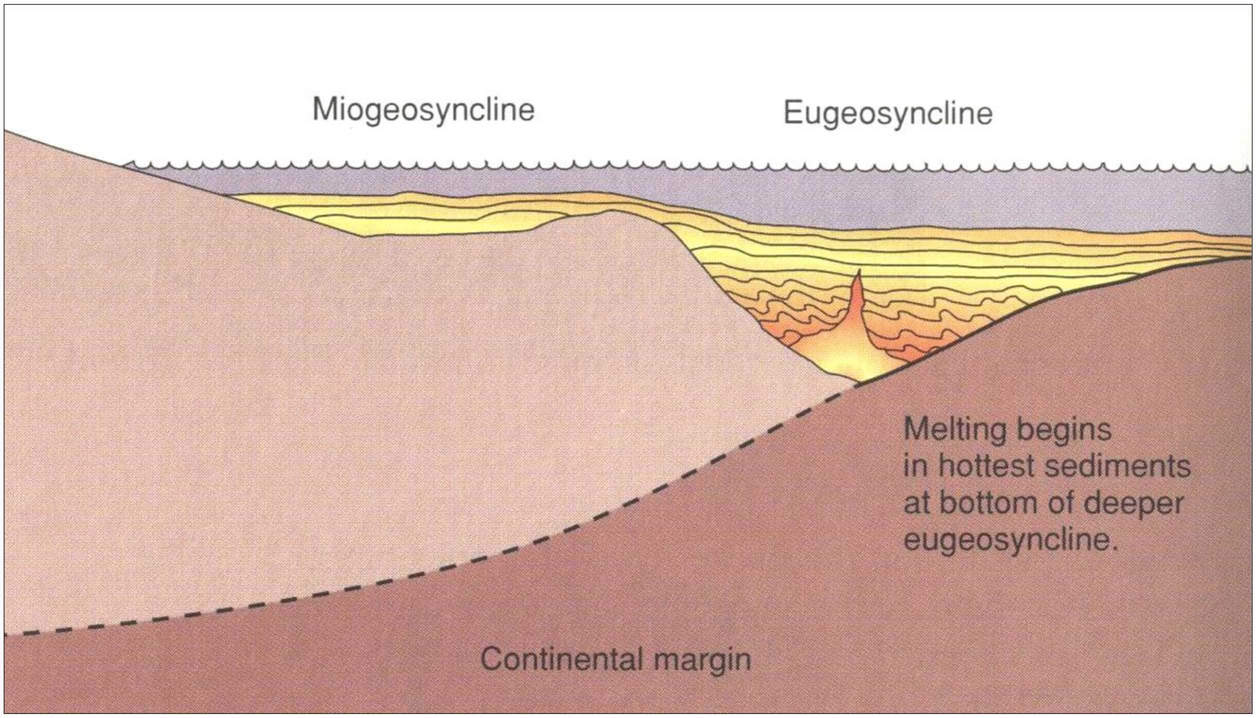


Figure 1 Eugeosyncline and miogeosyncline, part of a pre-plate-tectonics theory of mountain building.

4. Continental Drift Theory

What were some early ideas about Earth's past geography?

The idea that Earth's past geography was different from today is not new. The earliest maps showing the east coast of South America and the west coast of Africa probably provided people with the first evidence that continents may have once been joined together, then broken apart and moved to their present locations.

During the late 19th century, the Austrian geologist *Edward Suess* noted the similarities between the Late Paleozoic plant fossils of India, Australia, South Africa, and South America as well as evidence of glaciation in the rock sequences of these southern continents. The plant fossils make up a unique flora in the coal layers just above the glacial deposits of these southern continents. This flora is very different from the contemporaneous coal swamp flora of the northern continents and is collectively known as the Glossopteris flora, after its most conspicuous genus (Figure 2).

Figure 2 Fossil Glossopteris Leaves Plant fossils, such as these Glossopteris leaves from the Upper Permian Dunedoo Formation in Australia, are found on all five Gondwana continents. The presence of these fossil plants on continents with widely varying climates today is evidence that the continents were at one time connected. The distribution of the plants at that time was in the same climatic latitudinal belt.

In his book, *The Face of the Earth*, published in 1885, Suess proposed the name Gondwanaland (or Gondwana as we will use here) for a supercontinent composed of the aforementioned southern continents. Abundant fossils of the Glossopteris flora are found in coal beds in Gondwana, a province in India. Suess thought these southern continents were at one time connected by land bridges over which plants and animals migrated. Thus, in his view, the similarities of fossils on these continents were due to the appearance and disappearance of the connecting land bridges.

The American geologist *Frank Taylor* published a pamphlet in 1910 presenting his own theory of continental drift. He explained the formation of mountain ranges as a result of the lateral movement of continents. He also envisioned the present-day continents as parts of larger polar continents that eventually broke apart and migrated toward the equator after Earth's rotation was supposedly slowed by gigantic tidal forces. According to Taylor, these tidal forces were generated when Earth captured the Moon about 100 million years ago.

Although we now know that Taylor's mechanism is incorrect, one of his most significant contributions was his suggestion that the Mid-Atlantic Ridge, discovered by the 1872–1876 British HMS Challenger expeditions, might mark the site along which an ancient continent broke apart to form the present-day Atlantic Ocean.

What is the continental drift hypothesis and who proposed it?

Alfred Wegener, a German meteorologist (Figure 3), is generally credited with developing the hypothesis of continental drift. In his monumental book, *The Origin of Continents and Oceans* (first published in 1915), Wegener proposed that all landmasses were originally united in a single supercontinent that he named *Pangaea*, from the Greek meaning "all land." Pangaea are surrounded by a great ocean named *Panthalassa*, from the Greek meaning "all sea." Wegener portrayed his grand concept of continental movement in a series of maps showing the breakup of Pangaea and the movement of the various continents to their present-day locations (Figure 4). Wegener amassed a tremendous amount of geologic, paleontologic, and climatologic evidence in support of continental drift, but the initial reaction of scientists to his then-heretical ideas can best be described as mixed.

Opposition to Wegener's ideas became particularly widespread in North America after 1928, when the American Association of Petroleum Geologists held an international symposium to review the hypothesis of continental drift.

After each side had presented its arguments, the opponents of continental drift were clearly in the majority, even though the evidence in support of continental drift, most of which came from the Southern Hemisphere, was impressive and difficult to refute. The main problem with the hypothesis was its lack of a mechanism to explain how continents, composed of granitic rocks, could seemingly move through the denser basaltic oceanic crust.

Figure 3 Alfred Wegener. Alfred Wegener, a German meteorologist, proposed the continental drift hypothesis in 1912 based on a tremendous amount of geologic, paleontologic, and climatologic evidence. He is shown here waiting out the Arctic winter in an expedition hut in Greenland.

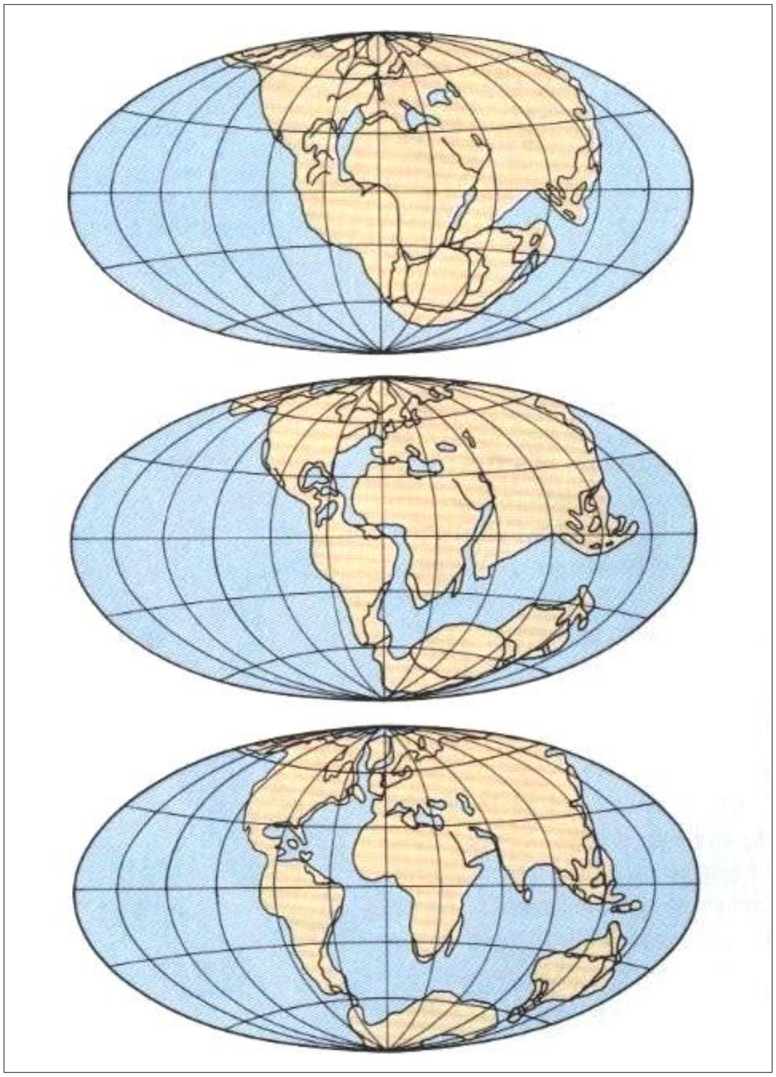


Figure 4 A series of maps portrayed by Wegener in 1915 to explain his grand concept of continental movement. The figure shows the breakup of Pangaea and the movement of the various continents to their present-day locations.

Nevertheless, the eminent South African geologist *Alexander du Toit* further developed Wegener's arguments and gathered more geologic and paleontologic evidence in support of continental drift. In 1937, du Toit published *Our Wandering Continents*, in which he contrasted the glacial deposits of Gondwana with coal deposits of the same age found in the continents of the Northern Hemisphere. To resolve this apparent climatologic paradox, du Toit moved the Gondwana continents to the South Pole and brought the northern continents together such that the coal deposits were located at the equator. He named this northern landmass Laurasia. It consisted of present-day North America, Greenland, Europe, and Asia (except for India).

Despite what seemed to be overwhelming evidence, most geologists still refused to accept the idea that the continents moved. Not until the 1960s, when oceanographic research provided convincing evidence that the continents had once been joined together and subsequently separated, did the hypothesis of continental drift finally become widely accepted.

5 Evidence for Continental Drift

What is the evidence for continental drift?

What, then, was the evidence Wegener, du Toit, and others used to support the hypothesis of continental drift? It includes the fit of the shorelines of continents, the appearance of the same rock sequences and mountain ranges of the same age on continents now widely separated, the matching of glacial deposits and paleoclimatic zones, and the similarities of many extinct plant and animal groups whose fossil remains are found today on widely separated continents.

Wegener and his supporters argued that this vast amount of evidence from a variety of sources surely indicated that the continents must have been close together in the past.

1. Continental Fit

Wegener, like some before him, was impressed by the close resemblance between the coastlines of continents on opposite sides of the Atlantic Ocean, particularly South America and Africa. He cited these similarities as partial evidence that the continents were at one time joined together as a supercontinent that subsequently split apart. As his critics pointed out, though, the configuration of coastlines results from erosional and depositional processes and therefore is continuously being modified. So, even if the continents had separated during the Mesozoic Era, as Wegener proposed, it is not likely that the coastlines would fit exactly.

A more realistic approach is to fit the continents together along the continental slope, where erosion would be minimal. In 1965 Sir Edward Bullard, an English geophysicist, and two associates showed that the best fit between the continents occurs at a depth of about 2000 m (Figure 6). Since then, other reconstructions using the latest ocean basin data have confirmed the close fit between continents when they are reassembled to form Pangaea.

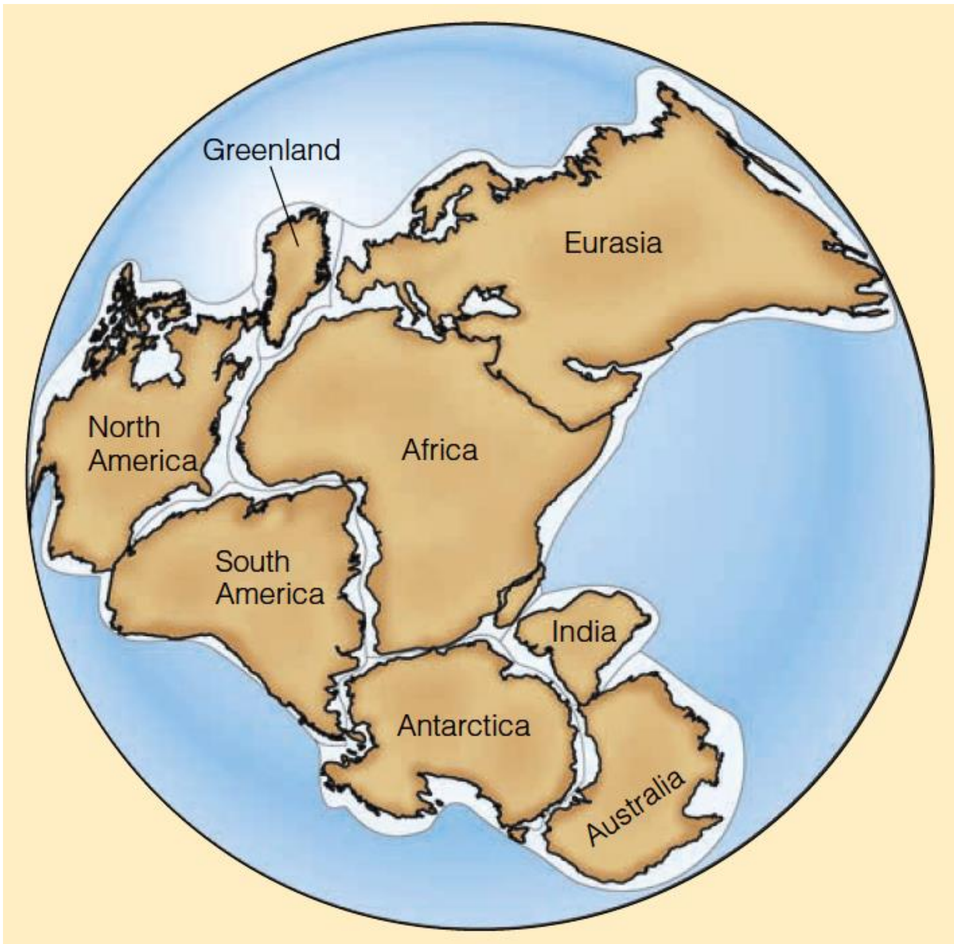


Figure 6 Continental Fit. When continents are placed together based on their outlines, the best fit is not along their present-day coastlines, but rather along the continental slope at a depth of about 2000 m. **Why is this?** Because the coastlines are continuously being modified by erosional and depositional processes, and thus one would not expect them to be the same today as they were at any time in the geologic past.

2. Similarity of Rock Sequences

If the continents were at one time joined, then the rocks of the same age in adjoining locations on the opposite continents should closely match. Such is the case for the Gondwana continents (Figure 7). Marine, nonmarine, and glacial rock sequences of Pennsylvanian to Jurassic age are almost identical on all five Gondwana continents, strongly indicating that they were joined at one time.

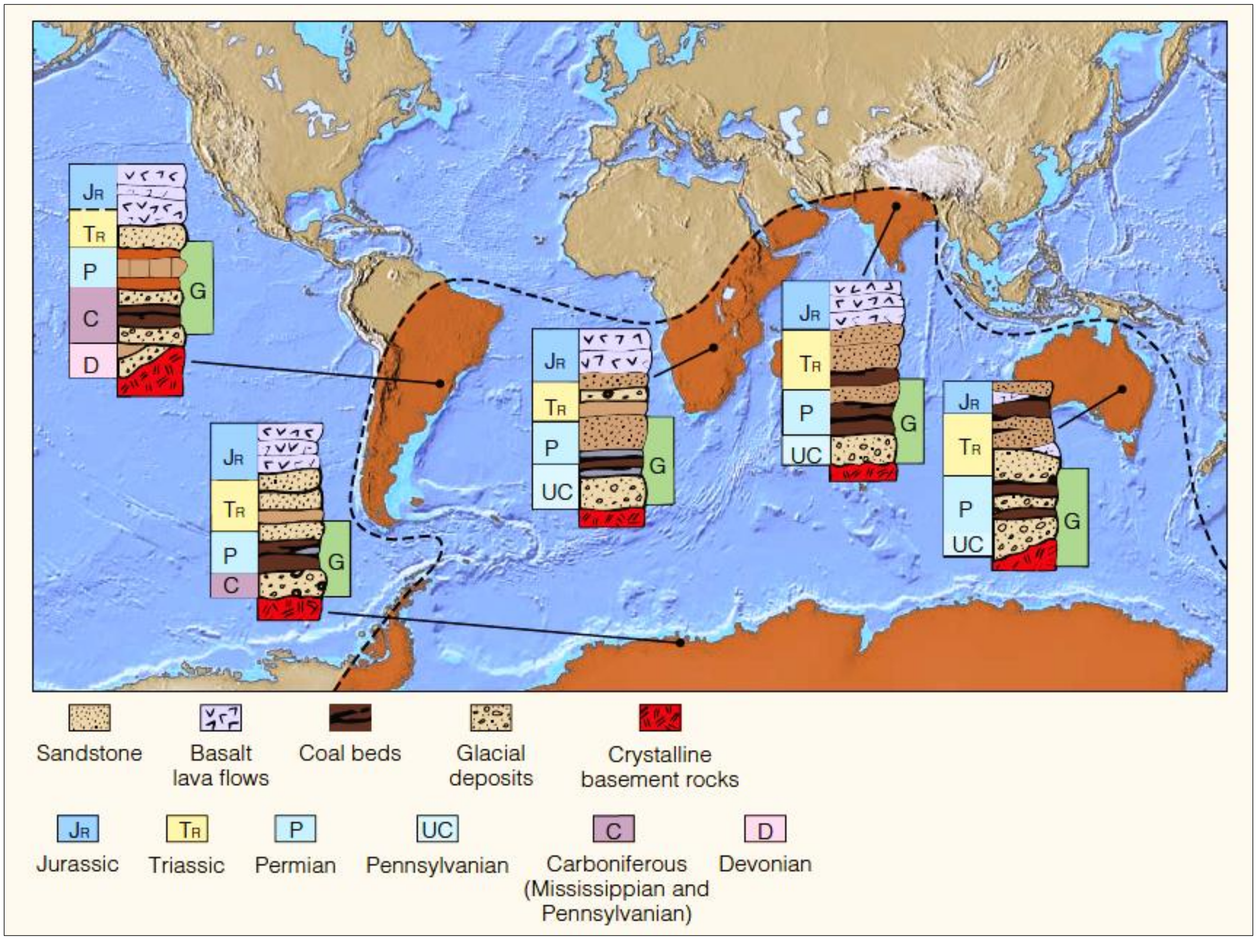


Figure 7 Similarity of Rock Sequences on the Gondwana. Continents Sequences of marine, nonmarine, and glacial rocks of Pennsylvanian (UC) to Jurassic (JR) age are nearly the same on all five Gondwana continents (South America, Africa, India, Australia, and Antarctica). These continents are widely separated today and have different environments and climates ranging from tropical to polar. Thus, the rocks forming on each continent are very different. When the continents were all joined together in the past, however, the environments of adjacent continents were similar and the rocks forming in those areas were similar. The range indicated by G in each column is the age range (Carboniferous–Permian) of the Glossopteris flora.

3. Mountain Ranges

The trends of several major mountain ranges also support the hypothesis of continental drift. These mountain ranges seemingly end at the coastline of one continent only to apparently continue on another continent across the ocean.

The folded Appalachian Mountains of North America, for example, trend northeastward through the eastern United States and Canada and terminate abruptly at the Newfoundland coastline. Mountain ranges of the same age and deformational style are found in eastern Greenland, Ireland, Great Britain, and Norway. In fact, the same red sandstones used in the construction of many English and Scottish castles are used in various buildings throughout New York. So, even though the Appalachian Mountains and their equivalent-age mountain ranges in Great Britain are currently separated by the Atlantic Ocean, they form an essentially continuous mountain range when the continents are positioned next to each other as they were during the Paleozoic Era.

4. Glacial Evidence

During the Late Paleozoic Era, massive glaciers covered large continental areas of the Southern Hemisphere. Evidence for this glaciation includes layers of till (sediments deposited by glaciers) and striations (scratch marks) in the bedrock beneath the till. Fossils and sedimentary rocks of the same age from the Northern Hemisphere, however, give no indication of glaciation. Fossil plants found in coals indicate that the Northern Hemisphere had a tropical climate during the time the Southern Hemisphere was glaciated.

All the Gondwana continents except Antarctica are currently located near the equator in subtropical to tropical climates. Mapping of glacial striations in bedrock in Australia, India, and South America indicates that the glaciers moved from the areas of the present-day oceans onto land. This would be highly unlikely because large continental glaciers (such as occurred on the Gondwana continents during the Late Paleozoic Era) flow outward from their central area of accumulation toward the sea.

If the continents did not move during the past, one would have to explain how glaciers moved from the oceans onto land and how large-scale continental glaciers formed near the equator. But if the continents are reassembled as a single landmass with South Africa located at the South Pole, the direction of movement of Late Paleozoic continental glaciers makes sense (Figure 8). Furthermore, this geographic arrangement places the northern continents nearer the tropics, which is consistent with the fossil and climatologic evidence from Laurasia.

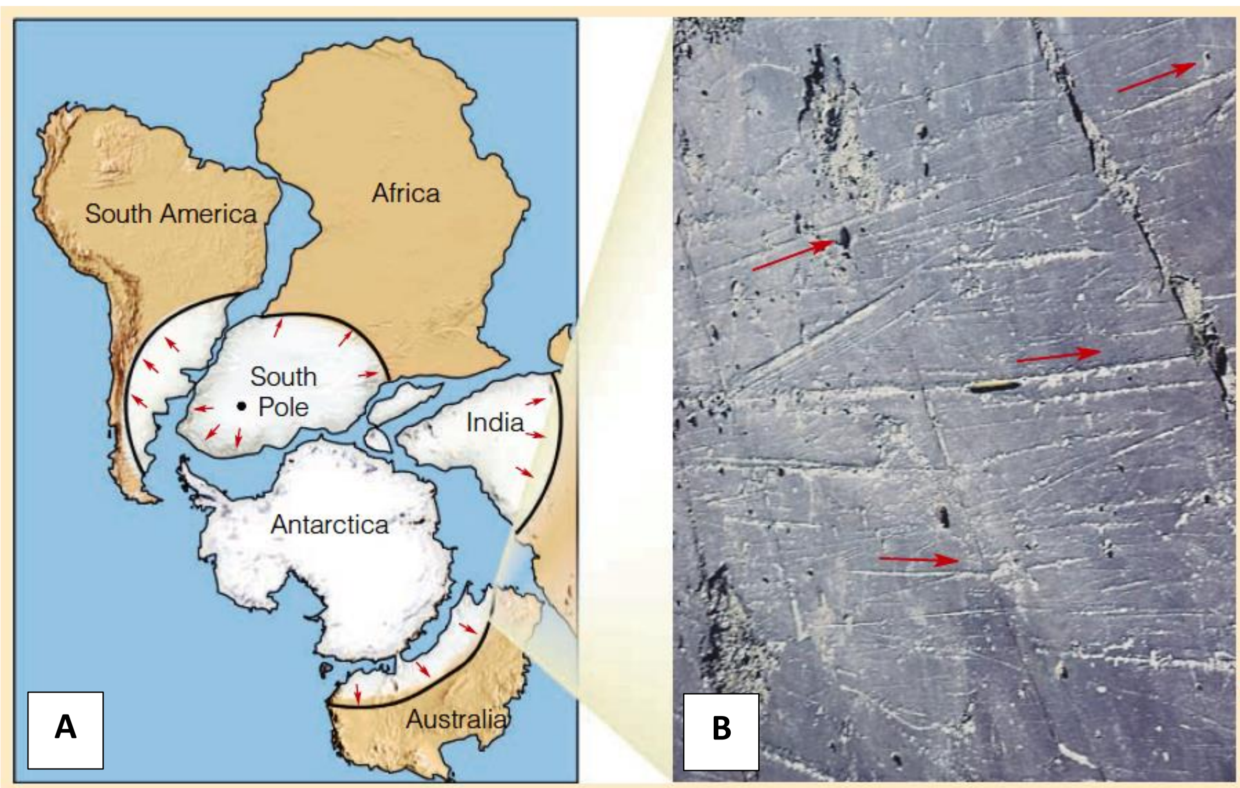


Figure 8 Glacial Evidence Indicating Continental Drift. (A) When the Gondwana continents are placed together so that South Africa is located at the South Pole, the glacial movements indicated by striations (red arrows) found on rock outcrops on each continent make sense. In this situation, the glacier (white area) is located in a polar climate and has moved radially outward from its thick central area toward its periphery. (B) Glacial striations (scratch marks) on an outcrop of Permian-age bedrock exposed at Hallet's Cove, Australia, indicate the general direction of glacial movement more than 200 million years ago. As a glacier moves over a continent's surface, it grinds and scratches the underlying rock. The scratch marks that are preserved on a rock's surface (glacial striations) thus provide evidence of the direction (red arrows) the glacier moved at that time.

5. Fossil Evidence

Some of the most compelling evidence for continental drift comes from the fossil record. Fossils of the *Glossopteris* flora are found in equivalent Pennsylvanian- and Permian-aged coal deposits on all five Gondwana continents. The *Glossopteris* flora is characterized by the seed fern Glossopteris (Figure 9) as well as by many other distinctive and easily identifiable plants. Pollen and spores of plants can be dispersed over great distances by wind, but Glossopteris-type plants produced seeds that are too large to have been carried by winds. Even if the seeds had floated across the ocean, they probably would not have remained viable for any length of time in saltwater.

The present-day climates of South America, Africa, India, Australia, and Antarctica range from tropical to polar and are much too diverse to support the type of plants in the *Glossopteris* flora. Wegener therefore reasoned that these continents must once have been joined so that these widely separated localities were all in the same latitudinal climatic belt (Figure 9).

The fossil remains of animals also provide strong evidence for continental drift. One of the best examples is *Mesosaurus*, a freshwater reptile whose fossils are found in Permian-aged rocks in certain regions of Brazil and South Africa and nowhere else in the world (Figure 9). Because the physiologies of freshwater and marine animals are completely different, it is hard to imagine how a freshwater reptile could have swum across the Atlantic Ocean and found a freshwater environment nearly identical to its former habitat. Moreover, if *Mesosaurus* could have swum across the ocean, its fossil remains should be widely dispersed. It is more logical to assume that *Mesosaurus* lived in lakes in what are now adjacent areas of South America and Africa but were then united into a single continent.

Lystrosaurus and *Cynognathus* are both land-dwelling reptiles that lived during the Triassic Period; their fossils are found only on the present-day continental fragments of Gondwana (Figure 9). Because they are both land animals, they certainly could not have swum across the oceans currently separating the Gondwana continents. Therefore, it is logical to assume that the continents must once have been connected. Recent discoveries of dinosaur fossils in Gondwana continents further solidifies the argument that these landmasses were close to each other during the Early Mesozoic Era.

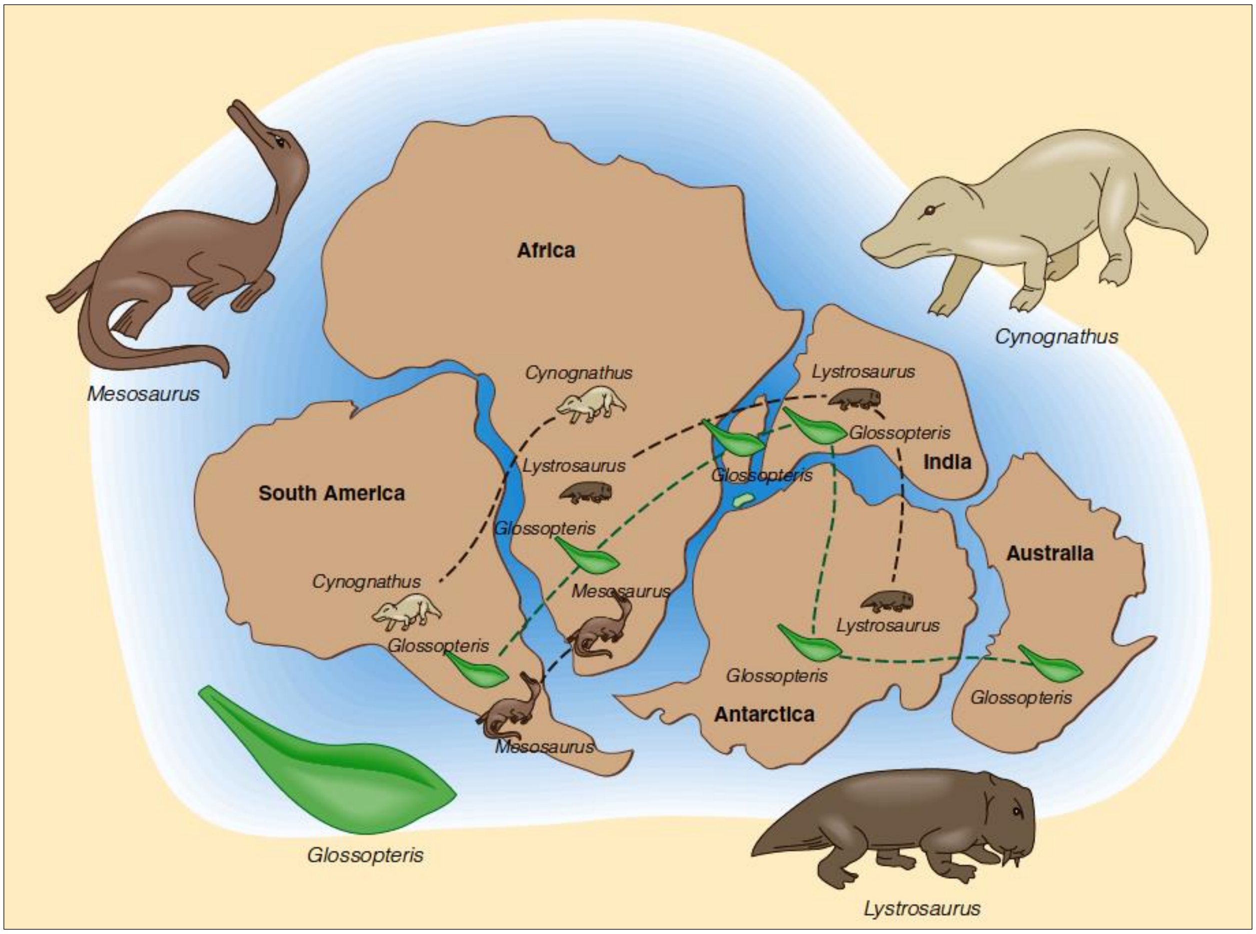


Figure 9 Fossil Evidence Supporting Continental Drift. Some of the plants and animals whose fossils are found today on the widely separated continents of South America, Africa, India, Australia, and Antarctica. During the Late Paleozoic Era, these continents were joined together to form Gondwana, the southern landmass of Pangaea. Plants of the Glossopteris flora are found on all five continents, which today have widely different climates, but during the Pennsylvanian and Permian periods, they were all located in the same general climatic belt. *Mesosaurus* is a freshwater reptile whose fossils are found only in similar nonmarine Permian-age rocks in Brazil and South Africa. *Cynognathus* and *Lystrosaurus* are land reptiles that lived during the Early Triassic Period. Fossils of *Cynognathus* are found in South America and Africa, whereas fossils of *Lystrosaurus* have been recovered from Africa, India, and Antarctica. It is hard to imagine how a freshwater reptile and land-dwelling reptiles could have swum across the wide oceans that presently separate these continents. It is more logical to assume that the continents were at one time connected.

Notwithstanding all of the empirical evidence presented by Wegener and later by du Toit and others, most geologists simply refused to entertain the idea that continents might have moved during the past. The geologists were not necessarily being obstinate about accepting new ideas; rather, they found the evidence for continental drift inadequate and unconvincing. In part, this was because no one could provide a suitable mechanism to explain how continents could move over Earth's surface. Interest in continental drift waned until new evidence from oceanographic research and studies of Earth's magnetic field showed that the present-day ocean basins were not as old as the continents but were geologically young features that resulted from the breakup of Pangaea.

