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PLATE TECTONICS

Plate tectonics is a scientific theory that provides a unifying understanding of the links between Earth's internal dynamics and geologic change on Earth's surface. In this theory, Earth is covered by about fifteen rigid tectonic plates that move across Earth's surface at speeds of a few centimeters per year. Plate tectonics has since been shown to explain the locations of earthquakes and volcanoes on Earth's surface, the topography of the seafloor, the formation of Earth's mountain ranges, the tectonic history of the continents, and the long-term transfer of Earth's interior heat. As a result, plate tectonics forms the foundation for scientists' understanding of Earth dynamics and Earth history.

THE SURFACE EXPRESSION OF EARTH'S INTERIOR DYNAMICS

Planet Earth is thought to have formed about 4.5 billion years ago as the result of the collision of numerous rocky and metallic particles. These collisions, and the sinking of dense iron metal into the metallic core of the new planet, produced an abundance of heat. This original heat has since been supplemented by heat produced by the radioactive decay of uranium, thorium, and potassium within Earth's rocks. This heat is lost to space as Earth cools, and it is this cooling that powers Earth's interior dynamics. Plate tectonics is the surface expression of these dynamics.

Earth's rocky mantle, which extends to the core-mantle boundary at a depth of 2,860 km, transfers heat by physically moving the materials that contain the heat in a process called convection. As rocks near Earth's surface cool, they become more dense than the hot rocks that lie beneath them and eventually become dense enough that they begin to sink into the mantle's interior, forming a downwelling of downward-moving mantle. At the base of the mantle, movement of the opposite sense occurs as hot mantle rocks, which are less dense than the surrounding mantle, rise in an upwelling toward the surface. This vertical transport of hot rocks upward and cold rocks downward efficiently transfers heat out of the mantle, but it requires ductile deformation of mantle rocks occurring over millions of years. This constant deformation takes the form of convection cells within the mantle interior, in which mantle rocks draw heat upward as they cycle between upwellings and downwellings. Near Earth's surface, rocks tend to move away from upwellings and toward downwellings. These surface motions are manifested on Earth as plate tectonics (see Figure 1).

Most planets larger than Earth's moon are thought to be convecting, but the surface expression of this convection varies greatly. The surfaces of Mars, Venus, and Mercury are thought to be old and stationary, which indicates that the rocky mantles of these planets are convecting beneath a layer of rock that is too cold and stiff to deform. On Earth, however, this layer, which is known as the lithosphere, is broken into a number of different tectonic plates that move relative to each other at rates of a few centimeters per year. It is not well understood why Earth exhibits plate tectonics whereas the other terrestrial planets do not. However, Earth's larger size may have helped it to maintain higher interior temperatures for longer periods of time compared to smaller planets, and its abundance of water may help weaken lithospheric rocks, allowing them to break into plates.

The basic patterns of plate tectonics have been well understood since the original ideas about plate tectonics were developed in the 1960s. Mantle upwellings tend to occur beneath the major ocean basins. Above the upwellings, two oceanic plates tend to spread apart at the crest of major ridges that run down the center of the ocean basins. As the plates spread, the hot upwelling rocks between the plates melt and quickly refreeze beneath the ocean to form new lithosphere. The resulting tectonic plate then moves away from the mid-ocean ridge as it rides atop the mantle convection cell. As the plate continues to cool away from the ridge, it becomes denser and thicker until it eventually becomes dense enough to sink into the interior. This sinking typically occurs on the margins of the continents, where the entire thickness of oceanic lithosphere dives beneath the continental lithosphere in a process known as subduction. This process of plate creation at mid-ocean ridges and destruction at

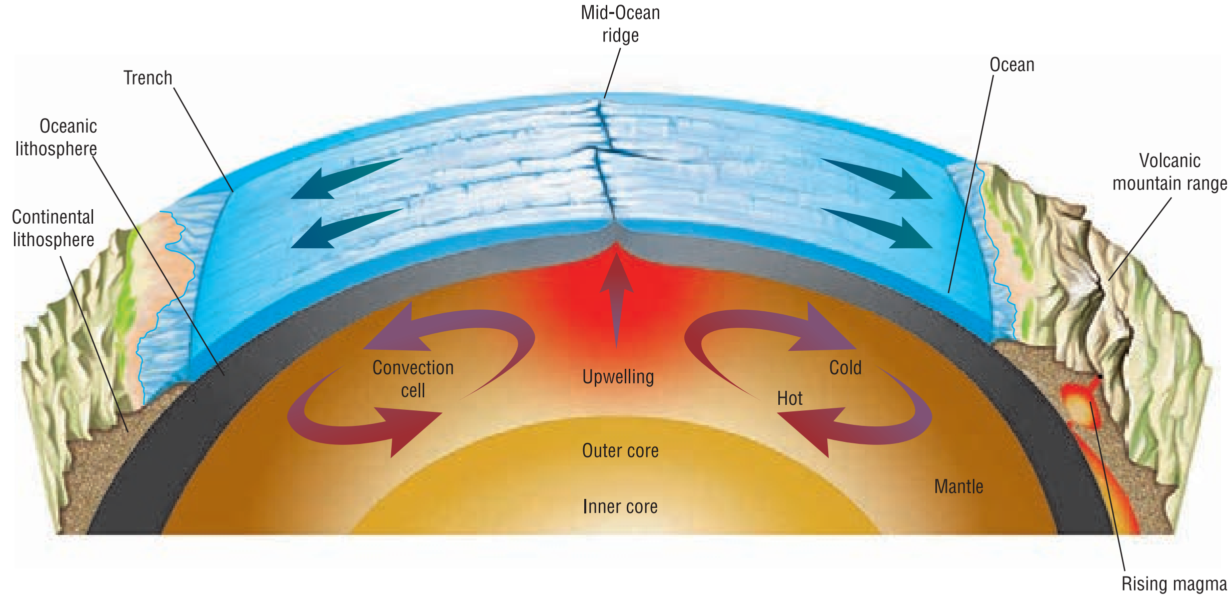


Figure 1. *The theory of plate tectonics explains patterns of geological deformation, seismicity, and volcanism at the Earth's surface. The tectonic plate motions are the surface expression of thermal convection in the Earth's rocky mantle.*

subduction zones constantly recycles mantle materials through the plate tectonic system (see Figure 1). It is also the reason that Earth's surface is relatively young and geologically active.

