Theory of Plate Tectonics in Geophysics

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Table of Contents

Chapter 1 - Plate Tectonics

Chapter 2 - Plate Reconstruction

Chapter 3 - Continental Drift

Chapter 4 - Seafloor Spreading and Mantle Convection

Chapter 5 - Craton

Chapter 6 - Orogeny

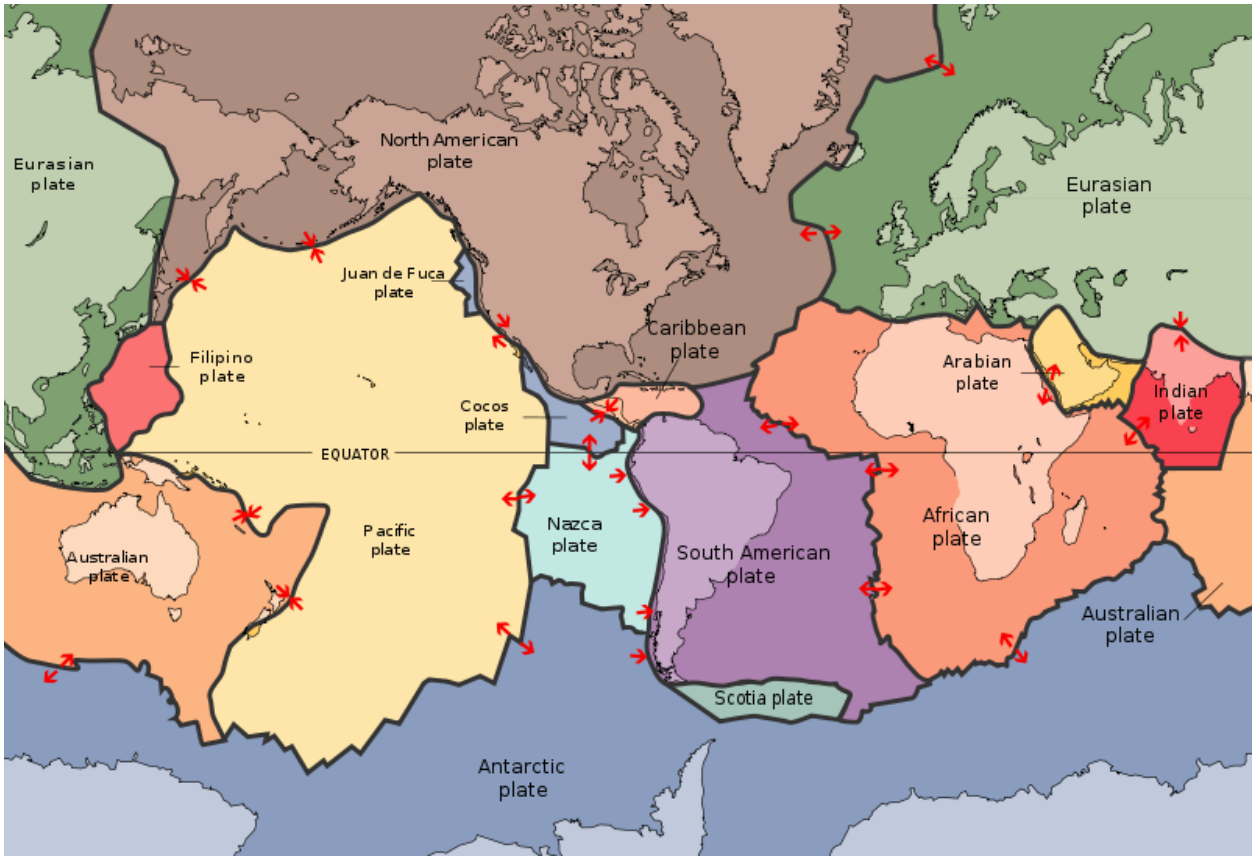
Chapter 7 - Oceanic Trench

Chapter 8 - Mid-ocean Ridge

Chapter 9 - Volcanic Arc and Volcanogenic Massive Sulfide Ore Deposit

Chapter- 1

Plate Tectonics



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

Plate tectonics (from the Late Latin *tectonicus*, from the Greek: *τεκτονικός* "pertaining to building") is a scientific theory which describes the large scale motions of Earth's lithosphere. The theory builds on the older concepts of continental drift, developed during the first decades of the 20th century (one of the most famous advocates was Alfred Wegener), and was accepted by the majority of the geoscientific community when the concepts of seafloor spreading were developed in the late 1950s and early 1960s. The lithosphere is broken up into what are called

"tectonic plates". In the case of the Earth, there are currently seven to eight major (depending on how they are defined) and many minor plates. 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 collisional boundaries; divergent boundaries, also called spreading centers; and conservative transform boundaries. Earthquakes, volcanic activity, mountain-building, and oceanic trench formation occur along these plate boundaries. The lateral relative movement of the plates varies, though it is typically 0–100 mm annually.

The tectonic plates are composed of two types of lithosphere: thicker continental and thin oceanic. The upper part is called the crust, again of two types (continental and oceanic). This means that a plate can be of one type, or of both types. One of the main points the theory proposes is that the amount of surface of the (continental and oceanic) plates that disappear in the mantle along the convergent boundaries by subduction is more or less in equilibrium with the new (oceanic) crust that is formed along the divergent margins by seafloor spreading. This is also referred to as the "conveyor belt" principle. In this way, the total surface of the globe remains the same. This is in contrast with earlier theories advocated before the Plate Tectonics "paradigm", as it is sometimes called, became the main scientific model, theories that proposed gradual shrinking (contraction) or gradual expansion of the globe, and that still exist in science as alternative models.

Regarding the driving mechanism of the plates various models co-exist: Tectonic plates are able to move because the Earth's lithosphere has a higher strength and lower density than the underlying asthenosphere. Lateral density variations in the mantle result in convection. Their movement is thought to be driven by a combination of the motion of seafloor away from the spreading ridge (due to variations in topography and density of the crust that result in differences in gravitational forces) and drag, downward suction, at the subduction zones. A different explanation lies in different forces generated by the rotation of the globe and tidal forces of the Sun and the Moon. The relative importance of each of these factors is unclear, and is still subject to debate.

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

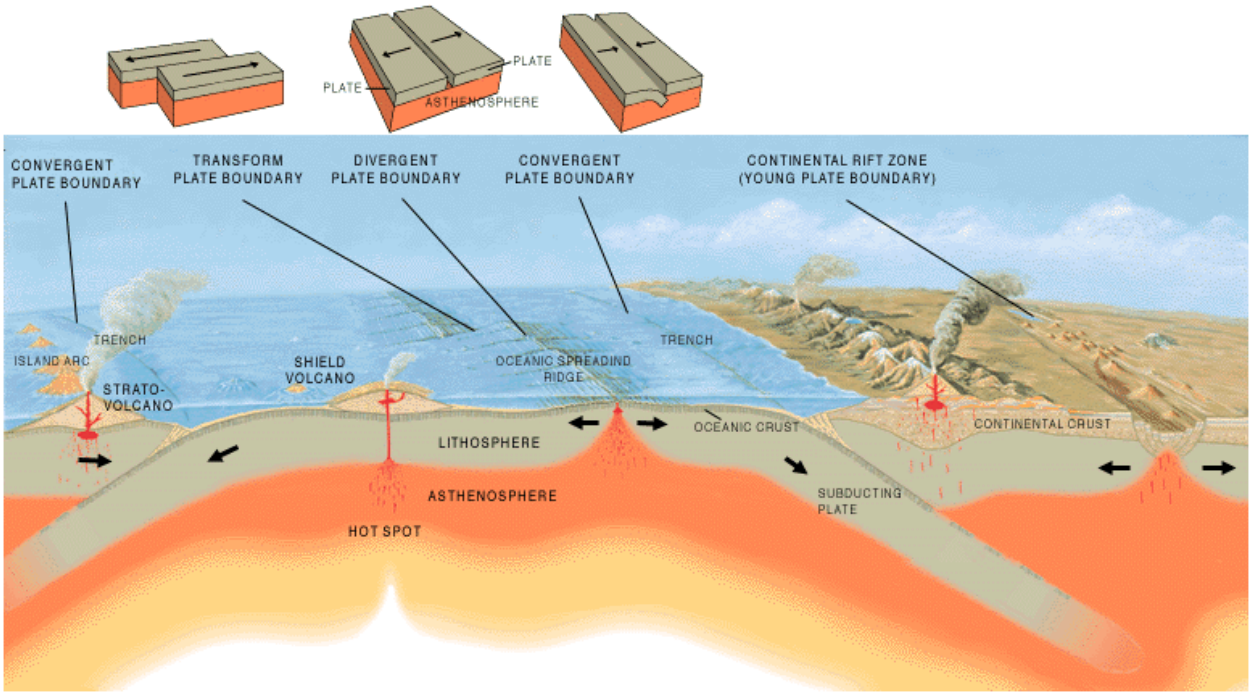
(Nazca Plate; about as fast as hair grows). The driving mechanism behind this movement is described separately below.

Tectonic lithosphere plates consist of lithospheric mantle overlain by either or both 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). Average oceanic lithosphere is typically 100 km thick; its thickness is a function of its age: as time passes, it conductively cools and becomes thicker. Because it is formed at mid-ocean ridges and spreads outwards, its thickness is therefore a function of its distance from the mid-ocean ridge where it was formed. For a typical distance oceanic lithosphere must travel before being subducted, the thickness varies from about 6 km thick at mid-ocean ridges to greater than 100 km at subduction zones; for shorter or longer distances, the subduction zone (and therefore also the mean) thickness becomes smaller or larger, respectively. Continental lithosphere is typically ~200 km thick, though this also varies considerably between basins, mountain ranges, and stable cratonic interiors of continents. The two types of crust also differ in thickness, with continental crust being considerably thicker than oceanic (35 km vs. 6 km).

The location where two plates meet is called a *plate boundary*, and plate boundaries are commonly associated with geological events such as earthquakes and the creation of topographic features such as mountains, volcanoes, mid-ocean ridges, 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. Some volcanoes occur in the interiors of plates, and these have been variously attributed to internal plate deformation and to mantle plumes.

As explained above, tectonic plates can include continental crust or oceanic crust, and many plates contain both. For example, the African Plate includes the continent and parts of the floor of the Atlantic and Indian Oceans. The distinction between oceanic crust and continental crust is based on their modes of formation. Oceanic crust is formed at sea-floor spreading centers, and continental crust is formed through arc volcanism and accretion of terranes through tectonic processes; though some of these terranes may contain ophiolite sequences, which are pieces of oceanic crust, these are considered part of the continent when they exit the standard cycle of formation and spreading centers and subduction beneath continents. Oceanic crust is also denser than continental crust owing to their different compositions. Oceanic crust is denser because it has less silicon and more heavier elements ("mafic") than continental crust ("felsic"). As a result of this density stratification, oceanic crust generally lies below sea level (for example most of the Pacific Plate), while the continental crust buoyantly projects above sea level.

Types of plate boundaries



Three types of plate boundary

Basically, three types of plate boundaries exist, with a fourth, mixed type, 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:

1. *Transform boundaries (Conservative)* 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 an example of a transform boundary exhibiting dextral motion.
2. *Divergent boundaries (Constructive)* 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 (Destructive)* (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, and the basins that develop along the active boundary are often called "foreland basins". 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.
4. *Plate boundary zones* occur where the effects of the interactions are unclear and the boundaries, usually occurring along a broad belt, are not well defined, and may show various types of movements in different episodes.

Driving forces of plate motion

Plate tectonics is basically a kinematic phenomenon: Earth scientists agree upon the observation and deduction that the plates have moved one with respect to the other, and debate and find agreements on how and when. But still a major question remains on what the motor behind this movement is; the geodynamic mechanism, and here science diverges in different theories.

Generally, it is accepted that 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, through convection or large scale upwelling and doming. As a consequence, in the current view, although it is still a matter of some debate, because of the excess density of the oceanic lithosphere sinking in subduction zones a powerful source of plate motion is generated. When the new crust forms at mid-ocean ridges, this oceanic lithosphere is initially less dense than the underlying asthenosphere, but it becomes denser 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. 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. One of the main points is that the kinematic pattern of the movements itself should be separated clearly from the possible geodynamic mechanism that is invoked as the driving force of the observed movements, as some patterns may be explained by more than one mechanism. Basically, the driving forces that are advocated at the moment, can be divided in three categories: mantle dynamics related, gravity related (mostly secondary forces), and Earth rotation related.

Mantle dynamics related driving forces

For a considerable period of around 25 years (last quarter of the twentieth century) the leading theory envisaged large scale convection currents in the upper mantle which are transmitted through the asthenosphere as the main driving force of the tectonic plates. This theory was launched by Arthur Holmes and some forerunners in the 1930s and was immediately recognised as the solution for the acceptance of the theory discussed since its occurrence in the papers of Alfred Wegener in the early years of the century. It was, though, long debated because the leading ("fixist") theory was still envisaging a static Earth without moving continents, up until the major break–throughs in the early sixties.

Two– and three–dimensional imaging of the Earth's interior (seismic tomography) shows that there is a laterally varying 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 varying lateral density is mantle convection from buoyancy forces.

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.

- **Basal drag** (friction): The plate motion is in this way driven by friction between the convection currents in the asthenosphere and the more rigid overlying floating lithosphere.
- **Slab suction** (gravity): 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).

Lately, the convection theory is much debated as modern techniques based on 3D seismic tomography of imaging the internal structure of the Earth's mantle still fail to recognise these predicted large scale convection cells. Therefore, alternative views have been proposed:

In the theory of plume tectonics developed during the 1990s, a modified concept of mantle convection currents is used, related to super plumes rising from the deeper mantle which would be the drivers or the substitutes of the major convection cells. These ideas, which find their roots in the early 1930s with the so-called "fixistic" ideas of the European and Russian Earth Science Schools, find resonance in the modern theories which envisage hot spots/mantle plumes in the mantle which remain fixed and are overridden by oceanic and continental lithosphere plates during time, and leave their traces in the geological record (though these phenomena are not invoked as real driving mechanisms, but rather as a modulator). The modern theories that continue building on the older mantle doming concepts and see the movements of the plates a secondary phenomena, are beyond the scope of this page and are discussed elsewhere for example on the plume tectonics page.

Another suggestion is that the mantle flows neither in cells nor large plumes, but rather as a series of channels just below the Earth's crust which then provide basal friction to the lithosphere. This theory is called "surge tectonics" and became quite popular in geophysics and geodynamics during the 1980s and 1990s.

Gravity related driving forces

Gravity related forces are usually invoked as secondary phenomena within the framework of a more general driving mechanism such as the various forms of mantle dynamics described above.

Gravitational sliding away from a spreading ridge: According to many authors, 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.

This force is regarded as a secondary force often referred to as "ridge push". This is a misnomer as nothing is "pushing" horizontally 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. Other mechanisms generating this gravitational secondary force include flexural bulging of the lithosphere before it dives underneath an adjacent plate, which produces a clear topographical feature that can offset or at least affect the influence of topographical ocean ridges, and mantle plumes and hot spots, which are postulated to impinge on the underside of tectonic plates.

Slab-pull: Current scientific opinion is that the asthenosphere is insufficiently competent or rigid to directly cause motion by friction along the base of the lithosphere. Slab pull is therefore most widely thought to be the greatest force acting on the plates. In this current understanding, plate motion is mostly driven by the weight of cold, dense plates sinking into the mantle at trenches. Recent models indicate that trench suction plays an important role as well. However, as the North American Plate is nowhere being subducted, yet it is in motion presents a problem. The same holds for the African, Eurasian, and Antarctic plates.

Gravitational sliding away from mantle doming: According to older theories one of the driving mechanisms of the plates is the existence of large scale asthenosphere/mantle domes, which cause the gravitational sliding of lithosphere plates away from them. This gravitational sliding represents a secondary phenomenon of this, basically vertically oriented mechanism. This can act on various scales, from the small scale of one island arc up to the larger scale of an entire ocean basin.

Earth rotation related driving forces

Alfred Wegener, being a meteorologist, had proposed tidal forces and pole flight force as main driving mechanisms for continental drift. However, these forces were considered far too small to cause continental motion as the concept then was of continents plowing through oceanic crust. Therefore, also Wegener in his last edition of his book in 1929 converted to convection currents as the main driving force.

In the plate tectonics context (accepted since the seafloor spreading proposals of Heezen, Hess, Dietz, Morley, Vine and Matthews -see below- during the early 1960s), though, oceanic crust in motion *with* the continents which made the proposals related to Earth rotation to be reconsidered, also in more recent literature, these are:

1. Tidal drag due to the gravitational force the Moon (and the Sun) exerts on the crust of the Earth
2. Shear strain of the Earth globe due to N-S compression related to the rotation and modulations of it;
3. Pole flight force: equatorial drift due to rotation and centrifugal effects: tendency of the plates to move from the poles to the equator ("*Polflucht*");
4. Coriolis effect acting on plates when they move around the globe;
5. Global deformation of the geoid due to small displacements of rotational pole with respect to the Earth crust;

6. Other smaller deformation effects of the crust due to wobbles and spin movements of the Earth rotation on a smaller time scale.

In order for these mechanisms to be overall valid, systematic relationships should exist all over the globe between the orientation and kinematics of deformation, and the geographical latitudinal and longitudinal grid of the Earth itself. Ironically, these systematic relations studies in the second half of the nineteenth century and the first half of the twentieth century do underline exactly the opposite: that the plates had not moved in time, that the deformation grid was fixed with respect to the Earth equator and axis, and that gravitational driving forces were generally acting vertically and caused only locally horizontal movements (the so-called pre-plate tectonic, "fixist theories"). Later studies (discussed below on this page) therefore invoked many of the relationships recognised during this pre-plate tectonics period, to support their theories.

Of the many forces discussed in this paragraph, tidal force is still highly debated and defended as a possible principle driving force, whereas the other forces are used or in global geodynamic models not using the plate tectonics concepts, or proposed as minor modulations within the overall plate tectonics model.

In 1973 George W. Moore of the USGS and R. C. Bostrom presented evidence for a general westward drift of the Earth's lithosphere with respect to the mantle, and, therefore, tidal forces or tidal lag or "friction" due to the Earth's rotation and the forces acting upon it by the Moon being a driving force for plate tectonics: as the Earth spins eastward beneath the moon, the moon's gravity ever so slightly pulls the Earth's surface layer back westward, just like proposed by Alfred Wegener (see above). In a more recent 2006 study, scientists rediscussed and advocated these earlier proposed ideas. It has also been suggested recently in Lovett (2006) 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. In a recent paper it was suggested that, on the other hand, it can easily be observed that many plates are moving north and eastward, and that the dominantly westward motion of the Pacific ocean basins derives simply from the eastward bias of the Pacific spreading center (which is not a predicted manifestation of such lunar forces). In the same paper the authors admit, however, that relative to the lower mantle, there is a slight westward component in the motions of all the plates. They demonstrated though that the westward drift, seen only for the past 30 Ma, is attributed to the increased dominance of the steadily growing and accelerating Pacific plate. The debate is still open.

Relative significance of each driving force 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.

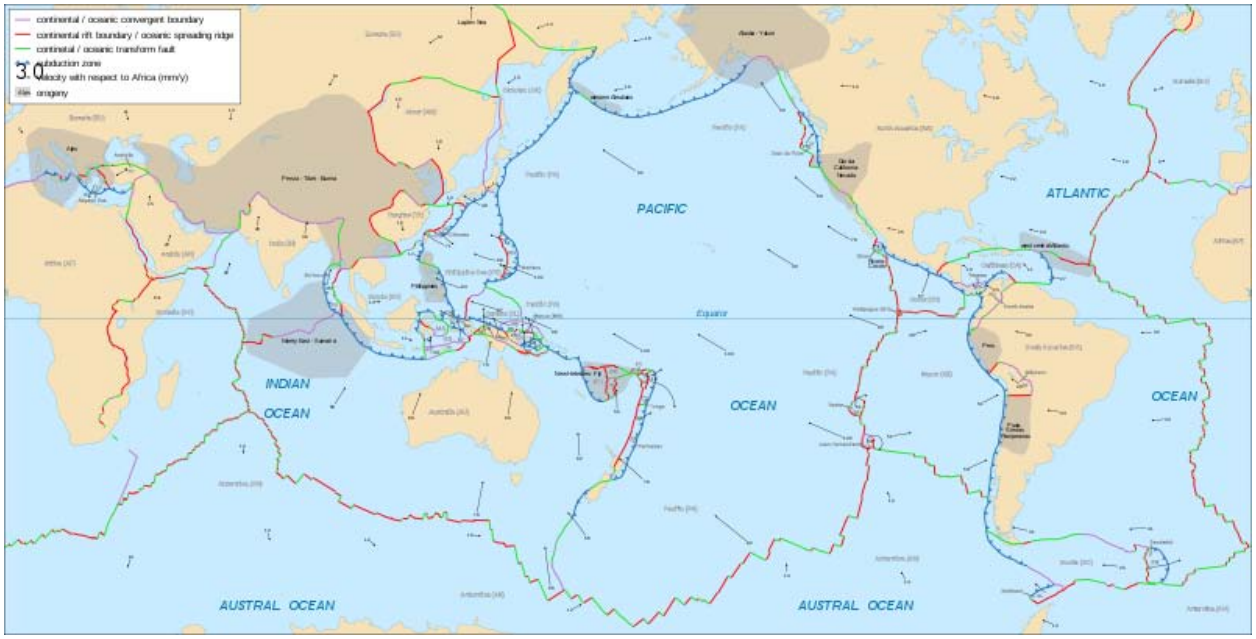
The diversity of geodynamic settings and properties of each plate must clearly result in differences in the degree to which such processes are actively driving the plates. One method of dealing with this problem is to consider the relative rate at which each plate is moving and to consider the available 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 continue to be active subjects of on-going research within geophysics and tectonophysics.

Development of the theory

Plate tectonics is the main current theory in Earth Sciences regarding the development of our planet Earth. It is, therefore, appropriate to dedicate some space to explain how the Earth Science community, step by step, has built this theory, from early speculations, through the gathering of proof and severe debates, up to the refinement and quantification, and still ongoing confrontations with alternative ideas.

Summary



Detailed map showing the tectonic plates with their movement vectors

In line with other previous and contemporaneous proposals, in 1912 the meteorologist Alfred Wegener amply described what he called continental drift, expanded in his 1915 book *The Origin of Continents and Oceans* and the scientific debate started that would end up fifty years later in the theory of plate tectonics. Starting from the idea (also expressed by his forerunners) that the present continents once formed a single land mass (which was called Pangea later on) that drifted apart, thus releasing the continents from the Earth's mantle and likening them to

"icebergs" of low density granite floating on a sea of denser basalt. Supporting evidence for the idea came from the dove-tailing outlines of South America's east coast and Africa's west coast, and from the matching of the rock formations along these edges. Confirmation of their previous contiguous nature also came from the fossil plants *Glossopteris* and *Gangamopteris*, and the therapsid or mammal-like reptile *Lystrosaurus*, all widely distributed over South America, Africa, Antarctica, India and Australia. The evidence for such an erstwhile joining of these continents was patent to field geologists working in the southern hemisphere. The South African Alex du Toit put together a mass of such information in his 1937 publication *Our Wandering Continents*, and went further than Wegener in recognising the strong links between the Gondwana fragments.

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 mantle and a liquid core, but there seemed to be no way that portions of the crust could move around. Distinguished scientists, such as Harold Jeffreys and Charles Schuchert, were outspoken critics of continental drift.

Notwithstanding much opposition, the view of continental drift gained support and a lively debate started between "drifters" or "mobilists" (proponents of the theory) and "fixists" (opponents). During the 1920s, 1930s and 1940s, the former reached important milestones proposing that convection currents might have driven the plate movements, and that spreading may have occurred below the sea within the oceanic crust. Concepts close to the elements now incorporated in plate tectonics were proposed by geophysisists and geologists (both fixists and mobilists) like Vening-Meinesz, Holmes, and Umbgrove.

