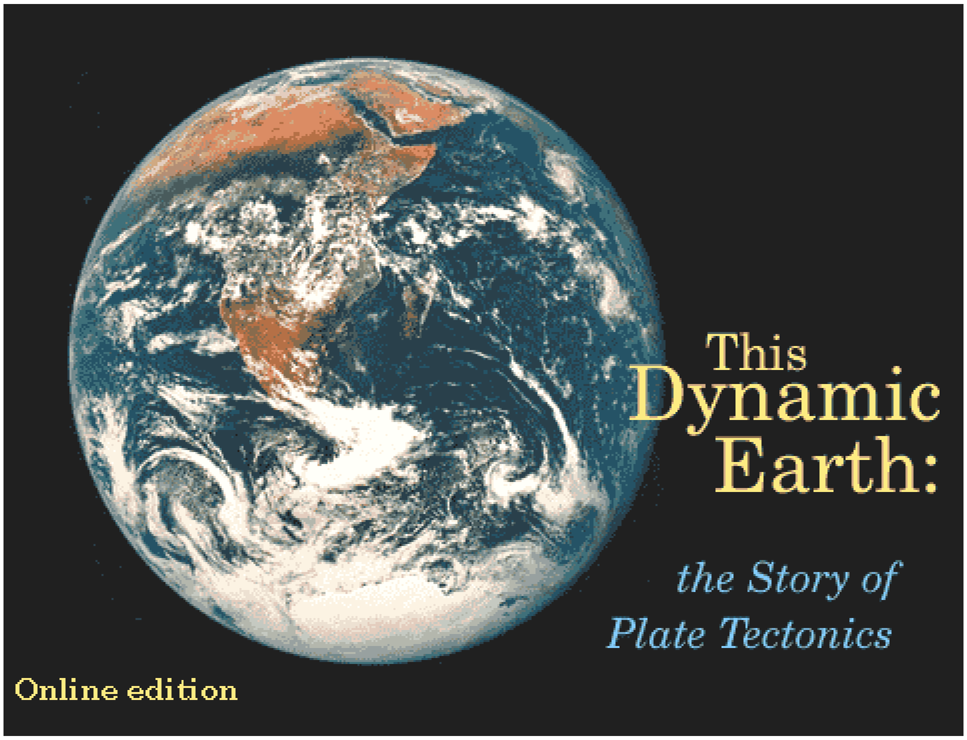
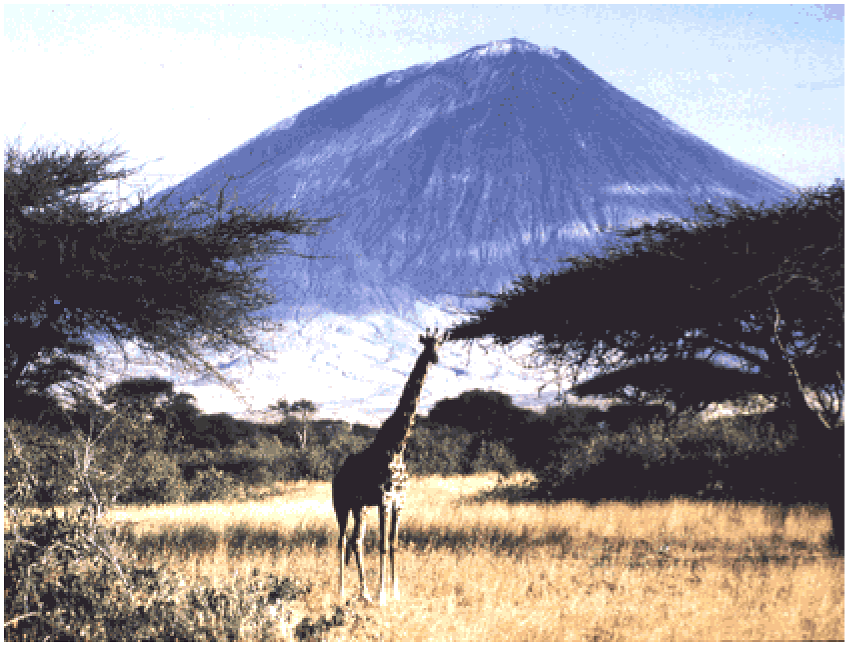


Preface

In the early 1960s, the emergence of the *theory of plate tectonics* started a revolution in the earth sciences. Since then, scientists have verified and refined this theory, and now have a much better understanding of how our planet has been shaped by plate-tectonic processes. We now know that, directly or indirectly, plate tectonics influences nearly all geologic processes, past and present. Indeed, the notion that the entire Earth's surface is continually shifting has profoundly changed the way we view our world.

People benefit from, and are at the mercy of, the forces and consequences of plate tectonics. With little or no warning, an earthquake or volcanic eruption can unleash bursts of energy far more powerful than anything we can generate. While we have no control over plate-tectonic processes, we now have the knowledge to learn from them. The more we know about plate tectonics, the better we can appreciate the grandeur and beauty of the land upon which we live, as well as the occasional violent displays of the Earth's awesome power.

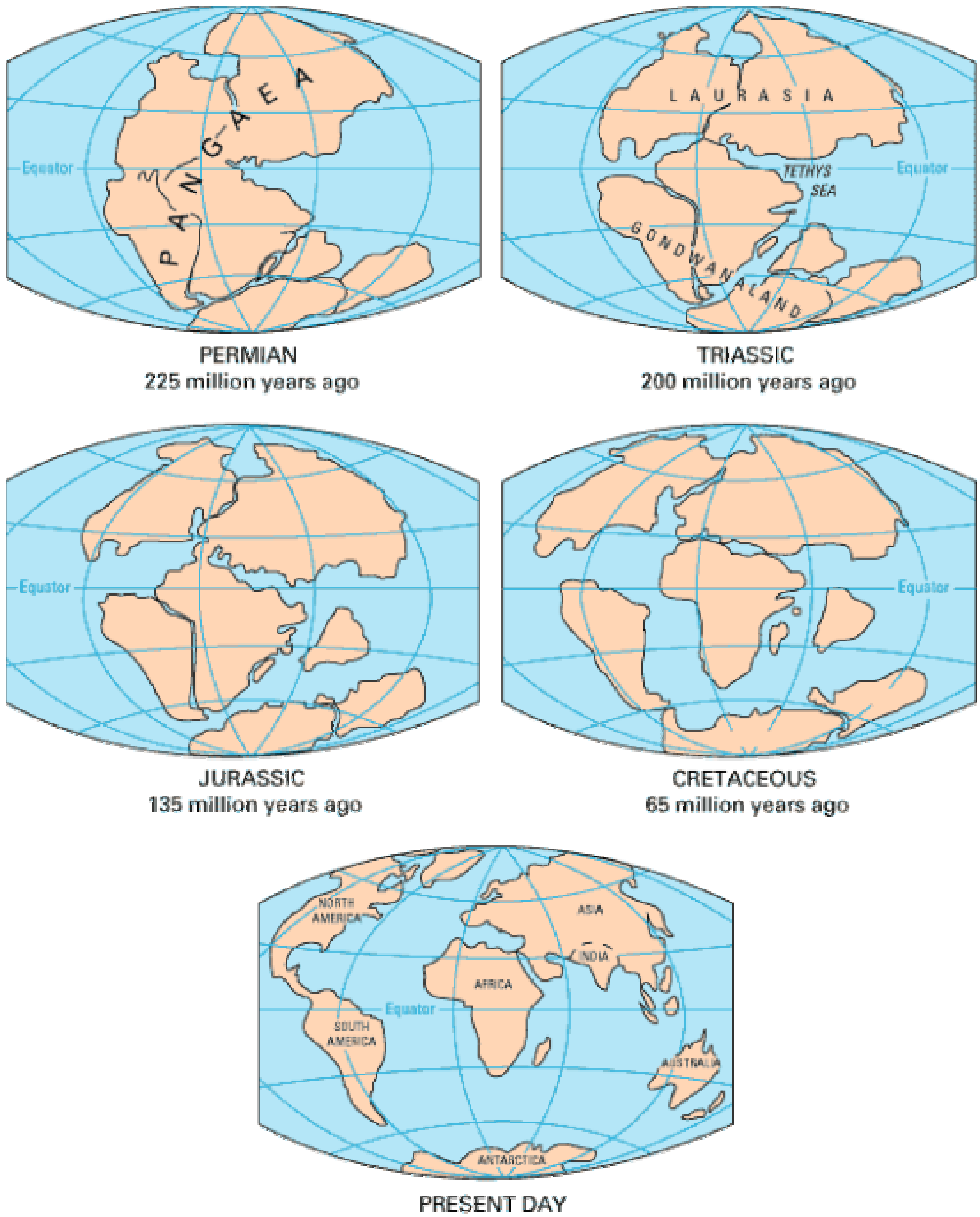
This booklet gives a brief introduction to the concept of plate tectonics and complements the visual and written information in *This Dynamic Planet* (see **Further reading**), a map published in 1994 by the U.S. Geological Survey (USGS) and the Smithsonian Institution. The booklet highlights some of the people and discoveries that advanced the development of the theory and traces its progress since its proposal. Although the general idea of plate tectonics is now widely accepted, many aspects still continue to confound and challenge scientists. The earth-science revolution launched by the theory of plate tectonics is not finished.



Oldoinyo Lengai, an active volcano in the East African Rift Zone, where Africa is being pulled apart by plate-tectonic processes. (Photograph by Jorg Keller, Albert-Ludwigs-Universität Freiburg, Germany.)

Historical Perspective

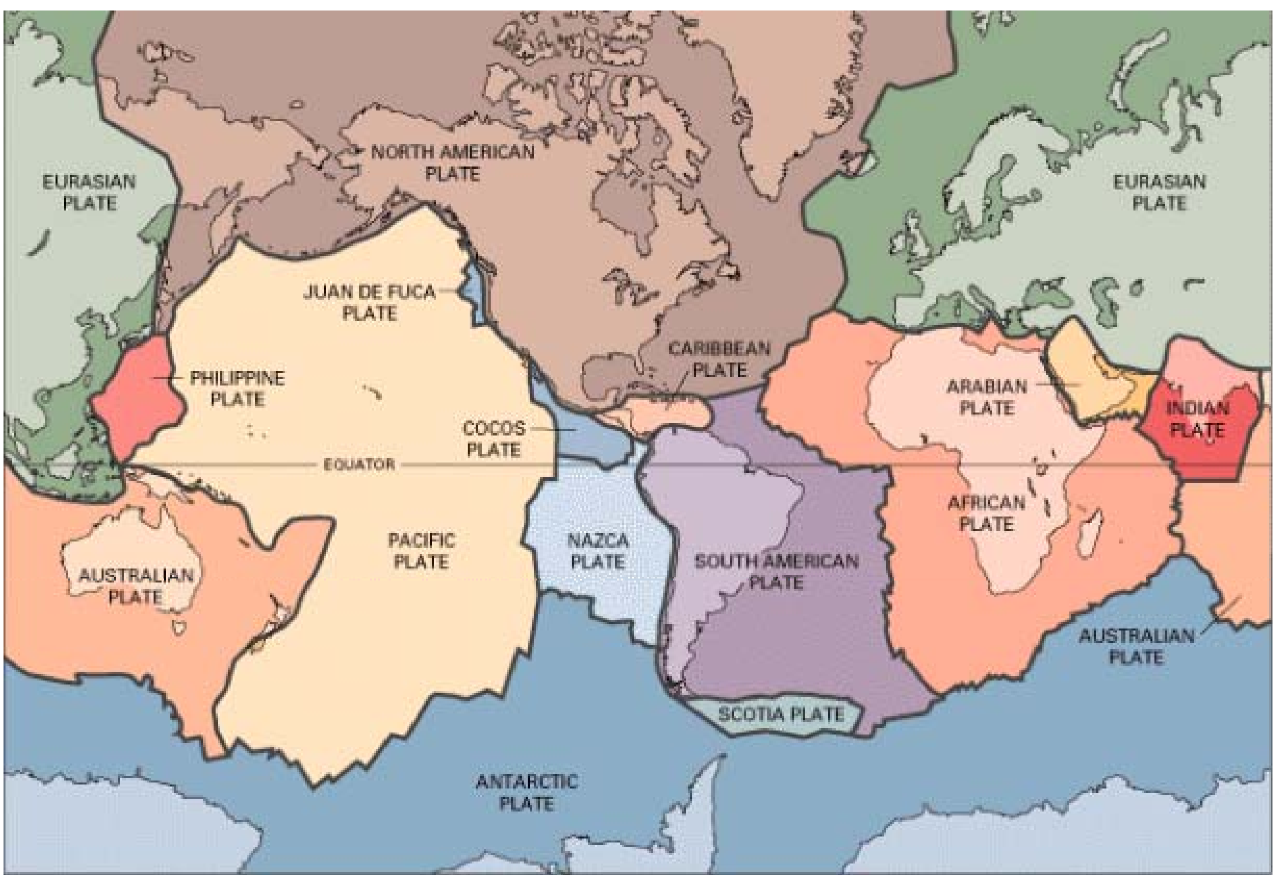
In geologic terms, a *plate* is a large, rigid slab of solid rock. The word *tectonics* comes from the Greek root "to build." Putting these two words together, we get the term *plate tectonics,* which refers to how the Earth's surface is built of plates. The *theory of plate tectonics* states that the Earth's outermost layer is fragmented into a dozen or more large and small plates that are moving relative to one another as they ride atop hotter, more mobile material. Before the advent of plate tectonics, however, some people already believed that the present-day continents were the fragmented pieces of preexisting larger landmasses ("supercontinents"). The diagrams below show the break-up of the supercontinent *Pangaea* (meaning "all lands" in Greek), which figured prominently in the *theory of continental drift* -- the forerunner to the theory of plate tectonics.



According to the continental drift theory, the supercontinent Pangaea *began to break up about 225-200 million years ago, eventually fragmenting into the continents as we know them today.*

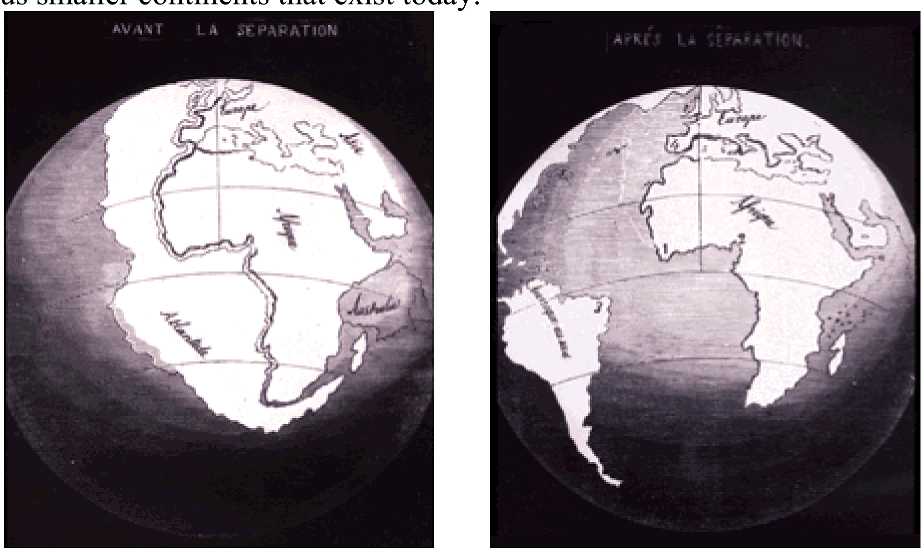
Plate tectonics is a relatively new scientific concept, introduced some 30 years ago, but it has revolutionized our understanding of the dynamic planet upon which we live. The theory has unified the study of the Earth by drawing together many branches of the earth sciences, from *paleontology* (the study of fossils) to *seismology* (the study of earthquakes). It has provided explanations to questions that scientists had speculated upon for centuries -- such as why earthquakes and volcanic eruptions occur in very specific areas around the world, and how and why great mountain ranges like the Alps and Himalayas formed.

Why is the Earth so restless? What causes the ground to shake violently, volcanoes to erupt with explosive force, and great mountain ranges to rise to incredible heights? Scientists, philosophers, and theologians have wrestled with questions such as these for centuries. Until the 1700s, most Europeans thought that a Biblical Flood played a major role in shaping the Earth's surface. This way of thinking was known as "catastrophism," and *geology* (the study of the Earth) was based on the belief that all earthly changes were sudden and caused by a series of catastrophes. However, by the mid-19th century, catastrophism gave way to "uniformitarianism," a new way of thinking centered around the "Uniformitarian Principle" proposed in 1785 by James Hutton, a Scottish geologist. This principle is commonly stated as follows: *The present is the key to the past.* Those holding this viewpoint assume that the geologic forces and processes -- gradual as well as catastrophic -- acting on the Earth today are the same as those that have acted in the geologic past.



