Plate tectonics

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The tectonic plates of the world were mapped in the second half of the 20th century.

Plate tectonics (from Greek τέκτων, *tektōn* "builder" or "mason") describes the large scale motions of Earth's lithosphere. The theory encompasses the older concepts of continental drift, developed during the first half of the 20th century, and seafloor spreading, understood during the 1960s.

The outermost part of the Earth's interior is made up of two layers: above is the lithosphere, comprising the crust and the rigid uppermost part of the mantle. Below the lithosphere lies the asthenosphere. Although solid, the asthenosphere has relatively low viscosity and shear strength and can flow like a liquid on geological time scales. The deeper mantle below the asthenosphere is more rigid again due to the higher pressure.

The lithosphere is broken up into what are called *tectonic plates* — in the case of Earth, there are seven major and many minor plates (see list below). The lithospheric plates ride on the asthenosphere. These plates move in relation to one another at one of three types of plate boundaries: convergent or collision boundaries, divergent or spreading boundaries, and transform boundaries. Earthquakes, volcanic activity, mountain-building, and oceanic trench formation occur along plate boundaries. The lateral movement of the plates is typically at speeds of 50—100 mm/a.[1]

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Synopsis of the development of the theory

Detailed map showing the tectonic plates with their movement vectors.

In the late 19th and early 20th centuries, geologists assumed that the Earth's major features were fixed, and that most geologic features such as mountain ranges could be explained by vertical crustal movement, as explained by geosynclinal theory. It was observed as early as 1596 that the opposite coasts of the Atlantic Ocean — or, more precisely, the edges of the continental shelves — have similar shapes and seem once to have fitted together.[2] Since that time many theories were proposed to explain this apparent compatibility, but the assumption of a solid earth made the various proposals difficult to explain.[3]

The discovery of radium and its associated heating properties in 1896 prompted a re-examination of the apparent age of the Earth,[4] since this had been estimated by its cooling rate and assumption the Earth's surface radiated like a black body.[5] Those calculations implied that, even if it started at red heat, the Earth would have dropped to its present temperature in a few tens of millions of years. Armed with the knowledge of a new heat source, scientists reasoned it was credible that the Earth was much older, and also that its core was still sufficiently hot to be liquid.

Plate tectonic theory arose out of the hypothesis of continental drift proposed by Alfred Wegener in 1912[6] and expanded in his 1915 book *The Origin of Continents and Oceans*. He suggested that the present continents once formed a single land mass that drifted apart, thus releasing the continents from the Earth's core and likening them to "icebergs" of low density granite floating on a sea of more dense basalt.[7][8] But without detailed evidence and a force sufficient to drive the movement, the theory was not generally accepted: the Earth might have a solid crust and a liquid core, but there seemed to be no way that portions of the crust could move around. Later science supported theories proposed by English geologist Arthur Holmes in 1920 that plate junctions might lie beneath the sea and Holmes' 1928 suggestion of convection currents within the mantle as the driving force.[9][10][3]

The first evidence that the lithospheric plates did move came with the discovery of variable magnetic field direction in rocks of differing ages, first revealed at a symposium in Tasmania in 1956. Initially theorized as an expansion of the global crust,[11] later collaborations developed the plate tectonics theory, which accounted for spreading as the consequence of new rock upwelling, but avoided the need for an expanding globe by recognizing subduction zones and conservative translation faults. It was at this point that Wegener's theory became generally accepted by the scientific community. Additional work on the association of seafloor spreading and magnetic field reversals by Harry Hess and Ron G. Mason[12][13][14][15] pinpointed the precise mechanism which accounted for new rock upwelling.

Following the recognition of magnetic anomalies defined by symmetric, parallel stripes of similar magnetization on the seafloor on either side of a mid-ocean ridge, plate tectonics quickly became broadly accepted. Simultaneous advances in early seismic imaging techniques in and around Wadati-Benioff zones together with many other geologic observations soon made plate tectonics a theory with extraordinary explanatory and predictive power.

Study of the deep ocean floor was critical to development of the theory; the field of deep sea marine geology accelerated in the 1960s. Correspondingly, plate tectonic theory was developed during the late 1960s and has since been accepted by almost all scientists throughout all geoscientific disciplines. The theory revolutionized the Earth sciences, explaining a diverse range of geological phenomena and their implications in other studies such as paleogeography and paleobiology.

Key principles

The outer layers of the Earth are divided into lithosphere and asthenosphere. This is based on differences in mechanical properties and in the method for the transfer of heat. Mechanically, the lithosphere is cooler and more rigid, while the asthenosphere is hotter and flows more easily. In terms of heat transfer, the lithosphere loses heat by conduction whereas the asthenosphere also transfers heat by convection and has a nearly adiabatic temperature gradient. This division should not be confused with the *chemical* subdivision of these same layers into the mantle (comprising both the asthenosphere and the mantle portion of the lithosphere) and the crust: a given piece of mantle may be part of the lithosphere or the asthenosphere at different times, depending on its temperature and pressure.

