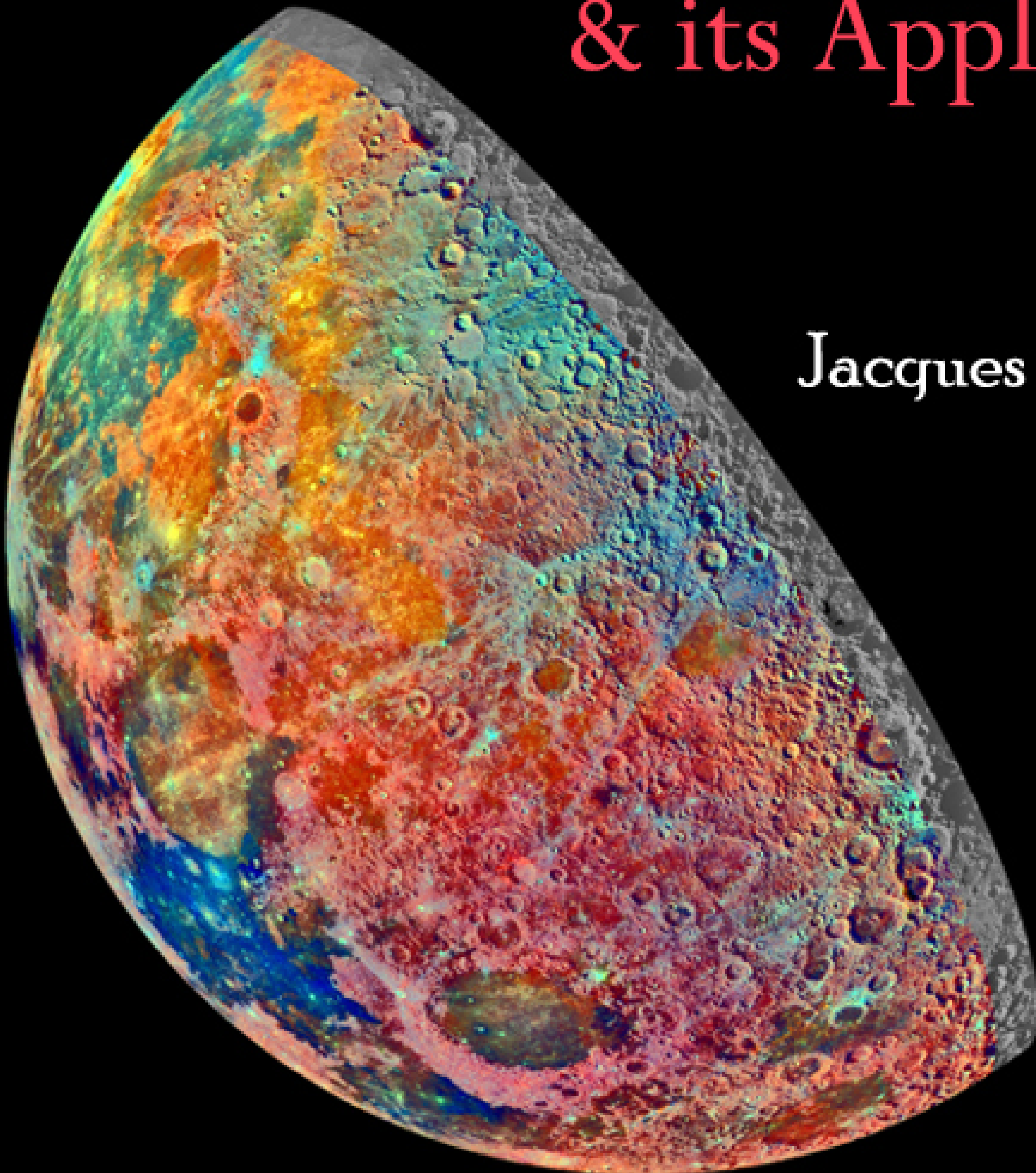
Geology & its Applications

Jacques Dugan



First Edition, 2012

ISBN 978-81-323-1956-6

Published by:
Learning Press
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

Table of Contents

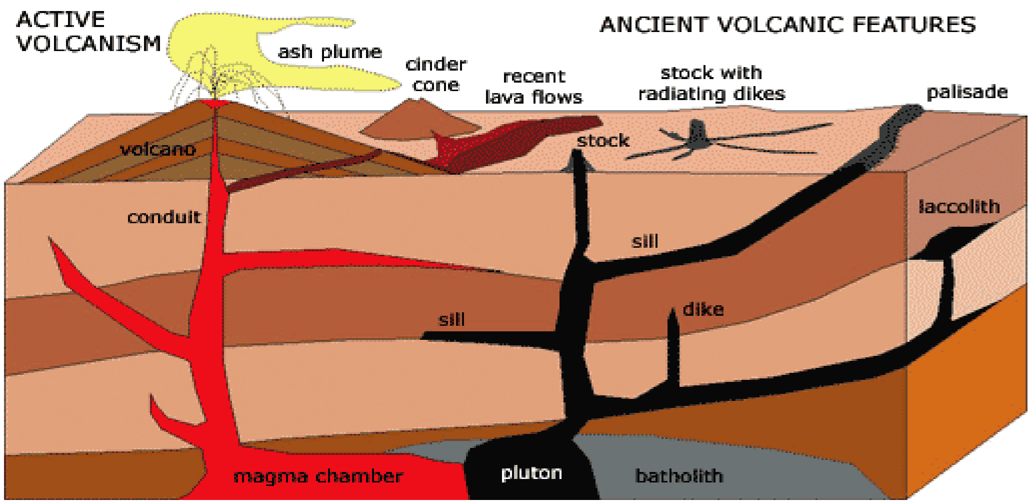
Chapter- 1

Introduction to Geology

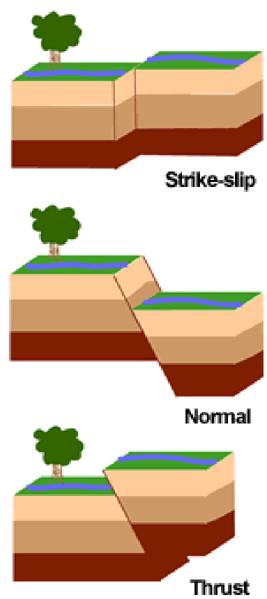
Students examining the Wasatch Fault near Salt Lake City, Utah

Geology (from the Greek γῆ, *gê*, "earth" and λόγος, *logos*, "study") is the science and study of the solid Earth and the processes by which it is shaped and changed. Geology provides primary evidence for plate tectonics, the history of life and evolution, and past climates. In modern times, geology is commercially important for mineral and hydrocarbon exploration, is publically important for predicting and understanding natural hazards, plays an essential role in geotechnical engineering, and is a major academic discipline.

Geological evolution of an area



An originally horizontal sequence of sedimentary rocks (in shades of tan) are affected by igneous activity. Deep below the surface are a magma chamber and large associated igneous bodies. The magma chamber feeds the volcano, and sends off shoots of magma that will later crystallize into dikes and sills. Magma also advances upwards to form intrusive igneous bodies. The diagram illustrates both a cinder cone volcano, which releases ash, and a composite volcano, which releases both lava and ash.



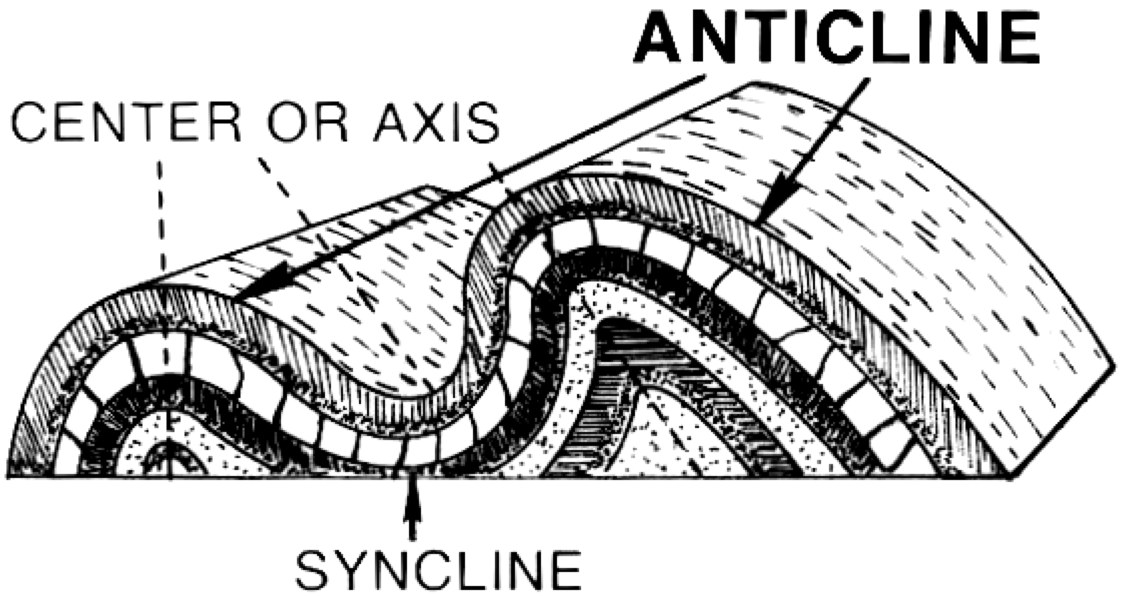
An illustration of the three types of faults. Strike-slip faults occur when rock units slide past one another, normal faults occur when rocks are undergoing horizontal extension, and thrust faults occur when rocks are undergoing horizontal shortening.

The geology of an area evolves through time as rock units are deposited and inserted and deformational processes change their shapes and locations.

Rock units are first emplaced either by deposition onto the surface or intrusion into the overlying rock. Deposition can occur when sediments settle onto the surface of the Earth and later lithify into sedimentary rock, or when as volcanic material such as volcanic ash or lava flows blanket the surface. Igneous intrusions such as batholiths, laccoliths, dikes, and sills, push upwards into the overlying rock, and crystallize as they intrude.

After the initial sequence of rocks has been deposited, the rock units can be deformed and/or metamorphosed. Deformation typically occurs as a result of horizontal shortening, horizontal extension, or side-to-side (strike-slip) motion. These structural regimes broadly relate to convergent boundaries, divergent boundaries, and transform boundaries, respectively, between tectonic plates.

When rock units are placed under horizontal compression, they shorten and become thicker. Because rock units, other than muds, do not significantly change in volume, this is accomplished in two primary ways: through faulting and folding. In the shallow crust, where brittle deformation can occur, thrust faults form, which cause deeper rock to move on top of shallower rock. Because deeper rock is often older, as noted by the principle of superposition, this can result in older rocks moving on top of younger ones. Movement along faults can result in folding, either because the faults are not planar, or because the rock layers are dragged along, forming drag folds, as slip occurs are along the fault. Deeper in the Earth, rocks behave plastically, and fold instead of faulting. These folds can either be those where the material in the center of the fold buckles upwards, creating "antiforms", or where it buckles downwards, creating "synforms". If the tops of the rock units within the folds remain pointing upwards, they are called anticlines and synclines, respectively. If some of the units in the fold are facing downward, the structure is called an overturned anticline or syncline, and if all of the rock units are overturned or the correct up-direction is unknown, they are simply called by the most general terms, antiforms and synforms.

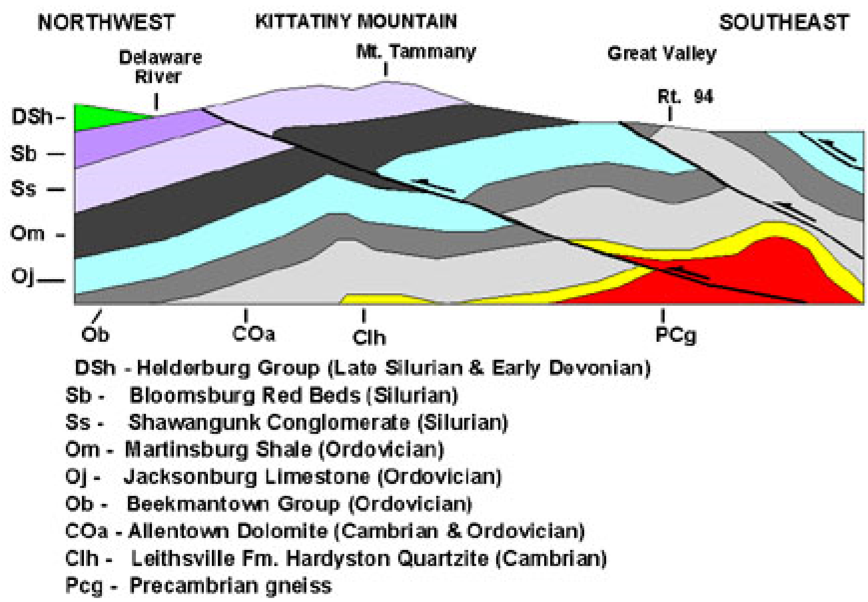


A diagram of folds, indicating an anticline and a syncline

Even higher pressures and temperatures during horizontal shortening can cause both folding and metamorphism of the rocks. This metamorphism causes changes in the mineral composition of the rocks; creates a foliation, or planar surface, that is related to mineral growth under stress; and can remove signs of the original textures of the rocks, such as bedding in sedimentary rocks, flow features of lavas, and crystal patterns in crystalline rocks.

Extension causes the rock units as a whole to become longer and thinner. This is primarily accomplished through normal faulting and through the ductile stretching and thinning. Normal faults drop rock units that are higher below those that are lower. This typically results in younger units being placed below older units. Stretching of units can result in their thinning; in fact, there is a location within the Maria Fold and Thrust Belt in which the entire sedimentary sequence of the Grand Canyon can be seen over a length of less than a meter. Rocks at the depth to be ductilely stretched are often also metamorphosed. These stretched rocks can also pinch into lenses, known as boudins, after the French word for "sausage", because of their visual similarity.

Where rock units slide past one another, strike-slip faults develop in shallow regions, and become shear zones at deeper depths where the rocks deform ductilely.



Geologic cross-section of Kittatinny Mountain. This cross-section shows metamorphic rocks, overlain by younger sediments deposited after the metamorphic event. These rock units were later folded and faulted during the uplift of the mountain.

The addition of new rock units, both depositionally and intrusively, often occurs during deformation. Faulting and other deformational processes result in the creation of topographic gradients, causing material on the rock unit that is increasing in elevation to be eroded by hillslopes and channels. These sediments are deposited on the rock unit that is going down. Continual motion along the fault maintains the topographic gradient in spite of the movement of sediment, and continues to create accommodation space for the material to deposit. Deformational events are often also associated with volcanism and igneous activity. Volcanic ashes and lavas accumulate on the surface, and igneous intrusions enter from below. Dikes, long, planar igneous intrusions, enter along cracks, and therefore often form in large numbers in areas that are being actively deformed. This can result in the emplacement of dike swarms, such as those that are observable across the Canadian shield, or rings of dikes around the lava tube of a volcano.

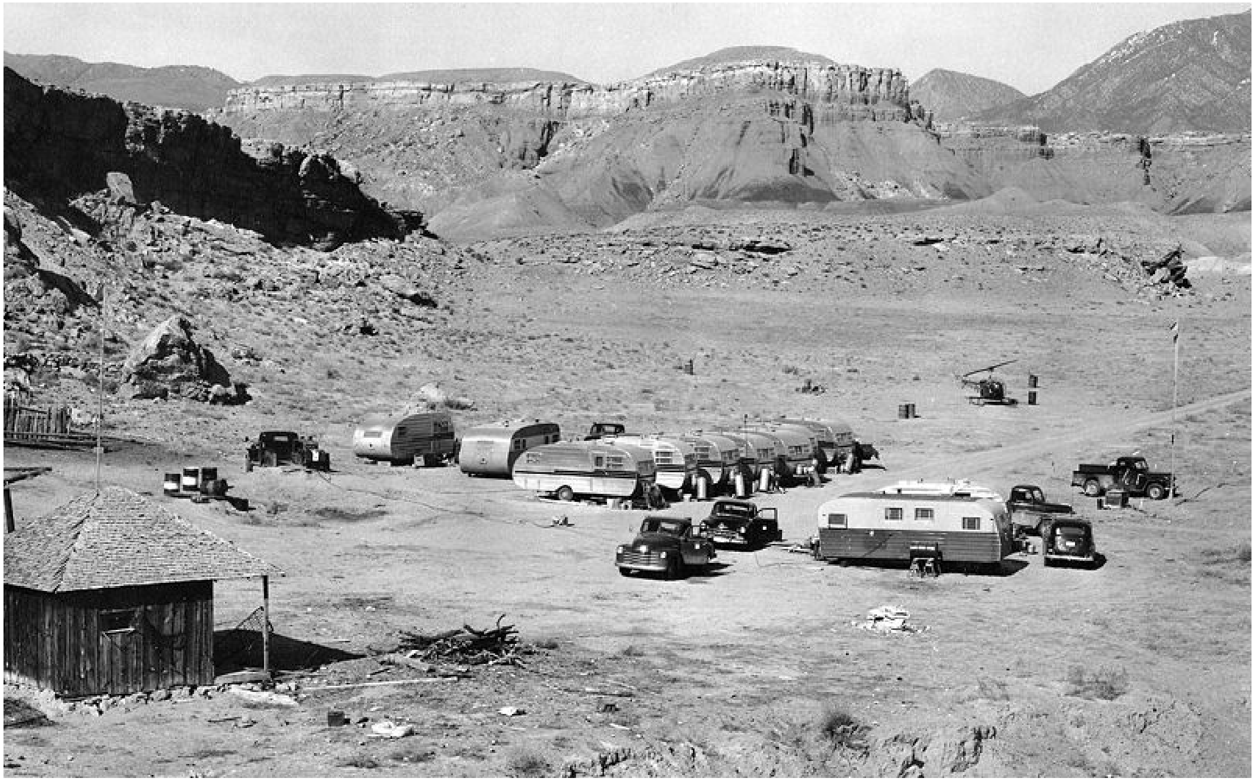
All of these processes do not necessarily occur in a single environment, and do not necessarily occur in a single order. The Hawaiian Islands, for example, consist almost entirely of layered basaltic lava flows. The sedimentary sequences of the mid-continental United States and the Grand Canyon in the southwestern United States contain almost-undeformed stacks of sedimentary rocks that have remained in place since Cambrian time. Other areas are much more geologically complex. In the southwestern United States, sedimentary, volcanic, and intrusive rocks have been metamorphosed, faulted, foliated, and folded. Even older rocks, such as the Acasta gneiss of the Slave craton in northwestern Canada, the oldest known rock in the world have been metamorphosed to the point where their origin is undiscernable without laboratory analysis. In addition, these processes can occur in stages. In many places, the Grand Canyon in the southwestern United States being a very visible example, the lower rock units were metamorphosed and deformed, and then deformation ended and the upper, undeformed units were deposited. Although any amount of rock emplacement and rock deformation can occur, and they can occur any number of times, these concepts provide a guide to understanding the geological history of an area.