The layer of the Earth we live on is broken into a dozen or so rigid slabs (called tectonic plates *by geologists) that are moving relative to one another.*

The belief that continents have not always been fixed in their present positions was suspected long before the 20th century; this notion was first suggested as early as 1596 by the Dutch map maker Abraham Ortelius in his work *Thesaurus Geographicus*. Ortelius suggested that the Americas were "torn away from Europe and Africa . . . by earthquakes and floods" and went on to say: "The vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three [continents]." Ortelius' idea surfaced again in the 19th century. However, it was not until 1912 that the idea of moving continents was seriously considered as a full-blown scientific theory -- called *Continental Drift* -- introduced in two articles published by a 32-year-old German meteorologist named Alfred Lothar Wegener. He contended that, around 200 million years ago, the supercontinent Pangaea began to split apart. Alexander Du Toit, Professor of Geology at Johannesburg University and one of Wegener's staunchest supporters, proposed that Pangaea first broke into two large continental landmasses, *Laurasia* in the northern hemisphere and *Gondwanaland* in the southern hemisphere. Laurasia and Gondwanaland then continued to break apart into the various smaller continents that exist today.

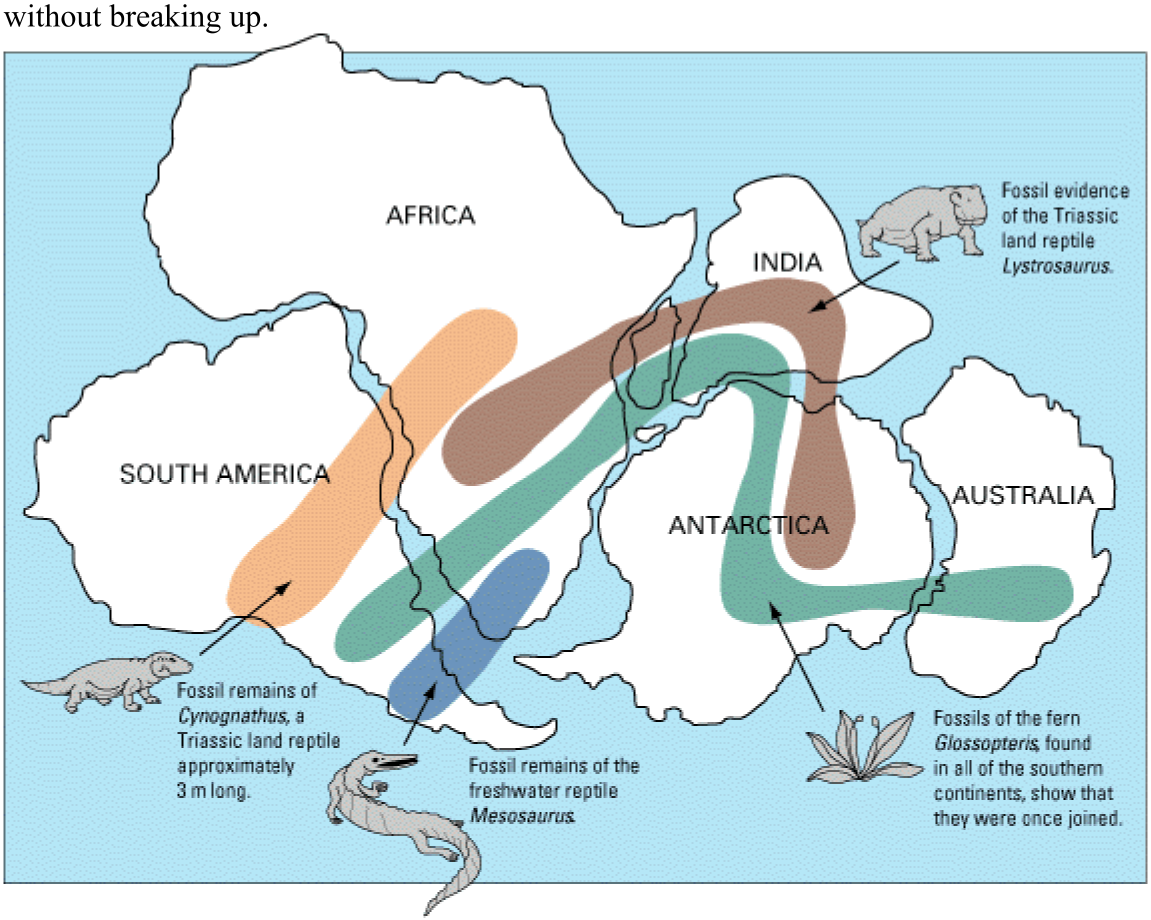


In 1858, geographer Antonio Snider-Pellegrini made these two maps showing his version of how the American and African continents may once have fit together, then later separated. Left: The formerly joined continents before (avant) their separation. Right: The continents after (aprés) the separation. (Reproductions of the original maps courtesy of University of California, Berkeley.)

Wegener's theory was based in part on what appeared to him to be the remarkable fit of the South American and African continents, first noted by Abraham Ortelius three centuries earlier. Wegener was also intrigued by the occurrences of unusual geologic structures and of plant and animal fossils found on the matching coastlines of South America and Africa, which are now widely separated by the Atlantic Ocean. He reasoned that it was physically impossible for most of these organisms to have swum or have been transported across the vast oceans. To him, the presence of identical fossil species along the coastal parts of Africa and South America was the most compelling evidence that the two continents were once joined.

In Wegener's mind, the drifting of continents after the break-up of Pangaea explained not only the matching fossil occurrences but also the evidence of dramatic climate changes on some continents. For example, the discovery of fossils of tropical plants (in the form of coal deposits) in Antarctica led to the conclusion that this frozen land previously must have been situated closer to the equator, in a more temperate climate where lush, swampy vegetation could grow. Other mismatches of geology and climate included distinctive fossil ferns *(Glossopteris)* discovered in now-polar regions, and the occurrence of glacial deposits in present-day arid Africa, such as the Vaal River valley of South Africa.

The *theory of continental drift* would become the spark that ignited a new way of viewing the Earth. But at the time Wegener introduced his theory, the scientific community firmly believed the continents and oceans to be permanent features on the Earth's surface. Not surprisingly, his proposal was not well received, even though it seemed to agree with the scientific information available at the time. A fatal weakness in Wegener's theory was that it could not satisfactorily answer the most fundamental question raised by his critics: What kind of forces could be strong enough to move such large masses of solid rock over such great distances? Wegener suggested that the continents simply plowed through the ocean floor, but Harold Jeffreys, a noted English geophysicist, argued correctly that it was physically impossible for a large mass of solid rock to plow through the ocean floor without breaking up.



As noted by Snider-Pellegrini and Wegener, the locations of certain fossil plants and animals on present-day, widely separated continents would form definite patterns (shown by the bands of colors), if the continents are rejoined.

Undaunted by rejection, Wegener devoted the rest of his life to doggedly pursuing additional evidence to defend his theory. He froze to death in 1930 during an expedition crossing the Greenland ice cap, but the controversy he spawned raged on. However, after his death, new evidence from ocean floor exploration and other studies rekindled interest in Wegener's theory, ultimately leading to the development of the *theory of plate tectonics.*

Plate tectonics has proven to be as important to the earth sciences as the discovery of the structure of the atom was to physics and chemistry and the theory of evolution was to the life sciences. Even though the theory of plate tectonics is now widely accepted by the scientific community, aspects of the theory are still being debated today. Ironically, one of the chief outstanding questions is the one Wegener failed to resolve: What is the nature of the forces propelling the plates? Scientists also debate how plate tectonics may have operated (if at all) earlier in the Earth's history and whether similar processes operate, or have ever operated, on other planets in our solar system.

Developing the Theory

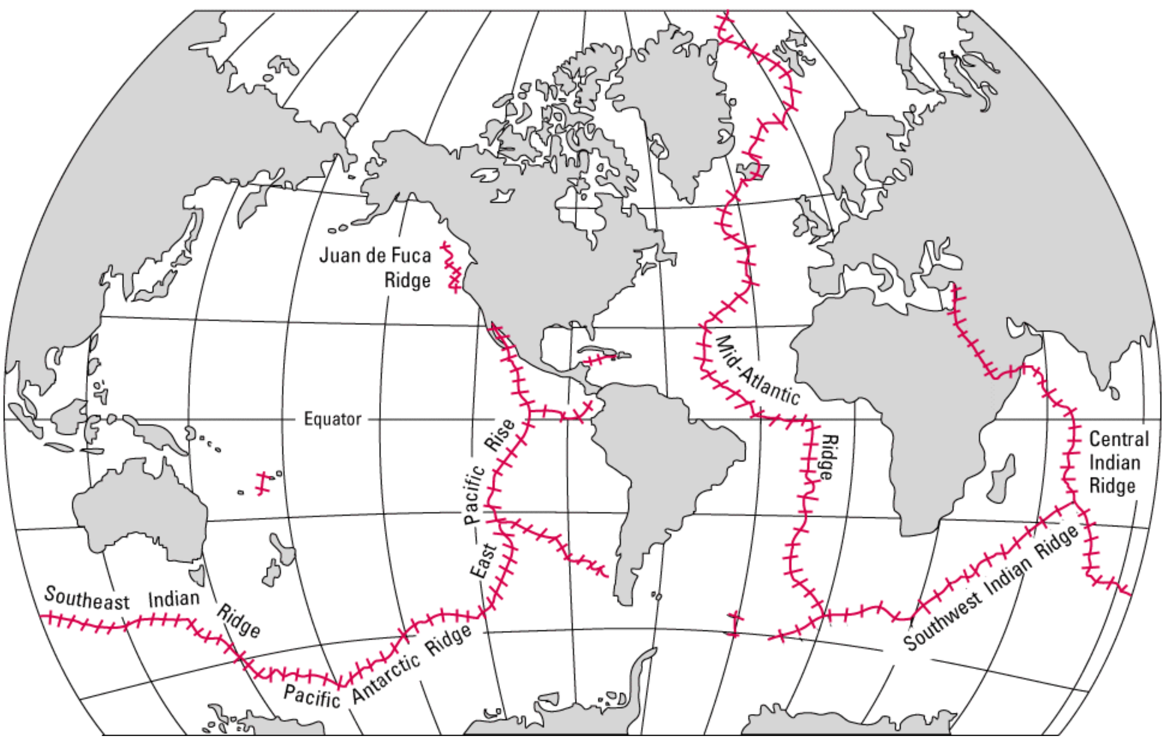
Continental drift was hotly debated off and on for decades following Wegener's death before it was largely dismissed as being eccentric, preposterous, and improbable. However, beginning in the 1950s, a wealth of new evidence emerged to revive the debate about Wegener's provocative ideas and their implications. In particular, four major scientific developments spurred the formulation of the plate-tectonics theory: (1) demonstration of the ruggedness and youth of the ocean floor; (2) confirmation of repeated reversals of the Earth magnetic field in the geologic past; (3) emergence of the seafloor-spreading hypothesis and associated recycling of oceanic crust; and (4) precise documentation that the world's earthquake and volcanic activity is concentrated along oceanic trenches and submarine mountain ranges.

Ocean floor mapping

About two thirds of the Earth's surface lies beneath the oceans. Before the 19th century, the depths of the open ocean were largely a matter of speculation, and most people thought that the ocean floor was relatively flat and featureless. However, as early as the

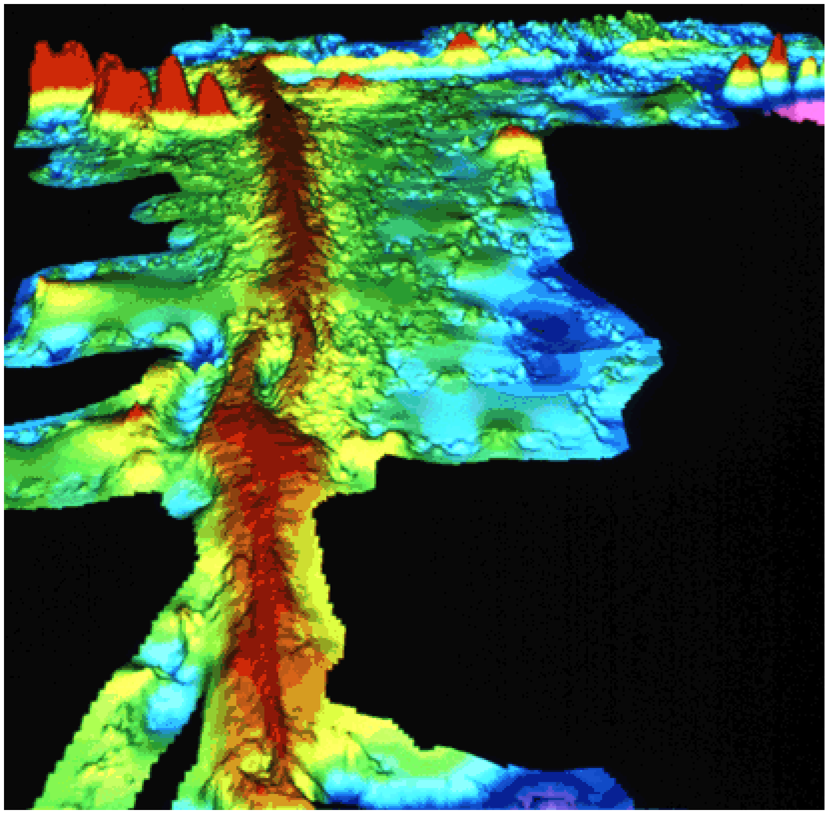
16th century, a few intrepid navigators, by taking soundings with hand lines, found that the open ocean can differ considerably in depth, showing that the ocean floor was not as flat as generally believed. Oceanic exploration during the next centuries dramatically improved our knowledge of the ocean floor. We now know that most of the geologic processes occurring on land are linked, directly or indirectly, to the dynamics of the ocean floor.

"Modern" measurements of ocean depths greatly increased in the 19th century, when deep-sea line soundings (*bathymetric* surveys) were routinely made in the Atlantic and Caribbean. In 1855, a bathymetric chart published by U.S. Navy Lieutenant Matthew Maury revealed the first evidence of underwater mountains in the central Atlantic (which he called "Middle Ground"). This was later confirmed by survey ships laying the trans-Atlantic telegraph cable. Our picture of the ocean floor greatly sharpened after World War I (1914-18), when echo-sounding devices -- primitive sonar systems -- began to measure ocean depth by recording the time it took for a sound signal (commonly an electrically generated "ping") from the ship to bounce off the ocean floor and return. Time graphs of the returned signals revealed that the ocean floor was much more rugged than previously thought. Such echo-sounding measurements clearly demonstrated the continuity and roughness of the submarine mountain chain in the central Atlantic (later called the *Mid-Atlantic Ridge*) suggested by the earlier bathymetric measurements.



The mid-ocean ridge (shown in red) winds its way between the continents much like the seam on a baseball.

In 1947, seismologists on the U.S. research ship *Atlantis* found that the sediment layer on the floor of the Atlantic was much thinner than originally thought. Scientists had previously believed that the oceans have existed for at least 4 billion years, so therefore the sediment layer should have been very thick. Why then was there so little accumulation of sedimentary rock and debris on the ocean floor? The answer to this question, which came after further exploration, would prove to be vital to advancing the concept of plate tectonics.

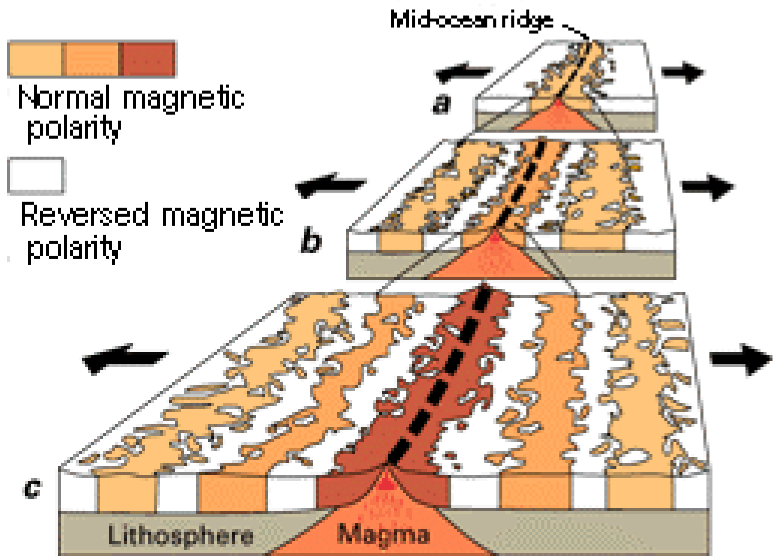


Computer-generated detailed topographic map of a segment of the Mid-Oceanic Ridge. "Warm" colors (yellow to red) indicate the ridge rising above the seafloor, and the "cool" colors (green to blue) represent lower elevations. This image (at latitude 9° north) is of a small part of the East Pacific Rise. (Imagery courtesy of Stacey Tighe, University of Rhode Island.)