The key principle of plate tectonics is that the lithosphere exists as separate and distinct *tectonic plates*, which ride on the fluid-like (visco-elastic solid) asthenosphere. Plate motions range up to a typical 10-40 mm/a (Mid-Atlantic Ridge; about as fast as fingernails grow), to about 160 mm/a (Nazca Plate; about as fast as hair grows).[16][17]

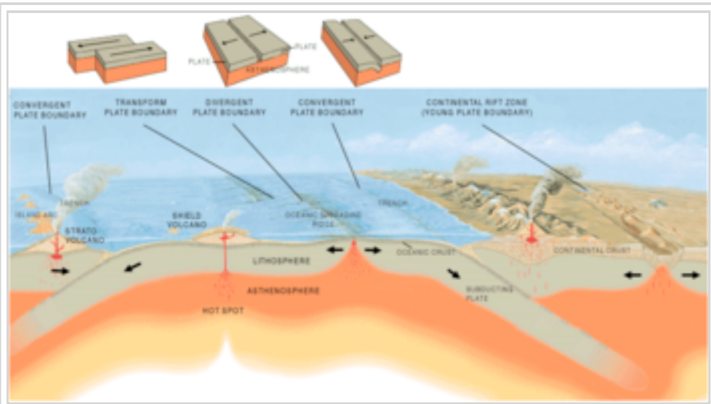
The plates are around 100 km (60 miles) thick and consist of lithospheric mantle overlain by either of two types of crustal material: oceanic crust (in older texts called *sima* from silicon and magnesium) and continental crust (*sial* from silicon and aluminium). The two types of crust differ in thickness, with continental crust considerably thicker than oceanic (50 km vs 5 km).

One plate meets another along a *plate boundary*, and plate boundaries are commonly associated with geological events such as earthquakes and the creation of topographic features like mountains, volcanoes and oceanic trenches. The majority of the world's active volcanoes occur along plate boundaries, with the Pacific Plate's Ring of Fire being most active and most widely known. These boundaries are discussed in further detail below.

Tectonic plates can include continental crust or oceanic crust, and a single plate typically carries both. For example, the African Plate includes the continent and parts of the floor of the Atlantic and Indian Oceans. The distinction between continental crust and oceanic crust is based on the density of constituent materials; oceanic crust is denser than continental crust owing to their different proportions of various elements, particularly silicon. Oceanic crust is denser because it has less silicon and more heavier elements ("mafic") than continental crust ("felsic").[18] As a result, oceanic crust generally lies below sea level (for example most of the Pacific Plate), while the continental crust projects above sea level (see isostasy for explanation of this principle).

Types of plate boundaries

Three types of plate boundaries exist, characterized by the way the plates move relative to each other. They are associated with different types of surface phenomena. The different types of plate boundaries are:



Three types of plate boundary.

1. **Transform boundaries** occur where plates slide or, perhaps more accurately, grind past each other along transform faults. The relative motion of the two plates is either sinistral (left side toward the observer) or dextral (right side toward the observer). The San Andreas Fault in California is one example.
2. **Divergent boundaries** occur where two plates slide apart from each other. Mid-ocean ridges (e.g., Mid-Atlantic Ridge) and active zones of rifting (such as Africa's Great Rift Valley) are both

examples of divergent boundaries.

3. **Convergent boundaries** (or *active margins*) occur where two plates slide towards each other commonly forming either a subduction zone (if one plate moves underneath the other) or a continental collision (if the two plates contain continental crust). Deep marine trenches are typically associated with subduction zones. The subducting slab contains many hydrous minerals, which release their water on heating; this water then causes the mantle to melt, producing volcanism. Examples of this are the Andes mountain range in South America and the Japanese island arc.

Transform (conservative) boundaries

John Tuzo Wilson recognized that because of friction, the plates cannot simply glide past each other. Rather, stress builds up in both plates and when it reaches a level that exceeds the strain threshold of rocks on either side of the fault the accumulated potential energy is released as strain. Strain is both accumulative and/or instantaneous depending on the rheology of the rock; the ductile lower crust and mantle accumulates deformation gradually via shearing whereas the brittle upper crust reacts by fracture, or instantaneous stress release to cause motion along the fault. The ductile surface of the fault can also release instantaneously when the strain rate is too great. The energy released by instantaneous strain release is the cause of earthquakes, a common phenomenon along transform boundaries.

A good example of this type of plate boundary is the San Andreas Fault which is found in the western coast of North America and is one part of a highly complex system of faults in this area. At this location, the Pacific and North American plates move relative to each other such that the Pacific plate is moving northwest with respect to North America. Other examples of transform faults include the Alpine Fault in New Zealand and the North Anatolian Fault in Turkey. Transform faults are also found offsetting the crests of mid-ocean ridges (for example, the Mendocino Fracture Zone offshore northern California).

Divergent (constructive) boundaries

Bridge across the Álfagjá rift valley in southwest Iceland, the boundary between the Eurasian and North American continental tectonic plates.

