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Geotectonics Lectures

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Lecture One

Geotectonics: Relating to the ***form***, ***arrangement***, and ***structure*** of rock masses of the earth crust resulting from folding or faulting.

The word **geotectonics** is derived from two Greek words **gê—earth**, and **tectonicon**—to build. It consequently means literally the science of the **Earth's structure**, but such a definition is too wide since it embraces, in essence, almost, the whole of geology.

Tectonics (from the Late Latin tectonicus from the Greek τεκτονικός, "pertaining to building") *is concerned with the* ***processes*** *which control the* ***structure*** *and* ***properties*** *of the Earth's crust*, *and its evolution through time*. In particular, it describes:

1- the processes of mountain building, 2- the growth and behavior of the strong, old cores of continents known as cratons, and 3- the ways in which the relatively rigid plates that comprise the Earth's outer shell interact with each other. Tectonics also provides a framework to understand the **earthquake** and **volcanic belts** which directly affect much of the global population. Tectonic studies are important for understanding **erosion patterns** in geomorphology and as guides for the economic geologist searching for **petroleum** and **metallic ores**.

Plate tectonics

In plate tectonics the outermost part of the earth, the **crust and uppermostmantle**, act as a single mechanical layer, the **lithosphere.** The lithosphere is divided into separate 'plates' that move relative to each other on the underlying, relatively weak **asthenosphere** in a process ultimately driven by the continuous loss of heat from the earth's interior.

Neotectonics

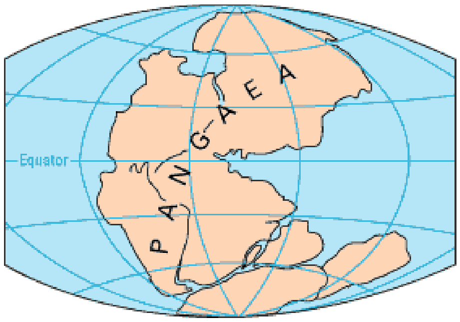
Neotectonics is the study of the motions and deformations of the Earth's crust (geological and geomorphological processes) that are **currentor recent** in geological time. The term may also refer to the motions/deformations in question themselves. The corresponding time frame is referred to as the neotectonic period. Accordingly, the preceding time is referred to as palaeotectonic period.

Historical perspective

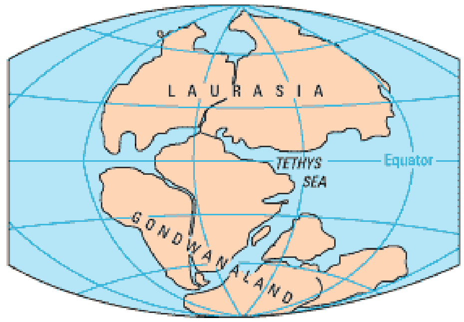
In geologic terms, a ***plate*** is a large, rigid slab of solid rock. The word ***tectonics*** comes from the Greek root "to build." Putting these two words together, we get the term plate tectonics, *which refer to how the Earth's surface is built of plates*. The theory of plate tectonics states that 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.

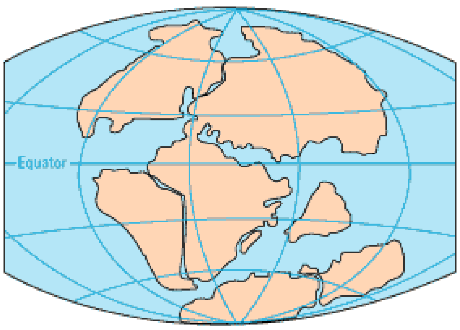
According to the **continental drift theory**, the supercontinent Pangaea began to break up about 225-200 million years ago, eventually fragmenting into the continents as we know them today. Plate tectonics is a relatively new scientific concept, introduced some 30 years ago, but it has revolutionized 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?.*



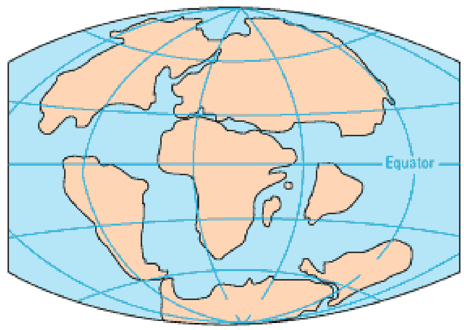
PERMIAN
225 million years ago



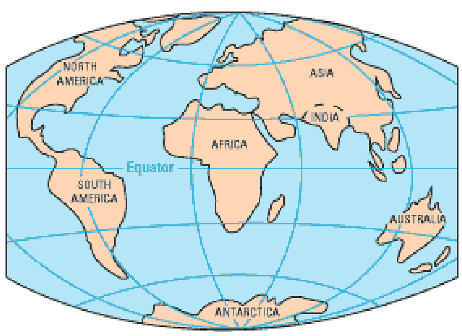
TRIASSIC
200 million years ago



JURASSIC
135 million years ago

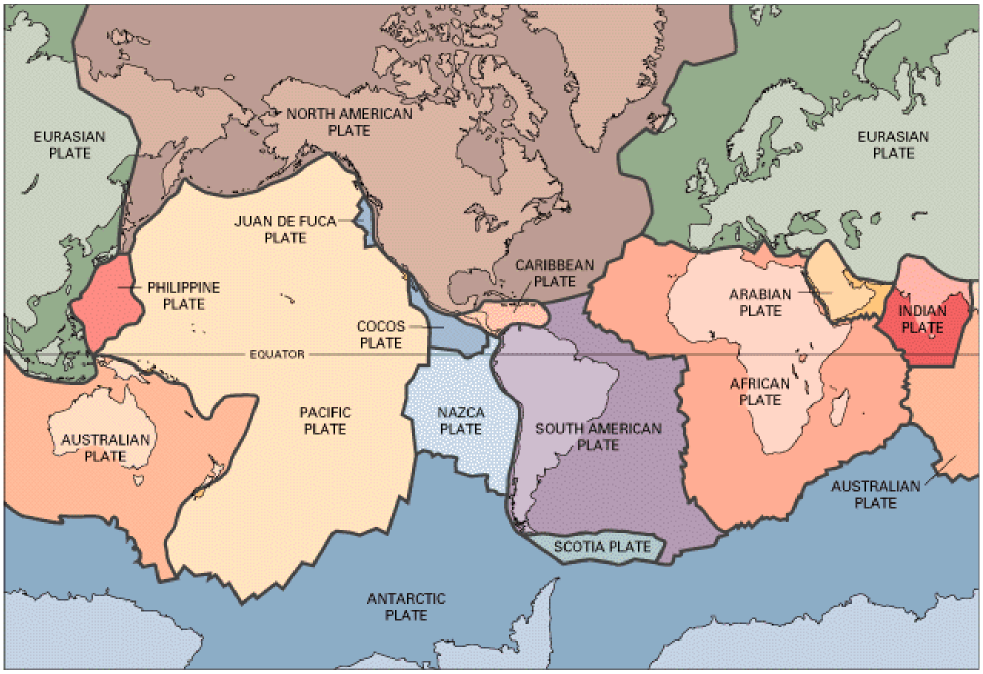


CRETACEOUS
65 million years ago

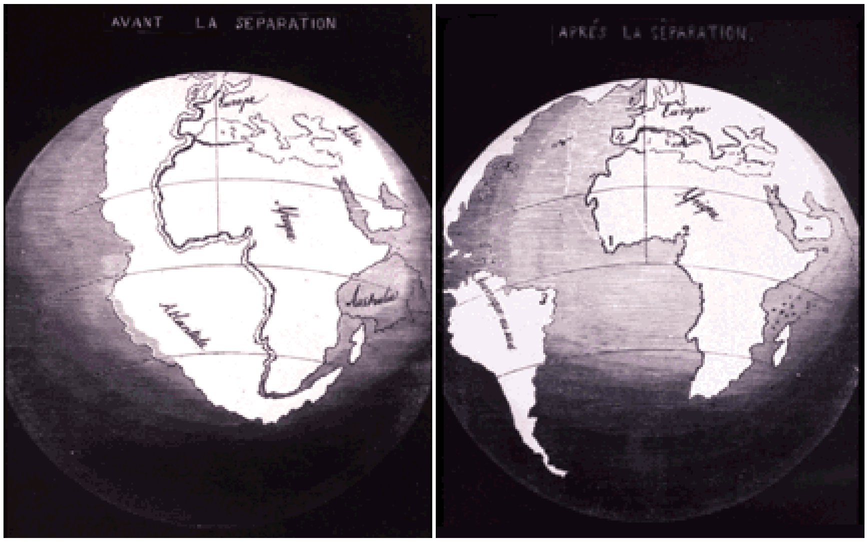


PRESENT DAY

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.

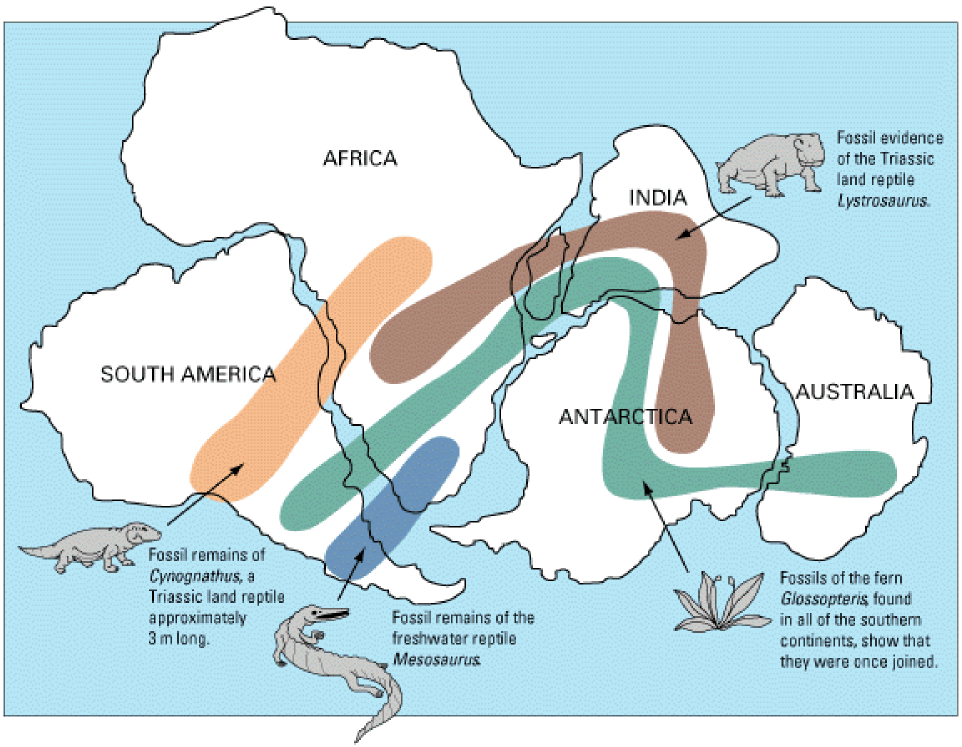


In 1858, geographer ***Antonio Snider-Pellegrini*** *made these two maps showing his version of how the American and African continents may once have fit together, then later separated. Left: The formerly joined continents before (avant) their separation. Right: The continents after (aprés) the separation.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

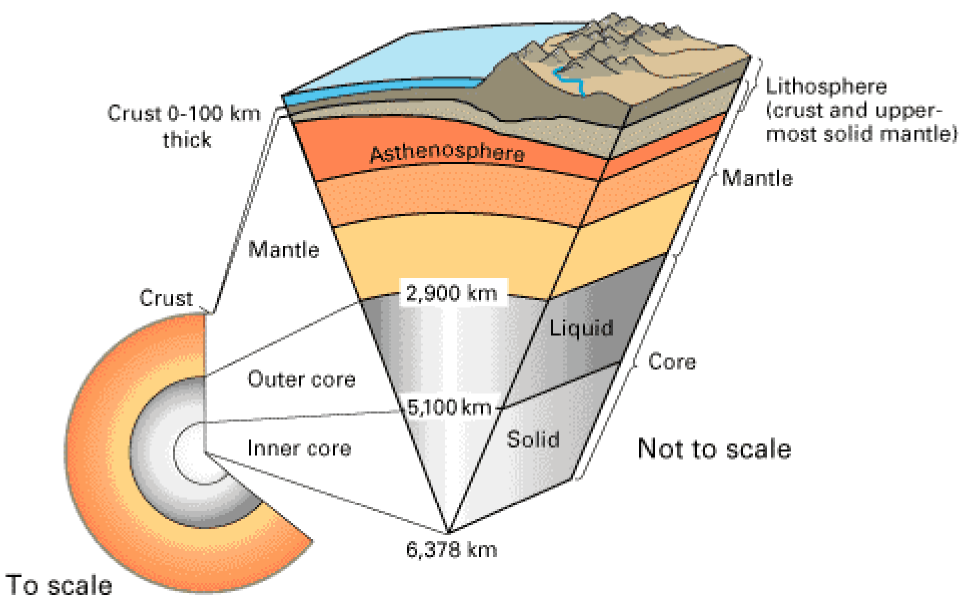
Plate tectonics has proven to be as important to the earth sciences as the discovery of the structure of the atom was to physics and chemistry and the theory of evolution was to the life sciences. Even though the theory of plate tectonics is now widely accepted by the scientific community, aspects of 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.

Lecture 2

Inside the Earth

The size of the Earth -- about 12,750 kilometers (km) in diameter-was known by the ancient Greeks, but it was not until the turn of the 20th century that scientists determined that our planet is made up of three main layers: **crust**, **mantle**, and **core**. This layered structure can be compared to that of a boiled egg. The **crust**, the outermost layer, is rigid and very thin compared with the other two. Beneath the oceans, the crust varies little in thickness, generally extending only to about **5** km. The thickness of the crust beneath continents is much more variable but averages about **30** km; under large mountain ranges, such as the Alps or the Sierra Nevada, however, the base of the crust can be as deep as 100 km. Like the shell of an egg, the Earth's crust is **brittle** and can break.

Cutaway views showing the internal structure of the Earth. Below: This view drawn to scale demonstrates that the Earth's crust literally is only skin deep. Below right: A view not drawn to scale to show the Earth's three main layers (crust, mantle, and core) in more detail (see text).