In the 1950s, oceanic exploration greatly expanded. Data gathered by oceanographic surveys conducted by many nations led to the discovery that a great mountain range on the ocean floor virtually encircled the Earth. Called the *global mid-ocean ridge,* this immense submarine mountain chain -- more than 50,000 kilometers (km) long and, in places, more than 800 km across -- zig-zags between the continents, winding its way around the globe like the seam on a baseball. Rising an average of about 4,500 meters(m) above the sea floor, the mid-ocean ridge overshadows all the mountains in the United States except for Mount McKinley (Denali) in Alaska (6,194 m). Though hidden beneath the ocean surface, the global mid-ocean ridge system is the most prominent topographic feature on the surface of our planet.

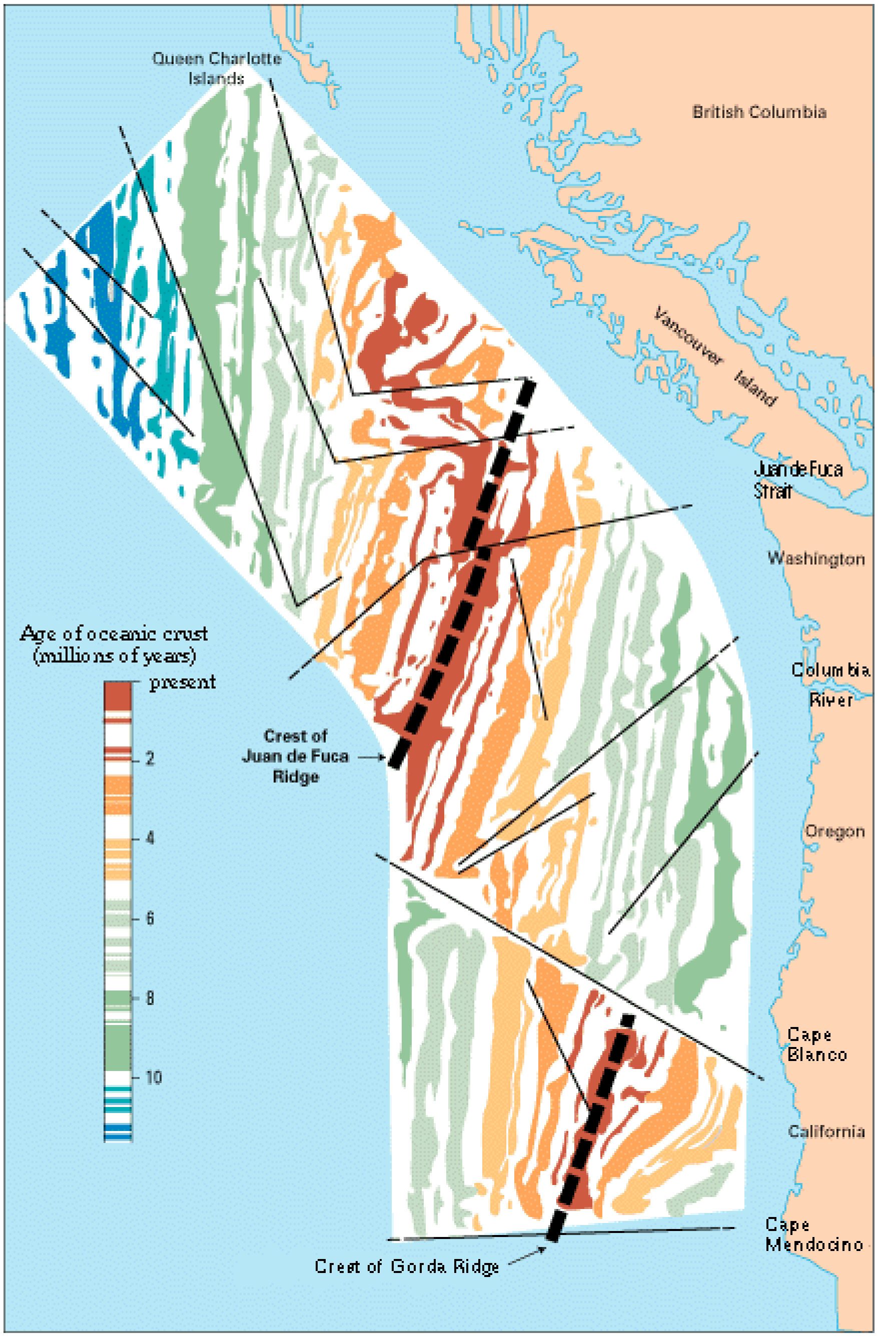
Magnetic striping and polar reversals

Beginning in the 1950s, scientists, using magnetic instruments *(magnetometers)* adapted from airborne devices developed during World War II to detect submarines, began recognizing odd magnetic variations across the ocean floor. This finding, though unexpected, was not entirely surprising because it was known that *basalt* -- the iron-rich, volcanic rock making up the ocean floor-- contains a strongly magnetic mineral *(magnetite)* and can locally distort compass readings. This distortion was recognized by Icelandic mariners as early as the late 18th century. More important, because the presence of magnetite gives the basalt measurable magnetic properties, these newly discovered magnetic variations provided another means to study the deep ocean floor.



A theoretical model of the formation of magnetic striping. New oceanic crust forming continuously at the crest of the mid-ocean ridge cools and becomes increasingly older as it moves away from the ridge crest with seafloor spreading (see text): ***a.*** *the spreading ridge about 5 million years ago;* ***b.*** *about 2 to 3 million years ago; and* ***c.*** *present-day.*

Early in the 20th century, *paleomagnetists* (those who study the Earth's ancient magnetic field) -- such as Bernard Brunhes in France (in 1906) and Motonari Matuyama in Japan (in the 1920s) -- recognized that rocks generally belong to two groups according to their magnetic properties. One group has so-called *normal polarity,* characterized by the magnetic minerals in the rock having the same polarity as that of the Earth's present magnetic field. This would result in the **north** end of the rock's "compass needle" pointing toward magnetic **north**. The other group, however, has *reversed polarity,* indicated by a polarity alignment opposite to that of the Earth's present magnetic field. In this case, the **north** end of the rock's compass needle would point **south**. How could this be? This answer lies in the magnetite in volcanic rock. Grains of magnetite -- behaving like little magnets -- can align themselves with the orientation of the Earth's magnetic field. When *magma* (molten rock containing minerals and gases) cools to form solid volcanic rock, the alignment of the magnetite grains is "locked in," recording the Earth's magnetic orientation or polarity (normal or reversed) at the time of cooling.



The center part of the figure -- representing the deep ocean floor with the sea magically removed -- shows the magnetic striping (see text) mapped by oceanographic surveys offshore of the Pacific Northwest. Thin black lines show transform faults (discussed later) that offset the striping.

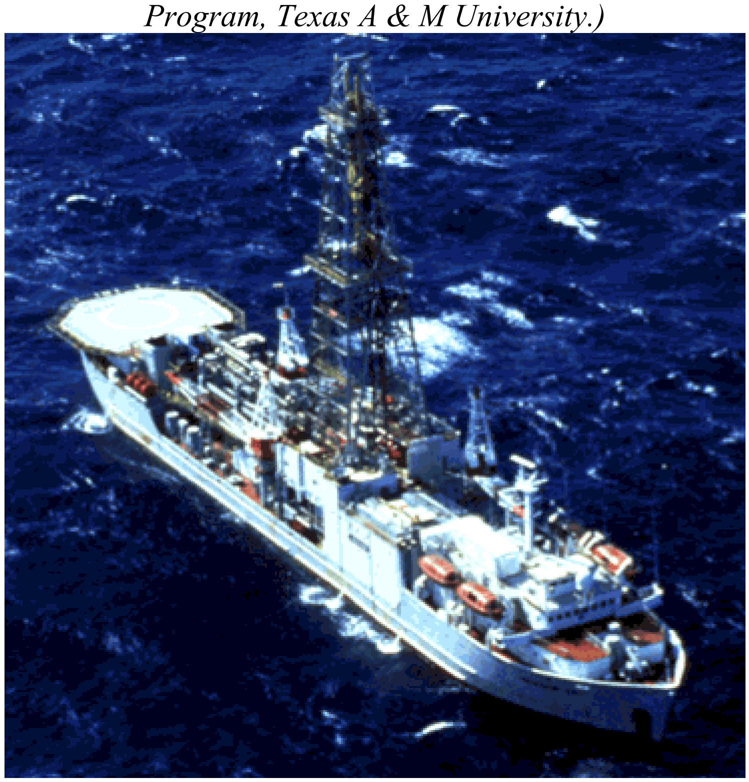
As more and more of the seafloor was mapped during the 1950s, the magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns. When these magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern. Alternating stripes of magnetically different rock were laid out in rows on either side of the mid-ocean ridge: one stripe with normal polarity and the adjoining stripe with reversed polarity. The overall pattern, defined by these alternating bands of normally and reversely polarized rock, became known as magnetic striping.

Seafloor spreading and recycling of oceanic crust

The discovery of magnetic striping naturally prompted more questions: How does the magnetic striping pattern form? And why are the stripes symmetrical around the crests of the mid-ocean ridges? These questions could not be answered without also knowing the significance of these ridges. In 1961, scientists began to theorize that mid-ocean ridges mark structurally weak zones where the ocean floor was being ripped in two lengthwise along the ridge crest. New magma from deep within the Earth rises easily through these weak zones and eventually erupts along the crest of the ridges to create new oceanic crust. This process, later called *seafloor spreading,* operating over many millions of years has built the 50,000 km-long system of mid-ocean ridges. This hypothesis was supported by several lines of evidence: (1) at or near the crest of the ridge, the rocks are very young, and they become progressively older away from the ridge crest; (2) the youngest rocks at the ridge crest always have present-day (normal) polarity; and (3) stripes of rock parallel to the ridge crest alternated in magnetic polarity (normal-reversed-normal, etc.), suggesting that the Earth's magnetic field has flip-flopped many times. By explaining both the zebralike magnetic striping and the construction of the mid-ocean ridge system, the seafloor spreading hypothesis quickly gained converts and represented another major advance in the development of the plate-tectonics theory. Furthermore, the oceanic crust now came to be appreciated as a natural "tape recording" of the history of the reversals in the Earth's magnetic field.

Additional evidence of seafloor spreading came from an unexpected source: petroleum exploration. In the years following World War II, continental oil reserves were being depleted rapidly and the search for offshore oil was on. To conduct offshore exploration, oil companies built ships equipped with a special drilling rig and the capacity to carry many kilometers of drill pipe. This basic idea later was adapted in constructing a research vessel, named the *Glomar Challenger,* designed specifically for marine geology studies, including the collection of drill-core samples from the deep ocean floor. In 1968, the vessel embarked on a year-long scientific expedition, criss-crossing the Mid-Atlantic Ridge between South America and Africa and drilling core samples at specific locations. When the ages of the samples were determined by paleontologic and isotopic dating studies, they provided the clinching evidence that proved the seafloor spreading hypothesis.

Above: *The* Glomar Challenger *was the first research vessel specifically designed in the late 1960s for the purpose of drilling into and taking core samples from the deep ocean floor.* Below: *The* JOIDES Resolution *is the deep-sea drilling ship of the 1990s (*JOIDES*= **J**oint **O**ceanographic **I**nstitutions for **D**eep **E**arth **S**ampling). This ship, which carries more than 9,000 m of drill pipe, is capable of more precise positioning and deeper drilling than the* Glomar Challenger. *(Photographs courtesy of Ocean Drilling Program, Texas A & M University.)*

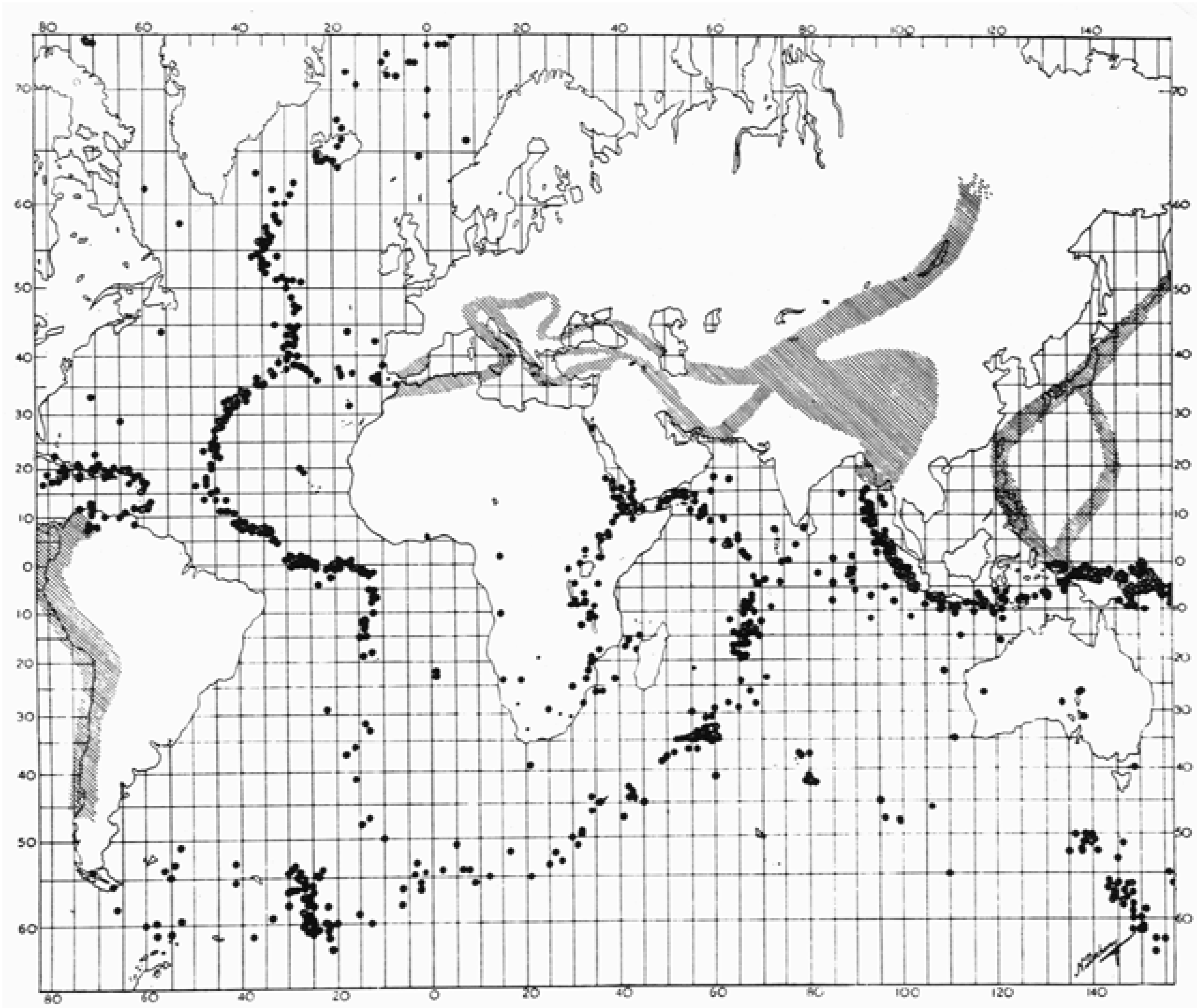


A profound consequence of seafloor spreading is that new crust was, and is now, being continually created along the oceanic ridges. This idea found great favor with some scientists who claimed that the shifting of the continents can be simply explained by a large increase in size of the Earth since its formation. However, this so-called "expanding Earth" hypothesis was unsatisfactory because its supporters could offer no convincing geologic mechanism to produce such a huge, sudden expansion. Most geologists believe that the Earth has changed little, if at all, in size since its formation 4.6 billion years ago, raising a key question: how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth?

This question particularly intrigued Harry H. Hess, a Princeton University geologist and a Naval Reserve Rear Admiral, and Robert S. Dietz, a scientist with the U.S. Coast and Geodetic Survey who first coined the term *seafloor spreading.* Dietz and Hess were among the small handful who really understood the broad implications of sea floor spreading. If the Earth's crust was expanding along the oceanic ridges, Hess reasoned, it must be shrinking elsewhere. He suggested that new oceanic crust continuously spread away from the ridges in a conveyor belt-like motion. Many millions of years later, the oceanic crust eventually descends into the oceanic *trenches* -- very deep, narrow canyons along the rim of the Pacific Ocean basin. According to Hess, the Atlantic Ocean was expanding while the Pacific Ocean was shrinking. As old oceanic crust was consumed in the trenches, new magma rose and erupted along the spreading ridges to form new crust. In effect, the ocean basins were perpetually being "recycled," with the creation of new crust and the destruction of old oceanic lithosphere occurring simultaneously. Thus, Hess' ideas neatly explained why the Earth does not get bigger with sea floor spreading, why there is so little sediment accumulation on the ocean floor, and why oceanic rocks are much younger than continental rocks.