At divergent boundaries, two plates move apart from each other and the space that this creates is filled with new crustal material sourced from molten magma that forms below. The origin of new divergent boundaries at triple junctions is sometimes thought to be associated with the phenomenon known as hotspots. Here, exceedingly large convective cells bring very large quantities of hot asthenospheric material near the surface and the kinetic energy is thought to be sufficient to break apart the lithosphere. The hot spot which may have initiated the Mid-Atlantic Ridge system currently underlies Iceland which is widening at a rate of a few centimeters per year.

Divergent boundaries are typified in the oceanic lithosphere by the rifts of the oceanic ridge system, including the Mid-Atlantic Ridge and the East Pacific Rise, and in the continental lithosphere by rift valleys such as the famous East African Great Rift Valley. Divergent boundaries can create massive fault zones in the oceanic ridge system. Spreading is generally not uniform, so where spreading rates of adjacent ridge blocks are different, massive transform faults occur. These are the fracture zones, many bearing names, that are a major source of submarine earthquakes. A sea floor map will show a rather strange pattern of blocky structures that are separated by linear features (http://pubs.usgs.gov/publications /text/baseball.html) perpendicular to the ridge axis. If one views the sea floor between the fracture zones as conveyor belts carrying the ridge on each side of the rift away from the spreading center the action becomes clear. Crest depths of the old ridges, parallel to the current spreading center, will be older and deeper (from thermal contraction and subsidence).

It is at mid-ocean ridges that one of the key pieces of evidence forcing acceptance of the seafloor spreading hypothesis was found. Airborne geomagnetic surveys showed a strange pattern of symmetrical magnetic reversals on opposite sides of ridge centers. The pattern was far too regular to be coincidental as the widths of the opposing bands were too closely matched. Scientists had been studying polar reversals and the link was made by Lawrence W. Morley, Frederick John Vine and Drummond Hoyle Matthews in the Morley-Vine-Matthews hypothesis. The magnetic banding directly corresponds with the Earth's polar reversals. This was confirmed by measuring the ages of the rocks within each band. The banding furnishes a map in time and space of both spreading rate and polar reversals.

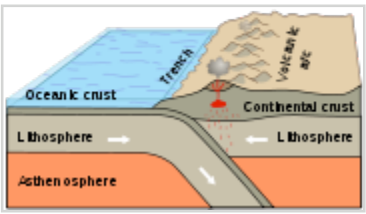
Convergent (destructive) boundaries

The nature of a convergent boundary depends on the type of lithosphere in the plates that are colliding. Where a dense oceanic plate collides with a less-dense continental plate, the oceanic plate is typically thrust underneath because of the greater buoyancy of the continental lithosphere, forming a subduction zone. At the surface, the topographic expression is commonly an oceanic trench on the ocean side and a mountain range on the continental side. An example of a continental-oceanic subduction zone is the area along the western coast of South America where the oceanic Nazca Plate is being subducted beneath the continental South American Plate.

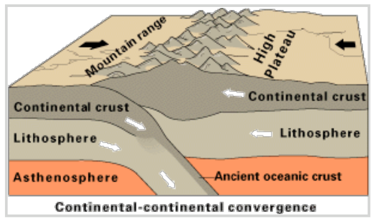
While the processes directly associated with the production of melts directly above downgoing plates producing surface volcanism is the subject of some debate in the geologic community, the general consensus from ongoing research suggests that the release of volatiles is the primary contributor. As the subducting plate descends, its temperature rises driving off volatiles (most importantly water) encased in the porous oceanic crust. As this water rises into the mantle of the overriding plate, it lowers the melting temperature of surrounding mantle, producing melts (magma) with large amounts of dissolved gases. These melts rise to the surface and are the source of some of the most explosive volcanism on Earth because of their high volumes of extremely pressurized gases (consider Mount St. Helens). The melts rise to the surface and cool forming long chains of volcanoes inland from the continental shelf and parallel to it. The continental spine of western South America is dense with this type of volcanic mountain building from the subduction of the Nazca plate. In North America the Cascade mountain range, extending north from California's Sierra Nevada, is also of this type. Such volcanoes are characterized by alternating periods of quiet and episodic eruptions that start with explosive gas expulsion with fine particles of glassy volcanic ash and spongy cinders, followed by a rebuilding phase with hot magma. The entire Pacific Ocean boundary is surrounded by long stretches of volcanoes and is known collectively as *The Ring of Fire*.

Where two continental plates collide the plates either buckle and compress or one plate delves under or (in some cases) overrides the other. Either action will create extensive mountain ranges. The most dramatic effect seen is where the northern margin of the Indian Plate is being thrust under a portion of the Eurasian plate, lifting it and creating the Himalayas and the Tibetan Plateau beyond. It may have also pushed nearby parts of the Asian continent aside to the east.[19]

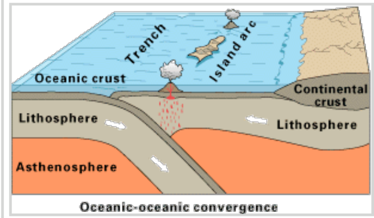
When two plates with oceanic crust converge they typically create an island arc as one plate is subducted below the other. The arc is formed from volcanoes which erupt through the overriding plate as the descending plate melts below it. The arc shape occurs because of the spherical surface of the earth (nick the peel of an orange with a knife and note the arc formed by the straight-edge of the knife). A deep undersea trench is located in front of such arcs where the descending slab dips downward. Good examples of this type of plate convergence would be Japan and the Aleutian Islands in Alaska.