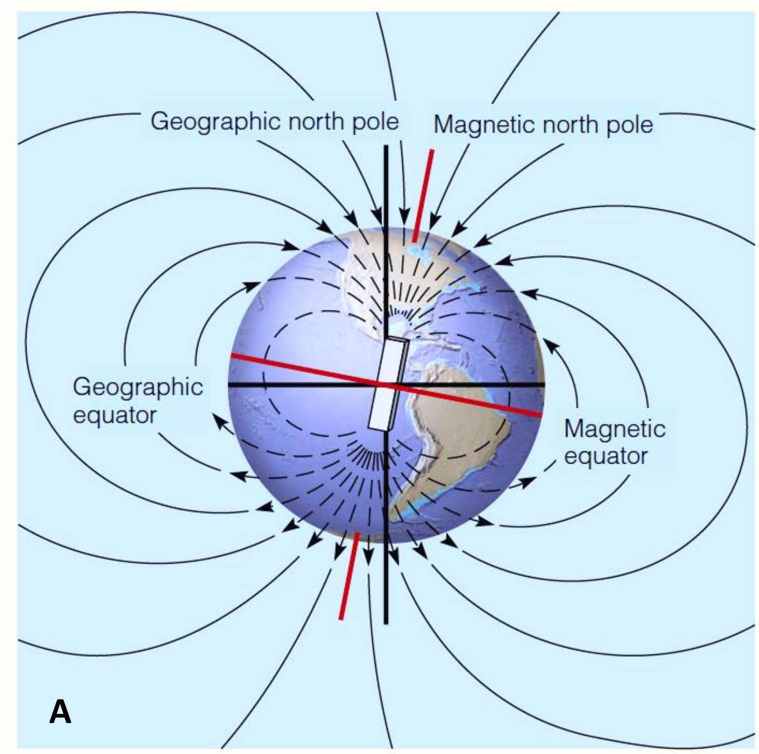
6 Paleomagnetism

What is paleomagnetism?

Interest in continental drift revived during the 1950s as a result of evidence from paleomagnetic studies, a relatively new discipline at the time. Paleomagnetism is the remanent magnetism in ancient rocks recording the direction and intensity of Earth's magnetic field at the time of the rock's formation. Earth can be thought of as a giant dipole magnet in which the magnetic poles essentially coincide with the geographic poles (Figure 10). This arrangement means that the strength of the magnetic field is not constant but varies, being weakest at the equator and strongest at the poles. Earth's magnetic field is thought to result from the different rotation speeds of the outer core and mantle.

What is the Curie point and why is it important?

When magma cools, the magnetic iron-bearing minerals align themselves with Earth's magnetic field, recording both its direction and its strength. The temperature at which iron-bearing minerals gain their magnetization is called the Curie point. As long as the rock is not subsequently heated above the Curie point, it will preserve that remnant magnetism. Thus, an ancient lava flow provides a record of the orientation and strength of Earth's magnetic field at the time the lava flow cooled.



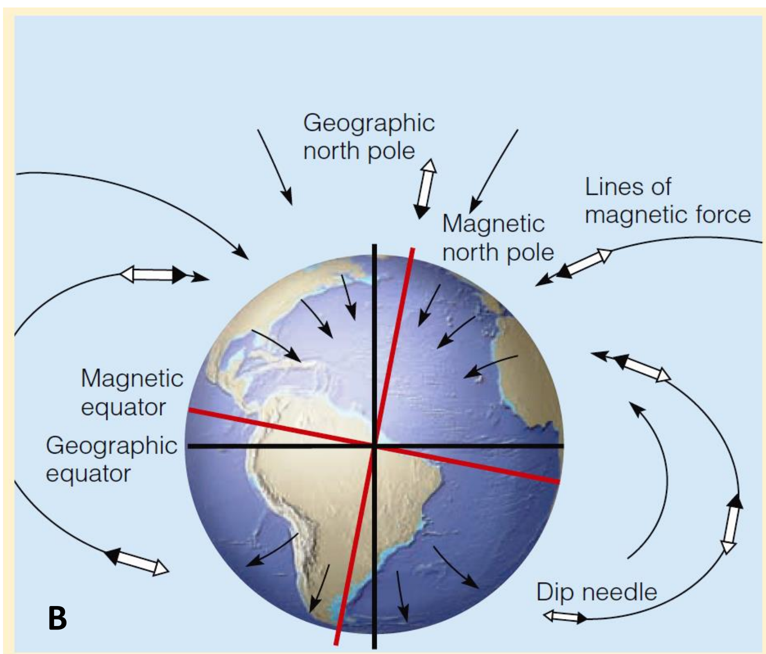


Figure 10 Earth's Magnetic Field. (A) Earth's magnetic field has lines of force like those of a bar magnet. (B) The strength of the magnetic field changes from the magnetic equator to the magnetic poles. This change in strength causes a dip needle (a magnetic needle that is balanced on the tip of a support so that it can freely move vertically) to be parallel to Earth's surface only at the magnetic equator, where the strength of the magnetic north and south poles are equally balanced. Its inclination or dip with respect to Earth's surface increases as it moves toward the magnetic poles, until it is at 90 degrees or perpendicular to Earth's surface at the magnetic poles.

1. Polar Wandering

How can the apparent wandering of the magnetic poles be best explained?

As paleomagnetic research progressed during the 1950s, some unexpected results emerged. When geologists measured the paleomagnetism of geologically recent rocks, they found it was generally consistent with Earth's current magnetic field. The paleomagnetism of ancient rocks, though, showed different orientations. For example, paleomagnetic studies of Silurian lava flows in North America indicated that the north magnetic pole was located in the western Pacific Ocean at that time, whereas the paleomagnetic evidence from Permian lava flows pointed to yet another location in Asia. When plotted on a map, the paleomagnetic readings of numerous lava flows from all ages in North America trace the apparent movement of the magnetic pole (called polar wandering) through time (Figure 11). This paleomagnetic evidence from a single continent could be interpreted in three ways: The continent remained fixed and the north magnetic pole moved; the north magnetic pole stood still and the continent moved; or both the continent and the north magnetic pole moved.

Upon additional analysis, magnetic minerals from European Silurian and Permian lava flows pointed to a different magnetic pole location from those of the same age in North America. Furthermore, analysis of lava flows from all continents indicated that each continent seemingly had its own series of magnetic poles. Does this really mean there were different north magnetic poles for each continent? That would be highly unlikely and difficult to reconcile with the theory accounting for Earth's magnetic field.

The best explanation for such data is that the magnetic poles have remained near their present locations at the geographic north and south poles and the continents have moved. When the continental margins are fitted together so that the paleomagnetic data point to only one magnetic pole, we find, just as Wegener did, that the rock sequences and glacial deposits match and that the fossil evidence is consistent with the reconstructed paleogeography (Figure 12).

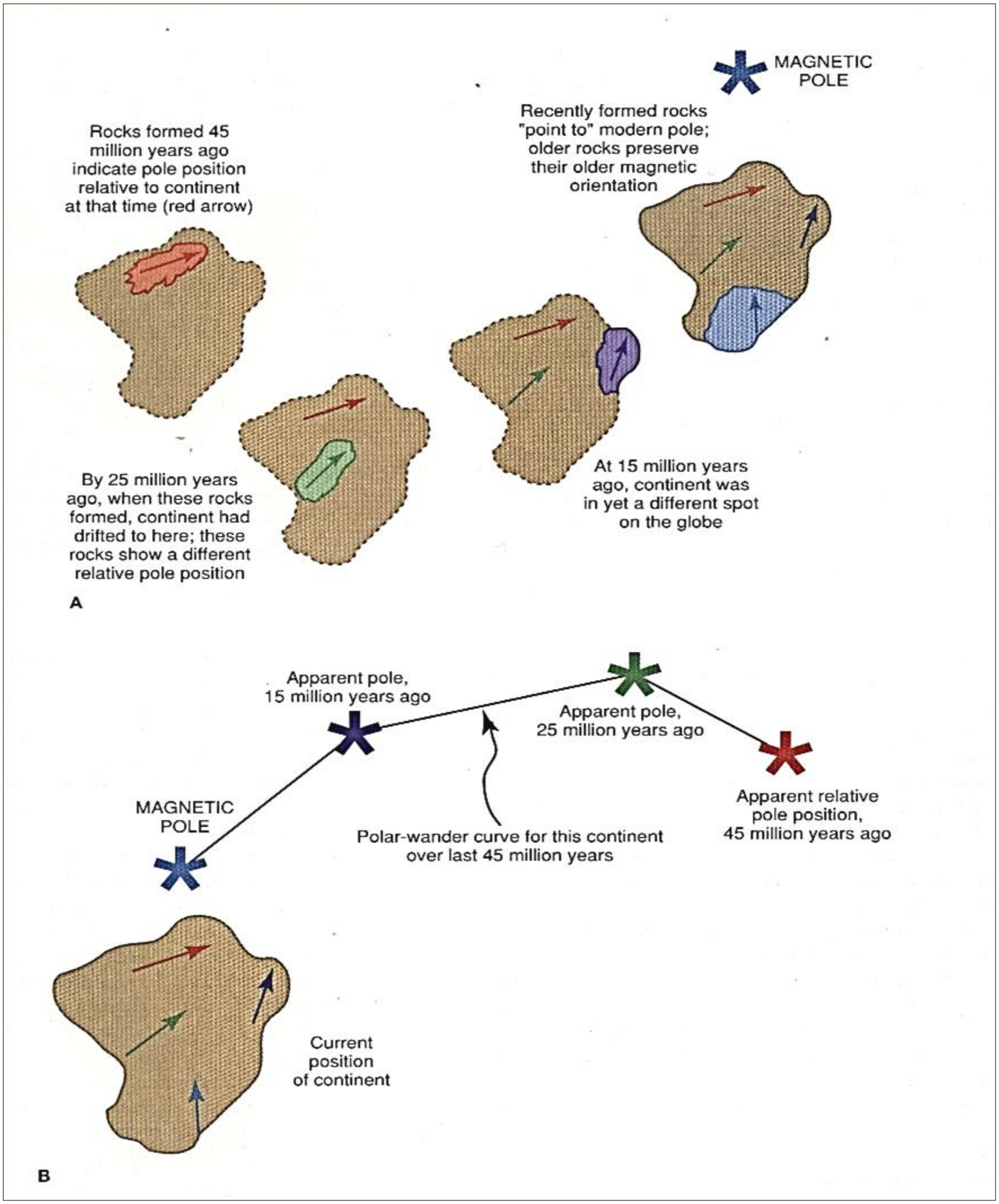


Figure 11 Polar-wander curves actually reflect wandering continents. (A) As rocks crystallize, their magnetic minerals align with the contemporary magnetic field. But continental drift changes the relative position of continent and magnetic pole over time. (B) Assuming a stationary continent, the shifting relative pole positions suggest “polar wander.”

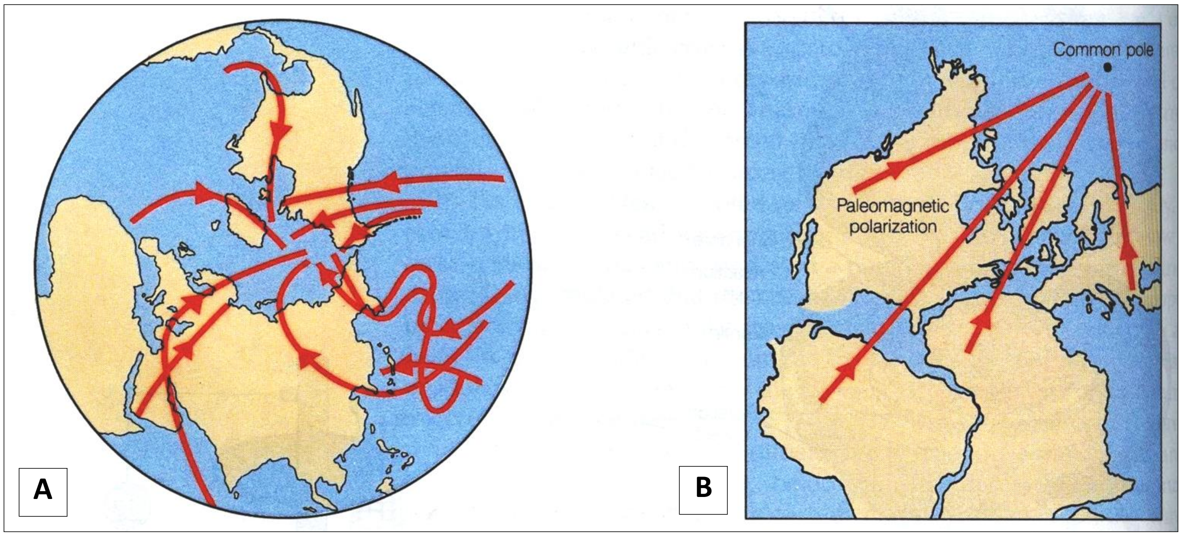


Figure 12 Polar Wandering. (A) The north magnetic pole has different locations for the same time in the past when measured on different continents, indicating multiple north magnetic poles. (B) Because Earth has only one magnetic pole, the paleomagnetic readings for the same time in the past taken on different continents should all point to the same location. The logical explanation for this dilemma is that the magnetic north pole has remained at the same approximate geographic location during the past, and the continents have moved.

2. Magnetic Reversals

What evidence is there that Earth's magnetic field has reversed in the past?

Geologists refer to Earth's present magnetic field as being normal—that is, with the north and south magnetic poles located approximately at the north and south geographic poles. At various times in the geologic past, however, Earth's magnetic field has completely reversed. The existence of such magnetic reversals was discovered by dating and determining the orientation of the remnant magnetism in lava flows on land (Figure 13).

Once magnetic reversals were well established for continental lava flows, magnetic reversals were also discovered in igneous rocks in the oceanic crust as part of the large scale mapping of the ocean basins during the 1960s. Although the cause of magnetic reversals is still uncertain, their occurrence in the geologic record is well documented.

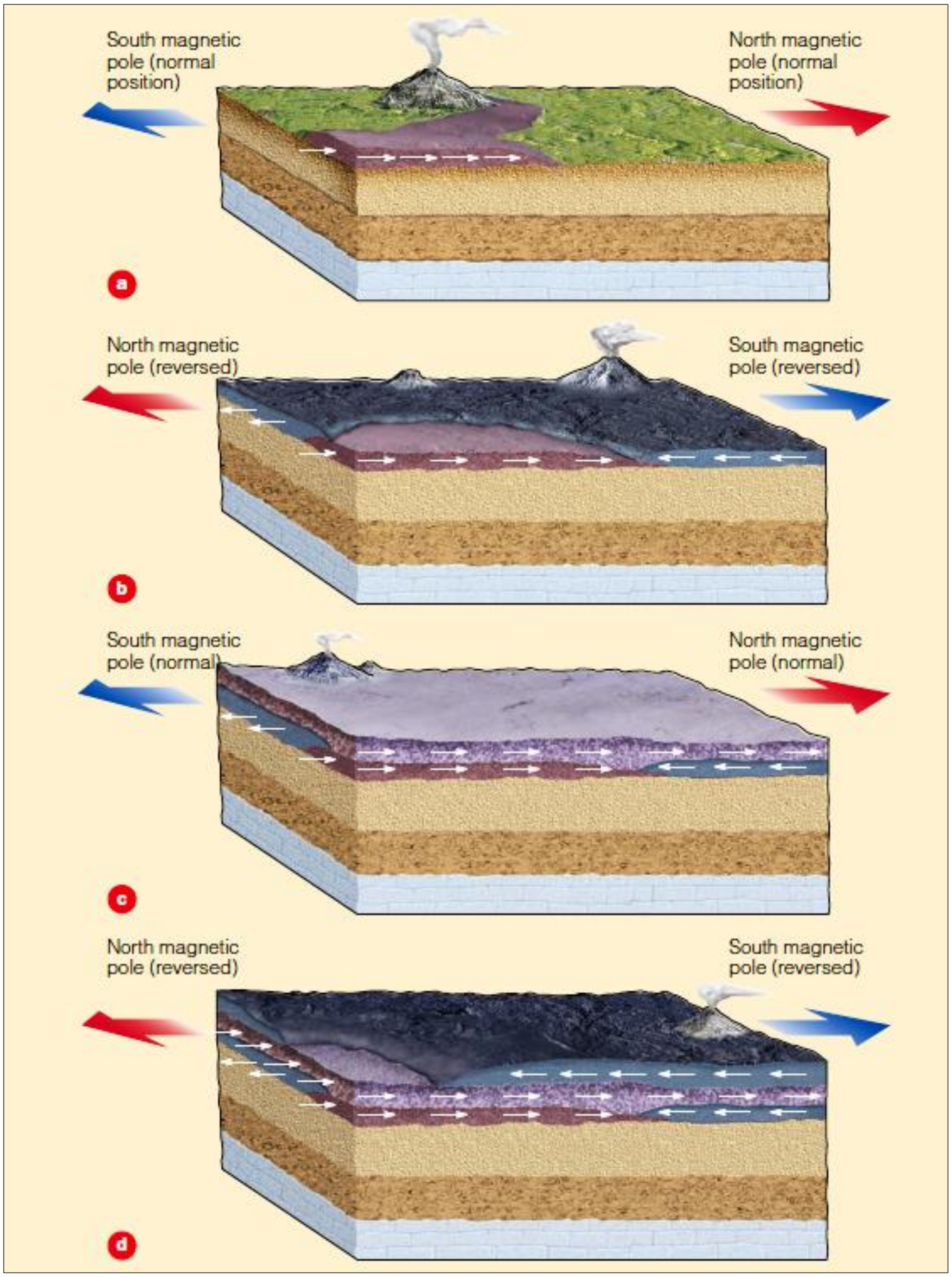


Figure 13 Magnetic Reversals During the time period shown (a–d), volcanic eruptions produced a succession of overlapping lava flows. At the time of these volcanic eruptions, Earth's magnetic field completely reversed; that is, the magnetic north pole moved to the geographic south pole, and the magnetic south pole moved to the geographic north pole. Thus, the end of the needle on a magnetic compass that today would point to the North Pole would point to the South Pole if the magnetic field should again suddenly reverse. We know that Earth's magnetic field has reversed numerous times in the past because when lava flows cool below the Curie point, magnetic minerals within the flow orient themselves parallel to the magnetic field at the time. They thus record whether the magnetic field was normal or reversed at that time. The white arrows in this diagram show the direction of the north magnetic pole for each individual lava flow, thus confirming that Earth's magnetic field has reversed in the past.

7 Seafloor Spreading

What is the theory of seafloor spreading, and how does it validate continental drift?

A renewed interest in oceanographic research led to extensive mapping of the ocean basins during the 1960s. Such mapping revealed an oceanic ridge system more than 65,000 km long, constituting the most extensive mountain range in the world. Perhaps the best-known part of the ridge system is the Mid-Atlantic Ridge, which divides the Atlantic Ocean basin into two nearly equal parts.

As a result of the oceanographic research conducted during the 1950s, Harry Hess of Princeton University proposed the theory of seafloor spreading in 1962 to account for continental movement. He suggested that continents do not move across oceanic crust, but rather the continents and oceanic crust move together. Thus, the theory of seafloor spreading answered a major objection of the opponents of continental drift—namely, how could continents move through oceanic crust? In fact, the continents moved with the oceanic crust as part of a lithospheric system.

Hess postulated that the seafloor separates at oceanic ridges, where new crust is formed by upwelling magma. As the magma cools, the newly formed oceanic crust moves laterally away from the ridge.

As a mechanism to drive this system, Hess revived the idea (proposed in the 1930s and 1940s by Arthur Holmes and others) of thermal convection cells in the mantle; that is, hot magma rises from the mantle, intrudes along fractures defining oceanic ridges, and thus forms new crust. Cold crust is subducted back into the mantle at oceanic trenches, where it is heated and recycled, thus completing a thermal convection cell (Figure 14).

Although geologists do not universally accept the idea of thermal convection cells as a driving mechanism for plate movement, most accept that plates are created at oceanic ridges and destroyed at deep-sea trenches, regardless of the driving mechanism involved.

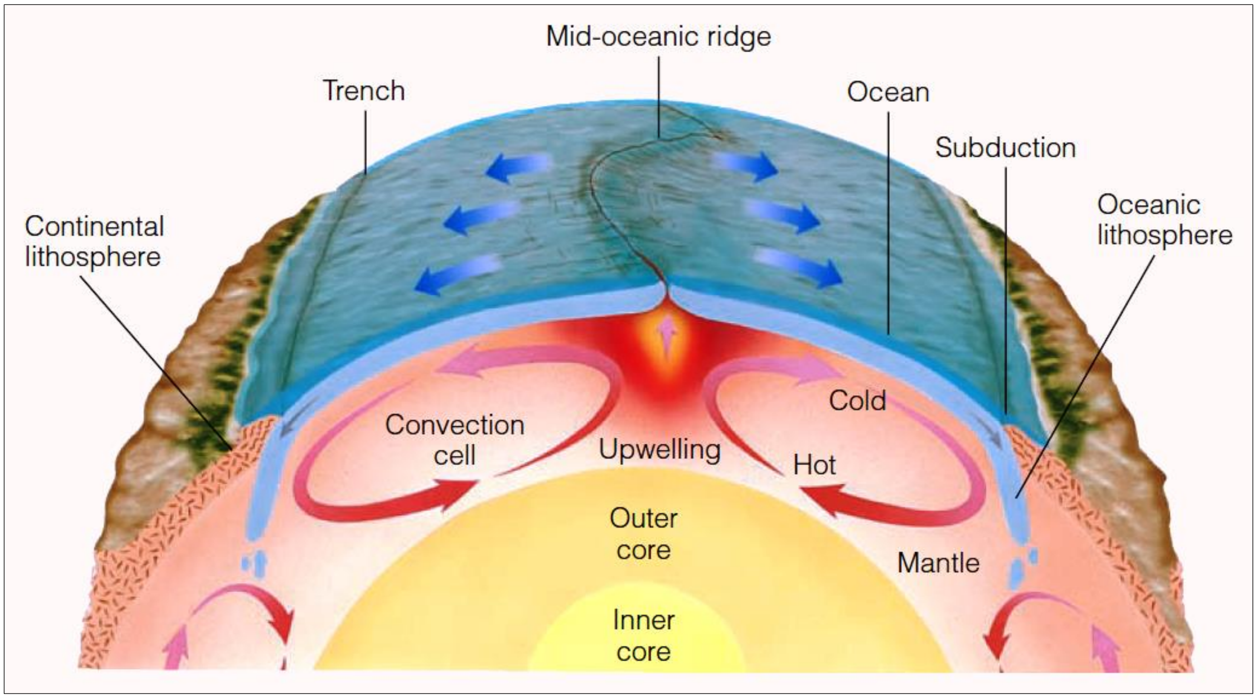


Figure 14 Movement of Earth's Plates. Earth's plates are thought to move partially as a result of underlying mantle convection cells in which warm material from deep within Earth rises toward the surface, cools, and then upon losing heat descends back into the interior, as shown in this diagrammatic cross section.

8 Evidence for Seafloor Spreading Theory

How was the theory of seafloor spreading confirmed?

1. Paleomagnetic Data

Magnetic surveys of the oceanic crust revealed striped magnetic anomalies (deviations from the average strength of Earth's magnetic field) in the rocks that are both parallel to and symmetric around the oceanic ridges (Figure 15). Furthermore, the pattern of oceanic magnetic anomalies matches the pattern of magnetic reversals already known from studies of continental lava flows (Figure 13). When magma wells up and cools along a ridge summit, it records Earth's magnetic field at that time as either normal or reversed.

As new crust forms at the summit, the previously formed crust moves laterally away from the ridge. These magnetic stripes represent times of normal and reversed polarity at oceanic ridges (where upwelling magma forms new oceanic crust), conclusively confirming Hess's theory of seafloor spreading.

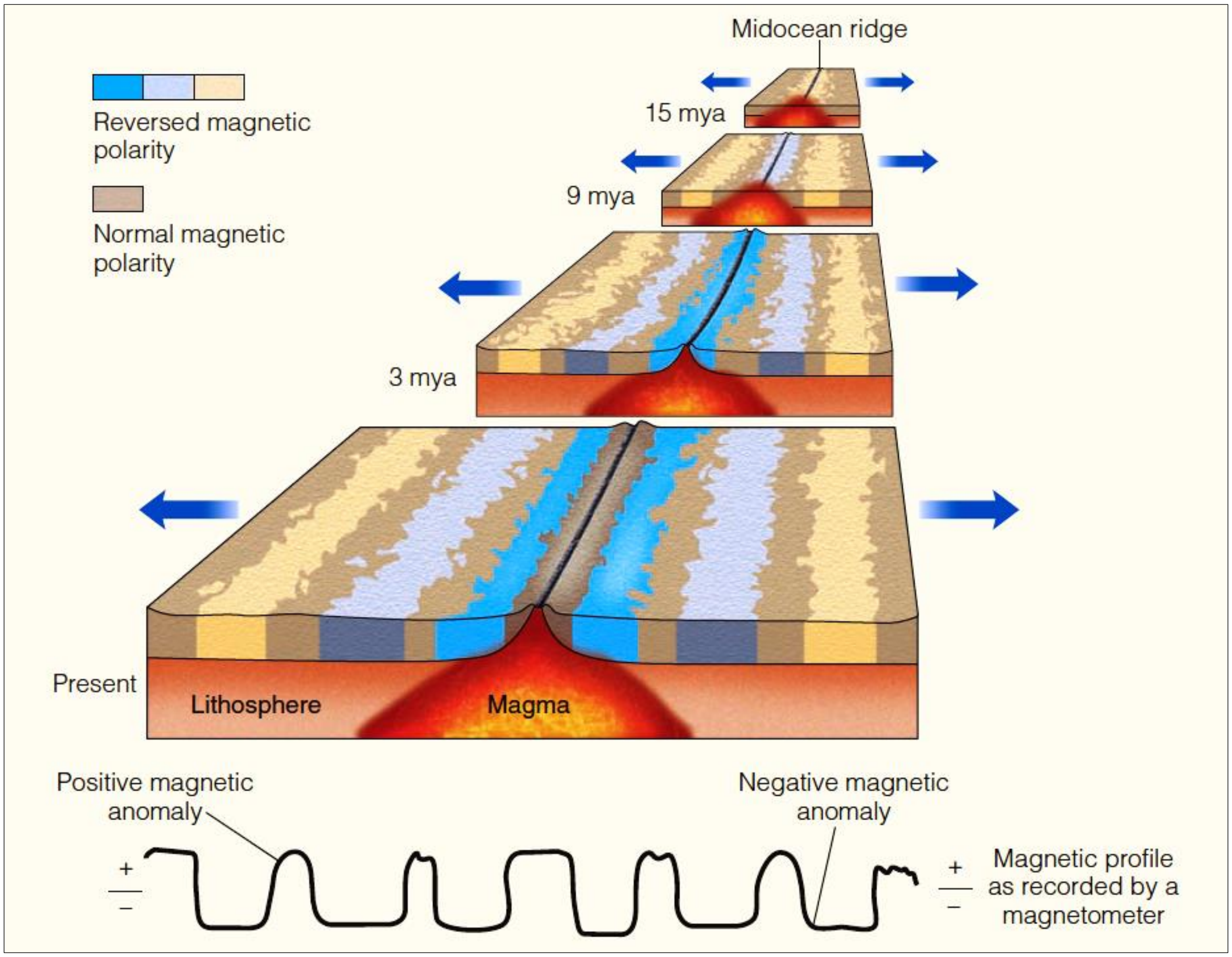


Figure 15 Magnetic Anomalies and Seafloor Spreading. The sequence of magnetic anomalies preserved within the oceanic crust is both parallel to and symmetric around oceanic ridges. Basaltic lava intruding into an oceanic ridge today and spreading laterally away from the ridge records Earth's current magnetic field or polarity (considered by convention to be normal). Basaltic intrusions 3, 9, and 15 million years ago record Earth's reversed magnetic field at that time. This schematic diagram shows how the solidified basalt moves away from the oceanic ridge (or spreading center), carrying with it the magnetic anomalies that are preserved in the oceanic crust. Magnetic anomalies are magnetic readings that are either higher (positive magnetic anomalies) or lower (negative magnetic anomalies) than Earth's current magnetic field strength. The magnetic anomalies are recorded by a magnetometer, which measures the strength of the magnetic field.

The seafloor spreading theory also confirms that ocean basins are geologically young features whose openings and closings are partially responsible for continental movement (Figure 16). Radiometric dating reveals that the oldest oceanic crust is somewhat less than 180 million years old, whereas the oldest continental crust is 3.96 billion years old.

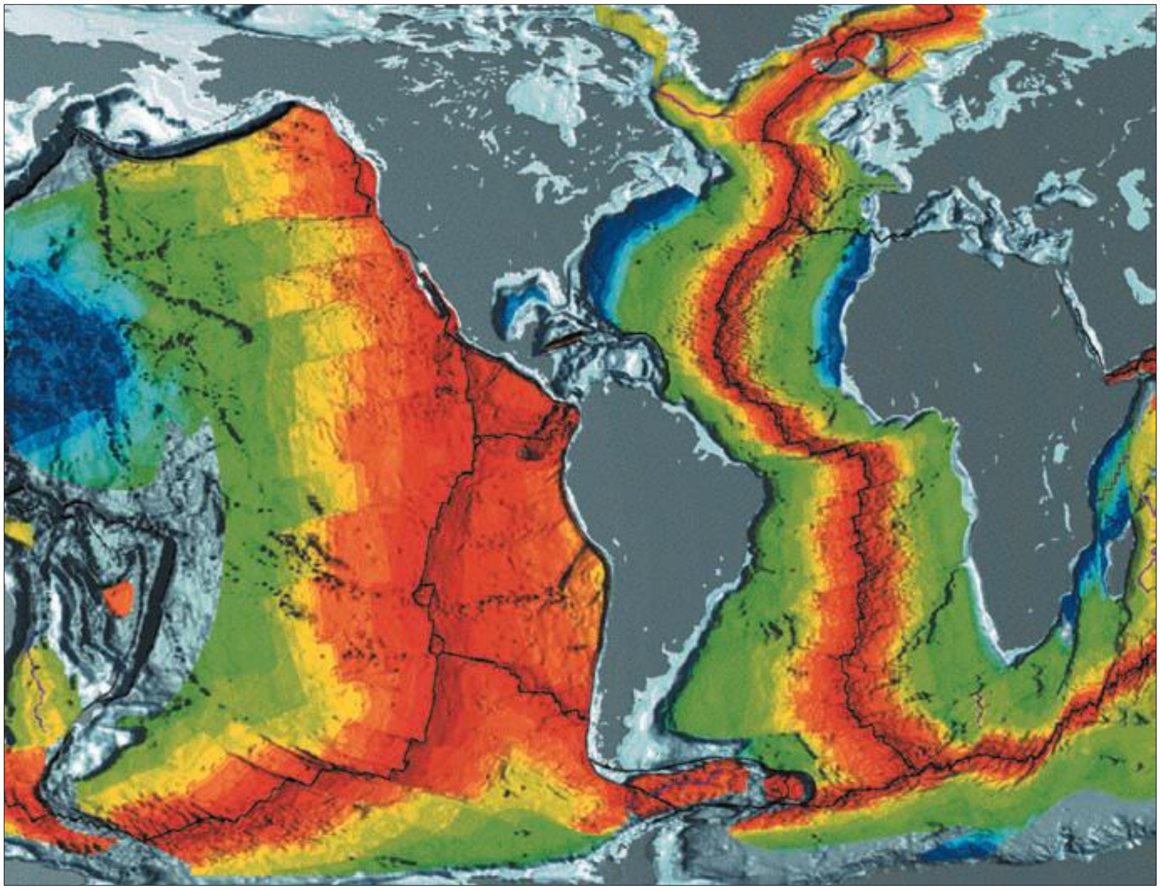


Figure 16 Age of the World's Ocean Basins. The age of the world's ocean basins have been determined from magnetic anomalies preserved in oceanic crust. The red colors adjacent to the oceanic ridges are the youngest oceanic crust. Moving laterally away from the ridges, the red colors grade to yellow at 48 million years, to green at 68 million years ago, and to dark blue some 155 million years ago. The darkest blue color is adjacent to the continental margins and is just somewhat less than 180 million years old. How does the age of the oceanic crust confirm the seafloor spreading theory? Based on magnetic anomalies, the age of the oceanic crust gets progressively older away from the oceanic ridges where it is being formed. This means it is moving away from the oceanic ridges; that is, the seafloor is spreading.

2. Deep-Sea Drilling Project Results

For many geologists, the paleomagnetic data amassed in support of continental drift and seafloor spreading were convincing. Results from the Deep-Sea Drilling Projet confirmed the interpretations made from earlier paleomagnetic studies. Cores of deep-sea sediments and seismic profiles obtained by the Glomar Challenger and other research vessels have provided much of the data that support the seafloor spreading theory.

According to this theory, oceanic crust is continuously forming at mid-oceanic ridges, moves away from these ridges by seafloor spreading, and is consumed at subduction zones. If this is the case, then oceanic crust should be youngest at the ridges and become progressively older with increasing distance away from them. Moreover, the age of the oceanic crust should be symmetrically distributed about the ridges. As we have just noted, paleomagnetic data confirm these statements. Furthermore, fossils from sediments overlying the oceanic crust and radiometric dating of rocks found on oceanic islands both substantiate this predicted age distribution.