Methods of geology

Geologists use a number of field, laboratory, and numerical modeling methods to decipher Earth history and understand the processes that occur on and in the Earth. In typical geological investigations, geologists use primary information related to petrology (the study of rocks), stratigraphy (the study of sedimentary layers), and structural geology (the study of positions of rock units and their deformation). In many cases, geologists also study modern soils, rivers, landscapes, and glaciers; investigate past and current life and biogeochemical pathways, and use geophysical methods to investigate the subsurface.

Field methods

A standard Brunton Geo compass, used commonly by geologists in mapping and surveying



A typical USGS field mapping camp in the 1950's

Today, handheld computers with GPS and geographic information systems software are often used in geological field work (digital geologic mapping).

Geological field work varies depending on the task at hand. Typical fieldwork could consist of:

- Geological mapping
  - Structural mapping: the locations of the major rock units and the faults and folds that led to their placement there.

    - Stratigraphic mapping: the locations of sedimentary facies (lithofacies and biofacies) or the mapping of isopachs of equal thickness of sedimentary rock
    - Surficial mapping: the locations of soils and surficial deposits
- Surveying of topographic features
    - Creation of topographic maps
    - Work to understand change across landscapes, including:
        - Patterns of erosion and deposition
        - River channel change through migration and avulsion
        - Hillslope processes
- Subsurface mapping through geophysical methods
    - These methods include:
        - Shallow seismic surveys
        - Ground-penetrating radar
        - Electrical resistivity tomography
    - They are used for:
        - Hydrocarbon exploration
        - Finding groundwater
        - Locating buried archaeological artifacts
- High-resolution stratigraphy
    - Measuring and describing stratigraphic sections on the surface
    - Well drilling and logging
- Biogeochemistry and geomicrobiology
    - Collecting samples to:
        - Determine biochemical pathways
        - Identify new species of organisms. These organisms may help to show:
        - Identify new chemical compounds
    - And to use these discoveries to
        - Understand early life on Earth and how it functioned and metabolized
        - Find important compounds for use in pharmaceuticals.
- Paleontology: excavation of fossil material
    - For research into past life and evolution
    - For museums and education
- Collection of samples for geochronology and thermochronology
- Glaciology: measurement of characteristics of glaciers and their motion

Chapter- 2

History of Geology

The **history of geology** is concerned with the development of the natural science of geology. Geology is the scientific study of the origin, history, and structure of the Earth. Throughout the ages geology provides essential theories and data that shape how society conceptualizes the Earth.

Antiquity

A mosquito and a fly in this Baltic amber necklace are between 40 and 60 million years old

The slightly misshapen octahedral shape of this rough diamond crystal in matrix is typical of the mineral. Its lustrous faces also indicate that this crystal is from a primary deposit.

Some of the first geological thoughts were about the origin of the Earth. With a lack of knowledge and technology, ancient philosophers created mythical stories and proposed theories to explain how the Earth came to be. Ancient Greece developed some primary geological concepts concerning the origin of the Earth. Additionally, in the 4th century BC Aristotle made critical observations of the slow rate of geological change. He observed the composition of the land and formulated a theory where the Earth changes at a slow rate and that these changes cannot be observed during one person's lifetime. Aristotle developed one of the first evidentially based concepts connected to the geological realm regarding the rate at which the Earth physically changes.

However, it was his successor at the Lyceum, the philosopher Theophrastus, who made the greatest progress in antiquity in his work *On Stones*. He described many minerals and ores both from local mines such as those at Laurium near Athens, and further afield. He also quite naturally discussed types of marble and building materials like limestones, and attempted a primitive classification of the properties of minerals by their properties such as hardness.

Much later in the Roman period, Pliny the Elder produced a very extensive discussion of many more minerals and metals then widely used for practical ends. He was among the first to correctly identify the origin of amber as a fossilized resin from trees by the observation of insects trapped within some pieces. He also laid the basis of crystallography by recognising the octahedral habit of diamond.

Middle Ages

Abu al-Rayhan al-Biruni (973-1048 AD) was one of the earliest Muslim geologists, whose works included the earliest writings on the geology of India, hypothesizing that the Indian subcontinent was once a sea:

Ibn Sina (Avicenna, 981-1037), a Persian polymath, made significant contributions to geology and the natural sciences (which he called *Attabieyat*) along with other natural philosophers such as Ikhwan AI-Safa and many others. Ibn Sina wrote an encyclopaedic work entitled "*Kitab al-Shifa*" (the Book of Cure, Healing or Remedy from ignorance), in which Part 2, Section 5, contains his commentary on Aristotle's Mineralogy and Meteorology, in six chapters: Formation of mountains, The advantages of mountains in the formation of clouds; Sources of water; Origin of earthquakes; Formation of minerals; The diversity of earth's terrain. Goodfield (1965), commented on Avicenna's contribution: "Around A.D. 1000, Avicenna was already suggesting a hypothesis about the origin of mountain ranges, which in the Christian world, would still have been considered quite radical eight hundred years later".

In medieval China, one of the most intriguing naturalists was Shen Kuo (1031-1095), a polymath personality who dabbled in many fields of study in his age. In terms of geology, Shen Kuo is one of the first naturalists to have formulated a theory of geomorphology. This was based on his observations of sedimentary uplift, soil erosion, deposition of silt, and marine fossils found in the Taihang Mountains, located hundreds of miles from the Pacific Ocean. He also formulated a theory of gradual climate change, after his observation of ancient petrified bamboos found in a preserved state underground near Yanzhou (modern Yan'an), in the dry northern climate of Shaanxi province. He formulated a hypothesis for the process of land formation: based on his observation of fossil shells in a geological stratum in a mountain hundreds of miles from the ocean, he inferred that the land was formed by erosion of the mountains and by deposition of silt.

Industrial Revolution

During the 17th century the heated debate between religion and science over the Earth's origin further propelled interest in the Earth and brought about more systematic identification techniques of the Earth's strata. The Earth's strata can be defined as horizontal layers of rock having approximately the same composition throughout.

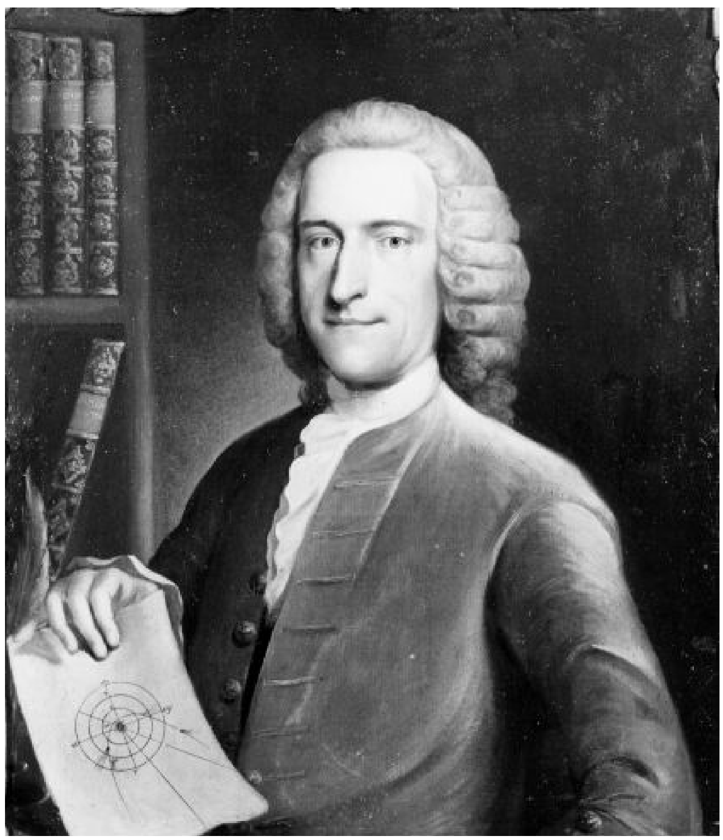
Bust of William Smith, in the Oxford University Museum of Natural History

The popular mining industry during the 18th century both increased social interest and drove scientists to form more systematic and detailed studies of the composition of the Earth's strata. From the increased societal interest of geology, in 1741 it became a specific field of study to be taught at the National Museum of Natural History in France. The controversial topic of the Earth's origin continued to circulate between religious and scientific circles. Two feuding theories developed to explain the Earth's origin with designated followers: the Neptunists whose theory supported that of the Bible's Great Flood and the Plutonists who believed the Earth gradually formed over an immeasurable amount of time.

The dialogue about the creation of the Earth occurring within the scientific community and the evidence being uncovered in Civil Engineering works during the 19th century drove the development of the stratigraphical column; many of the concepts behind this invention can be attributed to William Smith, Georges Cuvier and Alexander Broignart. Also in this period, imperialism motivated countries to sponsor voyages of exploration to distant lands. Charles Darwin made geological observations on such a voyage, providing evidential support of his revolutionary theory of evolution. Again a religious debate ensued; two conflicting groups, uniformitarians and catastrophists, argued over the age of the Earth. Charles Lyell, an influential uniformitarian, published his book in 1830 the “Principles of Geology” which proposed that the Earth changes very gradually and is immeasurably old.

The theory of Continental Drift was proposed in 1912 by Alfred Wegener. This idea, unaccepted at the time, suggested a method of continental movement that occurred throughout history. Supporting evidence of Continental Drift, including seafloor spreading and paleomagnetism, justified the theory of Continental Drift, which in the late 1960s was replaced and encompassed by Plate Tectonics. In the latter half of the 20th century the approach to the study of geology changed to evaluating the Earth in a broader perspective. To coincide with this perspective, satellites were first used in the 1970s and are still currently in use by the Landsat Program to produce images of the Earth that can be geologically studied.

17th century



A portrait of Whiston with a diagram demonstrating his theories of cometary catastrophism best described in *A New Theory of the Earth*

It was not until the 17th century that geology made great strides in its development. At this time, geology became its own entity in the world of natural science. It was discovered by the Christian world that different translations of the Bible contained different versions of the biblical text. The one entity that remained consistent through all of the interpretations was that the Deluge had formed the world’s geology and geography. To prove the Bible’s authenticity, individuals felt the need to demonstrate with scientific evidence that the Great Flood had in fact occurred. With this enhanced desire for data came an increase in observations of the Earth's composition, which in turn led to the discovery of fossils. Although theories that resulted from the heightened interest in the Earth's composition were often manipulated to support the concept of the Deluge, a genuine outcome was a greater interest in the makeup of the Earth. Due to the strength of Christian beliefs during the 17th century, the theory of the origin of the Earth that was most widely accepted was *A New Theory of the Earth* published in 1696, by William Whiston. Whiston used Christian reasoning to "prove" that the Great Flood had occurred and that the flood had formed the rock strata of the Earth.

18th century

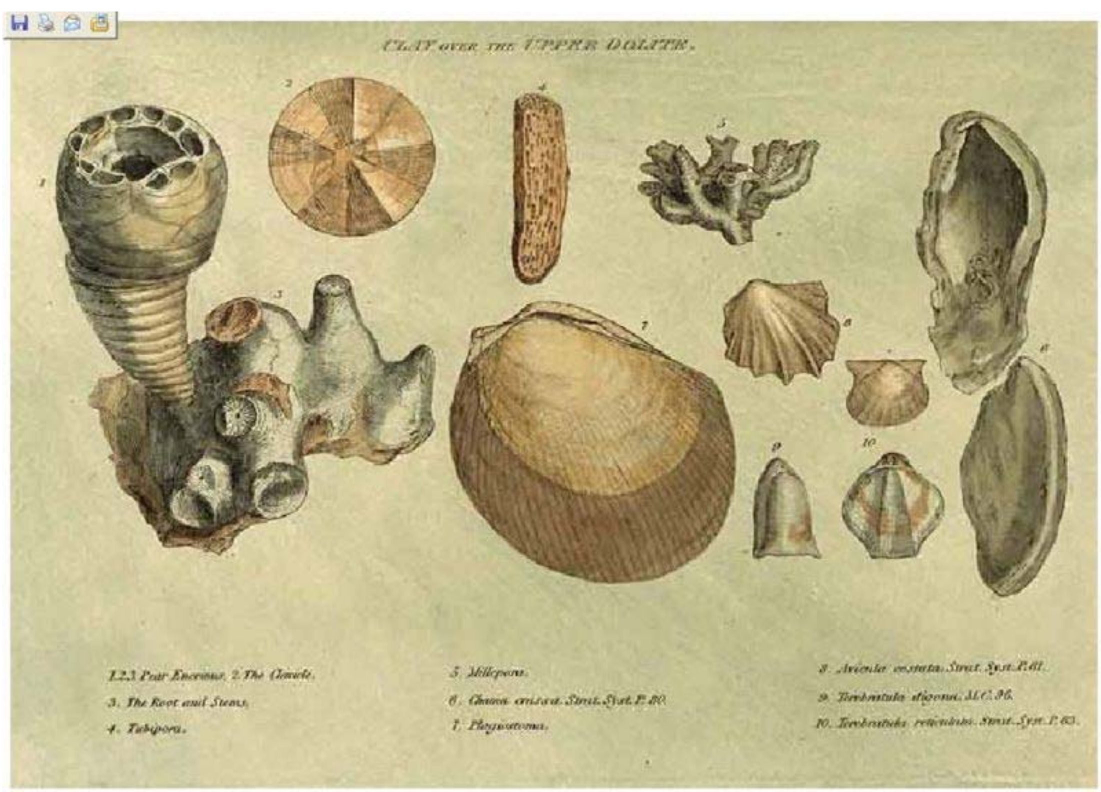
From this increased interest in the nature of the Earth and its origin, came a rise in the interest of minerals and other components of the Earth's crust. Moreover, the increasing commercial importance of mining in Europe during the mid to late 18th century made the possession of accurate knowledge about ores and their natural distribution essential. Scholars began to study the makeup of the Earth in a systematic manner, with detailed comparisons and descriptions not only of the land itself, but of the semi-precious metals that had such great value. For example, in 1774 Abraham Gottlob Werner published the book "Von den äusserlichen Kennzeichen der Fossilien" (*On the External Characters of Minerals*), which brought him widespread recognition because he presented a detailed system for identifying specific minerals based on external characteristics. The more efficiently that productive land for mining could be found and that the semi-precious metals could be identified, the more money that could be made. This drive for economic success fueled geology into the limelight and made it a popular subject to pursue. With an increased number of people studying it, came more detailed observations and more information about the Earth.

During the eighteenth century, the story of the history of the Earth; namely the religious concept versus factual evidence once again became a popular discussion in society. In 1749 the French naturalist Georges-Louis Leclerc, Comte de Buffon published his "Histoire Naturelle" in which he attacked the popular Christian concepts of Whiston and other Christian theorists on the topic of the history of Earth. From experimentation with cooling globes, he found that the age of the Earth was not 6,000 years as stated in the Bible, but rather 75,000 years. Another individual who attributed the history of the Earth to neither God nor the Bible was the philosopher Immanuel Kant who published this concept in 1755 in his "Allgemeine Naturgeschichte und Theories des Himmels." From the works of these educated men, as well as others, it became acceptable by the mid eighteenth century to question the age of the Earth. This questioning represented a turning point in the study of the Earth. It was now possible to study the history of the Earth from a scientific perspective rather than a religious one.

With science as a driving force behind the investigation of the Earth's history, the study of geology could now become a distinct field of science. First, the terminology and definition of what geological study consisted of had to be determined. The term geology was first used professionally in publications by two Genevian naturalists, Jean-Andre Deluc and Horace-Benedict de Saussure. Geology was not well received as a term until it was used in the very popular encyclopedia, the "Encyclopedie," published in 1751 by Denis Diderot. Once the term was coined as the study of the Earth and its history, geology slowly became a more prevalent and recognized science of its own standing that could be taught as a field of study at educational institutions. In 1741 the most well-known institution in the field of natural history, the National Museum of Natural History in France designated the first teaching position specifically for geology. This was an important step in the further development of geology as a science and in the recognition of the importance of widely distributing this knowledge.

After the designation of geology as a specific field of study in an institution, this subject flourished in educated society. By the 1770s two feuding theories with designated followers were established. These contrasting theories explained how the rock layers of the Earth's surface had formed. The German geologist, Abraham Werner proposed the theory that the Earth's layers, including basalt and granite, had formed as a precipitate from an ocean that covered the entire Earth, referring to the Deluge. Werner's system was influential and those that believed his theory were known as Neptunists. The Scottish naturalist, James Hutton, argued against the theory of Neptunism. Hutton proposed the theory of Plutonism; the Earth formed through the gradual solidification of a molten mass at a slow rate by the same processes that occurred throughout history and continues in present day. This led him to the conclusion that the Earth was immeasurably old and could not possibly fit within the limits of the Bible's 6,000 years. Plutonists believed that volcanic processes were the chief agent in rock formation, not water from a Great Flood.