THE DISCOVERY OF PLATE TECTONICS

The discovery of plate tectonics was a revolutionary event in Earth sciences because it provided a framework for understanding the geological processes that shape the planet. The underpinnings of plate tectonics date from the sixteenth through eighteenth centuries, when the first maps of the New World were published. Scientific thinkers of the time, such as the English natural philosopher Francis Bacon (1561–1626) and the American polymath Benjamin Franklin (1706–1790), speculated that the newly discovered continents of North and South America were once connected to the continents of Africa and Eurasia, because their parallel coastlines seemed to fit together like a jigsaw puzzle. In the nineteenth century, the geometrical fit of the continents was supported by evidence that some fossils and rock types matched each other on opposite sides of the Atlantic. This evidence was compiled by the German meteorologist Alfred Wegener (1880–1930), who in 1915 published a book, *The Origin of Continents and Oceans*, in which he proposed the breakup of a previous supercontinent (now called Pangaea) via a process that he called *continental drift*. This process involved continents' plowing through the oceanic crust like icebergs moving through water, but Wegener's theory was largely discounted at the time because no recognized force was sufficient to drive the continental movements. Wegener's ideas about continental drift, however, set the stage for the development of plate tectonics fifty years later.

Meanwhile, observations of ground uplift following deglaciations in Europe and North America since the last ice age provided evidence that Earth's interior was deformable on continental-length scales, and even provided the first estimates of the material strength, or viscosity, of the mantle (Haskell 1935). Other scholars demonstrated that mantle viscosity was low enough to permit, and even promote, convection within the mantle (Holmes 1928; Pekeris 1935). Although mantle convection did not provide a force large enough to power Wegener's continental drift, it did support the idea that continental motions may be related to convection currents in the mantle.

Continental motion was also supported by observations of paleomagnetism, which is the record of Earth's magnetic field that is recorded in Earth's rocks. In particular, volcanic rocks known as basalts contain magnetic minerals that tend to align themselves in the direction of Earth's magnetic field as they cool. Thus, paleomagnetic observations can be used to determine the orientation of the magnetic field at the time that a rock formed. In basalts erupted on continents, such observations often pointed toward a magnetic pole in the past that was significantly misaligned with the current magnetic pole. Some sequences of continental lavas showed paleomagnetic poles gradually drifting farther away from the present pole for older rocks. Most scientists attributed these observations to the gradual movement of the magnetic pole with time; indeed, some observations indicated that the pole location occasionally reversed its orientation. Some scientists, such as S. K. Runcorn (1956), proposed a reverse explanation: that the magnetic pole had remained fixed while the continents had moved gradually with time.

One problem for understanding continental motions was that geological change in the surrounding oceans was difficult to study because it occurred in an underwater environment. Over time, however, an accumulation of depth-sounding data from across the world's oceans allowed scientists to finally map the broad features of the seafloor. In the 1940s the American oceanographer Maurice Ewing (1906–1974) traveled on a research ship named the *Atlantis* to explore the seafloor beneath the Atlantic Ocean. He discovered a broad ridge, more than a thousand kilometers wide, running down the middle of the basin that had no explanation within the geological literature. The seafloor itself was found to consist of sediments draped over basaltic rocks, which are of volcanic origin and of different composition from the rocks that compose the continents. This broad submerged mountain range was later discovered to extend over 40,000 km through the middle of all the world's major ocean basins. Furthermore, detailed mapping showed a deep canyon running along the crest of this range, which Bruce C. Heezen (1960) interpreted as a "Great Global Rift," with characteristics similar in nature to exposed extensional rifts in Iceland and eastern Africa.

The discovery of rifting on the ocean floor suggested that new seafloor was being created in the ocean basins, but the cause of this rifting was debated. Heezen proposed that these rifts represented a slow expansion of the planet, but most scientists rejected this idea because no reasonable mechanism for increasing the volume of Earth could be put forward. Instead, two scientists, the American geophysicist Robert S. Dietz (1914–1995) and the American navy admiral and geologist Harry H. Hess (1906–1969)—writing in 1961 and 1962, respectively—interpreted the oceanic rifting as the top part of massive convection cells occurring in the mantle interior. In this view, the oceanic plates are geologically young because they are constantly being formed at the mid-ocean spreading ridges, and they ride like a conveyor belt along the top surface of a mantle convection cell. These two papers were thus the first attempts to present the main ideas about plate tectonics within the published literature. Although Dietz was the first person to publish and to use the term *seafloor spreading* when referring to global tectonics, Hess is credited with the "discovery" of seafloor spreading because he circulated drafts of his paper, titled "History of Ocean Basins," before Dietz's publication.

The new ideas about plate tectonics were immediately useful for explaining several puzzling observations about the ocean basins. For example, scientists had wondered why the ocean basins had not become filled with accumulated sediments eroded from the continents over geologic time. Similarly, why were there so few volcanoes in the ocean? Hess's theory was able to answer both of these questions because he showed that all seafloor is constantly being recycled into Earth's interior and is therefore young. In fact, Hess was able to use rates of volcanism and sedimentation to correctly estimate seafloor ages at a few hundred million years, which is geologically young compared to the age of Earth itself. Hess also noted that bathymetric surveys had detected chains of submerged flat-topped mountains, known as guyots, on the flanks of the mid-ocean ridge system. Hess interpreted these structures as former volcanic islands that had been eroded into atolls and then submerged beneath sea level as the seafloor beneath them moved down the flanks of the mid-ocean ridges.

Unlike Wegener's concept of continental drift, which required continents to plow through the oceanic crust, Hess's idea provided a mechanically reasonable mechanism for continental motions. By riding passively atop mantle convection cells, the continents move along with the mantle below them and the seafloor around them. In general, Hess's original concept of seafloor spreading revolutionized geology by linking ongoing geological change on Earth's surface to the active dynamics of the planetary interior.

REFINING THE PLATE TECTONIC IDEA

The 1960s were a period of great controversy and debate about the new theory of plate tectonics. As part of this debate, geologists tested the new theory against a variety of geologic observations. This process resulted in great advancement in scientific understanding of how plate tectonics operated on Earth, as well as how it explained patterns of volcanism, seismicity, mountain building, and geologic change.