One of the first pieces of geophysical evidence that was used to support the movement of lithospheric plates came from paleomagnetism. This is based on the fact that rocks of different ages show a variable magnetic field direction, evidenced by studies since the mid–nineteenth century. The magnetic north and south poles reverse through time, and, especially important in paleotectonic studies, the relative position of the magnetic north pole varies through time. Initially, during the first half of the twentieth century, the latter phenomenon was explained by introducing what was called "polar wander", i.e., it was assumed that the north pole location had been shifting through time. An alternative explanation, though, was that the continents had moved (shifted and rotated) relative to the north pole, and each continent, in fact, shows its own "polar wander path". During the late 1950s it was successfully shown on two occasions that these data could show the validity of continental drift: by Keith Runcorn in a paper in 1956, and by Warren Carey in a symposium held in March 1956.

The second piece of evidence in support of continental drift came during the late 1950s and early 60s from data on the bathymetry of the deep ocean floors and the nature of the oceanic crust such as magnetic properties and, more generally, with the development of marine geology which gave evidence for the association of seafloor spreading along the mid-oceanic ridges and magnetic field reversals, published between 1959 and 1963 by Heezen, Dietz, Hess, Mason, Vine & Matthews, and Morley.

Simultaneous advances in early seismic imaging techniques in and around Wadati-Benioff zones along the trenches bounding many continental margins, together with many other geophysical

(e.g. gravimetric) and geological observations, showed how the oceanic crust could disappear into the mantle, providing the mechanism to balance the extension of the ocean basins with shortening along its margins.

All this evidence, both from the ocean floor and from the continental margins, made it clear around 1965 that continental drift was feasible and the theory of plate tectonics, which was defined in a series of papers between 1965 and 1967, was born, with all its extraordinary explanatory and predictive power. The theory revolutionized the Earth sciences, explaining a diverse range of geological phenomena and their implications in other studies such as paleogeography and paleobiology.

Continental drift

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 basin development and mountain ranges could be explained by vertical crustal movement, described in what is called the geosynclinal theory. Generally, this was placed in the context of a contracting planet Earth due to heat loss in the course of a relatively short geological time.

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 to have once fitted together.

Since that time many theories were proposed to explain this apparent complementarity, but the assumption of a solid Earth made these various proposals difficult to accept.

The discovery of radioactivity and its associated heating properties in 1895 prompted a re-examination of the apparent age of the Earth. since this had previously been estimated by its cooling rate and assumption the Earth's surface radiated like a black body. Those calculations had 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 realized that the Earth would be much older, and that its core was still sufficiently hot to be liquid.

By 1915, after having published a first article in 1912, Alfred Wegener was making serious arguments for the idea of continental drift in the first edition of *The Origin of Continents and Oceans*. In that book (re-issued in four successive editions up to the final one in 1936), 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, Snider-Pellegrini, Roberto Mantovani and Frank Bursley Taylor preceded him just to mention a few), 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). Furthermore, when the rock strata of the margins 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.

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 drove continental drift, and his vindication did not come until after his death in 1930.

Floating continents - paleomagnetism - seismicity zones

As it was observed early that although granite existed on continents, seafloor seemed to be composed of denser basalt, the prevailing concept during the first half of the twentieth century was that there were two types of crust, named "sial" (continental type crust), and "sima" (oceanic type crust). Furthermore, it was supposed that a static shells of strata was present under the continents. It therefore looked apparent that a layer of basalt (sial) underlies the continental rocks.

However, based upon abnormalities in plumb line deflection by the Andes in Peru, Pierre Bouguer had 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. Therefore, by the mid–1950s the question remained unresolved of whether mountain roots were clenched in surrounding basalt or were floating upon it like an iceberg.

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 specific 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 world wide.

Meanwhile, debates developed around the phenomena of polar wander. Since the early debates of continental drift, scientists had discussed and used evidence that polar drift had occurred because continents seemed to have moved through different climatic zones during the past. Furthermore, paleomagnetic data had shown that the magnetic pole had also shifted during time. Reasoning in an opposite way, the continents might have shifted and rotated, while the pole remained relatively fixed. The first time the evidence of magnetic polar wander was used to support the movements of continents was in a paper by Keith Runcorn in 1956, and successive

papers by him and his students Ted Irving (who was actually the first to be convinced of the fact that paleomagnetism supported continental drift) and Ken Creer.

This was immediately followed by a symposium in Tasmania in March 1956. In this symposium, the evidence was used in the theory of an expansion of the global crust. In this hypothesis the shifting of the continents can be simply explained by a large increase in size of the Earth since its formation. However, this 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; other work would soon show that the evidence was equally in support of continental drift on a globe with a stable radius.

During the thirties up to the late fifties, numerous milestones were reached that would eventually lead to the development of plate tectonics. These are the works of Vening-Meinesz, Holmes, Umbgrove, and numerous others, in which concepts close or near identical to modern plate tectonics theory where defined and outlined. The most important milestone was reached when the English geologist Arthur Holmes proposed in 1920 that plate junctions might lie beneath the sea, and in 1928 that convection currents within the mantle might be the driving force.

Often, all these milestones are forgotten for various reasons:

- During this timespan, continental drift was not accepted.
- Some of these ideas were discussed in the context of abandoned fixistic ideas of a deforming globe without continental drift or an expanding Earth.
- They were published during an episode of extreme political and economic instability and scientific communication was obviously hampered by this.
- Many of these were published by European scientists and at first not mentioned or given little credit in the papers published by the American researchers which during the 1960s presented evidence for sea floor spreading.

Mid oceanic ridge spreading and convection

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.

The new data that had been collected on the ocean basins also showed particular characteristics regarding the bathymetry. One of the major outcomes of these datasets was that all along the globe, a system of mid-oceanic ridges was detected. An important conclusion was that along this system, new ocean floor was being created, which led to the concept of the "Great Global Rift". This was described in the crucial paper of Bruce Heezen (1960) which would trigger a real revolution in thinking. A profound consequence of seafloor spreading is that new crust was, and is now, being continually created along the oceanic ridges. Therefore, Heezen advocated the so-called "expanding Earth" hypothesis of S. Warren Carey (see above). So, still the question

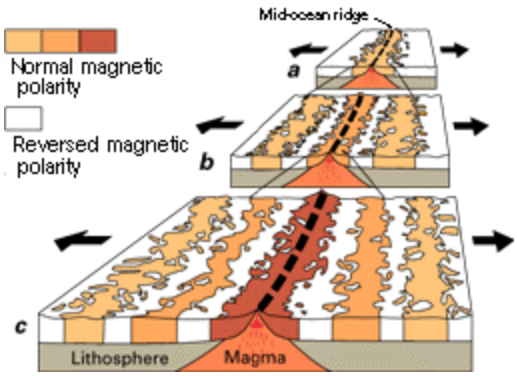
remained: how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth? In reality, this question had been solved already by numerous scientists during the forties and the fifties, like Arthur Holmes, Vening-Meinesz, Coates and many others: The crust in excess disappeared along what were called the oceanic trenches where so-called "subduction" occurred. Therefore, when various scientists during the early sixties started to reason on the data at their disposal regarding the ocean floor, the pieces of the theory fell quickly into place.

The question particularly intrigued Harry Hammond 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 (the former published the same idea one year earlier in *Nature*, but priority belongs to Hess who had already distributed an unpublished manuscript of his 1962 article by 1960) were among the small handful who really understood the broad implications of sea floor spreading and how it would eventually agree with the, at that time, unconventional and unaccepted ideas of continental drift and the elegant and mobilistic models proposed by previous workers like Holmes.

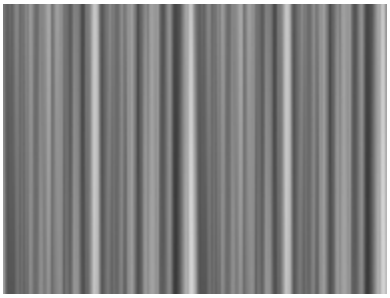
In the same year, Robert R. Coats of the U.S. Geological Survey described the main features of island arc subduction in the Aleutian Islands. His paper, though little–noted (and even ridiculed) at the time, has since been called "seminal" and "prescient". In reality, it actually shows that the work by the European scientists on island arcs and mountain belts performed and published during the 1930s up until the 1950s was applied and appreciated also in the United States.

If the Earth's crust was expanding along the oceanic ridges, Hess and Dietz reasoned like Holmes and others before them, it must be shrinking elsewhere. Hess followed Heezen suggesting that new oceanic crust continuously spreads away from the ridges in a conveyor belt–like motion. And, using the mobilistic concepts developed before, he correctly concluded that many millions of years later, the oceanic crust eventually descends along the continental margins where oceanic trenches – very deep, narrow canyons – are formed, e.g. along the rim of the Pacific Ocean basin. The important step Hess made was that convection currents would be the driving force in this process, arriving at the same conclusions as Holmes had decades before with the only difference that the thinning of the ocean crust was performed using the mechanism of Heezen of spreading along the ridges. Hess therefore concluded that the Atlantic Ocean was expanding while the Pacific Ocean was shrinking. As old oceanic crust is "consumed" in the trenches, (like Holmes and others, he believed this was done by thickening of the continental lithosphere, not, as nowadays believed, by underthrusting at a larger scale of the oceanic crust itself into the mantle) 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, in a way that later would be called the Wilson cycle (see below). Thus, the new mobilistic concepts 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.

The final proof: magnetic striping



Seafloor magnetic striping



A demonstration of magnetic striping. (The darker the color is the closer it is to normal polarity)

Beginning in the 1950s, scientists like Victor Vacquier, 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: 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, and was published by Ron G. Mason and co-workers in 1961, who didn't find, though, an explanation for these data in terms of sea floor spreading, like Vine, Matthews and Morley a few years later.

The discovery of magnetic striping called for an explanation. In the early 1960s scientists such as Heezen, Hess and Dietz had begun 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, at first denominated the "conveyer belt hypothesis" and 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.

Only four years after the maps with the "zebra pattern" of magnetic stripes were published, the link between sea floor spreading and these patterns was correctly placed, independently by Lawrence Morley, and by Fred Vine and Drummond Matthews, in 1963 now called the Vine-Matthews-Morley hypothesis. This hypothesis linked these patterns to geomagnetic reversals and was supported by several lines of evidence:

1. the stripes are symmetrical around the crests of the mid-ocean ridges; 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 alternate in magnetic polarity (normal-reversed-normal, etc.), suggesting that they were formed during different epochs documenting the (already known from independent studies) normal and reversal episodes of the Earth's magnetic field.

By explaining both the zebra-like magnetic striping and the construction of the mid-ocean ridge system, the seafloor spreading hypothesis (SFS) 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 geomagnetic field reversals (GMFR) of the Earth's magnetic field. Nowadays, extensive studies are dedicated to the calibration of the normal-reversal patterns in the oceanic crust on one hand and known timescales derived from the dating of basalt layers in sedimentary sequences (magnetostratigraphy) on the other, to arrive at estimates of past spreading rates and plate reconstructions.

Definition and refining of the theory - from new global tectonics to plate tectonics

After all these considerations, Plate Tectonics (or, as it was initially called "New Global Tectonics") became quickly accepted in the scientific world, and numerous papers followed that defined the concepts:

- In 1965, Tuzo Wilson who had been a promotor of the sea floor spreading hypothesis and continental drift from the very beginning added the concept of transform faults to the model, completing the classes of fault types necessary to make the mobility of the plates on the globe work out.
- A symposium on continental drift was held at the Royal Society of London in 1965 which must be regarded as the official start of the acceptance of plate tectonics by the scientific community, and which abstracts are issued as Blacket, Bullard & Runcorn (1965). In this symposium, Edward Bullard and co-workers showed with a computer calculation how the continents along both

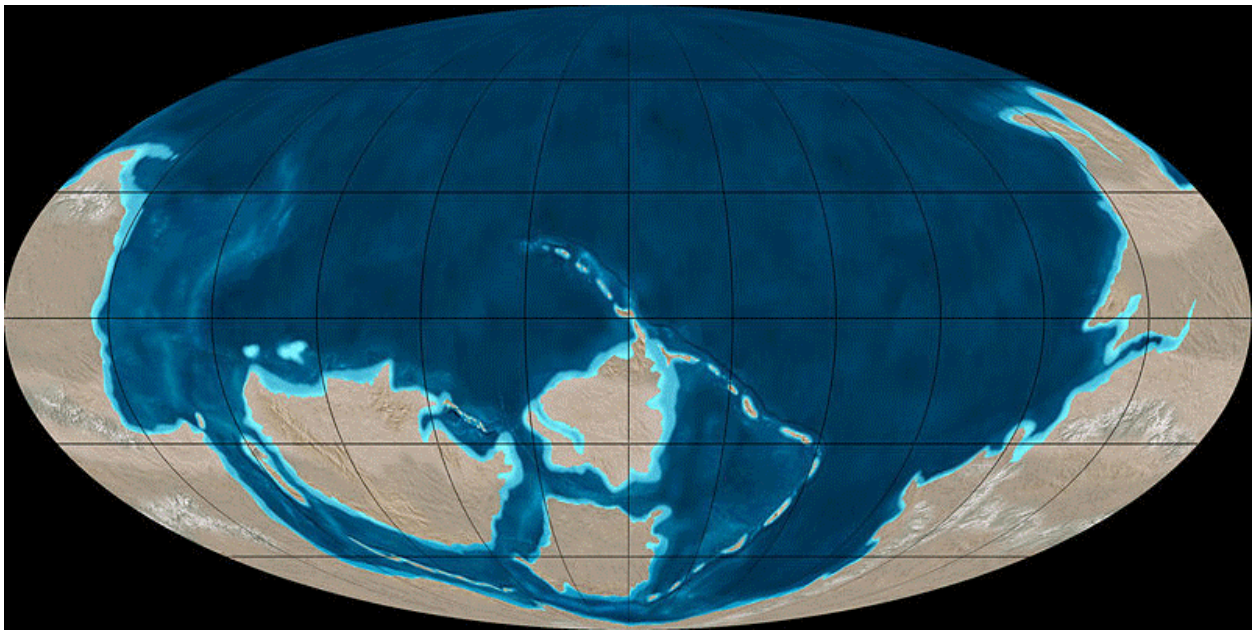
sides of the Atlantic would best fit to close the ocean, which became known as the famous "Bullard's Fit".

- In 1966 Wilson published the paper that referred to previous plate tectonic reconstructions, introducing the concept of what is now known as the "Wilson Cycle".
- In 1967, at the American Geophysical Union's meeting, W. Jason Morgan proposed that the Earth's surface consists of 12 rigid plates that move relative to each other.
- Two months later, Xavier Le Pichon published a complete model based on 6 major plates with their relative motions, which marked the final acceptance by the scientific community of plate tectonics.
- In the same year, McKenzie and Parker independently presented a model similar to Morgan's using translations and rotations on a sphere to define the plate motions.

Implications for biogeography

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

Plate reconstruction



Reconstruction of plate configurations for the whole Phanerozoic

Reconstruction is used to establish past (and future) plate configurations, helping determine the shape and make-up of ancient supercontinents and providing a basis for paleogeography.

Defining plate boundaries

Current plate boundaries are defined by their seismicity. Past plate boundaries within existing plates are identified from a variety of evidence, such as the presence of ophiolites that are indicative of vanished oceans.

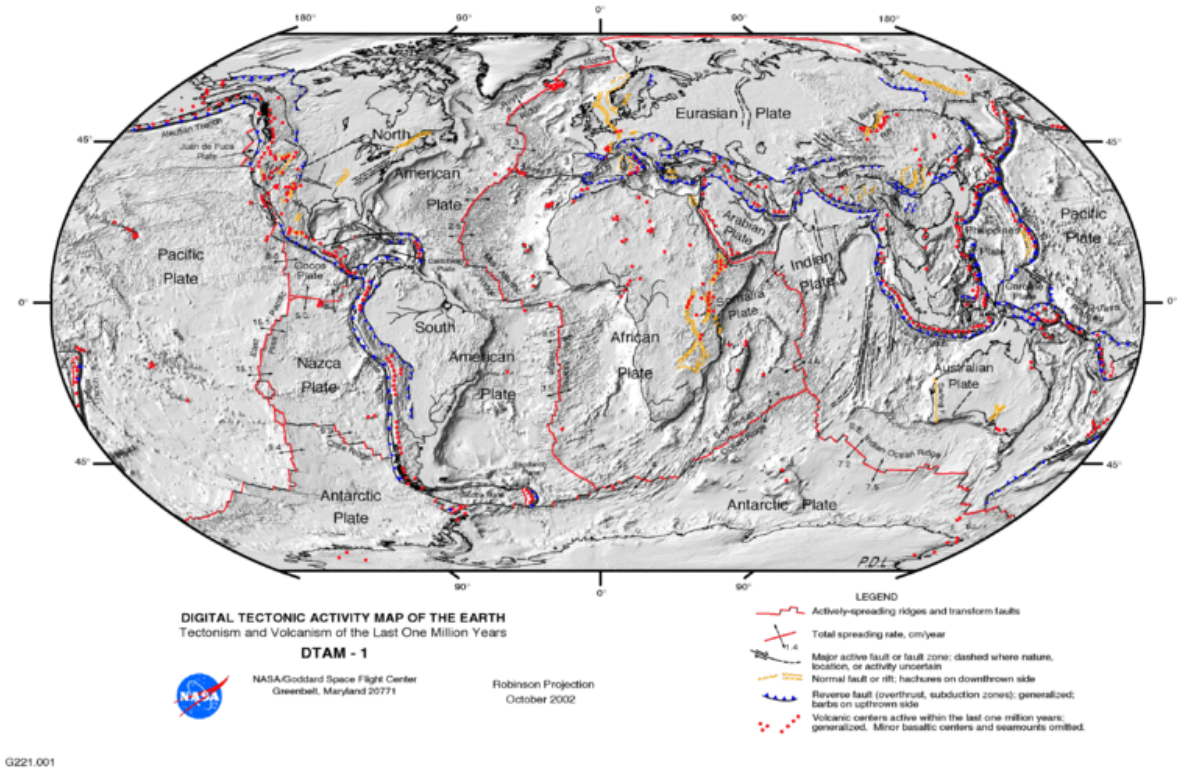
Past plate motions

Various types of quantitative and semi-quantitative information are available to constrain past plate motions. The geometric fit between continents, such as between west Africa and South America is still an important part of plate reconstruction. Magnetic stripe patterns provide a reliable guide to relative plate motions going back into the Jurassic period. The tracks of hotspots give absolute reconstructions but these are only available back to the Cretaceous. Older reconstructions rely mainly on paleomagnetic pole data, although these only constrain the latitude and rotation, but not the longitude. Combining poles of different ages in a particular plate to produce apparent polar wander paths provides a method for comparing the motions of different plates through time. Additional evidence comes from the distribution of certain sedimentary rock types, faunal provinces shown by particular fossil groups, and the position of orogenic belts.

Formation and break-up of continents

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 Columbia or Nuna formed during a period of 2.0–1.8 billion years and broke up about 1.5–1.3 billion years ago. 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 broke up into Laurasia (which became North America and Eurasia) and Gondwana (which became the remaining continents).

Current plates



Major plates

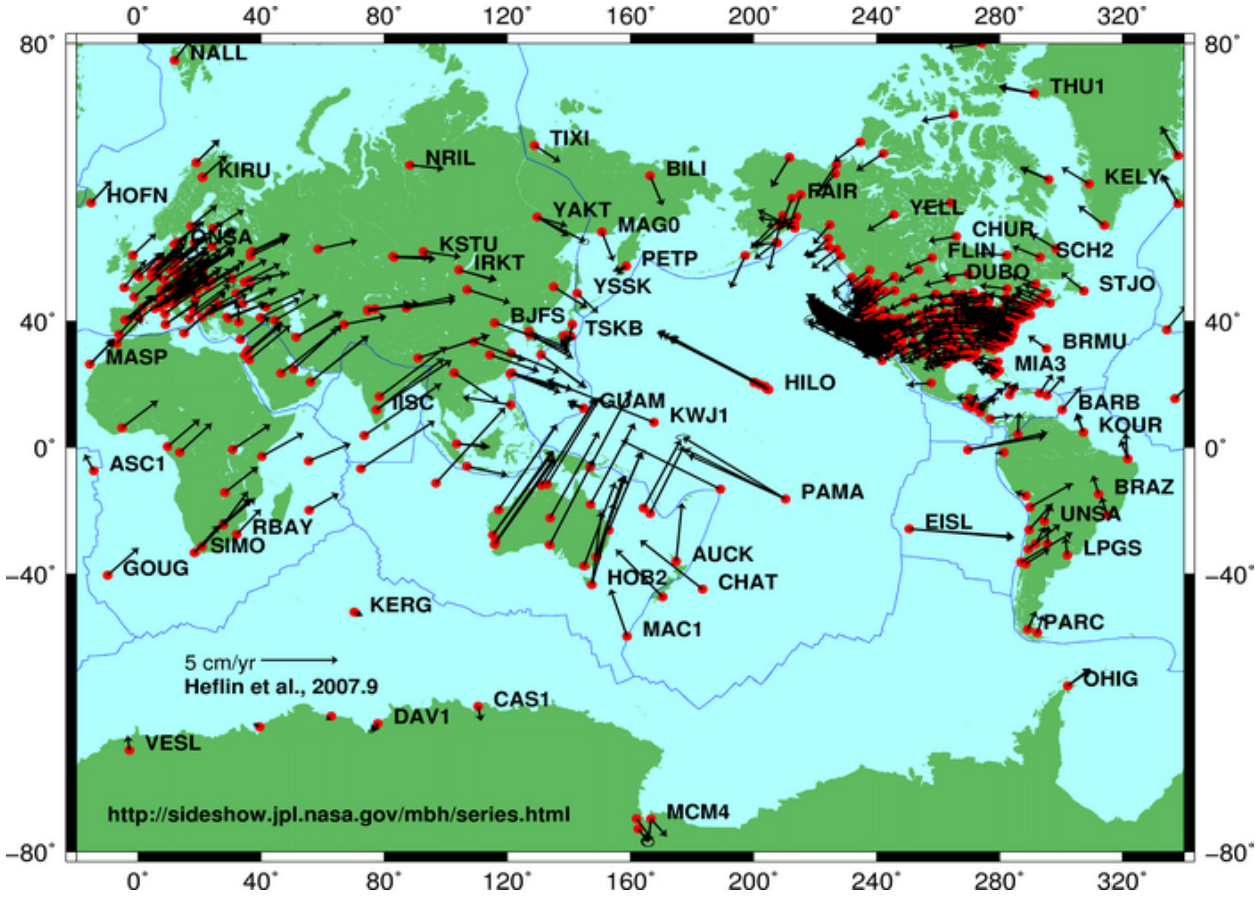


Plate motion based on Global Positioning System (GPS) satellite data from NASA JPL. The vectors show direction and magnitude of motion.

Depending on how they are defined, there are usually seven or eight "major" plates:

- African Plate
- Antarctic Plate
- Indo-Australian Plate, sometimes subdivided into:
  - Indian Plate
  - Australian Plate
- Eurasian Plate
- North American Plate
- South American Plate
- Pacific Plate

Minor plates

There are dozens of smaller plates, the seven largest of which are:

- Arabian Plate
- Caribbean Plate
- Juan de Fuca Plate
- Cocos Plate
- Nazca Plate
- Philippine Sea Plate
- Scotia Plate

Current motion

The current motion of the tectonic plates is nowadays revealed from remote sensing satellite data sets, calibrated with ground station measurements.

Plate tectonics on other celestial bodies (planets, moons)

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 (Silica and water form a deep eutectic.)

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 dominantly in the range c. 500 to 750 Ma, although ages of up to c. 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 impressive 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.. 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

Mars is considerably smaller than Earth and Venus, and there is evidence for ice on its surface and in its crust.

In the 1990s, it was proposed that Martian Crustal Dichotomy was created by plate tectonic processes. Scientists today disagree, and believe that it was created either by upwelling within the Martian mantle that thickened the crust of the Southern Highlands and formed Tharsis or by a giant impact that excavated the Northern Lowlands.

Observations made of the magnetic field of Mars by the *Mars Global Surveyor* spacecraft in 1999 showed patterns of magnetic striping discovered on this planet. Some scientists interpreted these as requiring plate tectonic processes, such as seafloor spreading. However, their data fail a "magnetic reversal test", which is used to see if they were formed by flipping polarities of a global magnetic field.