Below the crust is the **mantle**, a dense, hot layer of semi-solid rock approximately 2,900 km thick. The mantle, which contains more **iron**, **magnesium**, and **calcium** than the crust, is **hotter and denser** because temperature and pressure inside the Earth increase with depth. As a comparison, the mantle might be thought of as the white of a boiled egg. At the center of the Earth lies the **core**, which is nearly **twice** as dense as the mantle because its composition is **metallic** (**iron-nickel alloy**) rather than stony. Unlike the yolk of an egg, however, the Earth's core is actually made up of two distinct parts: a 2,200 km-thick *liquid* **outer core** and a 1,250 km-thick *solid* **inner core**. As the Earth rotates, the liquid outer core spins, creating the Earth's **magnetic field**.

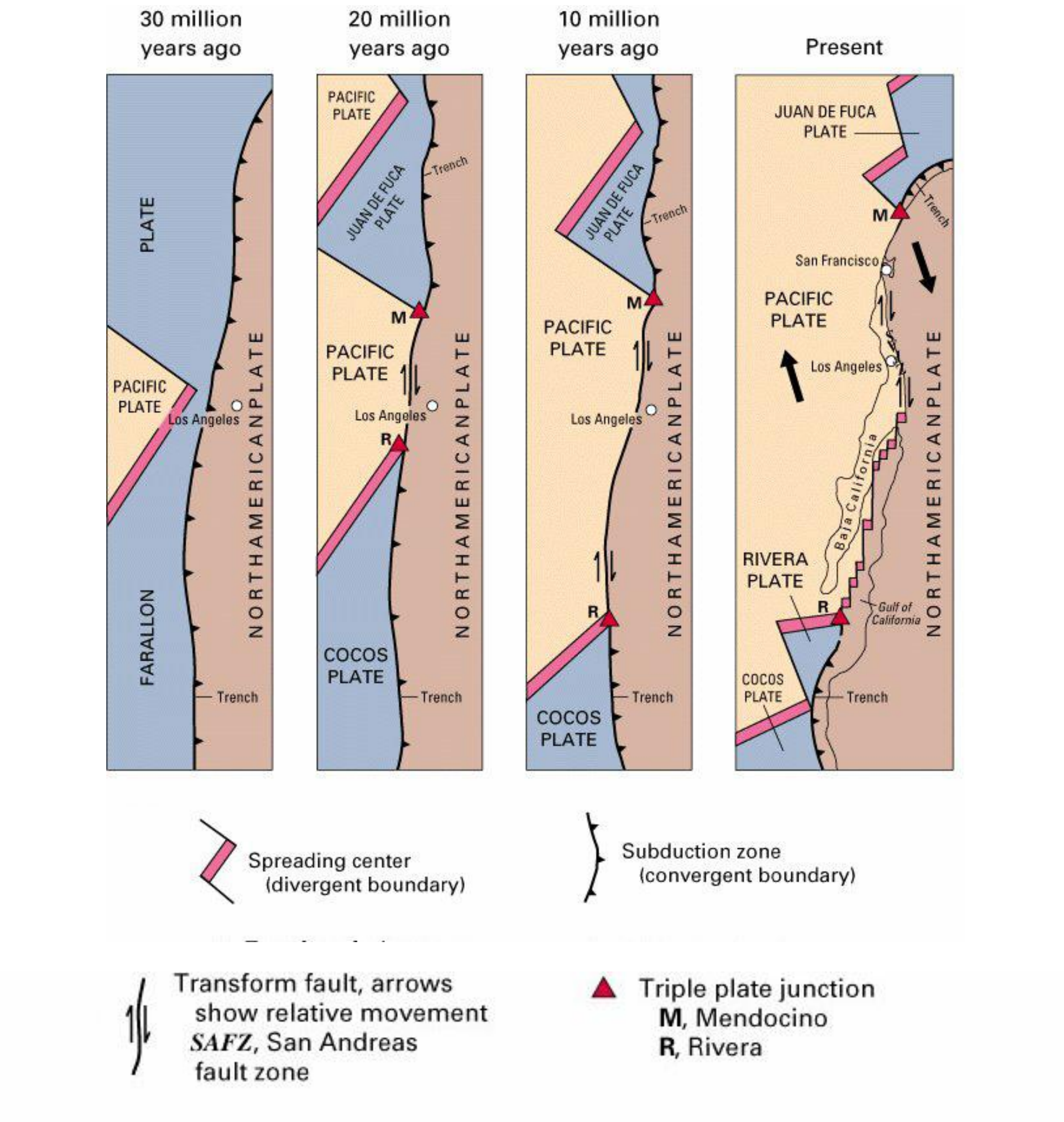
Not surprisingly, the Earth's internal structure *influences* plate tectonics. The upper part of the mantle is **cooler** and **more rigid** than the deep mantle; in many ways, it behaves like the overlying crust. Together they form a rigid layer of rock called the **lithosphere** (from lithos, Greek for stone). The lithosphere tends to be thinnest under the oceans and in volcanically active continental areas, such as the Western United States. Averaging at least **80 km** in thickness over much of the Earth, the lithosphere has been broken up into the moving plates that contain the world's continents and oceans. Scientists believe that below the lithosphere is a relatively *narrow*, *mobile zone* in the mantle called the **asthenosphere** (from asthenes, Greek for weak). This zone is composed of *hot*, *semi-solid* material, which can soften and flow after being subjected to high temperature and pressure over geologic time. The rigid lithosphere is thought to "float" or move about on the slowly flowing asthenosphere.

What is a tectonic plate?

A tectonic plate (also called lithospheric plate) is a *massive*, *irregularly shaped slab* of solid rock, generally composed of both *continental* and *oceanic* lithosphere. Plate size can vary greatly, from a few hundred to thousands of kilometers across; the Pacific and Antarctic Plates are among the largest. Plate thickness also varies greatly, ranging from less than 15 km for young oceanic lithosphere to about 200 km or more for ancient continental lithosphere (for example, the interior parts of North and South America).

How do these massive slabs of solid rock float despite their tremendous weight? The answer lies in the **composition** of the rocks. Continental crust is composed of **granitic rocks** which are made up of relatively lightweight minerals such as *quartz* and *feldspar*. By contrast, oceanic crust is composed of **basaltic rocks**, which are much denser and heavier. The variations in plate thickness are nature's way of partly compensating for the imbalance in the weight and density of the two types of crust. *Because continental rocks are much lighter, the crust under the continents is much thicker (as much as 100 km) whereas the crust under the oceans is generally only about 5 km thick.* Like icebergs, only the tips of which are visible above water, continents have deep "roots" to support their elevations. Most of the boundaries between individual plates cannot be seen, because they are hidden beneath the oceans. Yet oceanic plate boundaries can be mapped accurately from outer space by measurements from GEOSAT satellites. Earthquake and volcanic activity is concentrated near these boundaries. Tectonic plates probably developed very early in the Earth's 4.6-billion-year history, and they have been drifting about on the surface ever since-like slow-moving bumper cars repeatedly clustering together and then separating.

Like many features on the Earth's surface, plates change over time. Those composed partly or entirely of oceanic lithosphere can sink under another plate, usually a lighter, mostly continental plate, and eventually disappear completely. This process is happening now off the coast of Oregon and Washington. The small Juan de Fuca Plate, a remnant of the formerly much larger oceanic Farallon Plate, will someday be entirely consumed as it continues to sink beneath the North American Plate.



These four diagrams illustrate the shrinking of the formerly very large Farallon Plate, as it was progressively consumed beneath the North American and Caribbean Plates, leaving only the present-day Juan de Fuca, Rivera, and Cocos Plates as small remnants (see text). Large solid arrows show the present-day sense of relative movement between the Pacific and North American Plates. (Modified from USGS Professional Paper 1515).

Alfred Lothar Wegener: Moving continents

Perhaps Alfred Wegener's greatest contribution to the scientific world was his ability to weave seemingly dissimilar, unrelated facts into a theory, which was remarkably visionary for the time. Wegener was one of the first to realize that an understanding of how the Earth works required input and knowledge from all the earth sciences.

Wegener's scientific vision sharpened in 1914 as he was recuperating in a military hospital from an injury suffered as a German soldier during World War I. While bed-ridden, he had ample time to develop an idea that had intrigued him for years. Like others before him, Wegener had been struck by the remarkable fit of the coastlines of South America and Africa. But, unlike the others, to support his theory Wegener sought out many other lines of geologic and paleontologic evidence that these two continents were once joined. During his long convalescence, Wegener was able to fully develop his ideas into the Theory of Continental Drift, detailed in a book titled Die Entstehung der Kontinente und Ozeane (in German, The Origin of Continents and Oceans) published in 1915.

Wegener obtained his doctorate in planetary astronomy in 1905 but soon became interested in meteorology; during his lifetime, he participated in several meteorologic expeditions to Greenland. Tenacious by nature, Wegener spent much of his adult life vigorously defending his theory of continental drift, which was severely attacked from the start and never gained acceptance in his lifetime. Despite overwhelming criticism from most leading geologists, who regarded him as a mere meteorologist and outsider meddling in their field, Wegener did not back down but worked even harder to strengthen his theory.

A couple of years before his death, Wegener finally achieved one of his lifetime goals: an academic position. After a long but unsuccessful search for a university position in his native Germany, he accepted a professorship at the University of Graz in Austria. Wegener's frustration and long delay in gaining a university post perhaps stemmed from his broad scientific interests.

Ironically, shortly after achieving his academic goal, Wegener died on a meteorologic expedition to Greenland. Georgi had asked Wegener to coordinate an expedition to establish a winter weather station to study the jet stream (storm track) in the upper atmosphere. Wegener reluctantly agreed. After many delays due to severe weather, Wegener and 14 others set out for the winter station in September of 1930 with 15 sledges and 4,000 pounds of supplies. The extreme cold turned back all but one of the 13 Greenlanders, but Wegener was determined to push on to the station, where he knew the supplies were desperately needed by Georgi and the other researchers. Travelling under frigid conditions, with temperatures as low as minus 54 °C, Wegener reached the station five weeks later. Wanting to return home as soon as possible, he insisted upon starting back to the base camp the very next morning. But he never made it; his body was found the next summer.

Wegener was still an energetic, brilliant researcher when he died at the age of 50. A year before his untimely death, the fourth revised edition (1929) of his classic book was published; in this edition, he had already made the significant observation that shallower oceans were geologically younger. Had he not died in 1930, Wegener doubtless would have pounced upon the new Atlantic bathymetric data just acquired by the German research vessel Meteor in the late 1920s. These data showed the existence of a central valley along much of the crest of the Mid-Atlantic Ridge. Given his fertile mind, Wegener just possibly might have recognized the shallow Mid-Atlantic Ridge as a geologically young feature resulting from thermal expansion, and the central valley as a rift valley resulting from stretching of the oceanic crust. From stretched, young crust in the middle of the ocean to seafloor spreading and plate tectonics would have been short mental leaps for a big thinker like Wegener. This conjectural scenario by Dr. Peter R. Vogt (U.S. Naval Research Laboratory, Washington, D.C.), an acknowledged expert on plate tectonics, implies that "Wegener probably would have been part of the plate-tectonics revolution, if not the actual instigator, had he lived longer." In any case, many of Wegener's ideas clearly served as the catalyst and framework for the development of the theory of plate tectonics three decades later.

Polar dinosaurs in Australia?

As a meteorologist, Alfred Wegener was fascinated by questions such as: *Why do coal deposits*, *a relic of lush ancient forests*, occur in the icy barrenness of **Antarctica**? And why are *glacial deposits* found in now sweltering **tropical Africa**? Wegener reasoned that such anomalies could be explained if these two present-day continents -- together with South America, India, and Australia -- originally were part of a supercontinent that extended from the equator to the South Pole and encompassed a wide range of climatic and geologic environments. The break-up of Pangaea and subsequent movement of the individual continents to their present positions formed the basis for Wegener's continental drift theory. Recently, paleontologists (specialists in studies of fossils) have carefully studied some well-preserved **dinosaur** remains unearthed at Dinosaur Cove, at the southeastern tip of mainland Australia. Dinosaurs found in most other parts of the world are believed to have lived in **temperate or tropical** regions, but these Australian species, popularly called "polar" dinosaurs seemed well adapted to **cooler temperature** conditions. They apparently had keen night vision and were warm-blooded, enabling them to forage for food during long winter nights, at freezing or sub-freezing temperatures.

The last of the dinosaurs became extinct during a period of sharp global cooling toward the end of the Cretaceous period (about 65 million years ago). One current theory contends that the impact of one or more large comets or asteroids was responsible for the cooling trend ("impact winter") that killed off the dinosaurs; another theory attributes the sudden cooling to global climate change brought on by a series of huge volcanic eruptions over a short period of time ("volcanic winter"). The discovery of the polar dinosaurs clearly suggests that they survived the volcanic winter that apparently killed other dinosaur species. This then raises an intriguing question: Why did they become extinct if they were well adapted to a cold climate? Paleontologists do not have the answers. Regardless, this recently acquired paleontologic evidence convincingly demonstrates that Australia has drifted north toward the equator during the past 100 million years. At the time when the Australian polar dinosaurs thrived, their habitat was much farther south, well within the Antarctic Circle.

In 1991, paleontologists discovered the Cryolophosaurus ellioti, a previously unknown dinosaur species and the only one found on the continent of Antarctica. Cryolophosaurus fossils were found at Mount Kirkpatrick, located only 600 km from the present-day South Pole. This newly discovered carnivorous dinosaur probably was similar in appearance to the Allosaurus (see artwork above), except for a distinctive bony crest on its head, another meat-eating species found at Dinosaur Cove, Australia. Studies show that the Cryolophosaurus lived about 200 millions years ago, when Antarctica was still part of Gondwana and had a climate similar to that of Pacific Northwest--mild enough to support large plant-eating animal life, upon which the Cryolophosaurus preyed. With the break-up of Gondwana, Allosaurus and Cryolophosaurus parted company, as Australia drifted northward toward the equator and Antarctica drifted southward to the South Pole.

Had the Australian polar dinosaurs and the Cryolophosaurus been discovered while he was alive, the embattled Alfred Wegener would have been delighted!

Approximately 100 million years ago, the Dinosaur Cove area (small red outlined boxes) at the southern end of Australia was well within the Antarctic Circle, more than 40 degrees closer to the South Pole than it is today.