World War II (1939–1945) spurred the development of airborne and shipborne magnetometers, which were used in submarine warfare. When applied over the oceans in the 1950s, these devices detected a background pattern of periodic variations in the magnetic field. These "magnetic stripes" across the ocean floor were recognized

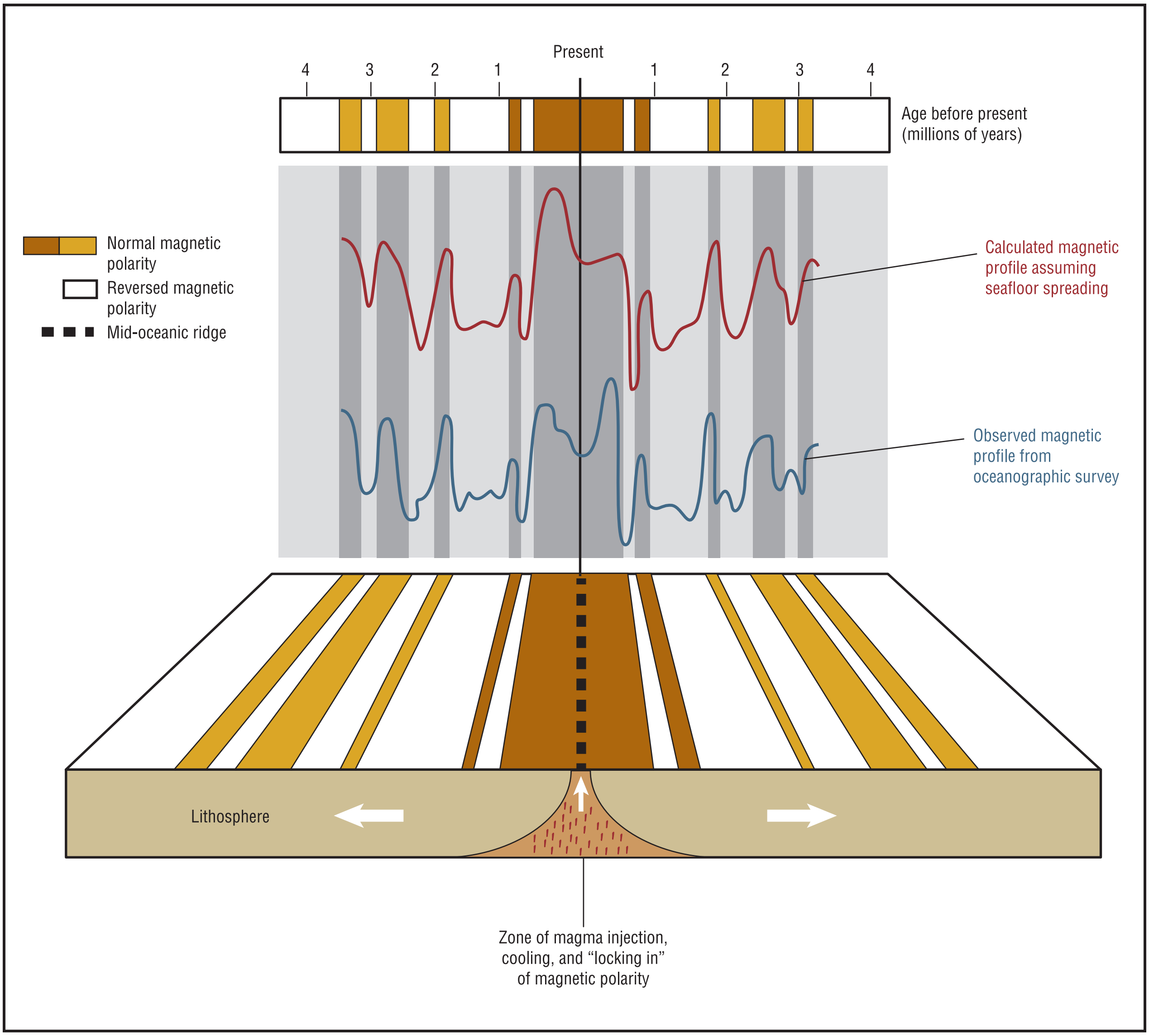


Figure 2. *The theory of plate tectonics was developed in the 1960s to explain symmetric patterns of magnetic anomalies that were observed on the seafloor. In the example shown here, rocks that were formed when Earth's magnetic field was oriented as it is today (normal magnetic polarity) are shown in gold and orange colors. Those formed when Earth's magnetic field was reversed (reversed magnetic polarity), are shown in white. The pattern of magnetic reversals is preserved in the rocks that make up seafloor and can be detected using magnetic field observations obtained from oceanographic surveys (blue line) and related to reversal patterns associated with the varying magnetic polarity of seafloor rocks (red line). Because oceanic lithosphere moves away from the mid-ocean ridges where it is created, the observed pattern of magnetic reversals identifies the age of the seafloor and allows scientists to deduce the motion of the tectonic plates.*

as variations in the magnetic properties of the basaltic rocks that composed the seafloor. Such variations were reminiscent of the vertical sequences of alternating magnetic orientations that were detected by paleomagnetic studies of continental basalts. Horizontal sequences of alternating magnetic orientations on the seafloor were more difficult to understand, until Hess and Dietz published their ideas about seafloor spreading. In particular, F. J. Vine and D. H. Matthews (1963) showed that magnetic stripes could be interpreted as a record of basaltic rocks being created at the mid-ocean ridge, recording the orientation of the magnetic field at the time, and being drawn away from the ridge by seafloor spreading. Periodic reversals of the magnetic field created the magnetic stripes, which were observed to run parallel to the mid-ocean ridges and were symmetrical about the central rift (see Figure 2). In fact, by relating the pattern of magnetic stripes on the seafloor to the dated sequence of polarity reversals that were determined from continental rocks, the age of the seafloor could be determined