Concentration of earthquakes

During the 20th century, improvements in seismic instrumentation and greater use of earthquake-recording instruments *(seismographs)* worldwide enabled scientists to learn that earthquakes tend to be concentrated in certain areas, most notably along the oceanic trenches and spreading ridges. By the late 1920s, seismologists were beginning to identify several prominent earthquake zones parallel to the trenches that typically were inclined 40-60° from the horizontal and extended several hundred kilometers into the Earth. These zones later became known as *Wadati-Benioff zones,* or simply *Benioff zones,* in honor of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of the United States. The study of global seismicity greatly advanced in the 1960s with the establishment of the Worldwide Standardized Seismograph Network (WWSSN) to monitor the compliance of the 1963 treaty banning above-ground testing of nuclear weapons. The much-improved data from the WWSSN instruments allowed seismologists to map precisely the zones of earthquake concentration worldwide.



As early as the 1920s, scientists noted that earthquakes are concentrated in very specific narrow zones (see text). In 1954, French seismologist J.P. Rothé published this map showing the concentration of earthquakes along the zones indicated by dots and cross-hatched areas. (Original illustration reproduced with permission of the Royal Society of London.)

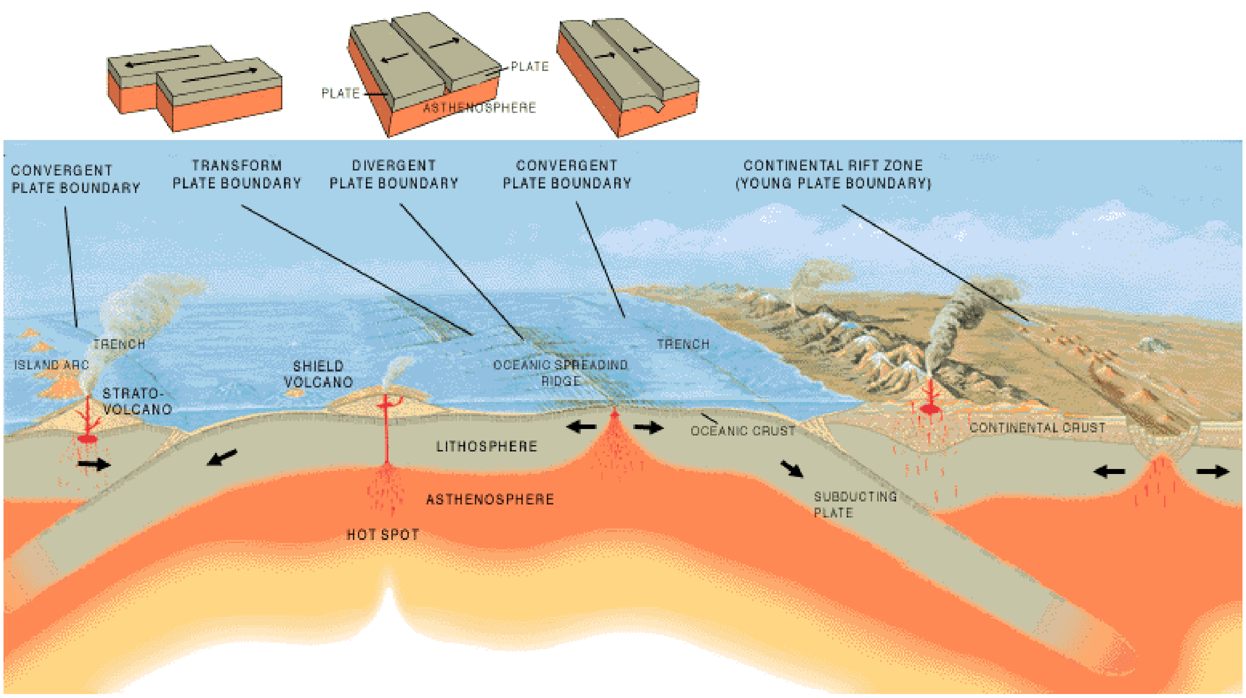
But what was the significance of the connection between earthquakes and oceanic trenches and ridges? The recognition of such a connection helped confirm the seafloor-spreading hypothesis by pin-pointing the zones where Hess had predicted oceanic crust is being generated (along the ridges) and the zones where oceanic lithosphere sinks back into the mantle (beneath the trenches).

Understanding Plate Motions

Scientists now have a fairly good understanding of how the plates move and how such movements relate to earthquake activity. Most movement occurs along narrow zones between plates where the results of plate-tectonic forces are most evident.

There are four types of plate boundaries:

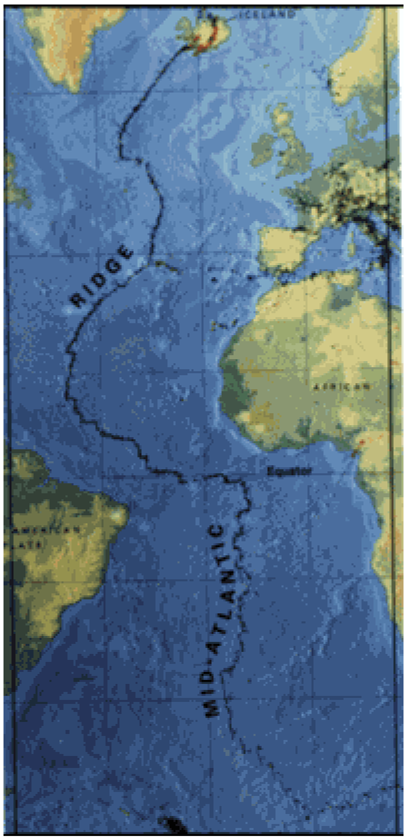
- Divergent boundaries -- where new crust is generated as the plates pull away from each other.
- Convergent boundaries -- where crust is destroyed as one plate dives under another.
- Transform boundaries -- where crust is neither produced nor destroyed as the plates slide horizontally past each other.
- Plate boundary zones -- broad belts in which boundaries are not well defined and the effects of plate interaction are unclear.



Artist's cross section illustrating the main types of plate boundaries (see text); East African Rift Zone is a good example of a continental rift zone. (Cross section by José F. Vigil from This Dynamic Planet *-- a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and the U.S. Naval Research Laboratory.)*

Divergent boundaries

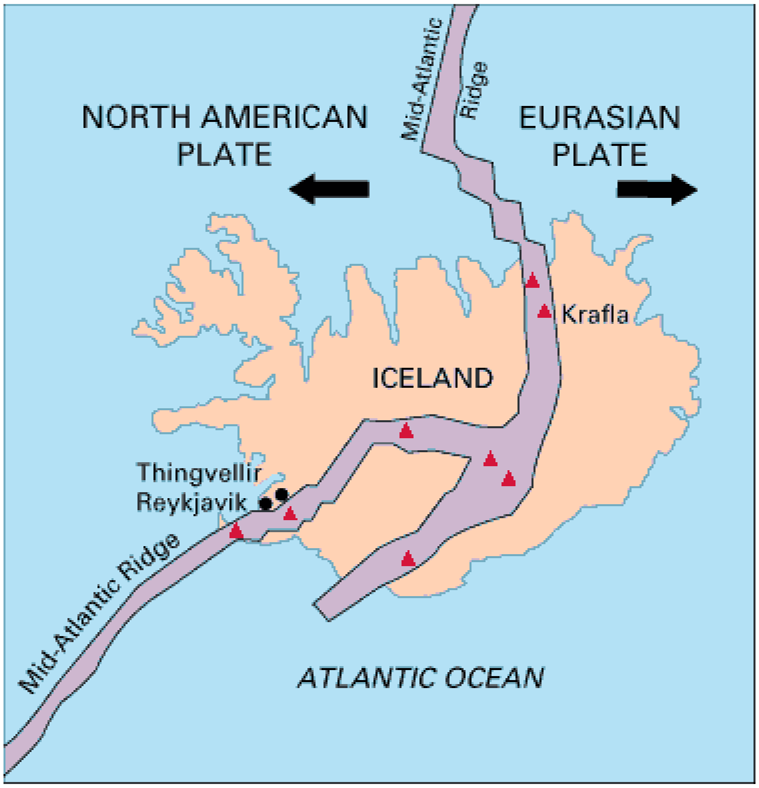
Divergent boundaries occur along spreading centers where plates are moving apart and new crust is created by magma pushing up from the mantle. Picture two giant conveyor belts, facing each other but slowly moving in opposite directions as they transport newly formed oceanic crust away from the ridge crest.



Perhaps the best known of the divergent boundaries is the Mid-Atlantic Ridge. This submerged mountain range, which extends from the Arctic Ocean to beyond the southern tip of Africa, is but one segment of the global mid-ocean ridge system that encircles the Earth. The rate of spreading along the Mid-Atlantic Ridge averages about 2.5 centimeters per year (cm/yr), or 25 km in a million years. This rate may seem slow by human standards, but because this process has been going on for millions of years, it has resulted in plate movement of thousands of kilometers. Seafloor spreading over the past 100 to 200 million years has caused the Atlantic Ocean to grow from a tiny inlet of water between the continents of Europe, Africa, and the Americas into the vast ocean that exists today.

The Mid-Atlantic Ridge, which splits nearly the entire Atlantic Ocean north to south, is probably the best-known and most-studied example of a divergent-plate boundary. (Illustration adapted from the map This Dynamic Planet.*)*

The volcanic country of Iceland, which straddles the Mid-Atlantic Ridge, offers scientists a natural laboratory for studying on land the processes also occurring along the submerged parts of a spreading ridge. Iceland is splitting along the spreading center between the North American and Eurasian Plates, as North America moves westward relative to Eurasia.



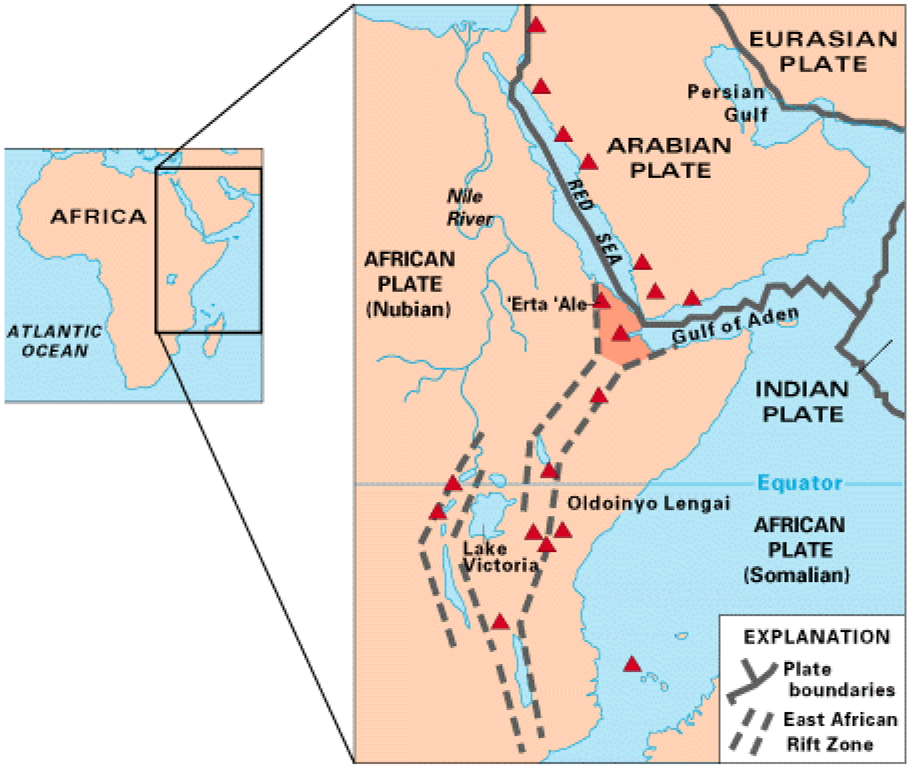
Map showing the Mid-Atlantic Ridge splitting Iceland and separating the North American and Eurasian Plates. The map also shows Reykjavik, the capital of Iceland, the Thingvellir area, and the locations of some of Iceland's active volcanoes (red triangles), including Krafla.

The consequences of plate movement are easy to see around Krafla Volcano, in the northeastern part of Iceland. Here, existing ground cracks have widened and new ones appear every few months. From 1975 to 1984, numerous episodes of *rifting* (surface cracking) took place along the Krafla fissure zone. Some of these rifting events were accompanied by volcanic activity; the ground would gradually rise 1-2 m before abruptly dropping, signalling an impending eruption. Between 1975 and 1984, the displacements caused by rifting totalled about 7 m.

Lava fountains (5p;10 m high) spouting from eruptive fissures during the October 1980 eruption of Krafla Volcano. (Photograph by Gudmundur E. Sigvaldason, Nordic Volcanological Institute, Reykjavik, Iceland.)

Aerial view of the area around Thingvellir, Iceland, showing a fissure zone (in shadow) that is an on-land exposure of the Mid-Atlantic Ridge. Right of the fissure, the North American Plate is pulling westward away from the Eurasian Plate (left of fissure). This photograph encompasses the historical tourist area of Thingvellir, the site of Iceland's first parliament, called the Althing, founded around the year A.D. 930. Large building (upper center) is a hotel for visitors. (Photograph by Oddur Sigurdsson, National Energy Authority, Iceland.)

In East Africa, spreading processes have already torn Saudi Arabia away from the rest of the African continent, forming the Red Sea. The actively splitting African Plate and the Arabian Plate meet in what geologists call a *triple junction,* where the Red Sea meets the Gulf of Aden. A new spreading center may be developing under Africa along the East African Rift Zone. When the continental crust stretches beyond its limits, tension cracks begin to appear on the Earth's surface. Magma rises and squeezes through the widening cracks, sometimes to erupt and form volcanoes. The rising magma, whether or not it erupts, puts more pressure on the crust to produce additional fractures and, ultimately, the rift zone.



Map of East Africa showing some of the historically active volcanoes(red triangles) and the Afar Triangle (shaded, center) -- a so-called triple junction *(or* triple point*), where three plates are pulling away from one another: the Arabian Plate, and the two parts of the African Plate (the Nubian and the Somalian) splitting along the East African Rift Zone.*

East Africa may be the site of the Earth's next major ocean. Plate interactions in the region provide scientists an opportunity to study first hand how the Atlantic may have begun to form about 200 million years ago. Geologists believe that, if spreading continues, the three plates that meet at the edge of the present-day African continent will separate completely, allowing the Indian Ocean to flood the area and making the easternmost corner of Africa (the Horn of Africa) a large island.

Helicopter view (in February 1994) of the active lava lake within the summit crater of 'Erta 'Ale (Ethiopia), one of the active volcanoes in the East African Rift Zone. Two helmeted, red-suited volcanologists -- observing the activity from the crater rim -- provide scale. Red color within the crater shows where molten lava is breaking through the lava lake's solidified, black crust. (Photograph by Jacques Durieux, Groupe Volcans Actifs.)

Oldoinyo Lengai, another active volcano in the East African Rift Zone, erupts explosively in 1966. (Photograph by Gordon Davies, courtesy of Celia Nyamweru, St. Lawrence University, Canton, New York.)

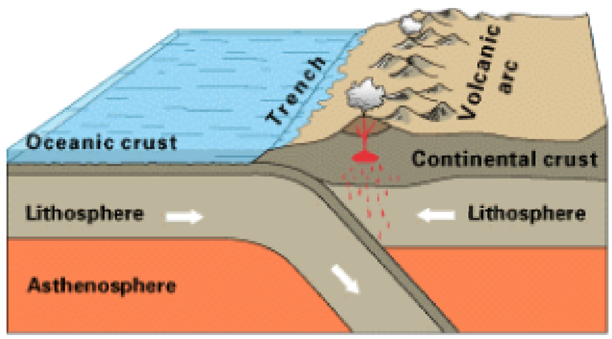
Convergent boundaries

The size of the Earth has not changed significantly during the past 600 million years, and very likely not since shortly after its formation 4.6 billion years ago. The Earth's unchanging size implies that the crust must be destroyed at about the same rate as it is being created, as Harry Hess surmised. Such destruction (recycling) of crust takes place along convergent boundaries where plates are moving toward each other, and sometimes one plate sinks (is *subducted*) under another. The location where sinking of a plate occurs is called a *subduction zone.*

The type of convergence -- called by some a very slow "collision" -- that takes place between plates depends on the kind of lithosphere involved. Convergence can occur between an oceanic and a largely continental plate, or between two largely oceanic plates, or between two largely continental plates.

Oceanic-continental convergence

If by magic we could pull a plug and drain the Pacific Ocean, we would see a most amazing sight -- a number of long narrow, curving *trenches* thousands of kilometers long and 8 to 10 km deep cutting into the ocean floor. Trenches are the deepest parts of the ocean floor and are created by subduction.