Oceanic / Continental



Continental / Continental



Oceanic / Oceanic

Plates may collide at an oblique angle rather than head-on to each other (e.g. one plate moving north, the other moving south-east), and this may cause strike-slip faulting along the collision zone, in addition to subduction or compression.

Not all plate boundaries are easily defined. Some are broad belts whose movements are unclear to scientists. One example would be the Mediterranean-Alpine boundary, which involves two major plates and several micro plates. The boundaries of the plates do not necessarily coincide with those of the continents. For instance, the North American Plate covers not only North America, but also far northeastern Siberia, plus a substantial portion of the Atlantic Ocean.

Driving forces of plate motion

Tectonic plates are able to move because of the relative density of oceanic lithosphere and the relative weakness of the asthenosphere. Dissipation of heat from the mantle is acknowledged to be the original source of energy driving plate tectonics. The current view, although it is still a matter of some debate, is that excess density of the oceanic lithosphere sinking in subduction zones is the most powerful source of plate motion. When it forms at mid-ocean ridges, the oceanic lithosphere is initially less dense than the underlying asthenosphere, but it becomes more dense with age, as it conductively cools and thickens. The greater density of old lithosphere relative to the underlying asthenosphere allows it to sink into the deep mantle at subduction zones, providing most of the driving force for plate motions. The weakness of the asthenosphere allows the tectonic plates to move easily towards a subduction zone.[20] Although subduction is believed to be the strongest force driving plate motions, it cannot be the only force since there are plates such as the North American Plate which are moving, yet are nowhere being subducted. The same is true for the enormous Eurasian Plate. The sources of plate motion are a matter of intensive research and discussion among earth scientists.

Two and three-dimensional imaging of the Earth's interior (seismic tomography) shows that there is a laterally heterogeneous density distribution throughout the mantle. Such density variations can be material (from rock chemistry), mineral (from variations in mineral structures), or thermal (through thermal expansion and contraction from heat energy). The manifestation of this lateral density heterogeneity is mantle convection from buoyancy forces.[21] How mantle convection relates directly and indirectly to the motion of the plates is a matter of ongoing study and discussion in geodynamics. Somehow, this energy must be transferred to the lithosphere in order for tectonic plates to move. There are essentially two types of forces that are thought to influence plate motion: friction and gravity.

Friction

Basal drag
: Large scale convection currents in the upper mantle are transmitted through the asthenosphere; motion is driven by friction between the asthenosphere and the lithosphere.

Slab suction
: Local convection currents exert a downward frictional pull on plates in subduction zones at ocean trenches. Slab suction may occur in a geodynamic setting wherein basal tractions continue to act on the plate as it dives into the mantle (although perhaps to a greater extent acting on both the under and upper side of the slab).

Gravitation

Gravitational sliding: Plate motion is driven by the higher elevation of plates at ocean ridges. As oceanic lithosphere is formed at spreading ridges from hot mantle material it gradually cools and thickens with age (and thus distance from the ridge). Cool oceanic lithosphere is significantly denser than the hot mantle material from which it is derived and so with increasing thickness it gradually subsides into the mantle to compensate the greater load. The result is a slight lateral incline with distance from the ridge axis.

Casually in the geophysical community and more typically in the geological literature in lower education this process is often referred to as "ridge-push". This is, in fact, a misnomer as nothing is "pushing" and tensional features are dominant along ridges. It is more accurate to refer to this mechanism as gravitational sliding as variable topography across the totality of the plate can vary considerably and the topography of spreading ridges is only the most prominent feature. For example:

1. Flexural bulging of the lithosphere before it dives underneath an adjacent plate, for instance, produces a clear topographical feature that can offset or at least affect the influence of topographical ocean ridges.
2. Mantle plumes impinging on the underside of tectonic plates can drastically alter the topography of the ocean floor.

Slab-pull
: Plate motion is partly driven by the weight of cold, dense plates sinking into the mantle at trenches.[22] There is considerable evidence that convection is occurring in the mantle at some

scale. The upwelling of material at mid-ocean ridges is almost certainly part of this convection. Some early models of plate tectonics envisioned the plates riding on top of convection cells like conveyor belts. However, most scientists working today believe that the asthenosphere is not strong enough to directly cause motion by the friction of such basal forces. Slab pull is most widely thought to be the greatest force acting on the plates. Recent models indicate that trench suction plays an important role as well. However, it should be noted that the North American Plate, for instance, is nowhere being subducted, yet it is in motion. Likewise the African, Eurasian and Antarctic Plates. The overall driving force for plate motion and its energy source remain subjects of ongoing research.