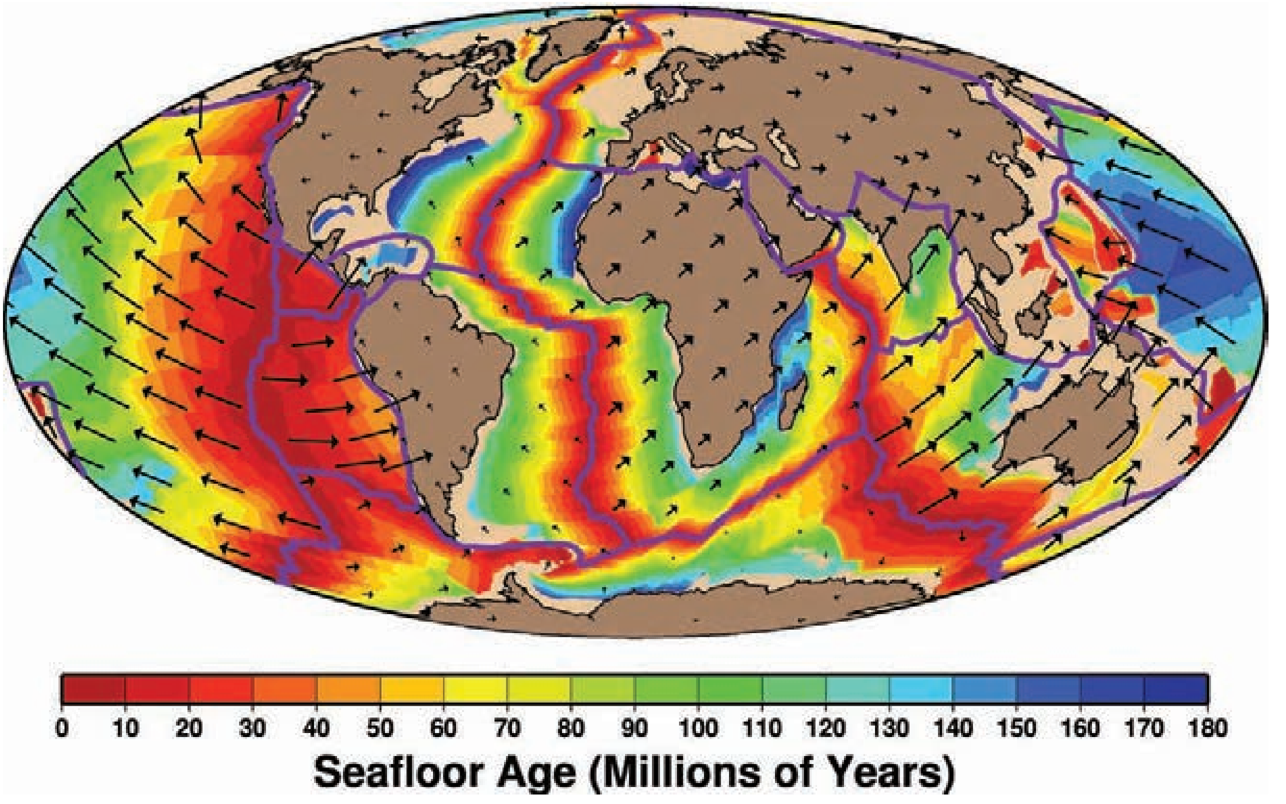


Figure 3. *The tectonic plates typically move away from mid-ocean ridges and toward subduction zones (plate boundaries here are shown by purple lines). This causes seafloor ages to increase moving away from the mid-ocean ridges (colors). Plate speeds range from 5–10 cm/yr in the Pacific basin to 1–3 cm/yr in the Atlantic basin (black arrows).*

from the magnetic stripes. By the end of the 1960s, enough magnetic measurements had been made to begin to develop maps of seafloor age across the ocean basins (see Figure 3).

Seafloor age provided a great deal of information about how the seafloor spreading system worked in practice. For example, the divergent spreading at mid-ocean ridges (see Figure 4a) was shown in places to end abruptly. Such discontinuities in Earth's system of spreading ridges were shown by J. Tuzo Wilson (1965) to be caused by a new type of fault that Wilson called a *transform fault.* These faults accommodated the side-to-side motion (see Figure 4b) that displaced ridge spreading laterally to a new location on the seafloor. This notion of a fault separating two coherently moving regions of Earth's surface suggested that Earth's surface deformation was concentrated in narrow zones that separated coherently moving blocks of lithosphere. Soon after, W. Jason Morgan (1968) showed that the entire surface of Earth could be composed of about a dozen or so such rigid units, which exhibited little if any internal deformation but moved relative to each other at rates of a few centimeters per year. These were the tectonic plates, and their relative movements were called plate tectonics. (The precise number of such plates is a matter of some disagreement among geologists.)

The earliest plate tectonic scientists recognized that divergence occurring at the mid-ocean ridges must be balanced by convergence elsewhere in the world to preserve global area. Initially Hess thought that convergence within continental areas achieved this balance, and indeed some mountain ranges (such as the Alps and the Himalayas) result from such convergence (see Figure 4c). However, Jack Oliver and Bryan Isacks (1967) showed, by examining the transmission of seismic energy from deep earthquakes through the mantle to the surface, that a 100-km-thick zone of anomalous mantle resided beneath the Tonga-Kermadec island arc in the South Pacific. This zone was seismically active and transmitted seismic energy faster and more completely than other parts of the mantle. These authors recognized the similarity of these properties to those of the tectonic plate beneath the neighboring Pacific basin, and they proposed that the entire thickness of the Pacific plate was being dragged down into the mantle beneath the island arc. This type of convergent plate boundary, which is now