Sediments in the open ocean accumulate, on average, at a rate of less than 0.3 cm in 1000 years. If the ocean basins were as old as the continents, we would expect deep-sea sediments to be several kilometers thick. However, data from numerous drill holes indicate that deep-sea sediments are at most only a few hundred meters thick and are thin or absent at oceanic ridges. Their near-absence at the ridges should come as no surprise because these are the areas where new crust is continuously produced by volcanism and seafloor spreading. Accordingly, sediments have had little time to accumulate at or very close to spreading ridges where the oceanic crust is young, but their thickness increases with distance away from the ridges (Figure 17).

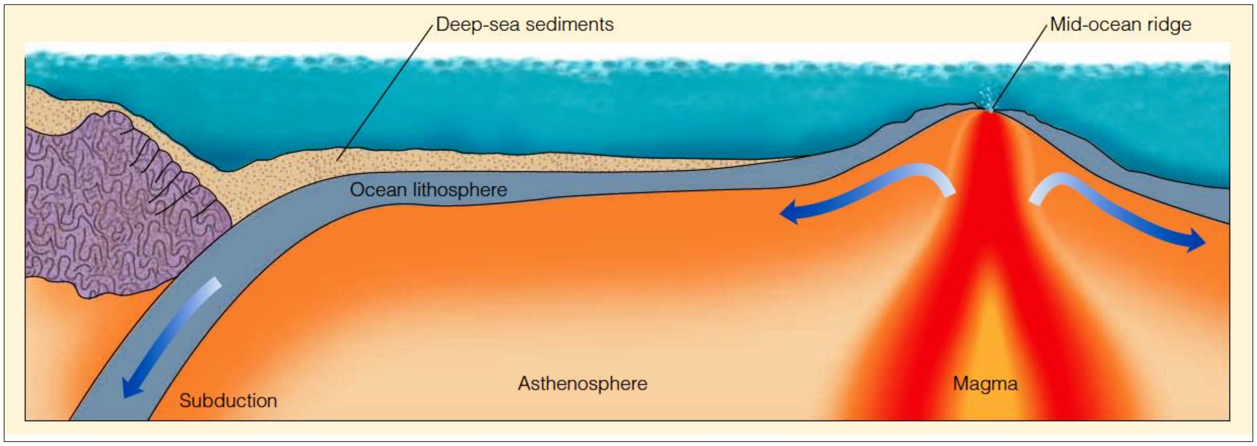


Figure 17 Deep-Sea Sediments and Seafloor Spreading. The total thickness of deep-sea sediments increases away from oceanic ridges. This is because oceanic crust becomes older away from oceanic ridges, and there has been more time for sediment to accumulate.

9 Plate Tectonics: A Unifying Theory

What are the main tenets of plate tectonic theory?

Plate tectonic theory is based on a simple model of Earth. The rigid lithosphere, composed of both oceanic and continental crust as well as the underlying upper mantle, consists of many variable-sized pieces called plates (Figures 18). The plates vary in thickness; those composed of upper mantle and continental crust are as much as 250 km thick, whereas those of upper mantle and oceanic crust are up to 100 km thick.

The lithosphere overlies the hotter and weaker semiplastic asthenosphere. It is thought that movement resulting from some type of heat-transfer system within the asthenosphere causes the overlying plates to move. As plates move over the asthenosphere, they separate, mostly at oceanic ridges; in other areas, such as at oceanic trenches, they collide and are subducted back into the mantle.

An easy way to visualize plate movement is to think of a conveyor belt moving luggage from an airplane's cargo hold to a baggage cart. The conveyor belt represents convection currents within the mantle, and the luggage represents Earth's lithospheric plates. The luggage is moved along by the conveyor belt until it is dumped into the baggage cart in the same way plates are moved by convection cells until they are subducted into Earth's interior. Although this analogy allows you to visualize how the mechanism of plate movement takes place, remember that this analogy is limited.

The major limitation is that, unlike the luggage, plates consist of continental and oceanic crust, which have different densities; only oceanic crust, because it is denser than continental crust, is subducted into Earth's interior.

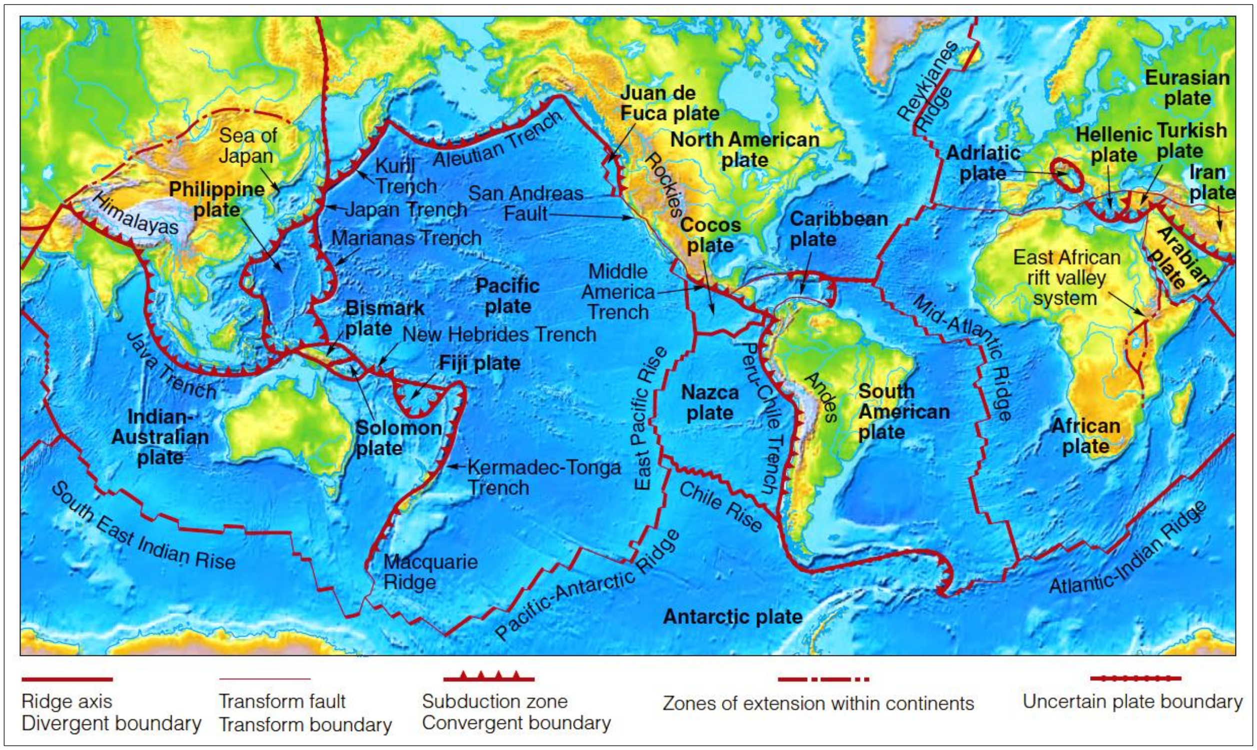


Figure 18 Earth's Plates. Earth's lithosphere is divided into rigid plates of various sizes that move over the asthenosphere.

Why is plate tectonics a unifying theory of geology?

A revolutionary concept when it was proposed in the 1960s, plate tectonic theory has had significant and far-reaching consequences in all fields of geology because of the following reasons:

1. Volcanic eruptions, mountain building, earthquakes, and tsunami are the result of interactions between plates.
2. Global weather patterns and oceanic currents are caused, in part, by the configuration of the continents and ocean basins. The interactions between moving plates determine the locations of continents, ocean basins, and mountain systems, which in turn affect atmospheric and oceanic circulation patterns that ultimately determine global climate.
3. Plate movements have also profoundly influenced the geographic distribution, evolution, and extinction of plants and animals.
4. The formation and distribution of many natural resources, such as metal ores, are related to plate movement and thus have an impact on the economic well-being and political decisions of nations.
5. Plate tectonic theory ties together many aspects of the geology that you have studied.

10 The Three Types of Plate Boundaries

What are the three types of plate boundaries?

Because it appears that plate tectonics have operated since at least the Proterozoic Eon, it is important that we understand how plates move and interact with each other and how ancient plate boundaries are recognized. After all, the movement of plates has profoundly affected the geologic and biologic history of this planet.

Geologists recognize three major types of plate boundaries: divergent, convergent, and transform (Figure 19 and Table 1). Along these boundaries new plates are formed, are consumed, or slide laterally past each other. Interaction of plates at their boundaries accounts for most of Earth's volcanic eruptions and earthquakes as well as the formation and evolution of its mountain systems.

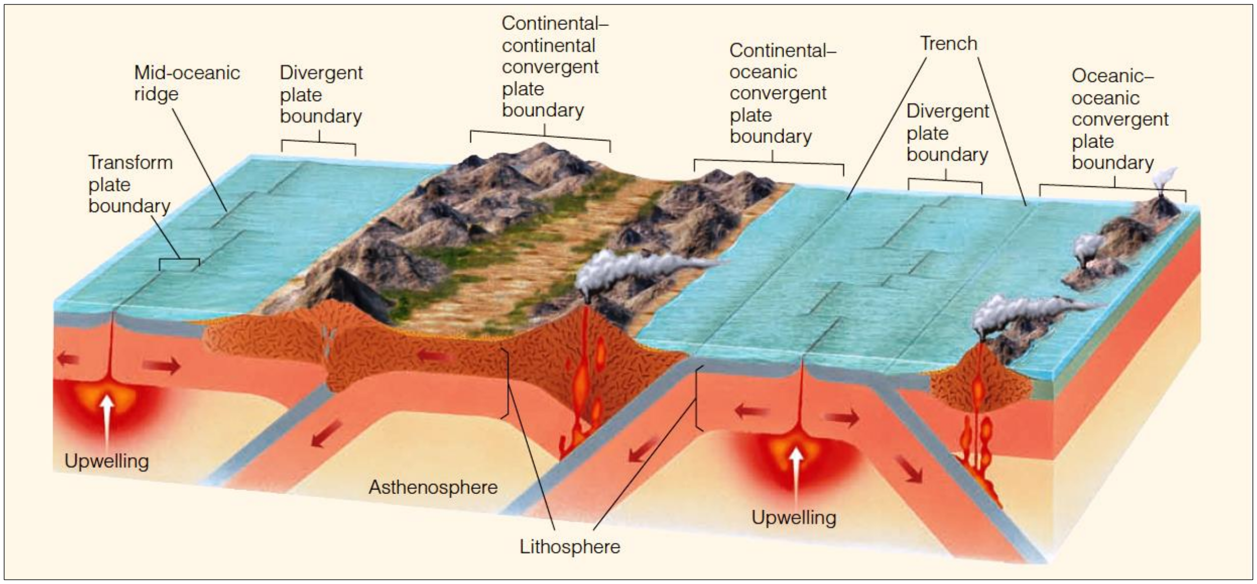


Figure 19 Relationship Between Lithosphere, Asthenosphere, and Plate Boundaries. An idealized cross section illustrating the relationship between the lithosphere and the underlying asthenosphere and the three principal types of plate boundaries: divergent, convergent, and transform.

Table 1 Types of plate boundaries.

Type	Example	Landforms	Volcanism
Divergent			
Oceanic	Mid-Atlantic Ridge	Mid-oceanic ridge with axial rift valley	Basalt
Continental	East African Rift Valley	Rift valley	Basalt and rhyolite, no andesite
Convergent			
Oceanic–oceanic	Aleutian Islands	Volcanic island arc, offshore oceanic trench	Andesite
Oceanic–continental	Andes	Offshore oceanic trench, volcanic mountain chain, mountain belt	Andesite
Continental–continental	Himalayas	Mountain belt	Minor
Transform	San Andreas fault	Fault valley	Minor

1. Divergent plate boundaries

Divergent plate boundaries or spreading ridges occur where plates are separating and new oceanic lithosphere is forming. Divergent boundaries are places where the crust is extended, thinned, and fractured as magma, derived from the partial melting of the mantle, rises to the surface. The magma is almost entirely basaltic and intrudes into vertical fractures to form dikes and pillow lava flows. As successive injections of magma cool and solidify, they form new oceanic crust and record the intensity and orientation of Earth's magnetic field (see Figure 15). Divergent boundaries most commonly occur along the crests of oceanic ridges—the Mid-Atlantic Ridge, for example. Oceanic ridges are thus characterized by rugged topography with high relief resulting from the displacement of rocks along large fractures, shallow-depth earthquakes, high heat flow, and basaltic flows or pillow lavas.

Divergent boundaries are also present under continents during the early stages of continental breakup. When magma wells up beneath a continent, the crust is initially elevated, stretched, and thinned, producing fractures, faults, rift valleys, and volcanic activity (Figure 20). As magma intrudes into faults and fractures, it solidifies or flows out onto the surface as lava flows; the latter often covering the rift valley floor (Figure 20b). The East African Rift Valley is an excellent example of continental breakup at this stage (Figure 21a).

As spreading proceeds, some rift valleys continue to lengthen and deepen until the continental crust eventually breaks and a narrow linear sea is formed, separating two continental blocks (Figure 20c). The Red Sea separating the Arabian Peninsula from Africa (Figure 216) and the Gulf of California, which separates Baja California from mainland Mexico, are good examples of this more advanced stage of rifting.

As a newly created narrow sea continues to enlarge, it may eventually become an expansive ocean basin such as the Atlantic Ocean basin is today, separating North and South America from Europe and Africa by thousands of kilometers (Figure 20d). The Mid-Atlantic Ridge is the boundary between these diverging plates; the American plates are moving westward, and the Eurasian and African plates are moving eastward.

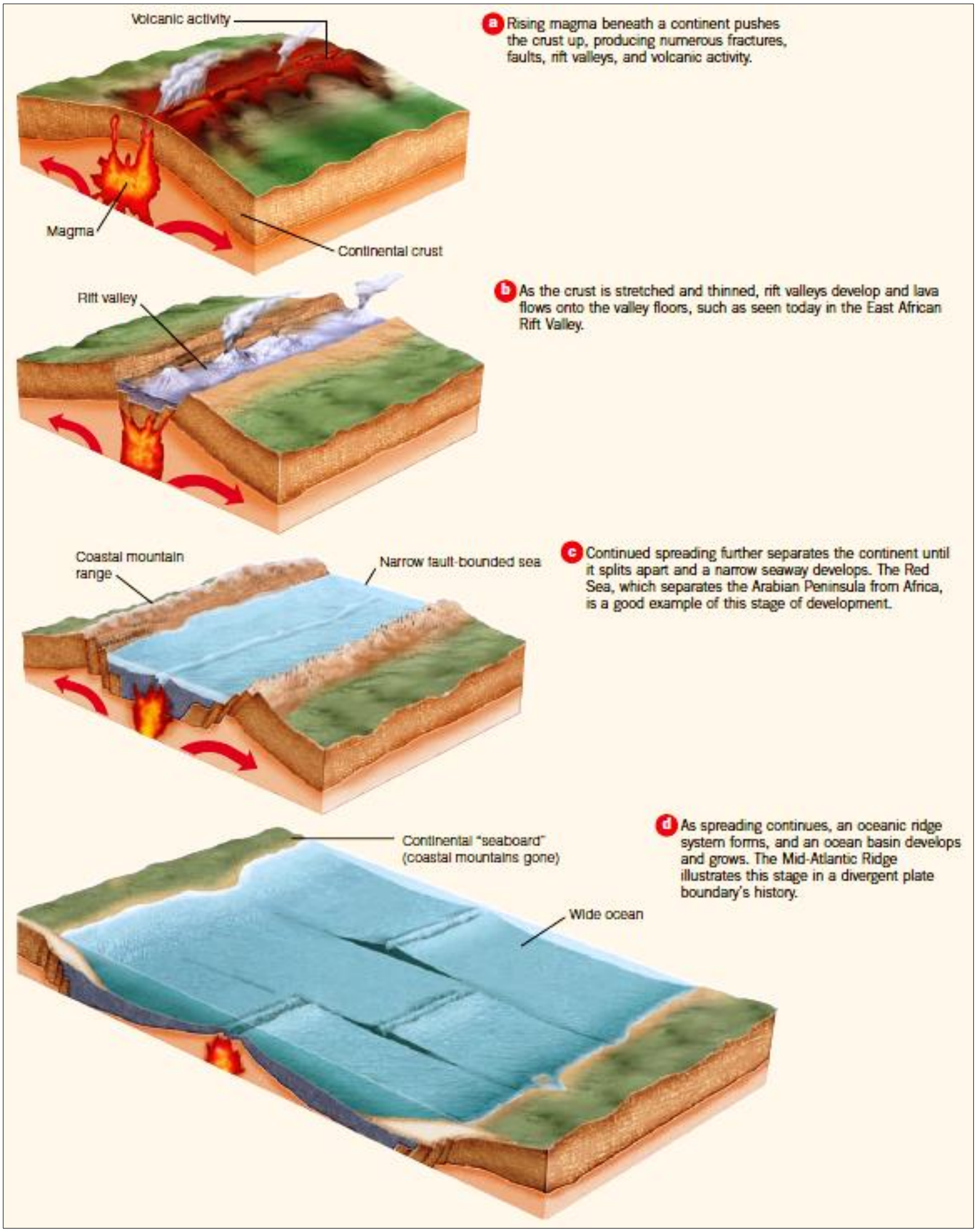


Figure 20 History of a Divergent Plate Boundary.

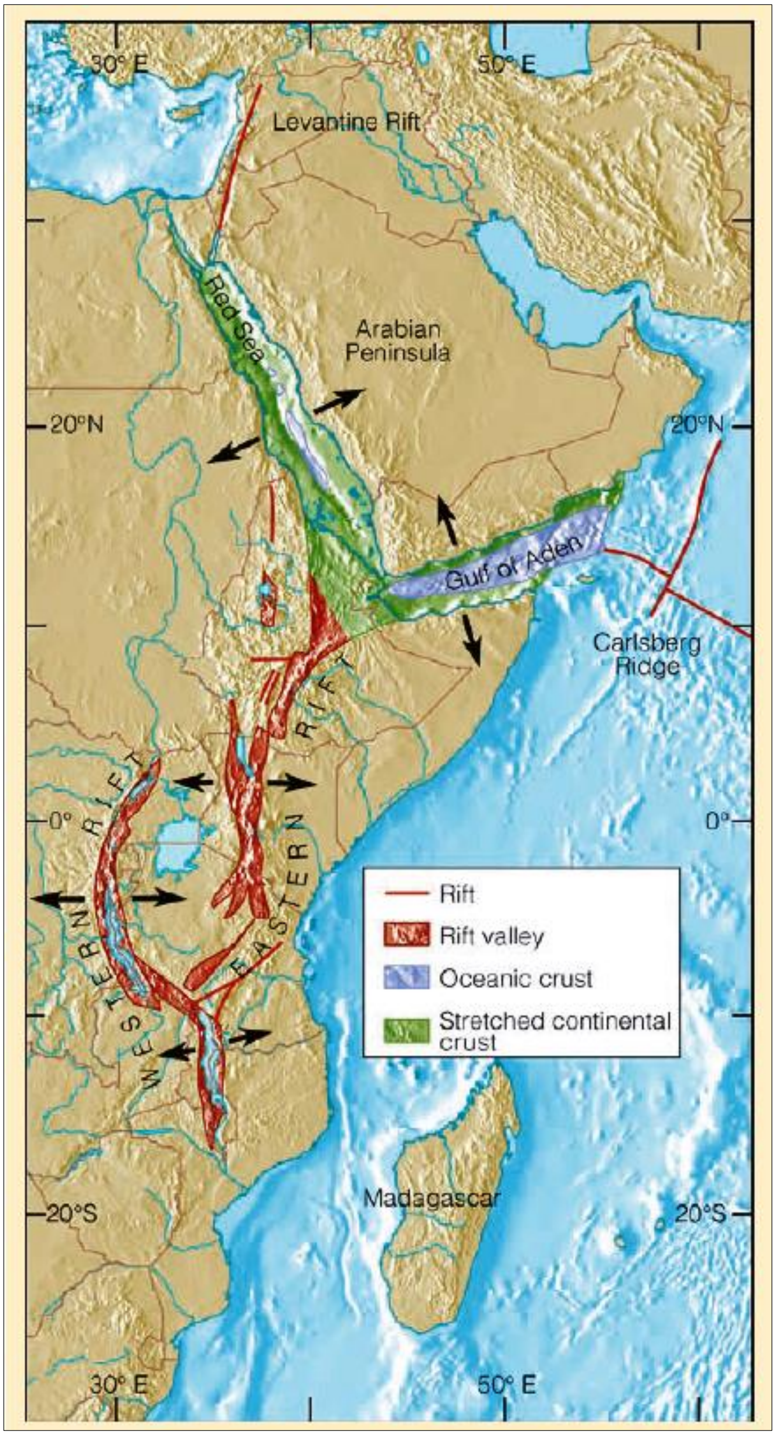


Figure 21 East African Rift Valley and the Red Sea—Present-Day Examples of Divergent Plate Boundaries. The East African Rift Valley and the Red Sea represent different stages in the history of a divergent plate boundary. The East African Rift Valley is being formed by the separation of eastern Africa from the rest of the continent along a divergent plate boundary.

What features in the geologic record indicate ancient rifting?

Associated with regions of continental rifting are faults, dikes (vertical intrusive igneous bodies), sills (horizontal intrusive igneous bodies), lava flows, and thick sedimentary sequences within rift valleys, all features that are preserved in the geologic record. The Triassic fault basins of the eastern United States are a good example of ancient continental rifting. These fault basins mark the zone of rifting that occurred when North America split apart from Africa. The basins contain thousands of meters of continental sediment and are riddled with dikes and sills.

Pillow lavas, in association with deep-sea sediment, are also evidence of ancient rifting. The presence of pillow lavas marks the formation of a spreading ridge in a narrow linear sea. A narrow linear sea forms when the continental crust in the rift valley finally breaks apart, and the area is flooded by seawater. Magma, intruding into the sea along this newly formed spreading ridge, solidifies as pillow lavas, which are preserved in the geologic record, along with the sediment being deposited on them.

2. Convergent plate boundaries

Whereas new crust forms at divergent plate boundaries, older crust must be destroyed and recycled in order for the entire surface area of Earth to remain the same. Otherwise, we would have an expanding Earth. Such plate destruction takes place at convergent plate boundaries, where two plates collide and the leading edge of one plate is subducted beneath the margin of the other plate and eventually is incorporated into the asthenosphere.

Most of these subducted plates (slabs) dip from oceanic trenches beneath adjacent island arcs or continents, marking the surface of slippage between the converging plates. Deformation, volcanism, mountain building, metamorphism, earthquake activity, and deposits of valuable mineral ores characterize convergent boundaries. Three types of convergent plate boundaries are recognized: oceanic–oceanic, oceanic–continental, and continental–continental (Figure 22).

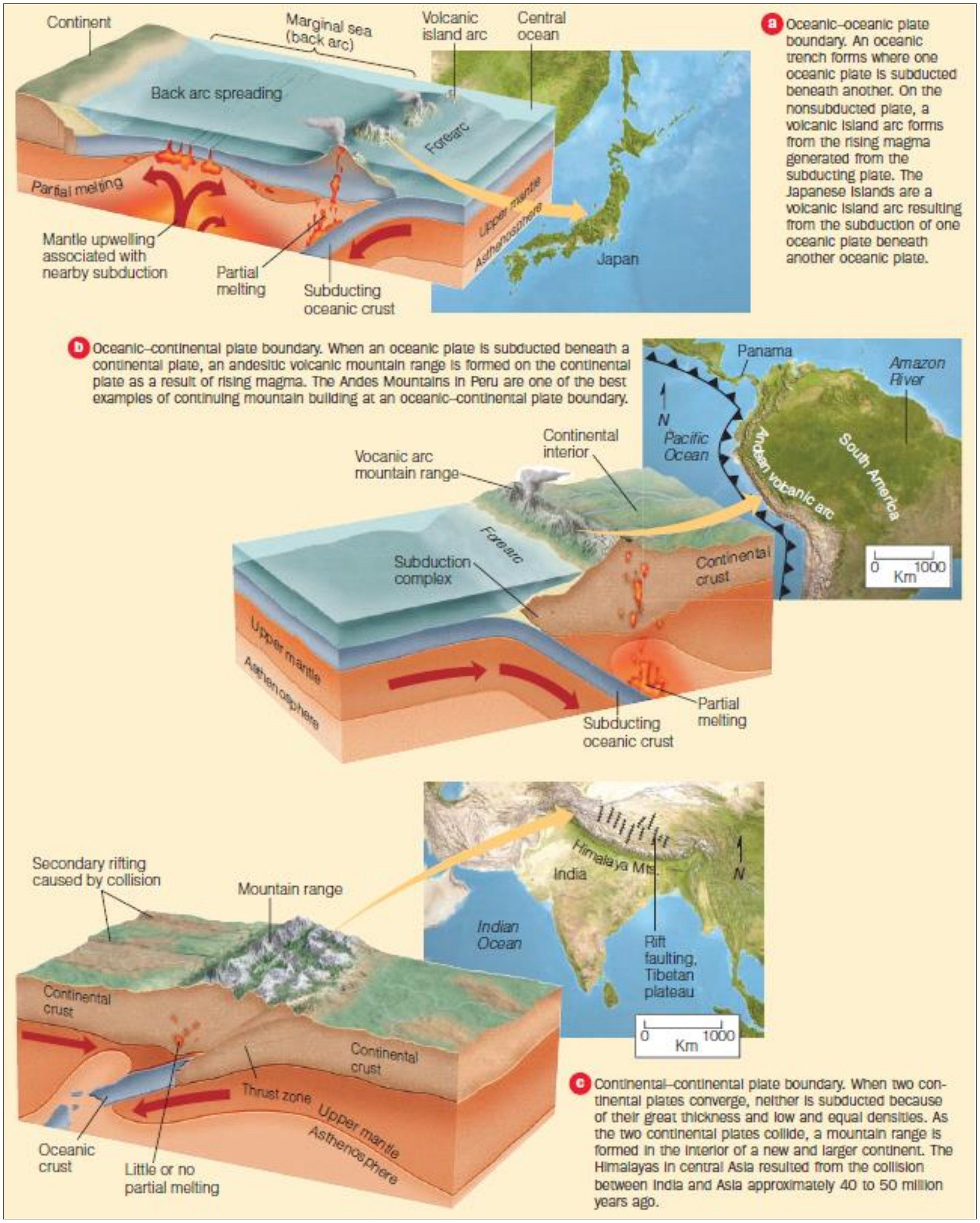


Figure 22 Three Types of Convergent Plate Boundaries.

Oceanic–Oceanic Boundaries

When two oceanic plates converge, one is subducted beneath the other along an oceanic–oceanic plate boundary (Figure 22a). The subducting plate bends downward to form the outer wall of an oceanic trench. A subduction complex, composed of wedge-shaped slices of highly folded and faulted marine sediments and oceanic lithosphere scraped off the descending plate, forms along the inner wall of the oceanic trench. As the subducting plate descends into the mantle, it is heated and partially melted, generating magma, commonly of andesitic composition. This rises to the surface of the nonsubducted plate to form a curved chain of volcanoes called a volcanic island arc (any plane intersecting a sphere makes an arc). This arc is nearly parallel to the oceanic trench and is separated from it by a distance of up to several hundred kilometers—the distance depending on the angle of dip of the subducting plate (Figure 22a).

In those areas where the rate of subduction is faster than the forward movement of the overriding plate, the lithosphere on the landward side of the volcanic island arc may be subjected to tensional stress and stretched and thinned, resulting in the formation of a back-arc basin. This back-arc basin may grow by spreading if magma breaks through the thin crust and forms new oceanic crust (Figure 22a). A good example of a back-arc basin associated with an oceanic–oceanic plate boundary is the Sea of Japan between the Asian continent and the islands of Japan.

Most present-day active volcanic island arcs are in the Pacific Ocean basin and include the Aleutian Islands, the Kermadec–Tonga arc, and the Japanese (Figure 22a) and Philippine Islands. The Scotia and Antillean (Caribbean) island arcs are in the Atlantic Ocean basin.

Oceanic–Continental Boundaries

When an oceanic and a continental plate converge, the denser oceanic plate is subducted under the continental plate along an oceanic–continental plate boundary (Figure 22b). Just as at oceanic–oceanic plate boundaries, the descending oceanic plate forms the outer wall of an oceanic trench.

The magma generated by subduction rises beneath the continent and either crystallizes as large intrusive igneous bodies (called plutons) before reaching the surface or erupts at the surface to produce a chain of andesitic volcanoes (also called a volcanic arc). An excellent example of an oceanic–continental plate boundary is the Pacific coast of South

America, where the oceanic Nazca plate is currently being subducted beneath South America (Figure 22b). The Peru–Chile Trench marks the site of subduction, and the Andes Mountains are the resulting volcanic mountain chain on the nonsubducting plate.

Continental–Continental Boundaries

Two continents approaching each other are initially separated by an ocean floor that is being subducted under one continent. The edge of that continent displays the features characteristic of oceanic–continental convergence. As the ocean floor continues to be subducted, the two continents come closer together until they eventually collide. Because continental lithosphere, which consists of continental crust and the upper mantle, is less dense than oceanic lithosphere (oceanic crust and upper mantle), it cannot sink into the asthenosphere. Although one continent may partly slide under the other, it cannot be pulled or pushed down into a subduction zone (Figure 22c).

When two continents collide, they are welded together along a zone marking the former site of subduction. At this continental–continental plate boundary, an interior mountain belt is formed consisting of deformed sediments and sedimentary rocks, igneous intrusions, metamorphic rocks, and fragments of oceanic crust. In addition, the entire region is subjected to numerous earthquakes. The Himalayas in central Asia, the world's youngest and highest mountain system, resulted from the collision between India and Asia that began 40 to 50 million years ago and is still continuing (Figure 22c).

How can ancient subduction zones be recognized in the geologic record?

Igneous rocks provide one clue to ancient subduction zones. The magma erupted at the surface, forming island arc volcanoes and continental volcanoes, is of andesitic composition. Another clue is the zone of intensely deformed rocks between the deep-sea trench where subduction is taking place and the area of igneous activity. Here, sediments and submarine rocks are folded, faulted, and metamorphosed into a chaotic mixture of rocks called a *mélange*.

During subduction, pieces of oceanic lithosphere are sometimes incorporated into the melange and accreted onto the edge of the continent. Such slices of oceanic crust and upper mantle are called *ophiolites* (Figure 23). They consist of a layer of deep-sea sediments, oceanic crust, and upper mantle.

1. Deep-sea sediments include graywackes (poorly sorted sandstones containing abundant feldspar minerals and rock fragments, usually in a clay-rich matrix), black shales, and cherts.
2. Oceanic crust consists of pillow lavas, a sheeted dike complex, and massive and layered gabbro (a dark intrusive igneous crust).
3. Upper mantle represented by peridotite that is located beneath the gabbro.

The presence of ophiolite in an outcrop or drilling core is a key indication of plate convergence along a subduction zone.

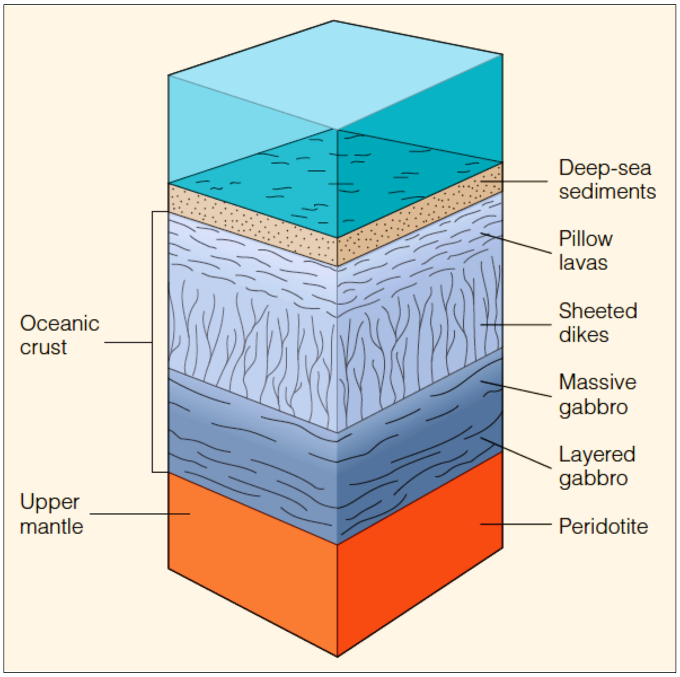


Figure 23 Ophiolites are sequences of rock on land consisting of deep-sea sediments, oceanic crust, and upper mantle. Ophiolites are one feature used to recognize ancient convergent plate boundaries.