19th century



Engraving from William Smith's 1815 monograph on identifying strata by fossils

The Neptunists and Plutonists supplied necessary data to help complete the stratigraphical column in the early 19th century. The stratigraphical column can be defined as “the sequence of rock formations arranged according to their order of formation in time.” William Smith, Georges Cuvier and Alexander Broignart can all be recognized for their roles during this century in furthering the concept of fossil-based stratigraphy. The English mineral surveyor William Smith found empirically that fossils were a highly effective means of distinguishing between otherwise similar formations of the landscape. At about the same time, the French comparative anatomist Georges Cuvier realized that the relative ages of fossils could be determined from a geological standpoint; in terms of what layer of rock the fossils are located and the distance these layers of rock are from the surface of the Earth. Cuvier’s mineralogist colleague Alexandre Brogniart augmented Cuvier’s practices. Through the synthesis of these findings, Brogniart and Cuvier realized that different strata could be identified by fossil contents and thus each stratum could be assigned to a unique position in a sequence. After the publication of Cuvier and Broignart’s book, “Description Geologiques des Environs de Paris” in 1811, which outlined the concept of stratigraphy, came a great interest in this new method. Stratigraphy became very popular amongst geologists; many hoped to apply this concept to all the rocks of the Earth. During this century various geologists further refined the stratigraphical column to completion. For instance, in 1833 while Adam Sedgwick was mapping rocks that he had established were from the Cambrian Period, Charles Lyell was elsewhere suggesting a subdivision of the Tertiary Period; whilst Roderick Murchison, mapping into Wales from a different direction, was assigning the upper parts of Sedgewick's *Cambrian* to the lower parts of his own Silurian Period. The stratigraphical column was significant because it now supplied a method to assign a relative age of these rocks by slotting them into different positions in their stratigraphical sequence. This created a global approach to dating the age of the Earth and allowed for further correlations to be drawn from similarities found in the makeup of the Earth’s crust in various countries.

Geological map of Great Britain by William Smith, published 1815

In early nineteenth-century Britain, catastrophism was adapted with the aim of reconciling geological science with religious traditions of the biblical Great Flood. In the early 1820s English geologists including William Buckland and Adam Sedgwick interpreted "diluvial" deposits as the outcome of Noah's flood, but by the end of the decade they revised their opinions in favour of local inundations. Charles Lyell challenged catastrophism with the publication in 1830 of the first volume of his book *Principles of Geology* which presented a variety of geological evidence from England, France, Italy and Spain to prove Hutton’s ideas of gradualism correct. He argued that most geological change had been very gradual in human history. Lyell provided evidence for Uniformitarianism; a geological doctrine that processes occur at the same rates in the present as they did in the past and account for all of the Earth’s geological features. Lyell’s works were popular and widely read, the concept of Uniformitarianism had taken a strong hold in geological society.

During the same time that the stratigraphical column was being completed, imperialism drove several countries in the early to mid 19th century to explore distant lands to expand their empires. This gave naturalists the opportunity to collect data on these voyages. In 1831 Captain Robert FitzRoy, given charge of the coastal survey expedition of HMS *Beagle*, sought a suitable naturalist to examine the land and give geological advice. This fell to Charles Darwin, who had just completed his BA degree and had accompanied Sedgwick on a two week Welsh mapping expedition after taking his Spring course on geology. Fitzroy gave Darwin Lyell's *Principles of Geology*, and Darwin became Lyell's first disciple, inventively theorising on uniformitarian principles about the geological processes he saw, and challenging some of Lyell's ideas. He speculated about the Earth expanding to explain uplift, then on the basis of the idea that ocean areas sank as land was uplifted, theorised that coral atolls grew from fringing coral reefs round sinking volcanic islands. This idea was confirmed when the *Beagle* surveyed the Cocos (Keeling) Islands. Darwin's discovery of giant fossils helped to establish his reputation as a geologist, and his theorising about the causes of their extinction led to his theory of evolution by natural selection published in *On the Origin of Species* in 1859.

Economic motivations for the practical use of geological data caused governments to support geological research. During the 19th century the governments of several countries including Canada, Australia, Great Britain and the United States funded geological surveying that would produce geological maps of vast areas of the countries. Geological surveying provides the location of useful minerals and such information could be used to benefit the country's mining industry. With the government funding of geological research, more individuals could study geology with better technology and techniques, leading to the expansion of the field of geology.

In the 19th century, scientific realms established the age of the Earth in terms of millions of years. By the early 20th century the Earth's estimated age was 2 billion years. Radiometric dating determined the age of minerals and rocks, which provided necessary data to help determine the Earth's age. With this new discovery based on verifiable scientific data and the possible age of the Earth extending billions of years, the dates of the geological time scale could now be refined. Theories that did not comply with the scientific evidence that established the age of the Earth could no longer be accepted.

20th century

Alfred Wegener, around 1925

The determined age of the Earth as 2 billion years opened doors for theories of continental movement during this vast amount of time. In 1912 Alfred Wegener proposed the theory of Continental Drift. This theory suggests that the continents were joined together at a certain time in the past and formed a single landmass known as Pangaea; thereafter they drifted like rafts over the ocean floor, finally reaching their present position. The shapes of continents and matching coastline geology between some continents indicated they were once attached together as Pangea. Additionally, the theory of continental drift offered a possible explanation as to the formation of mountains. From this, different theories developed as to how mountains were built. Unfortunately, Wegner's ideas were not accepted during his lifetime and his theory of Continental Drift was not accepted until the 1960s.

In the 1960s new found evidence supported the theory of Continental Drift. The term Continental Drift was no longer used but was replaced by the concept of Plate Tectonics that was well supported and accepted by almost all geologists by the end of the decade. Geophysical evidence suggested lateral motion of continents and that oceanic crust is younger than continental crust.

This geophysical evidence also spurred the hypotheses of seafloor spreading and paleomagnetism. The hypothesis of seafloor spreading, proposed by Robert S. Dietz and Harry H. Hess, holds that the oceanic crust forms as the seafloor spreads apart along mid-ocean ridges. Paleomagnetism is the record of the orientation of the Earth's magnetic field recorded in magnetic minerals. British geophysicist S. K. Runcorn suggested the concept of paleomagnetism from his finding that the continents had moved relative to the Earth's magnetic poles.

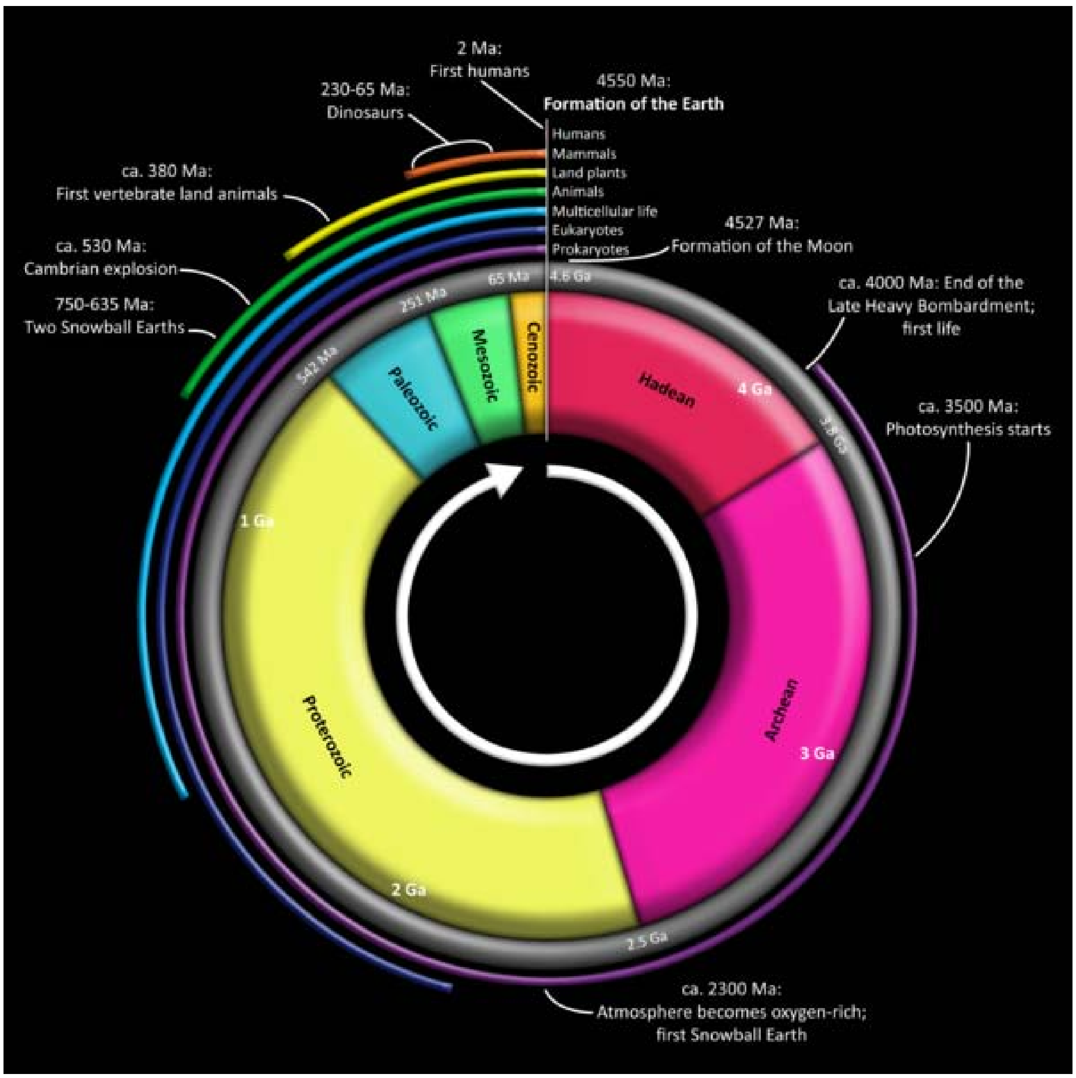
Modern geology

By applying sound stratigraphic principles to the distribution of craters on the Moon, it can be argued that almost overnight, Gene Shoemaker took the study of the Moon away from Lunar astronomers and gave it to Lunar geologists.

In recent years, geology has continued its tradition as the study of the character and origin of the Earth, its surface features and internal structure. What changed in the later 20th century is the perspective of geological study. Geology was now studied using a more integrative approach, considering the Earth in a broader context encompassing the atmosphere, biosphere and hydrosphere. Satellites located in space that take wide scope photographs of the Earth provide such a perspective. In 1972, The Landsat Program, a series of satellite missions jointly managed by NASA and the U.S. Geological Survey, began supplying satellite images that can be geologically analyzed. These images can be used to map major geological units, recognize and correlate rock types for vast regions and track the movements of Plate Tectonics. A few applications of this data include the ability to produce geologically detailed maps, locate sources of natural energy and predict possible natural disasters caused by plate shifts.

Chapter- 3

History of the Earth



Geological time put in a diagram called a geological clock, showing the relative lengths of the eons of the Earth's history.

The **history of the Earth** describes the most important events and fundamental stages in the development of the planet Earth from its formation 4.6 billion years ago to the present day. Nearly all branches of natural science have contributed to the understanding of the main events of the Earth's past. The age of Earth is approximately one-third of the age of the universe. Immense geological and biological changes have occurred during that time span.

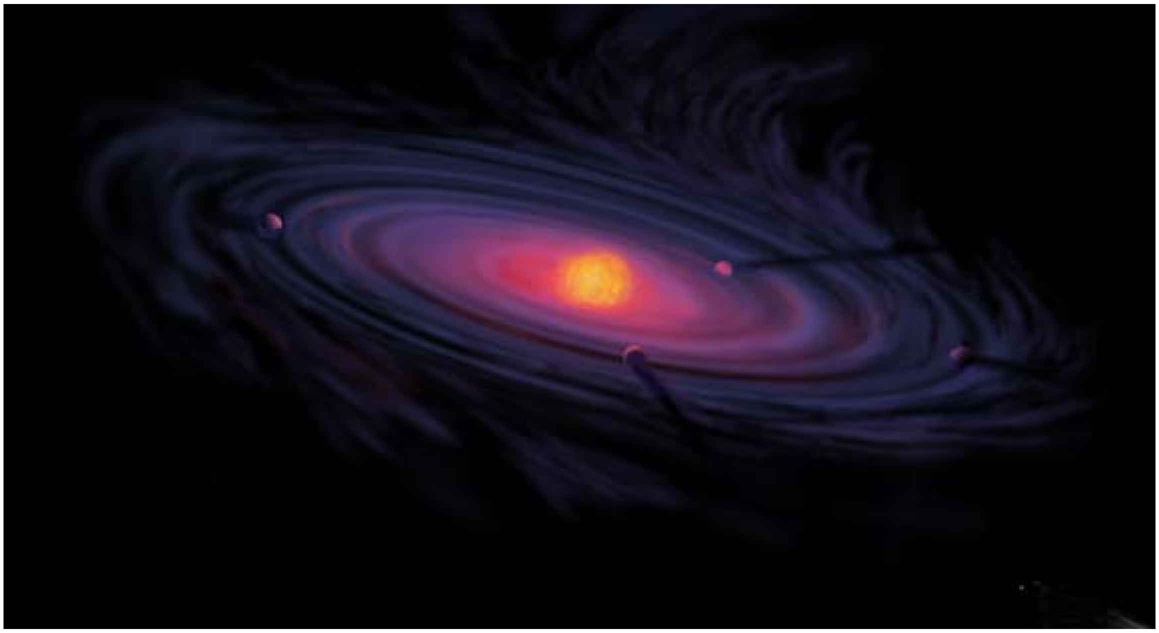
Hadean and Archaean

Starting with the Earth's formation by accretion from the solar nebula 4.54 billion years ago (4.54 Ga), the first eon in the Earth's history is called the Hadean. It lasted until the Archaean eon, which began 3.8 Ga. The oldest rocks found on Earth date to about 4.0 Ga, and the oldest detrital zircon crystals in some rocks have been dated to about 4.4 Ga, close to the formation of the Earth's crust and the Earth itself. Because not much material from this time is preserved, little is known about Hadean times, but scientists hypothesize at an estimated 4.53 Ga, shortly after formation of an initial crust, the proto-Earth was impacted by a smaller protoplanet, which ejected part of the mantle and crust into space and created the Moon.

During the Hadean, the Earth's surface was under a continuous bombardment by meteorites, and volcanism must have been severe due to the large heat flow and geothermal gradient. The detrital zircon crystals dated to 4.4 Ga show evidence of having undergone contact with liquid water, considered as proof that the planet already had oceans or seas at that time. From crater counts on other celestial bodies it is inferred that a period of intense meteorite impacts, called the "Late Heavy Bombardment", began about 4.1 Ga, and concluded around 3.8 Ga, at the end of the Hadean.

By the beginning of the Archaean, the Earth had cooled significantly. It would have been impossible for most present day life forms to exist due to the composition of the Archaean atmosphere, which lacked oxygen and an ozone layer. Nevertheless it is believed that primordial life began to evolve by the early Archaean, with some possible fossil finds dated to around 3.5 Ga. Some researchers, however, speculate that life could have begun during the early Hadean, as far back as 4.4 Ga, surviving the possible Late Heavy Bombardment period in hydrothermal vents below the Earth's surface.

Origin of the solar system



An artist's impression of protoplanetary disk

The Solar System (including the Earth) formed from a large, rotating cloud of interstellar dust and gas called the solar nebula, orbiting the Milky Way's galactic center. It was composed of hydrogen and helium created shortly after the Big Bang 13.7 Ga and heavier elements ejected by supernovas. About 4.6 Ga, the solar nebula began to contract, possibly due to the shock wave of a nearby supernova. Such a shock wave would have also caused the nebula to rotate and gain angular momentum. As the cloud began to accelerate its rotation, gravity and inertia flattened it into a protoplanetary disk oriented perpendicularly to its axis of rotation. Most of the mass concentrated in the middle and began to heat up, but small perturbations due to collisions and the angular momentum of other large debris created the means by which protoplanets up to several kilometres in length began to form, orbiting the nebular center.

The infall of material, increase in rotational speed and the crush of gravity created an enormous amount of kinetic heat at the center. Its inability to transfer that energy away through any other process at a rate capable of relieving the build-up resulted in the disk's center heating up. Ultimately, nuclear fusion of hydrogen into helium began, and eventually, after contraction, a T Tauri star ignited to create the Sun. Meanwhile, as gravity caused matter to condense around the previously perturbed objects outside the gravitational grasp of the new sun, dust particles and the rest of the protoplanetary disk began separating into rings. Successively larger fragments collided with one another and became larger objects, ultimately becoming protoplanets. These included one collection about 150 million kilometers from the center: Earth. The planet formed about 4.54 billion years ago (within an uncertainty of 1%) and was largely completed within 10–20 million years. The solar wind of the newly formed T Tauri star cleared out most of the material in the disk that had not already condensed into larger bodies.

Computer simulations have shown that planets with distances equal to the terrestrial planets in our solar system can be created from a protoplanetary disk. The now widely accepted nebular hypothesis suggests that the same process, which gave rise to the solar system's planets, produces accretion disks around virtually all newly forming stars in the universe, some of which yield planets.

Origin of the Earth's core and first atmosphere

The Proto-Earth grew by accretion, until the inner part of the protoplanet was hot enough to melt the heavy, siderophile metals. Such liquid metals, with now higher densities, began to sink to the Earth's center of mass. This so called iron catastrophe resulted in the separation of a primitive mantle and a (metallic) core only 10 million years after the Earth began to form, producing the layered structure of Earth and setting up the formation of Earth's magnetic field.

During the accretion of material to the protoplanet, a cloud of gaseous silica must have surrounded the Earth, to condense afterwards as solid rocks on the surface. What was left surrounding the planet was an early atmosphere of light (atmophile) elements from the solar nebula, mostly hydrogen and helium, but the solar wind and Earth's heat would have driven off this atmosphere.

This changed when Earth accreted to about 40% its present radius, and gravitational attraction retained an atmosphere which included water.

The giant impact hypothesis

The Earth's relatively large natural satellite, the Moon, is unique. During the Apollo program, rocks from the Moon's surface were brought to Earth. Radiometric dating of these rocks has shown the Moon to be 4527 ± 10 million years old, about 30 to 55 million years younger than other bodies in the solar system. (New evidence suggests the Moon formed even later, 4.48±0.02 Ga, or 70–110 Ma after the start of the Solar System.) Another notable feature is the relatively low density of the Moon, which must mean it does not have a large metallic core, like all other terrestrial bodies in the solar system. The Moon has a bulk composition closely resembling the Earth's mantle and crust together, without the Earth's core. This has led to the giant impact hypothesis, the idea that the Moon was formed during a giant impact of the proto-Earth with another protoplanet by accretion of the material blown off the mantles of the proto-Earth and impactor.