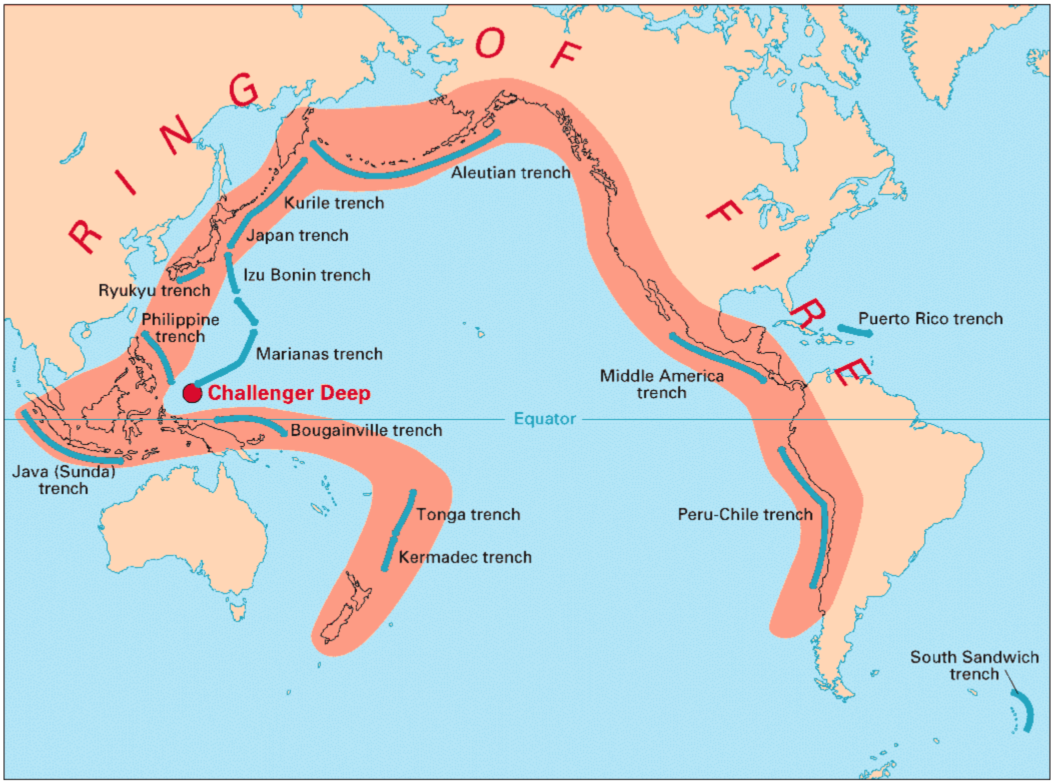


Oceanic-continental convergence

Off the coast of South America along the Peru-Chile trench, the oceanic Nazca Plate is pushing into and being subducted under the continental part of the South American Plate. In turn, the overriding South American Plate is being lifted up, creating the towering Andes mountains, the backbone of the continent. Strong, destructive earthquakes and the rapid uplift of mountain ranges are common in this region. Even though the Nazca Plate as a whole is sinking smoothly and continuously into the trench, the deepest part of the subducting plate breaks into smaller pieces that become locked in place for long periods of time before suddenly moving to generate large earthquakes. Such earthquakes are often accompanied by uplift of the land by as much as a few meters.

The convergence of the Nazca and South American Plates has deformed and pushed up limestone strata to form towering peaks of the Andes, as seen here in the Pachapaqui mining area in Peru. (Photograph by George Ericksen, USGS.)

On 9 June 1994, a magnitude-8.3 earthquake struck about 320 km northeast of La Paz, Bolivia, at a depth of 636 km. This earthquake, within the subduction zone between the Nazca Plate and the South American Plate, was one of deepest and largest subduction earthquakes recorded in South America. Fortunately, even though this powerful earthquake was felt as far away as Minnesota and Toronto, Canada, it caused no major damage because of its great depth.

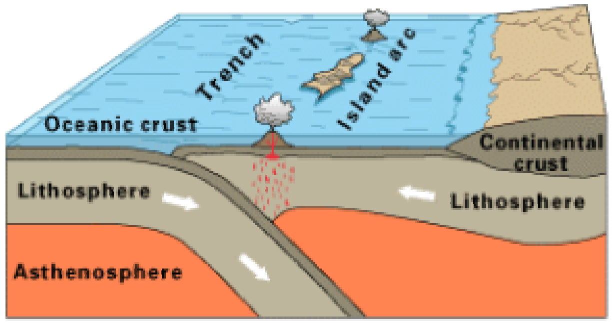


Volcanic arcs and oceanic trenches partly encircling the Pacific Basin form the so-called Ring of Fire, *a zone of frequent earthquakes and volcanic eruptions. The trenches are shown in blue-green. The volcanic island arcs, although not labelled, are parallel to, and always landward of, the trenches. For example, the island arc associated with the Aleutian Trench is represented by the long chain of volcanoes that make up the Aleutian Islands.*

Oceanic-continental convergence also sustains many of the Earth's active volcanoes, such as those in the Andes and the Cascade Range in the Pacific Northwest. The eruptive activity is clearly associated with subduction, but scientists vigorously debate the possible sources of magma: Is magma generated by the partial melting of the subducted oceanic slab, or the overlying continental lithosphere, or both?

Oceanic-oceanic convergence

As with oceanic-continental convergence, when two oceanic plates converge, one is usually subducted under the other, and in the process a trench is formed. The Marianas Trench (paralleling the Mariana Islands), for example, marks where the fast-moving Pacific Plate converges against the slower moving Philippine Plate. The Challenger Deep, at the southern end of the Marianas Trench, plunges deeper into the Earth's interior (nearly 11,000 m) than Mount Everest, the world's tallest mountain, rises above sea level (about 8,854 m).

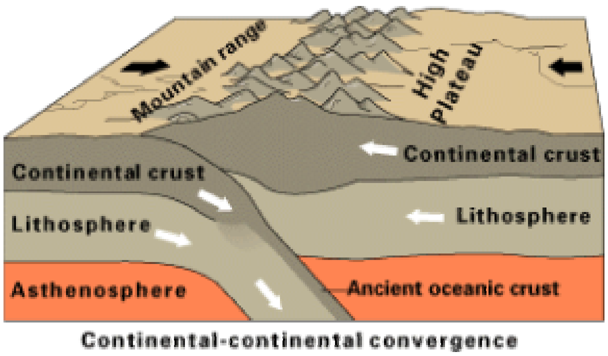


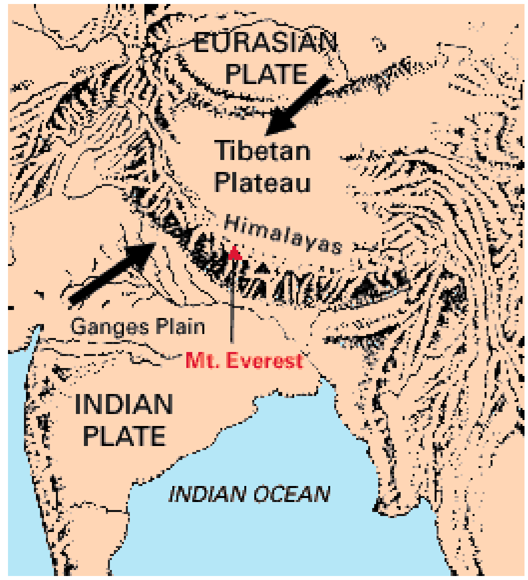
Oceanic-oceanic convergence

Subduction processes in oceanic-oceanic plate convergence also result in the formation of volcanoes. Over millions of years, the erupted lava and volcanic debris pile up on the ocean floor until a submarine volcano rises above sea level to form an island volcano. Such volcanoes are typically strung out in chains called *island arcs.* As the name implies, volcanic island arcs, which closely parallel the trenches, are generally curved. The trenches are the key to understanding how island arcs such as the Marianas and the Aleutian Islands have formed and why they experience numerous strong earthquakes. Magmas that form island arcs are produced by the partial melting of the descending plate and/or the overlying oceanic lithosphere. The descending plate also provides a source of stress as the two plates interact, leading to frequent moderate to strong earthquakes.

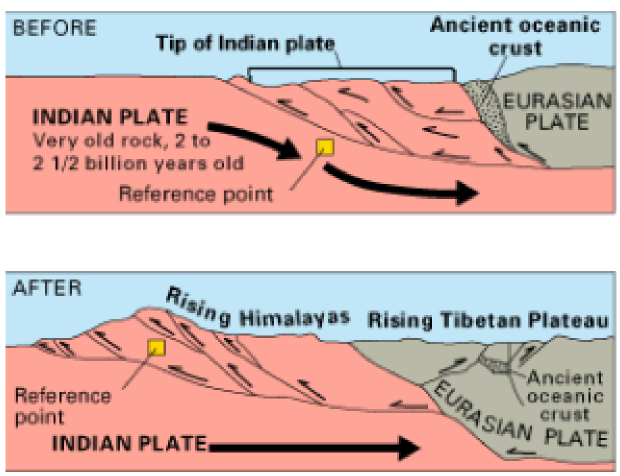
Continental-continental convergence

The Himalayan mountain range dramatically demonstrates one of the most visible and spectacular consequences of plate tectonics. When two continents meet head-on, neither is subducted because the continental rocks are relatively light and, like two colliding icebergs, resist downward motion. Instead, the crust tends to buckle and be pushed upward or sideways. The collision of India into Asia 50 million years ago caused the Eurasian Plate to crumple up and override the Indian Plate. After the collision, the slow continuous convergence of the two plates over millions of years pushed up the Himalayas and the Tibetan Plateau to their present heights. Most of this growth occurred during the past 10 million years. The Himalayas, towering as high as 8,854 m above sea level, form the highest continental mountains in the world. Moreover, the neighboring Tibetan Plateau, at an average elevation of about 4,600 m, is higher than all the peaks in the Alps except for Mont Blanc and Monte Rosa, and is well above the summits of most mountains in the United States.



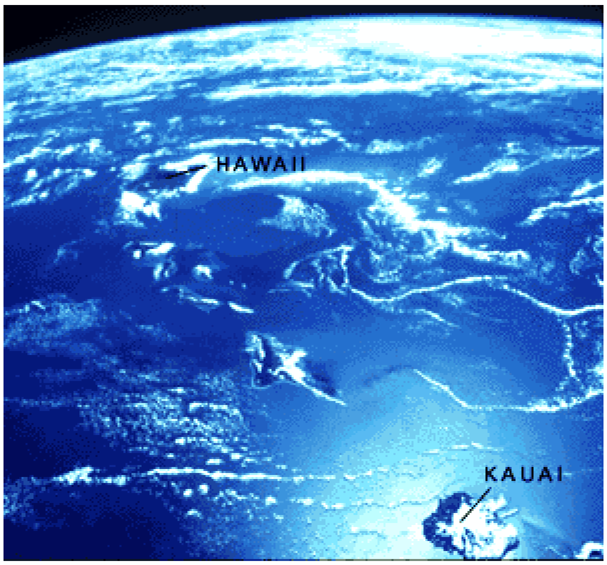


Left: The collision between the Indian and Eurasian plates has pushed up the Himalayas and the Tibetan Plateau. Right: Cartoon cross sections showing the meeting of these two plates before and after their collision. The reference points (small squares) show the amount of uplift of an imaginary point in the Earth's crust during this mountain-building process.



“Hotspots”: mantle thermal plumes

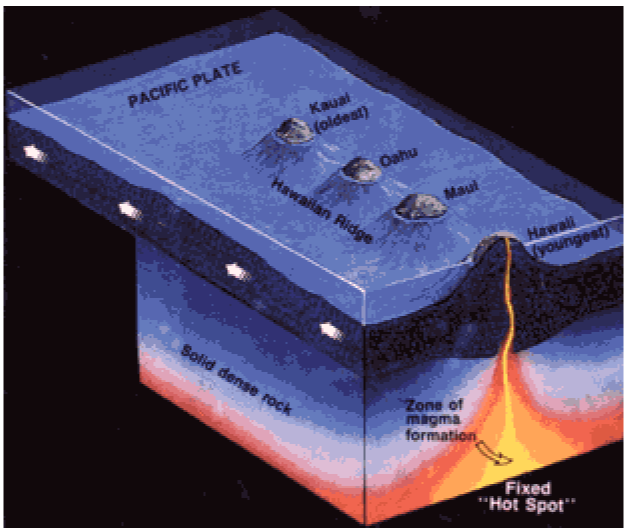
The vast majority of earthquakes and volcanic eruptions occur near plate boundaries, but there are some exceptions. For example, the Hawaiian Islands, which are entirely of volcanic origin, have formed in the middle of the Pacific Ocean more than 3,200 km from the nearest plate boundary. How do the Hawaiian Islands and other volcanoes that form in the interior of plates fit into the plate-tectonics picture?



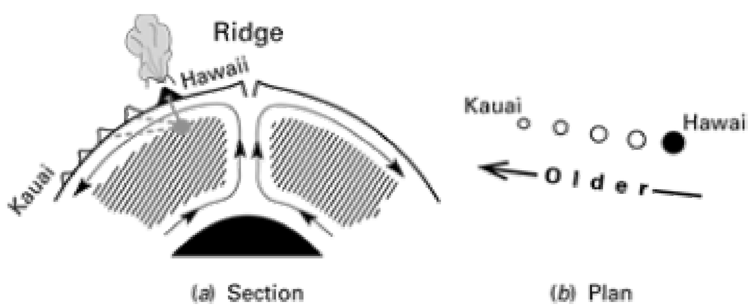
Space Shuttle photograph of the Hawaiian Islands, the southernmost part of the long volcanic trail of the "Hawaiian hotspot" (see text). Kauai is in the lower right corner (edge) and the Big Island of Hawaii in the upper left corner. Note the curvature of the Earth (top edge). (Photograph courtesy of NASA.)

In 1963, J. Tuzo Wilson, the Canadian geophysicist who discovered transform faults, came up with an ingenious idea that became known as the "hotspot" theory. Wilson noted that in certain locations around the world, such as Hawaii, volcanism has been active for very long periods of time. This could only happen, he reasoned, if relatively small, long-lasting, and exceptionally hot regions -- called *hotspots* -- existed below the plates that would provide localized sources of high heat energy *(thermal plumes)* to sustain volcanism. Specifically, Wilson hypothesized that the distinctive linear shape of the Hawaiian Island-Emperor Seamounts chain resulted from the Pacific Plate moving over a deep, stationary hotspot in the mantle, located beneath the present-day position of the Island of Hawaii. Heat from this hotspot produced a persistent source of magma by partly melting the overriding Pacific Plate. The magma, which is lighter than the surrounding solid rock, then rises through the mantle and crust to erupt onto the seafloor, forming an active seamount. Over time, countless eruptions cause the seamount to grow until it finally emerges above sea level to form an island volcano. Wilson suggested that continuing plate movement eventually carries the island beyond the hotspot, cutting it off from the magma source, and volcanism ceases. As one island volcano becomes extinct, another develops over the hotspot, and the cycle is repeated. This process of volcano growth and death, over many millions of years, has left a long trail of volcanic islands and seamounts across the Pacific Ocean floor.

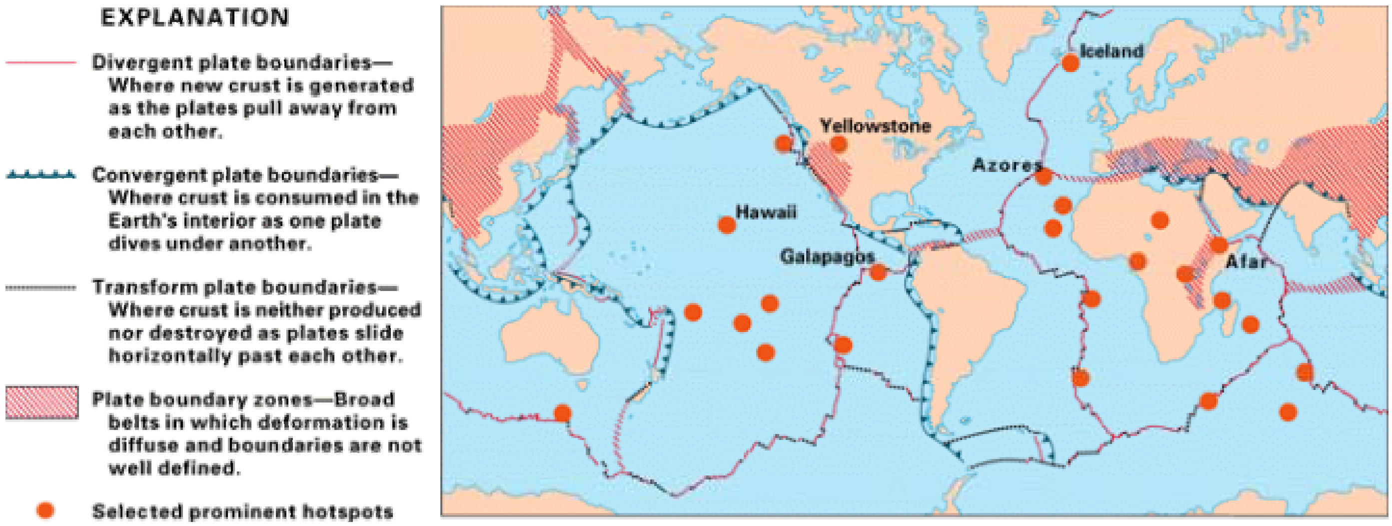
According to Wilson's hotspot theory, the volcanoes of the Hawaiian chain should get progressively older and become more eroded the farther they travel beyond the hotspot. The oldest volcanic rocks on Kauai, the northwesternmost inhabited Hawaiian island, are about 5.5 million years old and are deeply eroded. By comparison, on the "Big Island" of Hawaii -- southeasternmost in the chain and presumably still positioned over the hotspot -- the oldest exposed rocks are less than 0.7 million years old and new volcanic rock is continually being formed.