3. Transform plate boundaries

The third type of plate boundary is the transform plate boundary, where plates slide past one another without the production or destruction of crust. Transform faults "transform" or change one type of motion between plates into another type of motion. These faults either exist in the seafloor (oceanic crust) or land (continental crust).

Oceanic transform plate boundary

Oceanic transform plate boundaries consist of a single, narrow (a few kilometers wide) strike-slip fault connecting two mid-oceanic ridge segments, but they can also connect ridges to trenches and trenches to trenches (Figure 23). The majority of transform faults are in oceanic crust and are marked by distinct fracture zones.

Continental transform plate boundary

One of the best-known continental transform faults is the San Andreas fault in California. It separates the Pacific plate from the North American plate and connects spreading ridges in the Gulf of California with the Juan de Fuca and Pacific plates off the coast of northern California (Figure 24). Many of the earthquakes affecting California are the result of movement along this fault.

Unfortunately, transform faults generally do not leave any characteristic or diagnostic features except the obvious displacement of the rocks with which they are associated. This displacement is usually large, on the order of tens to hundreds of kilometers. Such large displacements in ancient rocks can sometimes be related to transform fault systems.

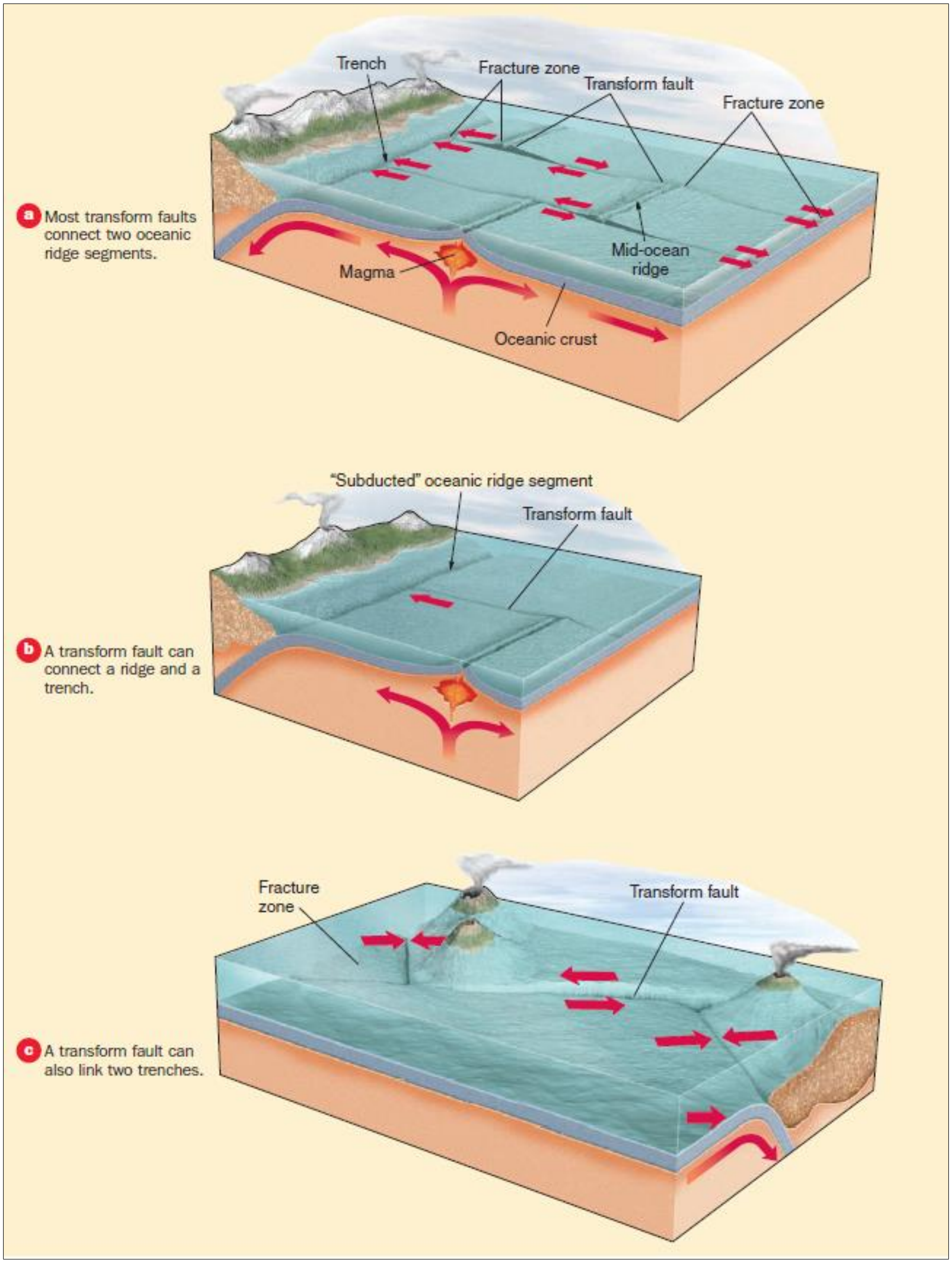


Figure 23 Oceanic Transform Plate Boundaries. Horizontal movement between plates occurs along transform faults. Extensions of transform faults on the seafloor form fracture zones.

Figure 24 Continental Transform Plate Boundary. The San Andreas fault is a transform fault separating the Pacific plate from the North American plate. It connects the spreading ridges in the Gulf of California with the Juan de Fuca and Pacific plates off the coast of northern California. Movement along the San Andreas fault has caused numerous earthquakes. The insert photograph shows a segment of the San Andreas fault as it cuts through the Carrizo Plain, California.

11 Wilson Cycle

What is the supercontinent cycle?

As a result of plate movement, all of the continents came together to form the supercontinent Pangaea by the end of the Paleozoic Era. Pangaea began fragmenting during the Triassic Period and continues to do so, thus accounting for the present distribution of continents and ocean basins. It has been proposed that supercontinents, consisting of all or most of Earth’s landmasses, form, break up, and re-form in a cycle spanning about 500 million years.

The supercontinent cycle hypothesis is an expansion on the ideas of the Canadian geologist J. Tuzo Wilson. During the early 1970s, Wilson proposed a cycle (now known as the Wilson cycle) that includes continental fragmentation, the opening and closing of an ocean basin, and re-assembly of the continent (Figure 25). According to the supercontinent cycle hypothesis, heat accumulates beneath a supercontinent because the rocks of continents are poor conductors of heat.

As a result of the heat accumulation, the supercontinent domes upward and fractures. Basaltic magma rising from below fills the fractures. As a basalt-filled fracture widens, it begins subsiding and forms a long, narrow ocean such as the present-day Red Sea. Continued rifting eventually forms an expansive ocean basin such as the Atlantic.

One of the most convincing arguments for the proponents of the supercontinent cycle hypothesis is the “surprising regularity” of mountain building caused by compression during continental collisions. These mountain-building episodes occur about every 400 to 500 million years and are followed by an episode of rifting about 100 million years later. In other words, a supercontinent fragments and its individual plates disperse following a rifting episode, an interior ocean forms, and then the dispersed fragments reassemble to form another supercontinent.

The supercontinent cycle is yet another example of how interrelated the various systems and subsystems of Earth are and how they operate over vast periods of geologic time.

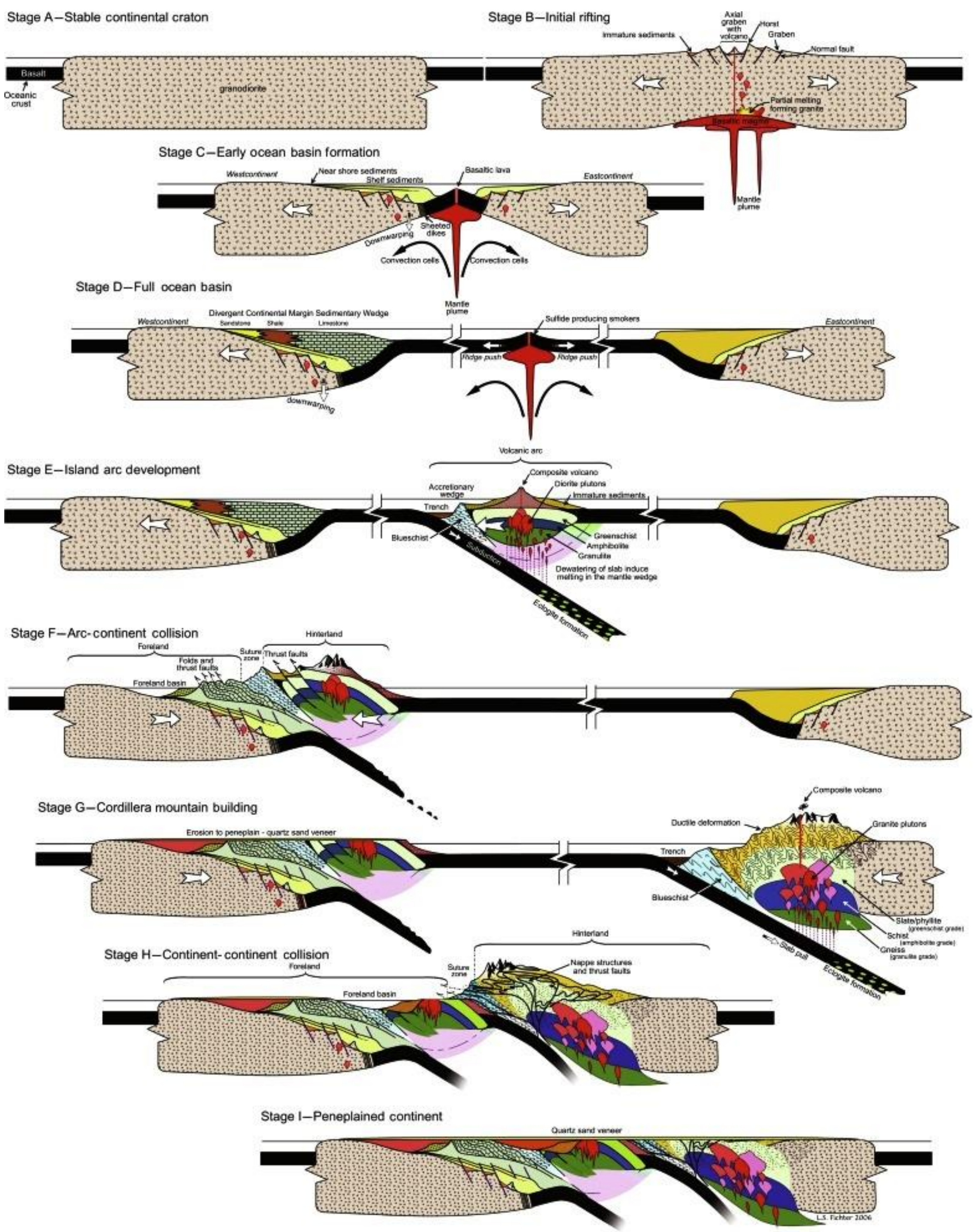


Figure 25 Wilson cycle. Opening and closing phases.

12 Hot Spots: An Intraplate Feature

What are hot spots and what do they tell us about plate movement?

Before leaving the topic of plate boundaries, we should mention an intraplate feature found beneath both oceanic and continental plates. A hot spot is the location on Earth's surface where a stationary column of magma, originating deep within the mantle (mantle plume), has slowly risen to the surface and formed a volcano (Figure 26). Because mantle plumes apparently remain stationary (although some evidence suggests that they might not) within the mantle while plates move over them, the resulting hot spots leave a trail of extinct and progressively older volcanoes called aseismic ridges that record the movement of the plate.

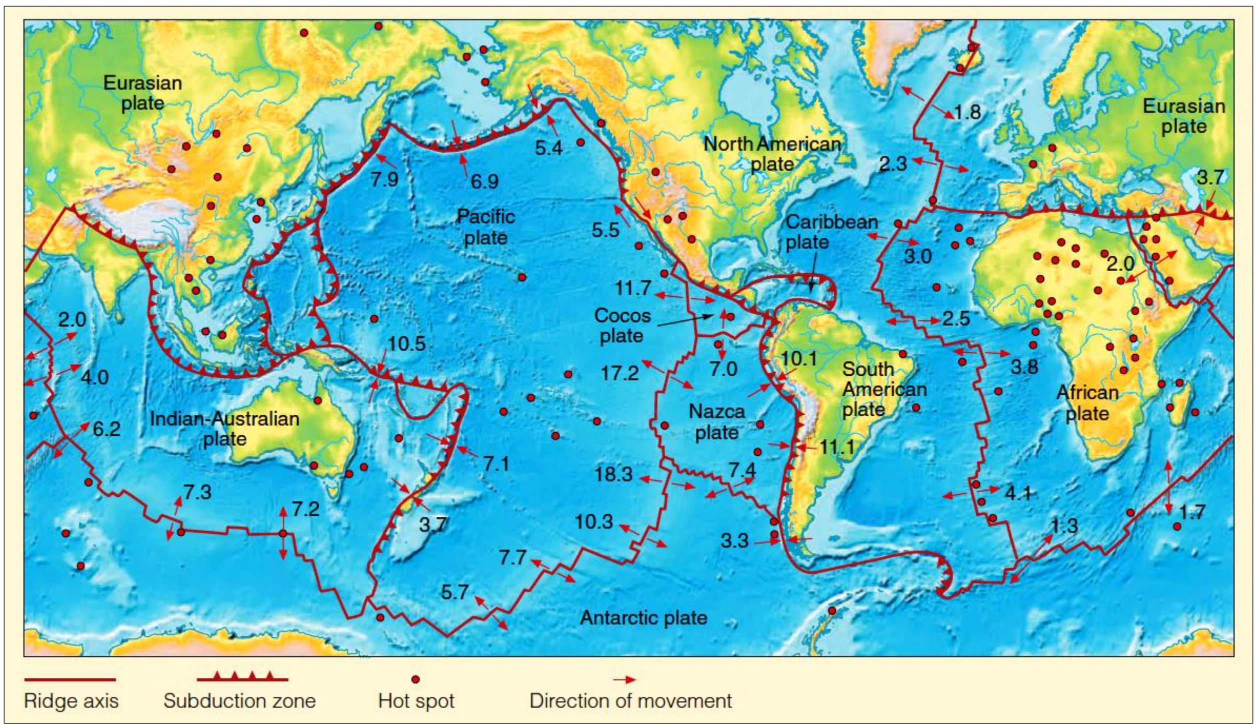


Figure 26 Earth's Plates. A world map showing Earth's plates, their boundaries, their relative motion and rates of movement in centimeters per year, and hot spots.

One of the best examples of aseismic ridges and hot spots is the Emperor Seamount–Hawaiian Island chain (Figure 27). This chain of islands and seamounts (structures of volcanic origin rising higher than 1 km above the seafloor) extends from the island of Hawaii to the Aleutian Trench off Alaska, a distance of some 6000 km, and consists of more than 80 volcanic structures.

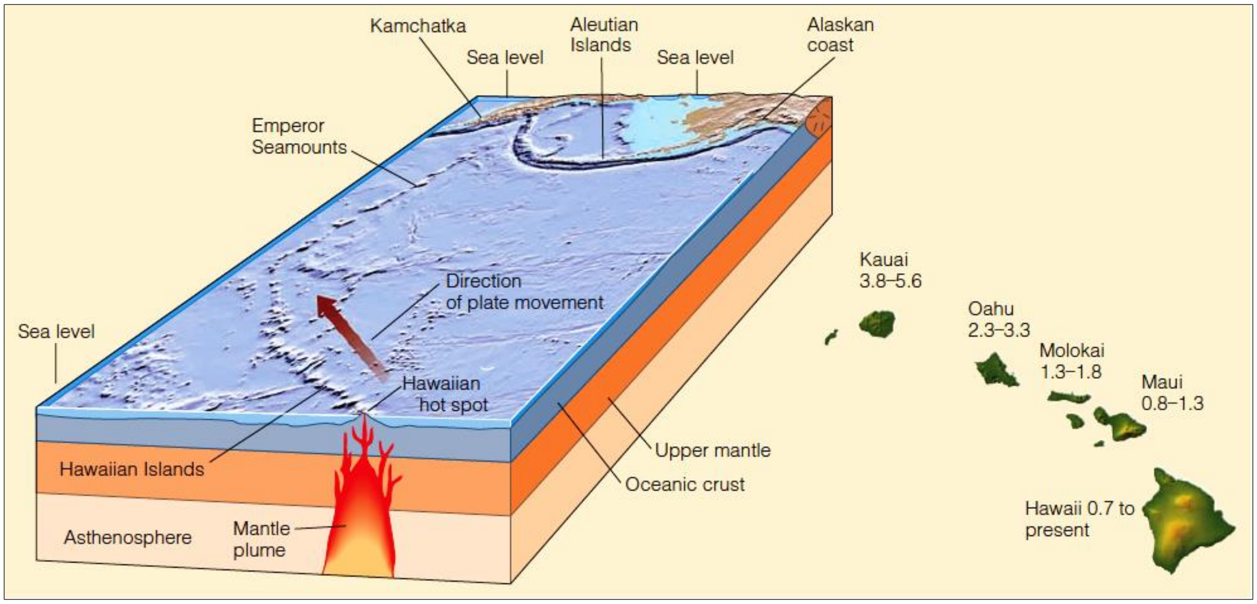


Figure 27 Hot Spots. A hot spot is the location where a stationary mantle plume has risen to the surface and formed a volcano. The Emperor Seamount–Hawaiian Island chain formed as a result of the Pacific plate moving over a mantle plume, and the line of volcanic islands in this chain traces the direction of plate movement. The Hawaiian hot spot currently underlies the southern half of the island of Hawaii and adjoining offshore area. The numbers indicate the ages of the Hawaiian Islands in millions of years.

Currently, the only active volcanoes in this island chain are on the islands of Hawaii and Maui and the Loihi Seamount. The rest of the islands are extinct volcanic structures that become progressively older toward the north and northwest. This means that the Emperor Seamount–Hawaiian Island chain records the direction that the Pacific plate traveled as it moved over an apparently stationary mantle plume. In this case, the Pacific plate first moved in a north-northwesterly direction and then, as indicated by the sharp bend in the chain, changed to a west-northwesterly direction about 43 million years ago. The reason the Pacific plate changed directions is not known, but the shift might be related to the collision of India with the Asian continent at around the same time.

Mantle plumes and hot spots help geologists explain some of the geologic activity occurring within plates as opposed to activity occurring at or near plate boundaries. In addition, if mantle plumes are essentially fixed with respect to Earth's rotational axis, they can be used to determine not only the direction of plate movement but also the rate of movement. They can also provide reference points for determining paleolatitude, an important tool when reconstructing the location of continents in the geologic past.

What are triple junctions?

The first scientific paper detailing the triple junction concept was published in 1969 by Dan McKenzie and W. Jason Morgan. The term had traditionally been used for the intersection of three divergent boundaries or spreading ridges. These three divergent boundaries ideally meet at near 120° angles (Figure 28).

In plate tectonics theory during the breakup of a continent, three divergent boundaries form, radiating out from a central point (the triple junction). One of these divergent plate boundaries fails and the other two continue spreading to form an ocean. The opening of the Red sea, Gulf of Aden, and African Rift is the best example (see Figure 21).

In the years since, the term triple-junction has come to refer to any point where three tectonic plates meet. So, a *triple junction* is the point where the boundaries of three tectonic plates meet (Figure 29). At the triple junction each of the three boundaries will be one of three types – a ridge (R), trench (T) or transform fault (F) - and triple junctions can be described according to the types of plate margin that meet at them (e.g. Transform-Transform-Trench, Ridge-Ridge-Ridge, or abbreviated F-F-T, R-R-R). Of the many possible types of triple junction, only a few are stable through time ('stable' in this context means that the geometrical configuration of the triple junction will not change through geologic time). The meeting of four or more plates is also theoretically possible but junctions will only exist instantaneously.

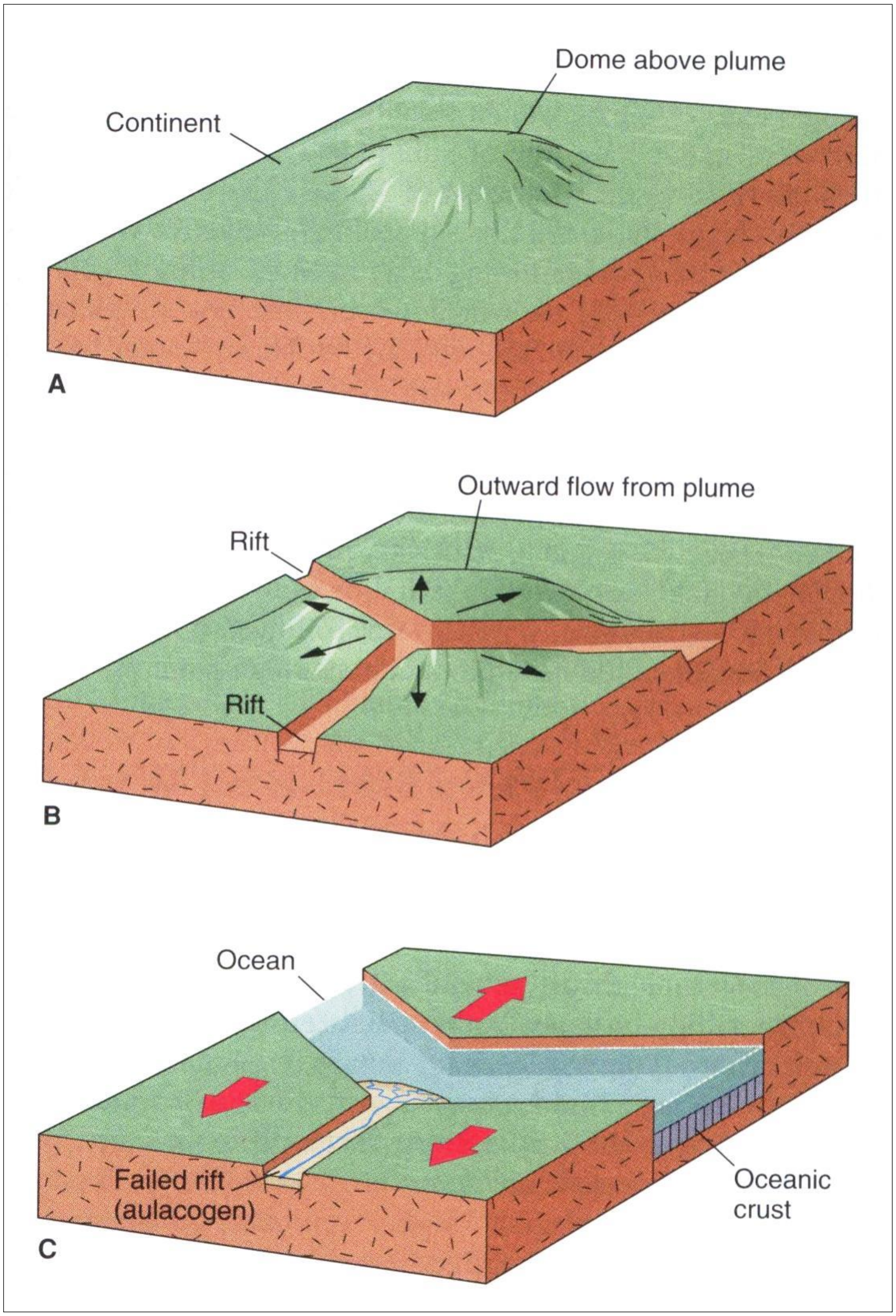


Figure 28 A triple junction is an intersection of three divergent boundaries or spreading ridges. These three divergent boundaries ideally meet at near 120° angles.

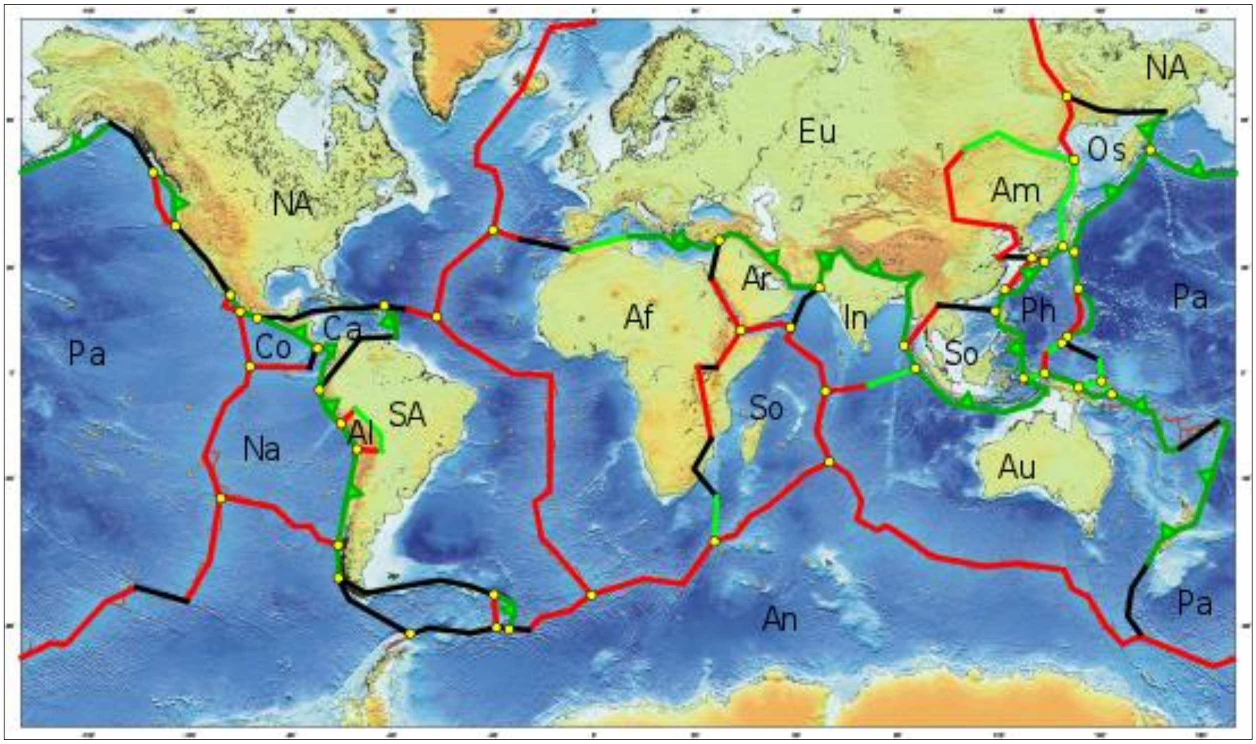


Figure 29 Main tectonic plates and corresponding triple junctions that are represented by yellow dots. Green, red, and black lines represent convergent, divergent, and transform plate boundaries respectively.

13 Plate Movement and Motion

How can the rate and direction of plate movement be determined?

How fast and in what direction are Earth's plates moving? Do they all move at the same rate? Rates of plate movement can be calculated in several ways.

1. The least accurate method is to determine the age of the sediments immediately above any portion of the oceanic crust and then divide the distance from the spreading ridge by that age. Such calculations give an average rate of movement.
2. A more accurate method of determining both the average rate of movement and the relative motion is by dating the magnetic anomalies in the crust of the seafloor. The distance from an oceanic ridge axis to any magnetic anomaly indicates the width of new seafloor that formed during that time interval. Thus, for a given interval of time,

the wider the strip of seafloor, the faster the plate has moved. In this way, not only can the present average rate of movement and relative motion be determined, but the average rate of movement during the past can also be calculated by dividing the distance between anomalies by the amount of time elapsed between anomalies. Unfortunately, subduction destroys oceanic crust and the magnetic record it carries. Thus, we have an excellent record of plate movements since the breakup of Pangaea, but not as good an understanding of plate movement before that time.

3. The average rate of movement as well as the relative motion between any two plates can also be determined by Satellite Laser Ranging (SLR) techniques. Laser beams from a station on one plate are bounced off a satellite (in geosynchronous orbit) and returned to a station on a different plate. As the plates move away from each other, the laser beam takes more time to go from the sending station to the stationary satellite and back to the receiving station. This difference in elapsed time is used to calculate the rate of movement and the relative motion between plates.
4. Plate motions derived from magnetic reversals and satellite–laser ranging techniques give only the relative motion of one plate with respect to another. Hot spots enable geologists to determine absolute motion because they provide an apparently fixed reference point from which the rate and direction of plate movement can be measured. The previously mentioned Emperor Seamount–Hawaiian Island chain formed as a result of movement over a hot spot. Thus, the line of the volcanic islands traces the direction of plate movement, and dating the volcanoes enables geologists to determine the rate of movement.

14 The Driving Mechanism of Plate Tectonics

What drives plates?

A major obstacle to the acceptance of the continental drift hypothesis was the lack of a driving mechanism to explain continental movement. When it was shown that continents and ocean floors moved together, not separately, and that new crust formed at spreading ridges by rising magma, most geologists accepted some type of convective heat system as the basic process responsible for plate motion. The question still remains, however: What exactly drives the plates?

How do thermal convection cells move plates?

Two models involving thermal convection cells have been proposed to explain plate movement (Figure 30). In one model, thermal convection cells are restricted to the asthenosphere; in the second model, the entire mantle is involved. In both models, spreading ridges mark the ascending limbs of adjacent convection cells, and trenches are present where convection cells descend back into Earth's interior. The convection cells therefore determine the location of spreading ridges and trenches, with the lithosphere lying above the thermal convection cells. Each plate thus corresponds to a single convection cell and moves as a result of the convective movement of the cell itself.

Although most geologists agree that Earth's internal heat plays an important role in plate movement, there are problems with both models. The major problem associated with the first model is the difficulty in explaining the source of heat for the convection cells and why they are restricted to the asthenosphere. In the second model, the heat comes from the outer core, but it is still not known how heat is transferred from the outer core to the mantle. Nor is it clear how convection can involve both the lower mantle and the asthenosphere.

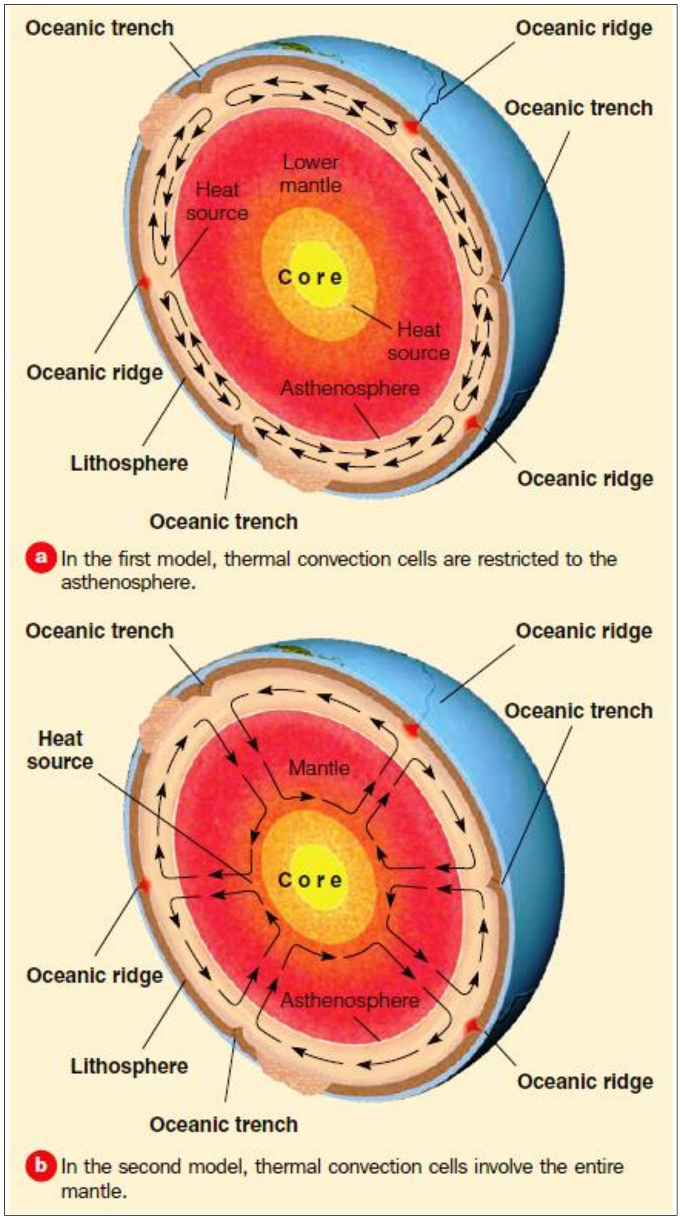


Figure 30 Thermal Convection Cells as the Driving Force of Plate Movement. Two models involving thermal convection cells have been proposed to explain plate movement.

Can plate movement be gravity driven?