The impactor, sometimes named Theia, is thought to have been a little smaller than the current planet Mars. It could have formed by accretion of matter about 150 million kilometres from the Sun and Earth, at their fourth or fifth Lagrangian point. Its orbit may have been stable at first, but destabilized as Theia's mass increased due to the accretion of matter. Theia oscillated in larger and larger orbits around the Lagrangian point until it finally collided with Earth about 4.533 Ga. Models reveal that when an impactor this size struck the proto-Earth at a low angle and relatively low speed (8–20 km/sec), much material from the mantles and crusts of the proto-Earth and the impactor was ejected into space, where much of it stayed in orbit around the Earth. This material would eventually form the Moon. However, the metallic cores of the impactor would have sunk through the Earth's mantle to fuse with the Earth's core, depleting the Moon of metallic material. The giant impact hypothesis thus explains the Moon's abnormal composition. The ejecta in orbit around the Earth could have condensed into a single body within a couple of weeks. Under the influence of its own gravity, the ejected material became a more spherical body: the Moon.

The radiometric ages show the Earth existed already for at least 10 million years before the impact, enough time to allow for differentiation of the Earth's primitive mantle and core. Then, when the impact occurred, only material from the mantle was ejected, leaving the Earth's core of heavy siderophile elements untouched.

The impact had some important consequences for the young Earth. It released an enormous amount of energy, causing both the Earth and Moon to be completely molten. Immediately after the impact, the Earth's mantle was vigorously convecting, the surface was a large magma ocean. The planet's first atmosphere must have been completely blown away by the impact. The impact is also thought to have changed Earth’s axis to produce the large 23.5° axial tilt that is responsible for Earth’s seasons (a simple, ideal model of the planets’ origins would have axial tilts of 0° with no recognizable seasons). It may also have sped up Earth’s rotation.

Origin of the oceans and atmosphere

Because the Earth lacked an atmosphere immediately after the giant impact, cooling must have occurred quickly. Within 150 million years, a solid crust with a basaltic composition must have formed. The felsic continental crust of today did not yet exist. Within the Earth, further differentiation could only begin when the mantle had at least partly solidified again. Nevertheless, during the early Archaean (about 3.0 Ga) the mantle was still much hotter than today, probably around 1600°C. This means the fraction of partially molten material was still much larger than today.

Steam escaped from the crust, and more gases were released by volcanoes, completing the second atmosphere. Additional water was imported by bolide collisions, probably from asteroids ejected from the outer asteroid belt under the influence of Jupiter's gravity.

The large amount of water on Earth can never have been produced by volcanism and degassing alone. It is assumed the water was derived from impacting comets that contained ice. Though most comets are today in orbits farther away from the Sun than Neptune, computer simulations show they were originally far more common in the inner parts of the solar system. However, most of the water on Earth was probably derived from small impacting protoplanets, objects comparable with today's small icy moons of the outer planets. Impacts of these objects can have enriched the terrestrial planets (Mercury, Venus, the Earth and Mars) with water, carbon dioxide, methane, ammonia, nitrogen and other volatiles. If all water on Earth was derived from comets alone, millions of comet impacts would be required to support this theory. Computer simulations illustrate that this is not an unreasonable number.

As the planet cooled, clouds formed. Rain created the oceans. Recent evidence suggests the oceans may have begun forming by 4.2 Ga, or as early as 4.4 Ga. In any event, by the start of the Archaean eon the Earth was already covered with oceans. The new atmosphere probably contained water vapor, carbon dioxide, nitrogen, and smaller amounts of other gases. As the output of the Sun was only 70% of the current amount, significant amounts of greenhouse gas in the atmosphere most likely prevented the surface water from freezing. Free oxygen would have been bound by hydrogen or minerals on the surface. Volcanic activity was intense and, without an ozone layer to hinder its entry, ultraviolet radiation flooded the surface.

Lithified stromatolites on the shores of Lake Thetis (Western Australia). Stromatolites are formed by colonies of single celled organisms like cyanobacteria or chlorophyta. These colonies of algae entrap sedimentary grains, thus forming the draped sedimentary layers of a stromatolite. Archaean stromatolites are the first direct fossil traces of life on Earth, even though little preserved fossilized cells have been found inside them. The Archaean and Proterozoic oceans could have been full of algal mats like these.

The first continents

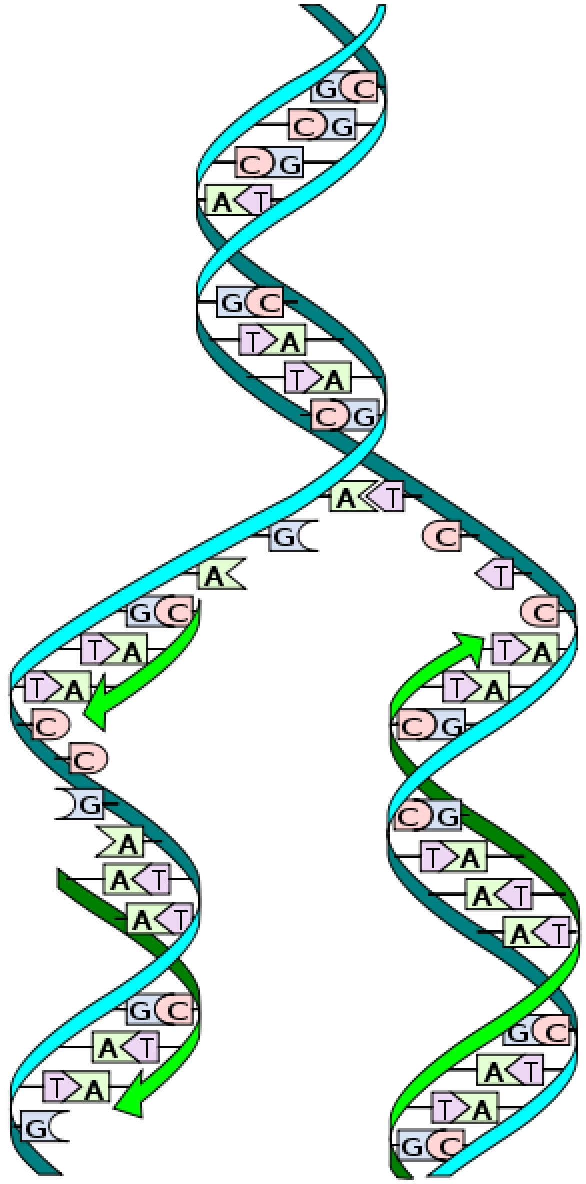
Mantle convection, the process that drives plate tectonics today, is a result of heat flow from the core to the Earth's surface. It involves the creation of rigid tectonic plates at mid-oceanic ridges. These plates are destroyed by subduction into the mantle at subduction zones. The inner Earth was warmer during the Hadean and Archaean eons, so convection in the mantle must have been faster. When a process similar to present day plate tectonics did occur, this would have gone faster too. Most geologists believe that during the Hadean and Archaean, subduction zones were more common, and therefore tectonic plates were smaller.

The initial crust, formed when the Earth's surface first solidified, totally disappeared from a combination of this fast Hadean plate tectonics and the intense impacts of the Late Heavy Bombardment. It is, however, assumed that this crust must have been basaltic in composition, like today's oceanic crust, because little crustal differentiation had yet taken place. The first larger pieces of continental crust, which is a product of differentiation of lighter elements during partial melting in the lower crust, appeared at the end of the Hadean, about 4.0 Ga. What is left of these first small continents are called cratons. These pieces of late Hadean and early Archaean crust form the cores around which today's continents grew.

The oldest rocks on Earth are found in the North American craton of Canada. They are tonalites from about 4.0 Ga. They show traces of metamorphism by high temperature, but also sedimentary grains that have been rounded by erosion during transport by water, showing rivers and seas existed then.

Cratons consist primarily of two alternating types of terranes. The first are so called greenstone belts, consisting of low grade metamorphosed sedimentary rocks. These "greenstones" are similar to the sediments today found in oceanic trenches, above subduction zones. For this reason, greenstones are sometimes seen as evidence for subduction during the Archaean. The second type is a complex of felsic magmatic rocks. These rocks are mostly tonalite, trondhjemite or granodiorite, types of rock similar in composition to granite (hence such terranes are called TTG-terranes). TTG-complexes are seen as the relicts of the first continental crust, formed by partial melting in basalt. The alternation between greenstone belts and TTG-complexes is interpreted as a tectonic situation in which small proto-continents were separated by a thorough network of subduction zones.

Origin of life



The replicator in virtually all known life is deoxyribonucleic acid. DNA is far more complex than the original replicator and its replication systems are highly elaborate.

The details of the origin of life are unknown, but the basic principles have been established. There are two schools of thought about the origin of life. One suggests that organic components arrived on Earth from space, while the other argues that they originated on Earth. Nevertheless, both schools suggest similar mechanisms by which life initially arose.

If life arose on Earth, the timing of this event is highly speculative—perhaps it arose around 4 Ga. It is possible that, as a result of repeated formation and destruction of oceans during that time period caused by high energy asteroid bombardment, life may have arisen and extinguished more than once.

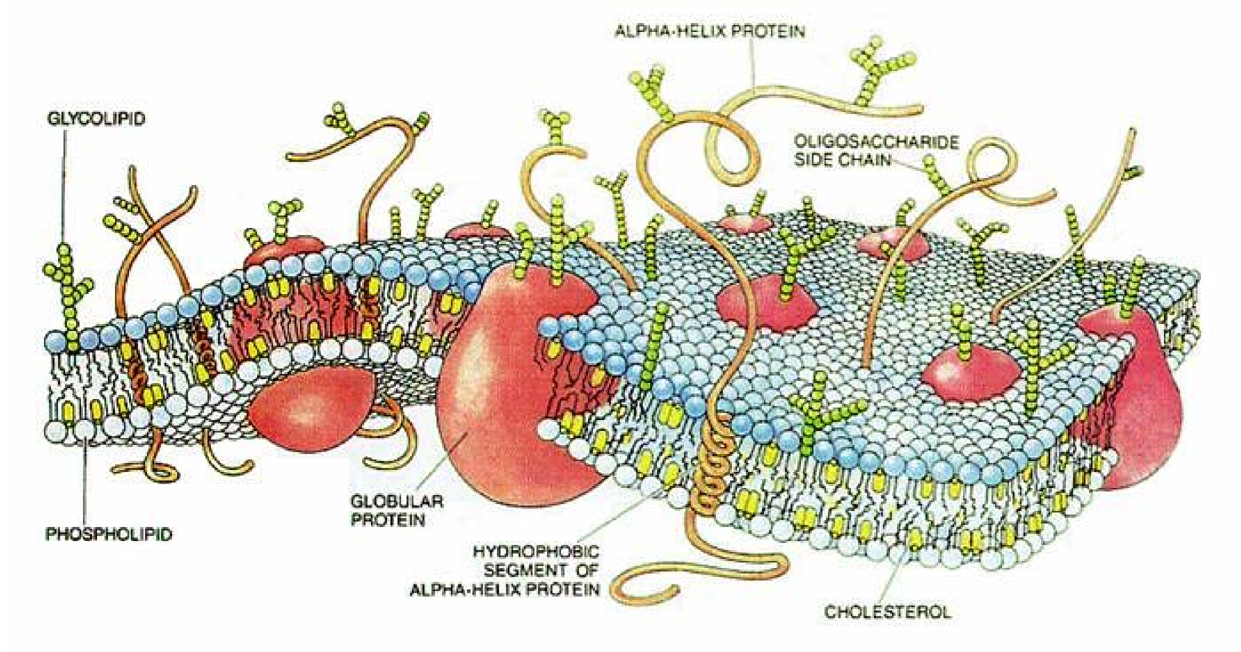
In the energetic chemistry of early Earth, a molecule gained the ability to make copies of itself — a replicator. (More accurately, it promoted the chemical reactions which produced a copy of itself.) The replication was not always accurate: some copies were slightly different from their parent.

If the change destroyed the copying ability of the molecule, the molecule did not produce any copies, and the line "died out". On the other hand, a few rare changes might have made the molecule replicate faster or better: those "strains" would become more numerous and "successful". This is an early example of evolution on abiotic material. The variations present in matter and molecules combined with the universal tendency for systems to move towards a lower energy state allowed for an early method of natural selection. As choice raw materials ("food") became depleted, strains which could utilize different materials, or perhaps halt the development of other strains and steal their resources, became more numerous.

The nature of the first replicator is unknown because its function was long since superseded by life's current replicator, DNA. Several models have been proposed explaining how a replicator might have developed. Different replicators have been posited, including organic chemicals such as modern proteins, nucleic acids, phospholipids, crystals, or even quantum systems. There is currently no way to determine whether any of these models closely fits the origin of life on Earth.

One of the older theories, one which has been worked out in some detail, will serve as an example of how this might occur. The high energy from volcanoes, lightning, and ultraviolet radiation could help drive chemical reactions producing more complex molecules from simple compounds such as methane and ammonia. Among these were many of the simpler organic compounds, including nucleobases and amino acids, which are the building blocks of life. As the amount and concentration of this "organic soup" increased, different molecules reacted with one another. Sometimes more complex molecules would result—perhaps clay provided a framework to collect and concentrate organic material.

Certain molecules could speed up a chemical reaction. All this continued for a long time, with reactions occurring at random, until by chance it produced a replicator molecule. In any case, at some point, the function of the replicator was superseded by DNA; all known life (except some viruses and prions) use DNA as their replicator, in an almost identical manner.



A small section of a cell membrane. This modern cell membrane is far more sophisticated than the original simple phospholipid bilayer (the small blue spheres with two tails). Proteins and carbohydrates serve various functions in regulating the passage of material through the membrane and in reacting to the environment.

Modern life has its replicating material packaged inside a cellular membrane. It is easier to understand the origin of the cell membrane than the origin of the replicator, because a cell membrane is made of phospholipid molecules, which often form a bilayer spontaneously when placed in water. Under certain conditions, many such spheres can be formed.

The prevailing theory is that the membrane formed after the replicator, which perhaps by then was RNA (the RNA world hypothesis), along with its replicating apparatus and other biomolecules. Initial protocells may have simply burst when they grew too large; the scattered contents may then have recolonized other “bubbles”. Proteins that stabilized the membrane, or that later assisted in an orderly division, would have promoted the proliferation of those cell lines.

RNA is a likely candidate for an early replicator, because it can both store genetic information and catalyze reactions. At some point DNA took over the genetic storage role from RNA, and proteins known as enzymes took over the catalysis role, leaving RNA to transfer information, synthesize proteins and regulate the process. There is increasing belief that these early cells evolved in association with undersea volcanic vents known as *black smoker* or even hot, deep rocks.

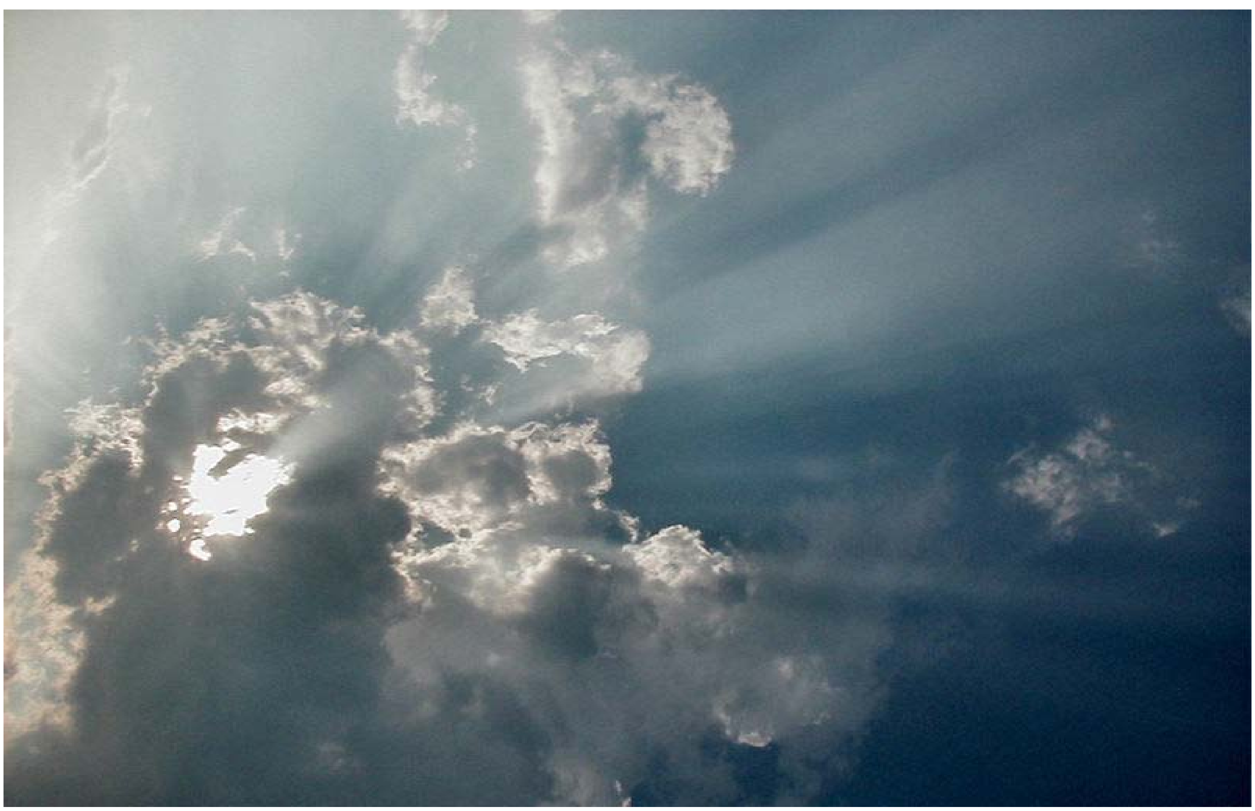
It is believed that of this multiplicity of protocells, only one line survived. Current phylogentic evidence suggests that the last universal common ancestor lived during the early Archean eon, perhaps roughly 3.5 Ga or earlier. This “LUCA” cell is the ancestor of all life on Earth today. It was probably a prokaryote, possessing a cell membrane and probably ribosomes, but lacking a nucleus or membrane-bound organelles such as mitochondria or chloroplasts.

Like all modern cells, it used DNA as its genetic code, RNA for information transfer and protein synthesis, and enzymes to catalyze reactions. Some scientists believe that instead of a single organism being the last universal common ancestor, there were populations of organisms exchanging genes in lateral gene transfer.