Above: *Artist's conception of the movement of the Pacific Plate over the fixed Hawaiian "Hot Spot," illustrating the formation of the Hawaiian Ridge-Emperor Seamount Chain. (Modified from a drawing provided by Maurice Krafft, Centre de Volcanologie, France).* Below: *J. Tuzo Wilson's original diagram (slightly modified), published in 1963, to show his proposed origin of the Hawaiian Islands. (Reproduced with permission of the* Canadian Journal of Physics.*)*



The possibility that the Hawaiian Islands become younger to the southeast was suspected by the ancient Hawaiians, long before any scientific studies were done. During their voyages, sea-faring Hawaiians noticed the differences in erosion, soil formation, and vegetation and recognized that the islands to the northwest (Niihau and Kauai) were older than those to the southeast (Maui and Hawaii). This idea was handed down from generation to generation in the legends of Pele, the fiery Goddess of Volcanoes. Pele originally lived on Kauai. When her older sister Namakaokahai, the Goddess of the Sea, attacked her, Pele fled to the Island of Oahu. When she was forced by Namakaokahai to flee again, Pele moved southeast to Maui and finally to Hawaii, where she now lives in the Halemaumau Crater at the summit of Kilauea Volcano. The mythical flight of Pele from Kauai to Hawaii, which alludes to the eternal struggle between the growth of volcanic islands from eruptions and their later erosion by ocean waves, is consistent with geologic evidence obtained centuries later that clearly shows the islands becoming younger from northwest to southeast.



World map showing the locations of selected prominent hotspots; those labelled are mentioned in the text. (Modified from the map This Dynamic Planet.*)*

Although Hawaii is perhaps the best known hotspot, others are thought to exist beneath the oceans and continents. More than a hundred hotspots beneath the Earth's crust have been active during the past 10 million years. Most of these are located under plate interiors (for example, the African Plate), but some occur near diverging plate boundaries. Some are concentrated near the mid-oceanic ridge system, such as beneath Iceland, the Azores, and the Galapagos Islands.

A few hotspots are thought to exist below the North American Plate. Perhaps the best known is the hotspot presumed to exist under the continental crust in the region of Yellowstone National Park in northwestern Wyoming. Here are several *calderas* (large craters formed by the ground collapse accompanying explosive volcanism) that were produced by three gigantic eruptions during the past two million years, the most recent of which occurred about 600,000 years ago. Ash deposits from these powerful eruptions have been mapped as far away as Iowa, Missouri, Texas, and even northern Mexico. The thermal energy of the presumed Yellowstone hotspot fuels more than 10,000 hot pools and springs, geysers (like Old Faithful), and bubbling *mudpots* (pools of boiling mud). A large body of magma, capped by a *hydrothermal system* (a zone of pressurized steam and hot water), still exists beneath the caldera. Recent surveys demonstrate that parts of the Yellowstone region rise and fall by as much as 1 cm each year, indicating the area is still geologically restless. However, these measurable ground movements, which most likely reflect hydrothermal pressure changes, do not necessarily signal renewed volcanic activity in the area.

Authors' Note: Since this booklet's publication in 1996, vigorous scientific debate has ensued regarding volcanism at "hotspots." New studies suggest that hotspots are neither deep phenomena nor "fixed" in position over geologic time, as assumed in the popular plume model. See http://www.mantleplumes.org/."

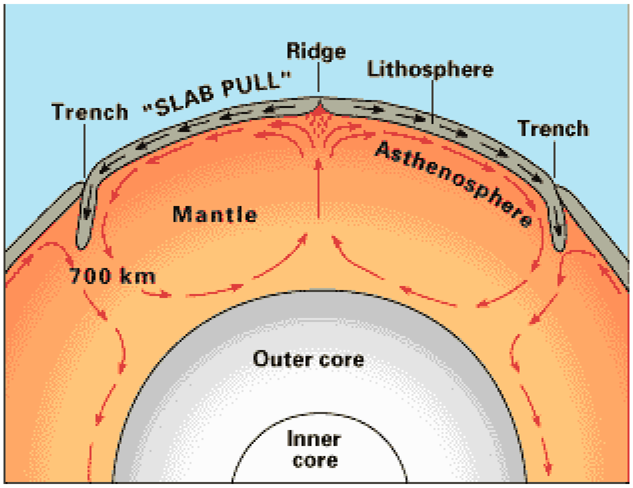
Snow-capped 4,169-m-high Mauna Loa Volcano, Island of Hawaii, seen from the USGS Hawaiian Volcano Observatory. Built by Hawaiian hotspot volcanism, Mauna Loa -- the largest mountain in the world -- is a classic example of a shield volcano. (Photograph by Robert I. Tilling, USGS.)

Some unanswered questions

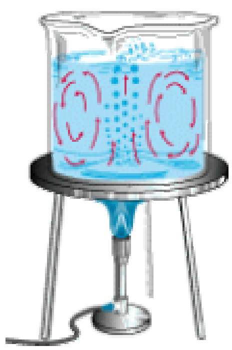
The tectonic plates do not randomly drift or wander about the Earth's surface; they are driven by definite yet unseen forces. Although scientists can neither precisely describe nor fully understand the forces, most believe that the relatively shallow forces driving the lithospheric plates are coupled with forces originating much deeper in the Earth.

What drives the plates?

From seismic and other geophysical evidence and laboratory experiments, scientists generally agree with Harry Hess' theory that the plate-driving force is the slow movement of hot, softened mantle that lies below the rigid plates. This idea was first considered in the 1930s by Arthur Holmes, the English geologist who later influenced Harry Hess' thinking about seafloor spreading. Holmes speculated that the circular motion of the mantle carried the continents along in much the same way as a conveyor belt. However, at the time that Wegener proposed his theory of continental drift, most scientists still believed the Earth was a solid, motionless body. We now know better. As J. Tuzo Wilson eloquently stated in 1968, "The earth, instead of appearing as an inert statue, is a living, mobile thing." Both the Earth's surface **and** its interior are in motion. Below the lithospheric plates, at some depth the mantle is partially molten and can flow, albeit slowly, in response to steady forces applied for long periods of time. Just as a solid metal like steel, when exposed to heat and pressure, can be softened and take different shapes, so too can solid rock in the mantle when subjected to heat and pressure in the Earth's interior over millions of years.



Left: *Conceptual drawing of assumed convection cells in the mantle (see text). Below a depth of about 700 km, the descending slab begins to soften and flow, losing its form.* Below: *Sketch showing convection cells commonly seen in boiling water or soup. This analogy, however, does not take into account the huge differences in the size and the flow rates of these cells.*



The mobile rock beneath the rigid plates is believed to be moving in a circular manner somewhat like a pot of thick soup when heated to boiling. The heated soup rises to the surface, spreads and begins to cool, and then sinks back to the bottom of the pot where it is reheated and rises again. This cycle is repeated over and over to generate what scientists call a *convection cell* or *convective flow.* While convective flow can be observed easily in a pot of boiling soup, the idea of such a process stirring up the Earth's interior is much more difficult to grasp. While we know that convective motion in the Earth is much, much slower than that of boiling soup, many unanswered questions remain: How many convection cells exist? Where and how do they originate? What is their structure?

Convection cannot take place without a source of heat. Heat within the Earth comes from two main sources: *radioactive decay* and *residual heat.* Radioactive decay, a spontaneous process that is the basis of "isotopic clocks" used to date rocks, involves the loss of particles from the nucleus of an isotope (the *parent*) to form an isotope of a new element (the *daughter*). The radioactive decay of naturally occurring chemical elements -- most notably uranium, thorium, and potassium -- releases energy in the form of heat, which slowly migrates toward the Earth's surface. Residual heat is gravitational energy left over from the formation of the Earth -- 4.6 billion years ago -- by the "falling together" and compression of cosmic debris. How and why the escape of interior heat becomes concentrated in certain regions to form convection cells remains a mystery.

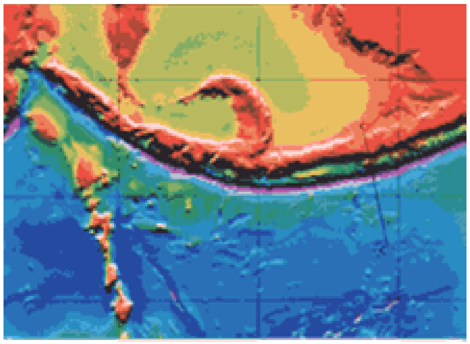
Until the 1990s, prevailing explanations about what drives plate tectonics have emphasized mantle convection, and most earth scientists believed that seafloor spreading was the primary mechanism. Cold, denser material convects downward and hotter, lighter material rises because of gravity; this movement of material is an essential part of convection. In addition to the convective forces, some geologists argue that the intrusion of magma into the spreading ridge provides an additional force (called "ridge push") to propel and maintain plate movement. Thus, subduction processes are considered to be secondary, a logical but largely passive consequence of seafloor spreading. In recent years however, the tide has turned. Most scientists now favor the notion that forces associated with subduction are more important than seafloor spreading. Professor Seiya Uyeda (Tokai University, Japan), a world-renowned expert in plate tectonics, concluded in his keynote address at a major scientific conference on subduction processes in June 1994 that "subduction . . . plays a more fundamental role than seafloor spreading in shaping the earth's surface features" and "running the plate tectonic machinery." The gravity-controlled sinking of a cold, denser oceanic slab into the subduction zone (called "slab pull") -- dragging the rest of the plate along with it -- is now considered to be the driving force of plate tectonics.

We know that forces at work deep within the Earth's interior drive plate motion, but we may never fully understand the details. At present, none of the proposed mechanisms can explain all the facets of plate movement; because these forces are buried so deeply, no mechanism can be tested directly and proven beyond reasonable doubt. The fact that the tectonic plates have moved in the past and are still moving today is beyond dispute, but the details of why and how they move will continue to challenge scientists far into the future.

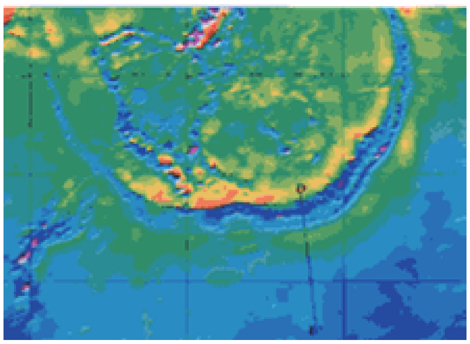
Extraterrestrial plate tectonics?

The Earth may be unique in our solar system because it appears to be the only planet that is still volcanically and tectonically active; our planet therefore remains very much alive, while the others apparently have long ceased activity. Volcanic activity requires a source of internal heat, and it is the escape of this heat that fuels plate tectonics. While volcanism played a major role in the early history of Mars, the Moon, and probably Mercury, their small sizes relative to Earth resulted in the loss of internal heat at a much faster rate. They have been inactive globes for the last billion years or so.

Venus may still be active, though the evidence is questionable. In 1979, the Pioneer-Venus spacecraft measured a high amount of sulfur in the upper atmosphere of the planet; the sulfur amount then decreased over the next few years. This observation suggested that the high sulfur concentration measured in 1979 may have resulted from a catastrophic



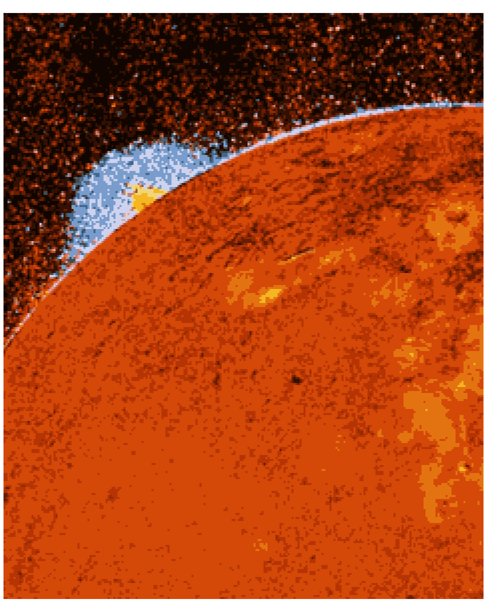
event, perhaps a volcanic eruption. Beginning in 1990, radar images made by the Magellan spacecraft revealed dramatic volcanic features and long, deep valleys similar in size and shape to oceanic trenches on Earth.



Left: *A computer-generated image of the Aleutian Trench (in violet); "warm" colors (yellow to red) indicate topographic highs, and "cool" colors (green to blue) represent lower elevations.*
Below: *The topography of Artemis Corona, a trench-like feature on Venus, shown at the same vertical and horizontal scale as the Aleutian Trench. (Imagery courtesy of David T. Sandwell, Scripps Institution of Oceanography.)*

The Voyager spacecraft discovered several volcanic plumes rising many hundreds of kilometers above the surface of Io, one of the moons of Jupiter and about the size of our Moon. Scientists speculate that large pools of liquid sulfur may exist on Io, possibly heated by tidal forces resulting from gravitational attraction between Io and Jupiter. The thermal energy generated by such tidal forces may be enough to produce convection in Io's interior, although no one has clearly recognized any surface feature that may have formed from such convection.

The surface of Ganymede, another moon of Jupiter and about the size of Mercury, is broken into many plate-like blocks, with long narrow depressions between some of them. Whether these surface features represent ancient "fossil" plate tectonics, or are actively forming, remains to be answered. Crucial to determining whether plate tectonics is occurring on Ganymede is the search for evidence of a deep ocean beneath its icy surface. Such a body of water, if it exists, might contribute to internal convection.



A volcanic plume of sulfur dioxide (SO_2) gas rising about 150 km above the surface of Io. This computer-enhanced image was captured "live" by the Voyager 2 spacecraft on 4 March 1979. (Imagery courtesy of NASA.)

The rate of heat loss is critical to a planet's tectonic activity. Size is one determining factor: larger bodies lose heat more slowly and will therefore remain active longer. Another factor is composition, which influences the ability of a body to convect. For example, a liquid interior, such as may exist within Ganymede, is more likely to convect and drive plate tectonics than the "stony" interiors of the Moon, Mercury, Venus, and Mars. The amount of radioactive elements present in the planet's composition also affects the likelihood of internal convection, because the decay of these elements produces heat. Apparently, the interiors of the Moon, Mercury, and Mars are either too rigid or have lost too much of their internal heat to convect and drive plate tectonics.

Eventually the Earth, too, will lose so much heat that its interior will stop convecting. Earthquake and volcanic activity will then cease. No new mountains will form, and the geologic cycle of mountain building, erosion, sedimentation, and soil formation will be disrupted and also will cease. Exactly how a cooled-down Earth will change surface conditions -- and whether our planet will still be habitable -- nobody knows. Fortunately, these changes will not happen for many billions of years!

Plate tectonics and people

Over geologic time, plate movements in concert with other geologic processes, such as glacial and stream erosion, have created some of nature's most magnificent scenery. The Himalayas, the Swiss Alps, and the Andes are some spectacular examples. Yet violent earthquakes related to plate tectonics have caused terrible catastrophes -- such as the magnitude-7.7 earthquake that struck the Chinese province of Hebei in 1976 and killed as many as 800,000 people.

Natural hazards

Most earthquakes and volcanic eruptions do not strike randomly but occur in specific areas, such as along plate boundaries. One such area is the circum-Pacific *Ring of Fire,* where the Pacific Plate meets many surrounding plates. The Ring of Fire is the most seismically and volcanically active zone in the world.