Galilean satellites of Jupiter

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, moon of Saturn

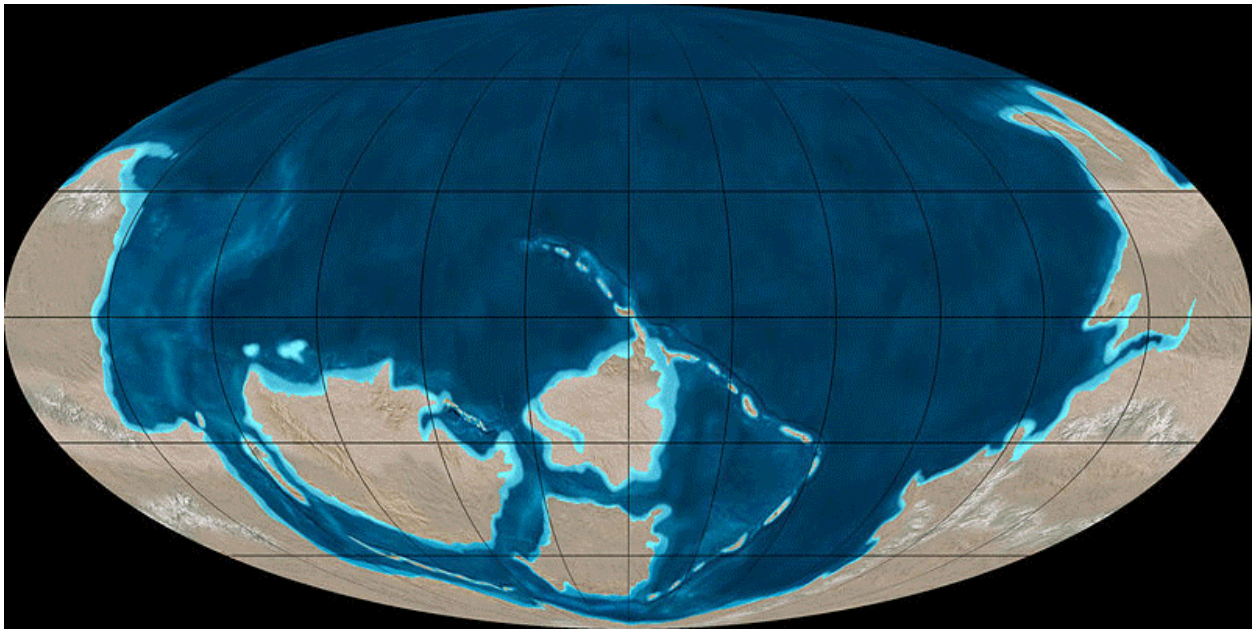
Titan, the largest moon of Saturn, was reported to show tectonic activity in images taken by the Huygens Probe, which landed on Titan on January 14, 2005.

Exoplanets

It is believed that many planets around other stars will have plate tectonics. On Earth-sized planets, plate tectonics is more likely if there are oceans of water, but on larger super-earths plate tectonics is very likely even if the planet is dry.

Chapter- 2

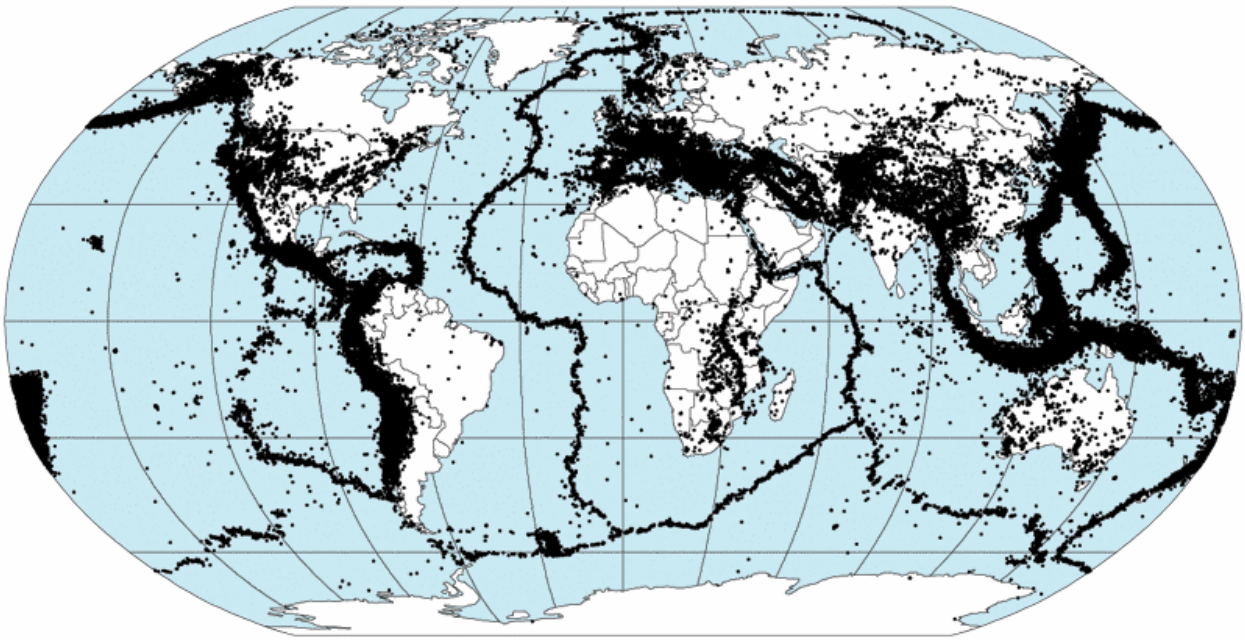
Plate Reconstruction



Reconstruction of plate configurations for the whole Phanerozoic

Plate reconstruction is the process of reconstructing the positions of tectonic plates relative to each other (relative motion) or to other reference frames, such as the earth's magnetic field or groups of hotspots, in the geological past. This helps determine the shape and make-up of ancient supercontinents and provides a basis for paleogeographic reconstructions.

Defining plate boundaries



Earthquake epicenters 1963-1998

An important part of reconstructing past plate configurations is to define the edges of areas of the lithosphere that have acted independently at some time in the past.

Present plate boundaries

Most present plate boundaries are easily identifiable from the pattern of recent seismicity. This is now backed up by the use of GPS data, to confirm the presence of significant relative movement between plates.

Past plate boundaries

Identifying past (but now inactive) plate boundaries within current plates is generally based on evidence for an ocean that has now closed up. The line where the ocean used to be is normally marked by pieces of the crust from that ocean, included in the collision zone, known as ophiolites. The line across which two plates became joined to form a single larger plate, is known as a suture.

In many orogenic belts, the collision is not just between two plates, but involves the sequential accretion of smaller terranes. Terranes are smaller pieces of continental crust that have been caught up in an orogeny, such as continental fragments or island arcs.

Reference frames

Plate motions, both those observable now and in the past, are referred ideally to a reference frame that allows other plate motions to be calculated. For example, a central plate, such as the African plate, may have the motions of adjacent plates referred to it. By composition of reconstructions, additional plates can be reconstructed to the central plate. In turn, the reference plate may be reconstructed, together with the other plates, to another reference frame, such as the earth's magnetic field, as determined from paleomagnetic measurements of rocks of known age. A global hotspot reference frame has been postulated (see, e.g., W. Jason Morgan) but there is now evidence that not all hotspots are necessarily fixed in their locations relative to one another or the earth's spin axis. However, there are groups of such hotspots that appear to be fixed within the constraints of available data, within particular mesoplates.

Euler poles

The movement of a rigid body, such as a plate, on the surface of a sphere can be described as rotation about a fixed axis (relative to the chosen reference frame). This pole of rotation is known as an Euler pole. The movement of a plate is completely specified in terms of its Euler pole and the angular rate of rotation about the pole. Euler poles defined for current plate motions can be used to reconstruct plates in the recent past (few million years). At earlier stages of earth's history, new Euler poles need to be defined.

Estimating past plate motions

In order to move plates backward in time it is necessary to provide information on either relative or absolute positions of the plates being reconstructed such that an Euler pole can be calculated. These are quantitative methods of reconstruction.

Geometric matching of continental borders

Certain fits between continents, particularly that between South America and Africa, were known long before the development of a theory that could adequately explain them. The reconstruction before Atlantic rifting by Bullard based on a least-squares fitting at the 500 fathom contour still provides the best match to paleomagnetic pole data for the two sides from the middle of Paleozoic to Late Triassic.

Plate motion from magnetic stripes

Plate reconstructions in the recent geological past mainly use the pattern of magnetic stripes in oceanic crust to remove the effects of seafloor spreading. The individual stripes are dated from magnetostratigraphy so that their time of formation is known. Each stripe (and its mirror image) represents a plate boundary at a particular time in the past, allowing the two plates to be repositioned relative to one another. The oldest oceanic crust is of Jurassic age, providing a lower age limit of about 175 Ma for the use of such data. Reconstructions derived in this way are only relative.

Paleomagnetic pole data

Sampling

Paleomagnetic pole data is obtained by taking oriented samples of rock. Good quality poles have been recovered from many different rock types. In igneous rocks, the magnetic minerals have cooled through the curie point, typically providing good quality poles. Metamorphic rocks may contain new magnetic minerals but are not normally used to obtain poles due to their typically high magnetic anisotropy. Sedimentary rocks generally have a complex set of magnetic components such as derived clasts and mineral grains with their own inherited magnetization, primary magnetization acquired at the time of sedimentation and secondary magnetization related to subsequent diagenesis and authigenic mineral growth. Progressive demagnetization is used to discriminate between the components to identify the primary magnetization. The poles shown by the primary magnetization represent a record of their position relative to the magnetic pole at the time when the rock was formed. Suitable rocks of the right age are not present everywhere, so some pieces of the puzzle remain very unconstrained.

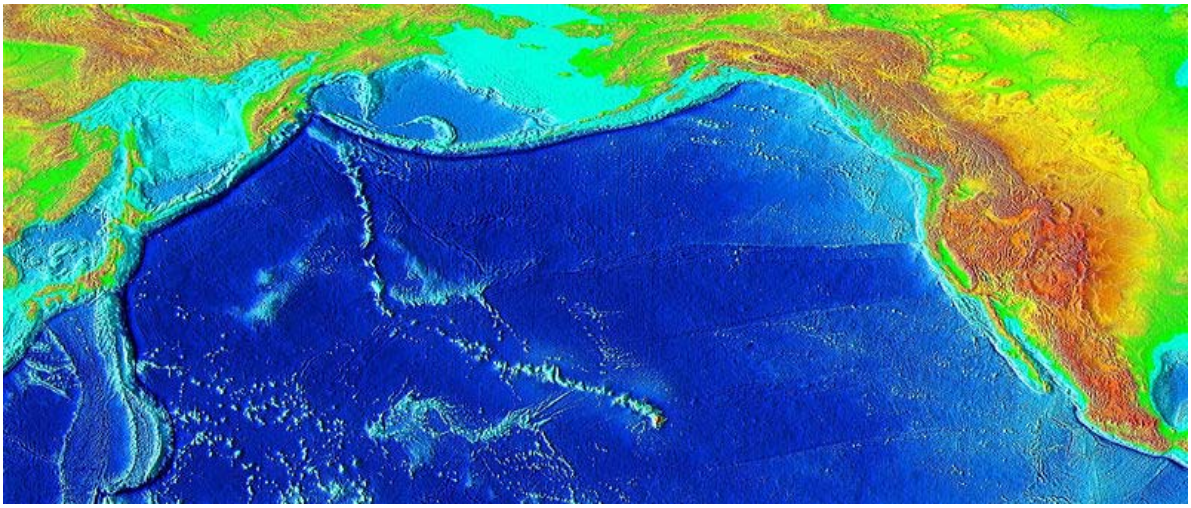
Good quality magnetic poles are added to the *Global Paleomagnetic Database*, which is accessible from the World Data Center A in the USA at Boulder, Colorado; and from the Norwegian Geological Survey in Trondheim.

Apparent polar wander paths

Poles from different ages in a single area can be used to construct an apparent polar wander (APW) path. If paths from adjacent crustal fragments are identical, this is taken to indicate that there has been no relative movement between them during the period covered by the path. Divergence of APW paths indicates that the areas in question have acted independently in the past with the point of divergence marking the time at which they became joined.

Observed paleomagnetic poles show only the approximate latitude at the time but provide no constraint on the longitude. For this reason older plate reconstructions have much larger uncertainties associated with them.

Hotspot tracks



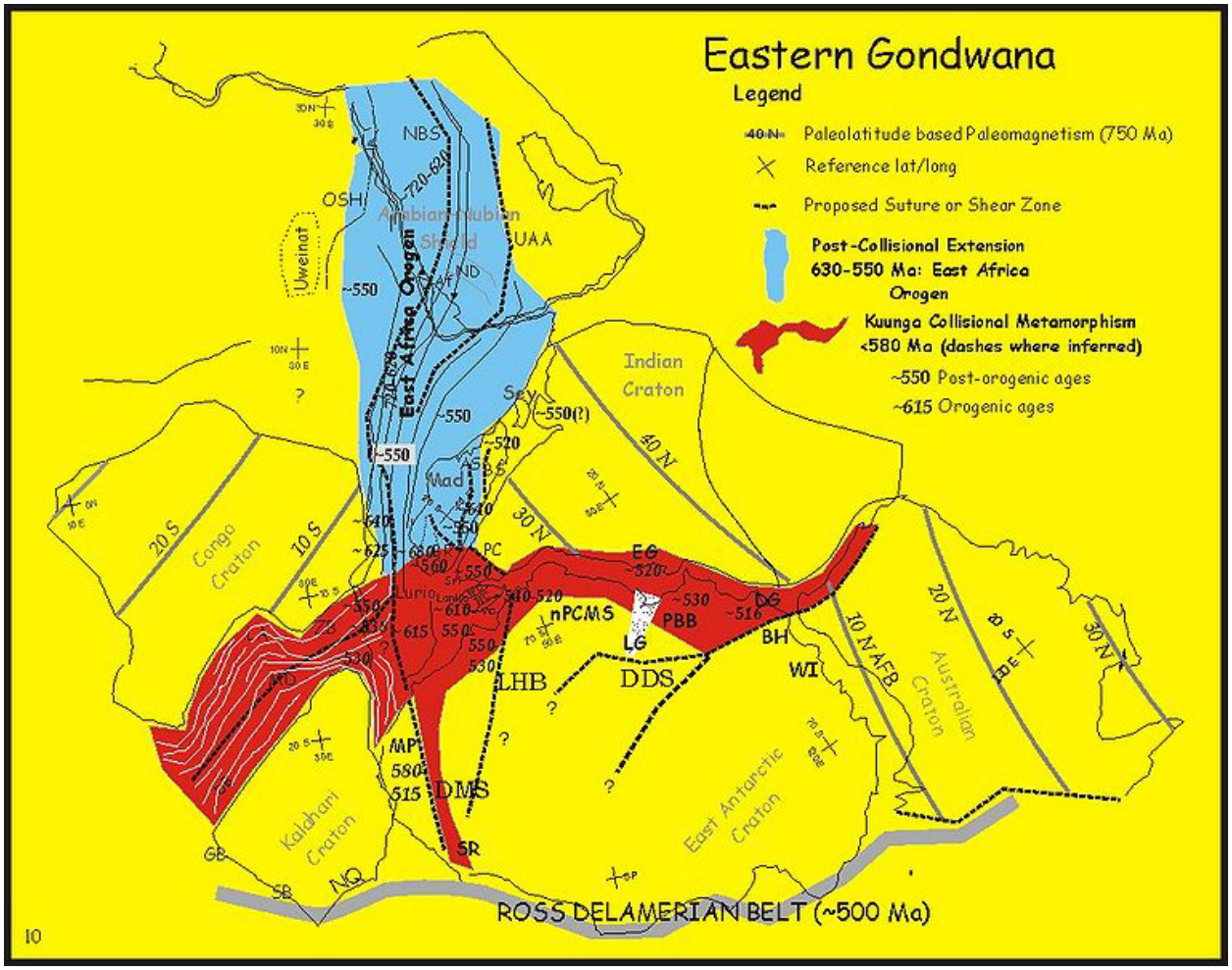
The Hawaiian-Emperor seamount chain

The presence of chains of volcanic islands and seamounts interpreted to have formed from fixed hotspots allows the plate on which they sit to be progressively restored so that a seamount is moved back over the hotspot at its time of formation. This method can be used back to the Early Cretaceous, the age of the oldest evidence for hotspot activity. This method gives an absolute reconstruction of both latitude and longitude, although before about 90 Ma there is evidence of relative motion between hotspot groups.

Slab constraints

Once oceanic plates subduct in the lower mantle (slabs), they are assumed to sink near-vertical. With the help of seismic wave tomography, this can be used to constrain plate reconstructions at first order back to the Permian.

Other evidence for past plate configurations



Reconstruction of eastern Gondwana showing position of orogenic belts

Some plate reconstructions are supported by other geological evidence, such as the distribution of sedimentary rock types, the position of orogenic belts and faunal provinces shown by particular fossils. These are semi-quantitative methods of reconstruction.

Sedimentary rock types

Some types of sedimentary rock are restricted to certain latitudinal belts. Glacial deposits for instance are generally confined to high latitudes, whereas evaporites are generally formed in the tropics.

Faunal provinces

Oceans between continents provide barriers to plant and animal migration. Areas that have become separated tend to develop their own fauna and flora. This is particularly the case for

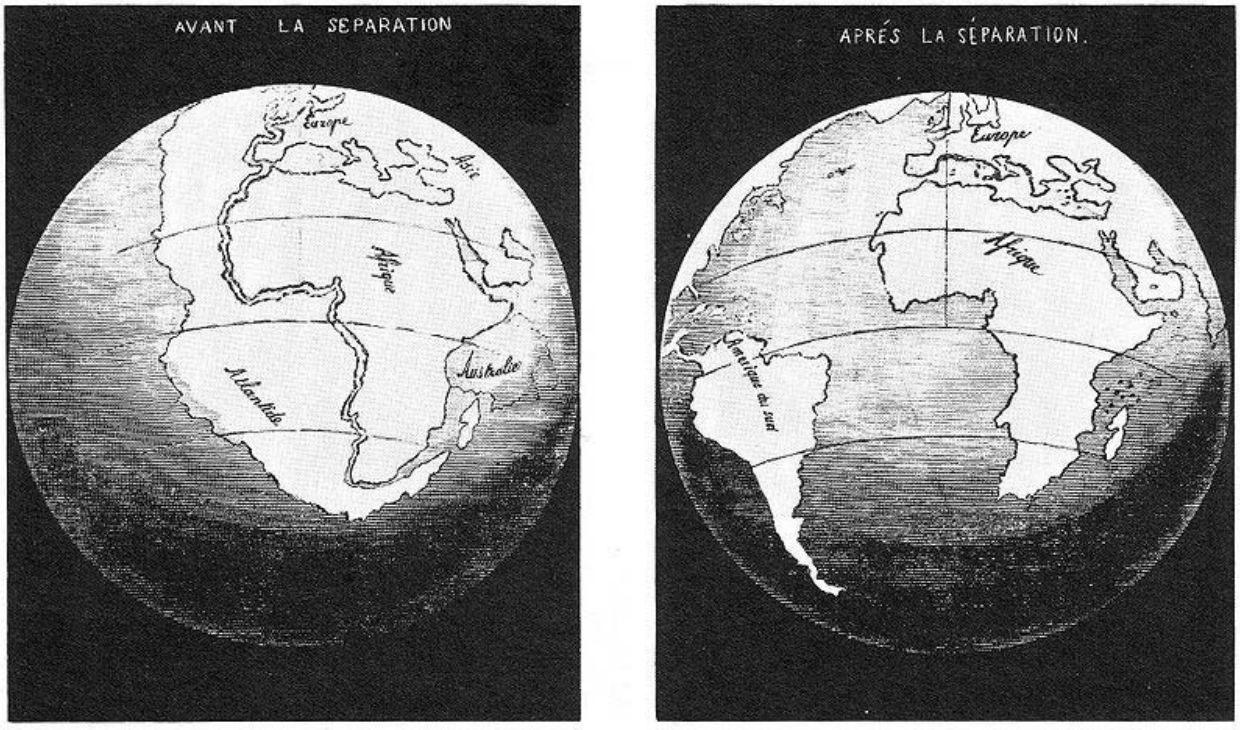
plants and land animals but is also true for shallow water marine species, such as trilobites and brachiopods, although their planktonic larvae mean that they were able to migrate over smaller deep water areas. As oceans narrow before a collision occurs, the faunas start to become mixed again, providing supporting evidence for the closure and its timing.

Orogenic belts

When supercontinents break up, older linear geological structures such as orogenic belts may be become split between the resulting fragments. When a reconstruction effectively joins up orogenic belts of the same age of formation, this provides further support for the reconstruction's validity.

Chapter- 3

Continental Drift



Antonio Snider-Pellegrini's Illustration of the closed and opened Atlantic Ocean (1858)

Continental drift is the movement of the Earth's continents relative to each other. The hypothesis that continents 'drift' was first put forward by Abraham Ortelius in 1596 and was fully developed by Alfred Wegener in 1912. However, it was not until the development of the theory of plate tectonics in the 1960s, that a sufficient geological explanation of that movement was found.

History

Early history

Abraham Ortelius (Ortelius 1596), Theodor Christoph Lilienthal (1756), Alexander von Humboldt (1801 and 1845), Antonio Snider-Pellegrini (Snider-Pellegrini 1858), and others had noted earlier that the shapes of continents on opposite sides of the Atlantic Ocean (most notably, Africa and South America) seem to fit together. W. J. Kious described Ortelius' thoughts in this way:

> Abraham Ortelius in his work Thesaurus Geographicus ... 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]."

Wegener and his predecessors

The hypothesis that the continents had once formed a single landmass before breaking apart and drifting to their present locations was fully formulated by Alfred Wegener in 1912. Although Wegener's theory was formed independently and was more complete than those of his predecessors, Wegener later credited a number of past authors with similar ideas: Franklin Coxworthy (between 1848 and 1890), Roberto Mantovani (between 1889 and 1909), William Henry Pickering (1907) and Frank Bursley Taylor (1908).

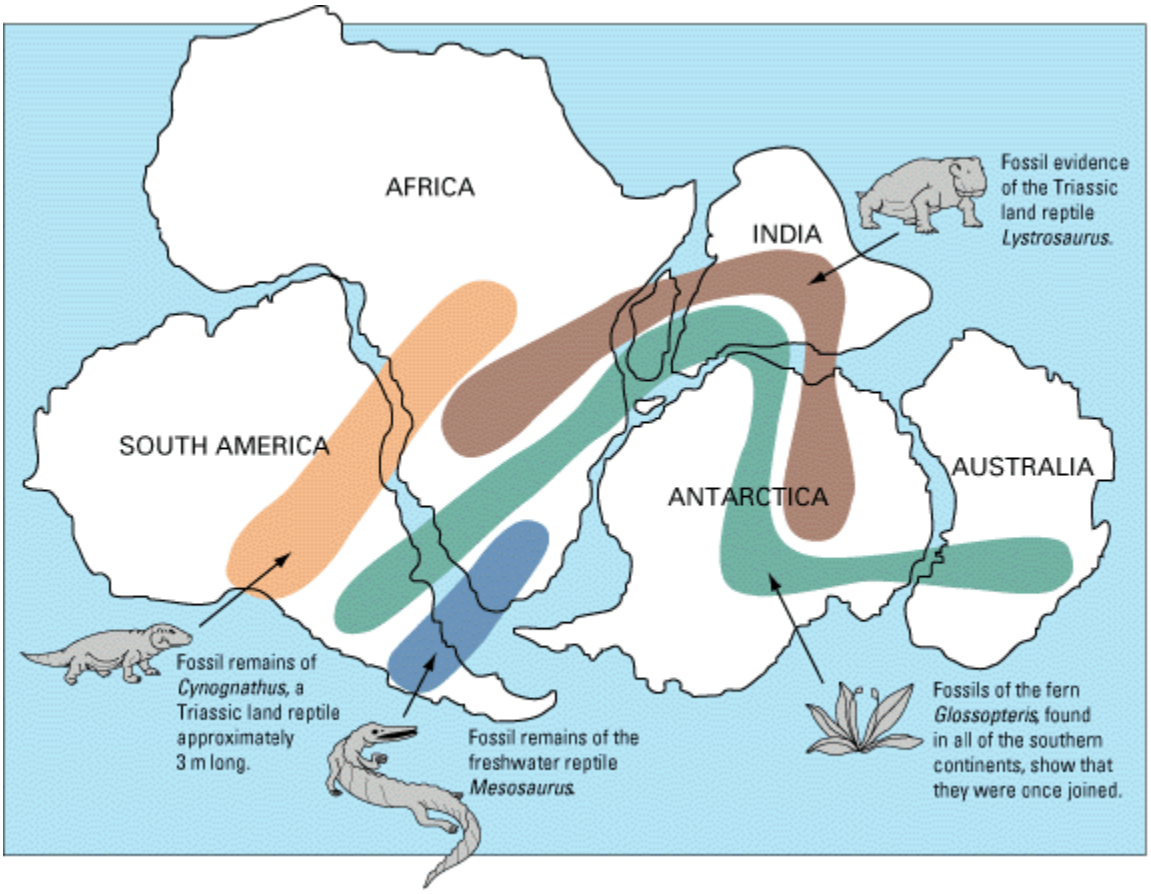
For example: the similarity of southern continent geological formations had led Roberto Mantovani to conjecture in 1889 and 1909 that all the continents had once been joined into a supercontinent (now known as Pangaea); Wegener noted the similarity of Mantovani's and his own maps of the former positions of the southern continents. Through volcanic activity due to thermal expansion this continent broke and the new continents drifted away from each other because of further expansion of the rip-zones, where the oceans now lie. This led Mantovani to propose an Expanding Earth theory which has since been shown to be incorrect.