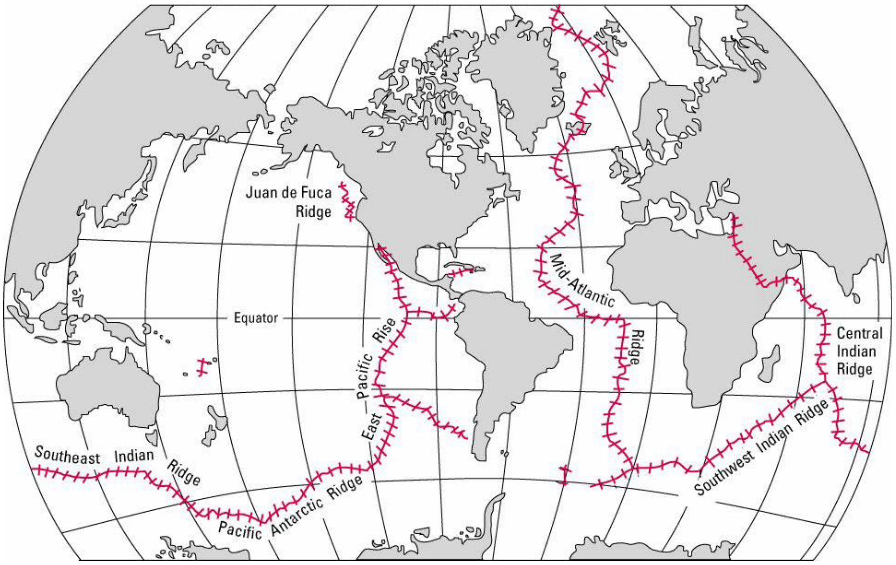
Developing the theory

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

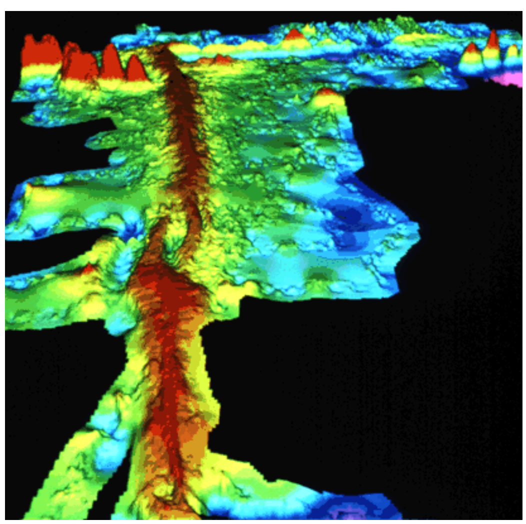
About two thirds of the Earth's surface lies beneath the oceans. Before the 19th century, the depths of the open ocean were largely a matter of speculation, and most people thought that the ocean floor was relatively flat and featureless. However, as early as the 16th century, a few intrepid navigators, 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.

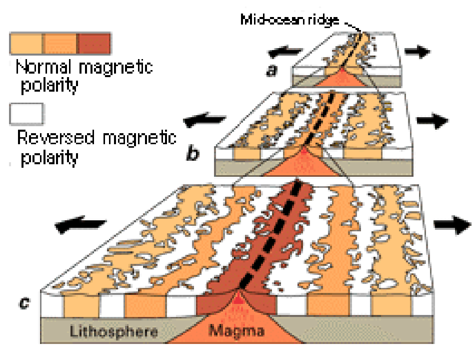


Computer-generated detailed topographic map of a segment of the Mid-Oceanic Ridge. "Warm" colors (yellow to red) indicate the ridge rising above the seafloor, and the "cool" colors (green to blue) represent lower elevations. This image (at latitude 9° north) is of a small part of the East Pacific Rise.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

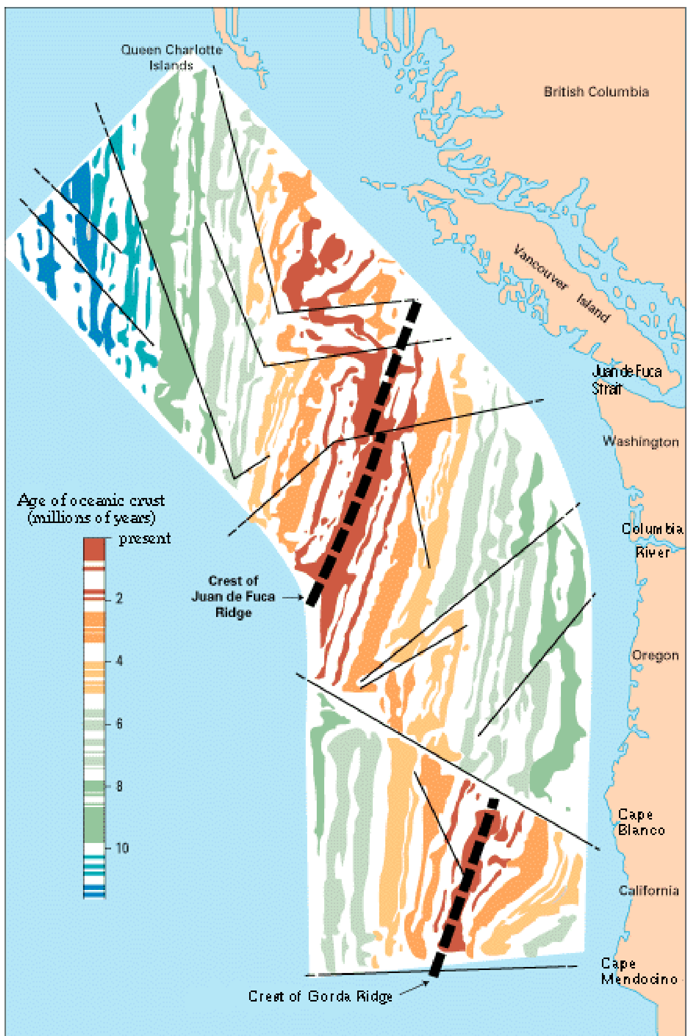
Beginning in the 1950s, scientists, using magnetic instruments (magnetometers) adapted from airborne devices developed during World War II to detect submarines, began recognizing odd magnetic variations across the ocean floor. This finding, though unexpected, was not entirely surprising because it was known that basalt -- the iron-rich, volcanic rock making up the ocean floor-- contains a strongly magnetic mineral (**magnetite Fe_3O_4**,) 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.

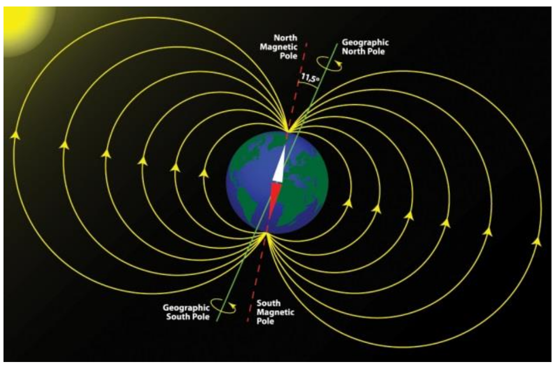
Early in the 20th century, paleomagnetists (those who study the Earth's ancient magnetic field) -- such as **Bernard Brunhes** in France (in 1906) and **Motonari Matuyama** in Japan (in the 1920s) -- recognized that rocks generally belong to **two groups** according to their magnetic properties. One 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.

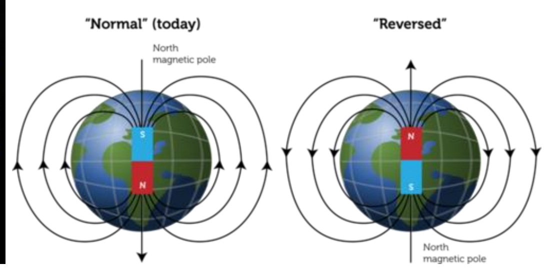
A geomagnetic reversal is a change in a planet's magnetic field such that the positions of magnetic north and magnetic south are interchanged. The Earth's field has alternated between periods of normal polarity, in which the direction of the field was the same as the present direction, and reverse polarity, in which the field was the opposite. Because of changing **temperatures** and **fluid flows**, the strength of the magnetic field varies, and the positions of the north and south magnetic poles shift. These periods are called chrons. The time spans of chrons are randomly distributed with most being between 0.1(100,000 years) and 1 million years with an average of 450,000 years.



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.

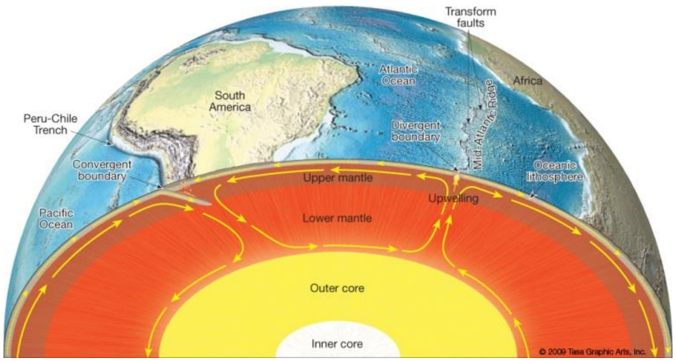
As more and more of the seafloor was mapped during the 1950s, the magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns. When these magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern. Alternating 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 zebra like 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.

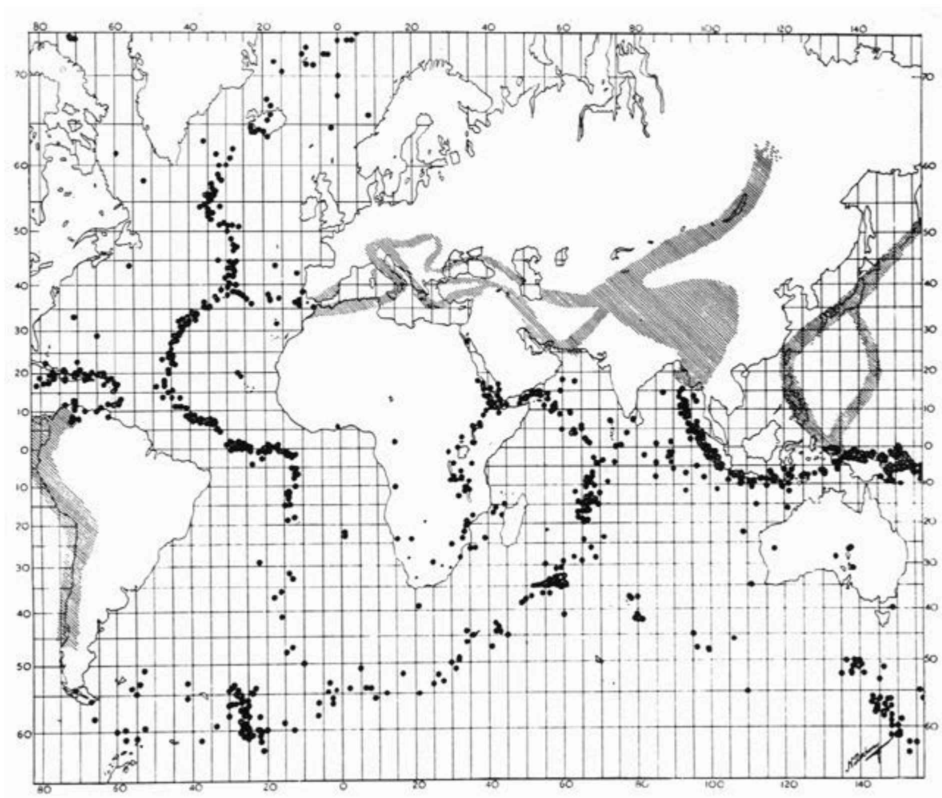
Above: The Glomar Challenger was the first research vessel specifically designed in the late1960s for the purpose of drilling into and taking core samples from the deep ocean floor. Below: The JOIDES Resolution is the deep-sea drilling ship of the 1990s (JOIDES= Joint Oceanographic Institutions for Deep Earth Sampling). 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.



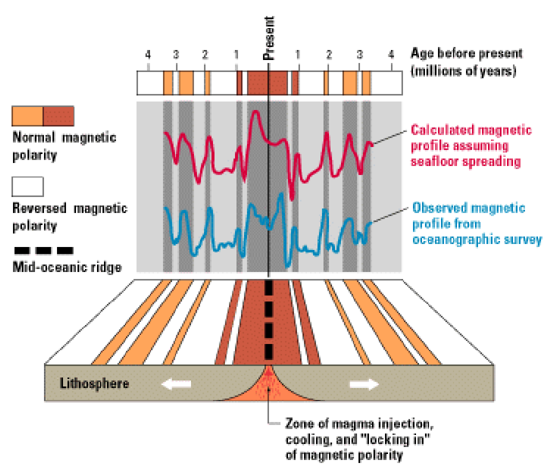
*As early as the 1920s, scientists noted that earthquakes are concentrated in very specific narrow zones (see text). In 1954, French seismologist J.P. Rothé published this map showing the concentration of earthquakes along the zones indicated by **dots** and **cross-hatched** areas. (Original illustration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

Magnetic stripes and isotopic clocks

Oceanographic exploration in the 1950s led to a much better understanding of the ocean floor. Among the new findings was the discovery of zebra stripe-like magnetic patterns for the rocks of the ocean floor. These patterns were unlike any seen for **continental rocks**. Obviously, the ocean floor had a story to tell, but what?

In 1962, scientists of the U.S. Naval Oceanographic Office prepared a report summarizing available information on the magnetic stripes mapped for the **volcanic rocks** making up the ocean floor. After digesting the data in this report, along with other information, two young British geologists, **Frederick Vine** and **Drummond Matthews**, and also **Lawrence Morley** of the Canadian Geological Survey, suspected that the magnetic pattern was **no accident**. In 1963, they hypothesized of the Earth's that the magnetic striping was produced by *repeated reversals magnetic field*, not as earlier thought, by *changes in intensity of the magnetic field* or by *other causes*. Field reversals had already been *demonstrated* for magnetic rocks on the continents, and a logical next step was to see if these *continental magnetic reversals* might be correlated in geologic time with the *oceanic magnetic striping*. About the same time as these exciting discoveries were being made on the ocean floor, new techniques for determining the geologic ages of rocks ("dating") were also developing rapidly.