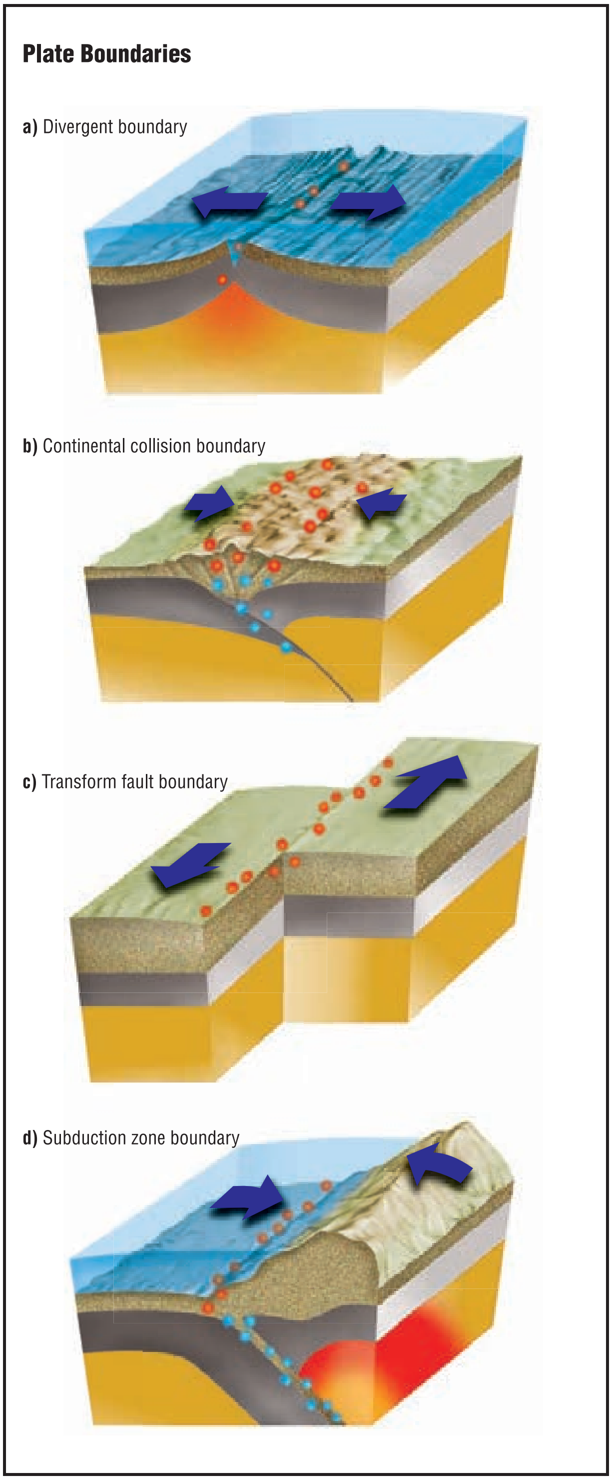


Figure 4. *There are three different types of plate boundaries: Divergent (occurring at mid-ocean ridges), Convergent (occurring at subduction zones and continent-continent collisions), and Transform (side-to-side motion of plates). Orange circles indicate regions where earthquakes shallower than 50 km are produced; blue circles indicate deeper earthquakes.*

referred to as a subduction zone (see Figure 4d), consumes the oceanic plates and recycles them into the mantle interior. The concept of subduction also explained the Wadati-Benioff zones, which are zones of deep seismicity occurring beneath the overriding plate. These seismic zones, which were named after the seismologists who discovered them in the 1950s, result from the bending deformation that the subducting plate must undergo in order to descend into the mantle.

The plate tectonic revolution of the 1960s represented a major upheaval in the geosciences. By the end of the 1960s, however, the major elements of the theory of plate tectonics were already in place. About a dozen rigid plates move at speeds of a few centimeters per year across the surface of Earth (see Figure 3) and are separated by several different types of plate boundaries (see Figure 4). The tectonic plates are created at mid-ocean ridges, where hot mantle rises to fill the gap between spreading plates. Spreading occurs in all major ocean basins around the world, and it serves to widen the Atlantic basin as North and South America move away from Europe and Africa. The plates are destroyed at subduction zones, where one plate dives into the mantle interior beneath another plate. Subduction occurs around the periphery of the Pacific basin, accommodating the shrinkage of that basin. Oceanic plates age as they move from ridge to subduction zone, a process that typically requires 100 million to 200 million years. Plate tectonics allows the continents to move laterally with respect to each other as they ride passively atop convection cells in Earth's mantle.

EARTH'S CONVECTIVE ENGINE

Since its inception in the 1960s, plate tectonics has been intimately linked to convection in Earth's mantle. By the end of that decade, D. L. Turcotte and E. R. Oxburgh (1967) had showed that a convecting layer with the mantle's size, temperature distribution, and material properties should convect vigorously. Such vigorous convection takes the form of a cell consisting of a "core" of relatively uniform temperature that is bounded above and below by thin layers of cold and hot mantle, respectively. The cold temperatures of the upper layer cause this layer to become extremely stiff, making it mechanically stronger than the mantle below. The stiffness of this layer causes it to move rigidly in coherent blocks—these are the tectonic plates.

Near the mid-ocean ridges, where the oceanic plates are formed, the lithospheric plates are very thin because hot mantle is drawn close to Earth's surface in these locations. The lithosphere continues to cool as it moves away from the ridge, however, and it becomes colder, stiffer, and thicker as a result. By the time a plate is about 80 million years old, which typically occurs several thousand kilometers away from the ridge, the oceanic lithosphere achieves a thickness

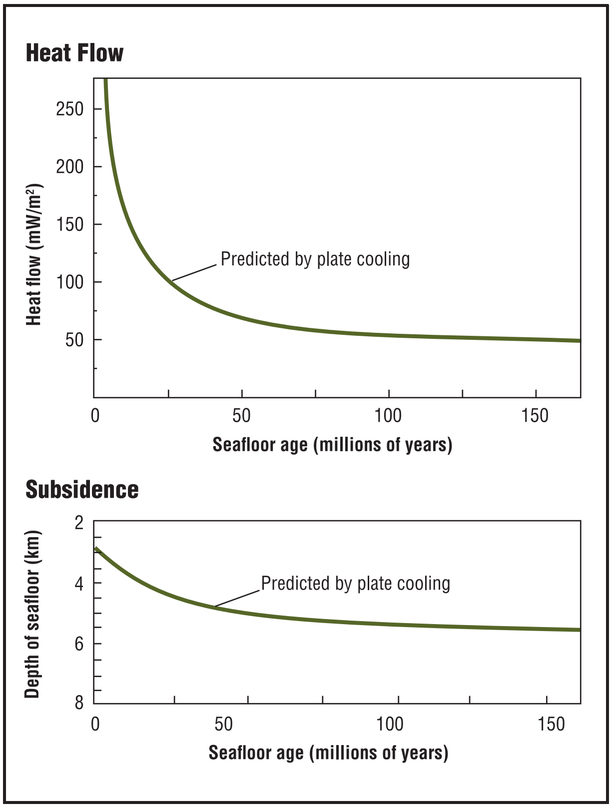


Figure 5. *The tectonic plates cool as they move away from ridges. This can be observed as a decrease in heat flow with increasing seafloor age (top) as well as subsidence of the seafloor moving away from the mid-ocean ridges (bottom).*

of about 100 km. This thickening of the plate has two important consequences. First, the flow of heat across the lithosphere decreases dramatically as the lithosphere gets older because heat is transferred more slowly across a thicker layer. Thus, heat flow near the ridge is significantly greater than heat flow on the flanks of the ridge. This prediction was confirmed by Barry Parsons and John G. Sclater (1977), who compared observations of heat flow in every ocean basin with theoretical predictions based on convection theory. Second, because lithospheric rocks contract as they cool, the seafloor subsides as aging lithosphere accumulates an increasingly larger thickness of cold rocks. This trend causes the oceans to deepen significantly away from the mid-ocean ridges, and it in fact explains the presence of the mid-ocean ridge system that Heezen discovered in the center of the ocean basins. Parsons and Sclater also used their theory of lithospheric cooling to successfully predict global patterns of subsidence with increasing seafloor age (see Figure 5). Later, Carol A. Stein and Seth Stein (1992) investigated these trends for updated observations, finding that both heat flow and bathymetry tend to flatten after about 80 million years, which indicates that the plates cease to thicken beyond this age (see Figure 5).