In addition to some type of thermal convection system driving plate movement, some geologists think plate movement occurs because of a mechanism involving "*slab-pull*" or "*ridge-push*," both of which are gravity driven but still dependent on thermal differences within Earth (Figure 31). In slab-pull, the subducting cold slab of lithosphere, being denser than the surrounding warmer asthenosphere, pulls the rest of the plate along as it descends into the asthenosphere. As the lithosphere moves downward, there is a corresponding upward flow back into the spreading ridge.

Operating in conjunction with slab-pull is the ridge-push mechanism. As a result of rising magma, the oceanic ridges are higher than the surrounding oceanic crust. It is thought that gravity pushes the oceanic lithosphere away from the higher spreading ridges and toward the trenches.

Currently, geologists are fairly certain that some type of convective system is involved in plate movement, but the extent to which other mechanisms such as slab-pull and ridge-push are involved is still unresolved. However, the fact that plates have moved in the past and are still moving today has been proven beyond a doubt. And although a comprehensive theory of plate movement has not yet been developed, more and more of the pieces are falling into place as geologists learn more about Earth's interior.

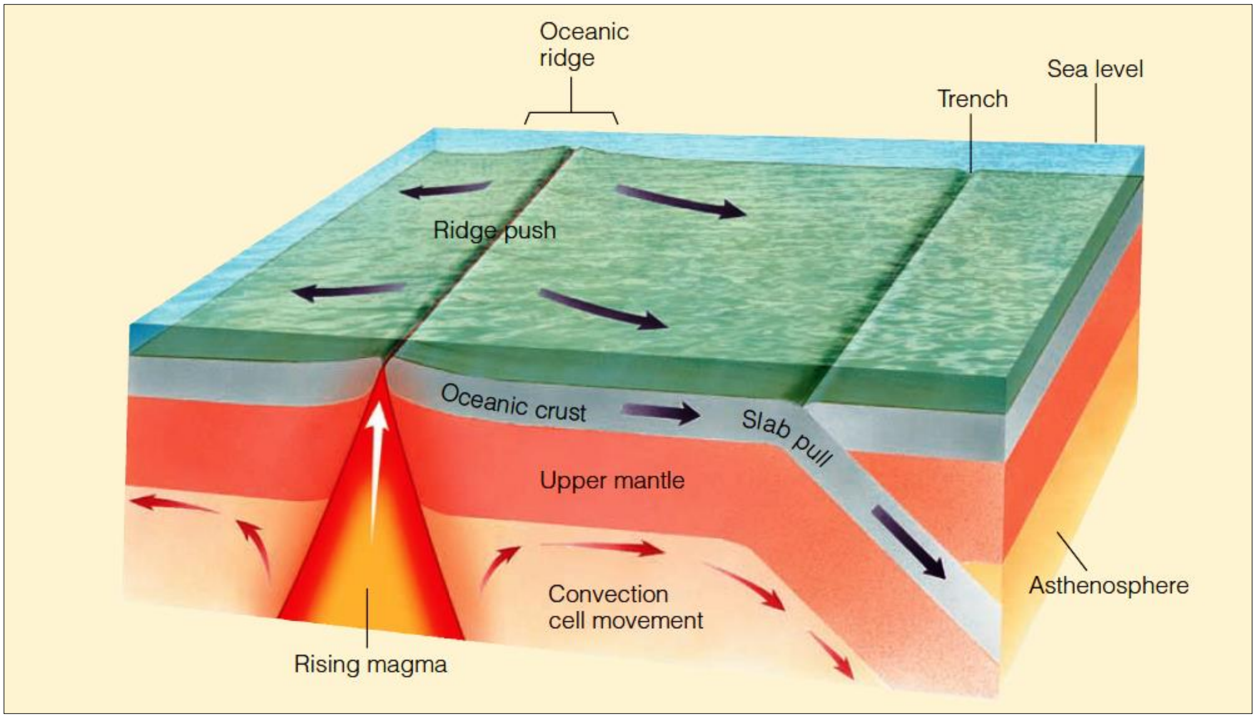


Figure 31 Plate Movement Resulting from Gravity-Driven Mechanisms. Plate movement is also thought to result, at least partially, from gravity-driven "slab-pull" or "ridge-push" mechanisms. In slab-pull, the edge of the subducting plate descends into the interior, and the rest of the plate is pulled downward. In ridge-push, rising magma pushes the oceanic ridges higher than the rest of the oceanic crust. Gravity thus pushes the oceanic lithosphere away from the ridges and toward the trenches.

15 Plate Tectonics and Distribution of Earthquakes

Where do most earthquakes occur?

No place on Earth is immune to earthquakes, but almost 95% take place in seismic belts corresponding to plate boundaries where plates converge, diverge, and slide past each other. Earthquake activity distant from plate margins is minimal but can be devastating when it occurs. The relationship between plate margins and the distribution of earthquakes is readily apparent when the locations of earthquake epicenters are superimposed on a map showing the boundaries of Earth's plates (Figure 32).

The majority of all earthquakes (approximately 80%) occur in the circum-Pacific belt, a zone of seismic activity nearly encircling the Pacific Ocean basin. Most of these earthquakes result from convergence along plate margins, as in the case of the 1995 Kobe, Japan, earthquake. The earthquakes along the North American Pacific Coast, especially in California, are also in this belt, but here plates slide past one another rather than converge. The October 17, 1989, Loma Prieta earthquake in the San Francisco area and the January 17, 1994, Northridge earthquake happened along this plate boundary.

The second major seismic belt, accounting for 15% of all earthquakes, is the Mediterranean–Asiatic belt. This belt extends westerly from Indonesia through the Himalayas, across Iran and Turkey, and through the Mediterranean region of Europe. The devastating 1990 and 2003 earthquakes in Iran that killed 40,000 and 43,000 people, respectively, the 1999 Turkey earthquake that killed about 17,000 people, the 2001 India earthquake that killed more than 20,000 people, and the 2005 earthquake in Pakistan that killed more than 86,000 people are recent examples of the destructive earthquakes that strike this region.

The remaining 5% of earthquakes occur mostly in the interiors of plates and along oceanic spreading-ridge systems. Most of these earthquakes are not strong, although several major intraplate earthquakes are worthy of mention. For example, the 1811 and 1812 earthquakes near New Madrid, Missouri, killed approximately 20 people and nearly destroyed the town. So strong were these earthquakes that they were felt from the Rocky

Mountains to the Atlantic Ocean and from the Canadian border to the Gulf of Mexico. Within the immediate area, numerous buildings were destroyed and forests were flattened. The land sank several meters in some areas, causing flooding; and reportedly the Mississippi River reversed its flow during the shaking and changed its course slightly.

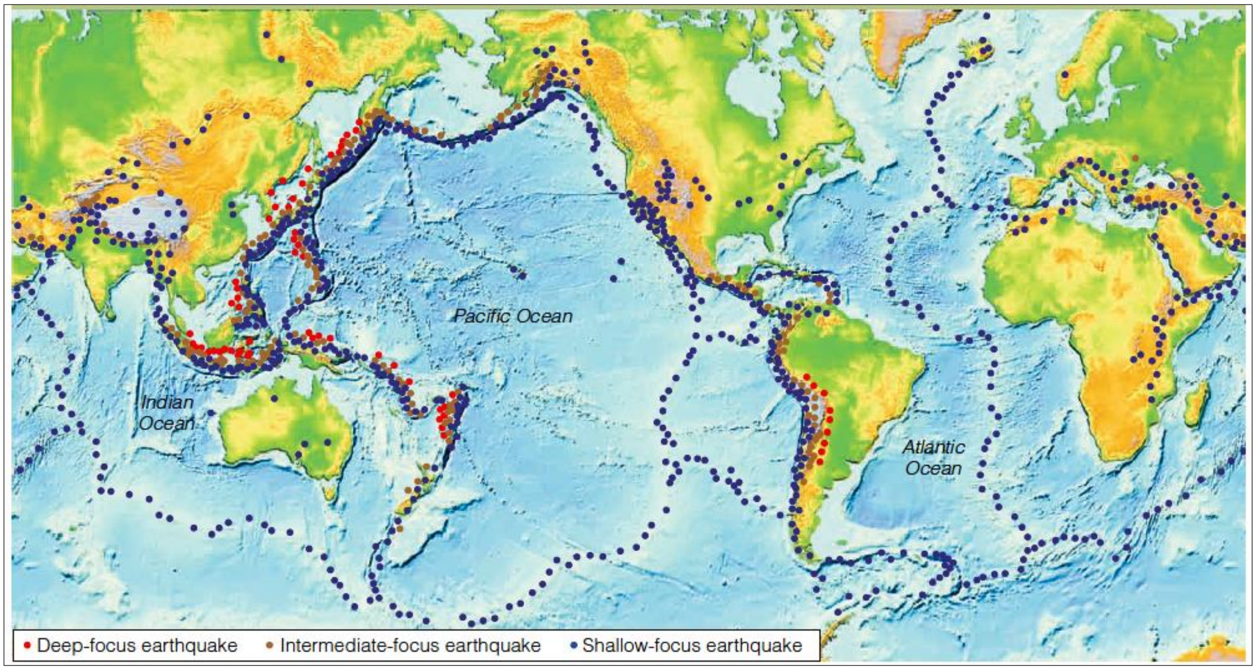


Figure 32 Earthquake Epicenters and Plate Boundaries This map of earthquake epicenters shows that most earthquakes occur within seismic zones that correspond closely to plate boundaries. Approximately 80% of earthquakes occur within the circum-Pacific belt, 15% within the Mediterranean–Asiatic belt, and the remaining 5% within plate interiors and along oceanic spreading ridges. The dots represent earthquake epicenters and are divided into shallow-, intermediate-, and deep-focus earthquakes. Along with shallow-focus earthquakes, nearly all intermediate- and deep-focus earthquakes occur along convergent plate boundaries.

Another major intraplate earthquake struck Charleston, South Carolina, on August 31, 1886, killing 60 people and causing $23 million in property damage. In December 1988 a large intraplate earthquake struck near Tennant Creek in Australia's Northern Territory.

The cause of intraplate earthquakes is not well understood, but geologists think they arise from localized stresses caused by the compression that most plates experience along their margins. A useful analogy is moving a house. Regardless of how careful the movers are, moving something so large without its internal parts shifting slightly is impossible.

Similarly, plates are not likely to move without some internal stresses that occasionally cause earthquakes. It is interesting that many intraplate earthquakes are associated with ancient and presumed inactive faults that are reactivated at various intervals.

How many earthquakes occur per year?

More than 900,000 earthquakes are recorded annually by the worldwide network of seismograph stations. Many of these, however, are too small to be felt but are nonetheless recorded. These small earthquakes result from the energy released as continuous adjustments take place between the various plates. However, more than 31,000 earthquakes, on average per year, are strong enough to be felt, and can cause various amounts of damage, depending on how strong they are and where they occur.

What is Benioff-Wadati zone?

Seismologists recognize three categories of earthquakes based on focal depth. *Shallow-focus earthquakes* have focal depths of less than 70 km from the surface, whereas those with foci between 70 and 300 km are *intermediate focus*, and the foci of those characterized as *deep focus* are more than 300 km deep.

A definite relationship exists between earthquake foci and plate boundaries. Earthquakes generated along divergent or transform plate boundaries are invariably shallow focus, whereas many shallow- and nearly all intermediate- and deep-focus earthquakes occur along convergent margins (Figure 33). Furthermore, a pattern emerges when the focal depths of earthquakes near island arcs and their adjacent ocean trenches are plotted.

Benioff-Wadati zone is a dipping seismic zone defines a subduction zone. Such dipping seismic zones indicate the angle of plate descent along a convergent plate boundary (Figure 31). Notice in Figure 31 that the focal depth increases beneath the Tonga Trench in a narrow, well-defined zone that dips approximately 45 degrees.

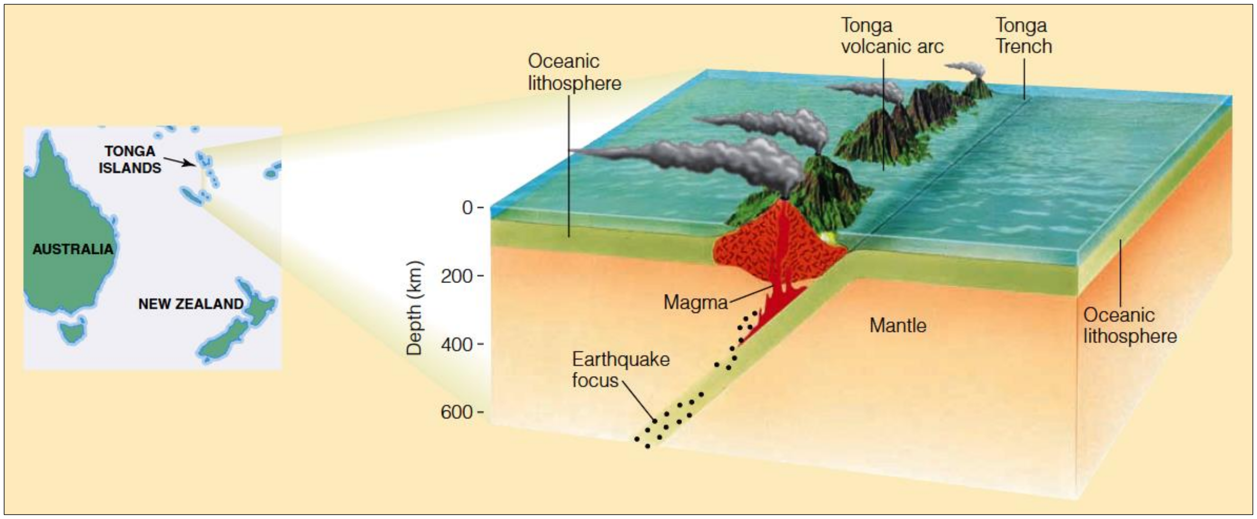


Figure 33 Benioff Zones. Focal depth increases in a well-defined zone that dips approximately 45 degrees beneath the Tonga volcanic arc in the South Pacific. Dipping seismic zones are called Benioff or Benioff–Wadati zones.

16 Plate Tectonics and Distribution of Volcanoes

Where are the three zones or belts with most of Earth's volcanoes?

Rather than being randomly distributed volcanoes are found mostly in three well-defined belts: the circum-Pacific belt, the Mediterranean belt, and along the mid-oceanic ridges.

You have probably heard of the *Ring of Fire*, a phrase that alludes to the fact that a nearly continuous belt of volcanoes encircles the Pacific Ocean basin. Geologists refer to this as the circum-Pacific belt, where more than 60% of all active volcanoes are found. It includes the volcanoes in South and Central America, those in the Cascade Range of North America, and the volcanoes in Alaska, Japan, the Philippines, Indonesia, and New Zealand (Figure 34). Also included in this belt are the southernmost active volcanoes at Mount Erebus in Antarctica, and a large caldera at Deception Island that last erupted in 1970.

The second major area of volcanism is the Mediterranean belt, with about 20% of all active volcanoes (Figure 34). The famous Italian volcanoes include Mount Etna, which has issued lava flows on more than 200 occasions since 1500 B.C., when activity was first recorded. Mount Vesuvius, also in the Mediterranean belt, erupted violently in A.D.

79 and destroyed Pompeii, Herculaneum, and Stabiae. Remember that Mount Vesuvius has erupted 80 times since A.D. 79. Another important volcano in this belt is the Greek island of Santorini.

Most of the remaining 20% of active volcanoes are at or near mid-oceanic ridges or their extensions onto land (Figure 34). The volcanoes at or near mid-oceanic ridges include those along the East Pacific Rise, the Mid-Atlantic Ridge, and the Indian Ridge, which account for submarine eruptions as well as the volcanic islands in the Pacific, Atlantic, and Indian Oceans. Iceland in the Atlantic Ocean, for instance, is found on the Mid-Atlantic Ridge. Branches of the Indian Ridge extend into the Red Sea and East Africa, where several volcanoes are found, including Kilamanjaro in Tanzania, Nyiragongo in the Democratic Republic of Congo, and Erta Ale in Ethiopia with its continuously active lava lake.

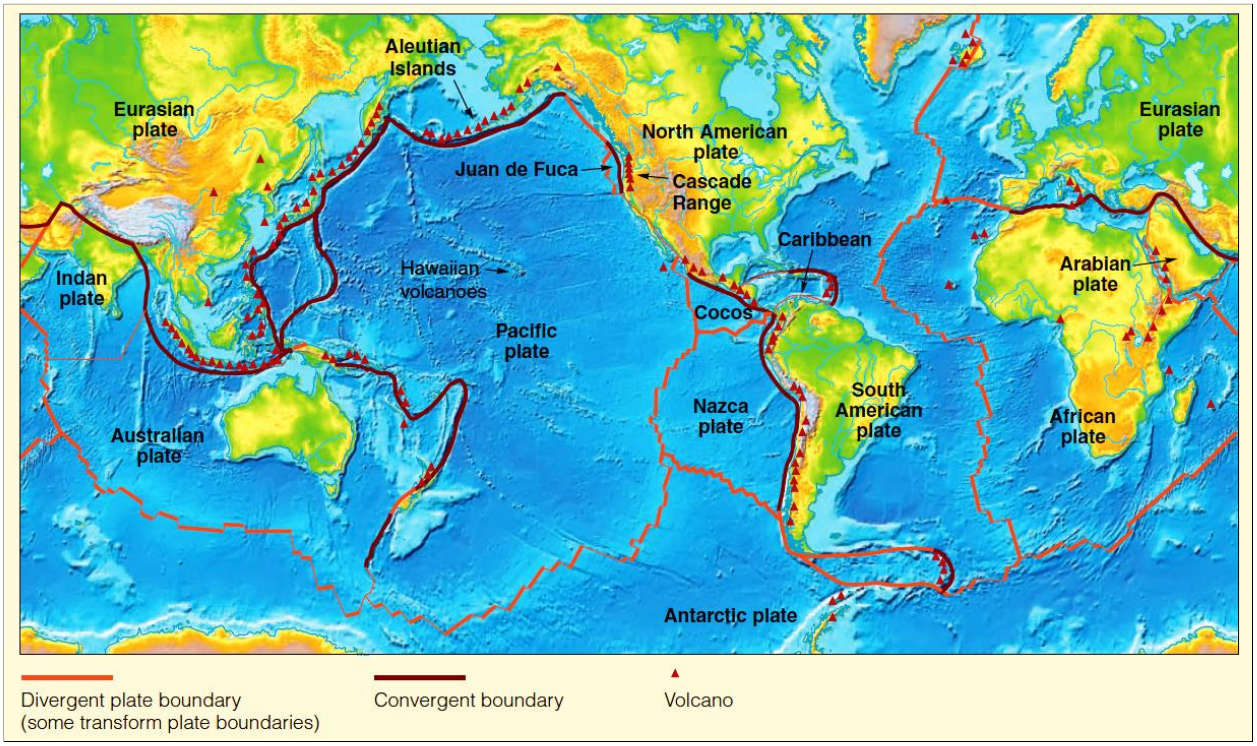


Figure 32 Volcanoes at Convergent and Divergent Plate Boundaries. Most volcanoes are at or near convergent and divergent plate boundaries in two main belts. The circum-Pacific belt has about 60% of all active volcanoes, and about 20% of all active volcanoes are in the Mediterranean belt. Most of the rest are near mid-oceanic ridges (divergent plate boundaries), but not all of them are shown on this map. For example, axial volcano lies on the Juan de Fuca Ridge west of Oregon.

Anyone with a passing familiarity with volcanoes will have noticed that we have not mentioned the Hawaiian volcanoes. This is not an oversight; they are the notable exceptions to the distribution of active volcanoes in well-defined belts. We discuss their location and significance in Section 12.

17 The Rock Cycle

What is a rock?

A rock is an aggregate of minerals, which are naturally occurring, inorganic, crystalline solids that have definite physical and chemical properties. Minerals are composed of elements such as oxygen, silicon, and aluminum, and elements are made up of atoms, the smallest particles of matter that retain the characteristics of an element. More than 3500 minerals have been identified and described, but only about a dozen make up the bulk of the rocks in Earth’s crust (see Table 2).

Geologists recognize three major groups of rocks—igneous, sedimentary, and metamorphic—each of which is characterized by its mode of formation. Each group contains a variety of individual rock types that differ from one another on the basis of their composition or texture (the size, shape, and arrangement of mineral grains).

Table 2: Important rock-forming minerals.

Important Rock-Forming Minerals	
Mineral	**Primary Occurrence**
Ferromagnesian silicates	
Olivine	Igneous, metamorphic rocks
Pyroxene group	
Augite most common	Igneous, metamorphic rocks
Amphibole group	
Hornblende most common	Igneous, metamorphic rocks
Biotite	All rock types
Nonferromagnesian silicates	
Quartz	All rock types
Potassium feldspar group	
Orthoclase, microcline	All rock types
Plagioclase feldspar group	All rock types
Muscovite	All rock types
Clay mineral group	Soils, sedimentary rocks, some metamorphic rocks
Carbonates	
Calcite	Sedimentary rocks
Dolomite	Sedimentary rocks
Sulfates	
Anhydrite	Sedimentary rocks
Gypsum	Sedimentary rocks
Halides	
Halite	Sedimentary rocks

What is the rock cycle?

The *rock cycle* provides a way of viewing the interrelationships between Earth's internal and external processes (Figure 35). It relates the three rock groups to each other; to surficial processes such as weathering, transportation, and deposition; and to internal processes such as magma generation and metamorphism.

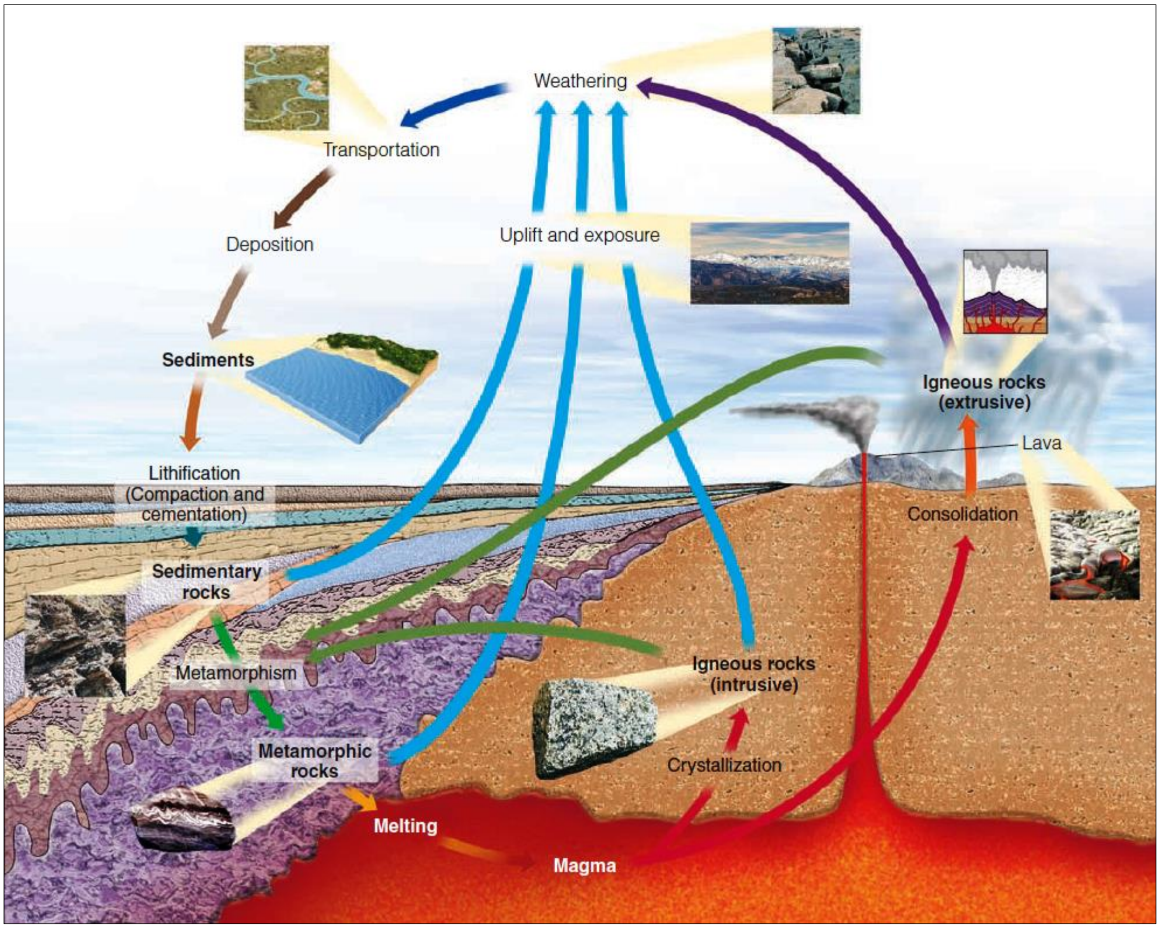


Figure 35 The Rock Cycle. This cycle shows the interrelationships between Earth's internal and external processes and how the three major rock groups are related.

What are the characteristics of each of the three major rock groups?

Igneous rocks result when magma crystallizes or volcanic ejecta such as ash accumulate and consolidate. As magma cools, minerals crystallize, and the resulting rock is characterized by interlocking mineral grains. Magma that cools slowly beneath the surface produces intrusive igneous rocks; magma that cools at the surface produces extrusive igneous rocks.

Rocks exposed at Earth's surface are broken into particles and dissolved by various weathering processes. The particles and dissolved materials may be transported by wind, water, or ice and eventually deposited as sediment. This sediment may then be compacted or cemented (lithified) into sedimentary rock.

Sedimentary rocks form in one of three ways: consolidation of rock fragments, precipitation of mineral matter from solution, or compaction of plant or animal remains. Because sedimentary rocks form at or near Earth's surface, geologists can make inferences about the environment in which they were deposited, the transporting agent, and perhaps even something about the source from which the sediments were derived. Accordingly, sedimentary rocks are especially useful for interpreting Earth history.

Metamorphic rocks result from the alteration of other rocks, usually beneath the surface, by heat, pressure, and the chemical activity of fluids. For example, marble, a rock preferred by many sculptors and builders, is a metamorphic rock produced when the agents of metamorphism are applied to the sedimentary rocks limestone or dolostone. Metamorphic rocks are either *foliated* or *nonfoliated*. Foliation, the parallel alignment of minerals due to pressure, gives the rock a layered or banded appearance.

How are the rock cycle and plate tectonics related?

Interactions between plates determine, to some extent, which of the three rock groups will form (Figure 36). For example, when plates converge, heat and pressure generated along the plate boundary may lead to igneous activity and metamorphism within the descending oceanic plate, thus producing various igneous and metamorphic rocks.

Some of the sediments and sedimentary rocks on the descending plate are melted, whereas other sediments and sedimentary rocks along the boundary of the nondescending plate are metamorphosed by the heat and pressure generated along the converging plate boundary. Later, the mountain range or chain of volcanic islands formed along the convergent plate boundary will be weathered and eroded, and the new sediments will be transported to the ocean to begin yet another cycle.

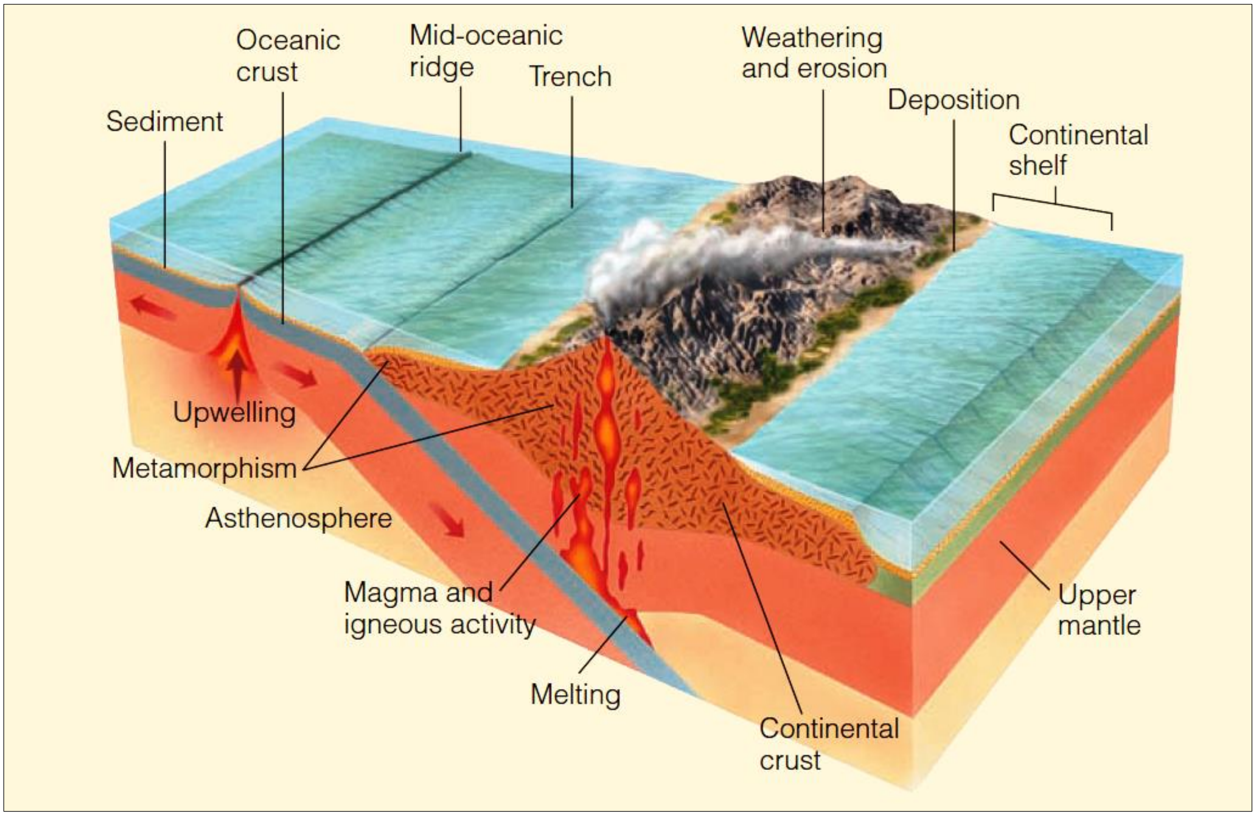


Figure 36 Plate Tectonics and the Rock Cycle. Plate movement provides the driving mechanism that recycles Earth materials. The cross section shows how the three major rock groups—igneous, metamorphic, and sedimentary—are recycled through both the continental and oceanic regions. Subducting plates are partially melted to produce magma, which rises and either crystallizes beneath Earth's surface as intrusive igneous rock or spills out on the surface, solidifying as extrusive igneous rock. Rocks exposed at the surface are weathered and eroded to produce sediments that are transported and eventually lithified into sedimentary rocks. Metamorphic rocks result from pressure generated along converging plates or adjacent to rising magma.

The interrelationship between the rock cycle and plate tectonics is just one example of how Earth's subsystems and cycles are all interrelated. Heating within Earth's interior results in convection cells that power the movement of plates, and also in magma, which forms intrusive and extrusive igneous rocks. Movement along plate boundaries may result in volcanic activity, earthquakes, and in some cases mountain building. The interaction between the atmosphere, hydrosphere, and biosphere contributes to the weathering of rocks exposed on Earth's surface. Plates descending back into Earth's interior are subjected to increasing heat and pressure, which may lead to metamorphism as well as the generation of magma and yet another recycling of materials.

18 Plate Tectonics and Igneous Activity

In the previous sections, we noted that plate tectonic theory is a unifying theory in geology that explains many seemingly unrelated geologic phenomena. So how do we relate the eruption of volcanoes and the emplacement of plutons to plate tectonics? You already know that (1) mafic magma is generated beneath spreading ridges and (2) intermediate magma and felsic magma form where an oceanic plate is subducted beneath another oceanic plate or where an oceanic plate is subducted beneath a continental plate. Accordingly, most of Earth's volcanism and emplacement of plutons take place at or near divergent and convergent plate boundaries (see Figure 34).

Divergent Plate Boundaries and Igneous Activity

Much of the mafic magma that forms beneath spreading ridges is emplaced at depth as vertical dikes and gabbro plutons. But some rises to the surface, where it forms submarine lava flows and pillow lava. Indeed, the oceanic crust is composed largely of gabbro and basalt. Much of this submarine volcanism goes undetected, but researchers in submersible craft have observed the results of these eruptions.

Pyroclastic materials are not common in this environment because mafic lava is very fluid, allowing gases to escape easily, and at great depth, water pressure prevents gases from expanding. Accordingly, the explosive eruptions that yield pyroclastic materials are not common. If an eruptive center along a ridge builds above sea level, however, pyroclastic materials may be erupted at lava fountains, but most of the magma issues forth as fluid lava flows that form shield volcanoes.