Some sort of continental drift without expansion was proposed by Frank Bursley Taylor, who suggested in 1908 (published in 1910) that the continents were dragged towards the equator by increased lunar gravity during the Cretaceous, thus forming the Himalayas and Alps on the southern faces. Wegener said that of all those theories, Taylor's, although not fully developed, had the most similarities to his own.

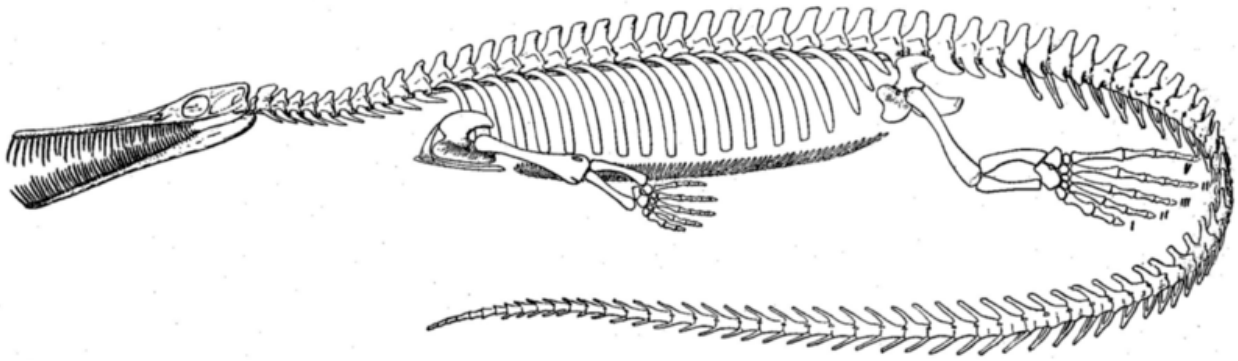
Wegener was the first to use the phrase "continental drift" (1912, 1915) (in German "die Verschiebung der Kontinente" – translated into English in 1922) and formally publish the hypothesis that the continents had somehow "drifted" apart. Although he presented much evidence for continental drift, he was unable to provide a convincing explanation for the physical processes which might have caused this drift. His suggestion that the continents had been pulled apart by the centrifugal pseudoforce (*Polflucht*) of the Earth's rotation or by a small component of astronomical precession was rejected as calculations showed that the force was not sufficient.

The Polflucht hypothesis was also studied by Paul Sophus Epstein in 1920 and found to be implausible.

Evidence that continents 'drift'



Fossil patterns across continents (Gondwanaland)



Mesosaurus skeleton, MacGregor, 1908

Evidence for continental drift is now extensive. Similar plant and animal fossils are found around different continent shores, suggesting that they were once joined. The fossils of Mesosaurus, a freshwater reptile rather like a small crocodile, found both in Brazil and South Africa, are one example; another is the discovery of fossils of the land reptile *Lystrosaurus* from rocks of the same age from locations in South America, Africa, and Antarctica. There is also living evidence — the same animals being found on two continents. Some earthworm families (e.g.: Ocnerodrilidae, Acanthodrilidae, Octochaetidae) are found in South America and Africa, for instance.

The complementary arrangement of the facing sides of South America and Africa is obvious, but is a temporary coincidence. In millions of years, slab pull and ridge-push, and other forces of tectonophysics will further separate and rotate those two continents. It was this temporary feature which inspired Wegener to study what he defined as continental drift, although he did not live to see his hypothesis become generally accepted.

Widespread distribution of Permo-Carboniferous glacial sediments in South America, Africa, Madagascar, Arabia, India, Antarctica and Australia was one of the major pieces of evidence for the theory of continental drift. The continuity of glaciers, inferred from oriented glacial striations and deposits called tillites, suggested the existence of the supercontinent of Gondwana, which became a central element of the concept of continental drift. Striations indicated glacial flow away from the equator and toward the poles, in modern coordinates, and supported the idea that the southern continents had previously been in dramatically different locations, as well as contiguous with each other.

Rejection of Wegener's theory, and subsequent vindication

While it is now accepted that the continents do move across the Earth's surface – though more in a driven mode than the aimlessness suggested by "drift" – as a *theory*, continental drift was not accepted for many years. One problem was that a plausible driving force was missing. And it did not help that Wegener was not a geologist.

The British geologist Arthur Holmes championed the theory of continental drift at a time when it was deeply unfashionable. He proposed that the Earth's mantle contained convection cells that dissipated radioactive heat and moved the crust at the surface. His *Principles of Physical Geology*, ending with a chapter on continental drift, was published in 1944.

As late as 1953 – just five years before Carey introduced the theory of plate tectonics – the theory of continental drift was rejected by the physicist Scheiddiger on the following grounds.

- First, it had been shown that floating masses on a rotating geoid would collect at the equator, and stay there. This would explain one, but only one, mountain building episode between any pair of continents; it failed to account for earlier orogenic episodes.

- Second, masses floating freely in a fluid substratum, like icebergs in the ocean, should be in isostatic equilibrium (where the forces of gravity and buoyancy are in balance). Gravitational measurements were showing that many areas are not in isostatic equilibrium.
- Third, there was the problem of why some parts of the Earth's surface (crust) should have solidifed while other parts were still fluid. Various attempts to explain this foundered on other difficulties.

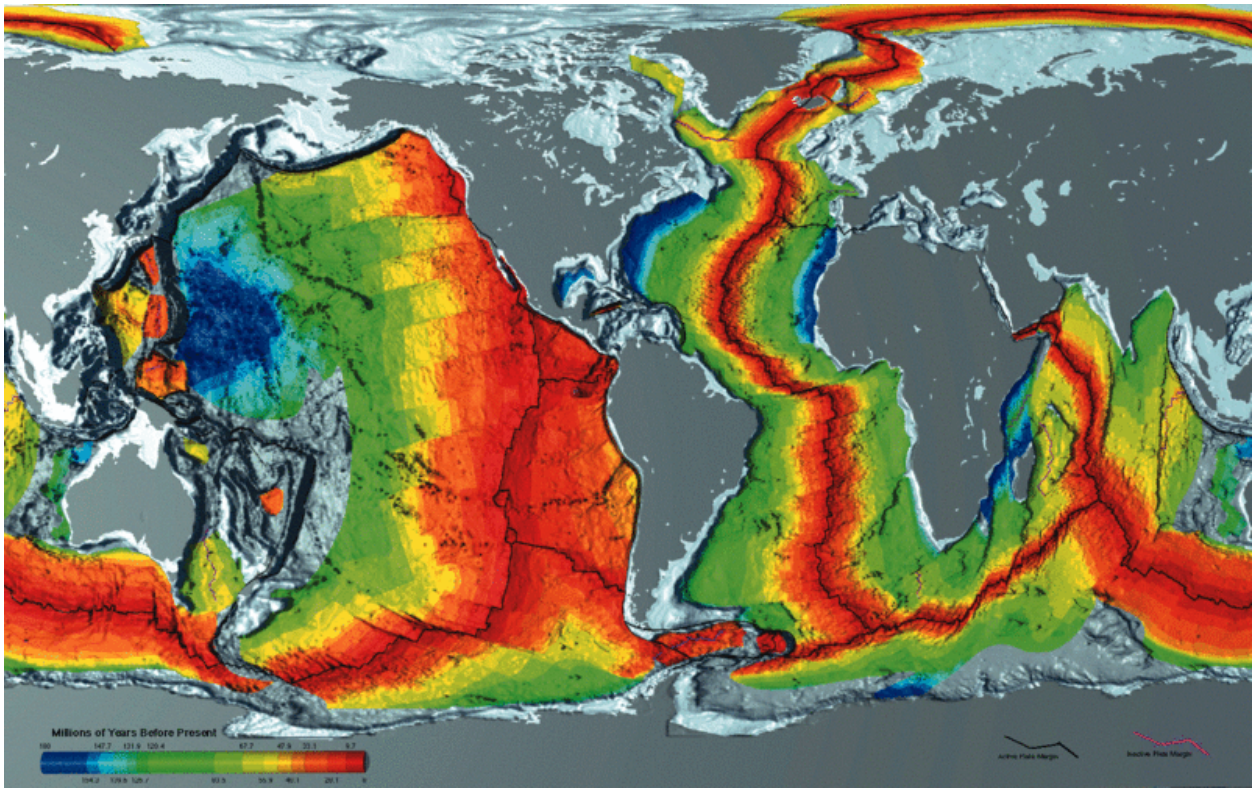
Geophysicist Jack Oliver is credited with providing seismologic evidence supporting plate tectonics which encompassed and superseded continental drift with "Seismology and the New Global Tectonics," published in 1968, using data collected from seismologic stations, including those he set up in the South Pacific.

It is now known that there are two kinds of crust, continental crust and oceanic crust. Continental crust is inherently lighter and of a different composition to oceanic crust, but both kinds reside above a much deeper fluid mantle. Oceanic crust is created at spreading centers, and this, along with subduction, drives the system of plates in a chaotic manner, resulting in continuous orogeny and areas of isostatic imbalance. The theory of plate tectonics explains all this, including the movement of the continents, better than Wegener's theory.

Chapter- 4

Seafloor Spreading and Mantle Convection

Seafloor spreading

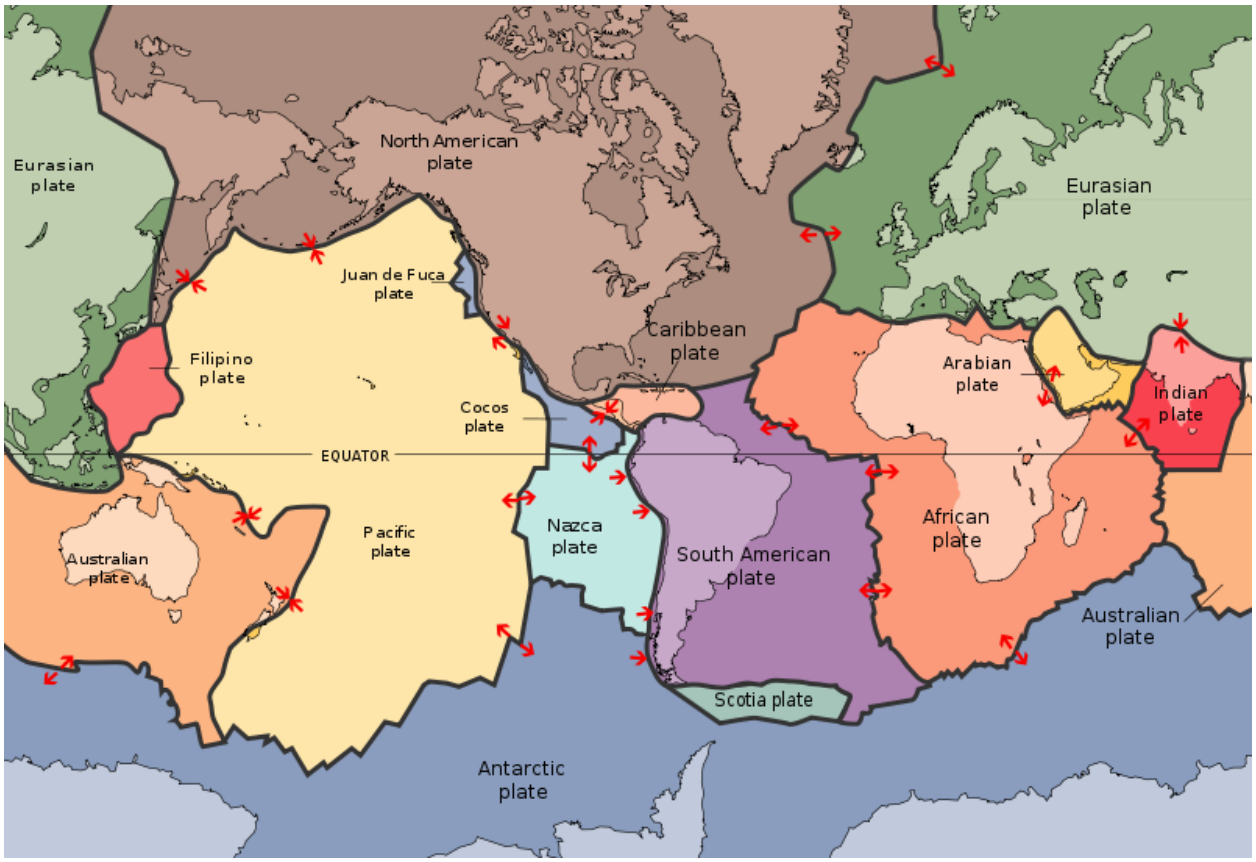


Age of oceanic crust; youngest (red) is along spreading centers

Seafloor spreading is a process that occurs at mid-ocean ridges, where new oceanic crust is formed through volcanic activity and then gradually moves away from the ridge. Seafloor spreading helps explain continental drift in the theory of plate tectonics.

Earlier theories (e.g., by Alfred Wegener and Alexander du Toit) of continental drift were that continents "plowed" through the sea. The idea that the seafloor itself moves (and carries the continents with it) as it expands from a central axis was proposed by Harry Hess from Princeton University in the 1960s. The theory is well-accepted now, and the phenomenon is known to be caused by convection currents in the plastic, very weak upper mantle, or asthenosphere.

Incipient spreading



Plates in the crust of the earth, according to the plate tectonics theory

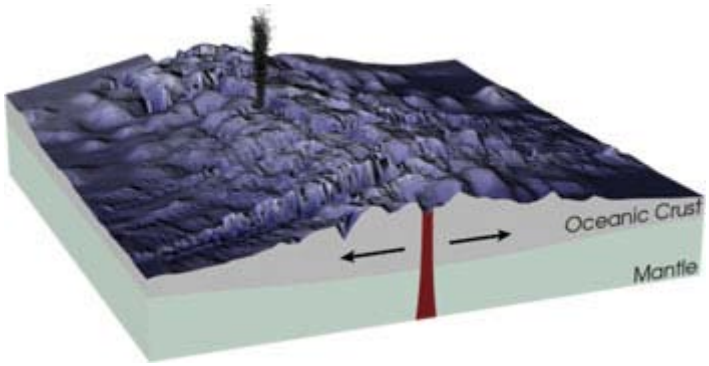
In the general case, sea floor spreading starts as a rift in a continental land mass, similar to the Red Sea-East Africa Rift System today. The process starts with heating at the base of the continental crust which causes it to become more plastic and less dense. Because less dense objects rise in relation to denser objects, the area being heated becomes a broad dome. As the crust bows upward, fractures occur that gradually grow into rifts. The typical rift system consists of three rift arms at approximately 120 degree angles. These areas are named triple junctions and can be found in several places across the world today. The separated margins of the continents evolve to form passive margins. Hess' theory was that new seafloor is formed when magma is forced upward toward the surface at a mid-ocean ridge.

Early spreading

If spreading continues past the incipient stage described above, two of the rift arms will open while the third arm stops opening and becomes a 'failed rift'. As the two active rifts continue to open, eventually the continental crust is attenuated as far as it will stretch. At this point basaltic oceanic crust begins to form between the separating continental fragments. When one of the rifts opens into the existing ocean, the rift system is flooded with seawater and becomes a new sea. The Red Sea is an example of a new arm of the sea. The East African rift was thought to be a "failed" arm that was opening somewhat more slowly than the other two arms, but in 2005 the Ethiopian Afar Geophysical Lithospheric Experiment reported that in the Afar region last September, a 60 km fissure opened as wide as eight meters. During this period of initial flooding the new sea is sensitive to changes in climate and eustasy. As a result the new sea will evaporate (partially or completely) several times before the elevation of the rift valley has been lowered to the point that the sea becomes stable. During this period of evaporation large evaporite deposits will be made in the rift valley. Later these deposits have the potential to become hydrocarbon seals and are of particular interest to petroleum geologists.

Sea floor spreading can stop during the process, but if it continues to the point that the continent is completely severed, then a new ocean basin is created. The Red Sea has not yet completely split Arabia from Africa, but a similar feature can be found on the other side of Africa that has broken completely free. South America once fit into the area of the Niger Delta. The Niger River has formed in the failed rift arm of the triple junction.

Continued spreading and subduction



Spreading at a mid-ocean ridge

The new oceanic crust is quite hot relative to old oceanic crust, so the new oceanic basin is shallower than older oceanic basins. If the diameter of the earth remains relatively constant despite the production of new crust, a mechanism must exist by which crust is also destroyed. The destruction of oceanic crust occurs at subduction zones where oceanic crust is forced under either continental crust or oceanic crust. Today, the Atlantic basin is actively spreading at the Mid-Atlantic Ridge. Only a small portion of the oceanic crust produced in the Atlantic is subducted. However, the plates making up the Pacific Ocean are experiencing subduction along many of their boundaries which causes the volcanic activity in what has been termed the Ring of

Fire of the Pacific Ocean. The Pacific is also home to one of the world's most active spreading centres (the East Pacific Rise (EPR)) with spreading rates of up to 13 cm/yr. The Mid-Atlantic Ridge is a "textbook" slow spreading centre while the EPR is used as an example of fast spreading. The differences in spreading rates affect not only the geometries of the ridges but also the geochemistry of the basalts that are produced.

Since the new oceanic basins are shallower than the old oceanic basins, the total capacity of the world's ocean basins decreases during times of active sea floor spreading. During the opening of the Atlantic Ocean, sea level was so high that a Western Interior Seaway formed across North America from the Gulf of Mexico to the Arctic Ocean.

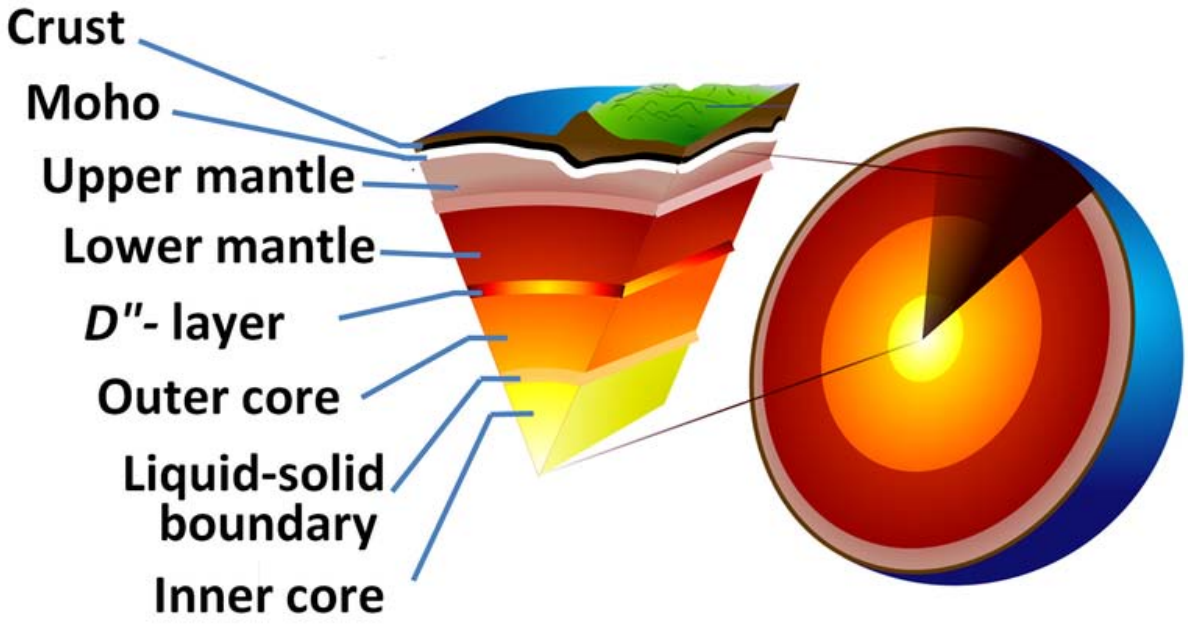
Debate and search for mechanism

At the Mid-Atlantic Ridge (and other places), material from the upper mantle rises through the faults between oceanic plates to form new crust as the plates move away from each other, a phenomenon first observed as continental drift. When Alfred Wegener first presented a hypothesis of continental drift in 1912, conservative geologists, especially in North America, demanded to know where the motive force could possibly lie. Wegener suggested that the continents ploughed through the ocean crust.

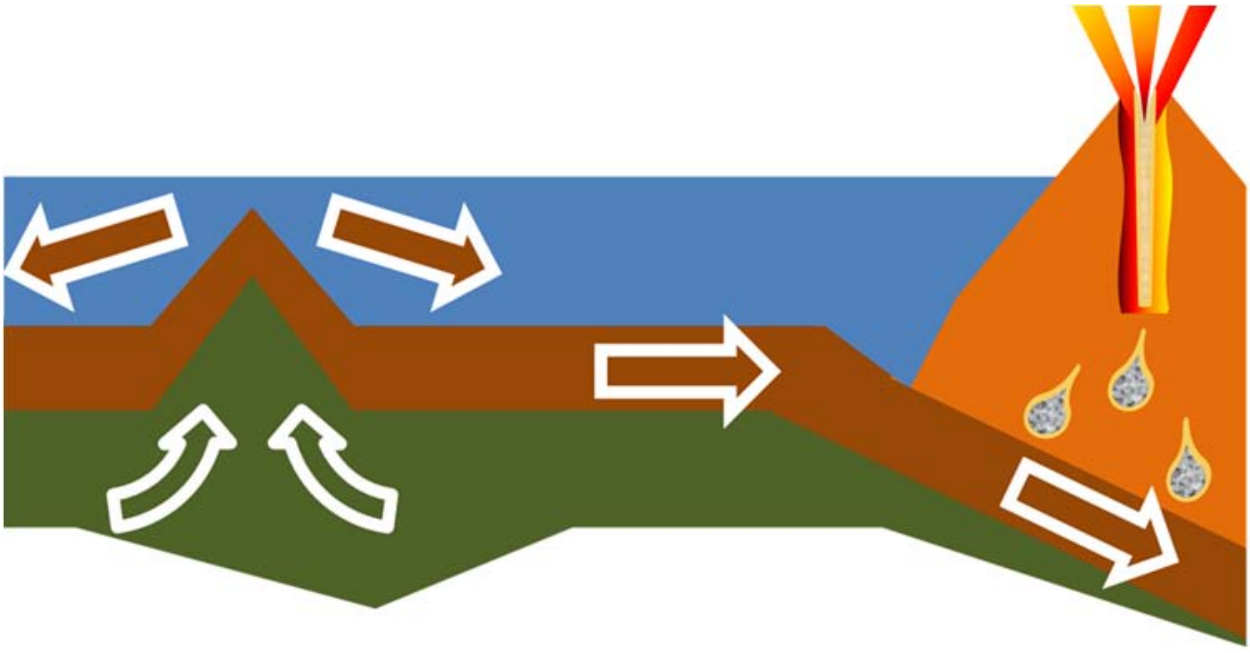
Since then, it has been shown that the motion of the continents is linked to seafloor spreading. In the 1960s, the past record of geomagnetic reversals was noticed by observing the magnetic stripe "anomalies" on the ocean floor. This results in broadly evident "stripes" from which the past magnetic field polarity can be inferred by looking at the data gathered from simply towing a magnetometer on the sea surface or from an aircraft. The stripes on one side of the mid-ocean ridge were the mirror image of those on the other side. The seafloor must have originated on the Earth's great fiery welts, like the Mid-Atlantic Ridge and the East Pacific Rise.