Earth's system of plate tectonics efficiently transfers about 44 terawatts of heat energy out of Earth's interior, which is about 4,000 times smaller than the 175 petawatts of energy that Earth receives in incoming solar radiation. Other planets without plate tectonics, such as Mars and Venus, exhibit significantly slower heat loss from their interiors. Without such an efficient convective engine to power planetary deformation, such planets exhibit significantly less geological activity than Earth. On Earth, the efficiency of convective heat transfer depends on the viscosity, or stiffness, of the mantle itself and has likely changed only slowly with time. As plate tectonics cools the mantle, the viscosity of the mantle increases, which slows the plates. Thus, as plate tectonics cools the mantle, the rate of mantle heat loss is also slowed, which slows the rate of cooling. Therefore, plate tectonics acts as a temperature regulator for the mantle, allowing mantle temperatures, and plate tectonic rates, to change only slowly over geologic time.

PLATE TECTONIC DRIVING FORCES

Although it is clear that Earth's internal heat powers plate tectonics, the specific forces that drive the individual plates have remained a topic of debate. The largest force available for driving the plates is the force of gravity acting on the plates themselves, which are colder and therefore denser than the hot mantle rocks below. Gravity acting on the plates can drive plate tectonics in three ways (see Figure 6). In the first mechanism (referred to as slab pull), the dense slabs of lithosphere that have subducted into the mantle pull directly on the oceanic plates to which they are attached. These slabs drag the plates into the subduction zone. In the second mechanism (mantle drag), the subducted slab becomes detached from the surface plate and sinks into the mantle, propelling the surrounding mantle material along with it. The resulting mantle circulation can drag on the base of the surface plates, propelling them toward the subduction zones. A third mechanism (ridge push) recognizes that the mid-ocean ridges are elevated above the surrounding seafloor and that gravity acting on these ridges will tend to push the tectonic plates away from the ridges.

All three mechanisms for driving plate motions are probably important, but different forces may be more or less important for different plates (Conrad and Lithgow-Bertelloni 2002). For example, slab pull operates only on plates that are actively subducting along at least one edge. Additionally, rocks within the slab may break under the weight of the dangling portion of that slab, so the magnitude of the slab-pull force may be limited. Nevertheless, subducting plates in the Pacific basin (such as the Pacific, Nazca, and Australian plates) seem to be moving several times faster than the other, nonsubducting, plates, which

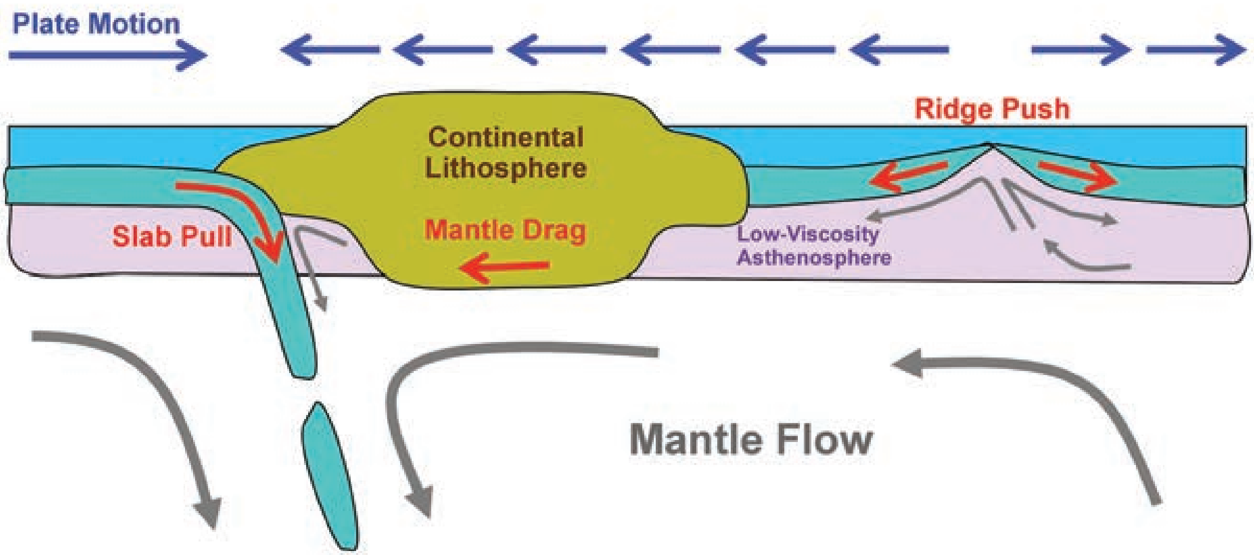


Figure 6. *Major forces acting on tectonic plates. The orientations of slab pull, mantle drag, and ridge force forces are shown with red arrows. These forces drive plates in the directions shown by the blue arrows.*

suggests the importance of slab pull. By contrast, mantle drag can operate on all plates because the slabs tend to drive viscous flow throughout the mantle. This mechanism, however, requires efficient coupling between the surface plates and the flowing mantle beneath them. In fact, plate motions may be lubricated by a hot, low-viscosity layer known as the asthenosphere that may partly decouple plate motions from mantle flow. Uncertainty about the strength of this layer has led to debate about the importance of the mantle-drag force. The fact that this layer may be thinner or nonexistent beneath parts of the continents, however, may help to explain the motions of the continental plates. The third mechanism, ridge push, is thought to be an order of magnitude weaker than slab pull, but it may be important for driving plates that have ridges but no major subduction zones (such as North and South America, Africa, Eurasia, and Antarctica).

Plate motions are occasionally observed to change directions or speeds within time periods as short as a million years. Such rapid changes are difficult to explain based on the above three mechanisms, which propel plates via lateral variations in density that evolve over timescales of several tens of millions of years. Instead, forces acting on the boundaries between the plates may evolve more quickly and may exert important controls on plate motions. For example, the collision between India and Eurasia, which formed the Tibetan plateau and the Himalaya Mountains, may have rapidly slowed the northward motion of the Indian plate starting about 50 million years ago. Indeed, geological deformation in the form of seismicity, volcanism, and mountain building often is associated with tectonic interactions that resist plate motions. By modifying or counterbalancing the driving forces on plates, these deformations may also exert important controls on the motions of plates.