*An **observed** magnetic profile (blue) for the ocean floor across the East Pacific Rise is matched quite well by a **calculated** profile (red) based on the Earth's magnetic reversals for the past 4 million years and an assumed constant rate of movement of ocean floor away from a hypothetical spreading center (bottom). The remarkable similarity of these two profiles provided one of the clinching arguments in support of the seafloor spreading hypothesis.*

A team of U.S. Geological Survey scientists -- geophysicists **Allan Cox** and **Richard Doell**, and isotope geochemist **Brent Dalrymple** -- reconstructed the history of magnetic reversals for the past 4 million years using a dating technique based on the isotopes of the chemical elements **potassium** and **argon**. The potassium-argon technique -- like other "isotopic clocks" -- works because certain elements, such as **potassium**, contain unstable, **parent** radioactive isotopes that decay at a steady rate over geologic time to produce **daughter** isotopes. The rate of decay is expressed in terms of an element's **"half-life,"** the time it takes for **half** of the radioactive isotope of the element to decay. The decay of the radioactive potassium isotope (potassium-40) yields a stable daughter isotope (**argon-40**), which does not decay further. *The age of a rock can be determined ("dated") by measuring the total amount of potassium in the rock, the amount of the remaining radioactive potassium-40 that has not decayed, and the amount of argon-40.* Potassium is found in common rock-forming minerals, and because the potassium-40 isotope has a half-life of **1,310** million years, it can be used in dating rocks millions of years old.

Other commonly used isotopic clocks are based on radioactive decay of certain isotopes of the elements **uranium**, **thorium**, **strontium**, and **rubidium**. However, it was the potassium-argon dating method that unlocked the riddle of the magnetic striping on the ocean floor and provided convincing evidence for the seafloor spreading hypothesis. **Cox** and his colleagues used this method to date continental volcanic rocks from around the world. They also measured the magnetic orientation of these same rocks, allowing them to assign ages to the Earth's recent magnetic reversals. In 1966, **Vine** and **Matthews** -- and also **Morley** working independently -- compared these known ages of magnetic reversals with the magnetic striping pattern found on the ocean floor. Assuming that the ocean floor moved away from the spreading center at a rate of several centimeters per year, they found there was a remarkable correlation between the ages of the Earth's magnetic reversals and the striping pattern. Following their break-through discovery, similar studies were repeated for other spreading centers. Eventually, scientists were able to date and correlate the magnetic striping patterns for nearly all of the ocean floor, parts of which are as old as 180 million years.

Harry Hammond Hess, a professor of geology at Princeton University, was very influential in setting the stage for the emerging plate-tectonics theory in the early 1960s. He believed in many of the observations Wegener used in defending his theory of continental drift, but he had very different views about large-scale movements of the Earth.

Even while serving in the U.S. Navy during World War II, **Hess** was keenly interested in the geology of the ocean basins. In between taking part in the fighting in the Marianas, Leyte, Linguayan, and Iwo Jima, Hess -- with the cooperation of his crew -- was able to conduct echo-sounding surveys in the Pacific while cruising from one battle to the next. Building on the work of English geologist **Arthur Holmes** in the 1930s, Hess' research ultimately resulted in a ground-breaking hypothesis that later would be called seafloor spreading. In 1959, he informally presented this hypothesis in a manuscript that was widely circulated. **Hess**, like Wegener, ran into resistance because *little ocean-floor data existed for testing his ideas*. In 1962, these ideas were published in a paper titled **"History of Ocean Basins,"** which was one of the most important contributions in the development of plate tectonics. In this classic paper, Hess outlined the basics of how seafloor spreading works: molten rock (magma) oozes up from the Earth's interior along the mid-oceanic ridges, creating new seafloor that spreads away from the active ridge crest and, eventually, sinks into the deep oceanic trenches.

Hess' concept of a mobile seafloor explained several very puzzling geologic questions. If the oceans have existed for **at least 4 billion years**, as most geologists believed, *why is there so little* ***sediment deposited*** *on the ocean floor*? Hess reasoned that the sediment has been accumulating for about **300** million years at most. This interval is approximately the time needed for the ocean floor to move from the ridge crest to the trenches, where oceanic crust **descends** into the trench and is destroyed. Meanwhile, magma is continually rising along the mid-oceanic ridges, where the "recycling" process is completed by the creation of new oceanic crust. *This recycling of the seafloor also explained why the oldest fossils found on the seafloor are no more than about 180 million years old*. In contrast, marine fossils in rock strata on **land** -- some of which are found high in the Himalayas, over **8,500** m above sea level -- can be considerably **older**. Most important, however, Hess' ideas also resolved a question that plagued Wegener's theory of continental drift: how do the continents move? Wegener had a vague notion that the continents must simply "plow" through the ocean floor, which his critics rightly argued was physically impossible. With seafloor spreading, the continents did not have to push through the ocean floor but were carried along as the ocean floor spread from the ridges.

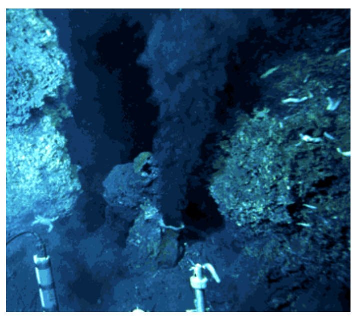
In 1962, Hess was well aware that **solid evidence** was still lacking to test his hypothesis and to convince a more receptive but still skeptical scientific community. But the Vine-Matthews explanation of magnetic striping of the seafloor a year later and additional oceanic exploration during subsequent years ultimately provided the arguments to confirm Hess' model of seafloor spreading. The theory was **strengthened** further when **dating** studies showed that the seafloor becomes older with distance away from the ridge crests. Finally, improved seismic data confirmed that oceanic crust was indeed sinking into the trenches, fully proving Hess' hypothesis, which was based largely on intuitive geologic reasoning. His basic idea of seafloor spreading along mid-oceanic ridges has well withstood the test of time.

Hess, who served for years as the head of Princeton's Geology Department, died in **1969**. Unlike Wegener, he was able to see his seafloor-spreading hypothesis largely accepted and confirmed as knowledge of the ocean floor increased dramatically during his lifetime. Like Wegener, he was keenly interested in other sciences in addition to geology. In recognition of his enormous stature worldwide, in 1962 Hess -- best known for his geologic research -- was **appointed** by President John F. Kennedy to the prestigious position of *Chairman of the Space Science Board of the National Academy of Sciences*. Thus, in addition to being a major force in the development of plate tectonics, Hess also played a prominent role in designing the nation's space program.

Exploring the deep ocean floor: Hot springs and strange creatures

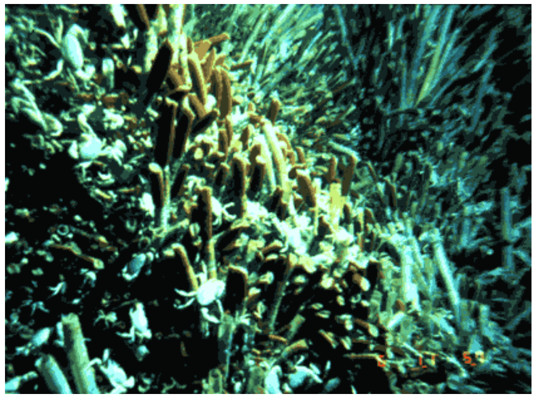
The ocean floor is home to many unique communities of plants and animals. Most of these marine ecosystems are near the water surface, such as the **Great Barrier Reef**, a 2,000-km-long coral formation off the *northeastern coast of Australia*. **Coral reefs**, like nearly all complex living communities, depend on solar energy for growth (photosynthesis). The sun's energy, however, penetrates at most only about **300 m** below the surface of the water. The relatively shallow penetration of solar energy and the sinking of cold, subpolar water combine to make most of the deep ocean floor a frigid environment with few life forms.

In 1977, scientists discovered **hot springs** at a depth of **2.5 km**, on the *Galapagos Rift* (spreading ridge) off the coast of **Ecuador**. This exciting discovery was not really a surprise. Since the early 1970s, scientists had predicted that **hot springs** (geothermal vents) should be found at the active spreading centers along the mid-oceanic ridges, where magma, at temperatures over **1,000 °C**, presumably was being erupted to form new oceanic crust. More exciting, because it was totally unexpected, was the discovery of abundant and **unusual sea life** -- *giant tube worms*, *huge clams*, and *mussels* -- that thrived around the hot springs.



View of the first high-temperature vent (380 °C) ever seen by scientists during a dive of the deep-sea submersible Alvin on the East Pacific Rise (latitude 21° north) in 1979. Such geothermal vents--called smokers because they resemble chimneys--spew dark, mineral-rich, fluids heated by contact with the newly formed, still-hot oceanic crust. This photograph shows a black smoker, but smokers can also be white, grey, or clear depending on the material being ejected. (Photograph by Dudley Foster from RISE expedition, courtesy of William R. Normark, USGS.)

Since 1977, other **hot springs** and associated **sea life** have been found at a number of sites along the mid-oceanic ridges, many on the East Pacific Rise. The waters around these deep-ocean hot springs, which can be as hot as 380 °C, are home to a unique ecosystem. Detailed studies have shown that **hydrogen sulfide-oxidizing bacteria**, which live **symbiotically** with the larger organisms, form the base of this ecosystem's food chain. The hydrogen sulfide (H_2S--the gas that smells like rotten eggs) needed by these bacteria to live is contained in the volcanic gases that spew out of the hot springs. Most of the sulfur comes from the Earth's interior; a small portion (less than 15 percent) is produced by chemical reaction of the sulfate (SO_4) present in the sea water. Thus, the energy source that sustains this deep-ocean ecosystem is not sunlight but rather the energy from chemical reaction (chemosynthesis).



The deep-sea hot-spring environment supports abundant and bizarre sea life, including tube worms, crabs, giant clams. This hot-spring "neighborhood" is at 13° N along the East Pacific Rise. (Photograph by Richard A. Lutz, Rutgers University, New Brunswick, New Jersey.)

The manipulator arm of the research submersible Alvin collecting a giant clam from the deep ocean floor. (Photograph by John M. Edmond, Massachusetts Institute of Technology.)

The size of deep-sea giant clams is evident from the hands of a scientist holding them. (Photograph by William R. Normark, USGS.)

But the story about the source of life-sustaining energy in the deep sea is still unfolding. In the late 1980s, scientists documented the existence of a dim glow at some of the hot geothermal vents, which are the targets of current intensive research. The occurrence of "natural" light on the dark seafloor has great significance, because it implies that photosynthesis may be possible at deep-sea geothermal vents. Thus, the base of the deep-sea ecosystem's **food chain** may comprise **both** chemosynthetic and, probably in small proportion, photosynthetic bacteria.

A colony of tube worms, some as long as 1.5 m, clustered around an ocean floor hot spring. (Photograph by Daniel Fornari, Woods Hole Oceanographic Institution.)

Close-up of spider crab that was observed to be eating tube worms. (Photograph by William R. Normark, USGS.)

Scientists discovered the hot-springs ecosystems with the help of **Alvin**, *the world's first deep-sea submersible*. Constructed in the early 1960s for the U.S. Navy, Alvin is a three-person, self-propelling capsule-like submarine nearly eight meters long. In **1975**, scientists of Project FAMOUS (French-American Mid-Ocean Undersea Study) used Alvin to dive on a segment of the Mid-Atlantic Ridge in an attempt to make the first direct observation of seafloor spreading. **No** hot springs were observed on this expedition; it was during the next Alvin expedition, the one in **1977** to the Galapagos Rift, that the **hot springs** and **strange creatures** were discovered. Since the advent of Alvin, other manned submersibles have been built and used successfully to explore the deep ocean floor. Alvin has an operational maximum depth of about **4,000 m**, more than four times greater than that of the deepest diving military submarine. **Shinkai 6500**, a

Japanese research submarine built in 1989, can work at depths down to **6,400** m. The United States and Japan are developing research submersible systems that will be able to explore the ocean floor's deepest spot: the **10,920**-m Challenger Deep at the southern end of the **Marianas Trench** off the *Mariana Islands*.

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.

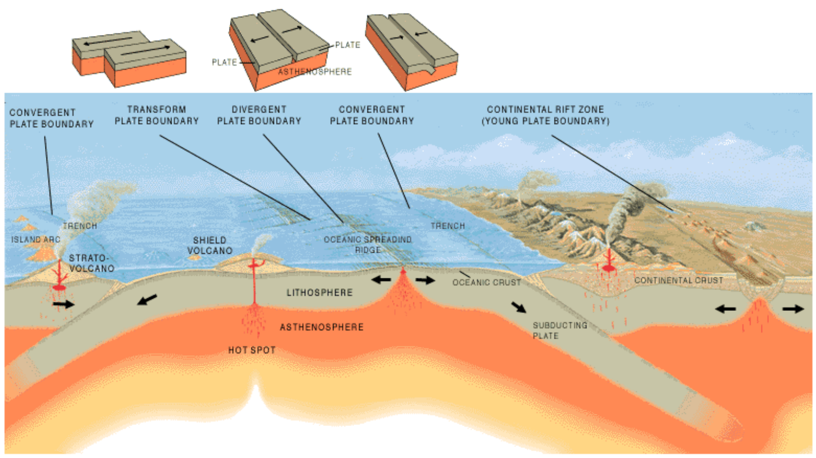
There are four types of plate boundaries:

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.

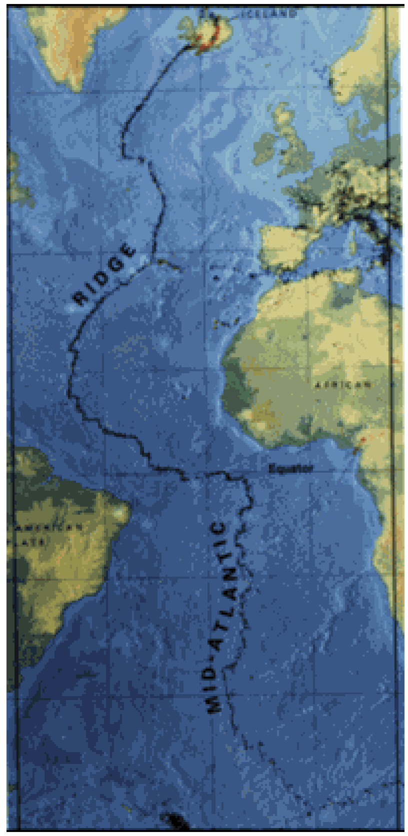
Plate boundary zones -- broad belts in which boundaries are not well defined and the effects of plate interaction are unclear.