The driver for seafloor spreading in plates with active margins the weight of the cool, dense, subducting slabs that pull them along. The magmatism at the ridge is considered to be "passive upswelling", which is caused by the plates being pulled apart under the weight of their own slabs. This can be thought of as analogous to a rug on a table with little friction: when part of the rug is off of the table, its weight pulls the rest of the rug down with it.

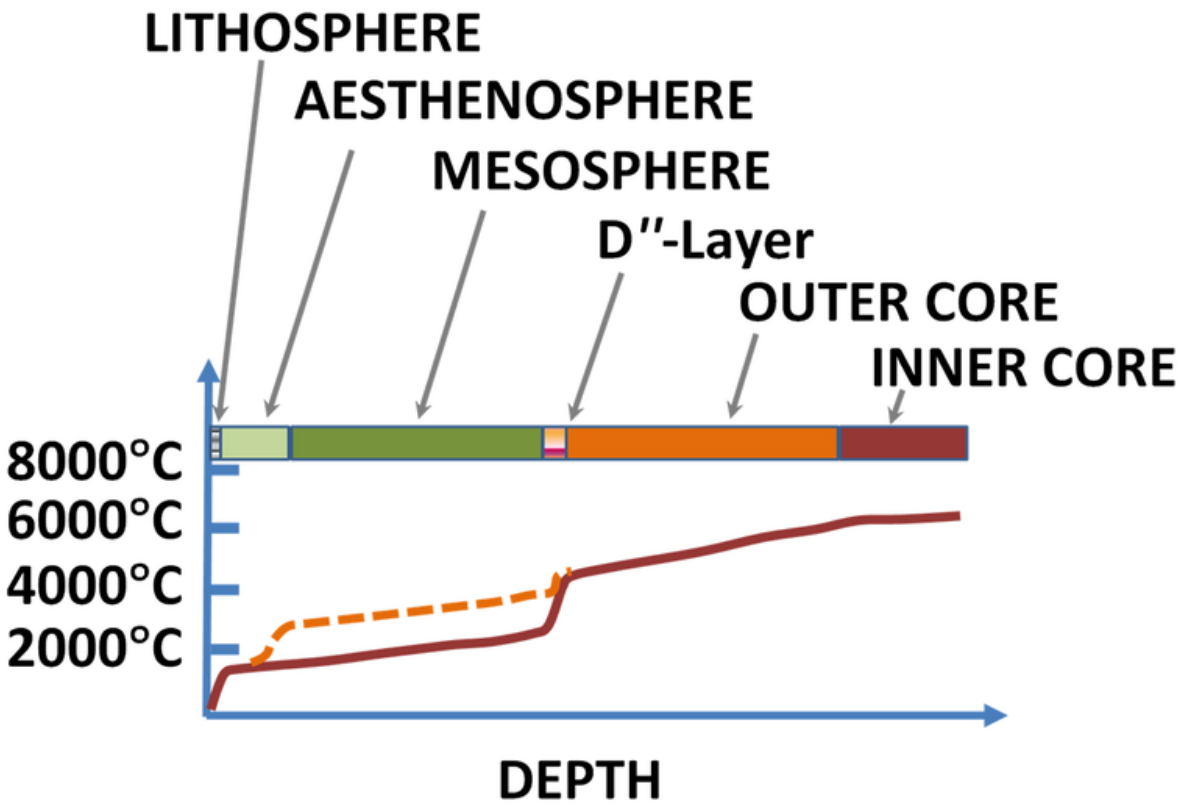
Mantle convection



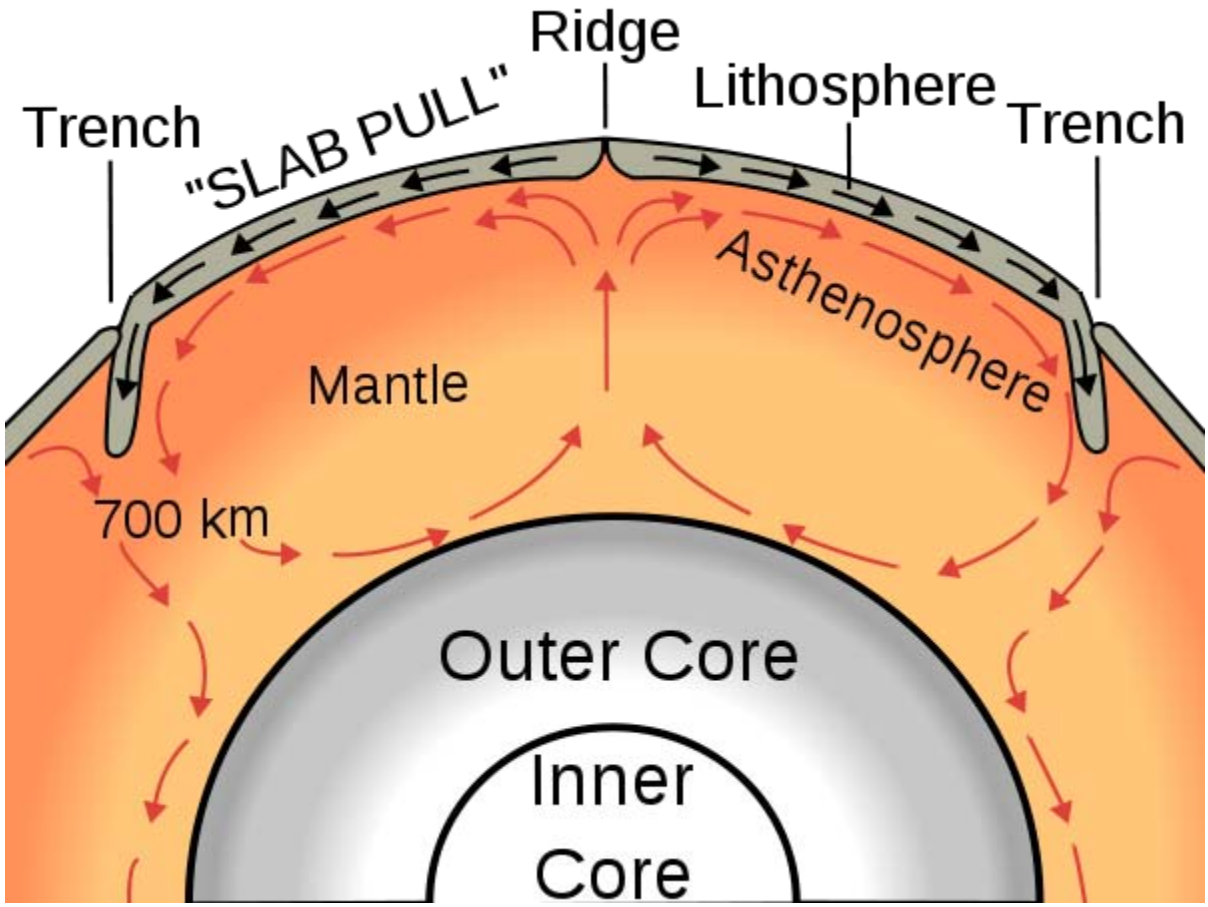
Earth cross-section showing location of upper and lower mantle



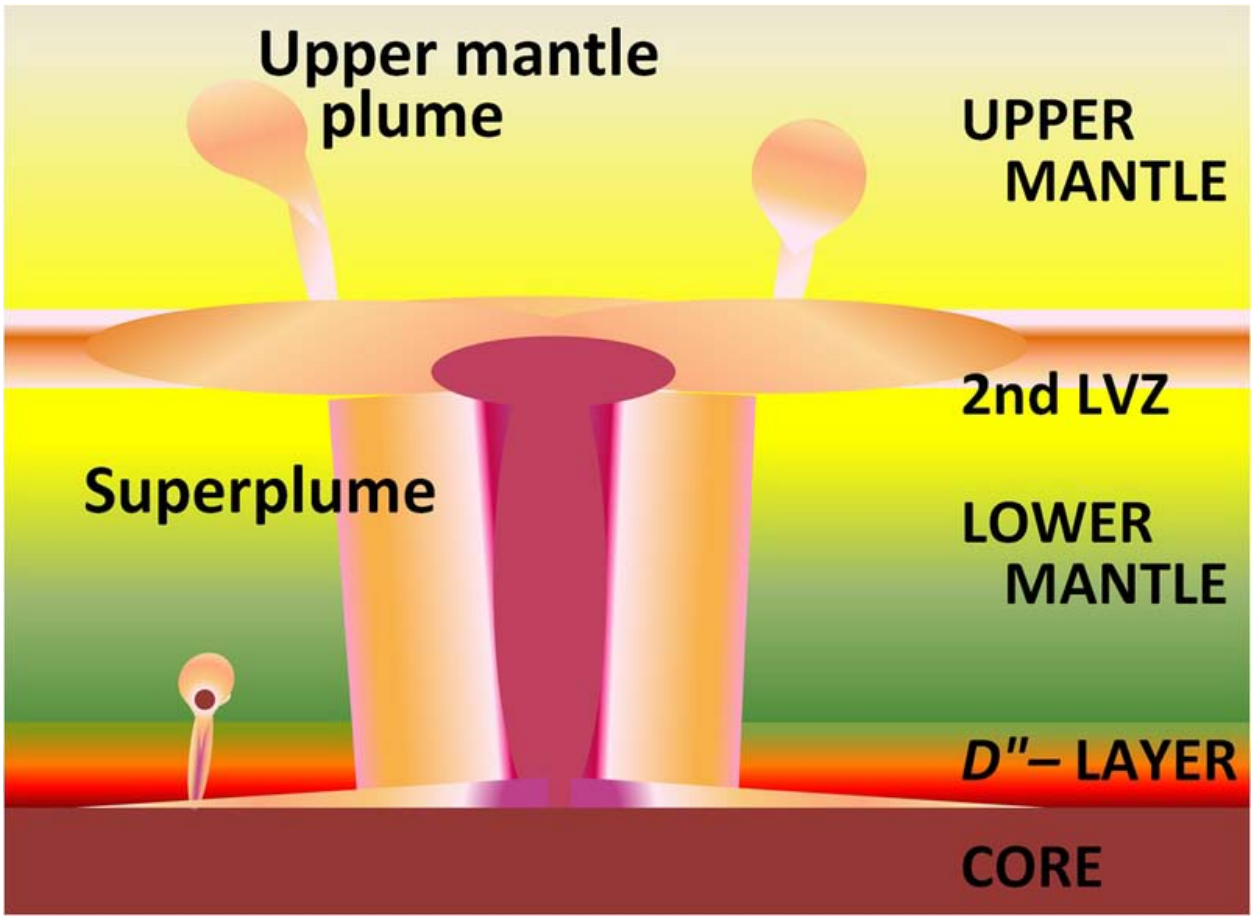
An oceanic plate of the lithosphere is added to by upwelling asthenosphere at a spreading ridge (left) and consumed at a subduction zone (right), causing stratovolcanoes at the convergent boundary with the continental plate.



Calculated Earth's temperature vs. depth. Dashed curve: Layered mantle convection; Solid curve: Whole mantle convection.



Whole mantle convection



A superplume generated by cooling processes in the mantle

Mantle convection is the slow creeping motion of Earth's rocky mantle caused by convection currents carrying heat from the interior of the Earth to the surface. The Earth's surface lithosphere, which rides atop the asthenosphere (the two components of the upper mantle), is divided into a number of plates that are continuously being created and consumed at their opposite plate boundaries. Accretion occurs as mantle is added to the growing edges of a plate, usually associated with seafloor spreading. This hot added material cools down by conduction and convection of heat. At the consumption edges of the plate, the material has thermally contracted to become dense, and it sinks under its own weight in the process of subduction at an ocean trench.

This *subducted* material sinks to a depth of 660 kilometers in the Earth's interior where it is impeded from sinking further, possibly due to a phase change from spinel to perovskite and magnesiowustite, an endothermic reaction.

The subducted oceanic crust triggers volcanism, although the basic mechanisms are varied. Volcanism may occur due to processes that add buoyancy to partially melted mantle causing an upward flow due to a decrease in density of the partial melt.

Secondary forms of convection that may result in surface volcanism are postulated to occur as a consequence of intraplate extension and mantle plumes.

It is because the mantle can convect that the tectonic plates are able to move around the Earth's surface.

Types of convection

There is a current debate within the geophysics community as to whether convection is likely to be 'layered' or 'whole'. This debate is linked to the controversy regarding whether intraplate volcanism is caused by shallow, upper-mantle processes or by plumes from the lower mantle. Geochemists have argued that the lavas erupted in intraplate areas are different in composition from shallow-derived mid ocean ridge basalts (MORB). This has been interpreted as their originating from a different region, suggested to be the lower mantle. Others, however, have pointed out that the differences indicate the inclusion of a small component of near-surface material from the lithosphere. Seismologists are also divided, with some arguing that there is no evidence for whole-mantle convection, and others arguing that there is.

Chapter- 5

Craton

A **craton** (Greek: κράτος *kratos* "strength") is an old and stable part of the continental lithosphere. Having often survived cycles of merging and rifting of continents, cratons are generally found in the interiors of tectonic plates. They are characteristically composed of ancient crystalline basement rock, which may be covered by younger sedimentary rock. They have a thick crust and deep lithospheric roots that extend as much as a few hundred kilometers into the Earth's mantle.

The term craton is used to distinguish the stable portion of the continental crust from regions that are more geologically active and unstable. Cratons can be described as shields, in which the basement rock crops out at the surface, and platforms, in which the basement is overlain by sediments and sedimentary rock.

The word craton was first proposed by the German geologist L. Kober in 1921 as *"Kratogen"*, referring to stable continental platforms, and *"orogen"* as a term for mountain or orogenic belts. Later authors shortened the former term to kraton and then to craton.

Examples of cratons are the Slave craton in Canada, the Wyoming craton in the United States, the Amazonia craton in South America, and the Kaapvaal craton in South Africa.

Provinces

Cratons are subdivided geographically into geologic provinces. A geologic province is a spatial entity with common geologic attributes. A province may include a single dominant structural element such as a structural basin or a fold belt, or a number of contiguous related elements. Adjoining provinces may be similar in structure but be considered separate due to differing histories. There are several meanings of geologic provinces, as used in specific contexts.

Structure

Cratons have thick lithospheric roots. Mantle tomography shows that cratons are underlain by anomalously cold mantle corresponding to lithosphere more than twice the typical 60 mile

(100 km) thickness of mature oceanic or noncratonic, continental lithosphere. At that depth, craton roots extend into the asthenosphere. Craton lithosphere is distinctly different from oceanic lithosphere because cratons have a neutral or positive buoyancy, and a low intrinsic, isopycnic density. This low density offsets density increases due to geothermal contraction and prevents the craton from sinking into the deep mantle. Cratonic lithosphere is much older than oceanic lithosphere — up to 4 billion years versus 180 million years.

Rock fragments (xenoliths) carried up from the mantle by magmas containing peridotite have been delivered to the surface as inclusions in subvolcanic pipes called kimberlites. These inclusions have densities consistent with craton composition and are composed of mantle material residual from high degrees of partial melt. Peridotite is strongly influenced by the inclusion of moisture. Craton perodotite moisture content is unusually low which leads to much greater strength. It also contains high percentages of low weight magnesium instead of higher weight calcium and iron. Peridotites are important for understanding the deep composition and origin of cratons because peridotite nodules are pieces of mantle rock modified by partial melting. Harzburgite peridotites represent the crystalline residues after extraction of melts of compositions like basalt and komatiite.

An associated class of inclusions called eclogites, consists of rocks corresponding compositionally to oceanic crust (basalt), but that metamorphosed under deep mantle conditions. Isotopic studies reveal that many eclogite inclusions are samples of ancient oceanic crust subducted billions of years ago to depths exceeding 90 mi (150 km) into the deep kimberlite diamond areas. They remained fixed there within the drifting tectonic plates until carried to the surface by deep-rooted magmatic eruptions.

If peridotite and eclogite inclusions are of the same temporal origin, then peridotite must have also originated from sea-floor spreading ridges billions of years ago, or from mantle affected by subduction of oceanic crust then. During the early years of Earth's existence, when the planet was much hotter, greater degrees of melting at oceanic spreading ridges generated oceanic lithosphere with thick crust, much thicker than 12 miles (20 km), and a highly depleted mantle. Such a lithosphere would not sink deeply or subduct because of its buoyancy, and because of the removal of denser melt that in turn lowered the density of the residual mantle. Accordingly, cratonic mantle roots are probably composed of buoyantly subducted slabs of a highly depleted oceanic lithosphere. These deep mantle roots increase the stability, anchoring and survivability of cratons and makes them much less susceptible to tectonic thickening by collisions, or destruction by sediment subduction.

Formation

The process by which cratons are formed from early rock is called cratonization. The first large cratonic landmasses formed during the Archean eon. During the Early Archean, Earth's heat flow was nearly three times higher than it is today because of the greater concentration of radioactive isotopes and the residual heat from the Earth's accretion. There was considerably greater tectonic and volcanic activity; the mantle was much more fluid and the crust much thinner. This resulted in rapid formation of oceanic crust at ridges and hot spots, and rapid recycling of oceanic crust at subduction zones. There are at least three hypotheses of how cratons have been formed: 1)

surface crust was thickened by a rising plume of deep molten material, 2) successive subducting plates of oceanic lithosphere became lodged beneath a proto-craton in an under-plating process, 3) accretion from island arcs or continental fragments rafting together to thicken into a craton.

Earth's surface was probably broken up into many small plates with volcanic islands and arcs in great abundance. Small protocontinents (cratons) formed as crustal rock was melted and remelted by hot spots and recycled in subduction zones.

There were no large continents in the Early Archean, and small protocontinents were probably the norm in the Mesoarchean because they were prevented from coalescing into larger units by the high rate of geologic activity. These felsic protocontinents (cratons) probably formed at hot spots from a variety of sources: mafic magma melting more felsic rocks, partial melting of mafic rock, and from the metamorphic alteration of felsic sedimentary rocks. Although the first continents formed during the Archean, rock of this age makes up only 7% of the world's current cratons; even allowing for erosion and destruction of past formations, evidence suggests that only 5-40% of the present continental crust formed during the Archean.

One evolutionary perspective of how the cratonization process "might" have first begun in the Archean is given by Warren B. Hamilton:

Very thick sections of mostly submarine mafic, and subordinate ultramafic, volcanic rocks, and mostly younger subaerial and submarine felsic volcanic rocks and sediments were oppressed into complex synforms between rising young domiform felsic batholiths mobilized by hydrous partial melting in the lower crust. Upper-crust granite-and-greenstone terrains underwent moderate regional shortening, decoupled from the lower crust, during compositional inversion accompanying doming, but cratonization soon followed. Tonalitic basement is preserved beneath some greenstone sections but supracrustal rocks commonly give way downward to correlative or younger plutonic rocks... Mantle plumes probably did not yet exist, and developing continents were concentrated in cool regions. Hot-region upper mantle was partly molten, and voluminous magmas, mostly ultramafic, erupted through many ephemeral submarine vents and rifts focussed at the thinnest crust.... Surviving Archean crust is from regions of cooler, and more depleted, mantle, wherein greater stability permitted uncommonly thick volcanic accumulations from which voluminous partial-melt, low-density felsic rocks could be generated.

Chapter- 6

Orogeny

Orogeny refers to forces and events leading to a severe structural deformation of the Earth's crust due to the engagement of tectonic plates. Response to such engagement results in the formation of long tracts of highly deformed rock called **orogens** or **orogenic belts**. The word "orogeny" comes from the Greek (*oros* for "mountain" plus *genesis* for "creation" or "origin"), and it is the primary mechanism by which mountains are built on continents. Orogens develop while a continental plate is crumpled and thickened to form mountain ranges, and involve a great range of geological processes collectively called **orogenesis**.

Physiography

Formation of an orogen is accomplished in part by the tectonic processes of subduction, where a continent rides forcefully over an oceanic plate (noncollisional orogens), or convergence of two or more continents (collisional orogens).

Orogeny usually produces long arcuate (from *arcuare*, to bend like a bow) structures, known as *orogenic belts*. Generally, orogenic belts consist of long parallel strips of rock exhibiting similar characteristics along the length of the belt. Orogenic belts are associated with subduction zones, which consume crust, produce volcanoes, and build island arcs. The arcuate structure is attributed to the rigidity of the descending plate, and island arc cusps are related to tears in the descending lithosphere. These island arcs may be added to a continent during an orogenic event.

The processes of orogeny can take tens of millions of years and build mountains from plains or the ocean floor. The topographic height of orogenic mountains is related to the principle of isostasy, that is, a balance of the downward gravitational force upon an upthrust mountain range (composed of light, continental crust material) and the buoyant upward forces exerted by the dense underlying mantle.

Frequently, rock formations that undergo orogeny are severely deformed and undergo metamorphism. During orogeny, deeply buried rocks may be pushed to the surface. Sea bottom and near shore material may cover some or all of the orogenic area. If the orogeny is due to two continents colliding, the resulting mountains can be very high.

An orogenic event may be studied as (a) a tectonic structural event, (b) as a geographical event, and (c) a chronological event. Orogenic events (a) cause distinctive structural phenomena related to tectonic activity, (b) affect rocks and crust in particular regions, and (c) happen within a specific period of time.

Orogenic cycle

Although orogeny involves plate tectonics, the tectonic forces result in a variety of associated phenomena, including magmatization, metamorphism, crustal melting, and crustal thickening. Just what happens in a specific orogen depends upon the strength and rheology of the continental lithosphere, and how these properties change during orogenesis.

In addition to orogeny, the orogen once formed is subject to other processes, such as sedimentation and erosion. The sequence of repeated cycles of sedimentation, deposition and erosion, followed by burial and metamorphism, and then by formation of granitic batholiths and tectonic uplift to form mountain chains, is called the *orogenic cycle*. For example, the *Caledonian Orogeny* refers to the Silurian and Devonian events that resulted from the collision of Laurentia with Eastern Avalonia and other former fragments of Gondwana. The *Caledonian Orogen* resulted from these events and various others that are part of its peculiar orogenic cycle.

In summary, an orogeny is a long-lived deformational episode in which many geological phenomena play a role. The orogeny of an orogen is only part of the orogen's orogenic cycle. Among the other phases is erosion, described next.

Erosion

Erosion inevitably removes much of the mountains, exposing the core or *mountain roots* (metamorphic rocks brought to the surface from a depth of several kilometres). Such exhumation may be helped by isostatic movements balancing out the buoyancy of the evolving orogen. There is debate about the extent to which erosion modifies the patterns of tectonic deformation. Thus, the final form of the majority of old orogenic belts is a long arcuate strip of crystalline metamorphic rocks sequentially below younger sediments which are thrust atop them and dip away from the orogenic core.

An orogen may be almost completely eroded away, and only recognizable by studying (old) rocks that bear traces of orogenesis. Orogens are usually long, thin, arcuate tracts of rock that have a pronounced linear structure resulting in terranes or blocks of deformed rocks, separated generally by suture zones or dipping thrust faults. These thrust faults carry relatively thin slices of rock (which are called nappes or thrust sheets, and differ from tectonic plates) from the core of the shortening orogen out toward the margins, and are intimately associated with folds and the development of metamorphism.

Biology

The study of orogeny, coupled with biogeography (the study of the distribution and evolution of flora and fauna), geography and mid ocean ridges in the 1950s and 1960s, contributed greatly to

the theory of plate tectonics. Even at a very early stage, life played a significant role in the continued existence of oceans, by affecting the composition of the atmosphere. The existence of oceans is critical to sea-floor spreading and subduction.

Relationship to mountain building

Sierra Nevada Mountains (a result of delamination) as seen from the International Space Station.

Mountain formation occurs through a number of mechanisms.

Mountain complexes result from irregular successions of tectonic responses due to sea-floor spreading, shifting lithosphere plates, transform faults, and colliding, coupled and uncoupled continental margins.

—

Large modern orogenies often lie on the margins of continents; the Alleghenian (Appalachian), Laramide, and Andean orogenies are examples of these in the Americas. Older inactive orogenies, such as the Algoman, Penokean and Antler, are represented by deformed rocks and sedimentary basins further inland.