Earthquakes

Because many major population centers are located near active fault zones, such as the San Andreas, millions of people have suffered personal and economic losses as a result of destructive earthquakes, and even more have experienced earthquake motions. Not surprisingly, some people believe that, when the "Big One" hits, California will suddenly "break off" and "fall into the Pacific," or that the Earth will "open up" along the fault and "swallow" people, cars, and houses. Such beliefs have no scientific basis whatsoever. Although ground slippage commonly takes place in a large earthquake, the Earth will not open up. Nor will California fall into the sea, because the fault zone only extends about

15 km deep, which is only about a quarter of the thickness of the continental crust. Furthermore, California is composed of continental crust, whose relatively low density keeps it riding high, like an iceberg above the ocean.

Aerial view, looking north toward San Francisco, of Crystal Springs Reservoir, which follows the San Andreas fault zone. (Photograph by Robert E. Wallace, USGS.)

Like all transform plate boundaries, the San Andreas is a *strike-slip* fault, movement along which is dominantly horizontal. Specifically, the San Andreas fault zone separates the Pacific and North American Plates, which are slowly grinding past each other in a roughly north-south direction. The Pacific Plate (western side of the fault) is moving horizontally in a northerly direction relative to the North American Plate (eastern side of the fault). Evidence of the sideways shift of these two landmasses can be found all along the fault zone, as seen from the differences in topography, geologic structures, and, sometimes, vegetation of the terrain from one side of the fault to the other. For example, the San Andreas runs directly along Crystal Springs Reservoir on the San Francisco Peninsula. Topographically, this reservoir fills a long, straight, narrow valley that was formed by erosion of the easily erodible rocks mashed within the fault zone.

Movement along the San Andreas can occur either in sudden jolts or in a slow, steady motion called *creep.* Fault segments that are actively creeping experience many small to moderate earthquakes that cause little or no damage. These creeping segments are separated by segments of infrequent earthquake activity (called *seismic gaps*), areas that are stuck or locked in place within the fault zone. Locked segments of the fault store a tremendous amount of energy that can build up for decades, or even centuries, before being unleashed in devastating earthquakes. For example, the Great San Francisco Earthquake (8.3-magnitude) in 1906 ruptured along a previously locked 430 km-long segment of the San Andreas, extending from Cape Mendocino south to San Juan Bautista.

Map of the San Andreas and a few of the other faults in California, segments of which display different behavior: locked or creeping (see text). (Simplified from USGS Professional Paper 1515.)

The stresses that accumulate along a locked segment of the fault and the sudden release can be visualized by bending a stick until it breaks. The stick will bend fairly easily, up to a certain point, until the stress becomes too great and it snaps. The vibrations felt when the stick breaks represent the sudden release of the stored-up energy. Similarly, the seismic vibrations produced when the ground suddenly ruptures radiate out through the Earth's interior from the rupture point, called the *earthquake focus.* The geographic point directly above the focus is called the *earthquake epicenter.* In a major earthquake, the energy released can cause damage hundreds to thousands of kilometers away from the epicenter.

A dramatic photograph of horses killed by falling debris during the Great San Francisco Earthquake of 1906, when a locked segment of the San Andreas fault suddenly lurched, causing a devastating magnitude-8.3 earthquake. (Photograph by Edith Irvine, courtesy of Brigham Young University Library, Provo, Utah.)

The magnitude-7.1 Loma Prieta earthquake of October 1989 occurred along a segment of the San Andreas Fault which had been locked since the great 1906 San Francisco earthquake. Even though the earthquake's focus (approximately 80 km south of San Francisco) was centered in a sparsely populated part of the Santa Cruz Mountains, the earthquake still caused 62 deaths and nearly $6 billion in damage. Following the Loma Prieta earthquake, the fault remains locked from Pt. Arena, where it enters California from the ocean, south through San Francisco and the peninsula west of San Francisco Bay, thus posing the threat of a potential destructive earthquake occurring in a much more densely populated area.

The lesser known Hayward Fault running east of San Francisco Bay, however, may pose a potential threat as great as, or perhaps even greater than, the San Andreas. From the televised scenes of the damage caused by the 7.2-magnitude earthquake that struck Kobe, Japan, on 16 January 1995, Bay Area residents saw the possible devastation that could occur if a comparable size earthquake were to strike along the Hayward Fault. This is because the Hayward and the Nojima fault that produced the Kobe earthquake are quite similar in several ways. Not only are they of the same type (strike-slip), they are also about the same length (60p;80 km) and both cut through densely populated urban areas, with many buildings, freeways, and other structures built on unstable bay landfill. <>

On 17 January 1994, one of the costliest natural disasters in United States history struck southern California. A magnitude-6.6 earthquake hit near Northridge, a city located in the populous San Fernando Valley just north of Los Angeles, California. This disaster, which killed more than 60 people, caused an estimated $30 billion in damage, nearly five times that resulting from the Loma Prieta earthquake. The Northridge earthquake did not directly involve movement along one of the strands of the San Andreas Fault system. It instead occurred along the Santa Monica Mountains Thrust Fault, one of several smaller, concealed faults (called *blind thrust faults*) south of the San Andreas Fault zone where it bends to the east, roughly paralleling the Transverse Mountain Range. With a *thrust fault,* whose plane is inclined to the Earth's surface, one side moves upward over the other. Movement along a blind thrust fault does not break the ground surface, thus making it difficult or impossible to map these hidden but potentially dangerous faults. Although scientists have found measurable uplift at several places in the Transverse Range, they have not found any conclusive evidence of ground rupture from the 1994 Northridge earthquake. Similar earthquakes struck the region in 1971 and 1987; the San Fernando earthquake (1971) caused substantial damage, including the collapse of a hospital and several freeway overpasses.

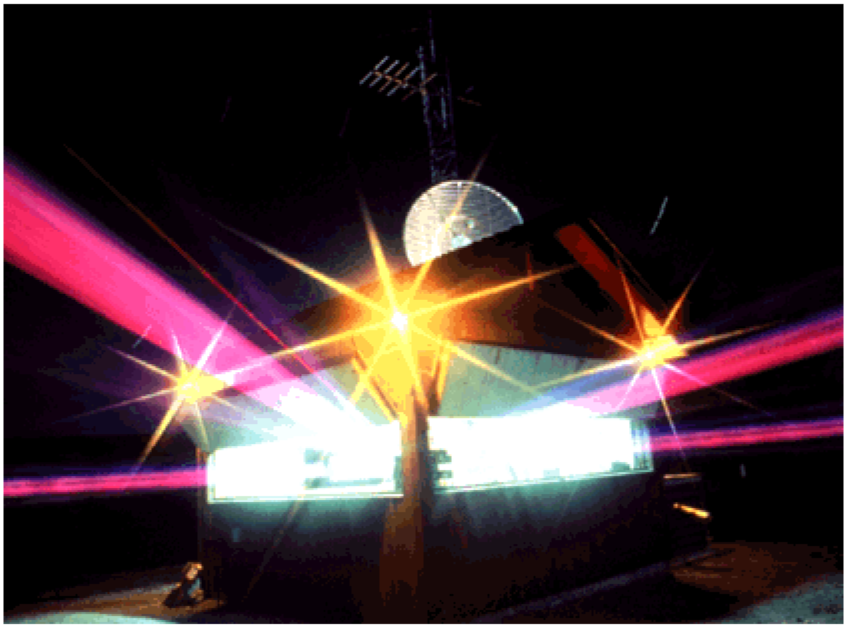
Not all fault movement is as violent and destructive. Near the city of Hollister in central California, the Calaveras Fault bends toward the San Andreas. Here, the Calaveras fault creeps at a slow, steady pace, posing little danger. Much of the Calaveras fault creeps at an average rate of 5 to 6 mm/yr. On average, Hollister has some 20,000 earthquakes a year, most of which are too small to be felt by residents. It is rare for an area undergoing creep to experience an earthquake with a magnitude greater than 6.0 because stress is continually being relieved and, therefore, does not accumulate. Fault-creep movement generally is non-threatening, resulting only in gradual offset of roads, fences, sidewalks, pipelines, and other structures that cross the fault. However, the persistence of fault creep does pose a costly nuisance in terms of maintenance and repair.

Mid-plate earthquakes -- those occurring in the interiors of plates -- are much less frequent than those along plate boundaries and more difficult to explain. Earthquakes along the Atlantic seaboard of the United States are most likely related in some way to the westward movement of the North American Plate away from the Mid-Atlantic Ridge, a continuing process begun with the break-up of Pangaea. However, the causes of these infrequent earthquakes are still not understood.

East Coast earthquakes, such as the one that struck Charleston, South Carolina, in 1886 are felt over a much larger area than earthquakes occurring on the West Coast, because the eastern half of the country is mainly composed of older rock that has not been fractured and cracked by frequent earthquake activity in the recent geologic past. Rock that is highly fractured and crushed absorbs more seismic energy than rock that is less fractured. The Charleston earthquake, with an estimated magnitude of about 7.0, was felt as far away as Chicago, more than 1,300 km to the northwest, whereas the 7.1-magnitude Loma Prieta earthquakes was felt no farther than Los Angeles, about 500 km south. The most widely felt earthquakes ever to strike the United States were centered near the town of New Madrid, Missouri, in 1811 and 1812. Three earthquakes, felt as far away as Washington D.C., were each estimated to be above 8.0 in magnitude. Most of us do not associate earthquakes with New York City, but beneath Manhattan is a network of intersecting faults, a few of which are capable of causing earthquakes. The most recent earthquake to strike New York City occurred in 1985 and measured 4.0 in magnitude, and a pair of earthquakes (magnitude 4.0 and 4.5) shook Reading, Pennsylvania, in January 1994 causing minor damage.

Left: *Creeping along the Calaveras fault has bent the retaining wall and offset the sidewalk along 5th Street in Hollister, California (about 75 km south-southeast of San Jose).* Right: *Close-up of the offset of the curb. (Photographs by W. Jacquelyne Kious.)*

We know in general how most earthquakes occur, but can we predict when they will strike? This question has challenged and frustrated scientists studying likely precursors to moderate and large earthquakes. Since the early 1980s, geologists and seismologists have been intensively studying a segment of the San Andreas near the small town of Parkfield, located about halfway between San Francisco and Los Angeles, to try to detect the physical and chemical changes that might take place -- both above and below ground -- before an earthquake strikes. The USGS and State and local agencies have blanketed Parkfield and the surrounding countryside with seismographs, creep meters, stress meters, and other ground-motion measurement devices.



Time-exposure photograph of the electronic-laser, ground-motion measurement system in operation at Parkfield, California, to track movement along the San Andreas fault (see text). (Photograph by John Nakata, USGS.)

The Parkfield segment has experienced earthquakes measuring magnitude 6.0 about every 22 years on average since 1881. During the most recent two earthquakes (1934, 1966), the same section of the fault slipped and the amount of slippage was about the same. In 1983, this evidence, in addition to the earlier recorded history of earthquake activity, led the USGS to predict that there was a 95 percent chance of a 6.0 earthquake striking Parkfield before 1993. But the anticipated earthquake of magnitude 6.0 or greater did not materialize. The Parkfield experiment is continuing, and its primary goals remain unchanged: to issue a short-term prediction; to monitor and analyze geophysical and geochemical effects before, during, and after the anticipated earthquake; and to develop effective communications between scientists, emergency-management officials, and the public in responding to earthquake hazards.

While scientists are studying and identifying possible precursors leading to the next Parkfield earthquake, they also are looking at these same precursors to see if they may be occurring along other segments of the fault. Studies of past earthquakes, together with data and experience gained from the Parkfield experiment, have been used by geoscientists to estimate the probabilities of major earthquakes occurring along the entire San Andreas Fault system. In 1988, the USGS identified six segments of the San Andreas as most likely to be hit by a magnitude 6.5 or larger earthquake within the next thirty years (1988-2018). The Loma Prieta earthquake in 1989 occurred along one of these six segments. The Parkfield experiment and other studies carried out by the USGS as part of the National Earthquake Hazards Reduction Program have led to an increased official and public awareness of the inevitability of future earthquake activity in California. Consequently, residents and State and local officials have become more diligent in planning and preparing for the next big earthquake.

Volcanic eruptions

As with earthquakes, volcanic activity is linked to plate-tectonic processes. Most of the world's active above-sea volcanoes are located near convergent plate boundaries where subduction is occurring, particularly around the Pacific basin. However, much more volcanism -- producing about three quarters of all lava erupted on Earth -- takes place unseen beneath the ocean, mostly along the oceanic spreading centers, such as the Mid-Atlantic Ridge and the East Pacific Rise.

Subduction-zone volcanoes like Mount St. Helens (in Washington State) and Mount Pinatubo (Luzon, Philippines), are called *composite cones* and typically erupt with explosive force, because the magma is too stiff to allow easy escape of volcanic gases. As a consequence, tremendous internal pressures mount as the trapped gases expand during ascent, before the pent-up pressure is suddenly released in a violent eruption. Such an explosive process can be compared to putting your thumb over an opened bottle of a carbonated drink, shaking it vigorously, and then quickly removing the thumb. The shaking action separates the gases from the liquid to form bubbles, increasing the internal pressure. Quick release of the thumb allows the gases and liquid to gush out with explosive speed and force.

In 1991, two volcanoes on the western edge of the Philippine Plate produced major eruptions. On June 15, Mount Pinatubo spewed ash 40 km into the air and produced huge ash flows (also called *pyroclastic flows*) and mudflows that devastated a large area around the volcano. Pinatubo, located 90 km from Manila, had been dormant for 600 years before the 1991 eruption, which ranks as one of the largest eruptions in this century. Also in 1991, Japan's Unzen Volcano, located on the Island of Kyushu about 40 km east of Nagasaki, awakened from its 200-year slumber to produce a new lava dome at its summit. Beginning in June, repeated collapses of this active dome generated destructive ash flows that swept down its slopes at speeds as high as 200 km per hour. Unzen is one of more than 75 active volcanoes in Japan; its eruption in 1792 killed more than 15,000 people--the worst volcanic disaster in the country's history.

An 18 km-high volcanic plume from one of a series of explosive eruptions of Mount Pinatubo beginning on 12 June 1991, viewed from Clark Air Base (about 20 km east of the volcano). Three days later, the most powerful eruption produced a plume that rose nearly 40 km, penetrating well into the stratosphere. (Photograph by David H. Harlow, USGS.)

While the Unzen eruptions have caused deaths and considerable local damage, the impact of the June 1991 eruption of Mount Pinatubo was global. Slightly cooler than usual temperatures recorded worldwide and the brilliant sunsets and sunrises have been attributed to this eruption that sent fine ash and gases high into the stratosphere, forming a large volcanic cloud that drifted around the world. The sulfur dioxide (SO2) in this cloud -- about 22 million tons -- combined with water to form droplets of sulfuric acid, blocking some of the sunlight from reaching the Earth and thereby cooling temperatures in some regions by as much as 0.5 °C. An eruption the size of Mount Pinatubo could affect the weather for a few years. A similar phenomenon occurred in April of 1815 with the cataclysmic eruption of Tambora Volcano in Indonesia, the most powerful eruption in recorded history. Tambora's volcanic cloud lowered global temperatures by as much as 3 °C. Even a year after the eruption, most of the northern hemisphere experienced sharply cooler temperatures during the summer months. In part of Europe and in North America, 1816 was known as "the year without a summer."

Apart from possibly affecting climate, volcanic clouds from explosive eruptions also pose a hazard to aviation safety. During the past two decades, more than 60 airplanes, mostly commercial jetliners, have been damaged by in-flight encounters with volcanic ash. Some of these encounters have resulted in the power loss of all engines, necessitating emergency landings. Luckily, to date no crashes have happened be-cause of jet aircraft flying into volcanic ash.

Diagram showing the lower two layers of the atmosphere: the troposphere and the stratosphere. The tropopause--the boundary between these two layers--varies in altitude from 8 to 18 km (dashed white lines), depending on Earth latitude and season of the year. The summit of Mt. Everest (inset photograph) and the altitudes commonly flown by commercial jetliners are given for reference. (Photograph by David G. Howell, USGS.)

Since the year A.D. 1600, nearly 300,000 people have been killed by volcanic eruptions. Most deaths were caused by *pyroclastic flows* and *mudflows,* deadly hazards which often accompany explosive eruptions of subduction-zone volcanoes. Pyroclastic flows, also called *nuées ardentes* ("glowing clouds" in French), are fast-moving, avalanche-like, ground-hugging incandescent mixtures of hot volcanic debris, ash, and gases that can travel at speeds in excess of 150 km per hour. Approximately 30,000 people were killed by pyroclastic flows during the 1902 eruption of Mont Pelée on the Island of Martinique in the Caribbean. In March-April 1982, three explosive eruptions of El Chichón Volcano in the State of Chiapas, southeastern Mexico, caused the worst volcanic disaster in that country's history. Villages within 8 km of the volcano were destroyed by pyroclastic flows, killing more than 2,000 people.