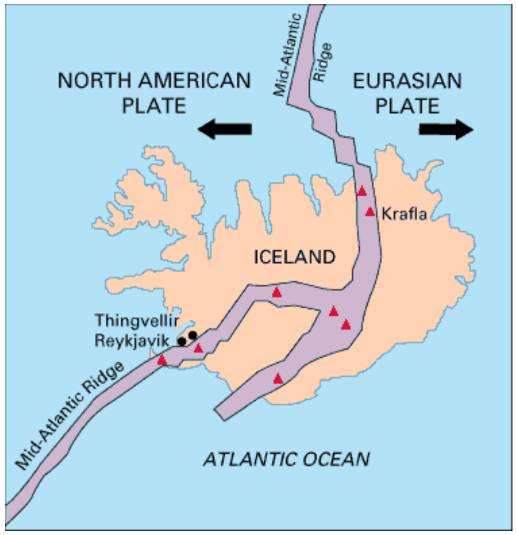
Artist's cross section illustrating the main types of plate boundaries (see text); East African Rift Zone is a good example of a continental rift zone. (Cross section by José F. Vigil from This Dynamic Planet -- a wall map produced jointly by the U.S. Geological Survey, the Smithsonian Institution, and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



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.

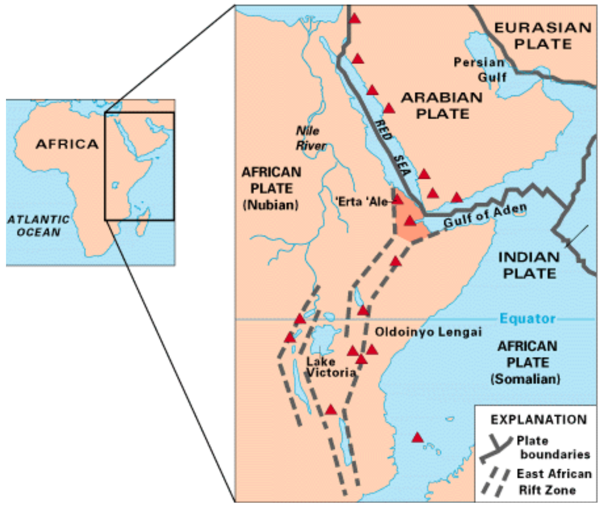
The volcanic country of Iceland, which straddles the Mid-Atlantic Ridge, offers scientists a natural laboratory for studying on land the processes also occurring along the submerged parts of a spreading ridge. Iceland is splitting along the spreading center between the North American and Eurasian Plates,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

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 (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. Left of the fissure, the North American Plate is pulling westward away from the Eurasian Plate (right 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.)

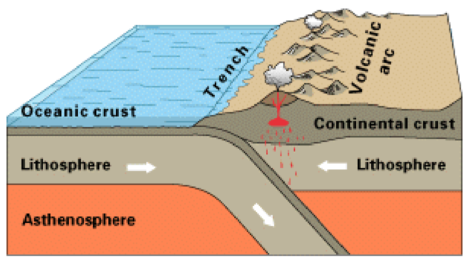
Convergent boundaries

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.

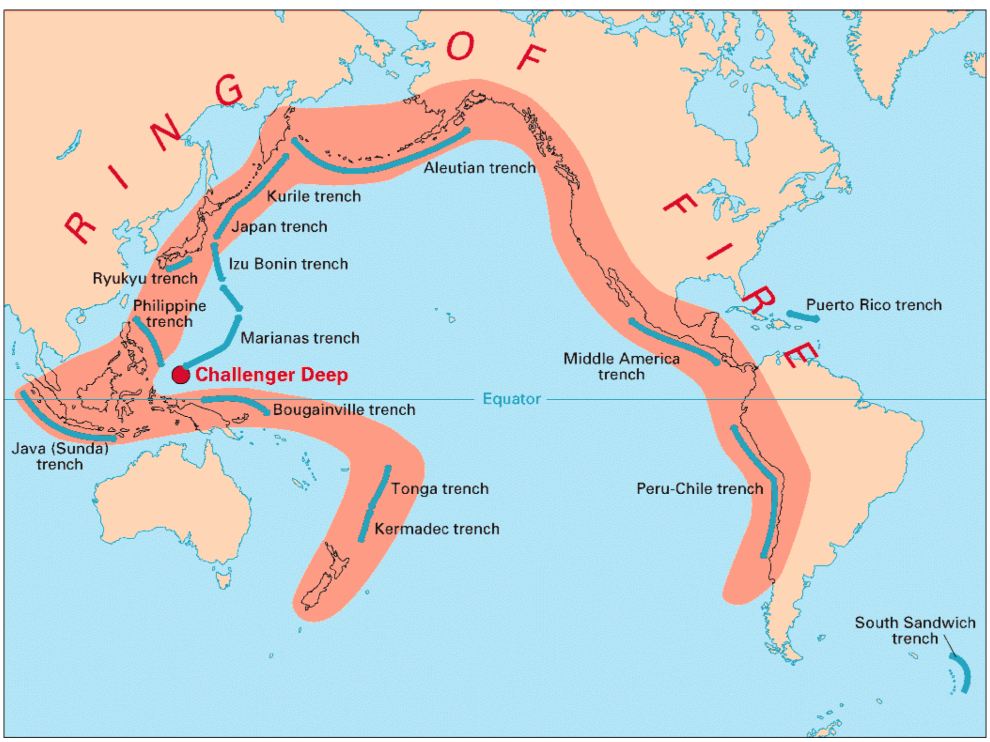


Oceanic-continental convergence

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**.

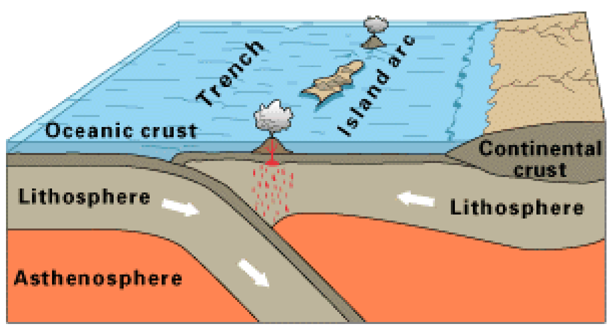


Volcanic arcs *and* ***oceanic trenches*** *partly encircling the Pacific Basin form the so-called* ***Ring of Fire****, a zone of frequent* ***earthquakes*** *and* ***volcanic eruptions****. The trenches are shown in blue-green. The volcanic island arcs, although not labelled, are parallel to, and always 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).

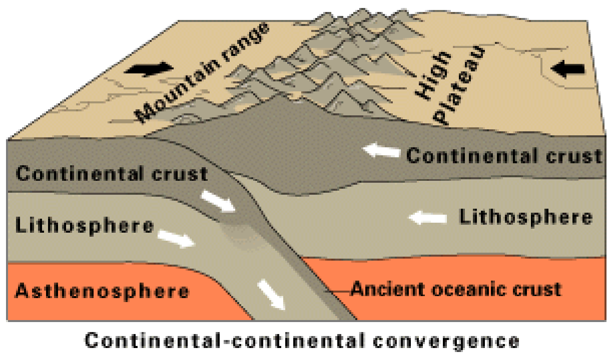


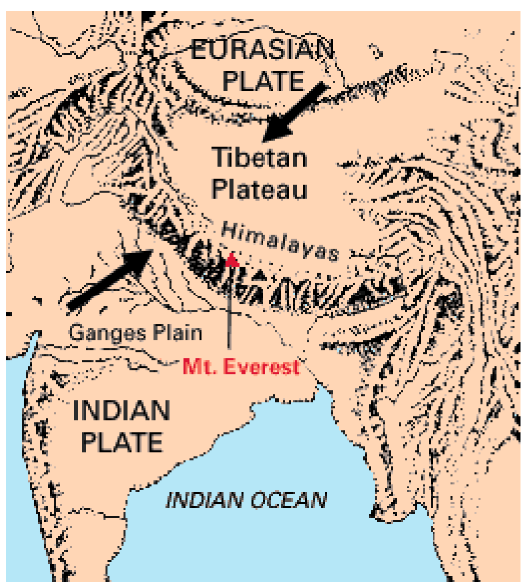
Oceanic-oceanic convergence

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.

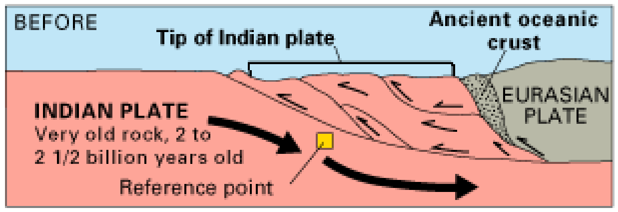
Continental-continental convergence

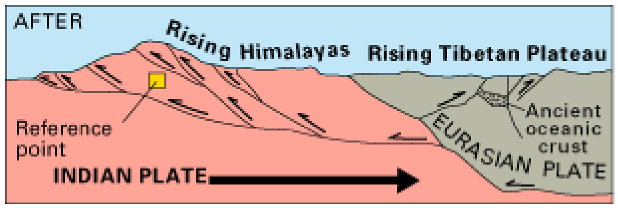
The Himalayan mountain range dramatically demonstrates one of the most visible and spectacular consequences of plate tectonics. When two continents meet head-on, neither is subducted because the continental rocks are relatively light and, like two colliding icebergs, resist downward motion. Instead, 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.





Above: The collision between the Indian and Eurasian plates has pushed up the Himalayas and the Tibetan Plateau. Below: 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*.

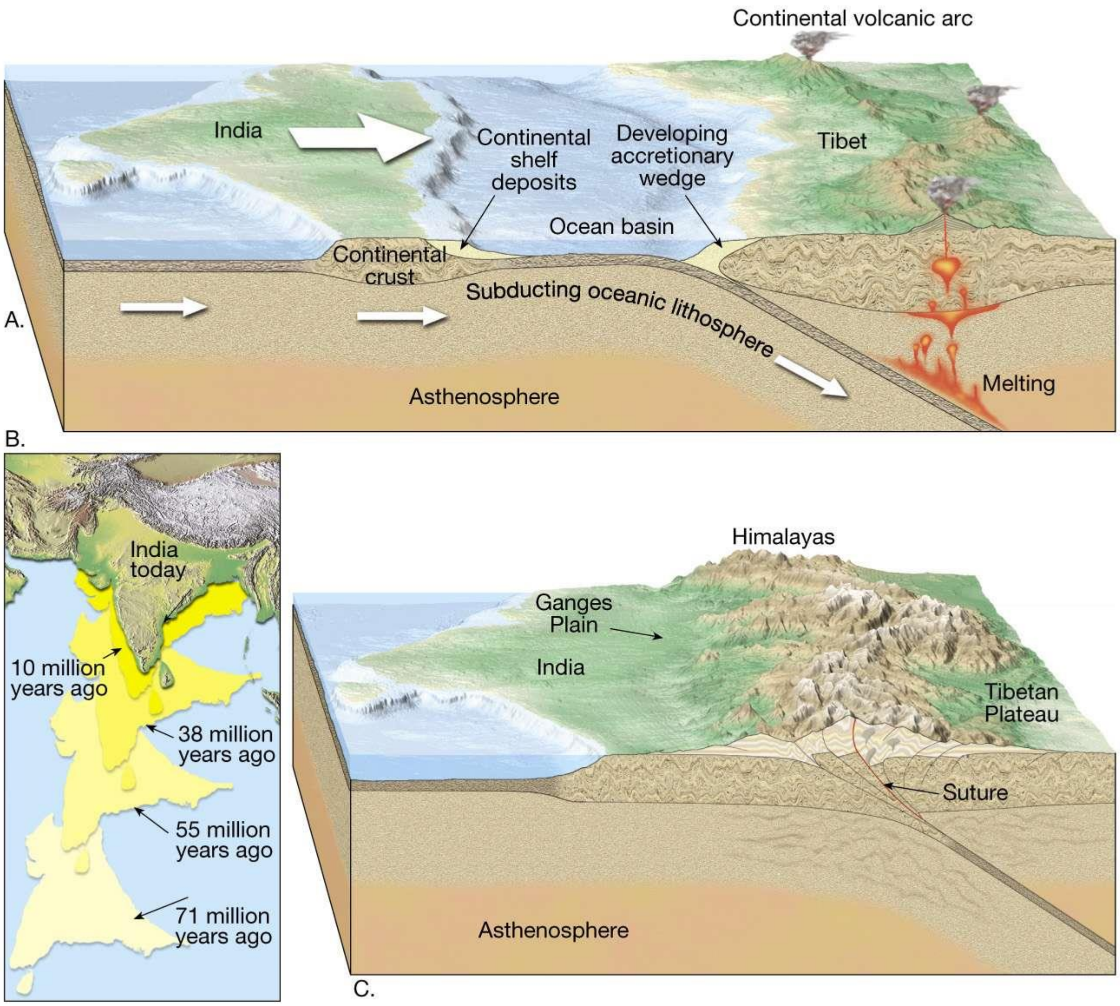


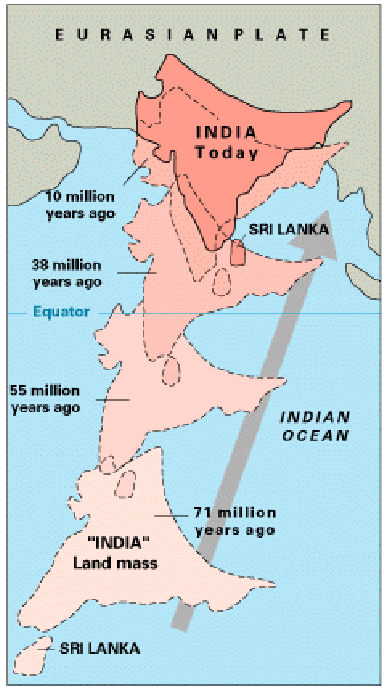


The Himalayas: Two continents collide

Among the most dramatic and visible creations of plate-tectonic forces are the lofty Himalayas, which stretch 2,900 km along the border between India and Tibet. This immense mountain range began to form between 40 and 50 million years ago, when two large landmasses, India and Eurasia, driven by plate movement, collided. Because both these continental landmasses have about the same rock density, one plate could not be subducted under the other. The pressure of the impinging plates could only be relieved by thrusting skyward, contorting the collision zone, and forming the jagged Himalayan peaks.

About 225 million years ago, India was a large island still situated off the Australian coast, and a vast ocean (called Tethys Sea) separated India from the Asian continent. When Pangaea broke apart about 200 million years ago, India began to forge northward. By studying the history -- and ultimately the closing-- of the Tethys, scientists have reconstructed India's northward journey. About 80 million years ago, India was located roughly 6,400 km south of the Asian continent, moving northward at a rate of about 9 m a century. When India rammed into Asia about 40 to 50 million years ago, its northward advance slowed by about half. The collision and associated decrease in the rate of plate movement are interpreted to mark the beginning of the rapid uplift of the Himalayas.