Areas that are rifting apart, such as mid-ocean ridges and the East African Rift, have mountains due to thermal buoyancy related to the hot mantle underneath them; this thermal buoyancy is known as dynamic topography. In strike-slip systems, such as the San Andreas Fault, restraining bends result in regions of localized crustal shortening and mountain building without a plate-margin-wide orogeny. Hotspot volcanism results in the formation of isolated mountains and mountain chains that are not necessarily on tectonic plate boundaries.

Regions can also experience uplift as a result of delamination of the lithosphere, in which an unstable portion of cold lithospheric root drips down into the mantle, decreasing the density of the lithosphere and causing buoyant uplift. An example is the Sierra Nevada in California. This

range of fault-block mountains experienced renewed uplift after a delamination of the lithosphere beneath them.

Finally, uplift and erosion related to epeirogenesis (large-scale vertical motions of portions of continents without much associated folding, metamorphism, or deformation) can create local topographic highs.

History of the concept

Before the development of geologic concepts during the 19th century, the presence of mountains was explained in Christian contexts as a result of the Biblical Deluge. This was an extension of Neoplatonic thought, which influenced early Christian writers.

Orogeny was used by Amanz Gressly (1840) and Jules Thurmann (1854) as *orogenic* in terms of the creation of mountain elevations, as the term *mountain building* was still used to describe the processes.

Elie de Beaumont (1852) used the evocative "Jaws of a Vise" theory to explain orogeny, but was more concerned with the height rather than the implicit structures created by and contained in orogenic belts. His theory essentially held that mountains were created by the squeezing of certain rocks.

Eduard Suess (1875) recognised the importance of horizontal movement of rocks. The concept of a *precursor geosyncline* or initial downward warping of the solid earth (Hall, 1859) prompted James Dwight Dana (1873) to include the concept of *compression* in the theories surrounding mountain-building. With hindsight, we can discount Dana's conjecture that this contraction was due to the cooling of the Earth (aka the cooling Earth theory).

The cooling Earth theory was the chief paradigm for most geologists until the 1960s. It was, in the context of orogeny, fiercely contested by proponents of vertical movements in the crust (similar to tephrotectonics), or convection within the asthenosphere or mantle.

Gustav Steinmann (1906) recognised different classes of orogenic belts, including the *Alpine type orogenic belt*, typified by a flysch and molasse geometry to the sediments; ophiolite sequences, tholeiitic basalts, and a nappe style fold structure.

In terms of recognising orogeny as an *event*, Leopold von Buch (1855) recognised that orogenies could be placed in time by bracketing between the youngest deformed rock and the oldest undeformed rock, a principle which is still in use today, though commonly investigated by geochronology using radiometric dating.

H.J. Zwart (1967) drew attention to the metamorphic differences in orogenic belts, proposing three types, modified by W. S. Pitcher in 1979 and further modified as:

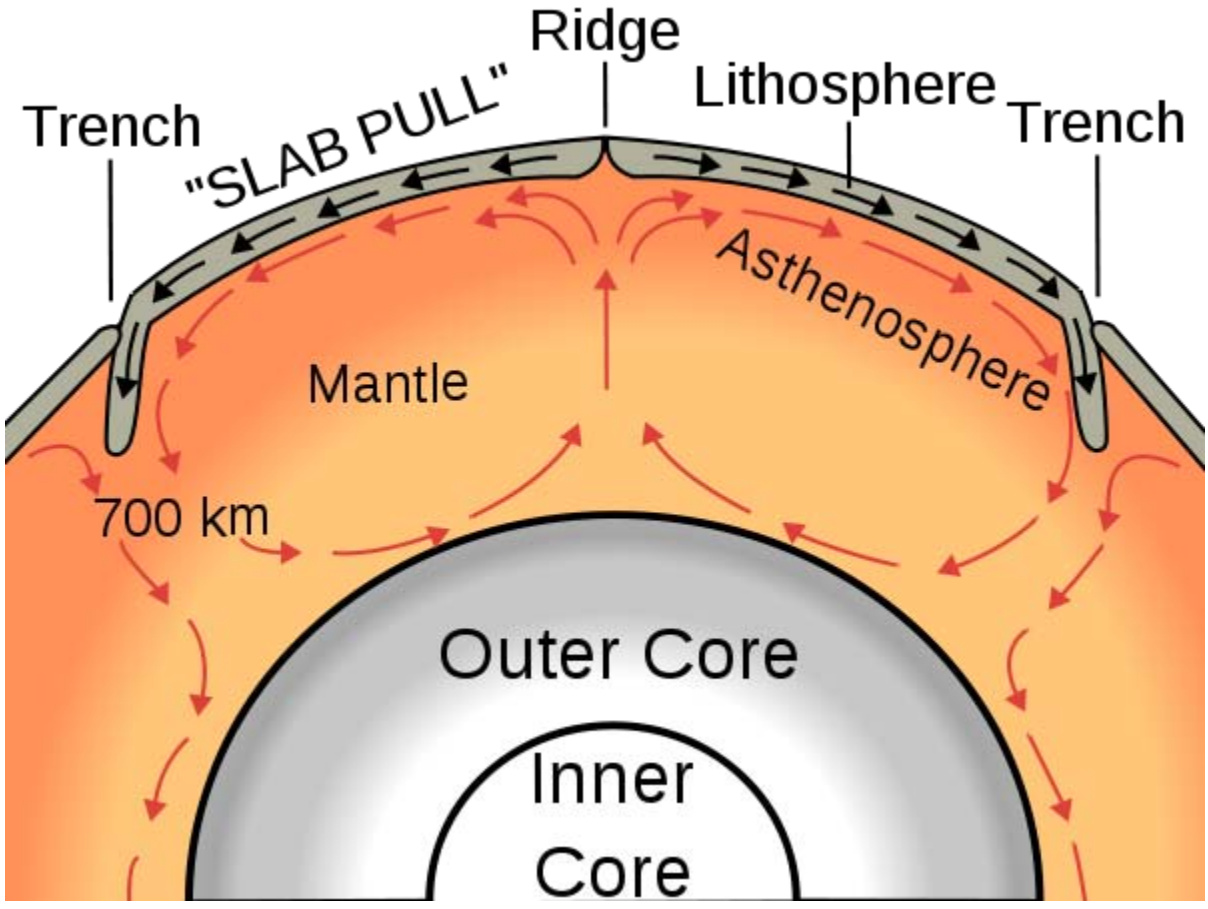
- Hercynotype (back-arc basin type);
    - Shallow, low-pressure metamorphism; thin metamorphic zones
    - Metamorphism dependent on increase in temperature
    - Abundant granite and migmatite
    - Few ophiolites, ultramafic rocks virtually absent
    - very wide orogen with small and slow uplift
    - nappe structures rare
- Alpinotype (ocean trench style);
    - deep, high pressure, thick metamorphic zones
    - metamorphism of many facies, dependent on decrease in pressure
    - few granites or migmatites
    - abundant ophiolites with ultramafic rocks
    - Relatively narrow orogen with large and rapid uplift
    - Nappe structures predominant
- Cordilleran (arc) type;
    - dominated by calc-alkaline igneous rocks, andesites, granite batholiths
    - general lack of migmatites, low geothermal gradient
    - lack of ophiolite and abyssal sedimentary rocks (black shale, chert, etcetera)
    - low-pressure metamorphism, moderate uplift
    - lack of nappes

The advent of plate tectonics has explained the vast majority of orogenic belts and their features. The cooling earth theory (principally advanced by Descartes) is dispensed with, and tephrotectonic style vertical movements have been explained primarily by the process of isostasy.

Some oddities exist, where simple collisional tectonics are modified in a transform plate boundary, such as in New Zealand, or where island arc orogenies, for instance in New Guinea occur away from a continental backstop. Further complications such as Proterozoic continent-continent collisional orogens, explicitly the Musgrave Block in Australia, previously inexplicable are being brought to light with the advent of seismic imaging techniques which can resolve the deep crust structure of orogenic belts.

Chapter- 7

Oceanic Trench



Oceanic crust is formed at an oceanic ridge, while the lithosphere is subducted back into the asthenosphere at trenches.

The **oceanic trenches** are hemispheric-scale long but narrow topographic depressions of the sea floor. They are also the deepest parts of the ocean floor.

Trenches define one of the most important natural boundaries on the Earth's solid surface: the one between two lithospheric plates. There are three types of lithospheric plate boundaries: divergent (where lithosphere and oceanic crust is created at mid-ocean ridges), convergent (where one lithospheric plate sinks beneath another and returns to the mantle), and transform (where two lithospheric plates slide past each other).

Trenches are a distinctive morphological feature of plate boundaries. Along convergent plate boundaries, plates move together at rates that vary from a few mm to over ten cm per year. A trench marks the position at which the flexed, subducting slab begins to descend beneath another lithospheric slab. Trenches are generally parallel to a volcanic island arc, and about 200 km (120 mi) from a volcanic arc. Oceanic trenches typically extend 3 to 4 km (1.9 to 2.5 mi) below the level of the surrounding oceanic floor. The greatest ocean depth to be sounded is in the Challenger Deep of the Mariana Trench, at a depth of 10,911 m (35,797 ft) below sea level. Oceanic lithosphere moves into trenches at a global rate of about a tenth of a square metre per second.

Geographic distribution

There are about 50,000 km (31,000 mi) of convergent plate margins, mostly around the Pacific Ocean—the reason for the reference "Pacific-type" margin—but they are also in the eastern Indian Ocean, with relatively short convergent margin segments in the Atlantic Ocean and in the Mediterranean Sea. Trenches are sometimes buried and lack bathymetric expression, but the fundamental structures that these represent mean that the great name should also be applied here. This applies to Cascadia, Makran, southern Lesser Antilles, and Calabrian trenches. Trenches along with volcanic arcs and zones of earthquakes that dip under the volcanic arc as deeply as 700 km (430 mi) are diagnostic of convergent plate boundaries and their deeper manifestations, subduction zones. Trenches are related to but distinguished from continental collision zones (like that between India and Asia to form the Himalaya), where continental crust enters the subduction zone. When buoyant continental crust enters a trench, subduction eventually stops and the convergent plate margin becomes a collision zone. Features analogous to trenches are associated with collisions zones; these are sediment-filled foredeeps referred to as peripheral foreland basins, such as that which the Ganges River and Tigris-Euphrates rivers flow along.

History of the term "trench"

Trenches were not clearly defined until the late 1940s and 1950s. The bathymetry of the ocean was of no real interest until the late 19th and early 20th centuries, with the initial laying of Transatlantic telegraph cables on the seafloor between the continents. Even then the elongated bathymetric expression of trenches was not recognized until well into the 20th century. The term "trench" does not appear in Murray and Hjort's (1912) classic oceanography book. Instead they applied the term "deep" for the deepest parts of the ocean, such as Challenger Deep. Experiences from World War I battlefields emblazoned the concept of the trench warfare as an elongate depression defining an important boundary, so it was no surprise that the term "trench" was used to describe natural features in the early 1920s. The term was first used in a geologic context by Scofield two years after the war ended to describe a structurally-controlled depression in the

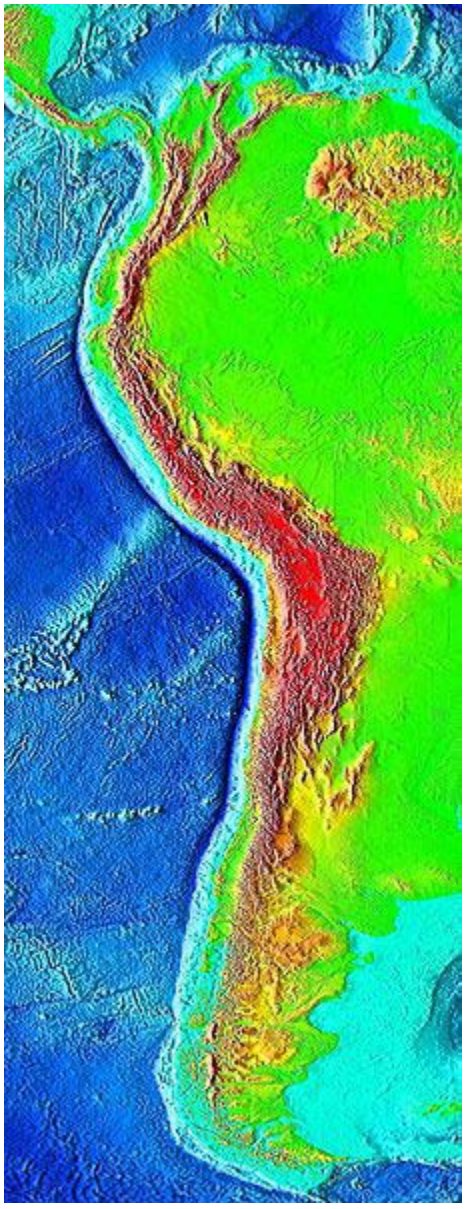
Rocky Mountains. Johnstone, in his 1923 textbook *An Introduction to Oceanography*, first used the term in its modern sense for any marked, elongate depression of the sea bottom.

During the 1920s and 1930s, Felix Andries Vening Meinesz developed a unique gravimeter that could measure gravity in the stable environment of a submarine and used it to measure gravity over trenches. His measurements revealed that trenches are sites of downwelling in the solid Earth. The concept of downwelling at trenches was characterized by Griggs in 1939 as the tectogene hypothesis, for which he developed an analogue model using a pair of rotating drums. World War II in the Pacific led to great improvements of bathymetry in especially the western and northern Pacific, and the linear nature of these deeps became clear. The rapid growth of deep sea research efforts, especially the widespread use of echosounders in the 1950s and 1960s confirmed the morphological utility of the term. The important trenches were identified, sampled, and their greatest depths sonically plumbed. The heroic phase of trench exploration culminated in the 1960 descent of the Bathyscaphe *Trieste*, which set an unbeatable world record by diving to the bottom of the Challenger Deep. Following Robert S. Dietz' and Harry Hess' articulation of the seafloor spreading hypothesis in the early 1960s and the plate tectonic revolution in the late 1960s the term "trench" has been redefined with plate tectonic as well as bathymetric connotations.

Trench rollback

Although trenches would seem to be positionally stable over time, it is hypothesized that some trenches, particularly those associated with subduction zones where two oceanic plates converge, retrograde, that is, they move backward into the plate which is subducting, akin to a backward-moving wave. This has been termed **trench rollback** (also **hinge rollback**). This is one explanation for the existence of back-arc basins.

Morphologic expression



The Peru-Chile Trench

Trenches are centerpieces of the distinctive physiography of a convergent plate margin. Transects across trenches yield asymmetric profiles, with relatively gentle (~5°) outer (seaward) slope and a steeper (~10–16°) inner (landward) slope. This asymmetry is due to the fact that the outer slope is defined by the top of the downgoing plate, which must bend as it starts its descent. The great thickness of the lithosphere requires that this bending be gentle. As the subducting plate approaches the trench, it is first bent upwards to form the outer trench swell, then descends to form the outer trench slope. The outer trench slope is disrupted by a set of subparallel normal faults which staircase the seafloor down to the trench. The plate boundary is defined by the

trench axis itself. Beneath the inner trench wall, the two plates slide past each other along the subduction decollement, the seafloor intersection of which defines the trench location. The overriding plate contains volcanic arc (generally) and a forearc. The volcanic arc is caused by physical and chemical interactions between the subducted plate at depth and asthenospheric mantle associated with the overriding plate. The forearc lies between the trench and the volcanic arc. Forearcs have the lowest heatflow from the interior Earth because there is no asthenosphere (convecting mantle) between the forearc lithosphere and the cold subducting plate.

The inner trench wall marks the edge of the overriding plate and the outermost forearc. The forearc consists of igneous and metamorphic crust, and this crust acts as buttress to a growing accretionary prism (sediments scraped off the downgoing plate onto the inner trench wall, depending on how much sediment is supplied to the trench). If the flux of sediments is high, material will be transferred from the subducting plate to the overriding plate. In this case an accretionary prism grows and the location of the trench migrates progressively away from the volcanic arc over the life of the convergent margin. Convergent margins with growing accretionary prisms are called accretionary convergent margins and make up nearly half of all convergent margins. If the sediment flux is low, material will be transferred from the overriding plate to the subducting plate by a process of tectonic ablation known as subduction erosion and carried down the subduction zone. Forearcs undergoing subduction erosion typically expose igneous rocks. In this case, the location of the trench will migrate towards the magmatic arc over the life of the convergent margin. Convergent margins experiencing subduction erosion are called nonaccretionary convergent margins and comprise more than half of convergent plate boundaries. This is an oversimplification, because different parts of a convergent margin can experience sediment accretion and subduction erosion over its life.

The asymmetric profile across a trench reflects fundamental differences in materials and tectonic evolution. The outer trench wall and outer swell comprise seafloor that takes a few million years to move from where subduction-related deformation begins near the outer trench swell until sinking beneath the trench. In contrast, the inner trench wall is deformed by plate interactions for the entire life of the convergent margin. The forearc is continuously subjected to subduction-related earthquakes. This protracted deformation and shaking ensures that the inner trench slope is controlled by the angle of repose of whatever material it is composed of. Because they are composed of igneous rocks instead of deformed sediments, non-accretionary trenches have steeper inner walls than accretionary trenches.

Filled trenches

The composition of the inner trench slope and a first-order control on trench morphology is determined by sediment supply. Active accretionary prisms are common for trenches near continents where large rivers or glaciers reach the sea and supply great volumes of sediment which naturally flow to the trench. These filled trenches are confusing because in a plate tectonic sense they are indistinguishable from other convergent margins but lack the bathymetric expression of a trench. The Cascadia margin of the northwest USA is a filled trench, the result of sediments delivered by the rivers of the NW USA and SW Canada. The Lesser Antilles convergent margin shows the importance of proximity to sediment sources for trench morphology. In the south, near the mouth of the Orinoco River, there is no morphological trench

and the forearc plus accretionary prism is almost 500 km (310 mi) wide. The accretionary prism is so large that it forms the islands of Barbados and Trinidad. Northward the forearc narrows, the accretionary prism disappears, and only north of 17°N the morphology of a trench is seen. In the extreme north, far away from sediment sources, the Puerto Rico Trench is over 8,600 m (28,200 ft) deep and there is no active accretionary prism. A similar relationship between proximity to rivers, forearc width, and trench morphology can be observed from east to west along the Alaskan-Aleutian convergent margin. The convergent plate boundary offshore Alaska changes along its strike from a filled trench with broad forearc in the east (near the coastal rivers of Alaska) to a deep trench with narrow forearc in the west (offshore the Aleutian islands). Another example is the Makran convergent margin offshore Pakistan and Iran, which is a trench filled by sediments from the Tigris-Euphrates and Indus rivers. Thick accumulations of turbidites along a trench can be supplied by down-axis transport of sediments that enter the trench 1,000–2,000 km (620–1,200 mi) away, as is found for the Peru-Chile Trench south of Valparaíso and for the Aleutian Trench. Convergence rate can also be important for controlling trench depth, especially for trenches near continents, because slow convergence causes the capacity of the convergent margin to dispose of sediment to be exceeded.

There an evolution in trench morphology can be expected as oceans close and continents converge. While the ocean is wide, the trench may be far away from continental sources of sediment and so may be deep. As the continents approach each other, the trench may become filled with continental sediments and become shallower. A simple way to approximate when the transition from subduction to collision has occurred is when the plate boundary previously marked by a trench is filled enough to rise above sealevel.

Accretionary prisms and sediment transport

Accretionary prisms grow by frontal accretion, whereby sediments are scraped off, bulldozer-fashion, near the trench, or by underplating of subducted sediments and perhaps oceanic crust along the shallow parts of the subduction decollement. Frontal accretion over the life of a convergent margin results in younger sediments defining the outermost part of the accretionary prism and the oldest sediments defining the innermost portion. Older (inner) parts of the accretionary prism are much more lithified and have steeper structures than the younger (outer) parts. Underplating is difficult to detect in modern subduction zones but may be recorded in ancient accretionary prisms such as the Franciscan Group of California in the form of tectonic mélanges and duplex structures. Different modes of accretion are reflected in morphology of the inner slope of the trench, which generally shows three morphological provinces. The lower slope comprises imbricate thrust slices that form ridges. The mid slope may comprise a bench or terraces. The upper slope is smoother but may be cut by submarine canyons. Because accretionary convergent margins have high relief, are continuously deformed, and accommodate a large flux of sediments, they are vigorous systems of sediment dispersal and accumulation. Sediment transport is controlled by submarine landslides, debris flows, turbidity currents, and contourites. Submarine canyons transport sediment from beaches and rivers down the upper slope. These canyons form by channelized turbidites and generally lose definition with depth because continuous faulting disrupts the submarine channels. Sediments move down the inner trench wall via channels and a series of fault-controlled basins. The trench itself serves as an axis of sediment transport. If enough sediment moves to the trench, it may be completely filled so that

turbidity currents are able to carry sediments well beyond the trench and may even surmount the outer swell. Sediments from the rivers of SW Canada and NW USA spill over where the Cascadia trench would be and cross the Juan de Fuca plate to reach the spreading ridge several hundred kilometres to the west.

The slope of the inner trench slope of an accretionary convergent margin reflects continuous adjustments to the thickness and width of the accretionary prism. The prism maintains a 'critical taper', established in conformance with Mohr-Coulomb Theory for the pertinent materials. A package of sediments scraped off the downgoing lithospheric plate will deform until it and the accretionary prism that it has been added to attain a critical taper (constant slope) geometry. Once critical taper is attained, the wedge slides stably along its basal decollement. Strain rate and hydrologic properties strongly influence the strength of the accretionary prism and thus the angle of critical taper. Fluid pore pressures modify rock strength and are important controls of critical taper angle. Low permeability and rapid convergence may result in pore pressures that exceed lithostatic pressure and a relatively weak accretionary prism with a shallowly tapered geometry, whereas high permeability and slow convergence result in lower pore pressure, stronger prisms, and steeper geometry.

The Hellenic trench system is unusual because this convergent margin subducts evaporites. The slope of the surface of the southern flank of the Mediterranean Ridge (its accretionary prism) is low, about 1°, which indicates very low shear stress on the decollement at the base of the wedge. Evaporites influence the critical taper of the accretionary complex, as their mechanical properties differ from those of siliciclastic sediments, and because of their effect upon fluid flow and fluid pressure, which control effective stress. In the 1970s, the linear deeps of the Hellenic trench south of Crete were interpreted to be similar to trenches at other subduction zones, but with the realization that the Mediterranean Ridge is an accretionary complex, it became apparent that the Hellenic trench is actually a starved forearc basin, and that the plate boundary lies south of the Mediterranean Ridge.

Water and biosphere

The volume of water escaping from within and beneath the forearc results in some of Earth's most dynamic and complex interactions between aqueous fluids and rocks. Most of this water is trapped in pores and fractures in the upper lithosphere and sediments of the subducting plate. The average forearc is underrun by a solid volume of oceanic sediment that is 400 m (1,300 ft) thick. This sediment enters the trench with 50-60% porosity. These sediments are progressively squeezed as they are subducted, reducing void space and forcing fluids out along the decollement and up into the overlying forearc, which may or may not have an accretionary prism. Sediments accreted to the forearc are another source of fluids. Water is also bound in hydrous minerals, especially clays and opal. Increasing pressure and temperature experienced by subducted materials converts the hydrous minerals to denser phases that contain progressively less structurally-bound water. Water released by dehydration accompanying phase transitions is another source of fluids introduced to the base of the overriding plate. These fluids may travel through the accretionary prism diffusely, via interconnected pore spaces in sediments, or may follow discrete channels along faults. Sites of venting may take the form of mud volcanoes or seeps and are often associated with chemosynthetic communities. Fluids escaping from the

shallowest parts of a subduction zone may also escape along the plate boundary but have rarely been observed draining along the trench axis. All of these fluids are dominated by water but also contain dissolved ions and organic molecules, especially methane. Methane is often sequestered in an ice-like form (methane clathrate, also called gas hydrate) in the forearc. These are a potential energy source and can rapidly break down. Destabilization of gas hydrates has contributed to global warming in the past and will likely do so in the future.