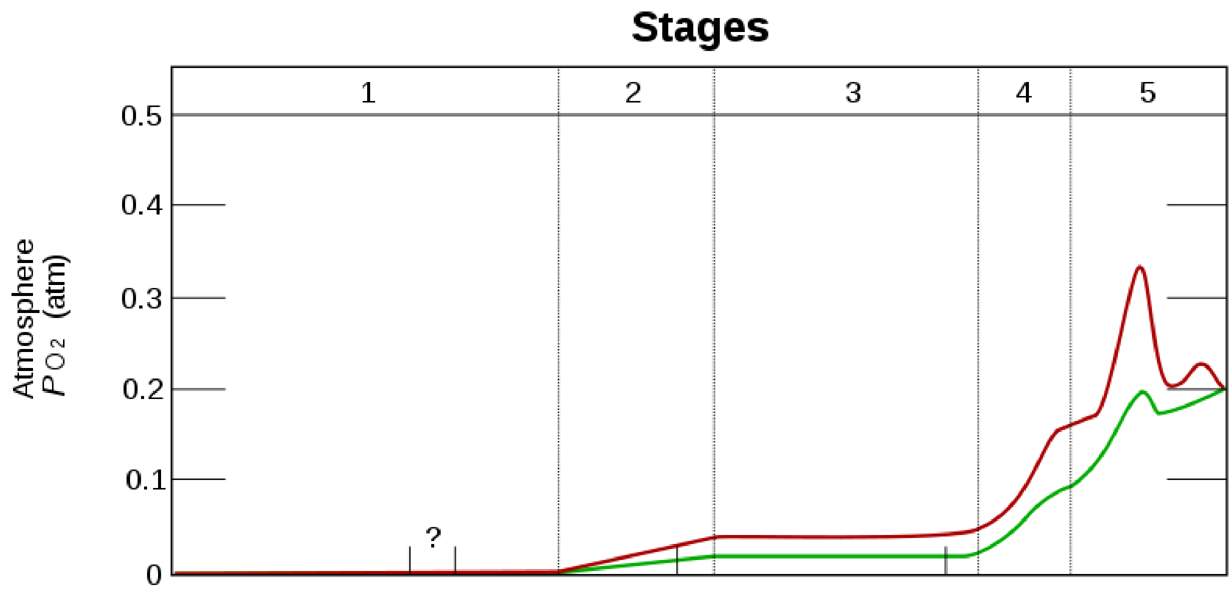
Proterozoic eon

The Proterozoic is the eon of Earth's history that lasted from 2.5 Ga to 542 Ma. In this time span, the cratons grew into continents with modern sizes. For the first time plate tectonics took place in a modern sense. The change to an oxygen-rich atmosphere was a crucial development. Life developed from prokaryotes into eukaryotes and multicellular forms. The Proterozoic saw a couple of severe ice ages called snowball Earths. After the end of the last Snowball Earth about 600 Ma, the evolution of life on Earth accelerated. About 580 Ma, the Ediacara biota formed the prelude for the Cambrian Explosion.

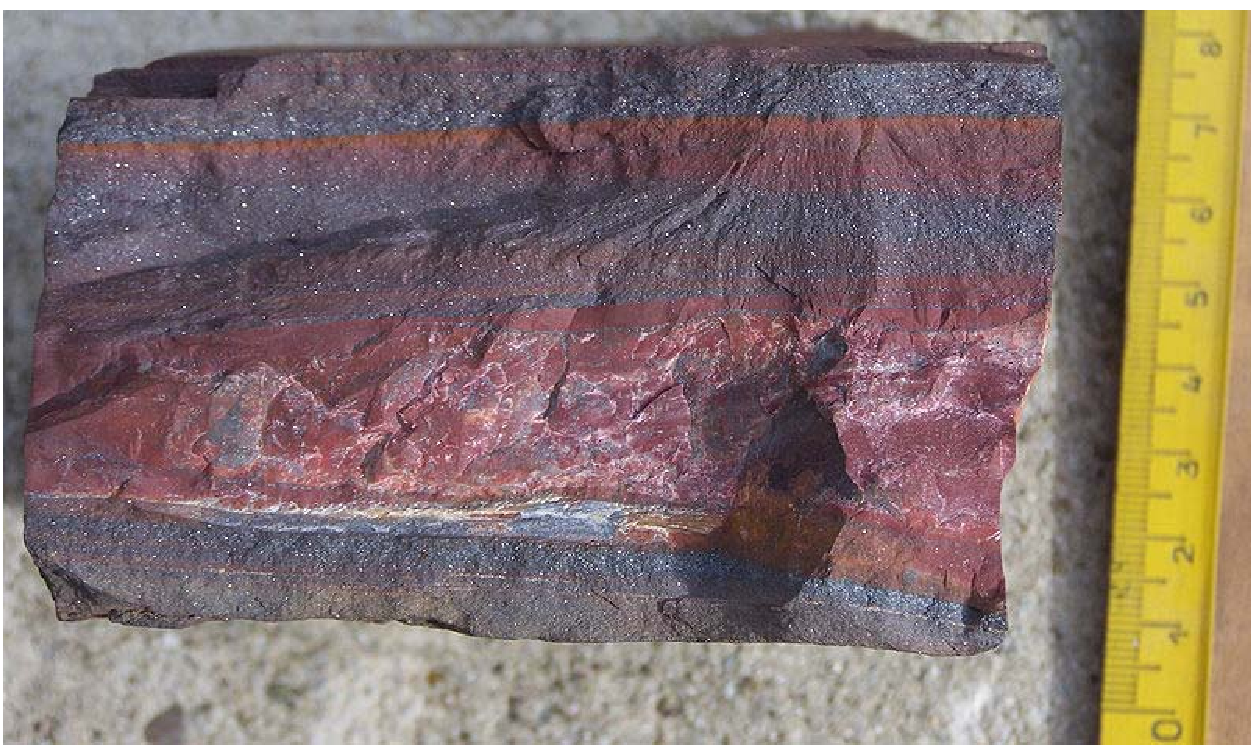
The oxygen revolution



The harnessing of the sun’s energy led to several major changes in life on Earth



Graph showing range of estimated partial pressure of atmospheric oxygen through geologic time



A banded iron formation from the 3.15 Ga Moories Group, Barberton Greenstone Belt, South Africa. Red layers represent the times when oxygen was available, gray layers were formed in anoxic circumstances.

The first cells were likely heterotrophs, using surrounding organic molecules (including those from other cells) as raw material and an energy source. As the food supply diminished, a new strategy evolved in some cells. Instead of relying on the diminishing amounts of free-existing organic molecules, these cells adopted sunlight as an energy source. Estimates vary, but by about 3 Ga, something similar to modern oxygenic photosynthesis had probably developed, which made the sun's energy available not only to autotrophs but also to the heterotrophs that consumed them. This type of photosynthesis, which became by far the most common, used the abundant carbon dioxide and water as raw materials and, with the energy of sunlight, produced energy-rich organic molecules (carbohydrates).

Moreover, oxygen was released as a waste product of the photosynthesis. At first, it became bound up with limestone, iron, and other minerals. There is substantial proof of this in iron-oxide rich layers in geological strata that correspond with this period. The reaction of the minerals with oxygen would have turned the oceans green. When most of the exposed readily reacting minerals were oxidized, oxygen finally began to accumulate in the atmosphere. Though each cell only produced a minute amount of oxygen, the combined metabolism of many cells over a vast time transformed Earth's atmosphere to its current state. Among the oldest examples of oxygen-producing lifeforms are fossil stromatolites. This was Earth's third atmosphere.

Some of the oxygen was stimulated by incoming ultraviolet radiation to form ozone, which collected in a layer near the upper part of the atmosphere. The ozone layer absorbed, and still absorbs, a significant amount of the ultraviolet radiation that once had passed through the atmosphere. It allowed cells to colonize the surface of the ocean and eventually the land: without the ozone layer, ultraviolet radiation bombarding the surface would have caused unsustainable levels of mutation in exposed cells.

Photosynthesis had another, major, and world-changing impact. Oxygen was toxic; probably much life on Earth died out as its levels rose in what is known as the "oxygen catastrophe". Resistant forms survived and thrived, and some developed the ability to use oxygen to increase their metabolism and obtain more energy from the same food.

Snowball Earth and the origin of the ozone layer

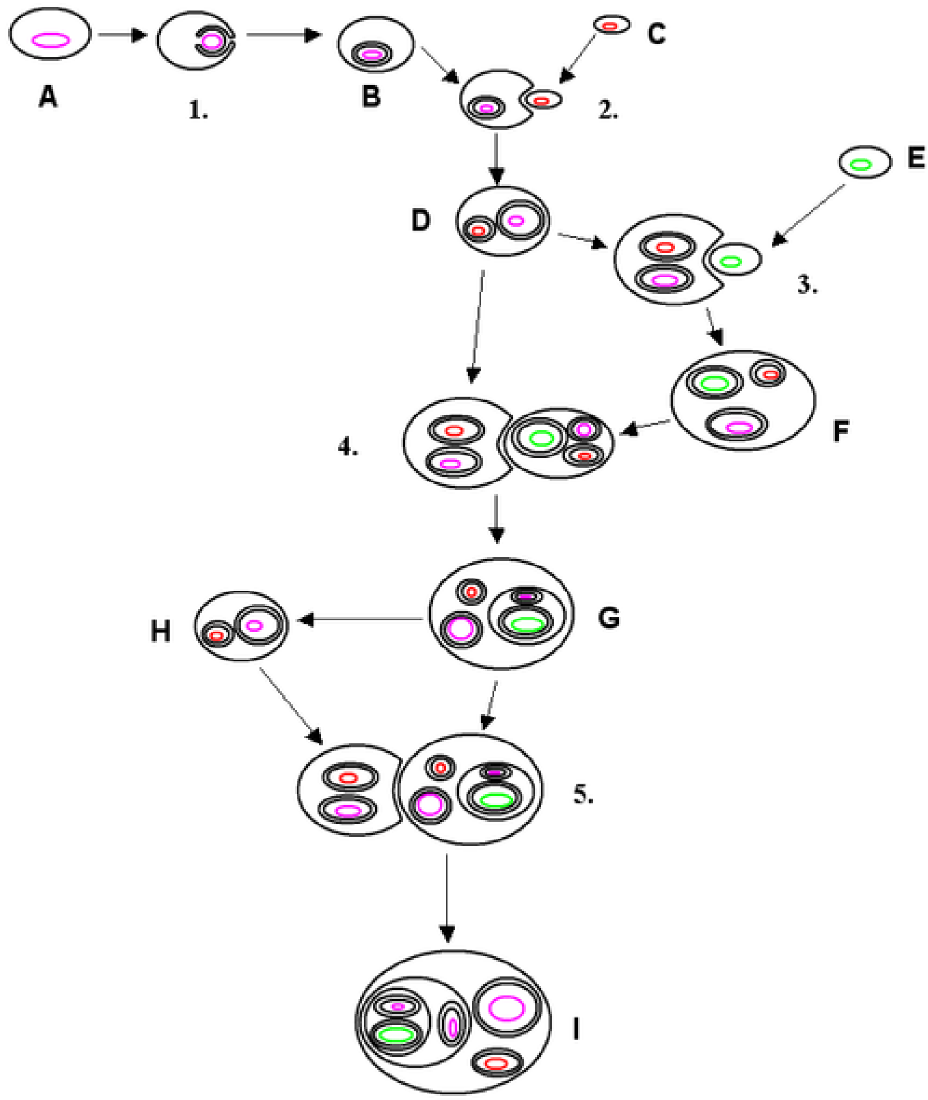
An oxygen-rich atmosphere had two principal advantages for life. Organisms not using oxygen for their metabolism, such as anaerobe bacteria, base their metabolism on fermentation. The abundance of oxygen makes respiration possible, a much more effective energy source for life than fermentation. The second advantage of an oxygen-rich atmosphere is that oxygen forms ozone in the higher atmosphere, causing the emergence of the Earth's ozone layer. The ozone layer protects the Earth's surface from ultraviolet radiation, which is harmful for life. Without the ozone layer, the development of more complex life later on would probably have been impossible.

The natural evolution of the Sun made it progressively more luminous during the Archaean and Proterozoic eons; the Sun's luminosity increases 6% every billion years. As a result, the Earth began to receive more heat from the Sun in the Proterozoic eon. However, the Earth did not get warmer. Instead, the geological record seems to suggest it cooled dramatically during the early Proterozoic. Glacial deposits found in all cratons show that about 2.3 Ga, the Earth underwent its first big ice age (the Makganyene ice age). Some scientists suggest this and following

Proterozoic ice ages were so severe that the planet was totally frozen over from the poles to the equator, a hypothesis called Snowball Earth. Not all geologists agree with this scenario and older, Archaean ice ages have been postulated, but the ice age 2.3 Ga is the first such event for which the evidence is widely accepted.

The ice age around 2.3 Ga could have been directly caused by the increased oxygen concentration in the atmosphere, which caused the decrease of methane (CH_4) in the atmosphere. Methane is a strong greenhouse gas, but with oxygen it reacts to form CO_2, a less effective greenhouse gas. When free oxygen became available in the atmosphere, the concentration of methane could have decreased dramatically, enough to counter the effect of the increasing heat flow from the Sun.

Proterozoic development of life

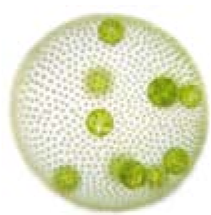


Some of the pathways by which the various endosymbionts might have arisen

Modern taxonomy classifies life into three domains. The time of the origin of these domains is uncertain. The Bacteria domain probably first split off from the other forms of life (sometimes called Neomura), but this supposition is controversial. Soon after this, by 2 Ga, the Neomura split into the Archaea and the Eukarya. Eukaryotic cells (Eukarya) are larger and more complex than prokaryotic cells (Bacteria and Archaea), and the origin of that complexity is only now becoming known.

Around this time, the first proto-mitochondrion was formed. A bacterial cell related to today's *Rickettsia*, which had learned how to metabolize oxygen, entered a larger prokaryotic cell, which lacked that capability. Perhaps the large cell attempted to ingest the smaller one but failed (possibly due to the evolution of prey defenses). The smaller cell may have tried to parasitize the larger one. In any case, the smaller cell survived inside the larger cell. Using oxygen, it metabolized the larger cell's waste products and derived more energy. Some of this excess energy was returned to the host. The smaller cell replicated inside the larger one. Soon, a stable symbiosis developed between the large cell and the smaller cells inside it. Over time, the host cell acquired some of the genes of the smaller cells, and the two kinds became dependent on each other: the larger cell could not survive without the energy produced by the smaller ones, and these in turn could not survive without the raw materials provided by the larger cell. The whole cell is now considered a single organism, and the smaller cells are classified as organelles called mitochondria.

A similar event occurred with photosynthetic cyanobacteria entering large heterotrophic cells and becoming chloroplasts. Probably as a result of these changes, a line of cells capable of photosynthesis split off from the other eukaryotes more than 1 billion years ago. There were probably several such inclusion events, as the figure at right suggests. Besides the well-established endosymbiotic theory of the cellular origin of mitochondria and chloroplasts, it has been suggested that cells led to peroxisomes, spirochetes led to cilia and flagella, and that perhaps a DNA virus led to the cell nucleus, though none of these theories is widely accepted.

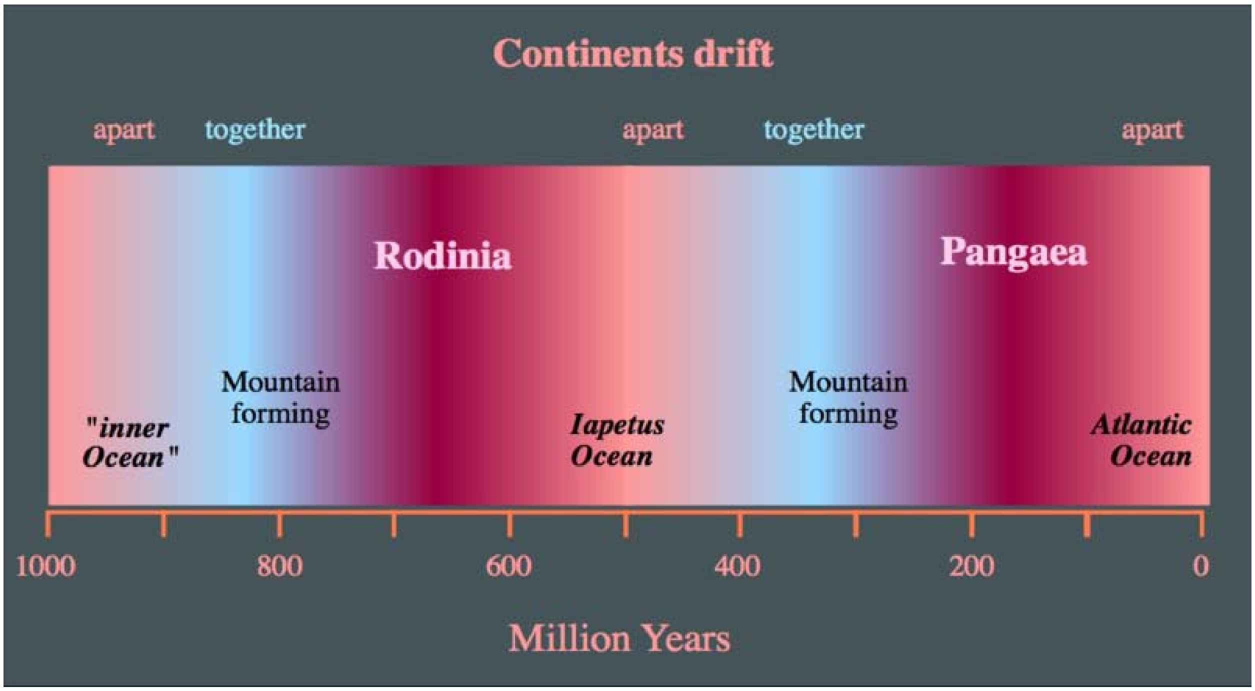


Green algae of the genus *Volvox* are believed to be similar to the first multicellular plants

Archaeans, bacteria, and eukaryotes continued to diversify and to become more complex and better adapted to their environments. Each domain repeatedly split into multiple lineages, although little is known about the history of the archaea and bacteria. Around 1.1 Ga, the supercontinent Rodinia was assembling. The plant, animal, and fungi lines had all split, though they still existed as solitary cells. Some of these lived in colonies, and gradually some division of labor began to take place; for instance, cells on the periphery might have started to assume different roles from those in the interior. Although the division between a colony with specialized cells and a multicellular organism is not always clear, around 1 billion years ago the first multicellular plants emerged, probably green algae. Possibly by around 900 Ma true multicellularity had also evolved in animals.