Excellent examples of divergent plate boundary volcanism are found along the Mid-Atlantic Ridge, particularly where it is above sea level as in Iceland (see Figure 34). In November 1963, a new volcanic island, later named Surtsey, rose from the sea just south of Iceland. The East Pacific Rise and the Indian Ridge are areas of similar volcanism. Not all divergent plate boundaries are beneath sea level as in the previous examples. For instance, divergence and igneous activity are taking place in Africa at the East African Rift system (Figure 34).

Igneous Activity at Convergent Plate Boundaries

Nearly all of the large active volcanoes in both the circum-Pacific and Mediterranean belts are composite volcanoes near the leading edges of overriding plates at convergent plate boundaries (Figure 34). The overriding plate, with its chain of volcanoes, may be oceanic as in the case of the Aleutian Islands, or it may be continental as is, for instance, the South American plate with its chain of volcanoes along its western edge.

As we have noted, these volcanoes at convergent plate boundaries consist largely of lava flows and pyroclastic materials of intermediate to felsic composition. Remember that when mafic oceanic crust partially melts, some of the magma generated is emplaced near plate boundaries as plutons and some is erupted to build up composite volcanoes. More viscous magmas, usually of felsic composition, are emplaced as lava domes, thus accounting for the explosive eruptions that typically occur at convergent plate boundaries.

In previous sections, we mentioned several eruptions at convergent plate boundaries. Good examples are the explosive eruptions of Mount Pinatubo and Mayon volcano in the Philippines, both of which are situated near a plate boundary beneath which an oceanic plate is subducted. Mount St. Helens in Washington is similarly situated, but it is on a continental rather than an oceanic plate (see “Cascade Range Volcanoes” on pp. 154–155). Mount Vesuvius in Italy, one of several active volcanoes in that region, lies on a plate that the northern margin of the African plate is subducted beneath.

Intraplate Volcanism

Mauna Loa and Kilauea on the island of Hawaii and Loihi just 32 km to the south are within the interior of a rigid plate far from any divergent or convergent plate boundary (see Figure 34). The magma is derived from the upper mantle, as it is at spreading ridges, and accordingly is mafic so it builds up shield volcanoes. Loihi is particularly interesting because it represents an early stage in the origin of a new Hawaiian island. It is a submarine volcano that rises higher than 3000 m above the seafloor, but its summit is still about 940 m below sea level.

Even though the Hawaiian volcanoes are not at a spreading ridge near a subduction zone, their evolution is related to plate movements. Notice in Figure 27 that the ages of the rocks that make up the various Hawaiian Islands increase toward the northwest; Kauai formed 3.8 to 5.6 million years ago, whereas Hawaii began forming less than 1 million years ago, and Loihi began to form even more recently. Continuous movement of the Pacific plate over the hot spot, now beneath Hawaii and Loihi, has formed the islands in succession.

19 Plate Tectonics and Metamorphism

Metamorphism is associated with all three types of plate boundaries. At mid-oceanic ridges, infiltration of seawater into hot crust and mantle leads to patchy low- to mediumgrade metamorphism. Along transform fault boundaries, dynamic metamorphism creates mylonites and cataclastites, especially in continental settings. At oceanic–continental convergent plate boundaries, temperatures and pressures create *paired metamorphic belts*. *A metamorphic belt* is a zone of metamorphic rocks sharing the same general conditions and age of formation. A typical paired metamorphic belt consists of a zone of dynamically metamorphosed rocks within the accretionary wedge and forearc basin adjoining a zone of regional and contact metamorphic rocks within the arc. Figure 37 illustrates the various metamorphic facies conditions present at a typical oceanic–continental convergent plate boundary. Where two continents converge, regional metamorphism becomes even more widespread, overprinting the dynamic metamorphism of forearcs and accretionary wedges.

One of the most important consequences of metamorphism at convergent plate boundaries is the production of mafic magma. Recall that subducting oceanic lithosphere carries with it large amounts of trapped seawater. Much of this is stored as H_2O or OH^{-2} bonded in the lattices of metamorphic minerals like chlorite, actinolite, and glaucophane. Once the slab reaches a depth of 75–100 km, heat and pressure combine to drive off the H_2O and replace these minerals with newer ones that lack H_2O, such as the “dry” minerals garnet and pyroxene. The fluid escapes from the subducting slab like bubbles from a sinking ship, and this promotes partial melting in the mantle wedge between the slab and continental crust.

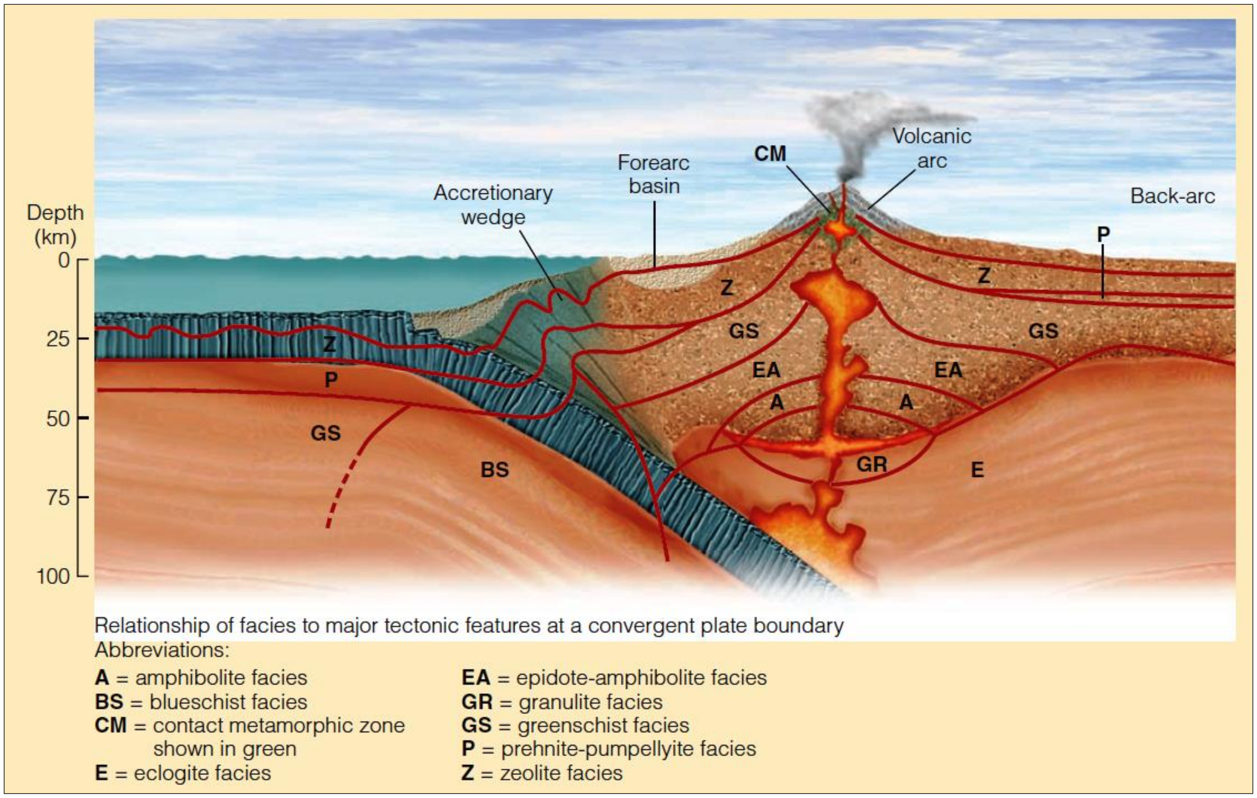


Figure 37 Relationship of facies to major tectonic features at a convergent plate boundary.

Some geologists think that metamorphism plays an important role in causing subduction. A deeply sinking slab transforms into metamorphic rock of the eclogite facies as it subsides past the point of fluid release. Eclogite is an especially dense rock, made all the heavier by the fact that it is somewhat cooler than the enclosing mantle. The eclogitic slabs may act like anchors, pulling the oceanic lithosphere hundreds of kilometers beneath the surface.

During regional metamorphism and mountain building, huge thrust faults called *nappes* may form, allowing the highly compressed central crust of a young mountain range to spread out horizontally within a few kilometers of the surface, somewhat like putty being squeezed from a tube. The presence of numerous garnet porphyroblasts in certain pelitic rocks shows that intensive metamorphism takes place concurrently with nappe thrusting. The shear stress generated by thrusting causes the garnets to rotate as they grow. The rotated garnets incorporate inclusions of other smaller mineral grains, giving them striking S-shaped or spiral inclusion patterns. Careful radiometric dating of rotated garnets can enable geologists indirectly to ascertain the rate at which thrust faulting related to mountain building takes place.

20 Plate Tectonics and the Distribution of Natural Resources

How does plate tectonic theory relate to the origin and distribution of natural resources?

Besides being responsible for the major features of Earth's crust and influencing the distribution and evolution of the world's biota, plate movements also affect the formation and distribution of some natural resources. The formation of many natural resources results from the interaction between plates, and economically valuable concentrations of such deposits are found associated with current and ancient plate boundaries. Consequently, geologists are using plate tectonic theory in their search for petroleum and mineral deposits and in explaining the occurrence of these natural resources.

It is becoming increasingly clear that if we are to keep up with the continuing demands of a global industrialized society, the application of plate tectonic theory to the origin and distribution of natural resources is essential.

What is the relationship between plate boundaries and various metallic mineral deposits?

Many metallic mineral deposits such as copper, gold, lead, silver, tin, and zinc are related to igneous and associated hydrothermal (hot water) activity, so it is not surprising that a close relationship exists between plate boundaries and the occurrence of these valuable deposits.

The magma generated by partial melting of a subducting plate rises toward the surface, and as it cools, it precipitates and concentrates various metallic ores. Many of the world's major metallic ore deposits are associated with convergent plate boundaries, including those in the Andes of South America, the Coast Ranges and Rockies of North America, Japan, the Philippines, Russia, and a zone extending from the eastern Mediterranean region to Pakistan. In addition, the majority of the world's gold is associated with sulfide deposits located at ancient convergent plate boundaries in such areas as South Africa, Canada, California, Alaska, Venezuela, Brazil, southern India, Russia, and western Australia.

The copper deposits of western North and South America are an excellent example of the relationship between convergent plate boundaries and the distribution, concentration, and exploitation of valuable metallic ores (Figure 38). The world's largest copper deposits are found along this belt. The majority of the copper deposits in the Andes and the southwestern United States formed less than 60 million years ago when oceanic plates were subducted under the North and South American plates. The rising magma and associated hydrothermal fluids carried minute amounts of copper, which was originally widely disseminated but eventually became concentrated in the cracks and fractures of the surrounding andesites. These low-grade copper deposits contain from 0.2 to 2% copper and are extracted from large open-pit mines (Figure 38).

Divergent plate boundaries also yield valuable ore deposits. The island of Cyprus in the Mediterranean is rich in copper and has been supplying all or part of the world's needs for the last 3000 years. The concentration of copper on Cyprus formed as a result of precipitation adjacent to hydrothermal vents along a divergent plate boundary. This deposit was brought to the surface when the copper-rich seafloor collided with the European plate, warping the seafloor and forming Cyprus.

Studies indicate that minerals of such metals as copper, gold, iron, lead, silver, and zinc are currently forming as sulfides in the Red Sea. The Red Sea is opening as a result of plate divergence and represents the earliest stage in the growth of an ocean basin.

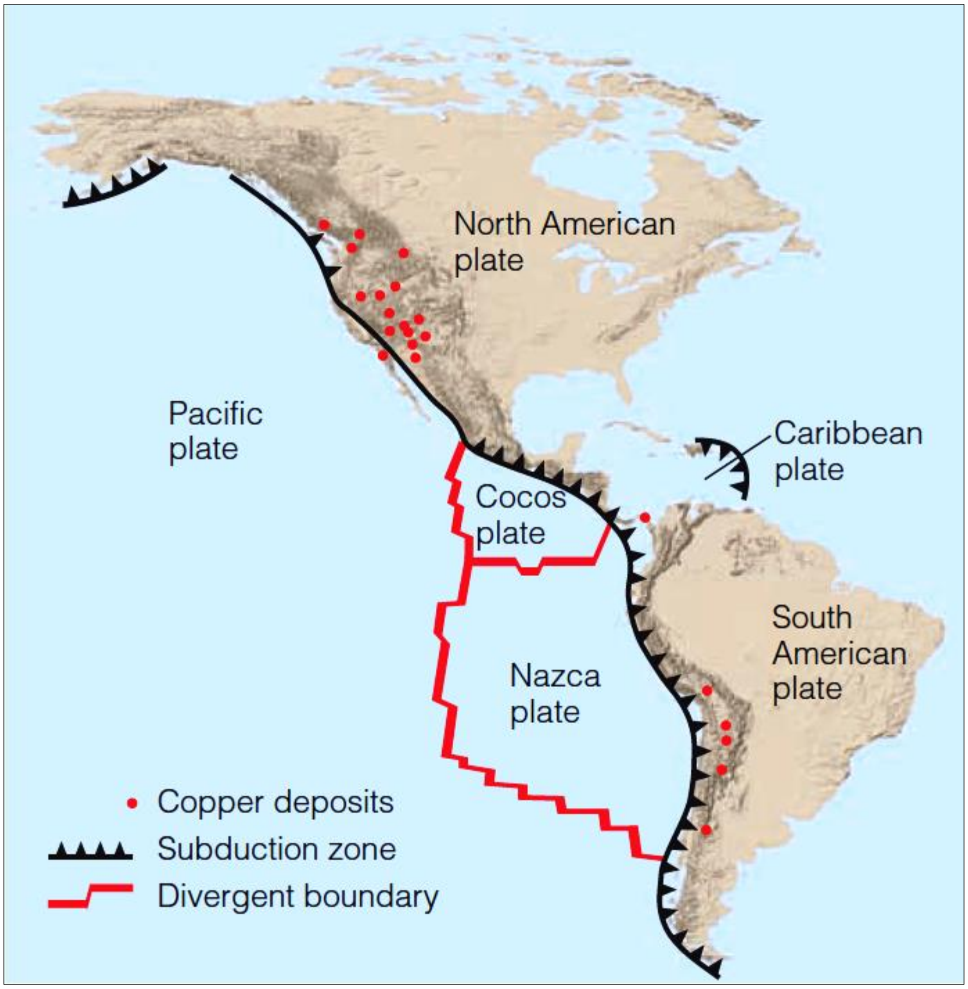


Figure 38 Copper Deposits and Convergent Plate Boundaries. Valuable copper deposits are located along the west coasts of North and South America in association with convergent plate boundaries. The rising magma and associated hydrothermal activity resulting from subduction carried small amounts of copper, which became trapped and concentrated in the surrounding rocks through time.

What is the relationship between plate boundaries and hydrocarbon accumulations?

Now there is a whole other large area of natural resource we have not even talked about yet. This is what most people think of when they hear the phrase natural resources. It is the hydrocarbons of coal, oil, and natural gas.

Coal, like diamond, also forms from carbon, yet in a very different way. Coal is a sedimentary rock that is essentially fossilized swamp and bog. It requires a particular condition where organic material is buried in an aerobic condition. In other words, an environment without a lot of free oxygen. Why is this important? Because it doesn't get eaten primarily by bacteria, before it is buried.

When most organic material, like plants, die, bacteria and other organisms eat them. The carbon then gets brought right back into the surface carbon cycle. Yet if the material sinks to the bottom of a swamp or bog, without a lot of free oxygen, it does not get eaten and gets buried and essentially gets removed from the surface carbon cycle.

Now if you have shorelines advancing and retreating, you get swamp material deposited over broad regions like shoreline sediments. Go to Florida and see the everglades. These are areas of future coal reserves. As the regions will get buried, especially with a rising sea level, all the swamp material is going to get buried over. In a few hundred million years, it will be coal, and form what we call coal seams. These are layers of coal that exist extensively horizontally like other sedimentary rocks.

The organic material that gets buried, goes through several stages of sedimentation and even metamorphosis, to get the coal that we use. The point is that you have to compact it, you have to squeeze out the other stuff and concentrate the carbon.

Now if you go to a current dry swamp, dig up the stuff, and dry it, then you get what we call peat. You go to any part of the world and people will still heat their homes using dried peat. It is about 50% carbon, so it burns. Yet it is a very dirty, smoky source of energy, because it is 50% other stuff as well!

It get compacted overtime, first becoming a coal called lignite, and then bituminous coal, and eventually anthracite. For instance, in bituminous coal, the material is about 86% carbon, and in anthracite you get up to 98% carbon, so that essentially all the other stuff has been removed and squeezed out.

Anthracite is obviously the more desired, yet it is actually the rarest. Most of the world's energy that comes from coal comes in the form of bituminous coal. Because coal requires certain geologic conditions to form, you need a swamp, it has not found everywhere. Yet because swamps and bogs have been in a lot of different places, coal is actually fairly abundant as far as resources go. Most of the coal comes from swamps and bogs that existed between two periods of time, about 300-250 million years ago, and 150-50 million years ago. Therefore, the coal that we use is really old.

Now coal is going to form continuously, yet it forms too slowly for much to occur in our lifetimes. That is why we call it a non-renewable energy source. Our coal formed back during warmer climates, when the sea level was high, continental shelves were flooded within shallow waters, and the material was buried deeply in basins, particularly if you were next to eroding mountains, and that gave us huge supplies of bituminous coal.

In particular, situations where you have metamorphism occurring, lets say in a continental collision, that bituminous coal can be converted into anthracite. The other major source of hydrocarbons, exist in petroleum, oil, and natural gas. These also come from carbon based organic materials, but an entirely different setting. Petroleum, oil, and natural gas, form from shallow marine sediments, mostly zooplankton and algae.

Unlike coal, petroleum needs special conditions not only to form, but also to survive underground. First of all, you need to rapidly bury and compact the organic sediment, and with increasing pressures and temperature, you essentially cook these sediments and begin to extract the hydrocarbons out. That process of heating and pressing the material breaks down the complex organic molecules into simpler, waxy, hydrocarbon molecules called kerogen. This is the stuff found in tar shales.

With further compaction and heating, the kerogen breaks down and forms simpler hydrocarbons, either in the liquid form of oil, or in gas, forming natural gas. However, unlike coal, oil and natural gas are mobile, lighter than rock, so they are going to rise to the surface. Almost all the petroleum that has happened in earth's history has quickly seeped right back up to the surface and back into the carbon cycle, being consumed by organisms like bacteria, and removed from the ground.

It is interesting that there is a town in western Pennsylvania called Slippery Rock. Where did this name come from? It is a place where these hydrocarbons are currently seeping right to the surface, and the rock in the streams have a slippery feel because of the presence of these hydrocarbons in the water.

Special geologic conditions are also required in order to trap these hydrocarbons underground and keep them from rising up. We talked about this previously when we discussed folding of sedimentary layers. You need either a dome-like structure or an anticline, where the sedimentary rock forms a fold that has a peak in the middle, where these liquids and gases, as they rise up, can be trapped. You need to have some sort of reservoir material that is usually both porous and permeable.

Sandstone is usually the ideal rock, and it needs to be overlain by some cap rock, an impermeable layer usually shale, so as they hydrocarbons rose up, they accumulate in the sandstone. They are covered over by the cap rock, and if you drill through the shale into the sandstone, you can quickly pull out the oil and natural gas.

Now petroleum has formed in several tectonic settings. The most common is actually in rift zones. Now we already talked about rift zones in terms of the formation of salt layers. Remember where you can have a situation where the ocean can flood into a growing ocean, like the Red Sea, that is just beginning to rift apart.

Yet if the sea level drops, the water evaporates and you end up with a layer of salt. Well when the ocean floods back in again during a period of warmer climate and higher sea levels, you get rich marine life on top of that salt layer, which then can dry out again. Overtime you get alternating layers of salt and these organic sediments.

That is exactly what happens with the Gulf of Mexico. There are rich organic sediments that formed when the Gulf of Mexico was forming, back when Africa was rifting away during the breakup of Pangea. These sediments were often trapped by the salt layers that exist on top of them.

With continental collisions, you can get the folding of rock underground, and the sedimentary layers can form large anticlines. This is what happened in the Middle East.

Arabia collided with Asia during the close-up of the Tethys Sea. Two thirds of the world’s petroleum, lies beneath a few anticlines under the Persian Gulf area. In other words, it's just the happenstance of where we are now in our plate tectonic process, of what's going on between Arabia and Africa and Asia, that has allowed the petroleum to not only occur at a period of rifting, but then to accumulate under these very broad anticlines.

Who knew hundreds of years ago, that beneath the desert sands of Arabia, would lie an ocean of oil? It is ironic that the Persian Gulf was the cradle of civilization, as we mentioned in the previous lecture. Mesopotamia, Akkadia, Sumeria, and Babylonia, and now that same region is the focal point for the world's civilization again, yet for a very different reason. That is where the petroleum is.

21 Plate Tectonics and Mountain Building

Mountain is the designation for any area of land that stands significantly higher, at least 300 m, than the surrounding country and has a restricted summit area. Some mountains are single, isolated peaks, but more commonly, they are part of a linear association of peaks and ridges known as mountain ranges that are related in age and origin. A mountain system is made up of many mountain ranges.

Types of Mountains

Generally, mountains be classified as: fold mountains, volcanic mountains, block mountains, dome mountains, and salt mountains.

1. Fold Mountains

When plates collide, the plates tend to buckle and fold, forming mountains. Most of the major continental mountain ranges are associated with thrusting and folding or orogenesis. To get a better idea of what this looks like, try to push two pieces of papers towards each other: some parts will rise up, representing the process of mountain formation.

This process is called orogeny (giving birth to mountains) and it generally takes millions of years for it to complete. Many of today's fold mountains are still developing as the tectonic process unfolds. The process does not occur on tectonic edges — sometimes the mountain-generating fold process can take place well inside a tectonic plate.

Fold mountains are the most common and most massive types of mountains (on Earth, at least). Fold mountain chains can spread over thousands of kilometers — we are talking about the Himalayas, the Alps, the Rockies, and the Andes— all the big boys. They are also relatively young (another reason they are so tall, as they have not been thoroughly eroded), but that's "young" in geological terms — still tens of millions of years.

2. Volcanic Mountains

Movements of tectonic plates create volcanoes along the plate boundaries, which erupt and form mountains. A volcanic arc system is a series of volcanoes that form near a subduction zone where the crust of a sinking oceanic plate melts and drags water down with the subducting crust.

Most volcanoes occur in a band encircling the Pacific Ocean (the Pacific Ring of Fire), and in another that extends from the Mediterranean across Asia to join the Pacific band in the Indonesian Archipelago. The most important types of volcanic mountain are composite cones or stratovolcanoes (Vesuvius, Kilimanjaro, and Mount Fuji are examples) and shield volcanoes (such as Mauna Loa on Hawaii, a hotspot volcano).

A shield volcano has a gently sloping cone due to the low viscosity of the emitted material, primarily basalt. Mauna Loa is the classic example, with a slope of 4°-6°. The composite volcano or stratovolcano has a more steeply rising cone (33°-40°), due to the higher viscosity of the emitted material, and eruptions are more violent and less frequent than for shield volcanoes.

3. Dome and Residual Mountains

Dome mountains are also the result of magmatic activity, though they are not volcanic in nature. Sometimes, a lot of magma can accumulate beneath the ground and start to swell the surface. Occasionally, this magma will not reach the surface but will still form a dome. As that magma cools down and solidifies, it is often tougher than other surrounding rocks and will eventually be exposed after millions of years of erosion. The mountain is this dome — a former accumulation of magma, which cooled, down and was exposed by erosion.

Round Mountain is a relatively recently formed dome mountain. It represents a volcanic feature of the Canadian Northern Cordilleran Volcanic Province that formed in the past 1.6 million years. Black Dome Mountain is another popular example, which is also located in Canada.

4. Block Mountains or Fault-Block Mountains

While the previous category was all about folds, this one is all about faults: geological faults, that is.

Let us revisit the previous idea for a moment. Let us say that while under pressure, some parts of a tectonic plate start to fold. As the pressure grows and grows, at one point the rock will simply break. Faults are those breaks: they are the planar fractures or discontinuities in volumes of rock. Their size can vary tremendously, from a few centimeters to mountain-sized.

Basically, when big blocks of rock are broken through faulting, some of them can get pushed up or down, thus resulting in block mountains. Higher blocks are called *horsts* and troughs are called *grabens*. Their size can also be impressive, though they're generally not as big as fold mountains because the process which generates them takes place on a smaller scale and involves less pressure. Still, the Sierra Nevada mountains (an example of block mountains), feature a block 650 km long and 80 km wide. Another good example is the Rhine Valley and the Vosges mountain in Europe. Rift valleys can also generate block mountains, as is the case in the Eastern African Rift.

It can be quite difficult to identify a block mountain without knowing its underlying geology but generally, they tend to have a steep side and a slowly sloping side.

5. Salt Mountains

The formation of a salt dome begins with the deposition of salt in a restricted marine basin. Because the flow of salt-rich seawater into the basin is not balanced by outflow, much to all water lost from the basin is via evaporation, resulting in the precipitation and deposition of salt evaporites. The rate of sedimentation of salt is significantly larger than the rate of sedimentation of clastics, but it is recognized that a single evaporation event is rarely enough to produce the vast quantities of salt needed to form a layer thick enough for salt diapirs to be formed. This indicates that a sustained period of episodic flooding and evaporation of the basin must occur. At the present day, evaporite deposits can be seen accumulating in basins that merely have restricted access but do not completely dry out; they provide an analogue to some deposits recognized in the geological record.

Over time, the layer of salt is covered with deposited sediment, becoming buried under an increasingly large overburden. The overlying sediment will undergo compaction, causing an increase in density and therefore a decrease in buoyancy. Unlike clastics, pressure has a significantly smaller effect on the density of salt due to its crystal structure and this eventually leads to it becoming more buoyant than the sediment above it. The ductility of salt initially allows it to plastically deform and flow laterally, decoupling the overlying sediment from the underlying sediment. Since the salt has a larger buoyancy than the sediment above—and if a significant faulting event affects the lower surface of the salt—the salt can begin to flow vertically, forming a salt pillow. The vertical growth of these salt pillows creates pressure on the upward surface, causing extension and faulting.

Possible forces that drive the flow of salt are differential loading on the source layer and density contrasts in the overburdening sediment. Forces that resist this flow are the mass of the roof block and the block's inherent resistance to faulting, i.e., strength. To accommodate common density contrast between the overburden sediment and the salt, beginning active diapirism, the diapir height must be more than two-thirds to three-quarters the thickness of the overburden. If the diapir is narrow, its height must be greater.

Eventually, over millions of years, the salt will pierce and break through the overlying sediment, first as a dome-shaped, and then a mushroom-shaped, fully formed salt diapir. If the rising salt diapir breaches the surface, it can become a flowing salt glacier. In cross section, these large domes may be anywhere from 1 to 10 km across, and extend as deep as 6.5 km.

Mountain Building

Now we turn our attention to the truly large mountain systems on the continents—the Appalachian Mountains of North America, the Andes in South America, the Himalayas in Asia, and the Alps of Europe. All these mountain systems formed at convergent plate boundaries and, although each system is unique, they share several characteristics. In fact, geologists call an episode of mountain building an orogeny during which intense deformation takes place, usually in response to compression, accompanied by metamorphism, the emplacement of plutons, and local thickening of Earth’s crust.

Any theory that accounts for orogeny must adequately explain the characteristics of mountain systems, such as their geometry and location. Most mountain ranges tend to be long and narrow and with few exceptions are at or near continental margins. Mountain systems also show intense deformation, especially compression-induced overturned and recumbent folds as well as reverse and thrust faults. Furthermore, granitic plutons and regional metamorphism are found in the interiors or cores of mountain systems. Finally, many have sedimentary rocks now far above sea level that were clearly deposited in marine environments.

Although not all aspects of orogenies are fully understood, geologists are convinced that plate tectonic theory provides an adequate explanation for many features of mountain systems. Convergence of lithospheric plates accounts for the geometry and location of mountain systems as well as the complex geologic structures, plutons, metamorphism, and crustal thickening. Yet the presentday topographic expression of mountains is also related to erosion by surface processes such as mass wasting (gravity driven processes including landslides), running water, and glaciers.

Most of Earth's geologically recent and ongoing orogenies are found in two major zones or belts: the Alpine–Himalayan orogenic belt and the circum-Pacific orogenic belt (Figure 39). Each belt consists of a number of smaller segments known as orogens, each of which is an area of deformation. In fact, most of Earth's past and present orogenies take place at convergent plate boundaries, but convergent boundaries may be oceanic–oceanic, oceanic–continental, or continental–continental.

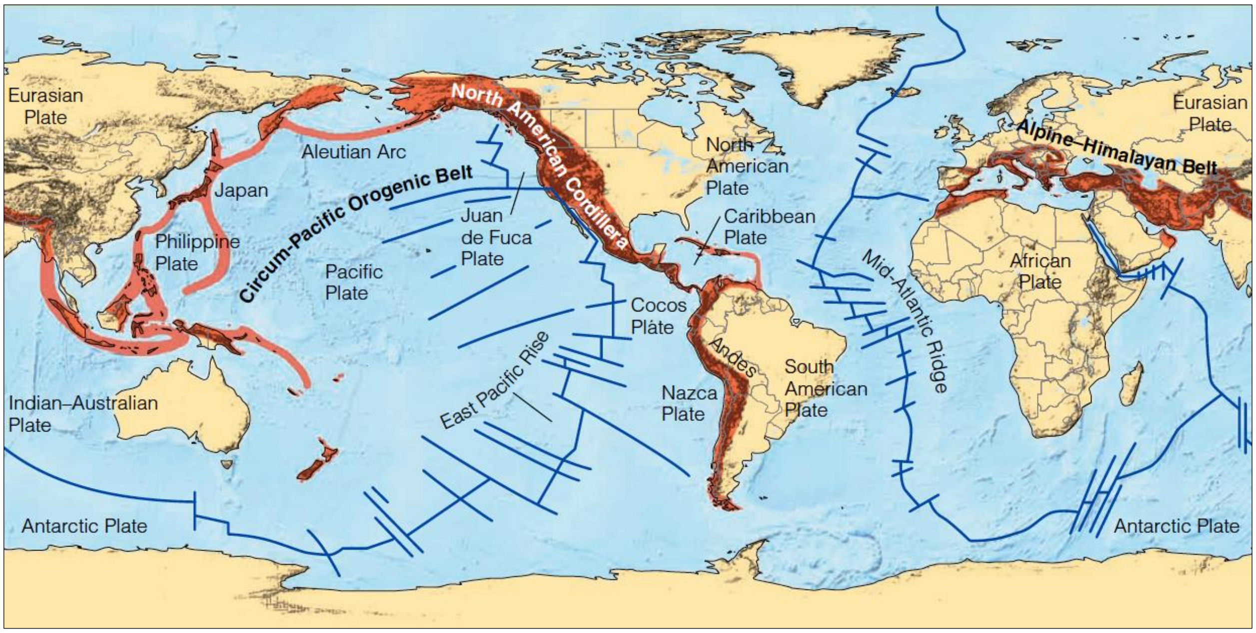


Figure 39 Present-Day Orogenic Activity. Most of Earth's geologically recent and present-day orogenic activity is concentrated in the circum-Pacific and Alpine–Himalayan orogenic belts.

1. Orogenies at Oceanic–Oceanic Plate Boundaries

Deformation, igneous activity, and the origin of a volcanic island arc characterize orogenies that take place where oceanic lithosphere is subducted beneath oceanic lithosphere. Sediments derived from the evolving island arc are deposited in an adjacent oceanic trench, and then deformed and scraped off against the landward side of the trench (Figure 40). These deformed sediments are part of a subduction complex, or accretionary wedge, of intricately folded rocks cut by numerous thrust faults. In addition, orogenies in this setting show the low-temperature, high-pressure metamorphism of the blueschist facies.