VOLCANOES, EARTHQUAKES, AND MOUNTAIN BUILDING

One major success of the theory of plate tectonics is that the theory provides an explanation for most patterns of geological deformation at the surface. In particular, most volcanoes, earthquakes, and mountains result from geological deformation operating on the edges of the tectonic plates (see Figure 4). For example, the collision of two continents tends to result in the formation of major mountain ranges such as the Alps or the Himalayas. Some subduction zones may also generate major mountain ranges, such as the Andes, if the upper plate rapidly overrides the subducting oceanic lithosphere.

Volcanoes typically occur above regions where hot mantle rises toward the surface. As the hot rocks experience lower pressures near the surface, they melt into magma. This magma then percolates toward the surface, eventually erupting in a volcano. At mid-ocean ridges, the separating plates draw mantle rocks upward into the ridge, producing minor volcanism at the ridge crest that produces basaltic seafloor. A different type of volcanism occurs at subduction zones. Here water and sediments that are subducted into the mantle along with oceanic lithosphere tend to lower the melting point of mantle rocks. As a result, parts of the slab

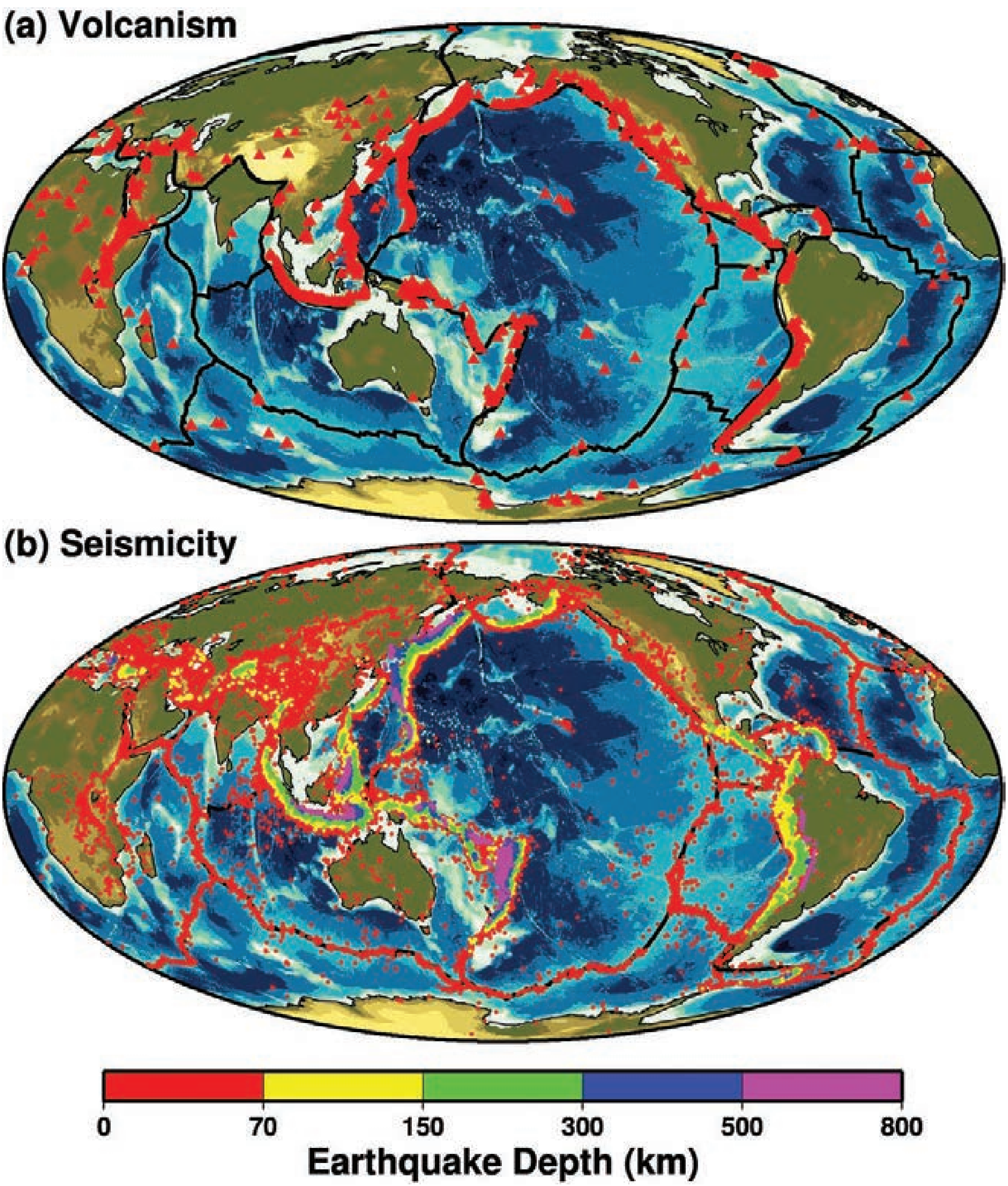


Figure 7. *Most (but not all) recent volcanism (top, from the Smithsonian Global Volcanism Program, http://www.volcano.si.edu) and earthquakes (bottom, from the USGS earthquake catalog http://earthquake.usgs.gov/earthquakes/search/, with colors representing earthquake depth) occur at plate boundaries (shown as black lines).*

begin to melt in the hot mantle, and this melt rises to the surface to produce a volcano. Such volcanoes occur above subducting slabs in every subduction zone and thus surround the Pacific Ocean (see Figure 7a). The magma produced by subduction-zone volcanism contains dissolved gases from the subducted lithosphere. These gases tend to expand when depressurized near the surface, making subduction-zone volcanism especially explosive.