Mudflows (also called *debris flows* or *lahars,* an Indonesian term for volcanic mudflows) are mixtures of volcanic debris and water. The water usually comes from two sources: rainfall or the melting of snow and ice by hot volcanic debris. Depending on the proportion of water to volcanic material, mudflows can range from soupy floods to thick flows that have the consistency of wet cement. As mudflows sweep down the steep sides of composite volcanoes, they have the strength and speed to flatten or bury everything in their paths. Hot ash and pyroclastic flows from the eruption of the Nevado del Ruiz Volcano in Colombia, South America, melted snow and ice atop the 5,390-m-high Andean peak; the ensuing mudflows buried the city of Armero, killing 25,000 people.

Aerial view of the city of Armero, Colombia, devastated by mudflows triggered by the eruption of Nevado del Ruiz in November 1985. The mudflows destroyed everything in their paths and killed about 25,000 people. (Photograph by Darrell G. Herd, USGS.)

Eruptions of Hawaiian and most other mid-plate volcanoes differ greatly from those of composite cones. Mauna Loa and Kilauea, on the island of Hawaii, are known as *shield volcanoes,* because they resemble the wide, rounded shape of an ancient warrior's shield. Shield volcanoes tend to erupt non-explosively, mainly pouring out huge volumes of fluid lava. Hawaiian-type eruptions are rarely life threatening because the lava advances slowly enough to allow safe evacuation of people, but large lava flows can cause considerable economic loss by destroying property and agricultural lands. For example, lava from the ongoing eruption of Kilauea, which began in January 1983, has destroyed more than 200 structures, buried kilometers of highways, and disrupted the daily lives of local residents. Because Hawaiian volcanoes erupt frequently and pose little danger to humans, they provide an ideal natural laboratory to safely study volcanic phenomena at close range. The USGS Hawaiian Volcano Observatory, on the rim of Kilauea, was among the world's first modern volcano observatories, established early in this century.

Wahaula Visitor Center, Hawaii Volcanoes National Park, was one of more than 200 structures overrun by lava flows (foreground) from the 1983-present eruption at Kilauea Volcano. (Photograph by J.D. Griggs, USGS.)

In recorded history, explosive eruptions at subduction-zone (convergent-boundary) volcanoes have posed the greatest hazard to civilizations. Yet scientists have estimated that about three quarters of the material erupted on Earth each year originates at spreading mid-ocean ridges. However, no deep submarine eruption has yet been observed "live" by scientists. Because the great water depths preclude easy observation, few detailed studies have been made of the numerous possible eruption sites along the tremendous length (50,000 km) of the global mid-oceanic ridge system. Recently however, repeated surveys of specific sites along the Juan de Fuca Ridge, off the coast of the Oregon and Washington, have mapped deposits of fresh lava, which must have been erupted sometime between the surveys. In June 1993, seismic signals typically associated with submarine eruptions -- called *T-phases* -- were detected along part of the spreading Juan de Fuca Ridge and interpreted as being caused by eruptive activity.

Iceland, where the Mid-Atlantic Ridge is exposed on land, is a different story. It is easy to see many Icelandic volcanoes erupt non-explosively from fissure vents, in similar fashion to typical Hawaiian eruptions; others, like Hekla Volcano, erupt explosively. (After Hekla's catastrophic eruption in 1104, it was thought in the Christian world to be the "Mouth to Hell.") The voluminous, but mostly non-explosive, eruption at Lakagígar (Laki), Iceland, in 1783, resulted in one of the world's worst volcanic disasters. About 9,000 people -- almost 20% of the country's population at the time -- died of starvation *after* the eruption, because their livestock had perished from grazing on grass contaminated by fluorine-rich gases emitted during this eight month-long eruption.

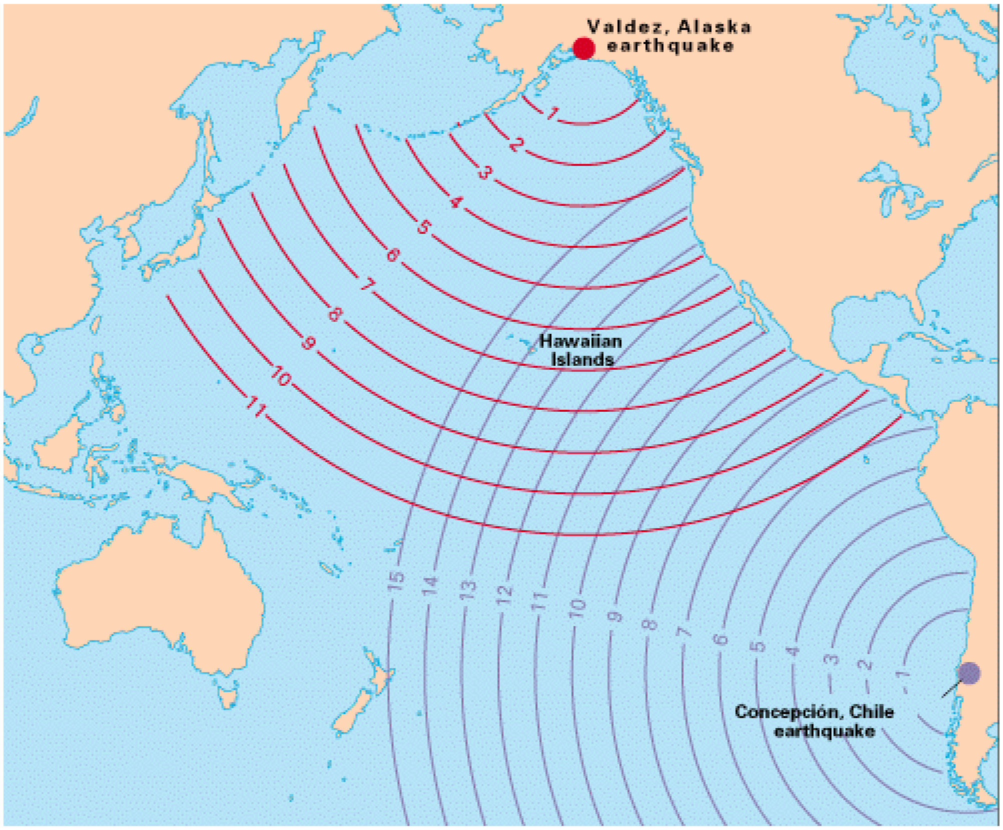
Tsunamis

Major earthquakes occurring along subduction zones are especially hazardous, because they can trigger tsunamis (from the Japanese word *tsunami* meaning "harbor wave") and pose a potential danger to coastal communities and islands that dot the Pacific. Tsunamis are often mistakenly called "tidal waves" when, in fact, they have nothing to do with tidal action. Rather, tsunamis are seismic sea waves caused by earthquakes, submarine landslides, and, infrequently, by eruptions of island volcanoes. During a major earthquake, the seafloor can move by several meters and an enormous amount of water is suddenly set into motion, sloshing back and forth for several hours. The result is a series of waves that race across the ocean at speeds of more than 800 km per hour, comparable to those of commercial jetliners. The energy and momentum of these transoceanic waves can take them thousands of kilometers from their origin before slamming into far-distant islands or coastal areas.

A giant wave engulfs the pier at Hilo, Hawaii, during the 1946 tsunami, which killed 159 people. The arrow points to a man who was swept away seconds later. (Retouched photograph courtesy of NOAA/EDIS.)

To someone on a ship in the open ocean, the passage of a tsunami wave would barely elevate the water surface. However, when it reaches shallower water near the coastline and "touches bottom," the tsunami wave increases in height, piling up into an enormous wall of water. As a tsunami approaches the shore, the water near shore commonly recedes for several minutes -- long enough for someone to be lured out to collect exposed sea shells, fish, etc. -- before suddenly rushing back toward land with frightening speed and height.

The 1883 eruption of Krakatau Volcano, located in the Sunda Straits between the islands of Sumatra and Java, Indonesia, provides an excellent example of an eruption-caused tsunami. A series of tsunamis washed away 165 coastal villages on Java and Sumatra, killing 36,000 people. The larger tsunamis were recorded by tide gauges as far away as the southern coast of the Arabian Peninsula-more than 7,000 km from Krakatau!



The Hawaiian Islands are especially vulnerable to destructive tsunamis generated by major earthquakes in the circum-Pacific Ring of Fire. Travel times (in hours) are shown for the tsunamis produced by the 1960 Concepción, Chile, earthquake (purple curves) and by the 1964 Good Friday, Valdez (Anchorage), Alaska earthquake (red curves). The 1960 tsunamis killed 61 people and caused about $24 million in damage.

Because of past killer tsunamis, which have caused hundreds of deaths on the Island of Hawaii and elsewhere, the International Tsunami Information Center was created in 1965. This center issues tsunami warnings based on earthquake and wave-height information gathered from seismic and tide-gauge stations located around the Pacific Ocean basin and on Hawaii.

Natural resources

Many of the Earth's natural resources of energy, minerals, and soil are concentrated near past or present plate boundaries. The utilization of these readily available resources have sustained human civilizations, both now and in the past.

Fertile soils

Volcanoes can clearly cause much damage and destruction, but in the long term they also have benefited people. Over thousands to millions of years, the physical breakdown and chemical weathering of volcanic rocks have formed some of the most fertile soils on Earth. In tropical, rainy regions, such as the windward (northeastern) side of the Island of Hawaii, the formation of fertile soil and growth of lush vegetation following an eruption can be as fast as a few hundred years. Some of the earliest civilizations (for example, Greek, Etruscan, and Roman) settled on the rich, fertile volcanic soils in the Mediterranean-Aegean region. Some of the best rice-growing regions of Indonesia are in the shadow of active volcanoes. Similarly, many prime agricultural regions in the western United States have fertile soils wholly or largely of volcanic origin.

Ore deposits

Most of the metallic minerals mined in the world, such as copper, gold, silver, lead, and zinc, are associated with magmas found deep within the roots of extinct volcanoes located above subduction zones. Rising magma does not always reach the surface to erupt; instead it may slowly cool and harden beneath the volcano to form a wide variety of crystalline rocks (generally called *plutonic* or *granitic* rocks). Some of the best examples of such deep-seated granitic rocks, later exposed by erosion, are magnificently displayed in California's Yosemite National Park. Ore deposits commonly form around the magma bodies that feed volcanoes because there is a ready supply of heat, which convectively moves and circulates ore-bearing fluids. The metals, originally scattered in trace amounts in magma or surrounding solid rocks, become concentrated by circulating hot fluids and can be redeposited, under favorable temperature and pressure conditions, to form rich mineral veins.

The active volcanic vents along the spreading mid-ocean ridges create ideal environments for the circulation of fluids rich in minerals and for ore deposition. Water as hot as 380 °C gushes out of geothermal springs along the spreading centers. The water has been heated during circulation by contact with the hot volcanic rocks forming the ridge. Deep-sea hot springs containing an abundance of dark-colored ore minerals (sulfides) of iron, copper, zinc, nickel, and other metals are called "black smokers." On rare occasions, such deep-sea ore deposits are later exposed in remnants of ancient oceanic crust that have been scraped off and left ("beached") on top of continental crust during past subduction processes. The Troodos Massif on the Island of Cyprus is perhaps the best known example of such ancient oceanic crust. Cyprus was an important source of copper in the ancient world, and Romans called copper the "Cyprian metal"; the Latin word for copper is cyprium.

Fossil fuels

Oil and natural gas are the products of the deep burial and decomposition of accumulated organic material in geologic basins that flank mountain ranges formed by plate-tectonic processes. Heat and pressure at depth transform the decomposed organic material into tiny pockets of gas and liquid petroleum, which then migrate through the pore spaces and larger openings in the surrounding rocks and collect in reservoirs, generally within 5 km of the Earth's surface. Coal is also a product of accumulated decomposed plant debris, later buried and compacted beneath overlying sediments. Most coal originated as peat in ancient swamps created many millions of years ago, associated with the draining and flooding of landmasses caused by changes in sea level related to plate tectonics and other geologic processes. For example, the Appalachian coal deposits formed about 300 million years ago in a low-lying basin that was alternately flooded and drained.

Half Dome as viewed from Glacier Point, Yosemite National Park, rises more than a kilometer above the valley floor. The granitic rocks that form Half Dome and other spectacular Park features represent unerupted magma later exposed by deep erosion and glaciation. (Photograph by Carroll Ann Hodges, USGS.)

Geothermal energy

Geothermal energy can be harnessed from the Earth's natural heat associated with active volcanoes or geologically young inactive volcanoes still giving off heat at depth. Steam from high-temperature geothermal fluids can be used to drive turbines and generate electrical power, while lower temperature fluids provide hot water for space-heating purposes, heat for greenhouses and industrial uses, and hot or warm springs at resort spas. For example, geothermal heat warms more than 70 percent of the homes in Iceland, and The Geysers geothermal field in Northern California produces enough electricity to meet the power demands of San Francisco. In addition to being an energy resource, some geothermal waters also contain sulfur, gold, silver, and mercury that can be recovered as a byproduct of energy production.

Geothermal powerplant at The Geysers near the city of Santa Rosa in northern California. The Geysers area is the largest geothermal development in the world. (Photograph by Julie Donnelly-Nolan, USGS.)

A formidable challenge

As global population increases and more countries become industrialized, the world demand for mineral and energy resources will continue to grow. Because people have been using natural resources for millennia, most of the easily located mineral, fossil-fuel, and geothermal resources have already been tapped. By necessity, the world's focus has turned to the more remote and inaccessible regions of the world, such as the ocean floor, the polar continents, and the resources that lie deeper in the Earth's crust. Finding and developing such resources without damage to the environment will present a formidable challenge in the coming decades. An improved knowledge of the relationship between plate tectonics and natural resources is essential to meeting this challenge.

Farmer plowing a lush rice paddy in central Java, Indonesia; Sundoro Volcano looms in the background. The most highly prized rice-growing areas have fertile soils formed from the breakdown of young volcanic deposits. (Photograph by Robert I. Tilling, USGS.)

The long-term benefits of plate tectonics should serve as a constant reminder to us that the planet Earth occupies a unique niche in our solar system. Appreciation of the concept of plate tectonics and its consequences has reinforced the notion that the Earth is an integrated whole, not a random collection of isolated parts. The global effort to better understand this revolutionary concept has helped to unite the earth-sciences community and to underscore the linkages between the many different scientific disciplines. As we enter the 21st century, when the Earth's finite resources will be further strained by explosive population growth, earth scientists must strive to better understand our dynamic planet. We must become more resourceful in reaping the long-term benefits of plate tectonics, while coping with its short-term adverse impacts, such as earthquakes and volcanic eruptions.

Endnotes

Snow-clad Mt. Rainier, a 4,392 m-high volcano built by plate-tectonic processes, dominates the pastoral scene around Orting, Washington. This valley is an inviting place for people to live, work, and play, but it is also highly vulnerable to destructive mudflows that could be generated by renewed eruptive activity at Mt. Rainier. Society must learn to "co-exist" intelligently with active volcanoes. (Photograph by David E. Wieprecht, USGS.)

Further reading

These works listed furnish additional information on topics not covered, or only briefly discussed, in the booklet.

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Ernst, W.G., 1990, The Dynamic Planet: Columbia University Press, New York, 280 p. (A comprehensive college-level textbook that includes good chapters on plate tectonics and related topics.)

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San Andreas Fault.)

McPhee, John, 1993, Assembling California: Farrar, Straus, & Giroux, New York, 303 p. (A fascinating account of the role of plate tectonics in the geology of California, told in the typical McPhee style of conversations with scientists.)

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Sullivan, Water, 1991, Continents in Motion: McGraw-Hill Book Co., New York, 430 p. (A comprehensive review of the developments that culminated in the plate tectonics theory. Science Editor of the New York Times, Sullivan is widely regarded as the "dean" of America's science writers.)

Tarbuck, Edward, and Lutgens, Frederick, 1985, Earth Science: Charles E. Merrill Publishing Co., Columbus, Ohio, 561 p. (A college-level geology textbook that contains good chapters on plate tectonics and related topics.)

Tilling, R.I., 1991, Born of fire: Volcanoes and igneous rocks: Enslow Publishers, Inc., Hillside, New Jersey, 64 p. (An introductory text about the kinds of volcanoes and their products and hazardous impacts-aimed at approximately junior high- to high-school level.)

Tilling, R.I., Heliker, C., and Wright, T.L., 1987, Eruptions of Hawaiian Volcanoes: Past, present, and future: U.S. Geological Survey general-interest publication, 54 p. (A nontechnical summary, illustrated by many color photographs, of the abundant data on Hawaiian volcanism; similar in format to this book.)

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Past, present, and future: U.S. Geological Survey general-interest publication, 56 p. (A nontechnical summary, illustrated by many color photographs and diagrams, of the abundant scientific data available for the volcano, with emphasis on the catastrophic eruption of 18 May 1980; similar in format to this book.)

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This publication is one of a series of general interest publications prepared by the U.S. Geological Survey to provide information about the earth sciences, natural resources, and the environment. To obtain a catalog of additional titles in the series "General Interest Publications of the U.S. Geological Survey," write:

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