The 6,000-km-plus journey of the India landmass (Indian Plate) before its collision with Asia (Eurasian Plate) about 40 to 50 million years ago (see text). India was once situated well south of the Equator, near the continent of Australia.

The Himalayas and the Tibetan Plateau to the north have risen very rapidly. In just 50 million years, peaks such as Mt. Everest have risen to heights of more than 9 km. The impinging of the two landmasses has yet to end. The Himalayas continue to rise more than 1 cm a year -- a growth rate of 10 km in a million years! If that is so, why aren't the Himalayas even higher? Scientists believe that the Eurasian Plate may now be stretching out rather than thrusting up, and such stretching would result in some subsidence due to gravity.

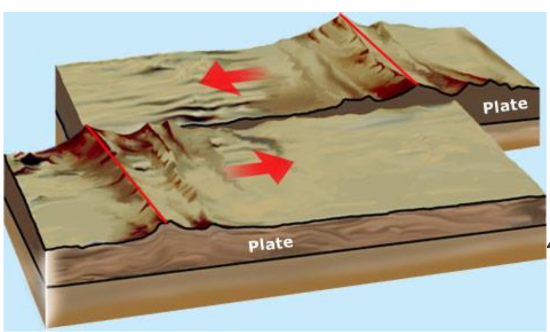
Sunset view of towering, snow-capped Mt. Everest, from the village of Lobuche (Solu-khumbu), Nepal. (Photograph by Gimmy Park Li.)

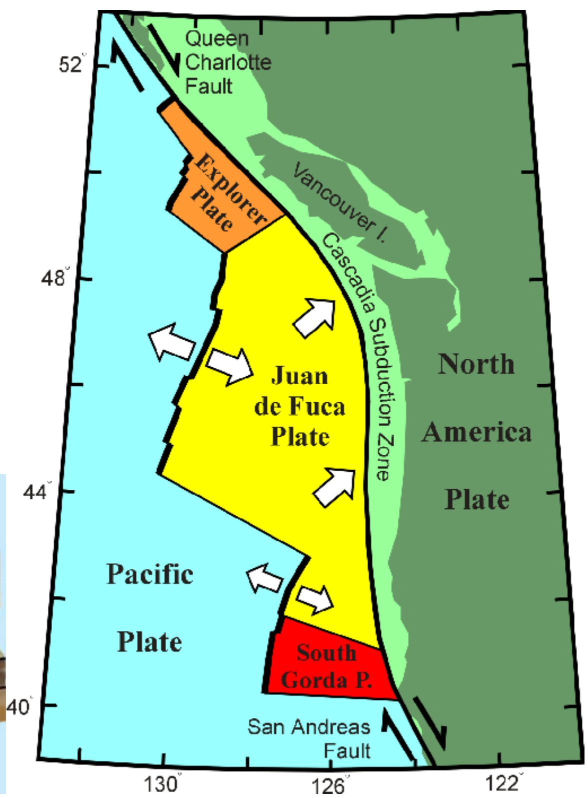
Fifty kilometers north of Lhasa (the capital of Tibet), scientists found layers of pink sandstone containing grains of magnetic minerals (magnetite) that have recorded the pattern of the Earth's flip-flopping magnetic field. These sandstones also contain **plant** and **animal** fossils that were deposited when the Tethys Sea periodically flooded the region. The study of these fossils has revealed not only their geologic age but also the type of environment and climate in which they formed. For example, such studies indicate that the fossils lived under a relatively mild, wet environment about 105 million years ago, when Tibet was closer to the equator. Today, Tibet's climate is much more arid, reflecting the region's uplift and northward shift of nearly 2,000 km. Fossils found in the sandstone layers offer dramatic evidence of the climate change in the Tibetan region due to plate movement over the past 100 million years.

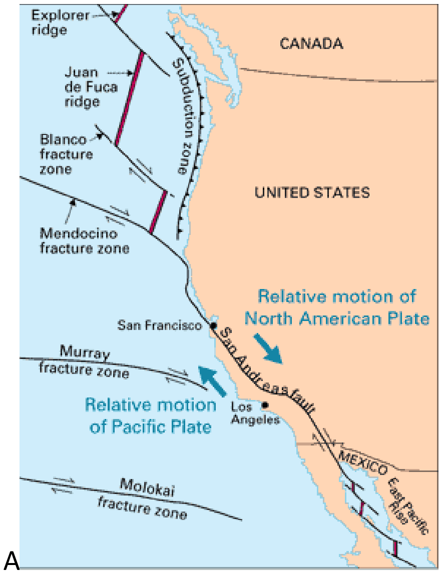
At present, the movement of India continues to put enormous pressure on the Asian continent, and Tibet in turn presses on the landmass to the north that is hemming it in. The net effect of plate-tectonics forces acting on this geologically complicated region is to squeeze parts of Asia eastward toward the Pacific Ocean. One serious consequence of these processes is a deadly "domino" effect: tremendous stresses build up within the Earth's crust, which are relieved periodically by earthquakes along the numerous faults that scar the landscape. Some of the world's most destructive earthquakes in history are related to continuing tectonic processes that began some 50 million years ago when the Indian and Eurasian continents first met.

Transform boundaries

The zone between two plates sliding horizontally past one another is called a transform-fault boundary, or simply a transform boundary. The concept of transform faults originated with Canadian geophysicist J. Tuzo Wilson, who proposed that these **large faults** or fracture zones connect **two spreading centers** (divergent plate boundaries) or, less commonly, **trenches** (convergent plate boundaries). Most **transform faults** are found on the **ocean floor**. They commonly offset the active spreading ridges, producing **zig-zag** plate margins, and are generally **defined** by shallow earthquakes. However, a **few** occur on **land**, for example the **San Andreas** fault zone in California. This transform fault connects the East Pacific Rise, a divergent boundary to the south, with the **South Gorda** -- **Juan de Fuca** -- **Explorer Ridge**, another divergent boundary to the north.







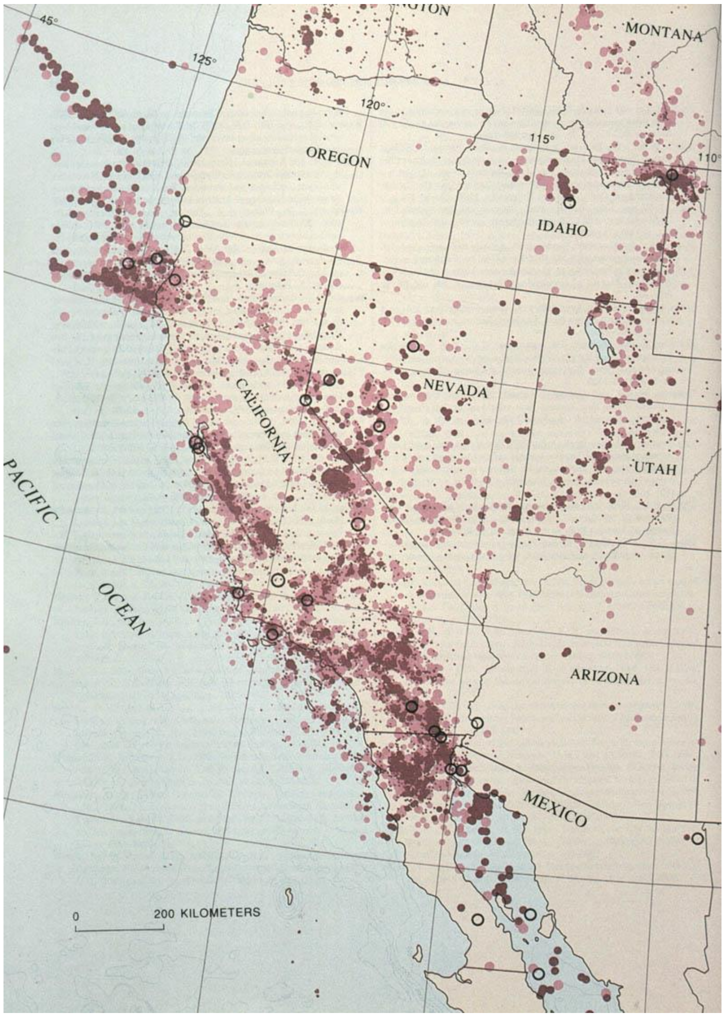
A

B

*A/The **Blanco**, **Mendocino**, **Murray**, and **Molokai** fracture zones are some of the many fracture zones (transform faults) that scar the ocean floor and offset ridges (see text). The San Andreas is one of the few transform faults exposed on land.*

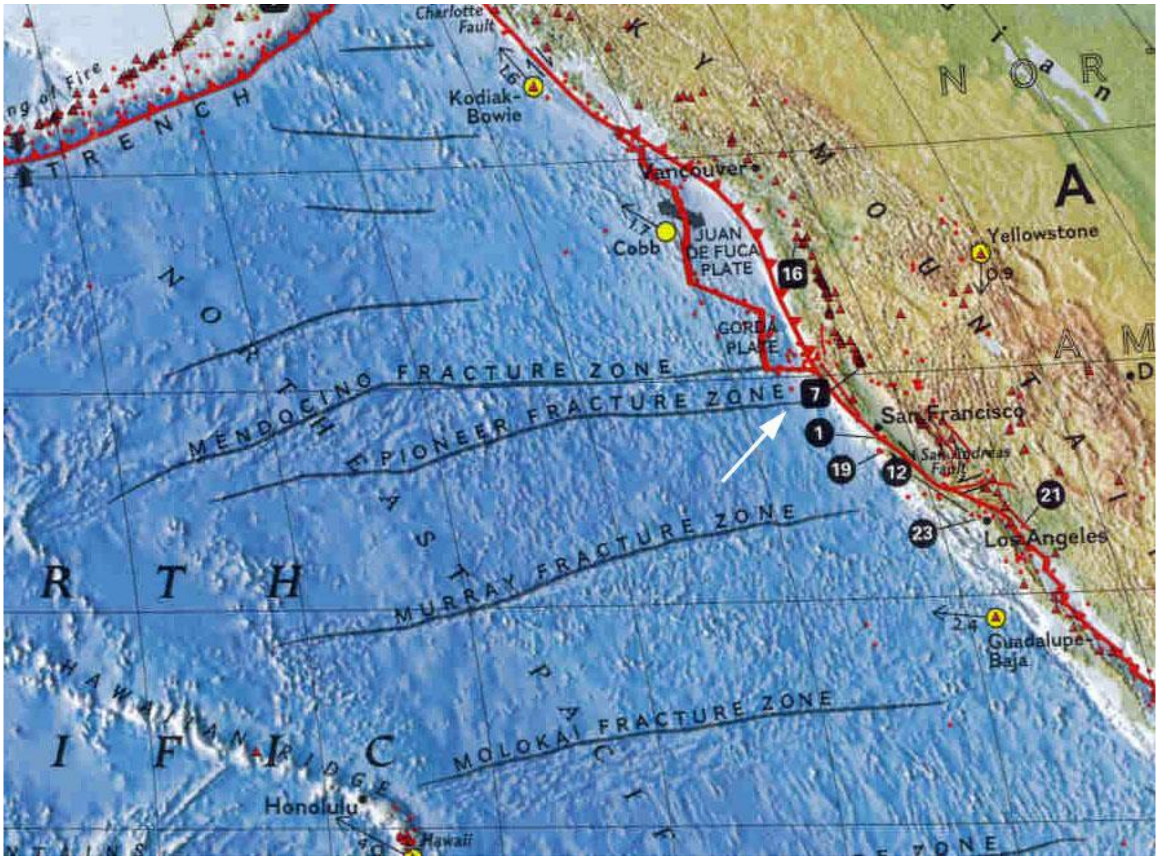
B/Aerial view of the San Andreas fault slicing through the Carrizo Plain in the Temblor Range east of the city of San Luis Obispo. (Photograph by Robert E. Wallace, USGS.)

The San Andreas fault zone, which is about **1,300** km long and in places **tens** of kilometers wide, slices through two thirds of the length of California. Along it, the Pacific Plate has been grinding horizontally past the North American Plate for **10 million years**, at an average rate of about **5 cm**/**yr**. Land on the **west** side of the fault zone (on the Pacific Plate) is moving in a **northwesterly** direction relative to the land on the **east** side of the fault zone (on the North American Plate).