Chemosynthetic communities thrive where cold fluids seep out of the forearc. Cold seep communities have been discovered in inner trench slopes down to depths of 7000 m in the western Pacific, especially around Japan, in the Eastern Pacific along North, Central and South America coasts from the Aleutian to the Peru-Chile trenches, on the Barbados prism, in the Mediterranean, and in the Indian Ocean along the Makran and Sunda convergent margins. These communities receive much less attention than the chemosynthetic communities associated with hydrothermal vents. Chemosynthetic communities are located in a variety of geological settings: above over-pressured sediments in accretionary prisms where fluids are expelled through mud volcanoes or ridges (Barbados, Nankai and Cascadia); along active erosive margins with faults; and along escarpments caused by debris slides (Japan trench, Peruvian margin). Surface seeps may be linked to massive hydrate deposits and destabilization (e.g. Cascadia margin). High concentrations of methane and sulfide in the fluids escaping from the seafloor are the principal energy sources for chemosynthesis.

Empty trenches and subduction erosion

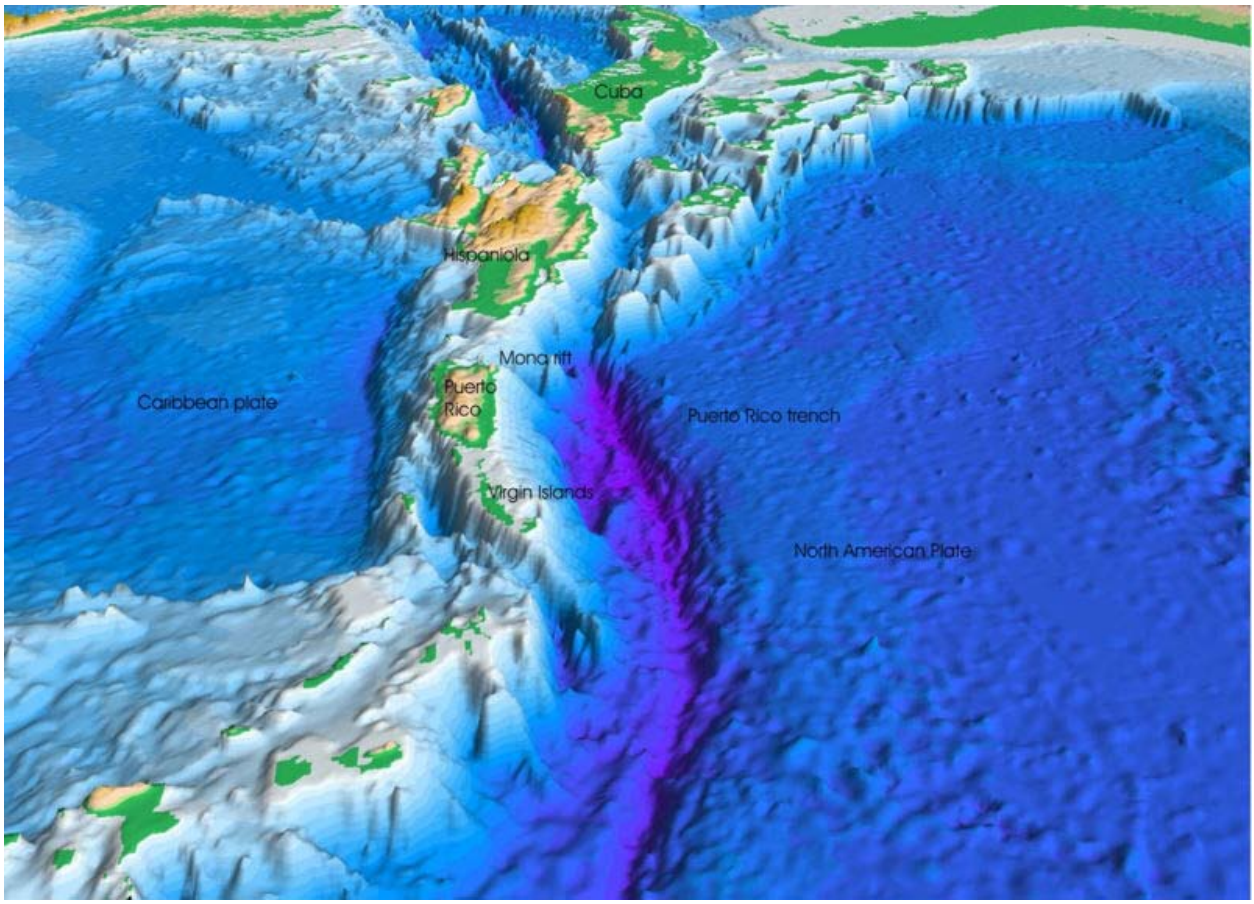
Trenches distant from an influx of continental sediments lack an accretionary prism, and the inner slope of such trenches is commonly composed of igneous or metamorphic rocks. Non-accretionary convergent margins are characteristic of (but not limited to) primitive arc systems. Primitive arc systems are those built on oceanic lithosphere, such as the Izu-Bonin-Mariana, Tonga-Kermadec, and Scotia (South Sandwich) arc systems. The inner trench slope of these convergent margins exposes the crust of the forearc, including basalt, gabbro, and serpentinized mantle peridotite. These exposures allow easy access to study the lower oceanic crust and upper mantle in place and provide a unique opportunity to study the magmatic products associated with the initiation of subduction zones. Most ophiolites probably originate in a forearc environment during the initiation of subduction, and this setting favors ophiolite emplacement during collision with blocks of thickened crust. Not all non-accretionary convergent margins are associated with primitive arcs. Trenches adjacent to continents where there is little influx of sediments carried by rivers, such as the central part of the Peru-Chile Trench, may also lack an accretionary prism.

Igneous basement of a nonaccretionary forearc may be continuously exposed by subduction erosion. This transfers material from the forearc to the subducting plate and can be accomplished by frontal erosion or basal erosion. Frontal erosion is most active in the wake of seamounts being subducted beneath the forearc. Subduction of large edifices (seamount tunneling) oversteepens the forearc, causing mass failures that carry debris towards and ultimately into the trench. This debris may be deposited in graben of the downgoing plate and subducted with it. In contrast, structures resulting from subduction erosion of the base of the forearc are difficult to recognize from seismic reflection profiles, so the possibility of basal erosion is difficult to confirm.

Subduction erosion may also diminish a once-robust accretionary prism if the flux of sediments to the trench diminishes.

Nonaccretionary forearcs may also be the site of serpentine mud volcanoes. These form where fluids released from the downgoing plate percolate upwards and interact with cold mantle lithosphere of the forearc. Mantle peridotite is hydrated into serpentinite, which is much less dense than peridotite and so will rise diapirically when there is an opportunity to do so. Some nonaccretionary forearcs are subjected to strong extensional stresses, for example the Marianas, and this allows buoyant serpentinite to rise to the seafloor where they form serpentinite mud volcanoes. Chemosynthetic communities are also found on non-accretionary margins such as the Marianas, where they thrive on vents associated with serpentinite mud volcanoes.

Factors affecting trench depth



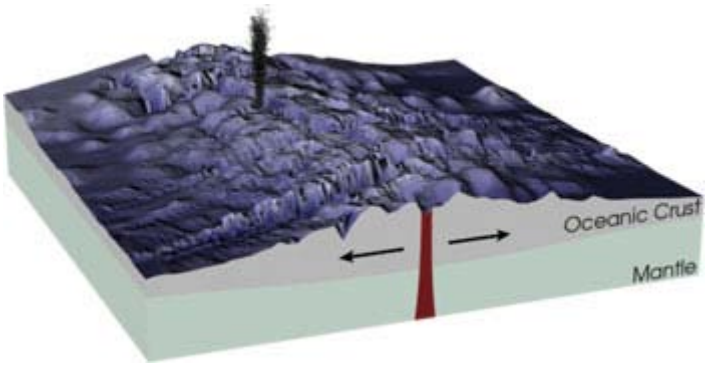
The Puerto Rico Trench

There are several factors that control the depth of trenches. The most important control is the supply of sediment, which fills the trench so that there is no bathymetric expression. It is therefore not surprising that the deepest trenches (deeper than 8,000 m (26,000 ft)) are all nonaccretionary. In contrast, all trenches with growing accretionary prisms are shallower than 8,000 m (26,000 ft). A second order control on trench depth is the age of the lithosphere at the

time of subduction. Because oceanic lithosphere cools and thickens as it ages, it subsides. The older the seafloor, the deeper it lies and this determines a minimum depth from which seafloor begins its descent. This obvious correlation can be removed by looking at the relative depth, the difference between regional seafloor depth and maximum trench depth. Relative depth may be controlled by the age of the lithosphere at the trench, the convergence rate, and the dip of the subducted slab at intermediate depths. Finally, narrow slabs can sink and roll back more rapidly than broad plates, because it is easier for underlying asthenosphere to flow around the edges of the sinking plate. Such slabs may have steep dips at relatively shallow depths and so may be associated with unusually deep trenches, such as the Challenger Deep.

Chapter- 8

Mid-ocean Ridge



Oceanic ridge

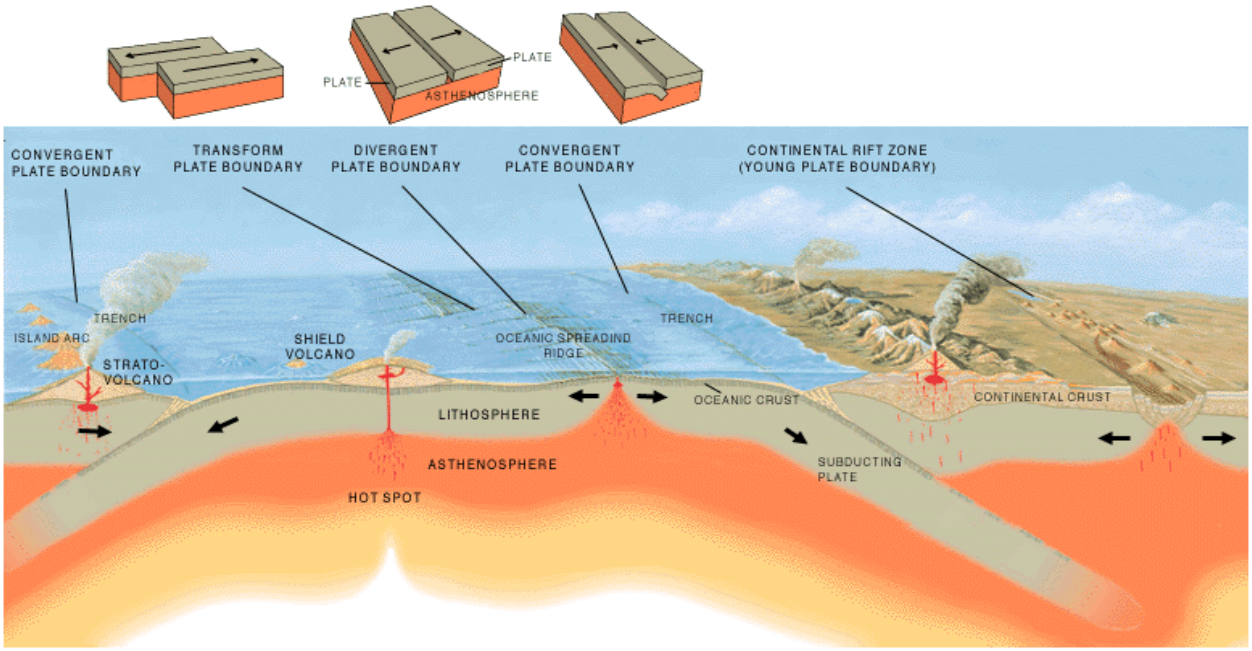
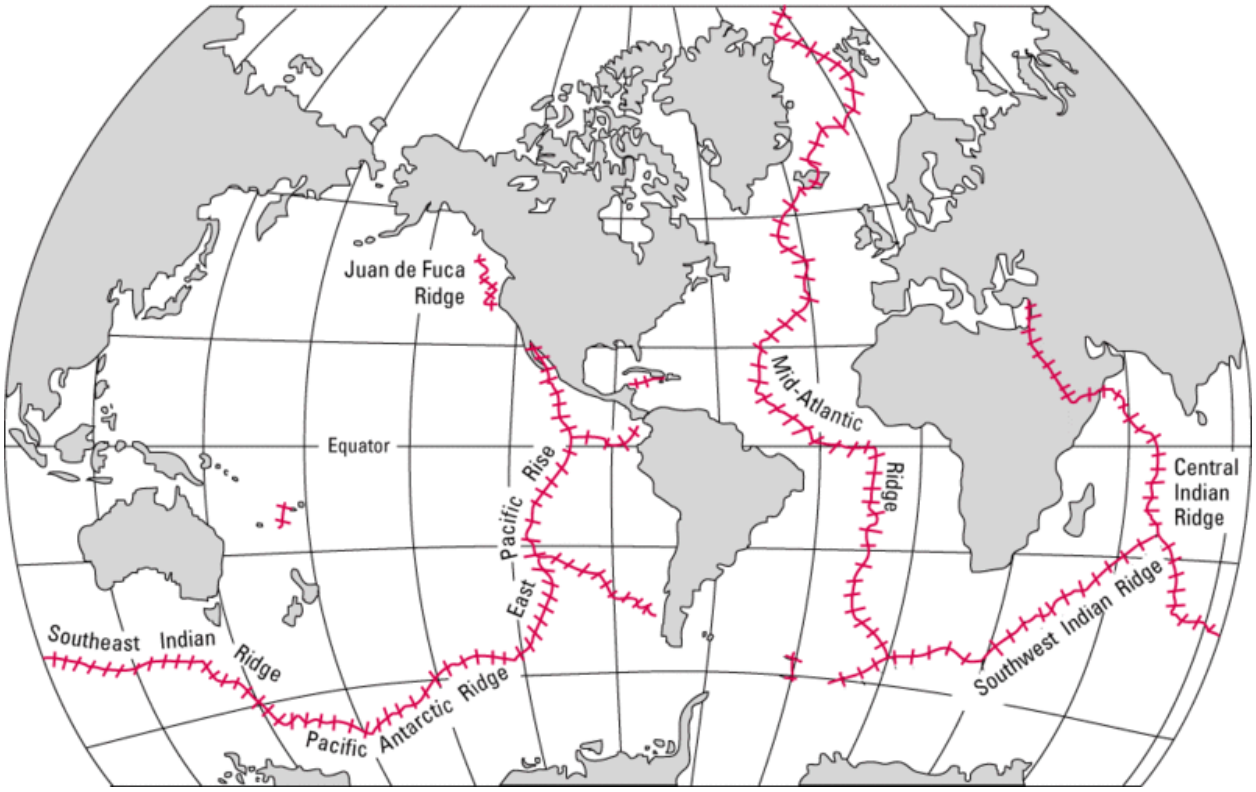


Diagram of oceanic ridge

A **mid-ocean ridge** (**MOR**) is a general term for an underwater mountain system that consists of various mountain ranges (chains), typically having a valley known as a rift running along its spine, formed by plate tectonics. This type of oceanic ridge is characteristic of what is known as an **oceanic spreading center**, which is responsible for seafloor spreading. The uplifted seafloor results from convection currents which rise in the mantle as magma at a linear weakness in the oceanic crust, and emerge as lava, creating new crust upon cooling. A mid-ocean ridge demarcates the boundary between two tectonic plates, and consequently is termed a divergent plate boundary.

The mid-ocean ridges of the world are connected and form a single global mid-oceanic ridge system that is part of every ocean, making the mid-oceanic ridge system the longest mountain range in the world. The continuous mountain range is 65,000 km (40,400 mi) long (several times longer than the Andes, the longest continental mountain range), and the total length of the oceanic ridge system is 80,000 km (49,700 mi) long.

Description



World Distribution of Mid-Oceanic Ridges; USGS

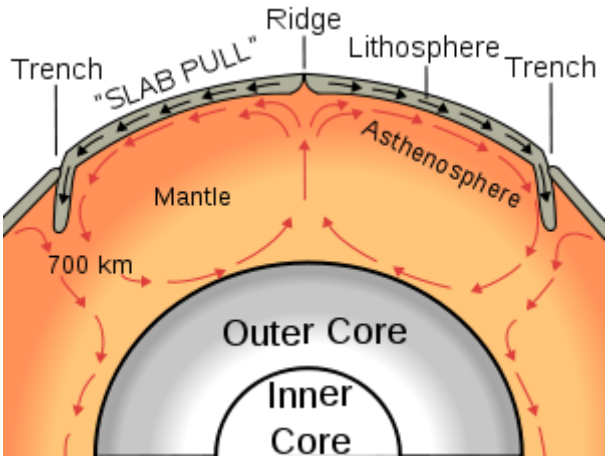
Mid-ocean ridges are geologically active, with new magma constantly emerging onto the ocean floor and into the crust at and near rifts along the ridge axes. The crystallized magma forms new crust of basalt (known as MORB for Mid-Ocean Ridge Basalt) and gabbro.

The rocks making up the crust below the sea floor are youngest at the axis of the ridge and age with increasing distance from that axis. New magma of basalt composition emerges at and near the axis because of decompression melting in the underlying Earth's mantle.

The oceanic crust is made up of rocks much younger than the Earth itself: most oceanic crust in the ocean basins is less than 200 million years old. The crust is in a constant state of "renewal" at the ocean ridges. Moving away from the mid-ocean ridge, ocean depth progressively increases; the greatest depths are in ocean trenches. As the oceanic crust moves away from the ridge axis, the peridotite in the underlying mantle cools and becomes more rigid. The crust and the relatively rigid peridotite below it make up the oceanic lithosphere.

Slow spreading ridges like the Mid-Atlantic Ridge generally have large, wide rift valleys, sometimes as big as 10–20 km (6.2–12 mi) wide and very rugged terrain at the ridge crest that can have relief of up to a 1,000 m (3,300 ft). By contrast, fast spreading ridges like the East Pacific Rise are narrow, sharp incisions surrounded by generally flat topography that slopes away from the ridge over many hundreds of miles.

Formation processes



Oceanic crust is formed at an oceanic ridge, while the lithosphere is subducted back into the asthenosphere at trenches.

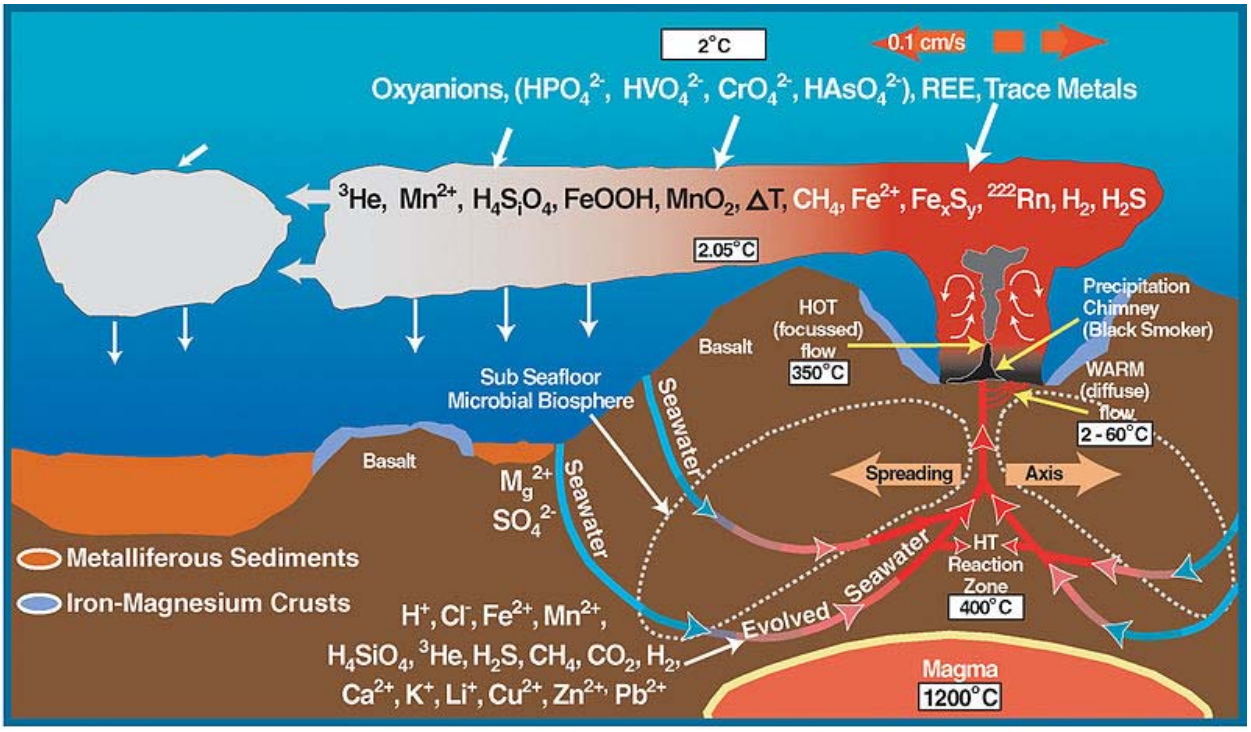


Diagram of oceanic ridge

There are two processes, ridge-push and slab pull, thought to be responsible for the spreading seen at mid-ocean ridges, and there is some uncertainty as to which is dominant. Ridge-push occurs when the growing bulk of the ridge pushes the rest of the tectonic plate away from the ridge, often towards a subduction zone. At the subduction zone, "slab-pull" comes into effect. This is simply the weight of the tectonic plate being subducted (pulled) below the overlying plate dragging the rest of the plate along behind it.

The other process proposed to contribute to the formation of new oceanic crust at mid-ocean ridges is the "mantle conveyor" (see image). However, there have been some studies which have shown that the upper mantle (asthenosphere) is too plastic (flexible) to generate enough friction to pull the tectonic plate along. Moreover, unlike in the image above, mantle upwelling that causes magma to form beneath the ocean ridges appears to involve only its upper 400 km (250 mi), as deduced from seismic tomography and from studies of the seismic discontinuity at about 400 km (250 mi). The relatively shallow depths from which the upwelling mantle rises below ridges are more consistent with the "slab-pull" process. On the other hand, some of the world's largest tectonic plates such as the North American Plate are in motion, yet are nowhere being subducted.

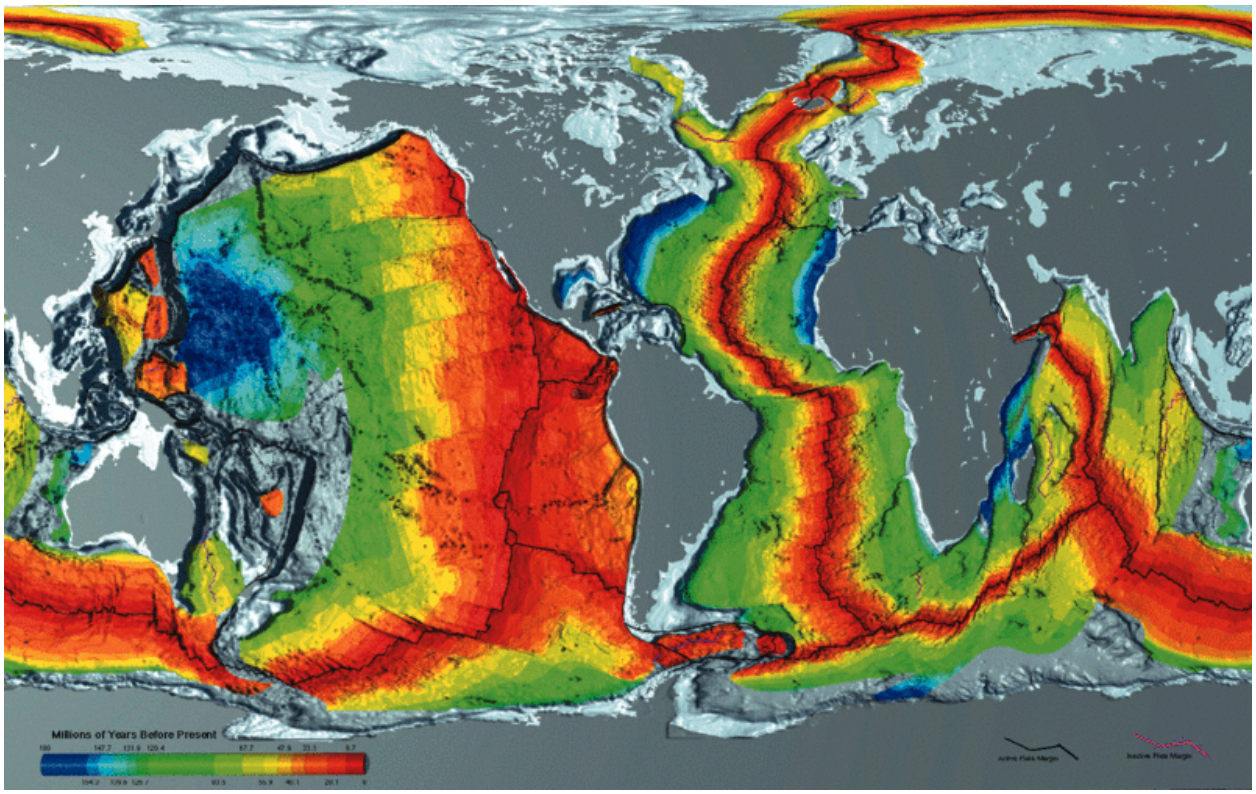
The rate at which the mid-ocean ridge creates new material is known as the spreading rate, and is generally measured in mm/yr. The common subdivisions of spreading rate are fast, medium and slow, whose values are generally >100 mm/yr, between 100 and 55 mm/yr and 55 to 20 mm/yr, respectively for full rates. The spreading rate of the north Atlantic Ocean is ~ 25 mm/yr, while in the Pacific region, it is 80–120 mm/yr. Ridges that spread at rates <20 mm/yr are referred to as ultraslow spreading ridges (e.g., the Gakkel ridge in the Arctic Ocean and the Southwest Indian

Ridge) and they provide a much different perspective on crustal formation than their faster spreading brethren.