At first it probably resembled today's sponges, which have totipotent cells that allow a disrupted organism to reassemble itself. As the division of labor was completed in all lines of multicellular organisms, cells became more specialized and more dependent on each other; isolated cells would die.

Rodinia and other supercontinents



Wilson cycle timeline from 1 Ga, depicting Rodinia and Pangaea supercontinent formation and separation

When the theory of Plate tectonics was developed around 1960, geologists began to reconstruct the movements and positions of the continents in the past. This appeared relatively easy until about 250 million years ago, when all continents were united in what is called the "supercontinent" Pangaea. Before that time, reconstructions cannot rely on apparent similarities in coastlines or ages of oceanic crust, but only on geologic observations and paleomagnetic data.

Throughout the history of the Earth, there have been times when the continental mass came together to form a supercontinent, followed by the break-up of the supercontinent and new continents moving apart again. This repetition of tectonic events is called a Wilson cycle. The further back in time, the scarcer and harder to interpret the data get. It is at least clear that, about 1000 to 830 Ma, most continental mass was united in the supercontinent Rodinia. It is highly probable Rodinia was not the first supercontinent, and many earlier supercontinents have been proposed. This means plate tectonic processes similar to today's must have been active during the Proterozoic.

After the break-up of Rodinia about 800 Ma, it is possible the continents joined again around 550 Ma. The hypothetical supercontinent is sometimes referred to as Pannotia or Vendia. The evidence for it is a phase of continental collision known as the Pan-African orogeny, which joined the continental masses of current-day Africa, South-America, Antarctica and Australia. It is extremely likely, however, that the aggregation of continental masses was not completed, since a continent called Laurentia (roughly equivalent to current-day North America) had already started breaking off around 610 Ma. It is at least certain that by the end of the Proterozoic eon, most of the continental mass lay united in a position around the south pole.

Late Proterozoic climate and life

A 580 million year old fossil of *Spriggina floundensi*, an animal from the Ediacaran period. Such life forms could have been ancestors to the many new forms that origined in the Cambrian Explosion.

The end of the Proterozoic saw at least two Snowball Earths, so severe that the surface of the oceans may have been completely frozen. This happened about 710 and 640 Ma, in the Cryogenian period. These severe glaciations are less easy to explain than the early Proterozoic

Snowball Earth. Most paleoclimatologists think the cold episodes had something to do with the formation of the supercontinent Rodinia. Because Rodinia was centered on the equator, rates of chemical weathering increased and carbon dioxide (CO_2) was taken from the atmosphere. Because CO_2 is an important greenhouse gas, climates cooled globally.

In the same way, during the Snowball Earths most of the continental surface was in permafrost, which decreased chemical weathering again, leading to the end of the glaciations. An alternative hypothesis is that enough carbon dioxide escaped through volcanic outgassing that the resulting greenhouse effect raised global temperatures. Increased volcanic activity resulted from the break-up of Rodinia at about the same time.

The Cryogenian period was followed by the Ediacaran period, which was characterized by a rapid development of new multicellular lifeforms. If there is a connection between the end of the severe ice ages and the increase in diversity of life, is not clear, but it does not seem coincidental. The new forms of life, called Ediacara biota, were larger and more diverse than ever. Most scientists think some of them may have been the precursors of the new life forms of the following Cambrian period. Though the taxonomy of most Ediacaran life forms is unclear, some are proposed to have been ancestors of groups of modern life. Important developments were the origin of muscular and neural cells. None of the Ediacaran fossils had hard body parts like skeletons. These first appear after the boundary between the Proterozoic and Phanerozoic eons or Ediacaran and Cambrian periods.

Paleozoic era

The Paleozoic era (meaning: *era of old life forms*) was the first era of the Phanerozoic eon, lasting from 542 to 251 Ma. During the Paleozoic, many modern groups of life came into existence. Life colonized the land, first plants, then animals. Life usually evolved slowly. At times, however, there are sudden radiations of new species or mass extinctions. These bursts of evolution were often caused by unexpected changes in the environment resulting from natural disasters such as volcanic activity, meteorite impacts or climate changes.

The continents formed at the break-up of Pannotia and Rodinia at the end of the Proterozoic would slowly move together again during the Paleozoic. This would eventually result in phases of mountain building that created the supercontinent Pangaea in the late Paleozoic.

Cambrian explosion

Apparently, the rate of the evolution of life accelerated in the Cambrian period (542-488 Ma). The sudden emergence of many new species, phyla, and forms in this period is called the Cambrian Explosion. The biological formenting in the Cambrian Explosion was unpreceded before and since that time. Whereas the Ediacaran life forms appear yet primitive and not easy to put in any modern group, at the end of the Cambrian most modern phyla were already present. The development of hard body parts such as shells, skeletons or exoskeletons in animals like molluscs, echinoderms, crinoids and arthropods (a well-known group of arthropods from the lower Paleozoic are the trilobites) made the preservation and fossilisation of such life forms easier than those of their Proterozoic ancestors. For this reason, much more is known about life in and after the Cambrian than about that of older periods. The boundary between the Cambrian and Ordovician (the following period, 488-444 Ma) is characterized by a large mass-extinction, in which some of the new groups disappeared altogether. Some of these Cambrian groups appear complex but are quite different from modern life; examples are *Anomalocaris* and *Haikouichthys*.

During the Cambrian, the first vertebrate animals, among them the first fishes, had appeared. A creature that could have been the ancestor of the fishes, or was probably closely related to it, was *Pikaia*. It had a primitive notochord, a structure that could have developed into a vertebral column later. The first fishes with jaws (Gnathostomata) appeared during the Ordovician. The colonisation of new niches resulted in massive body sizes. In this way, fishes with increasing sizes evolved during the early Paleozoic, such as the titanic placoderm *Dunkleosteus*, which could grow 7 meters long.

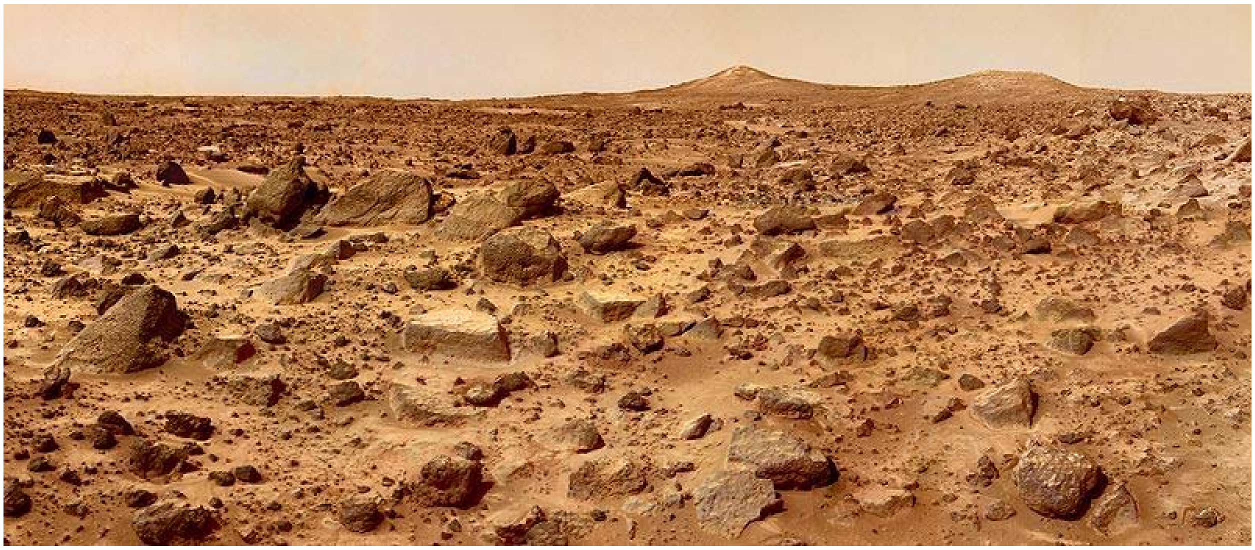
Paleozoic tectonics, paleogeography and climate

At the end of the Proterozoic, the supercontinent Pannotia had broken apart in the smaller continents Laurentia, Baltica, Siberia and Gondwana. During periods when continents move apart, more oceanic crust is formed by volcanic activity. Because young volcanic crust is relatively hotter and less dense than old oceanic crust, the ocean floors will rise during such periods. This causes the sea level to rise. Therefore, in the first half of the Paleozoic, large areas of the continents were below sea level.

Early Paleozoic climates were warmer than today, but the end of the Ordovician saw a short ice age during which glaciers covered the south pole, where the huge continent Gondwana was situated. Traces of glaciation from this period are only found on former Gondwana. During the Late Ordovician ice age, a number of mass extinctions took place, in which many brachiopods, trilobites, Bryozoa and corals disappeared. These marine species could probably not contend with the decreasing temperature of the sea water. After the extinctions new species evolved, more diverse and better adapted. They would fill the niches left by the extinct species.

The continents Laurentia and Baltica collided between 450 and 400 Ma, during the Caledonian Orogeny, to form Laurussia. Traces of the mountain belt which resulted from this collision can be found in Scandinavia, Scotland and the northern Appalachians. In the Devonian period (416-359 Ma) Gondwana and Siberia began to move towards Laurussia. The collision of Siberia with Laurussia caused the Uralian Orogeny, the collision of Gondwana with Laurussia is called the Variscan or Hercynian Orogeny in Europe or the Alleghenian Orogeny in North America. The latter phase took place during the Carboniferous period (359-299 Ma) and resulted in the formation of the last supercontinent, Pangaea.

Colonization of land

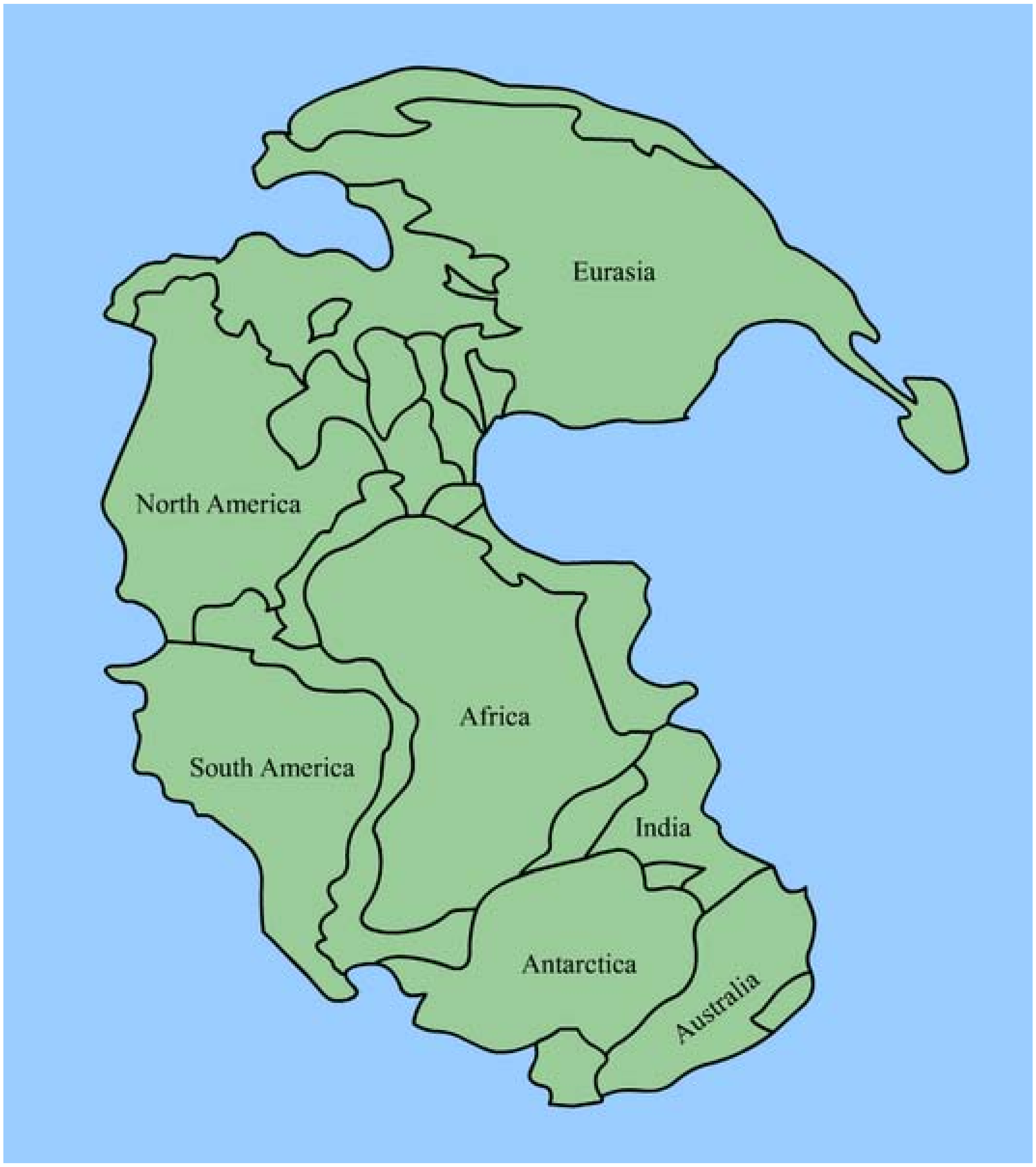


For most of Earth's history, there were no multicellular organisms on land. Parts of the surface may have vaguely resembled this view of Mars.

Oxygen accumulation from photosynthesis resulted in the formation of an ozone layer that absorbed much of Sun's ultraviolet radiation, meaning unicellular organisms that reached land were less likely to die, and prokaryotes began to multiply and become better adapted to survival out of the water. Prokaryotes had probably colonized the land as early as 2.6 Ga even before the origin of the eukaryotes. For a long time, the land remained barren of multicellular organisms. The supercontinent Pannotia formed around 600 Ma and then broke apart a short 50 million years later. Fish, the earliest vertebrates, evolved in the oceans around 530 Ma. A major extinction event occurred near the end of the Cambrian period, which ended 488 Ma.

Several hundred million years ago, plants (probably resembling algae) and fungi started growing at the edges of the water, and then out of it. The oldest fossils of land fungi and plants date to 480–460 Ma, though molecular evidence suggests the fungi may have colonized the land as early as 1000 Ma and the plants 700 Ma. Initially remaining close to the water's edge, mutations and variations resulted in further colonization of this new environment. The timing of the first animals to leave the oceans is not precisely known: the oldest clear evidence is of arthropods on land around 450 Ma, perhaps thriving and becoming better adapted due to the vast food source provided by the terrestrial plants. There is also some unconfirmed evidence that arthropods may have appeared on land as early as 530 Ma.

At the end of the Ordovician period, 440 Ma, additional extinction events occurred, perhaps due to a concurrent ice age. Around 380 to 375 Ma, the first tetrapods evolved from fish. It is thought that perhaps fins evolved to become limbs which allowed the first tetrapods to lift their heads out of the water to breathe air. This would allow them to live in oxygen-poor water or pursue small prey in shallow water. They may have later ventured on land for brief periods. Eventually, some of them became so well adapted to terrestrial life that they spent their adult lives on land, although they hatched in the water and returned to lay their eggs. This was the origin of the amphibians. About 365 Ma, another period of extinction occurred, perhaps as a result of global cooling. Plants evolved seeds, which dramatically accelerated their spread on land, around this time (by approximately 360 Ma).



Pangaea, the most recent supercontinent, existed from 300 to 180 Ma. The outlines of the modern continents and other land masses are indicated on this map.

Some 20 million years later (340 Ma), the amniotic egg evolved, which could be laid on land, giving a survival advantage to tetrapod embryos. This resulted in the divergence of amniotes from amphibians. Another 30 million years (310 Ma) saw the divergence of the synapsids (including mammals) from the sauropsids (including birds and reptiles). Other groups of organisms continued to evolve, and lines diverged—in fish, insects, bacteria, and so on—but less is known of the details. The most recent hypothesized supercontinent, called Pangaea, formed 300 Ma.

Mesozoic

The most severe extinction event to date took place 250 Ma, at the boundary of the Permian and Triassic periods; 95% of life on Earth died out. That started the Mesozoic era (meaning middle life) that spanned 187 million years, possibly due to the Siberian Traps volcanic event. The discovery of the Wilkes Land crater in Antarctica may indicate a connection with the Permian-Triassic extinction, but the age of that crater is not known. Among other speculative theories, it has been suggested that what is now the Gulf of Mexico was created by a large bolide impact event at that time. Life persevered, and around 230 Ma, dinosaurs split off from their reptilian ancestors. An extinction event between the Triassic and Jurassic periods 200 Ma spared many of the dinosaurs, and they soon became dominant among the vertebrates. Though some of the mammalian lines began to separate during this period, existing mammals were probably all small animals resembling shrews.

By 180 Ma, Pangaea broke up into Laurasia and Gondwana. The boundary between avian and non-avian dinosaurs is not clear, but *Archaeopteryx*, traditionally considered one of the first birds, lived around 150 Ma. The earliest evidence for the angiosperms evolving flowers is during the Cretaceous period, some 20 million years later (132 Ma). Competition with birds drove many pterosaurs to extinction and the dinosaurs were probably already in decline when, 65 Ma, a 10-kilometre (6.2 mi) meteorite probably struck Earth just off the Yucatán Peninsula where the Chicxulub crater is today. This ejected vast quantities of particulate matter and vapor into the air that occluded sunlight, inhibiting photosynthesis. Most large animals, including the non-avian dinosaurs, became extinct, marking the end of the Cretaceous period and Mesozoic era. Thereafter, in the Paleocene epoch, mammals rapidly diversified, grew larger, and became the dominant vertebrates. Perhaps a couple of million years later (around 63 Ma), the last common ancestor of primates lived. By the late Eocene epoch, 34 Ma, some terrestrial mammals had returned to the oceans to become animals such as *Basilosaurus* which eventually led to dolphins and baleen whales.