Each red dot marks an earthquake, Notice how many have occurred in California.They are not kidding when they talk about the "BIG ONE"

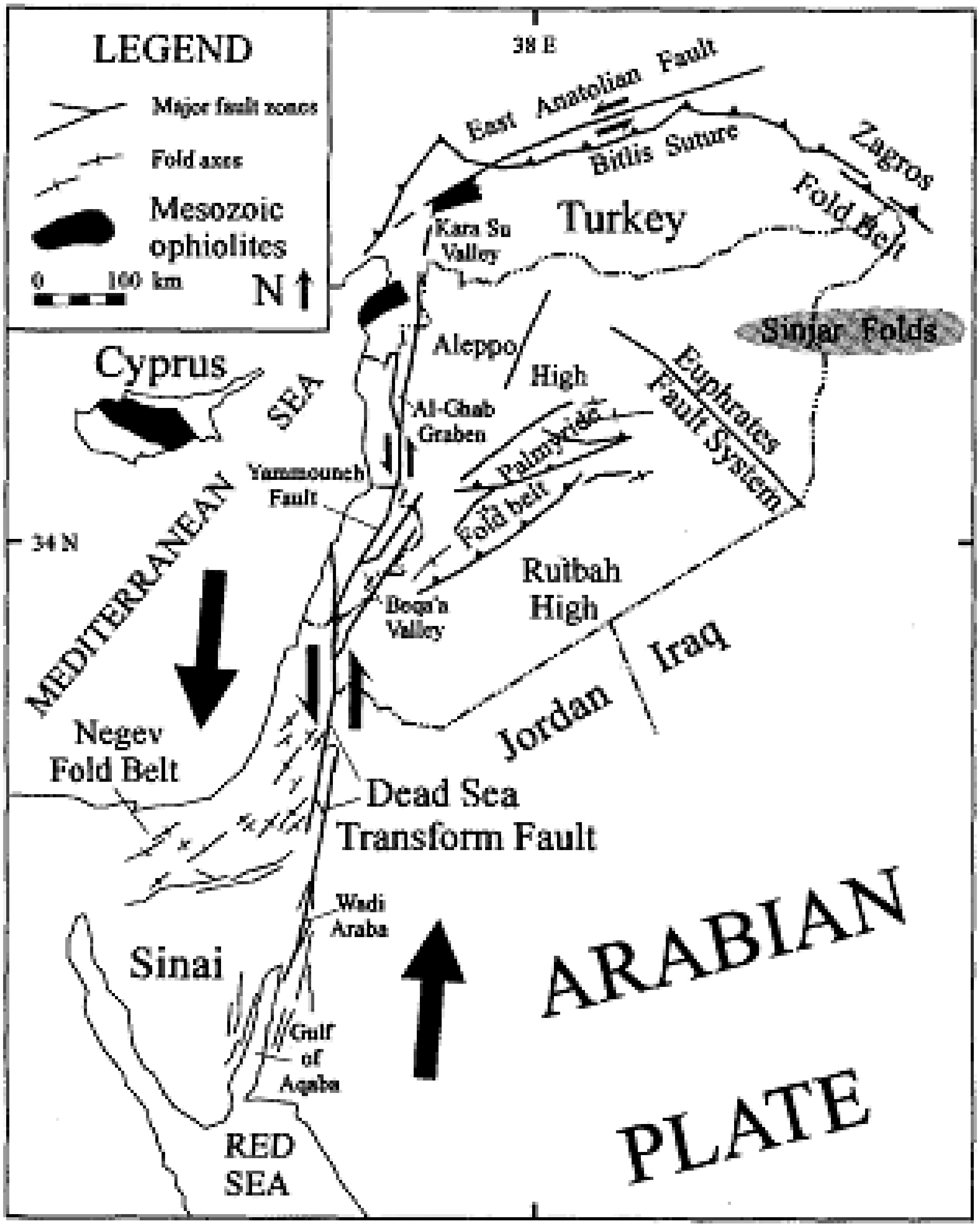
Oceanic fracture zones are ocean-floor valleys that horizontally offset spreading ridges; some of these zones are **hundreds** to **thousands** of kilometers long and as much as **8 km** deep. Examples of these large scars include the Clarion, Molokai, and Pioneer fracture zones in the Northeast Pacific off the coast of California and Mexico. These zones are presently inactive, but the offsets of the patterns of magnetic striping provide evidence of their previous transform-fault activity.



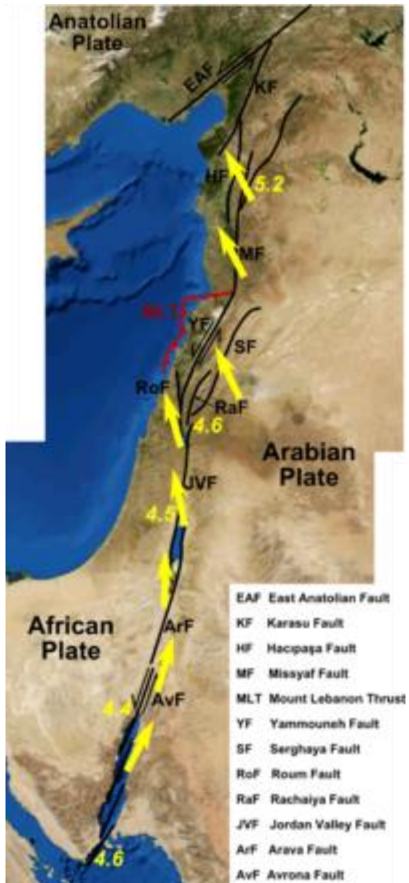
Displacement along the Dead Sea (Levant) transform fault

The Dead Sea (**Levant**) fault zone, trends roughly S-N for about 1100 km, extending from the Gulf of Aqaba through Wadi Araba, the Jordan Valley, the Huleh Depression, the Beqa'a Valley and the Al-Ghab Graben to the Kara Su Valley. Various lines of geological and geophysical evidence indicate about 105 km of left-lateral displacement along the southern segment of this fault. Although many studies looked for this amount of displacement in the northern segment, only about 60 km of displacement has been estimated, distributed between shortening across the Palmyride fold belt and left-lateral displacement along the Yammouneh, Serghaya and Roum faults. The other 40-45 km of displacement has been distributed on a hypothetical basis.

The Dead Sea Transform (DST) fault system, also sometimes referred to as the Dead Sea Rift, is a series of faults that run from the Maras Triple Junction (a junction with the East Anatolian Fault in southeastern Turkey) to the northern end of the Red Sea Rift (just offshore of the southern tip of the Sinai Peninsula). The fault system forms the transform boundary between the African Plate to the west and the Arabian Plate to the east. It is a zone of left lateral displacement, signifying the relative motions of the two plates. Both plates are moving in a general north-northeast direction, but the Arabian Plate is moving faster, resulting in the observed left lateral motions along the fault of approximately 107 km. A component of extension is also present in the southern part of the transform, which has contributed to a series of depressions, or pull-apart basins, forming the Gulf of Aqaba, Dead Sea, Sea of Galilee and Hula basins.



University of Diyala
College of Science
Department of Petroleum Geology and Minerals
Geotectonics Lectures
Prepared by: Prof. Dr. Mundher A. Taha


Anatolian Plate
EAF
KF
HF
5.2
MF
YF
SF
RoF
RaF
4.6
Arabian Plate
JVF
4.5
African Plate
ArF
AvF
4.4
4.6
EAF East Anatolian Fault
KF Karasu Fault
HF Hacıpaşa Fault
MF Missyaf Fault
MLT Mount Lebanon Thrust
YF Yammouneh Fault
SF Serghaya Fault
RoF Roum Fault
RaF Rachaiya Fault
JVF Jordan Valley Fault
ArF Arava Fault
AvF Avrona Fault

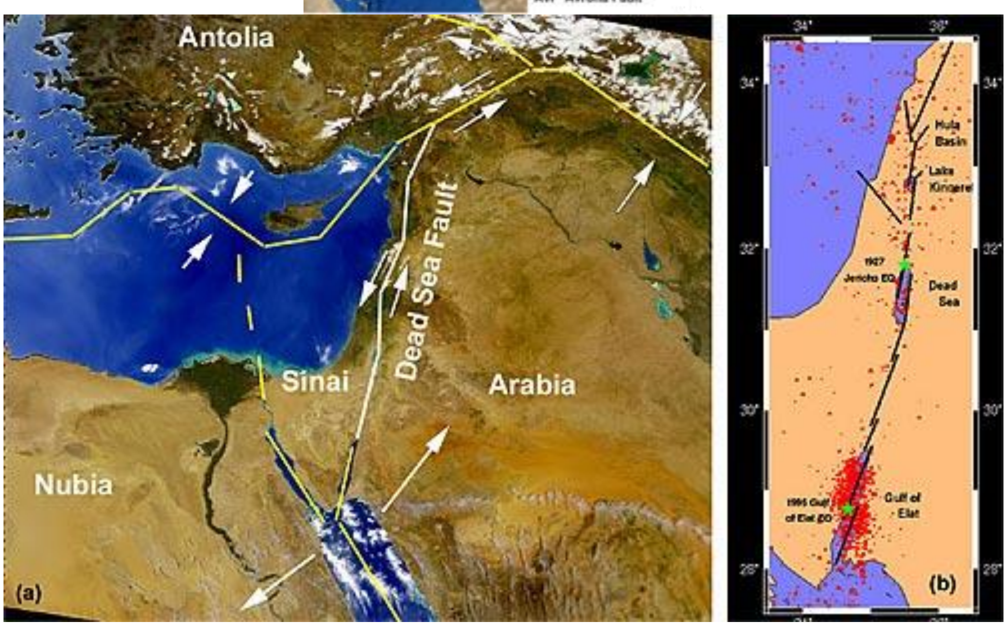
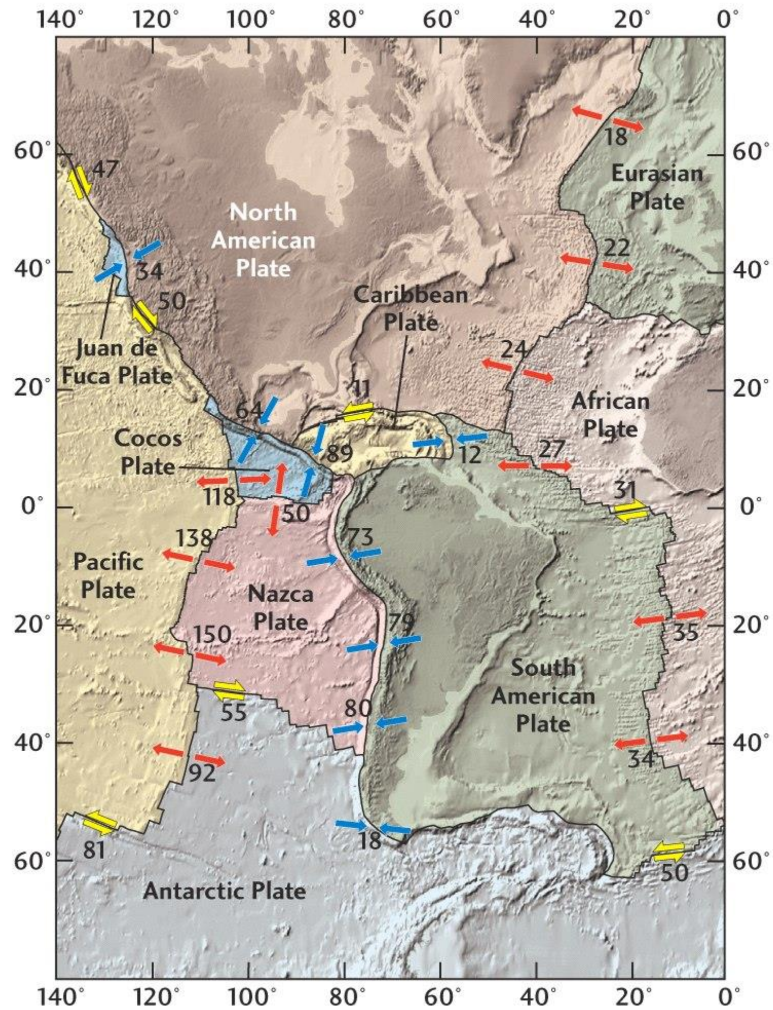

Antolia
Dead Sea Fault
Sinai
Arabia
Nubia
(a)
Hula Basin
Lake Kinneret
1927 Jericho EQ
Dead Sea
Gulf of Elat
(b)

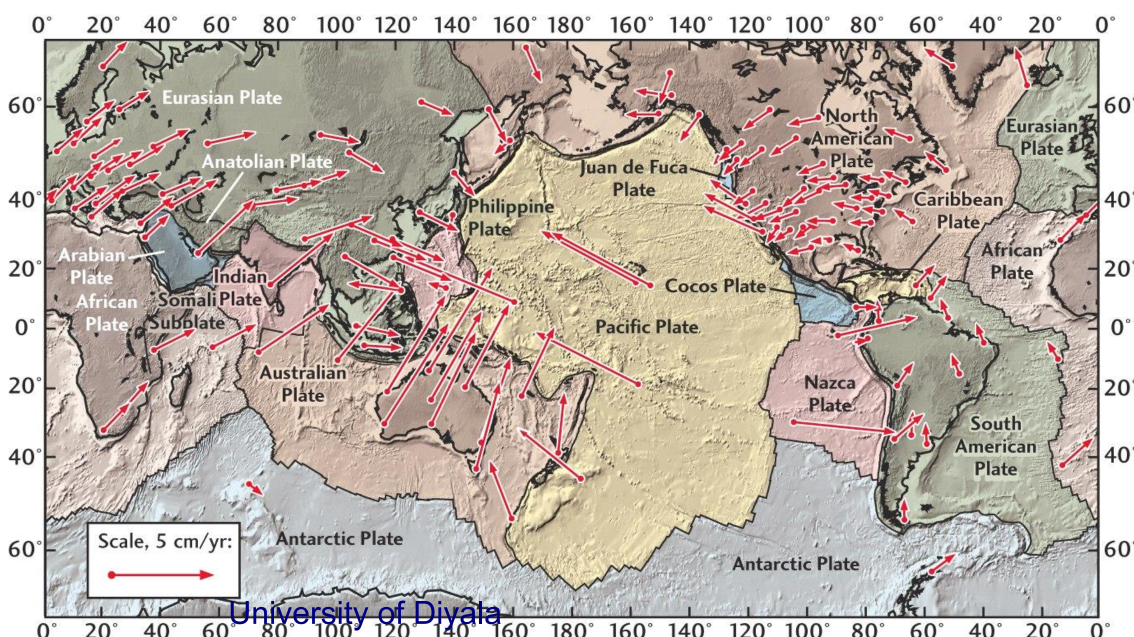
Plate-boundary zones

Not all plate boundaries are as simple as the main types discussed above. In some regions, the boundaries are not well defined because the **plate-movement deformation** occurring there extends over a broad belt (called a plate-boundary zone). One of these zones marks the **Mediterranean-Alpine** region between the **Eurasian** and **African** Plates, within which several smaller fragments of plates (microplates) have been recognized. Because plate-boundary zones involve at least two large plates and one or more microplates caught up between them, they tend to have complicated geological structures and earthquake patterns.

Rates of motion

We can measure how fast tectonic plates are moving today, but how do scientists know what the rates of plate movement have been over geologic time? The oceans hold one of the key pieces to the puzzle. Because the ocean-floor magnetic striping records the flip-flops in the Earth's magnetic field, scientists, knowing the approximate duration of the reversal, can calculate the average rate of plate movement during a given time span. These average rates of plate separations can range widely. The Arctic Ridge has the slowest rate (less than 2.5 cm/yr), and the East Pacific Rise near Easter Island, in the South Pacific about 3,400 km west of Chile, has the fastest rate (more than 15 cm/yr).