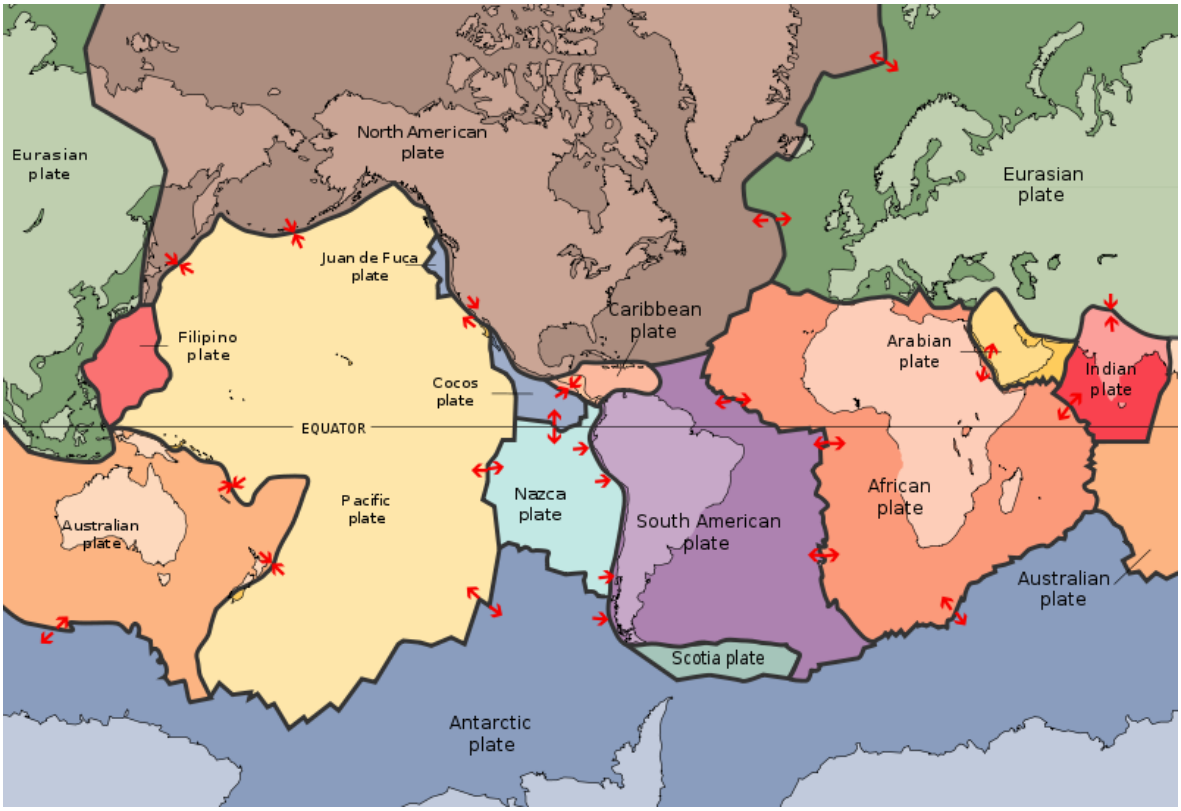
The mid-ocean ridge systems form new oceanic crust. As crystallized basalt extruded at a ridge axis cools below Curie points of appropriate iron-titanium oxides, magnetic field directions parallel to the Earth's magnetic field are recorded in those oxides. The orientations of the field in the oceanic crust record preserve a record of directions of the Earth's magnetic field with time. Because the field has reversed directions at irregular intervals throughout its history, the pattern of reversals in the ocean crust can be used as an indicator of age. Likewise, the pattern of reversals together with age measurements of the crust is used to help establish the history of the Earth's magnetic field.

History

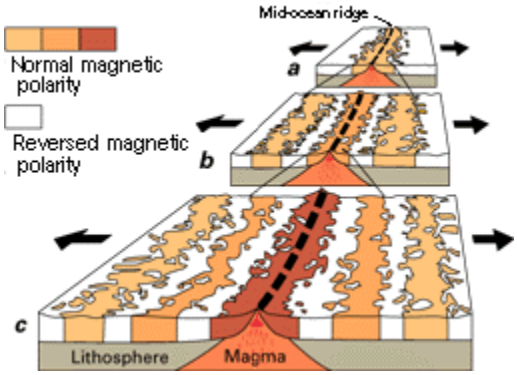
Discovery



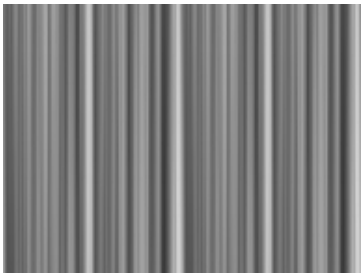
Age of oceanic crust. The red is most recent, and blue is the oldest



Plates in the crust of the earth, according to the plate tectonics theory



Seafloor magnetic striping



A demonstration of magnetic striping

Mid-ocean ridges are generally submerged deep in the ocean. It was not until the 1950s, when the ocean floor was surveyed in detail, that their full extent became known.

The *Vema*, a ship of the Lamont-Doherty Earth Observatory of Columbia University, traversed the Atlantic Ocean, recording data about the ocean floor from the ocean surface. A team led by Marie Tharp and Bruce Heezen analyzed the data and concluded that there was an enormous mountain chain running along the middle of floor of the Atlantic. Scientists gave the name "Mid-Atlantic Ridge" to the submarine mountain range.

At first, the ridge was thought to be a phenomenon specific to the Atlantic Ocean. However, as surveys of the ocean floor continued around the world, it was discovered that every ocean contains parts of the mid-ocean ridge system. Although the ridge system runs down the middle of the Atlantic Ocean, the ridge is located away from the center of other oceans.

Impact

Alfred Wegener proposed the theory of continental drift in 1912. He stated: *the Mid-Atlantic Ridge ... zone in which the floor of the Atlantic, as it keeps spreading, is continuously tearing open and making space for fresh, relatively fluid and hot sima [rising] from depth.* However, Wegener did not pursue this observation in his later works and his theory was dismissed by geologists because there was no mechanism to explain how continents could plow through ocean crust, and the theory became largely forgotten.

Following the discovery of the world-wide extent of the mid-ocean ridge in the 1950s, geologists faced a new task: explaining how such an enormous geological structure could have formed. In the 1960s, geologists discovered and began to propose mechanisms for sea floor spreading. Plate tectonics was a suitable explanation for sea floor spreading, and the acceptance of plate tectonics by the majority of geologists resulted in a major paradigm shift in geological thinking.

It is estimated that 20 volcanic eruptions occur each year along earth's mid-ocean ridges and that every year 2.5 km^2 (0.97 sq mi) of new sea floor is formed by this process. With a crustal thickness of 1 to 2 km (0.62 to 1.2 mi), this amounts to about 4 km^3 (0.96 cu mi) of new ocean crust formed every year.

Chapter- 9

Volcanic Arc and Volcanogenic Massive Sulfide Ore Deposit

Volcanic arc

A **volcanic arc** is a chain of volcanoes parallel to a mountain belt positioned in an arc shape as seen from above. Offshore volcanoes form islands, resulting in a volcanic island arc. Generally they are formed from subduction of an oceanic tectonic plate under another tectonic plate. The oceanic plate is saturated with water, and volatiles such as water drastically lower the melting point of the mantle. As the oceanic plate is subducted it is subjected to greater and greater pressures with increasing depth. This pressure squeezes water out of the plate and introduces it to the mantle. Here the mantle melts and forms magma at depth under the overriding plate. The magma ascends to form an arc of volcanoes parallel to the subduction zone.

These should not be confused with hotspot volcanic chains, where volcanos form one after another in the middle of a tectonic plate, as the plate moves over the hotspot. The Hawaiian Islands form a typical hotspot chain; the older islands (tens of millions of years) to the northwest are smaller and more lush than the recently-created (400,000 years ago) Hawaii island itself, which is more rocky.

There are two types of volcanic arcs:

- **oceanic arcs** form when oceanic crust subducts beneath other oceanic crust on an adjacent plate, creating a volcanic island arc. (Not all island arcs are volcanic island arcs.)
- **continental arcs** form when oceanic crust subducts beneath continental crust on an adjacent plate, creating an arc-shaped mountain belt. (Not all mountain belts are formed this way.)

In some situations, a single subduction zone may show both aspects along its length, as part of a plate subducts beneath a continent and part beneath adjacent oceanic crust.

(The term "volcanic arc" is often confused with the term "island arc". The former is a series of volcanos, but not necessary offshore. The latter is a series of islands, not necessarily composed solely of volcanos.)

Volcanoes are present in almost any mountain belt, but this does not make it a **volcanic arc**. Often there are isolated, but impressively huge volcanos in a mountain belt. For instance, Vesuvius and the Etna volcanos in Italy are part of separate but different kinds of mountainous volcanic ensembles.

The active front of a volcanic arc is the belt where volcanism develops at a given time. Active fronts may move over time (millions of years) changing their distance to the oceanic trench as well as their width.

Petrology

In the subduction zone, loss of water from the subducted slab induces partial melting of the overriding mantle and generates low-density, calc-alkaline magma that buoyantly rises to intrude and be extruded through the lithosphere of the overriding plate. This loss of water is due to the destabilization of the mineral chlorite at approximately 40-60 km depth. This is the reason for island arc volcanism at consistent distances from the subducting slab: because the temperature-pressure conditions for flux-melting volcanism due to chlorite destabilization will always occur at the same depth, the distance from the trench to the arc volcanoes is determined only by the dip angle of the subducting slab.

On the subducting side of the island arc is a deep and narrow oceanic trench, which is the trace at the Earth's surface of the boundary between the downgoing and overriding plates. This trench is created by the gravitational pull of the relatively dense subducting plate pulling the leading edge of the plate downward. Multiple earthquakes occur along this subduction boundary with the seismic hypocenters located at increasing depth under the island arc: these quakes define the Wadati-Benioff zones.

Ocean basins that are being reduced by subduction are called 'remnant oceans' as they will slowly be shrunken out of existence and crushed in the subsequent orogenic collision. This process has happened over and over in the geologic history of the Earth.

In the rock record, volcanic arcs can be seen as the volcanic rocks themselves, but because volcanic rock is easily weathered and eroded, it is more typical that they are seen as plutonic rocks, the rocks that formed underneath the arc (e.g. the Sierra Nevada batholith), or in the sedimentary record as lithic sandstones.

Examples

Two classic examples of oceanic island arcs are the Mariana Islands in the western Pacific Ocean and the Lesser Antilles in the western Atlantic Ocean. The Cascade Volcanic Arc in western North America and the Andes along the western edge of South America are examples of continental volcanic arcs. The best examples of volcanic arcs with both sets of characteristics are in the North Pacific, with the Aleutian Arc consisting of the Aleutian Islands and their extension the Aleutian Range on the Alaska Peninsula, and the Kuril-Kamchatka Arc comprising the Kuril Islands and southern Kamchatka Peninsula.

Continental arcs

- Cascade Volcanic Arc
- Alaska Peninsula and Aleutian Range
- Kamchatka
- Andes
    - North Volcanic Zone
    - Central Volcanic Zone
    - South Volcanic Zone
    - Austral Volcanic Zone
- Central America Volcanic Arc

Island arcs

- Aleutian Islands
- Kuril Islands
- Northeastern Japan arc
- Japan and Ryukyu Islands
- Izu-Bonin-Mariana Arc:
    - Izu Islands
    - Bonin Islands
    - Mariana Islands
- Luzon Volcanic Arc
- Philippines
- Tonga and Kermadec Islands
- Andaman and Nicobar Islands
- Mentawai Islands
- Sunda Arc
- Lesser Sunda Islands
- Tanimbar and Kai Islands
- Solomon Islands
- South Aegean Volcanic Arc
- Egean, or Hellenic arc
- Lesser Antilles, including the Leeward Antilles
- Scotia Arc:
    - South Sandwich Islands
- Mascarene Islands

Ancient island arcs

- Insular Islands
- Intermontane Islands
- Sakhalin island arc

Volcanogenic massive sulfide ore deposit

Volcanogentic massive sulfide ore deposit at Kidd Mine, Timmins, Ontario, Canada, formed 2.4 billion years ago on an ancient seafloor.

Volcanogenic massive sulfide ore deposits (**VMS**) are a type of metal sulfide ore deposit, mainly Cu-Zn-Pb which are associated with and created by volcanic-associated hydrothermal events in submarine environments.

These deposits are also sometimes called volcanic-hosted massive sulfide (VHMS) deposits. They are predominantly layered accumulations of sulfide minerals that precipitate from hydrothermal fluids on or below the seafloor in a wide range of ancient and modern geological settings. In modern oceans they are synonymous with sulfurous plumes called black smokers.

They occur within environments dominated by volcanic or volcanic-derived (e.g., volcano-sedimentary) rocks, and the deposits are contemporary and coincident with the formation of associated volcanic rocks. As a class, they represent a significant source of the world's Cu, Zn, Pb, Au, and Ag ores, with Co, Sn, Ba, S, Se, Mn, Cd, In, Bi, Te, Ga and Ge as mining by-products.

Volcanogenic massive sulfide deposits are forming today on the seafloor around undersea volcanoes along many mid ocean ridges, and within back-arc basins and forearc rifts. Mineral exploration companies are exploring for seafloor massive sulfide deposits; however, most exploration is concentrated in the search for land-based equivalents of these deposits.

The close association with volcanic rocks and eruptive centers sets VMS deposits apart from similar ore deposit types which share similar *source*, *transport* and *trap* processes. Some volcanogenic massive sulfide deposits are distinctive in that ore deposits are formed in close temporal association with submarine volcanism and are formed by hydrothermal circulation and exhalation of sulfides which are independent of sedimentary processes. This can set VMS deposits apart from sedimentary exhalative (SEDEX) deposits. Host rock assemblages, textural relationships in sulfide minerals and hydrothermal alteration mineralogy are the best tools for distinguishing SEDEX from VMS deposits (Robb, 2005).

There is a subclass of VMS deposits, the volcanic- and sediment-hosted massive sulfide (VSHMS) deposits, that do share characteristics that are hybrid between the VMS and SEDEX deposits. Notable examples of this class include the deposits of the Bathurst Camp, New Brunswick, Canada (e.g., Brunswick #12); the deposits of the Iberian Pyrite Belt, Portugal and Spain, and the Wolverine deposit, Yukon, Canada.

Genetic model

- The *source* of metal and sulfur in VMS deposits is a combination of incompatible elements that are leached from footwall rocks in the sub-seafloor hydrothermal alteration zone by hydrothermal circulation. In some deposits magmatic fluids have been suggested to be an additional source of metals and fluids. Hydrothermal circulation is generally considered to be driven via heat in the crust often related to deep-seated igneous intrusions.
- *Transport* of metals occurs via convection of hydrothermal fluids, the heat for this supplied by the magma chamber and subvolcanic intrusions that lie below the volcanic edifice. Cool ocean water is drawn into the hydrothermal zone and is heated by the volcanic rock and is then expelled into the ocean, the process enriching the hydrothermal fluid in sulfur and metal ions.
- The ore materials are precipitated within a fumarole field or a black smoker field when they are expelled into the ocean, cool and mix with seawater resulting in the precipitation of sulfide minerals as stratiform sulfide ore. Some deposits show evidence of formation via deposition of sulfide via replacement of volcanosedimentary or sedimentary rocks, whereas others may also form by invasion of sulfur-rich brines into unconsolidated sediments.

Geology

The typical location for VMS deposits is at the top of the felsic volcanic sequence, within a sequence of volcaniclastic tuffaceous epiclastics, cherts, sediments or perhaps fine tuffs which are usually related to the underlying volcanics. The hangingwall to the deposit is broadly related to a more mafic sequence of volcanic rocks, either Andesite (examples being Whim Creek & Mons Cupri, Western Australia or Millenbach, Canada), or basalt (Hellyer, Tasmania) or absent or sediments only (Kangaroo Caves, Western Australia).

VMS deposits are associated spatially and temporally with felsic volcanic rocks, usually present in the stratigraphy below the deposit, and often as the direct footwall to the deposit. Sediments are usually contiguous with VMS deposits in some form or another and typically are present as (manganiferous) cherts, volcanogenic tuffaceous sediments and chemical sediments deposited within a submarine environment.

The hanging wall to the deposit can be volcanic units essentially contiguous and contemporary with the footwall rocks, indicating mineralisation was developed in an inter-eruptive pause; it may be volcanic rock dissimilar to the footwall volcanics in bimodal volcanic subtypes, or it could be sedimentary strata if mineralisation occurred toward the end of an eruptive cycle.

Hybrid VMS-SEDEX deposits of the siliciclastic associations (see below) may be developed within interflow sediments or within units of sedimentary rocks which are present discontinuously throughout a larger and essentially contiguous volcanic package.

Altogether, these geological features have been interpreted to show an association of VMS deposits with hydrothermal systems developed above or around submarine volcanic centres.

Morphology

VMS deposits have a wide variety of morphologies, with mound shaped and bowl shaped deposits most typical. The bowl-shaped formations formed due to venting of hydrothermal solutions into submarine depressions - in many cases, this type of deposit can be confused with sedimentary exhalative deposits. The mound-shaped deposits formed in a way similar to that of modern massive sulfide deposits - via production of a hydrothermal mound formed by successive black smoker chimneys. Deposits that have formed in environments dominated by sedimentary rocks or highly permeable volcanic rocks can show a tabular morphology that mimics the geometry of the surrounding rocks.

VMS deposits have an ideal form of a conical area of highly altered volcanic or volcanogenic sedimentary rock within the feeder zone, which is called the **stringer sulfide** or **stockwork** zone, overlain by a mound of massive exhalites, and flanked by stratiform exhalative sulfides known as the **apron**.

The stockwork zone typically consists of vein-hosted sulfides (mostly chalcopyrite, pyrite, and pyrrhotite) with quartz, chlorite and lesser carbonates and barite.

The mound zone consists of laminated massive to brecciated pyrite, sphalerite (+/-galena), hematite, and barite. The mound can be up to several tens of metres thick and several hundred metres in diameter.

The apron zone is generally more oxidised, with stratiform, laminated sulfidic sediments, similar to SEDEX ores, and is generally manganese, barium and hematite enriched, with cherts, jaspers and chemical sediments common.

Metal zonation

Most VMS deposits show metal zonation, caused by the changing physical and chemical environments of the circulating hydrothermal fluid within the wall rock. Ideally, this forms a core of massive pyrite and chalcopyrite around the throat of the vent system, with a halo of chalcopyrite-sphalerite-pyrite grading into a distal sphalerite-galena and galena-manganese and finally a chert-manganese-hematite facies. Most VMS deposits show a vertical zonation of gold, with the cooler upper portions generally more enriched in gold and silver.

The mineralogy of VMS massive sulfide consists of over 90% iron sulfide, mainly in the form of pyrite, with chalcopyrite, sphalerite and galena also being major constituents. Magnetite is present in minor amounts; as magnetite content increases, the ores grade into massive oxide deposits. The gangue (the uneconomic waste material) is mainly quartz and pyrite or pyrrhotite. Due to the high density of the deposits some have marked gravity anomalies (Neves-Corvo, Portugal) which is of use in exploration.

Alteration morphology

Alteration haloes developed by VMS deposits are typically conical in shape, occur mostly stratigraphically below the original fluid flow location (not necessarily the ore itself), and are typically zoned.

The most intense alteration (containing the stringer sulfide zone) is generally located directly underneath the greatest concentration of massive sulfides, within the footwall volcanic sequence. If the stringer zone is displaced from the sulfides, it is often the product of tectonic deformation, or the formation of a hybrid SEDEX-like distal pool of sulfides.

The alteration assemblages of the footwall alteration zone is, from core outwards;

- *Silica alteration zone*, found in the most intensely altered examples, resulting in complete silica replacement of the host rocks, and associated with chalcopyrite-pyrite stringer zones.
- *Chlorite zone*, found in nearly all examples, consisting of chlorite +/- sericite +/- silica. Often the host rock is entirely replaced by chlorite, which may appear as a chlorite schist in deformed examples.
- *Sericite zone*, found in nearly all examples, consisting of sericite +/- chlorite +/- silica,
- *Silicification zone*, often gradational with background silica-albite metasomatism.

In all cases these alteration zones are metasomatism effects in the strictest sense, resulting in addition of potassium, silica, magnesium, and depletion of sodium. Chlorite minerals are usually more magnesian in composition within the footwall alteration zone of a VMS deposit than equivalent rocks within the same formation distally. The hangingwall to a VMS deposit is often weakly sodium depleted.

Alteration not associated with the ore forming process may also be omnipresent both above and below the massive sulfide deposit. Typical alteration textures associated with devitrification of submarine volcanic rocks such as rhyolitic glasses, notably formation of spherulites, of perlite, lithophysae, and low-temperature prehnite-pumpellyite facies sub-seafloor alteration is ubiquitous though often overprinted by later metamorphic events.

Metamorphic mineralogical, textural and structural changes within the host volcanic sequence may also further serve to disguise original metasomatic mineral assemblages.

Classification

Deposits of this class have been classified by numerous workers in different ways (e.g., metal sources, type examples, geodynamic setting. Recently, VMS deposits have been classified according to their setting and rock associations into five subclasses, including (after Barrie and Hannington (1999) and Franklin et al. (2005)):

Mafic Associated

VMS deposits associated with geological environments dominated by mafic rocks, commonly ophiolite sequences. The Cyprus, Oman ophiolites host examples and ophiolite-hosted deposits are found in the Newfoundland Appalachians represent classic districts of this subclass

Bimodal-mafic

VMS deposits associated with environments dominated by mafic volcanic rocks, but with up to 25% felsic volcanic rocks, the latter often hosting the deposits. The Noranda, Flin Flon-Snow Lake and Kidd Creek camps would be classic districts of this group

Mafic-siliciclastic

VMS deposits associated with sub-equal proportions of mafic volcanic and siliciclastic rocks; felsic rocks can be a minor component; and mafic (and ultramafic) intrusive rocks are common. In metamorphic terranes may be known as or pelitic-mafic associated VMS deposits. The Besshi deposits in Japan and Windy Craggy, BC represent classic districts of this group.

Felsic-siliciclastic

VMS deposits associated with siliciclastic sedimentary rock dominated settings with abundant felsic rocks and less than 10% mafic material. These settings are often shale-rich siliciclastic-felsic or bimodal siliciclastic. The Bathurst camp, New Brunswick, Canada; Iberian Pyrite Belt, Spain and Portugal; and Finlayson Lake areas, Yukon, Canada are classic districts of this group

Bimodal-felsic

VMS deposits associated with bimodal sequences where felsic rocks are in greater abundance than mafic rocks with only minor sedimentary rocks. The Kuroko deposits, Japan; Buchans deposits, Canada; and Skellefte deposits, Sweden are classic districts of this group.