External forces

In a study published in the January-February 2006 issue of the *Geological Society of America Bulletin*, a team of Italian and U.S. scientists argued that the westward component of plates is from Earth's rotation and consequent tidal friction of the moon. As the Earth spins eastward beneath the moon, they say, the moon's gravity ever so slightly pulls the Earth's surface layer back westward. It has also been suggested (albeit, controversially) that this observation may also explain why Venus and Mars have no plate tectonics since Venus has no moon, and Mars' moons are too small to have significant tidal effects on Mars.[23] This is not, however, a new argument.

It was originally raised by the "father" of the plate tectonics hypothesis, Alfred Wegener. It was challenged by the physicist Harold Jeffreys who calculated that the magnitude of tidal friction required would have quickly brought the Earth's rotation to a halt long ago. Many plates are moving north and eastward, and the dominantly westward motion of the Pacific ocean basins is simply from the eastward bias of the Pacific spreading center (which is not a predicted manifestation of such lunar forces). It is argued, however, that relative to the lower mantle, there is a slight westward component in the motions of all the plates.

Relative significance of each mechanism

The actual vector of a plate's motion must necessarily be a function of all the forces acting upon the plate. However, therein remains the problem regarding what degree each process contributes to the motion of each tectonic plate.

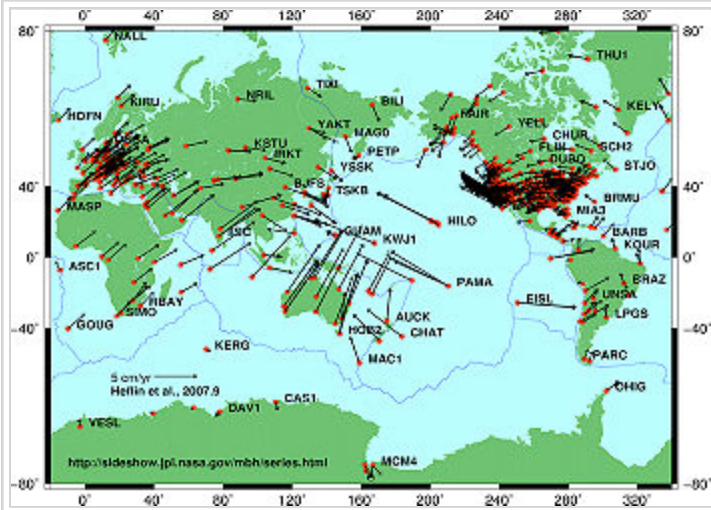


Plate motion based on Global Positioning System (GPS) satellite data from NASA JPL (http://sideshow.jpl.nasa.gov/mbh/series.html) . Vectors show direction and magnitude of motion.

The diversity of geodynamic settings and properties of each plate must clearly result in differences in the degree to which such processes are actively driving the plates. One method of dealing with this problem is to consider the relative rate at which each plate is moving and to consider the available evidence of each driving force upon the plate as far as possible.

One of the most significant correlations found is that lithospheric plates attached to downgoing (subducting) plates move much faster than plates not attached to subducting plates. The Pacific plate, for instance, is essentially surrounded by zones of subduction (the so-called Ring of Fire) and moves much faster than the plates of the Atlantic basin, which are attached (perhaps one could say 'welded') to adjacent continents instead of subducting plates. It is thus thought that forces associated with the downgoing plate (slab pull and slab suction) are the driving forces which determine the motion of plates, except for those plates which are not being subducted.

The driving forces of plate motion are, nevertheless, still very active subjects of on-going discussion and research in the geophysical community.