North American Plate
Eurasian Plate
Caribbean Plate
African Plate
Juan de Fuca Plate
Cocos Plate
Pacific Plate
Nazca Plate
South American Plate
Antarctic Plate


Eurasian Plate
Anatolian Plate
Arabian Plate
African Plate
Somali Subplate
Indian Plate
Philippine Plate
Australian Plate
Juan de Fuca Plate
North American Plate
Caribbean Plate
Cocos Plate
Pacific Plate
Nazca Plate
South American Plate
Antarctic Plate
Scale, 5 cm/yr:

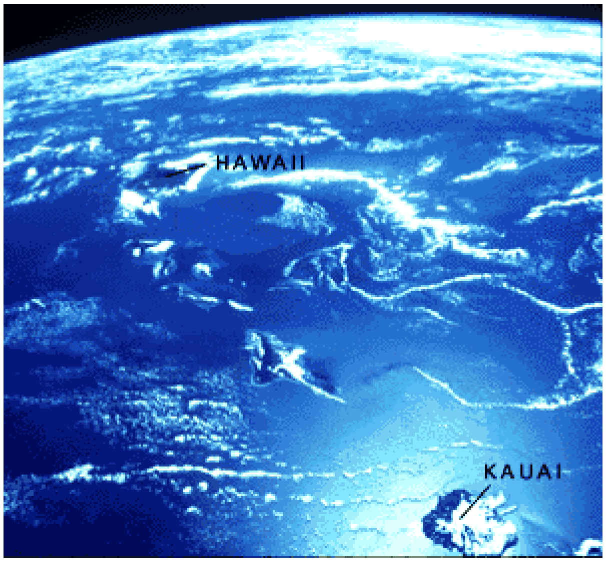
Evidence of past rates of plate movement also can be obtained from geologic mapping studies. If a rock formation of known age -- with distinctive composition, structure, or fossils -- mapped on one side of a plate boundary can be matched with the same formation on the other side of the boundary, then measuring the distance that the formation has been offset can give an estimate of the average rate of plate motion. This simple but effective technique has been used to determine the rates of plate motion at divergent boundaries, for example the Mid-Atlantic Ridge, and transform boundaries, such as the San Andreas Fault.

The three most commonly used space-geodetic techniques -- **very long baseline interferometry** (VLBI), **satellite laser ranging** (SLR), and the **Global Positioning System** (GPS) -- are based on technologies developed for military and aerospace research, notably radio astronomy and satellite tracking.

Among the three techniques, to date the **GPS** has been the most useful for studying the Earth's crustal movements. Twenty-one satellites are currently in orbit 20,000 km above the Earth as part of the NavStar system of the U.S. Department of Defense. These satellites continuously transmit radio signals back to Earth. To determine its precise position on Earth (longitude, latitude, elevation), each GPS ground site must simultaneously receive signals from at least four satellites, recording the exact time and location of each satellite when its signal was received. By repeatedly measuring distances between specific points, geologists can determine if there has been active movement along faults or between plates. The separations between GPS sites are already being measured regularly around the Pacific basin. By monitoring the interaction between the Pacific Plate and the surrounding, largely continental plates, scientists hope to learn more about the events building up to earthquakes and volcanic eruptions in the circum-Pacific Ring of Fire. Space-geodetic data have already confirmed that the rates and direction of plate movement, averaged over several years, compare well with rates and direction of plate movement averaged over millions of years.

"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?

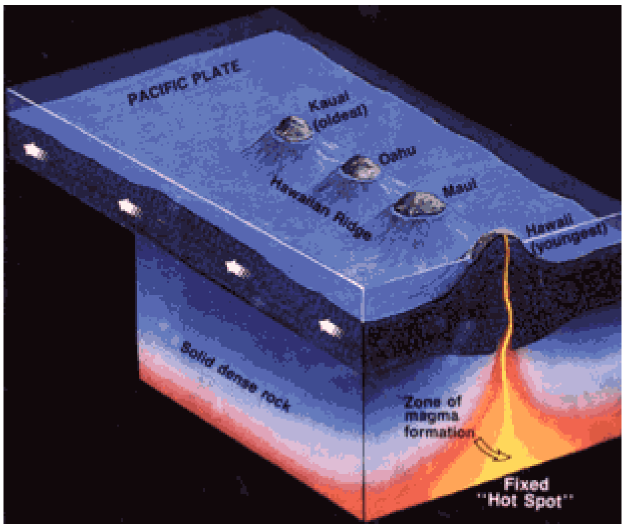


Space Shuttle photograph of the Hawaiian Islands, the southernmost part of the long volcanic trail of the "Hawaiian hotspot" (see text). Kauai is in the lower right corner (edge) and the Big Island of Hawaii in the upper left corner. Note the curvature of the Earth (top edge). (Photograph courtesy of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

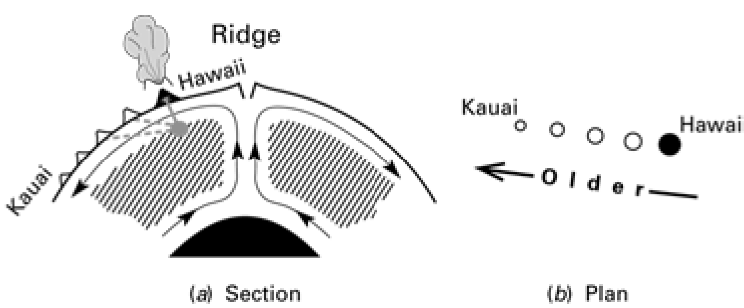
In 1963, J. **Tuzo Wilson**, the Canadian geophysicist who discovered transform faults, came up with an ingenious idea that became known as the "**hotspot**" theory. Wilson noted that in certain locations around the world, such as Hawaii, **volcanism has been active for very long periods of time.** This 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 northwestern most inhabited Hawaiian island, are about **5.5** million years old and are deeply eroded. By comparison, on the "Big Island" of Hawaii – southeastern most 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.

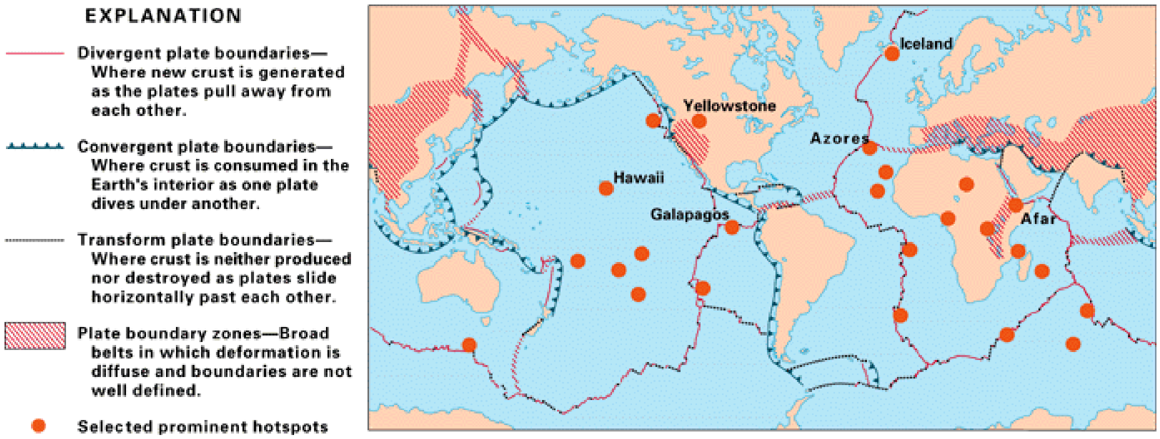


*Above: Artist's conception of the movement of the Pacific Plate over the **fixed Hawaiian** "Hot Spot," illustrating the formation of the Hawaiian Ridge-Emperor Seamount Chain. (Modified from a drawing provided by Maurice Krafft, Centre de Volcanologie, France). Below: J. Tuzo Wilson's original diagram (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).



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.

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.)

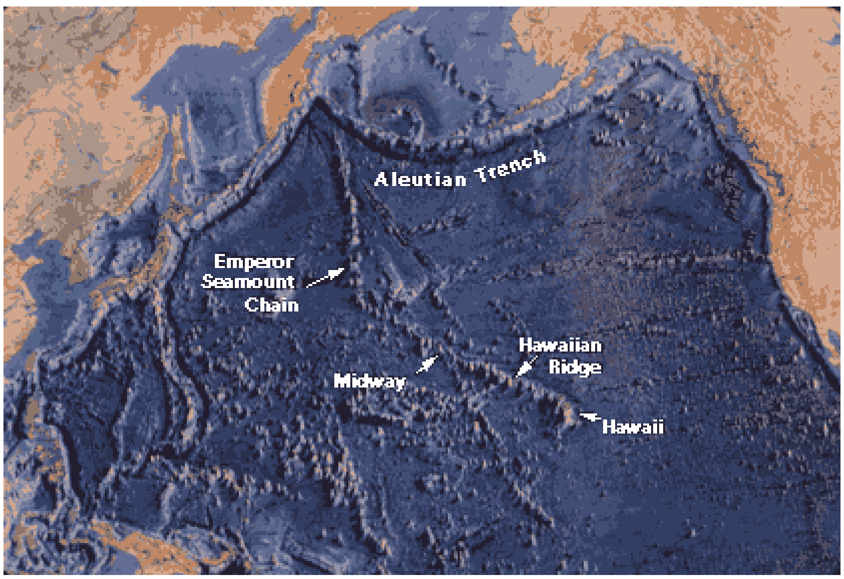
In 1963, Wilson developed a concept crucial to the plate-tectonics theory. He suggested that the **Hawaiian and other volcanic island chains** may have formed due to the movement of a plate over a **stationary** "hotspot" in the mantle. This hypothesis eliminated an apparent contradiction to the plate-tectonics theory -- the occurrence of active volcanoes located **many thousands** of kilometers from the nearest plate boundary. Hundreds of subsequent studies have proven Wilson **right**. However, in the early 1960s, his idea was considered so radical that his "hotspot" manuscript was rejected by all the major international scientific journals. This manuscript ultimately was published in 1963 in a relatively obscure publication, the Canadian Journal of Physics, and became a milestone in plate tectonics.

Another of Wilson's important contributions to the development of the plate-tectonics theory was published two years later. He proposed that there must be a **third type of plate boundary** to **connect** the oceanic ridges and trenches, which he noted can end abruptly and "**transform**" into major faults that slip horizontally. A well-known example of such a transform-fault boundary is the **San Andreas** Fault zone. Unlike ridges and trenches, transform faults offset the crust horizontally, without **creating** or **destroying** crust.

Wilson was a professor of geophysics at the University of **Toronto** from 1946 until 1974, when he **retired** from teaching and became the Director of the Ontario Science Centre. He was a tireless lecturer and traveller until his death in 1993. Like Hess, Wilson was able to see his concepts of **hotspots** and **transform faults** confirmed, as knowledge of the dynamics and seismicity of the ocean floor increased dramatically. Wilson and other scientists, including **Robert Dietz**, **Harry Hess**, **Drummond Matthews**, and **Frederick Vine**, were the principal architects in the early development of plate tectonics during the mid-1960s -- a theory that is as vibrant and exciting today as it was when it first began to evolve less than 30 years ago.

The long trail of the Hawaiian hotspot

Over the past **70** million years, the combined processes of *magma formation*, *volcano eruption* and *growth*, and *continued movement* of the Pacific Plate over the stationary Hawaiian "hot-spot" have left a *long trail of volcanoes across the Pacific Ocean floor*. The Hawaiian Ridge-Emperor Seamounts chain extends some **6,000** km from the "Big Island" of Hawaii to the **Aleutian Trench** off **Alaska**. The **Hawaiian Islands** themselves are a very small part of the chain and are the **youngest** islands in the immense, mostly submarine mountain chain composed of more than **80** volcanoes. The length of the Hawaiian Ridge segment alone, from the Big Island northwest to Midway Island, is about equal to the distance from Washington, D.C. to Denver, Colorado (2,600 km). The amount of lava erupted to form the Hawaiian-Emperor chain is calculated to be at least **750,000** cubic kilometers-more than enough to blanket the entire State of California with a layer of lava roughly **1.5** km thick.



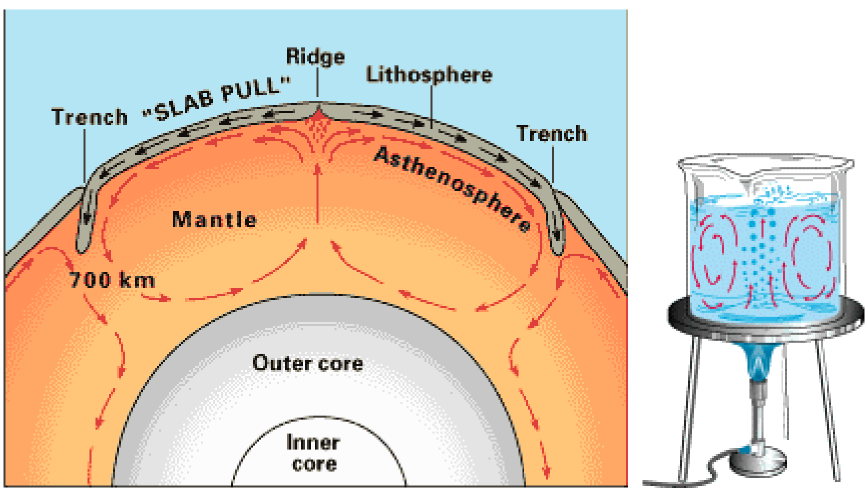
Map of part of the Pacific basin showing the volcanic trail of the Hawaiian hotspot-- 6,000-km-long Hawaiian Ridge-Emperor Seamounts chain. (Base map reprinted by permission from World Ocean Floor by Bruce C. Heezen and Marie Tharp, Copyright 1977.)

A sharp bend in the chain indicates that the motion of the Pacific Plate abruptly changed about **43 million** years ago, as it took a more westerly turn from its earlier northerly direction. Why the Pacific Plate changed direction is not known, but the change may be related in some way to the collision of **India** into the **Asian** continent, which began about the same time.

As the Pacific Plate continues to move **west-northwest**, the Island of Hawaii will be carried beyond the hotspot by plate motion, setting the stage for the formation of a new volcanic island in its place. In fact, this process may be under way. **Loihi Seamount**, an active submarine volcano, is forming about 35 km off the southern coast of Hawaii. Loihi already has risen about **3** km above the ocean floor to within **1** km of the ocean surface. According to the hotspot theory, assuming Loihi continues to grow, it will become the next island in the Hawaiian chain. In the geologic future, Loihi may eventually become fused with the Island of Hawaii, which itself is composed of five volcanoes knitted together-**Kohala**, **Mauna Kea**, **Hualalai**, **Mauna Loa**, and **Kilauea**.

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.Right: 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. <u>Cold, denser material convects downward and hotter, lighter material rises because of gravity</u>; <u>this movement of material is an essential part of convection</u>. 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.