Earthquakes also tend to occur near the boundaries of the plates (see Figure 7b). At the mid-ocean ridges, shallow and typically small earthquakes result as newly formed lithosphere deforms to accommodate plate material that is constantly being added at the ridge (see Figure 4a). Transform faults also tend to produce shallow earthquakes (see Figure 4b) as opposing plates stick together as they slide past each other. When the rocks along the transform fault can no longer withstand the accumulated stresses associated with ongoing plate motions, the rocks break and a major earthquake is released. The rock deformation associated with continental collision (see Figure 4c) also produces earthquakes, which can occur deep within the convergent zone as cold and brittle rocks are forced both upward and downward by the collision. Finally, subduction zones produce the largest earthquakes, as the convergent nature of these boundaries tends to cause plate-bounding faults to accumulate larger stresses before earthquake rupture (see Figure 4d). Such "meagthrust" earthquakes can generate major ocean-crossing tsunamis because overriding plates tend to lift large amounts of seawater as they snap upward. As cold and brittle subducting plates continue to descend into the mantle, they continue to deform and continue to produce earthquakes. These deep earthquakes, which include those of the Wadati-Benioff zone, persist to a depth of about 670 km. Subduction zones are the only locations where earthquakes occur deeper than about 100 km.

Volcanism and seismicity within the interiors of plates (see Figure 7) are not directly explained by plate tectonics. As a result, this activity remains somewhat enigmatic. Intraplate earthquakes may result from stresses transmitted great distances across the stiff tectonic plates. Intraplate volcanoes may result from localized mantle upwelling occurring beneath the plates. Such upwelling can produce chains of volcanoes (such as those in Hawaii) as surface plates move laterally above locations of mantle upwelling. Plate tectonic motions are thus important even for intraplate volcanism and earthquakes.

PLATE TECTONICS AND EARTH HISTORY

Plate tectonics has likely been operating on Earth for at least three billion years. During this time, plate motions have processed a large fraction of Earth's mantle through the subduction zones, have uplifted numerous mountain ranges, and have dramatically changed the configuration of continents and oceans on Earth's surface. Many of these changes have been scrutinized by examination of the rocks produced at past times in Earth history. Such studies have revealed a rich geological history for Earth, much of which can now be explained by plate tectonics.

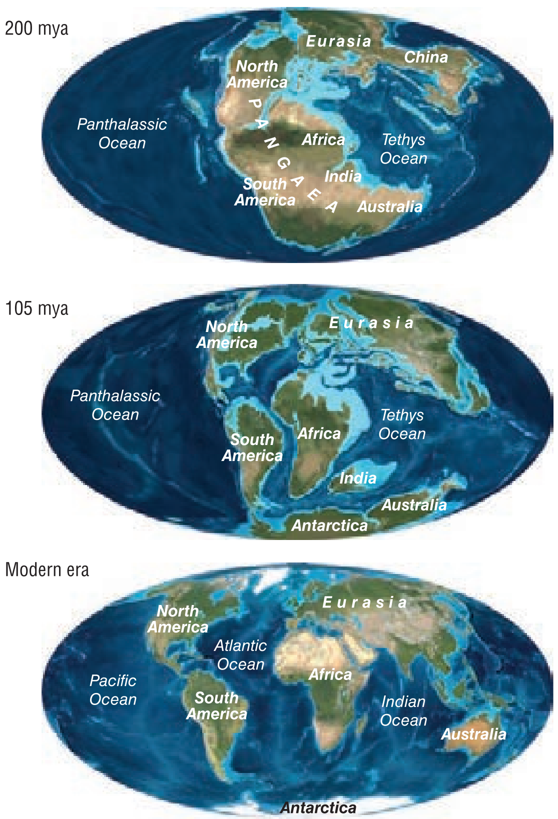
Paleomagnetic studies and fossil evidence suggest that Earth's major continents were once assembled in a single large supercontinent referred to as Pangaea (see Figure 8). Scientists now understand that plate tectonics provides a mechanism for the gradual dispersal of that continent into the present configuration. Using marine fossils found in rocks on both sides of the North Atlantic, Wilson (1966) showed that a former ocean existed in the same location prior to the formation of Pangaea. This observation suggests that the continents periodically assemble into supercontinents and then disperse in a cycle known as the Wilson cycle. Several previous supercontinents have been documented prior to Pangaea, opening and closing in cycles that lasted 400 million to 600 million years.

Past continental closures led to the growth of great mountain ranges that have since eroded. The Appalachian Range in North America formed from a previous closure of the Atlantic and was once as large as the Himalayas are today. As continents separated, groups of animals and plants became isolated from each other and evolved independently. The unique marsupial zoology of Australia is thought to have developed following geographic isolation caused by plate tectonics. Accompanying continental dispersal and assembly were major changes in the mid-ocean ridge system. As these ridges grew and shrank, they began to take up more or less space at the bottom of the ocean basins, resulting in major changes in sea level. About 100 million years ago, seawater flooded much of North America and Eurasia because oceanic plate motions were faster and therefore produced a wider mid-ocean ridge system. Since that time, plate motions have slowed, the ridges have narrowed, and sea level has fallen about 200 m. These are but a few examples of the numerous events in Earth's history that can be attributed to geological evolution caused by plate tectonics.

PLATE TECTONICS AS A UNIFYING THEORY FOR THE GEOSCIENCES

The theory of plate tectonics links geological processes with thermal convection of the mantle interior. Earth's internal heat is therefore ultimately responsible for continental motions, mountain building, earthquakes, volcanoes, and other geological changes at Earth's surface. Plate tectonic processes affect nearly every aspect of the geosciences, ranging across subdisciplines as diverse as paleontology, mineralogy, sedimentology, tectonics,

Continental Drift



SOURCE: Ron Blakey, Colorado Plateau Geosystems

Figure 8. *Plate tectonics explains numerous events in Earth's history, such as the breakup of the supercontinent Pangea (top, 200 Mya) into separate smaller continents (middle, 100 Mya), eventually leading to today's continental configuration (bottom, present-day). Many of Earth's mountain ranges (shown in brown colors) are the result of plate tectonic movements.*

seismology, volcanology, and planetary physics. The plate tectonic revolution was set in motion by an accumulation of unexplained geological observations, some key technological innovations that permitted new observations of Earth, and an abundance of clever thinking from insightful geoscientists during the 1960s. Plate tectonics represented a major paradigm shift for geoscientists at the time, and it has continued to provide a unifying framework for understanding Earth dynamics and geological change ever since.

SEE ALSO *Earthquakes; Earth's Core; Geologic Time; Igneous Rocks, Evolution of; Metamorphic Rocks, Origin of; Minerals, Chemical Classification of; Mohorovičić Discontinuity; Ocean Drilling Expeditions; Radiometric Dating; Seismic Tomography; Volcanoes.*

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PLUTO

The discovery of Pluto offers an instructive lesson in scientific discovery: if a flawed hypothesis leads to a major discovery, a deeper look may reveal something