Major plates

The main plates are

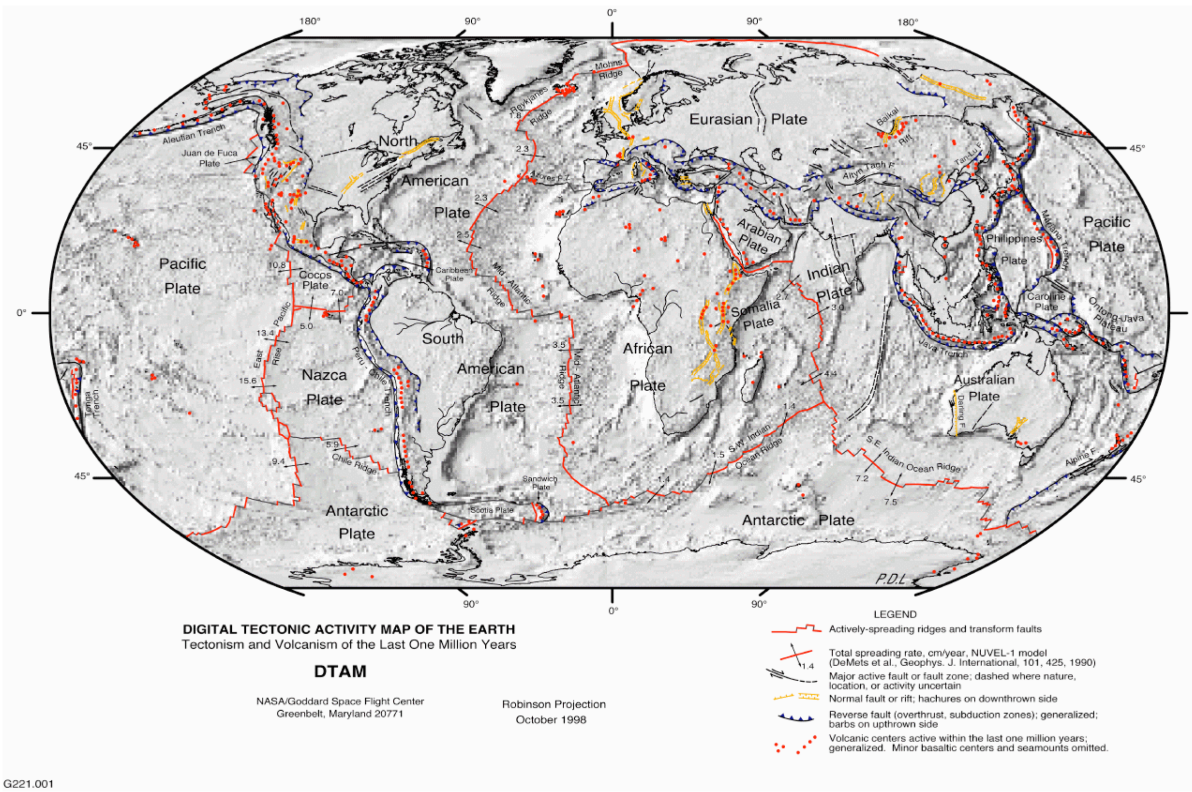
- African Plate covering Africa - Continental plate
- Antarctic Plate covering Antarctica - Continental plate
- Australian Plate covering Australia - Continental plate
- Indian Plate covering Indian subcontinent and a part of Indian Ocean - Continental plate
- Eurasian Plate covering Asia and Europe - Continental plate
- North American Plate covering North America and north-east Siberia - Continental plate
- South American Plate covering South America - Continental plate
- Pacific Plate covering the Pacific Ocean - Oceanic plate

Notable minor plates include the Arabian Plate, the Caribbean Plate, the Juan de Fuca Plate, the Cocos Plate, the Nazca Plate, the Philippine Plate and the Scotia Plate.

The movement of plates has caused the formation and break-up of continents over time, including occasional formation of a supercontinent that contains most or all of the continents. The supercontinent Rodinia is thought to have formed about 1 billion years ago and to have embodied most or all of Earth's continents, and broken up into eight continents around 600 million years ago. The eight continents later re-assembled into another supercontinent called Pangaea; Pangaea eventually broke up into Laurasia (which became North America and Eurasia) and Gondwana (which became the remaining continents).

Related article

- List of tectonic plates



Historical development of the theory

Continental drift

For more details on this topic, see Continental drift.

Continental drift was one of many ideas about tectonics proposed in the late 19th and early 20th centuries. The theory has been superseded and the concepts and data have been incorporated within plate tectonics.

By 1915, Alfred Wegener was making serious arguments for the idea in the first edition of *The Origin of Continents and Oceans*. In that book, he noted how the east coast of South America and the west coast of Africa looked as if they were once attached. Wegener wasn't the first to note this (Abraham Ortelius, Francis Bacon, Benjamin Franklin, Snider-Pellegrini, Roberto Mantovani and Frank Bursley Taylor preceded him), but he was the first to marshal significant fossil and paleo-topographical and climatological evidence to support this simple observation (and was supported in this by researchers such as Alex du Toit). However, his ideas were not taken seriously by many geologists, who pointed out that there was no apparent mechanism for continental drift. Specifically, they did not see how continental rock could plow through the much denser rock that makes up oceanic crust. Wegener could not explain the force that propelled continental drift.

Wegener's vindication did not come until after his death in 1930. In 1947, a team of scientists led by Maurice Ewing utilizing the Woods Hole Oceanographic Institution's research vessel *Atlantis* and an array of instruments, confirmed the existence of a rise in the central Atlantic Ocean, and found that the floor of the seabed beneath the layer of sediments consisted of basalt, not the granite which is the main constituent of continents. They also found that the oceanic crust was much thinner than continental crust. All these new findings raised important and intriguing questions.[24]

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

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.

When the rock strata of the tips of separate continents are very similar it suggests that these rocks were formed in the same way implying that they were joined initially. For instance, some parts of Scotland and Ireland contain rocks very similar to those found in Newfoundland and New Brunswick. Furthermore, the Caledonian Mountains of Europe and parts of the Appalachian Mountains of North America are very similar in structure and lithology.

Floating continents

The prevailing concept was that there were static shells of strata under the continents. It was observed early that although granite existed on continents, seafloor seemed to be composed of denser basalt. It was apparent that a layer of basalt underlies continental rocks.