Cenozoic era (Recent life)

Human evolution

Australopithecus africanus, an early hominid

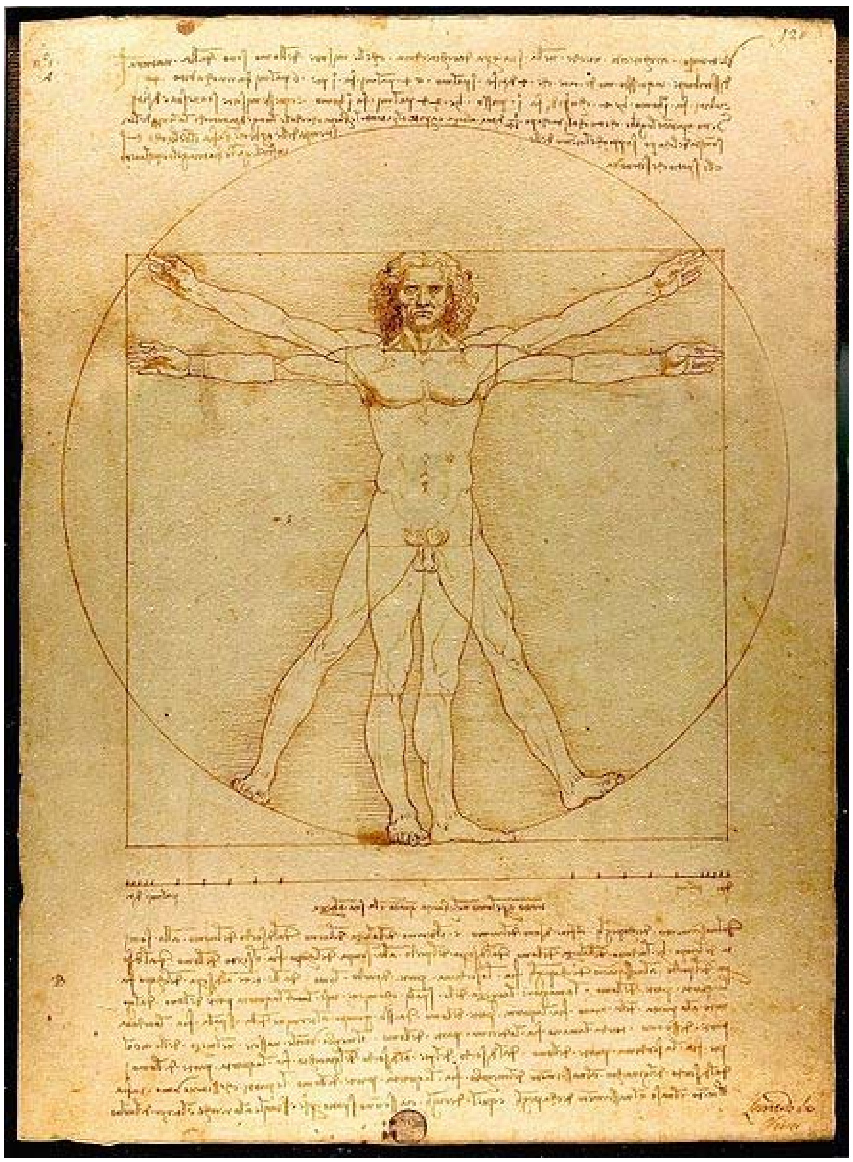
A small African ape living around six Ma was the last animal whose descendants would include both modern humans and their closest relatives, the bonobo and chimpanzees. Only two branches of its family tree have surviving descendants. Very soon after the split, for reasons that are still debated, apes in one branch developed the ability to walk upright. Brain size increased rapidly, and by 2 Ma, the first animals classified in the genus *Homo* had appeared. Of course, the line between different species or even genera is somewhat arbitrary as organisms continuously change over generations. Around the same time, the other branch split into the ancestors of the common chimpanzee and the ancestors of the bonobo as evolution continued simultaneously in all life forms.

The ability to control fire probably began in *Homo erectus* (or *Homo ergaster*), probably at least 790,000 years ago but perhaps as early as 1.5 Ma. In addition, it has sometimes suggested that the use and discovery of controlled fire may even predate *Homo erectus*. Fire was possibly used by the early Lower Paleolithic (Oldowan) hominid *Homo habilis* or strong australopithecines such as *Paranthropus.*

It is more difficult to establish the origin of language; it is unclear whether *Homo erectus* could speak or if that capability had not begun until *Homo sapiens*. As brain size increased, babies were born earlier, before their heads grew too large to pass through the pelvis. As a result, they exhibited more plasticity, and thus possessed an increased capacity to learn and required a longer period of dependence. Social skills became more complex, language became more sophisticated, and tools became more elaborate. This contributed to further cooperation and intellectual development. Modern humans (*Homo sapiens*) are believed to have originated somewhere around 200,000 years ago or earlier in Africa; the oldest fossils date back to around 160,000 years ago.

The first humans to show signs of spirituality are the Neanderthals (usually classified as a separate species with no surviving descendants); they buried their dead, often apparently with food or tools. However, evidence of more sophisticated beliefs, such as the early Cro-Magnon cave paintings (probably with magical or religious significance) did not appear until some 32,000 years ago. Cro-Magnons also left behind stone figurines such as Venus of Willendorf, probably also signifying religious belief. By 11,000 years ago, *Homo sapiens* had reached the southern tip of South America, the last of the uninhabited continents (except for Antarctica, which remained undiscovered until 1820 AD). Tool use and communication continued to improve, and interpersonal relationships became more intricate.

Civilization



Vitruvian Man by Leonardo da Vinci epitomizes the advances in art and science seen during the Renaissance.

Throughout more than 90% of its history, *Homo sapiens* lived in small bands as nomadic hunter-gatherers. As language became more complex, the ability to remember and communicate information resulted in a new replicator: the meme. Ideas could be exchanged quickly and passed down the generations.

Cultural evolution quickly outpaced biological evolution, and history proper began. Somewhere between 8500 and 7000 BC, humans in the Fertile Crescent in Middle East began the systematic husbandry of plants and animals: agriculture. This spread to neighboring regions, and developed independently elsewhere, until most *Homo sapiens* lived sedentary lives in permanent settlements as farmers.

Not all societies abandoned nomadism, especially those in isolated areas of the globe poor in domesticable plant species, such as Australia. However, among those civilizations that did adopt agriculture, the relative stability and increased productivity provided by farming allowed the population to expand.

Agriculture had a major impact; humans began to affect the environment as never before. Surplus food allowed a priestly or governing class to arise, followed by increasing division of labor. This led to Earth's first civilization at Sumer in the Middle East, between 4000 and 3000 BC. Additional civilizations quickly arose in ancient Egypt, at the Indus River valley and in China.

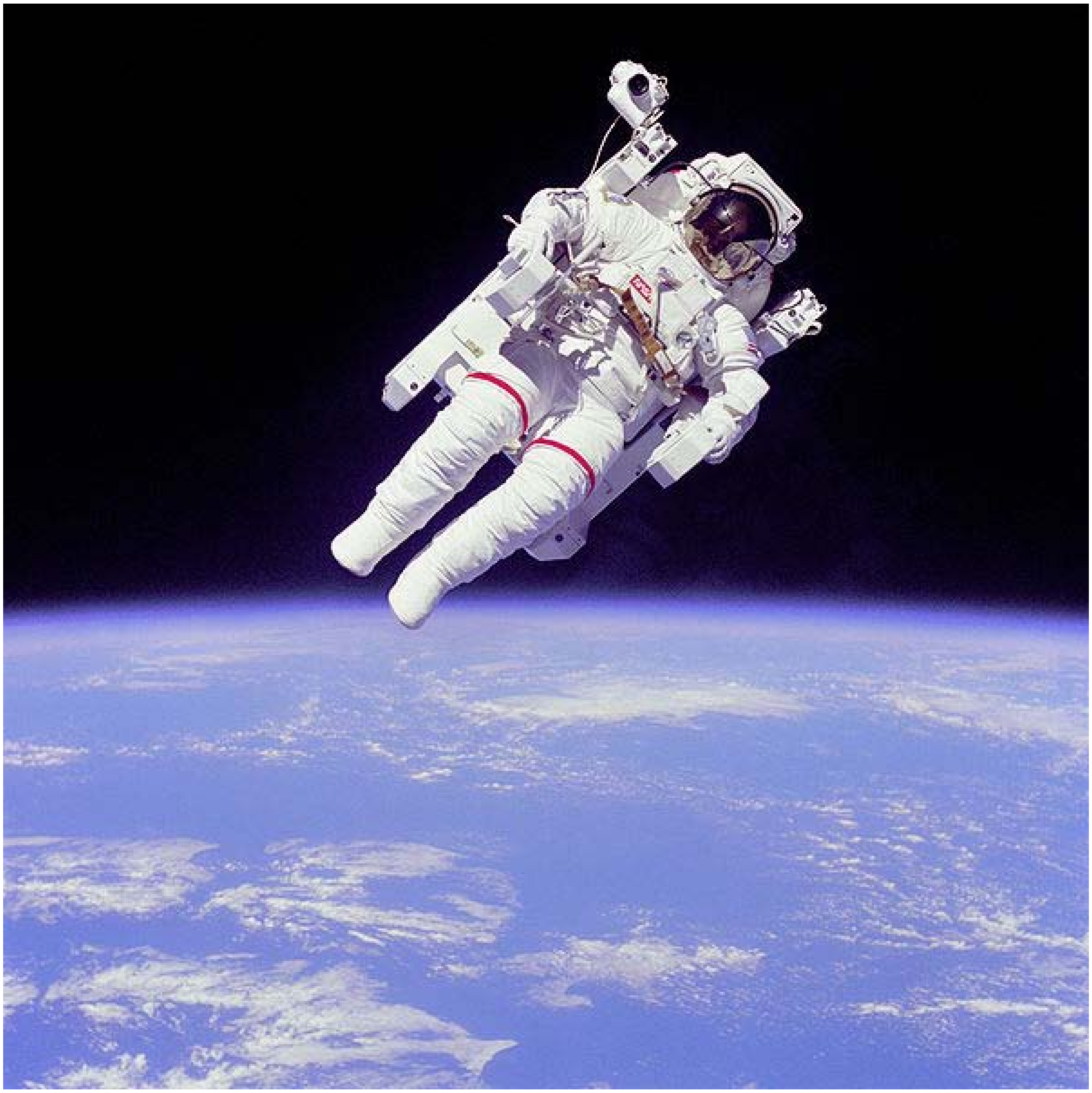
Starting around 3000 BC, Hinduism, one of the oldest religions still practiced today, began to take form. Others soon followed. The invention of writing enabled complex societies to arise: record-keeping and libraries served as a storehouse of knowledge and increased the cultural transmission of information. Humans no longer had to spend all their time working for survival—curiosity and education drove the pursuit of knowledge and wisdom.

Various disciplines, including science (in a primitive form), arose. New civilizations sprang up, traded with one another, and fought for territory and resources. Empires soon began to develop. By around 500 BC, there were empires in the Middle East, Iran, India, China, and Greece, on nearly equal footing; at times one empire expanded, only to decline or be driven back later.

In the fourteenth century, the Renaissance began in Italy with advances in religion, art, and science. European civilization began to change beginning in 1500, leading to the scientific and industrial revolutions. That continent began to exert political and cultural dominance over human societies around the planet. From 1914 to 1918 and 1939 to 1945, nations around the world were embroiled in world wars.

Established following World War I, the League of Nations was a first step in establishing international institutions to settle disputes peacefully. After failing to prevent World War II, it was replaced by the United Nations. In 1992, several European nations joined in the European Union. As transportation and communication improved, the economies and political affairs of nations around the world have become increasingly intertwined. This globalization has often produced both conflict and collaboration.

Recent events



Four and a half billion years after the planet's formation, Earth’s life broke free of the biosphere. For the first time in history, Earth was viewed from space.

Change has continued at a rapid pace from the mid-1940s to today. Technological developments include nuclear weapons, computers, genetic engineering, and nanotechnology. Economic globalization spurred by advances in communication and transportation technology has influenced everyday life in many parts of the world. Cultural and institutional forms such as democracy, capitalism, and environmentalism have increased influence. Major concerns and problems such as disease, war, poverty, violent radicalism, and recently, human-caused climate change have risen as the world population increases.

In 1957, the Soviet Union launched the first artificial satellite into orbit and, soon afterward, Yuri Gagarin became the first human in space. Neil Armstrong, an American, was the first to set foot on another astronomical object, the Moon. Unmanned probes have been sent to all the known planets in the solar system, with some (such as Voyager) having left the solar system. The Soviet Union and the United States were the earliest leaders in space exploration in the 20th Century. Five space agencies, representing over fifteen countries, have worked together to build the International Space Station. Aboard it, there has been a continuous human presence in space since 2000.

Chapter- 4

Relative Dating and Absolute Dating

Relative dating

Relative dating is the science determining the relative order of past events, without necessarily determining their absolute age.

In geology, rock or superficial deposits. Fossils and lithologies can be used to correlate one stratigraphic column with another, allowing relative dating to be used to show trends over long length-absolute dating in the 20th century, archaeologists and geologists were largely limited to the use of the relative dating techniques to determine the |geological]] events.

Though relative dating can only determine the *sequential order* in which a series of events occurred, not *when* they occur, it is in no way inferior to radiometric dating; in fact, relative dating by biostratigraphy is the preferred method in paleontology, and is in some respects more accurate (Stanley, 167–69). The Law of Superposition was the summary outcome of 'relative dating' as observed in geology from the 17th century to the 19th century.

The regular order of fossils in rock layers had been observed in prehistory, and was rediscovered around 1800 by a British canal surveyor named William Smith. While digging the Somerset Coal Canal in southwest England, he found that fossils were always in the same order in the rock layers. As he continued his job as a surveyor, he found the same patterns across England. He also found that certain animals were in only certain layers and that they were in the same layers all across England. Due to that discovery, Smith was able to recognize the order that the rocks were formed. Sixteen years after his discovery, he published a geological map of England showing the rocks of different geologic time eras. In 1831, Smith received recognition for his work in the form of the Wollaston Medal, the highest honor of the Geological Society of London.

Principles of relative chronology

- Uniformitarianism (Hutton) Popularized by Charles Lyell
- Law of superposition (Steno)
- Original Horizontality (Steno)

- Lateral continuity (Steno)
- Principle of faunal succession(Smith)
- Cross cutting relationships (Hutton)
- Inclusions of Igneous rocks (Hutton)'

Archaeology

Relative dating methods in archaeology are similar to some of those applied in geology. Form a partially ordered set so that the true chronological sequence cannot be reconstructed by stratigraphic means. The principles of typology can be compared to the biostratigraphic approach described above.

Planetology

Relative dating is used to determine the order of events on objects other than Earth; for decades, planetary scientists have used it to decipher the evolution of bodies in the Solar System, particularly in the vast majority of cases in which we have no surface samples. Many of the same principles are used; for instance, if a valley on Mars cuts across a crater, the valley must be younger than the crater.

Craters themselves are highly useful in relative dating; as a general rule, the younger a planetary surface is, the fewer craters it has. If long-term cratering rates are known to enough precision, crude absolute dates can be applied based on craters alone; however, cratering rates outside the Earth-Moon system are poorly known.(Hartmann, 258)

Absolute dating

Absolute dating is the process of determining an approximate age for an archaeological or palaeontological site or artifact. Some archaeologists prefer the terms *chronometric* or *calendar* dating, as use of the word "absolute" implies a certainty and precision that is rarely possible in archaeology. Absolute dating is usually based on the physical or chemical properties of the materials of artifacts, buildings, or other items that have been modified by humans. Absolute dates do not necessarily tell us when a particular cultural event happened, but when taken as part of the overall archaeological record they are invaluable in constructing a more specific sequence of events.

Absolute dating contrasts with the relative dating techniques employed, such as stratigraphy. Absolute dating provides a numerical age for the material tested, while relative dating can only provide a sequence of age.

Radiometric techniques

Radiometric dating is based on the constant rate of decay of radioactive isotopes. Given an initial and a present quantity of such an isotope and its half-life, the time elapsed may be calculated. Various methods apply to different materials and timescales. If a very short period of time has passed, as measured in number of half-lives, a particular technique will be less accurate and more susceptible to statistical fluctuations in the inherently random decay events. If many half lives of the isotope of interest have passed, too much of the sample may have decayed to provide an accurate reading.

Radiocarbon dating

One of the most widely used and well-known absolute dating techniques is carbon-14 (or radiocarbon) dating, which is used to date organic remains. This is a radiometric technique since it is based on radioactive decay. Carbon-14 is an unstable isotope of normal carbon, carbon-12. Cosmic radiation entering the earth's atmosphere produces carbon-14, and plants take in carbon-14 as they fix carbon dioxide. Carbon-14 moves up the food chain as animals eat plants and as predators eat other animals. With death, the uptake of carbon-14 stops. Then this unstable isotope starts to decay into nitrogen-14. It takes 5,730 years for half the carbon-14 to change to nitrogen; this is the half-life of carbon-14. After another 5,730 years only one-quarter of the original carbon-14 will remain. After yet another 5,730 years only one-eighth will be left. By measuring the proportion of carbon-14 in organic material, scientists can determine the date of death of the organic matter in an artifact or ecofact.

Limitations

Because the half-life of carbon-14 is 5730 years carbon dating is only reliable about up to 60,000 years, radiocarbon is less useful to date some recent sites. This technique usually cannot pinpoint the date of a site better than historic records.

A further issue is known as the "old wood" problem. It is possible, particularly in dry, desert climates, for organic materials such as from dead trees to remain in their natural state for hundreds of years before people use them as firewood or building materials, after which they become part of the archaeological record. Thus dating that particular tree does not necessarily indicate when the fire burned or the structure was built. For this reason, many archaeologists prefer to use samples from short-lived plants for radiocarbon dating. The development of accelerator mass spectrometry (AMS) dating, which allows a date to be obtained from a very small sample, has been very useful in this regard.

Potassium-argon dating

Other radiometric dating techniques are available for earlier periods. One of the most widely used is potassium-argon dating (K-Ar dating). Potassium-40 is a radioactive isotope of potassium that decays into argon-40. The half-life of potassium-40 is 1.3 billion years, far longer than that of carbon-14, allowing much older samples to be dated. Potassium is common in rocks and minerals, allowing many samples of geochronological or archeological interest to be dated.