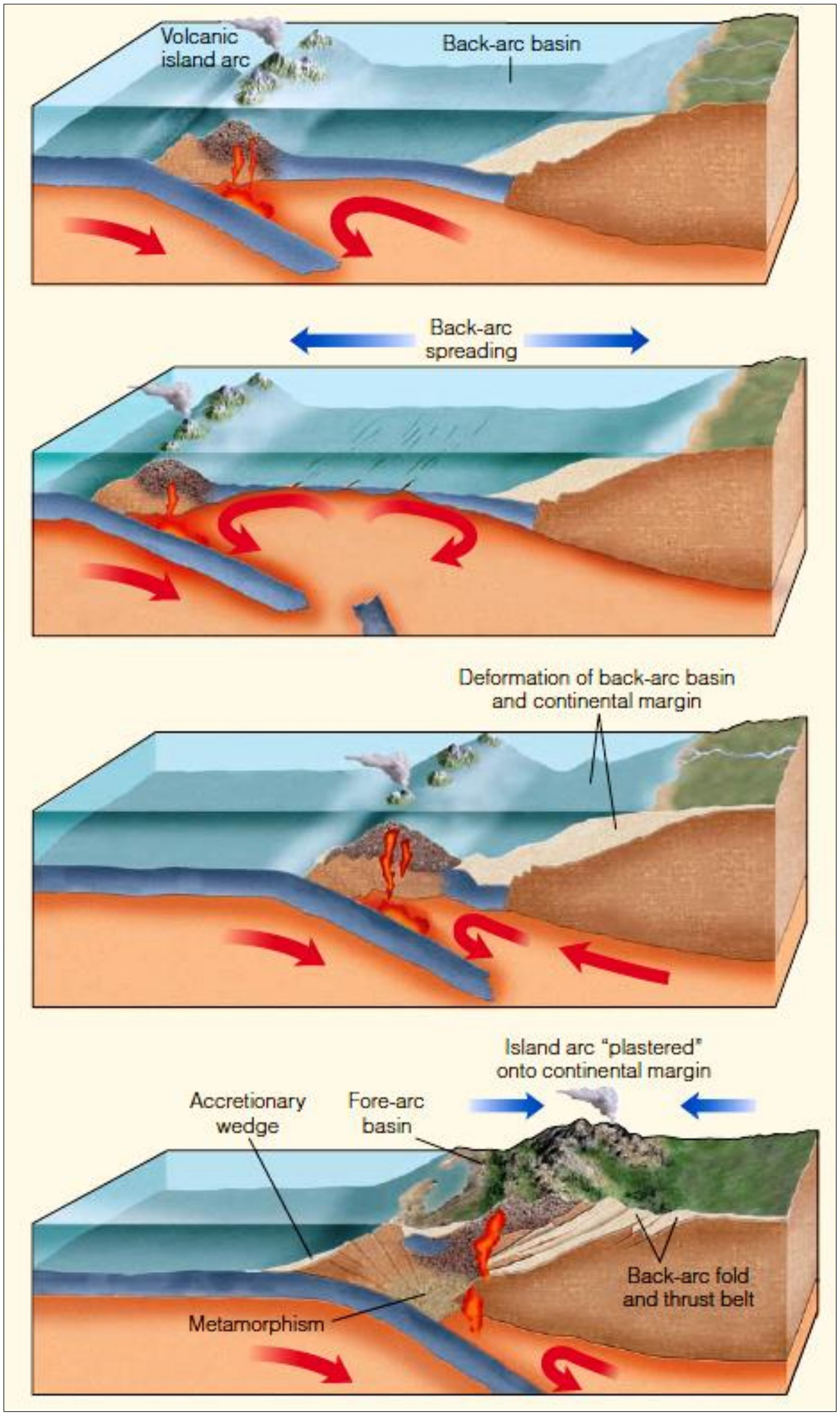


Figure 13.20 Orogeny and the Origin of a Volcanic Island Arc at an Oceanic–Oceanic Plate Boundary. (1) Subduction of an oceanic plate and the origin of a volcanic island arc and a back-arc basin. (2) Continued subduction and back-arc spreading. (3) Back-arc basin begins to close, resulting in deformation of back-arc basin and continental margin deposits. (4) Thrusting of back-arc sediments onto the adjacent continent and suturing of the island arc to the continent.

Emplacement of plutons also causes deformation in the island arc system, and many of the rocks show the effects of high-temperature, low-pressure metamorphism. The overall effect of an island arc orogeny is the origin of two more or less parallel belts consisting of a landward volcanic island arc intruded by batholiths and a seaward belt of deformed trench rocks (Figure 40). The Japanese islands are a good example of this type of orogeny.

In addition to deformation in the island arc, volcanic rocks and sediments deposited in the back-arc basin, the area between the island arc and its nearby continent, are also deformed, especially along low-angle thrust faults, as plate convergence continues. Eventually the entire island arc complex is fused to the edge of the continent, and the back-arc basin sediments are thrust onto the continent (Figure 40).

2. Orogenies at Oceanic–Continental Plate Boundaries

The Andes Mountains in South America are the best example of a continuing orogeny at an oceanic–continental plate boundary (Figure 41). Among the ranges of the Andes are many active volcanoes and the highest peaks in the world except for the Himalayas in Asia. In addition, the west coast of South America is a very active part of the circum-Pacific earthquake belt, and one of Earth's great oceanic trenches, the Peru–Chile Trench, lies just off the west coast.

Prior to 200 million years ago, the western edge of South America was a passive continental margin much like its eastern margin is now. When Pangaea started to separate along the Mid-Atlantic Ridge, however, the South American plate began moving west and oceanic lithosphere began subducting beneath the continent along its western margin (Figure 41). What had been a passive continental margin was now an active one and partial melting of the subducted plate yielded magma that rose to form huge batholiths and a chain of andesitic volcanoes.

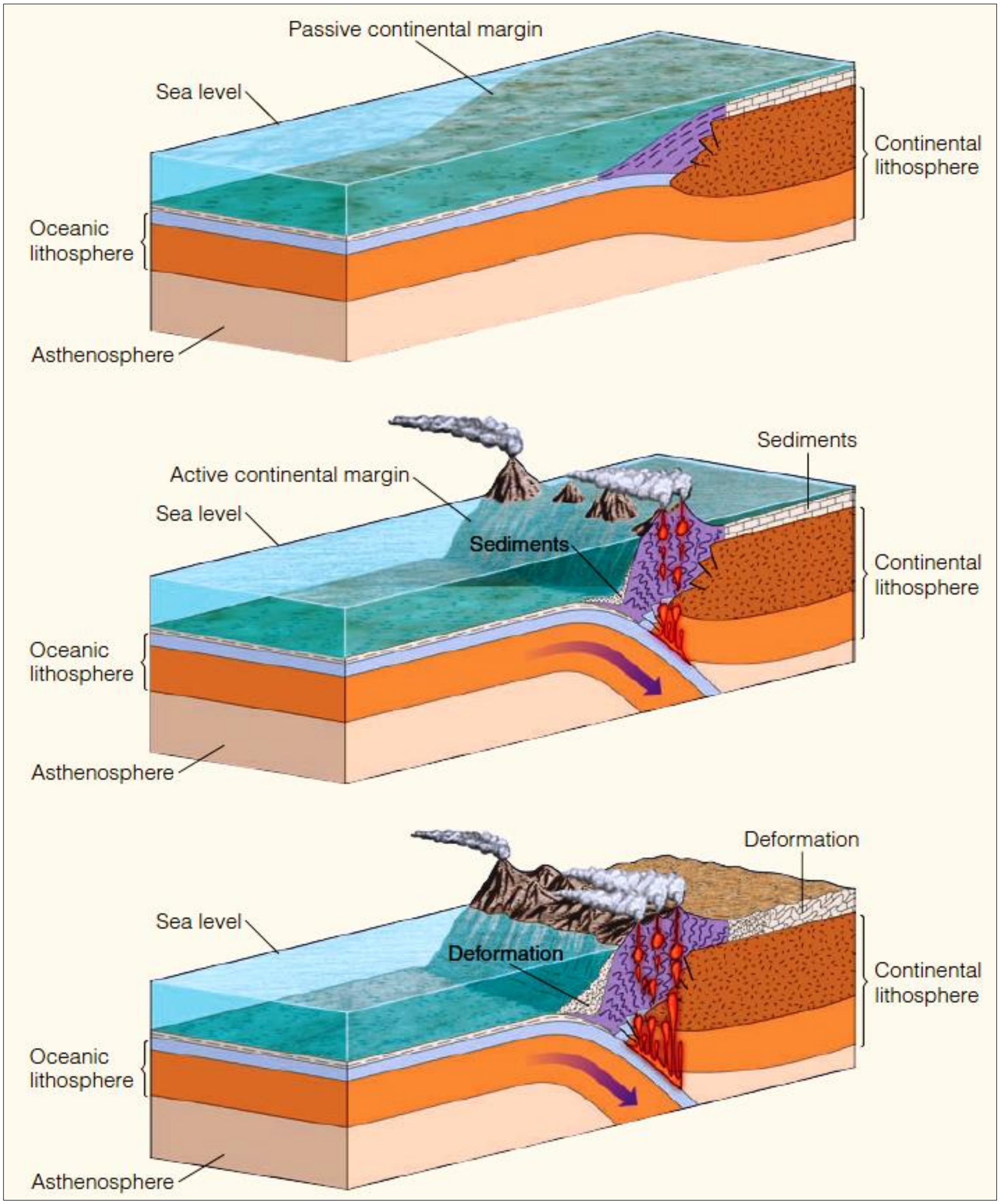


Figure 41 Stages of Development of the Andes at an Oceanic–Continental Plate Boundary. (1) Prior to 200 million years ago, the west coast of South America was a passive continental margin. (2) An orogeny began when the west coast of South America became an active continental margin. (3) Continued deformation, volcanism, and plutonism.

As a result of the events described above, the Andes consist of a central core of granitic rocks capped by andesitic volcanoes. To the west of the central core lie deformed rocks of an accretionary wedge, and to the east are folded sedimentary rocks that were thrust eastward onto the continent (Figure 41). Continuing volcanism and seismic activity along South America's western margin indicate that the Andes remain an evolving mountain system.

3. Orogenies at Continental–Continental Plate Boundaries

Several areas of colliding continents and the origin of mountain systems are well documented, but the best example taking place now is the Himalayas in Asia. Before this vast mountain system began to form, India lay far to the south and was separated from Asia by an ocean basin (Figure 42a). At this stage of development, there was a subduction zone along Asia's southern edge, partial melting generated magma that rose to form a volcanic arc, and large granitic plutons were emplaced in what is now Tibet. In short, it was much like the present situation along the west coast of South America.

As the ocean separating India from Asia continued to close, India eventually collided with Asia and what had been two continental plates were sutured together (Figure 42b). Thus, the Himalayas are within a continent, far from a continental margin. This collision probably began 40 to 50 million years ago because at that time India's northward rate of movement decreased abruptly from 15–20 cm per year to about 5 cm per year. Continental lithosphere is less dense than oceanic lithosphere, so this decrease marks the time of collision and India's resistance to subduction.

As a result of this continental–continental collision, the leading margin of India has been thrust 2000 km beneath Asia and continues moving north at about 5 cm per year. Sedimentary rocks that were deposited in the sea south of Asia were thrust northward, and two large thrust faults carried rocks of Asian origin onto the Indian plate (Figure 42b). In short, tremendous deformation occurred and Earth's crust was thickened and uplifted far above sea level (remember the principle of isostasy). In fact, sedimentary rocks that formed in shallow seas now make up the higher part of the Himalayas.

Other mountain systems with a similar history of continental–continental collision are the Urals in Russia and the ongoing collision of the Arabian plate with Asia along the Zagros Mountains of Iran. Even the Appalachian mountain system formed in a similar manner during the assembly of Pangaea, although subsequent rifting has separated this landmass.

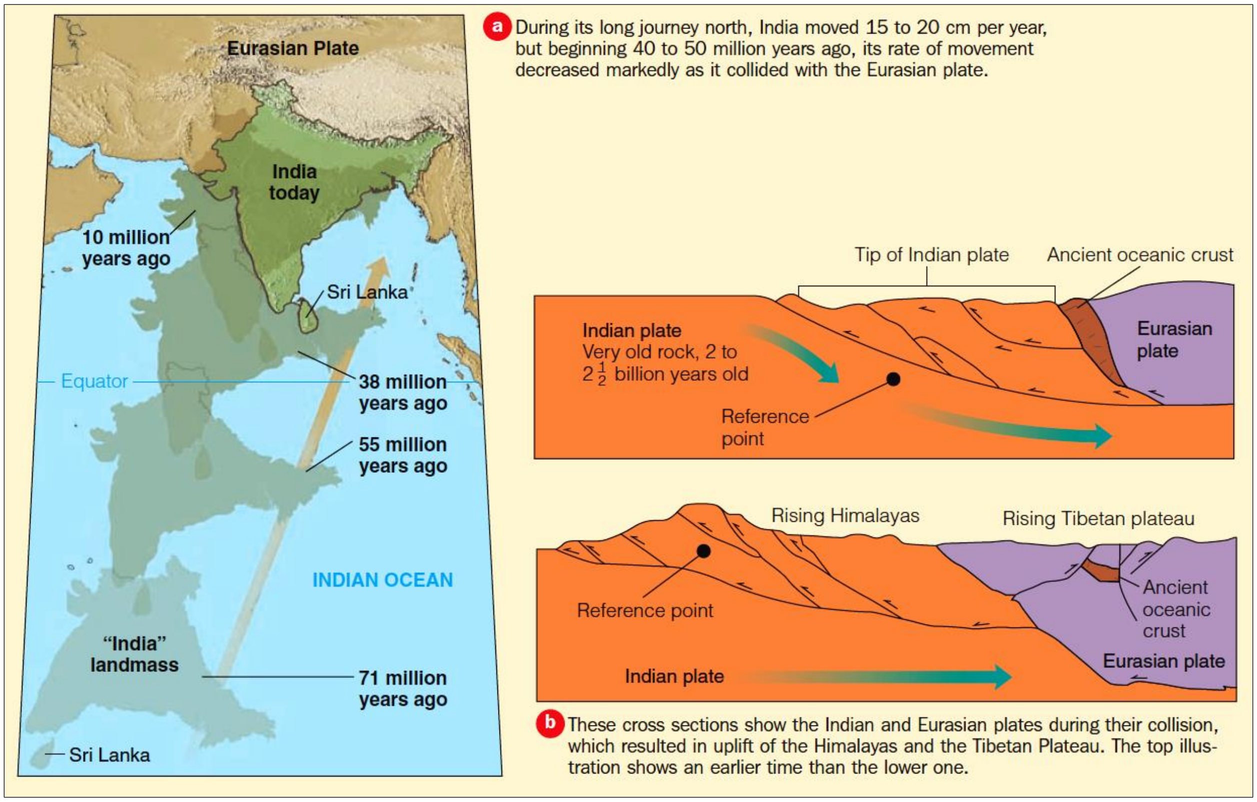


Figure 42 Orogeny at a Continental–Continental Plate Boundary and the Origin of the Himalayas of Asia

22 The Formation and Evolution of Continents

If we could somehow go back and visit Earth shortly after it formed 4.6 billion years ago, we would see a hot, barren, waterless planet bombarded by comets and meteorites, no continents, intense cosmic radiation, and ubiquitous volcanism. Judging from the oldest known rocks, the 3.96-billion-year-old Acasta Gneiss in Canada and ancient rocks in Montana, some continental crust existed by that time. And sedimentary rocks in Australia contain detrital zircons ($ZrSiO4$) dated at 4.2 billion years, so source rocks at least this old existed.

Terranes and the evolution of continents

Much of the material added to continental margins is eroded older continental crust, but some plutonic and volcanic rocks are new additions. During the 1970s and 1980s, however, geologists discovered that parts of many mountain systems are also made up of small, accreted lithospheric blocks that clearly originated elsewhere. These *terranes*, as they are called, are fragments of seamounts, island arcs, and small pieces of continents that were carried on oceanic plates that collided with continental plates, thus adding them to the continental margins (Figure 43). Therefore, terranes are mostly new additions to continents rather than reworked older continental material.

Geologic evidence indicates that much of the Pacific margin of North America from Alaska to Baja California is made up of accreted terranes or igneous intrusions. According to one estimate, more than 100 terranes have been added along the West Coast during the last 200 million years (Figure 43). Numerous potential terranes such as seamounts and aseismic ridges are present in the ocean basins today.

Most terranes identified so far are in the mountains of western North America, but a number of others are probably present in other mountain systems. About a dozen terranes have been identified in the Appalachian Mountains, but they are more difficult to identify in older mountain systems.

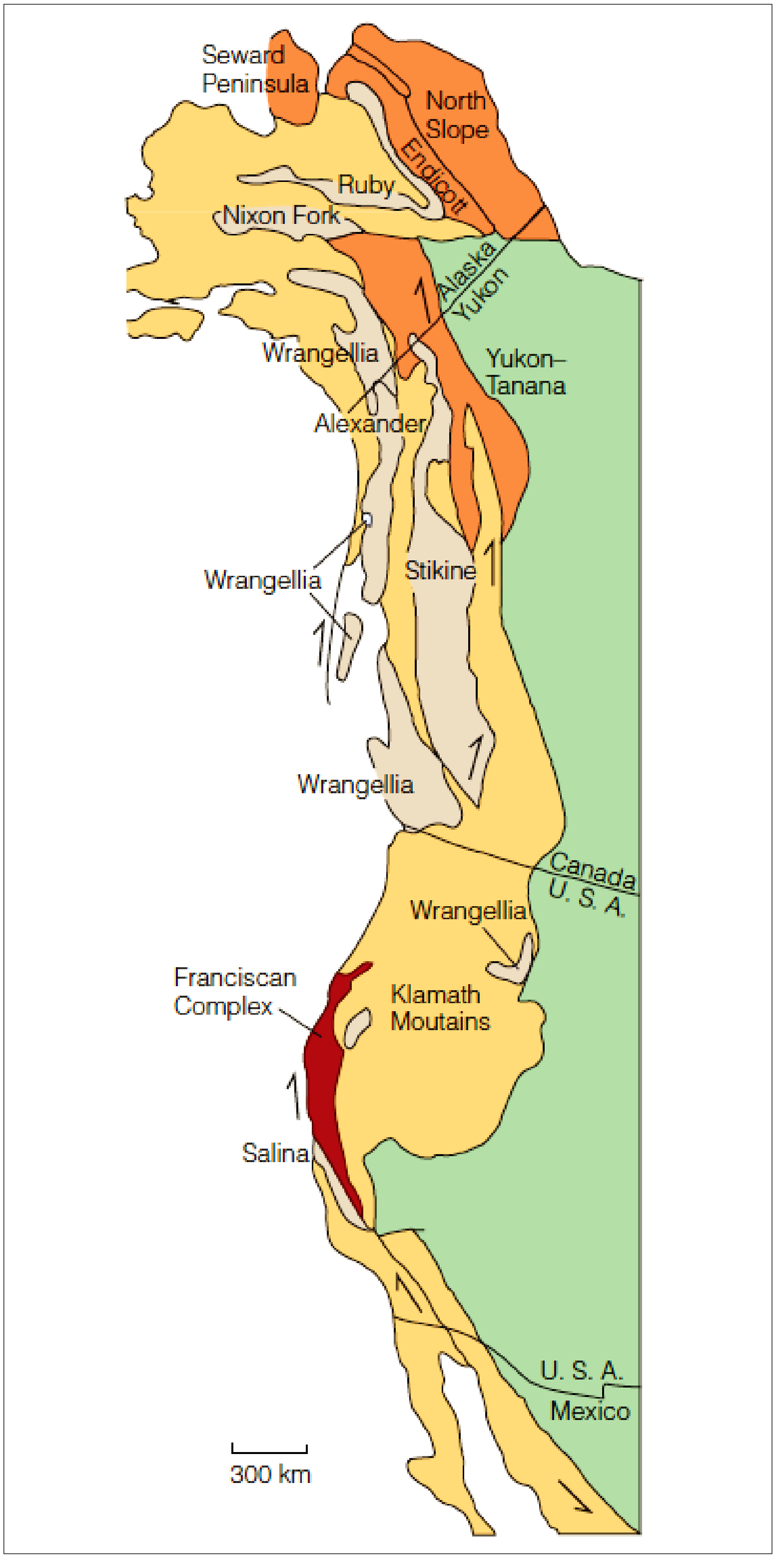


Figure 43 The Origin of Terranes Some of the accreted lithospheric blocks called terranes that form the western margin of North America. The light brown blocks probably originated as parts of continents other than North America. The reddish brown blocks are possibly displaced parts of North America. The Franciscan Complex consists of a variety of seafloor rocks.

Shields, Platforms, and Cratons

Continents are more than simply land areas above sea level. You already know that they have an overall composition similar to granite and that continental crust is thicker and less dense than oceanic crust, which is made up of basalt and gabbro. In addition, a shield consisting of a vast area or areas of exposed ancient (Precambrian) rocks is found on all continents. Continuing outward from shields are broad platforms of buried ancient rocks, merely extensions of the shields, that underlie much of each continent. Collectively, a shield and platform made up a craton, which we can think of as a continent's ancient nucleus (Figure 44).

The cratons are the foundations of the continents, and along their margins more continental crust was added as they evolved to their present size and shapes, a phenomenon called continental accretion. Many of the rocks along the margins of the cratons show evidence of deformation accompanied by metamorphism, igneous activity, and mountain building. In North America the exposed part of the craton is the Canadian shield, which occupies most of northeastern Canada, a large part of Greenland, the Adirondack Mountains of New York, and parts of the Lake Superior region of Minnesota, Wisconsin, and Michigan.

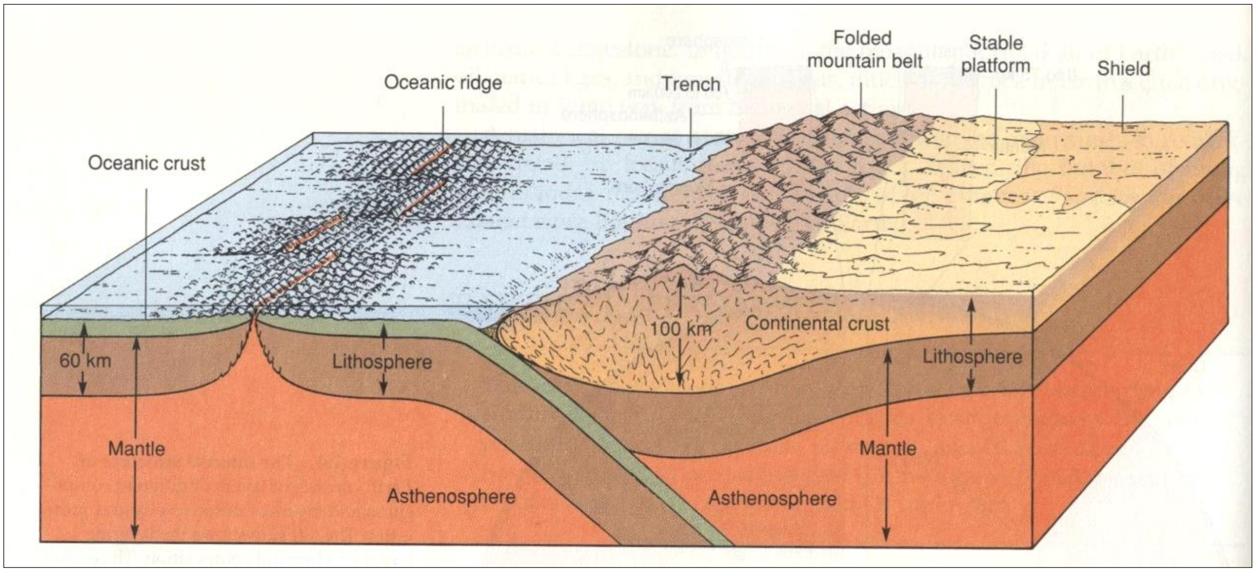


Figure 44 Features of oceanic and continental crusts.

Floating Continents—The Principle of Isostasy

We previously said that Earth's crust and mantle are solids except for pockets of magma, so how is it possible for a solid (continental crust) to float in another solid (the mantle)? Floating brings to mind a ship at sea or a block of wood in water, but continents certainly do not behave in this fashion. Or do they? Actually, they do float, in a manner of speaking, in the denser mantle below, but a complete answer requires much more discussion.

More than 150 years ago, British surveyors in India detected a discrepancy of 177 m when they compared the results of two measurements between points 600 km apart. Even though this discrepancy was small, only about 0.03%, it was an unacceptably large error. The surveyors realized that the gravitational attraction of the nearby Himalaya Mountains probably deflected the plumb line (a cord with a suspended weight) of their surveying instruments from the vertical, thus accounting for the error. Calculations revealed, however, that if the Himalayas were simply thicker crust piled on denser material, the error should have been greater than that observed (Figure 45a).

In 1865 George Airy proposed that, in addition to projecting high above sea level, the Himalayas—and other mountains as well—project far below the surface and thus have a low-density root (Figure 45b). In effect, he was saying that mountains float on denser rock at depth. Their excess mass above sea level is compensated for by a mass deficiency at depth, which would account for the observed deflection of the plumb line during the British survey (Figure 45).

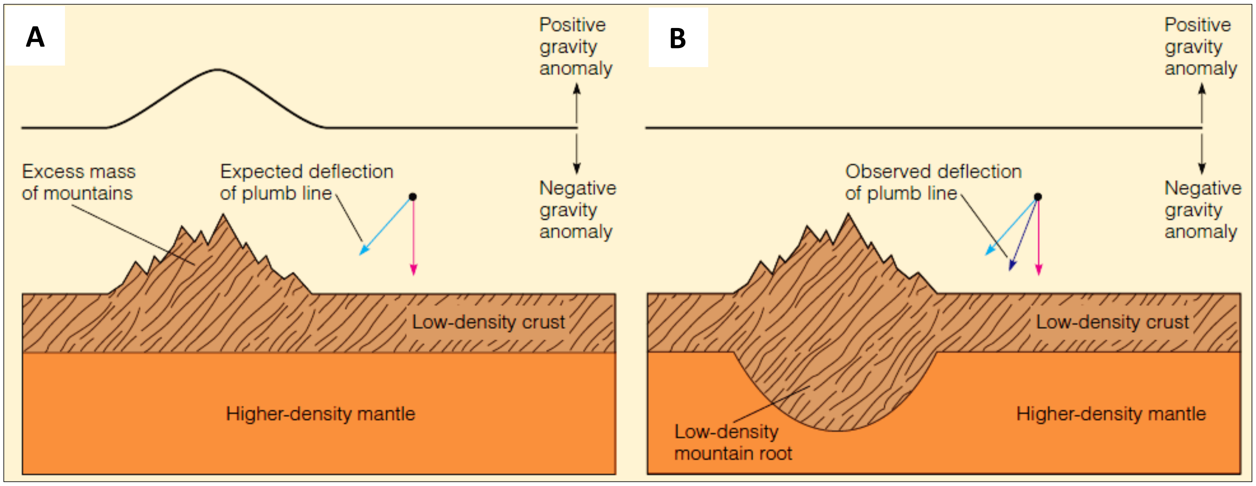


Figure 45 Hypothetical and Actual Deflection of a Plumb Line during a Survey in India. (A) A plumb line is normally vertical, pointing to the Earth's center of gravity. Near a mountain range, the plumb line should be deflected as shown if the mountains are simply thicker, low-density material resting on denser material, and a gravity survey across the mountains would indicate a positive gravity anomaly. (B) The actual deflection of the plumb line during the survey in India was less than expected. This was explained by postulating that the Himalayas have a low-density root. A gravity survey in this case would show no anomaly because the mass of the mountains about the surface is compensated for at depth by low-density material displacing denser material.

Another explanation was proposed by J. H. Pratt, who thought that the Himalayas were high because they were composed of rocks of lower density that those in adjacent regions. Although Airy was correct with respect to the Himalayas, and mountains in general, Pratt was correct in that there are indeed places where the crust's elevation is related to its density. For example, (1) continental crust is thicker and less dense than oceanic crust and thus stands high, and (2) the mid-oceanic ridges stand higher than adjacent areas because the crust there is hot and less dense than cooler oceanic crust elsewhere.

Gravity and seismic studies have revealed that mountains do indeed have a low-density "root" projecting deep into the mantle. If it were not for this low-density root, a gravity survey across a mountainous area would reveal a huge positive gravity anomaly. The fact that no such anomaly exists indicates that a mass excess is not present, so some of the dense mantle at depth must be displaced by lighter crustal rocks, as shown in Figure 45b.

Both Airy and Pratt agreed that Earth's crust is in floating equilibrium with the more dense mantle below, and now their proposal is known as *the principle of isostasy*. This phenomenon is easy to understand by analogy to a ship or an iceberg. Ice is slightly less dense than water, and thus it floats. According to Archimedes's principle of buoyancy, an iceberg sinks in water until it displaces a volume of water whose weight is equal to that of the ice. When the iceberg has sunk to an equilibrium position, only about 10% of its volume is above water level. If some of the ice above water level should melt, the iceberg rises in order to maintain the same proportion of ice above and below water.

Earth's crust is similar to the iceberg, or a ship, in that it sinks into the mantle to its equilibrium level. Where the crust is thickest, as beneath mountain ranges, it sinks farther down into the mantle but also rises higher above the equilibrium surface. Continental crust, being thicker and less dense than oceanic crust, stands higher than the ocean basins. Earth's crust responds isostatically to widespread erosion and sediment deposition (Figure 45). It also responds to loading when vast glaciers form and depress the crust into the mantle to maintain equilibrium. In Greenland and Antarctica, the crust has been depressed below sea level by the weight of glacial ice.

If the principle of isostasy is correct, it implies that the mantle behaves like a liquid. In preceding discussions, though, we said that the mantle must be solid because it transmits S-waves, which will not move through a liquid. How can this apparent paradox be resolved? When considered in terms of the short time necessary for S-waves to pass through it, the mantle is indeed solid. But when subjected to stress over long periods, it yields by flowage and at these timescales is a viscous liquid. Silly Putty, a familiar substance that has the properties of a solid or a liquid depending on how rapidly deforming forces are applied, will flow under its own weight if given enough time, but shatters as a brittle solid if struck a sharp blow.

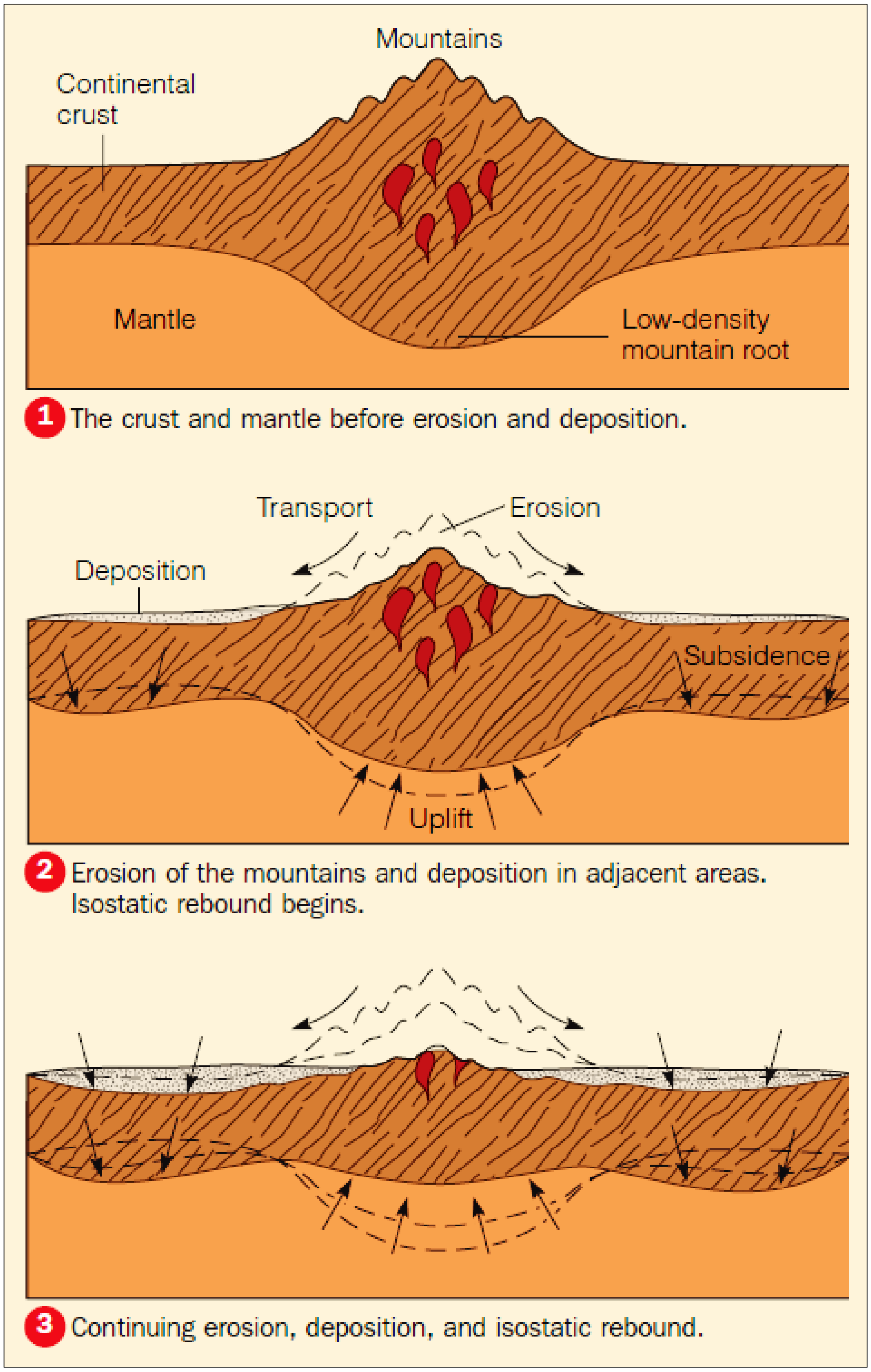


Figure 45 A Diagrammatic Representation Showing the Isostatic Response of Earth's Crust to Erosion (Unloading) and Widespread Deposition (Loading)

23 The Continental Margins

Many people perceive of continents as land areas outlined by sea level or, put another way, that part of Earth's crust that is not submerged by the oceans. The true margin of a continent—that is, where granitic continental crust changes to oceanic crust made up of basalt and gabbro—is found below sea level. Thus, the continental margin is the submerged outer edge of a continent; it separates those parts of continents above sea level from the deep seafloor.