However, based upon abnormalities in plumb line deflection by the Andes in Peru, Pierre Bouguer deduced that less-dense mountains must have a downward projection into the denser layer underneath.

The concept that mountains had "roots" was confirmed by George B. Airy a hundred years later during study of Himalayan gravitation, and seismic studies detected corresponding density variations.

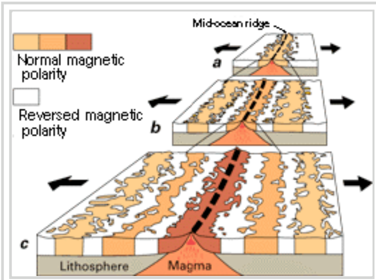
By the mid-1950s the question remained unresolved of whether mountain roots were clenched in surrounding basalt or were floating like an iceberg.

In 1958 the Tasmanian geologist Samuel Warren Carey published an essay *The tectonic approach to continental drift* in support of the expanding earth model.

Plate tectonic theory

Significant progress was made in the 1960s, and was prompted by a number of discoveries, most notably the Mid-Atlantic ridge. The most notable was the 1962 publication of a paper by American geologist Harry Hammond Hess (Robert S. Dietz published the same idea one year earlier in *Nature*. However, priority belongs to Hess, since he distributed an unpublished manuscript of his 1962 article already in 1960). Hess suggested that instead of continents moving *through* oceanic crust (as was suggested by continental drift) that an ocean basin and its adjoining continent moved together on the same crustal unit, or plate. In the same year, Robert R. Coats of the U.S. Geological Survey described the main features of island arc subduction in the Aleutian Islands. His paper, though little-noted (and even ridiculed) at the time, has since been called "seminal" and "prescient". In 1967, W. Jason Morgan proposed that the Earth's surface consists of 12 rigid plates that move relative to each other. Two months later, in 1968, Xavier Le Pichon published a complete model based on 6 major plates with their relative motions.

Explanation of magnetic striping



Seafloor magnetic striping.

The discovery of magnetic striping and the stripes being symmetrical around the crests of the mid-ocean ridges suggested a relationship. In 1961, scientists began to theorise 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 continues to form new ocean floor all across 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;
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 reversed many times.

By explaining both the zebralike magnetic striping and the construction of the mid-ocean ridge system, the seafloor spreading hypothesis quickly gained converts and represented another major advance in the development of the plate-tectonics theory. Furthermore, the oceanic crust now came to be appreciated as a natural "tape recording" of the history of the reversals in the Earth's magnetic field.

Subduction discovered

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, most notably S. Warren Carey, 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 theory" hypothesis was unsatisfactory because its supporters could offer no convincing mechanism to produce a significant expansion of the Earth. Certainly there is no evidence that the moon has expanded in the past 3 billion years. Still, the question remained: how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth?

This question particularly intrigued Harry 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 spreads 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 is consumed in the trenches, new magma rises and erupts along the spreading ridges to form new crust. In effect, the ocean basins are 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.

Mapping with earthquakes

During the 20th century, improvements in and greater use of seismic instruments such as seismographs 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 (http://neic.usgs.gov/neis/station_book/WWSS_NETWORK.html) (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 world wide.

Geological paradigm shift

The acceptance of the theories of continental drift and sea floor spreading (the two key elements of plate tectonics) may be compared to the Copernican revolution in astronomy (see Nicolaus Copernicus). Within a matter of only several years geophysics and geology in particular were revolutionized. The parallel is striking: just as pre-Copernican astronomy was highly descriptive but still unable to provide explanations for the motions of celestial objects, pre-tectonic plate geological theories described what was observed but struggled to provide any fundamental mechanisms. The problem lay in the question "How?". Before acceptance of plate tectonics, geology in particular was trapped in a "pre-Copernican" box.

However, by comparison to astronomy the geological revolution was much more sudden. What had been rejected for decades by any respectable scientific journal was eagerly accepted within a few short years in the 1960s and 1970s. Any geological description before this had been highly descriptive. All the rocks were described and assorted reasons, sometimes in excruciating detail, were given for why they were where they are. The descriptions are still valid. The reasons, however, today sound much like pre-Copernican astronomy.

One simply has to read the pre-plate descriptions of why the Alps or Himalaya exist to see the difference. In an attempt to answer "how" questions like "How can rocks that are clearly marine in origin exist thousands of meters above sea-level in the Dolomites?", or "How did the convex and concave margins of the Alpine chain form?", any true insight was hidden by complexity that boiled down to technical jargon without much fundamental insight as to the underlying mechanics.

With plate tectonics answers quickly fell into place or a path to the answer became clear. Collisions of converging plates had the force to lift the sea floor to great heights. The cause of marine trenches oddly placed just off island arcs or continents and their associated volcanoes became clear when the processes of subduction at converging plates were understood.

Mysteries were no longer mysteries. Forests of complex and obtuse answers were swept away. Why were there striking parallels in the geology of parts of Africa and South America? Why did Africa and South America look strangely like two pieces that should fit to anyone having done a jigsaw puzzle? Look at some pre-tectonics explanations for complexity. For simplicity and one that explained a great deal more look at plate tectonics. A great rift, similar to the Great Rift Valley in northeastern Africa, had split apart a single continent, eventually forming the Atlantic Ocean, and the forces were still at work in the Mid-Atlantic Ridge.

Biogeographic implications on biota

Continental drift theory helps biogeographers to explain the disjunct biogeographic distribution of present day life found on different continents but having similar ancestors.[25] In particular, it explains the Gondwanan distribution of ratites and the Antarctic flora.

Plate tectonics on other planets

The appearance of plate tectonics on terrestrial planets is related to planetary mass, with more massive planets than Earth expected to exhibit plate tectonics. Earth may be a borderline case, owing its tectonic activity to abundant water.[26]

Venus

See also: Geology of Venus

Venus shows no evidence of active plate tectonics. There is debatable evidence of active tectonics in the planet's distant past; however, events taking place since then (such as the plausible and generally accepted hypothesis that the Venusian lithosphere has thickened greatly over the course of several hundred million years) has made constraining the course of its geologic record difficult. However, the numerous well-preserved impact craters have been utilized as a dating method to approximately date the Venusian surface (since there are thus far no known samples of Venusian rock to be dated by more reliable methods). Dates derived are the dominantly in the range ~500 to 750 Ma, although ages of up to ~1.2 Ga have been calculated. This research has led to the fairly well accepted hypothesis that Venus has undergone an essentially complete volcanic resurfacing at least once in its distant past, with the last event taking place approximately within the range of estimated surface ages. While the mechanism of such an impressionable thermal event remains a debated issue in Venusian geosciences, some scientists are advocates of processes involving plate motion to some extent.

One explanation for Venus' lack of plate tectonics is that on Venus temperatures are too high for significant water to be present.[27][28] The Earth's crust is soaked with water, and water plays an important role in the development of shear zones. Plate tectonics requires weak surfaces in the crust along which crustal slices can move, and it may well be that such weakening never took place on Venus because of the absence of water. However, some researchers remain convinced that plate tectonics is or was once active on this planet.

Mars

See also: Geology of Mars

Unlike Venus, the crust of Mars has water in it and on it (mostly in the form of ice). This planet is considerably smaller than the Earth, but shows some indications that could suggest a similar style of tectonics. The gigantic volcanoes in the Tharsis area are linearly aligned like volcanic arcs on Earth; the enormous canyon Valles Marineris could have been formed by some form of crustal spreading.

As a result of observations made of the magnetic field of Mars by the *Mars Global Surveyor* spacecraft in 1999, large scale patterns of magnetic striping were discovered on this planet. To explain these magnetisation patterns in the Martian crust it has been proposed that a mechanism similar to plate tectonics may once have been active on the planet.[29][30] Further data from the *Mars Express* orbiter's *High Resolution Stereo Camera* in 2007 clearly showed an example in the Aeolis Mensae region.[31]

Galilean satellites

Some of the satellites of Jupiter have features that may be related to plate-tectonic style deformation, although the materials and specific mechanisms may be different from plate-tectonic activity on Earth.

Titan

Titan, the largest moon of Saturn, was reported to show tectonic activity in images taken by the Huygens Probe, which landed on Titan on January 14, 2005.[32]

See also

- List of plate tectonics topics
- List of tectonic plates
- List of tectonic plate interactions
- Geosyncline theory, obsolete explanation of mountain-building
- Plume tectonics, an extension of plate tectonics that attempts to explain other aspects of the field

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External links

- The PLATES Project (http://www.ig.utexas.edu/research/projects/plates/) , a comprehensive resource with reconstructions, movies, images, list of publications, and teaching resources, from the University of Texas Institute for Geophysics at the Jackson School of Geosciences.
- The Paleomap Project (http://www.scotese.com/) , Christopher Scotese's website with reconstructions in the past and future, paleogeographies, teaching material etc.
- Movie showing 750 million years of global tectonic activity (http://www.ucmp.berkeley.edu/geology/tectonics.html)
- Easy-to-draw illustrations for teaching plate tectonics (http://geology.com/nsta/)
- An explanation of tectonic forces (http://www.tectonic-forces.org)
- Bird, P. (2003) An updated digital model of plate boundaries (http://element.ess.ucla.edu/publications/2003_PB2002/2003_PB2002.htm) , also available as a large (13 mb) PDF file (http://element.ess.ucla.edu/publications/2003_PB2002/2001GC000252.pdf)
- Map of tectonic plates (http://snobear.colorado.edu/Markw/Mountains/03/week3.html)
- MantlePlumes.org (http://www.mantleplumes.org/) , a website debating the existence of deep mantle plumes
- USGS site on plate motions (http://pubs.usgs.gov/publications/text/understanding.html)
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- BBC Radio 4 *In Our Time* - Plate Tectonics (http://www.bbc.co.uk/radio4/history/inourtime/rams/inourtime_20080124.ram)