A continental margin is made up of a gently sloping continental shelf, a more steeply inclined continental slope, and in some cases, a deeper, gently sloping continental rise (Figure 46). Seaward of the continental margin lies the deep-ocean basin. Thus, the continental margins extend to increasingly greater depths until they merge with the deep seafloor. Continental crust changes to oceanic crust somewhere beneath the continental rise, so part of the continental slope and the continental rise actually rest on oceanic crust.

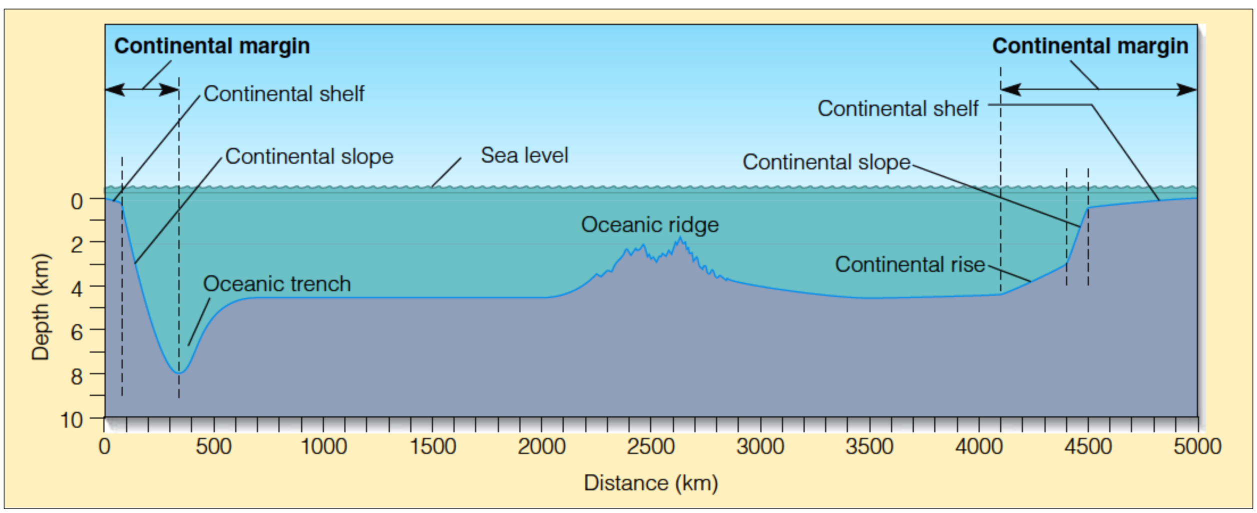


Figure 46 Features of a Continental Margin. A generalized profile of the seafloor showing features of the continental margins. The vertical dimensions of the features in this profile are greatly exaggerated because the vertical and horizontal scales differ.

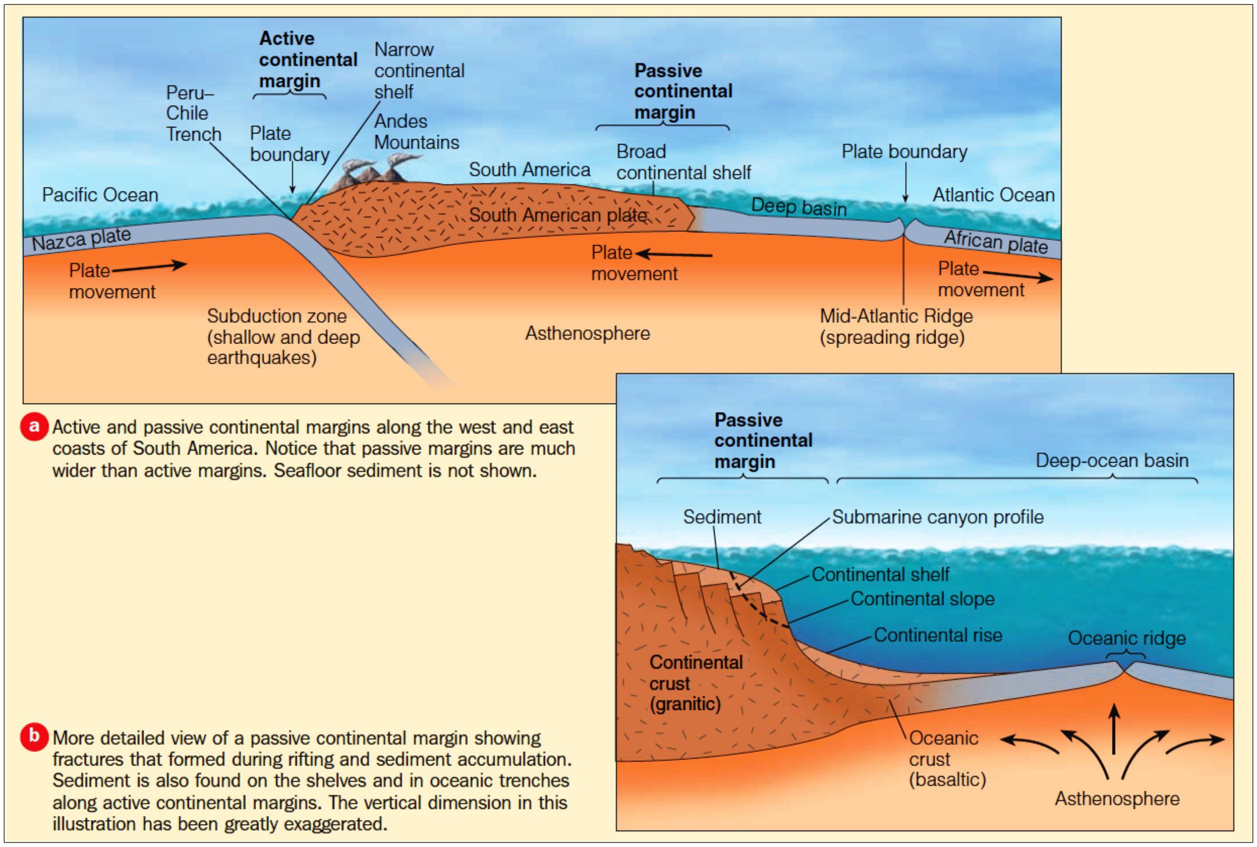
Types of Continental Margins

How do active and passive continental margins compare?

Continental margins are active or passive, depending on their relationship to plate boundaries. An active continental margin develops at the leading edge of a continental plate where oceanic lithosphere is subducted (Figure 47). The western margin of South America is a good example. Here, an oceanic plate is subducted beneath the continent, resulting in seismic activity, a geologically young mountain range, and active volcanism. In addition, the continental shelf is narrow, and the continental slope descends directly into the Peru–Chile Trench, so sediment is dumped into the trench and a continental rise does not develop. The western margin of North America is also considered an active continental margin, although much of it is now bounded by transform faults rather than a subduction zone. However, plate convergence and subduction still take place in the Pacific Northwest along the continental margins of northern California, Oregon, and Washington.

The continental margins of eastern North America and South America differ considerably from their western margins. For one thing, they possess broad continental shelves as well as a continental slope and rise; also, vast, flat areas known as abyssal plains are present adjacent to the rises (Figure 47). Furthermore, these passive continental margins are within a plate rather than at a plate boundary. The continental margin for eastern North America, for example, is far from the boundary of the North American plate, which is at the Mid-Atlantic Ridge. In addition, passive continental margins have no active volcanoes and seismicity is minimal, although large earthquakes do occur occasionally—the 1886 Charleston, South Carolina, earthquake, for example.

Active and passive continental margins are notably different in the widths of their continental shelves, and active margins have an oceanic trench but no continental rise. Why the differences? At both types of continental margins, turbidity currents transport sediment into deeper water. At passive margins, the sediment forms a series of overlapping submarine fans and thus develops a continental rise, whereas at an active margin, sediment is simply dumped into the trench, where much of it is eventually subducted, and no rise forms. The proximity of a trench to a continent also explains why the continental shelves of active margins are so narrow. In contrast, land-derived sedimentary deposits at passive margins have built a broad platform extending far out into the ocean.



a Active and passive continental margins along the west and east coasts of South America. Notice that passive margins are much wider than active margins. Seafloor sediment is not shown.

b More detailed view of a passive continental margin showing fractures that formed during rifting and sediment accumulation. Sediment is also found on the shelves and in oceanic trenches along active continental margins. The vertical dimension in this illustration has been greatly exaggerated.

Figure 47 Passive and Active Continental Margins.

24 Features Found in the Deep-Ocean Basins

Investigations during the 1800s revealed that the seafloor has broad plateaus and ridges, but the prevailing view was that it was mostly a flat, featureless plain. In fact, it does have flat, featureless plains, but we now know that it also has submarine mountains, plateaus, canyons, volcanoes, trenches, and huge fractures. In short, the seafloor has varied topography much like the continents do. Of course, we know less about the seafloor than the continents because it is more difficult to observe.

The oceans average more than 3.8 km deep, so most of the seafloor lies far below the depth of sunlight penetration, which is rarely more than 100 m. Accordingly, most of the seafloor is completely dark, the temperature is just above 0° C, and the pressure varies from 200 to more than 1000 atmospheres depending on depth, enough to squash a full grown adult down to the size of a grapefruit. Scientists in submersibles have descended to the greatest oceanic depths, the oceanic ridges, and elsewhere, so some of the seafloor has been observed. Nevertheless, much of the deep-ocean basin has been studied only by echo sounding, seismic profiling, sediment and oceanic crust sampling, and remote devices that have descended in excess of 11,000 m.

Abyssal Plains

Why are abyssal plains found mostly near passive continental margins?

Beyond the continental rises of passive continental margins are abyssal plains, flat surfaces covering vast areas of the seafloor. In some places, they are interrupted by peaks rising more than 1 km, but they are nevertheless the flattest, most featureless areas on Earth (Figure 48). The flat topography is a result of sediment deposition; where sediment accumulates in sufficient quantities it buries the rugged seafloor.

Seismic profiles and seafloor samples reveal that abyssal plains are covered with fine-grained sediment derived mostly from the continents and deposited by turbidity currents. Abyssal plains are invariably found adjacent to the continental rises, which are composed mostly of overlapping submarine fans that owe their origin to deposition by turbidity currents. Along active continental margins, sediments derived from the shelf and slope are trapped in an oceanic trench, and abyssal plains fail to develop. Accordingly, abyssal plains are common in the Atlantic Ocean basin but rare in the Pacific Ocean basin (Figure 48).

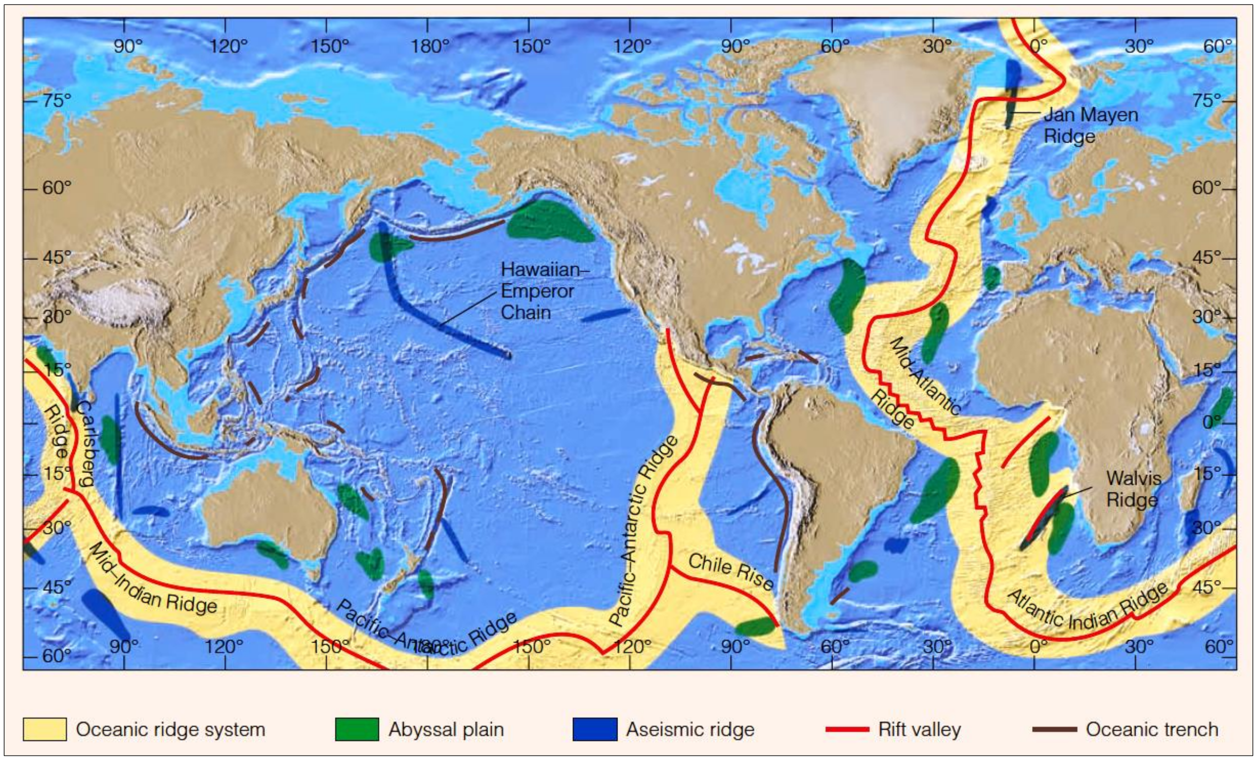


Figure 48 Deep Seafloor Features. Features found on the deep seafloor include oceanic trenches (brown), abyssal plains (green), the oceanic ridge system (yellow), rift valleys (red), and some aseismic ridges (blue). Other features such as seamounts and guyots are shown in Figure 50.

Oceanic Trenches

Oceanic trenches constitute a small percentage of the seafloor, probably less than 2%, but they are very important, for it is here that lithospheric plates are consumed by subduction. Oceanic trenches are long, narrow features restricted to active continental margins, so they are common around the margins of the Pacific Ocean basin (Figure 48). For instance, the 8000-m-deep Peru–Chile Trench west of South America is 5900 km long but only 100 km wide. On the landward side of oceanic trenches, the continental slope descends at angles of up to 25 degrees. Oceanic trenches are also the sites of the greatest oceanic depths; a depth of more than 11,000 m has been recorded in the Challenger Deep of the Marianas Trench in the Pacific Ocean.

Oceanic trenches show anomalously low heat flow compared with other areas of oceanic crust, indicating that the crust at trenches is cooler and slightly more dense than elsewhere. Gravity surveys across trenches reveal huge negative gravity anomalies because the crust is not in isostatic equilibrium. In fact, oceanic crust at trenches is subducted, giving rise to Benioff-Wadati zones in which earthquake foci become progressively deeper in the direction the subducted plate descends. These inclined seismic zones account for most intermediate- and deep-focus earthquakes—such as the June 1994 magnitude–8.2 earthquake in Bolivia, which had a focal depth of 640 km. Finally, subduction at oceanic trenches also results in volcanism, either as an arcuate chain of volcanic islands on oceanic crust or as a chain of volcanoes along the margin of a continent, as in western South America.

Oceanic Ridges

When the first submarine cable was laid between North America and Europe during the late 1800s, a feature called the Telegraph Plateau was discovered in the North Atlantic. Using data from the 1925–1927 voyage of the German research vessel Meteor, scientists proposed that the plateau was actually a continuous ridge extending the length of the Atlantic Ocean basin. Subsequent investigations revealed that this proposal was correct, and we now call this feature the Mid-Atlantic Ridge (Figure 48).

The Mid-Atlantic Ridge is more than 2000 km wide and rises 2 to 2.5 km above the adjacent seafloor. Furthermore, it is part of a much larger oceanic ridge system of mostly submarine mountainous topography. It runs from the Arctic Ocean through the middle of the Atlantic, curves around South Africa where the Indian Ridge continues into the Indian Ocean, then the Pacific–Antarctic Ridge extends eastward and a branch of this, the East Pacific Rise, trends northeast until it reaches the Gulf of California (Figure 48). The entire system is at least 65,000 km long, far longer than any mountain range on land. Oceanic ridges are composed almost entirely of basalt and gabbro and possess features produced by tensional forces, such as long, deep fractures. Mountain ranges on land, in contrast, consist of igneous, metamorphic, and sedimentary rocks, and formed when rocks were folded and fractured by compressive forces.

Oceanic ridges are mostly below sea level, but they rise above the sea in Iceland, the Azores, Easter Island, and several other places. Of course, oceanic ridges are the sites where new oceanic crust is generated and plates diverge. The rate of plate divergence is important because it determines the cross-section profile of a ridge. For example, the Mid-Atlantic Ridge has a comparatively steep profile because divergence is slow, allowing the new oceanic crust to cool, shrink, and subside closer to the ridge crest than it does in areas of faster divergence such as at the East Pacific Rise. A ridge may also have a rift along its crest that opens in response to tension. A rift is particularly obvious along the Mid-Atlantic Ridge but is absent along parts of the East Pacific Rise. Rifts are commonly 1 to 2 km deep and several kilometers wide. They open as seafloor spreading takes place and are characterized by shallow-focus earthquakes, basaltic volcanism, and high heat flow.

Even though most oceanographic research is still done by echo sounding, seismic profiling, and seafloor sampling, scientists have been making direct observations of oceanic ridges and their rifts since 1974. As part of project FAMOUS (French- American Mid-Ocean Undersea Study), submersibles have descended to the ridges and into their rifts in several areas. Researchers have not seen any active volcanism, but they have seen pillow lavas, lava tubes, and sheet lava flows, some of which formed very recently. In fact, on return visits to a site they have seen the effects of volcanism that occurred since their last visit. And on January 25, 1998, submarine Axial Volcano began erupting along the Juan de Fuca Ridge west of Oregon.

Seafloor Fractures

Oceanic ridges do not wind without interruption around the globe. They abruptly terminate where they are offset along fractures oriented more or less at right angles to ridge axes (Figure 49). These fractures run for hundreds of kilometers, although they are difficult to trace where buried beneath seafloor sediments. Many geologists are convinced that some geologic features on continents can best be accounted for by the extension of these fractures into continents.

Where oceanic ridges are offset, they are characterized by shallow seismic activity only in the area between the displaced ridge segments (Figure 49). Furthermore, because ridges are higher than the seafloor adjacent to them, the offset segments yield vertical relief on the seafloor. Nearly vertical escarpments 2 or 3 km high develop, as illustrated in Figure 49. The reason oceanic ridges show so many fractures is that plate divergence takes place irregularly on a sphere, resulting in stresses that cause fracturing.

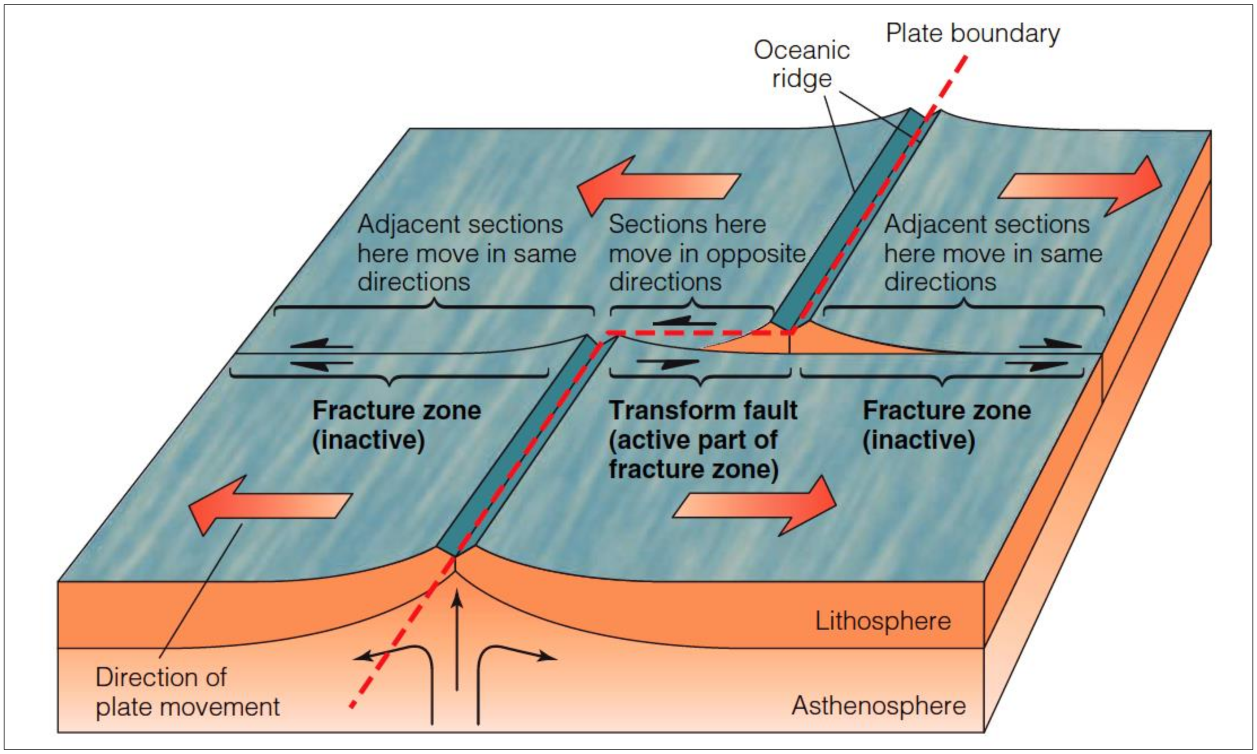


Figure 49 Seafloor Fractures Diagrammatic view of an oceanic ridge offset along a fracture. That part of the fracture between displaced segments of the ridge is a transform fault. Remember from Chapter 2 that transform faults are one type of plate boundary.

Seamounts, Guyots, and Aseismic Ridges

How do seamounts and guyots form?

As noted, the seafloor is not a flat, featureless plain except for the abyssal plains, and even these are underlain by rugged topography. In fact, a large number of volcanic hills, seamounts, and guyots rise above the seafloor in all ocean basins, but they are particularly abundant in the Pacific. All are volcanic and differ mostly in size. Seamounts rise more than 1 km above the seafloor; if they are flat topped, they are called guyots rather than seamounts (Figure 50). Guyots are volcanoes that originally extended above sea level. But as the plate they rested on continued to move, they were carried away from a spreading ridge, and the oceanic crust cooled and descended to greater oceanic depths. So what was an island was eroded by waves as it slowly sank beneath the sea, making it flat-topped.

Many other volcanic features smaller than seamounts are also present on the seafloor, but they probably originated in the same way. These so-called abyssal hills, averaging only about 250 m high, are common on the seafloor and underlie thick sediments on the abyssal plains.

Other features in the ocean basins are long, narrow ridges and broad plateaulike features rising as much as 2 to 3 km above the surrounding seafloor. Known as aseismic ridges, they lack seismic activity. A few of these ridges are probably small fragments separated from continents during rifting. These are referred to as microcontinents and are represented by such features as the Jan Mayen Ridge in the North Atlantic (Figure 48).

Most aseismic ridges form as a linear succession of hotspot volcanoes. These may develop at or near an oceanic ridge, but each volcano so formed is carried laterally with the plate on which it originated. The net result is a sequence of seamounts/guyots extending from an oceanic ridge; the Walvis Ridge in the South Atlantic is a good example (Figure 48). Aseismic ridges also form over hot spots unrelated to ridges. The Emperor Seamount–Hawaiian Island chain in the Pacific formed in such a manner (Figure 48).

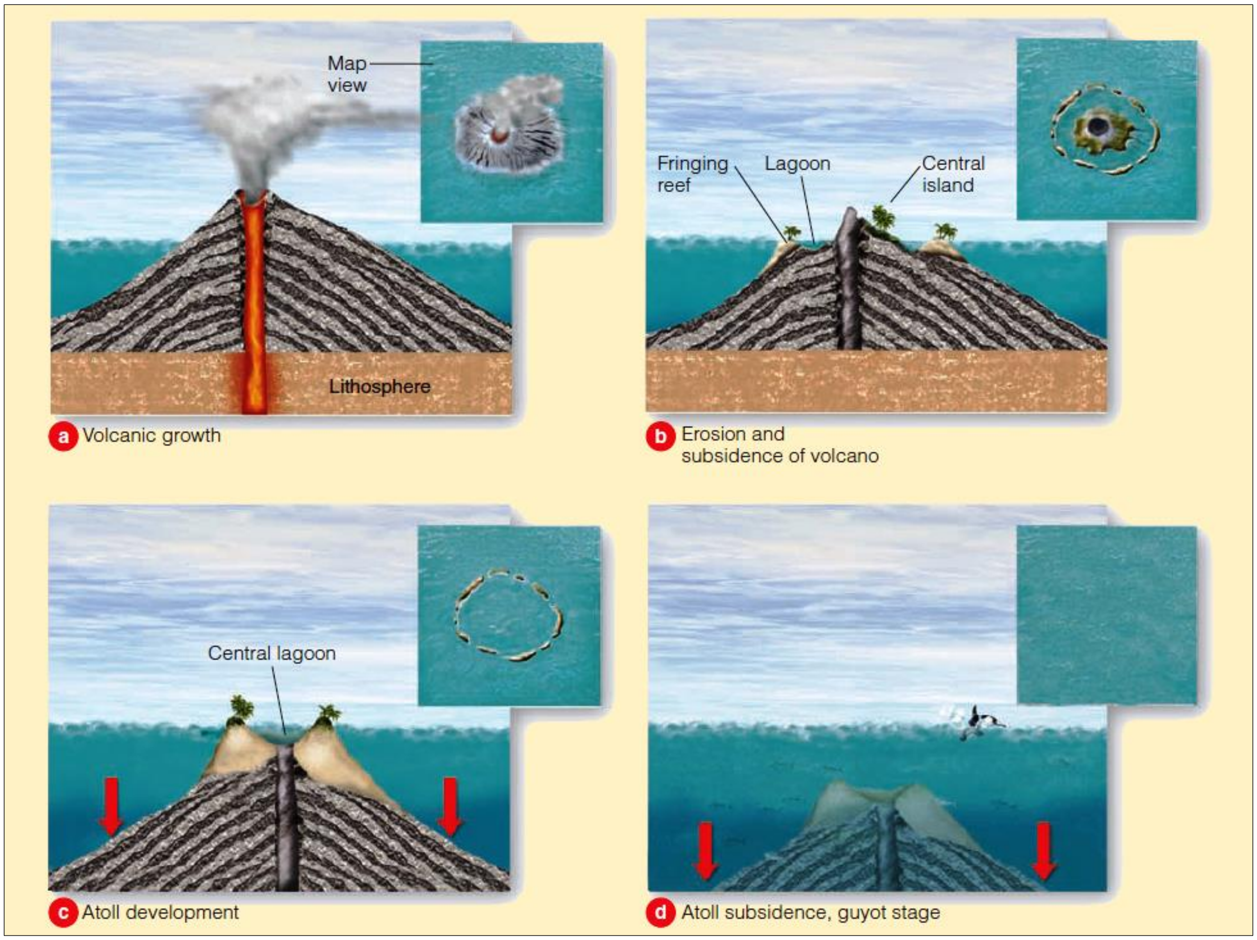


Figure 50 The Origin of Seamounts and Guyots. A seamount may start out as a volcano that extends above sea level. However, as the plate on which the volcano rests moves, it carries the volcano to greater depths and it subsides below sea level. If the volcano is eroded and becomes flat-topped, it is called a guyot.

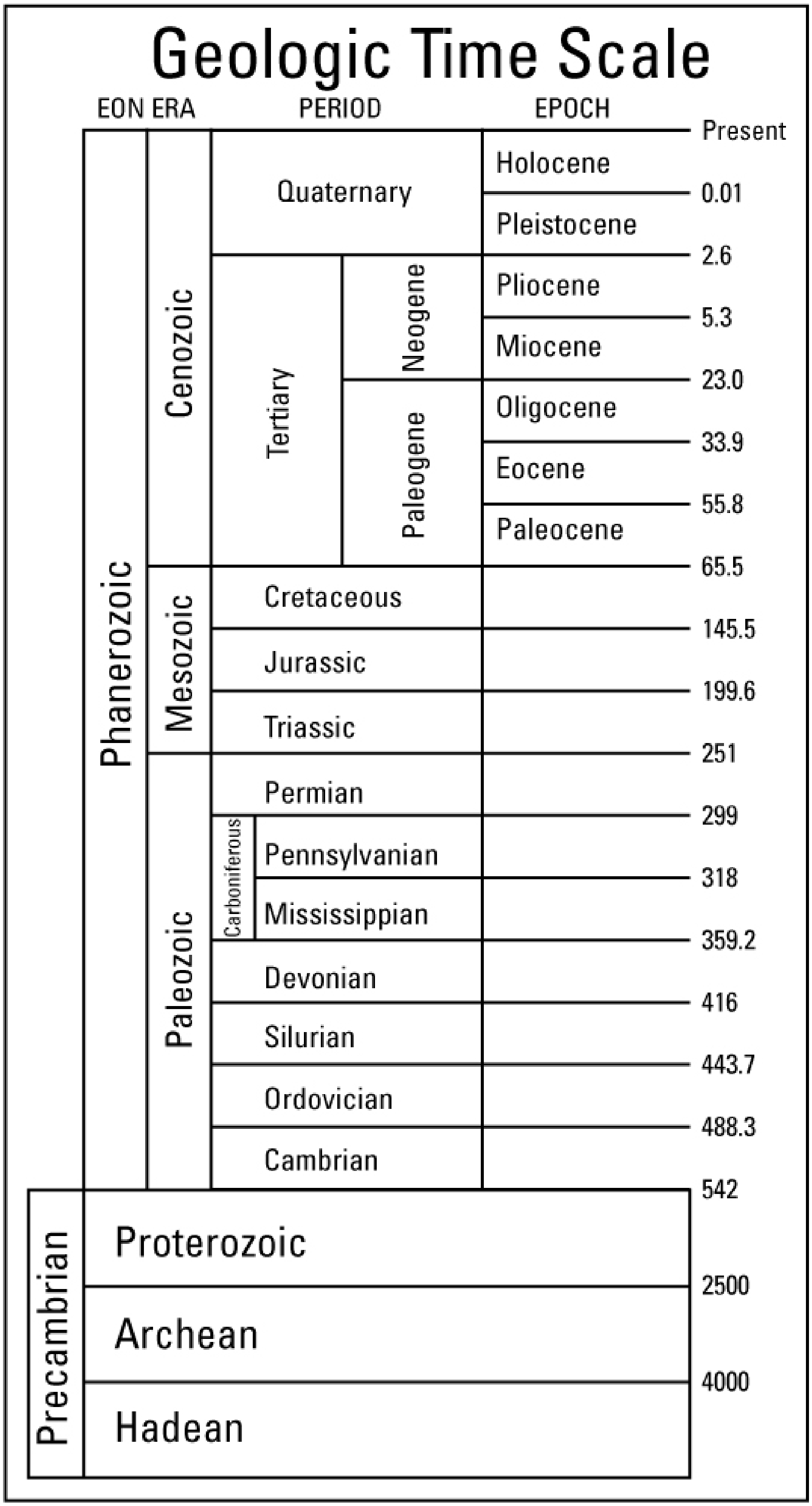
What are the major tectonic features?

First: Major tectonic features on the oceanic crust

1. Oceanic ridge systems
2. Seafloor Fractures
3. Abyssal plains
4. Island arcs
5. Sea mountains
6. Trenches

Second: Major tectonic features on the continental crust

1. Continental margins (Passive or Active continental margins)
2. Folded mountains
3. Volcanic mountains
4. Cratons (Shields + Platforms)


Geologic Time Scale
EON ERA
PERIOD
EPOCH
Present
Phanerozoic
Cenozoic
Quaternary
Holocene
0.01
Pleistocene
2.6
Tertiary
Neogene
Pliocene
5.3
Miocene
23.0
Paleogene
Oligocene
33.9
Eocene
55.8
Paleocene
65.5
Mesozoic
Cretaceous
145.5
Jurassic
199.6
Triassic
251
Paleozoic
Permian
299
Carboniferous
Pennsylvanian
318
Mississippian
359.2
Devonian
416
Silurian
443.7
Ordovician
488.3
Cambrian
542
Precambrian
Proterozoic
2500
Archean
4000
Hadean