Argon, a noble gas, is not commonly incorporated into such samples except when produced *in situ* through radioactive decay. The date measured reveals the last time that the object was heated past the closure temperature at which the trapped argon can escape the lattice. K-Ar dating was used to calibrate the geomagnetic polarity time scale.

Thermoluminescence

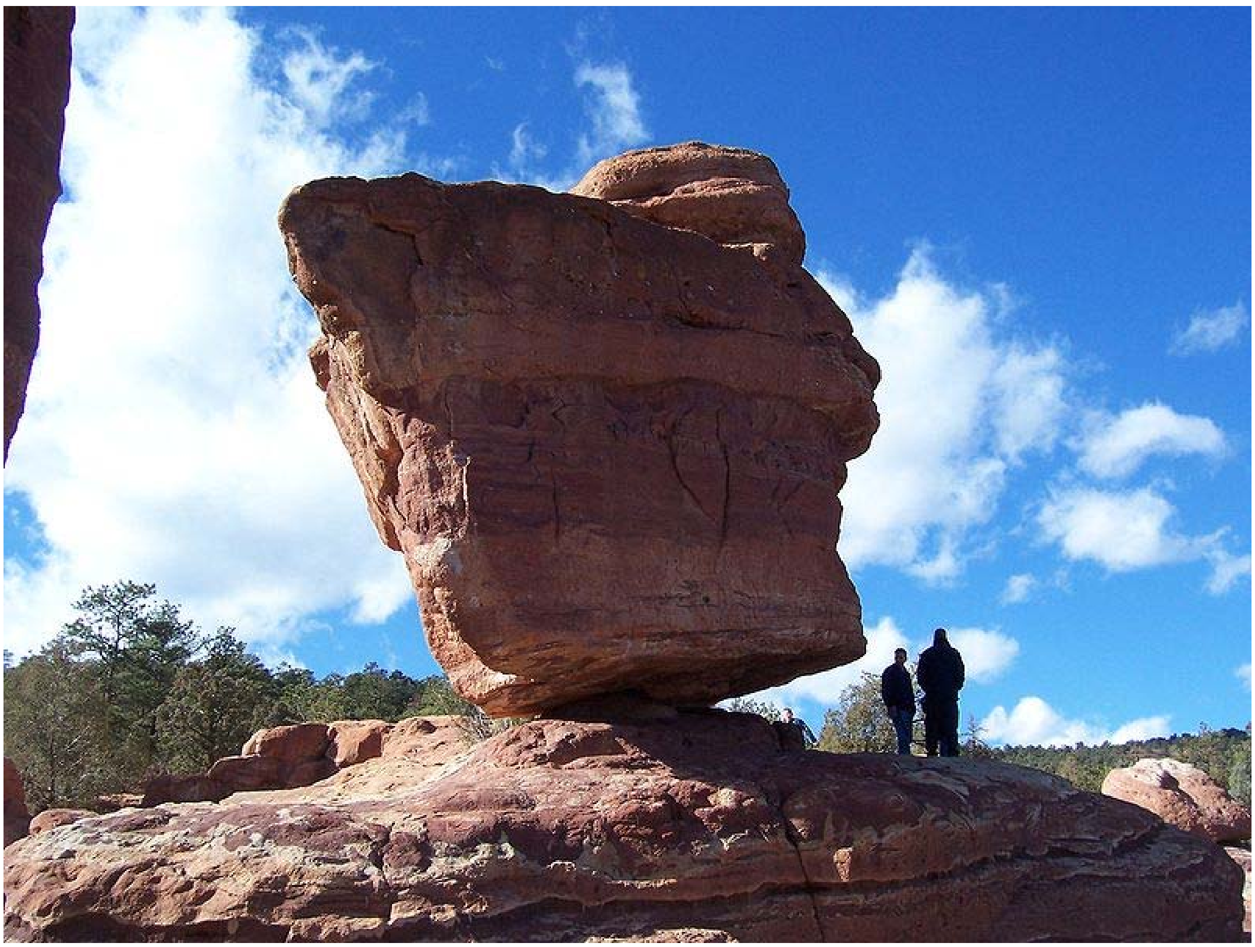
Thermoluminesence testing also dates items to the last time they were heated. This technique is based on the principle that all objects absorb radiation from the environment. This process frees electrons within minerals that remain caught within the item. Heating an item to 350 degrees Celsius or higher releases the trapped electrons, producing light. This light can be measured to determine the last time the item was heated.

Limitations

Radiation levels do not remain constant over time. Fluctuating levels can skew results - for example, if an item went through several high radiation eras, thermoluminesence will return an older date for the item. Many factors can spoil the sample before testing as well, exposing the sample to heat or direct light may cause some of the electrons to dissipate, causing the item to date younger. Because of these and other factors, Thermoluminesence is at the most about 15% accurate. It cannot be used to accurately date a site on its own. However, it can be used to authenticate an item as antiquity.

Chapter- 5

Rock



Balanced Rock stands in Garden of the Gods park in Colorado Springs, CO

In geology, **rock** or **stone** is a naturally occurring solid aggregate of minerals and/or mineraloids.

The Earth's outer solid layer, the lithosphere, is made of rock. In general rocks are of three types, namely, igneous, sedimentary, and metamorphic. The scientific study of rocks is called petrology, and petrology is an essential component of geology.

Rock classification

The rocky side of a mountain creek near Orosí, Costa Rica

Rocks are generally classified by mineral and chemical composition, by the texture of the constituent particles and by the processes that formed them. These indicators separate rocks into igneous, sedimentary, and metamorphic. They are further classified according to particle size. The transformation of one rock type to another is described by the geological model called the rock cycle.

Sample of igneous gabbro

Igneous rocks are formed when molten magma cools and are divided into two main categories: plutonic rock and volcanic. Plutonic or intrusive rocks result when magma cools and crystallizes slowly within the Earth's crust (example granite), while volcanic or extrusive rocks result from magma reaching the surface either as lava or fragmental ejecta (examples pumice and basalt).

Sedimentary sandstone with iron oxide bands

Sedimentary rocks are formed by deposition of either clastic sediments, organic matter, or chemical precipitates (evaporites), followed by compaction of the particulate matter and cementation during diagenesis. Sedimentary rocks form at or near the Earth's surface. Mud rocks comprise 65% (mudstone, shale and siltstone); sandstones 20 to 25% and carbonate rocks 10 to 15% (limestone and dolostone).

Metamorphic banded gneiss

Metamorphic rocks are formed by subjecting any rock type (including previously formed metamorphic rock) to different temperature and pressure conditions than those in which the original rock was formed. These temperatures and pressures are always higher than those at the Earth's surface and must be sufficiently high so as to change the original minerals into other mineral types or else into other forms of the same minerals (e.g. by recrystallisation).

The three classes of rocks — the igneous, the sedimentary and the metamorphic — are subdivided into many groups. There are, however, no hard and fast boundaries between allied rocks. By increase or decrease in the proportions of their constituent minerals they pass by every gradation into one another, the distinctive structures also of one kind of rock may often be traced gradually merging into those of another. Hence the definitions adopted in establishing rock nomenclature merely correspond to selected points (more or less arbitrary) in a continuously graduated series.

Human use

Ceremonial cairn of rocks, an ovoo, from Mongolia

Uranium mine near Moab, Utah

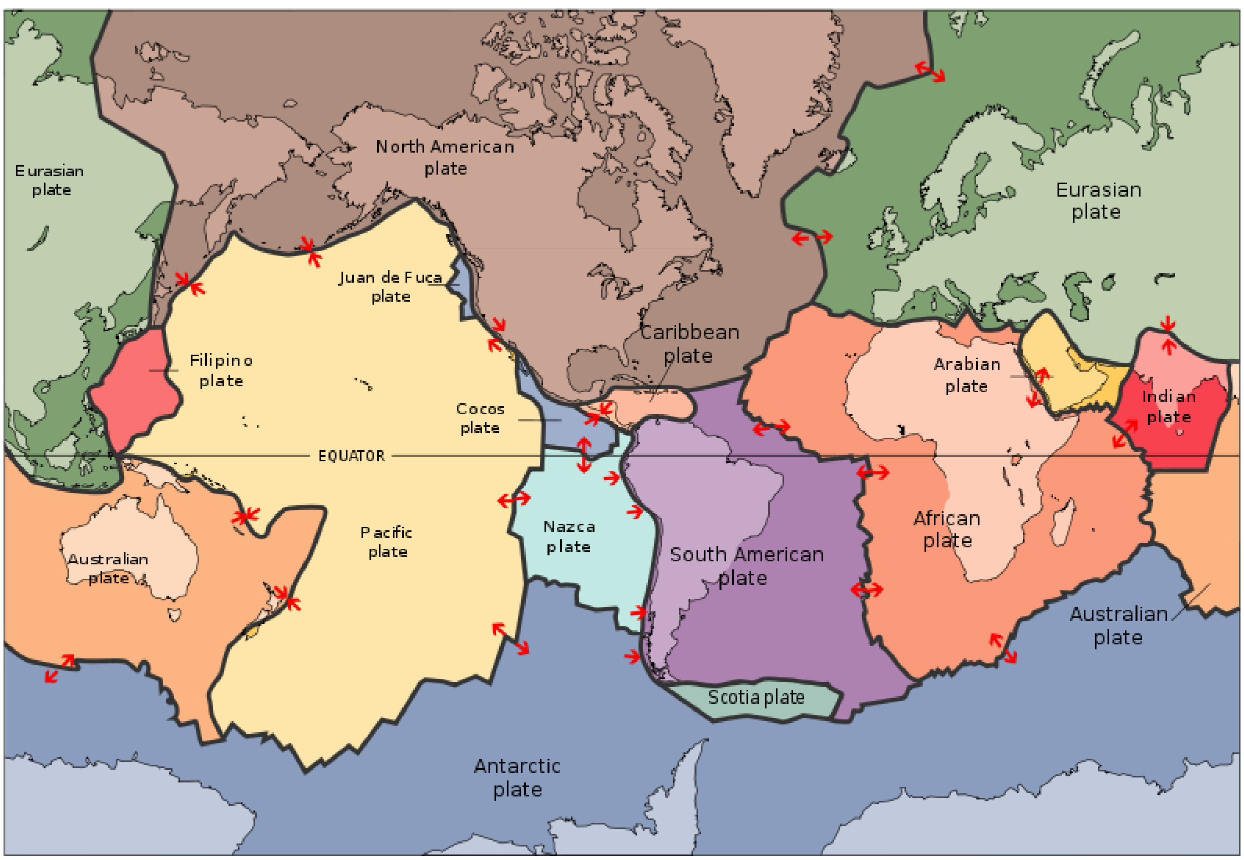
The use of rocks has had a huge impact on the cultural and technological development of the human race. Rocks have been used by humans and other hominids for more than 2 million years. Lithic technology marks some of the oldest and continuously used technologies. The mining of rocks for their metal ore content has been one of the most important factors of human advancement, which has progressed at different rates in different places in part because of the kind of metals available from the rocks of a region.

The prehistory and history of civilization is classified into the Stone Age, Bronze Age, and Iron Age. Although the stone age has ended virtually everywhere, rocks continue to be used to construct buildings and infrastructure. When so used, rocks are called dimension stone.

Chapter- 6

Whole-Earth Structure & Theories

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") (Little, Fowler & Coulson 1990) 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 (Read & Watson 1975).

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.

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.

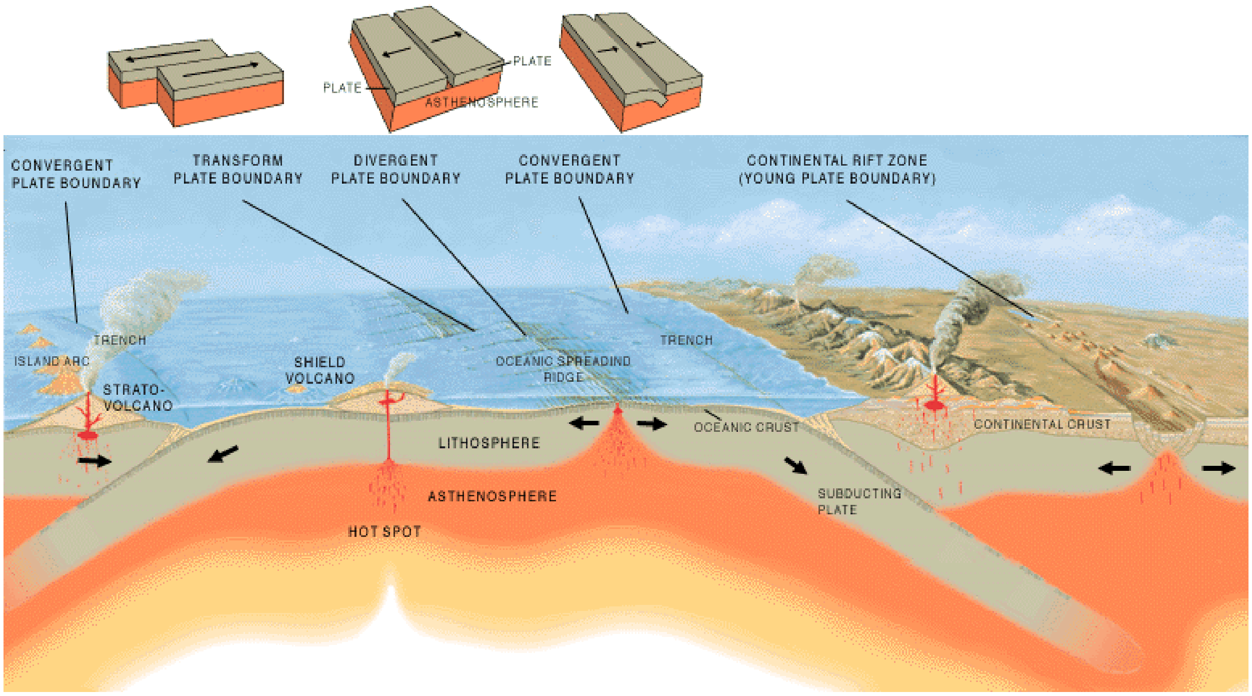
The key principle of plate tectonics is that the lithosphere exists as separate and distinct *tectonic plates*, which ride on the fluid-like (visco-elastic solid) asthenosphere. Plate motions range up to a typical 10–40 mm/a (Mid-Atlantic Ridge; about as fast as fingernails grow), to about 160 mm/a (Nazca Plate; about as fast as hair grows) (Zhen Shao 1997; Hancock, Skinner & Dineley 2000). The driving mechanism behind this movement is described below in a separate section.

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 (Turcotte & Schubert 2002); 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 (Turcotte & Schubert 2002). 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) (Turcotte & Schubert 2002).

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.

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") (Schmidt & Harbert 1998). 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 (Meissner 2002, p. 100), 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. 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 broad belt boundaries are not well defined.

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 is the motor behind this movement; 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 (van Dijk 1992, van Dijk & Okkes 1991). 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 (Tanimoto & Lay 2000).

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 patterns of mantle dynamics 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 (Smoot et al. 1996).

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 are for example:

Flexural bulging of the lithosphere before it dives underneath an adjacent plate, for instance, produces a clear topographical feature that can offset or at least affect the influence of topographical ocean ridges.
Mantle plumes and hot spots impinging on the underside of tectonic plates can drastically alter the topography of the ocean floor. Some of these, on a larger scale, are seen as the major driving force of the plates (see below).

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 (Conrad & Lithgow-Bertelloni 2002). 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. Slab pull is especially invoked in areas where remnants of older lithosphere become trapped along convergence zones e.g. as relicts in collisional belts, which, sinking into the mantle and rolling backwards, exert a pull on the overlying crust.

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 the plates suffer when they move around the globe (coriolis effect/law of Buys Ballot)
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 (Scoppola et al. 2006), 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 by Torsvik et al. (2010) 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.

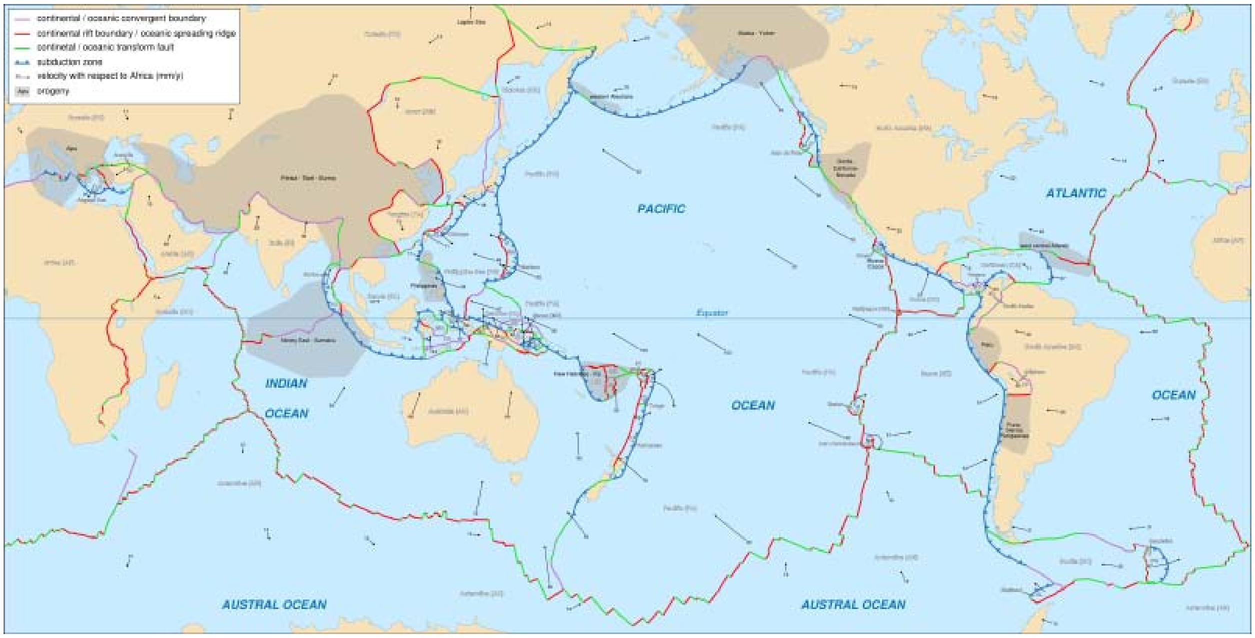
The diversity of geodynamic settings and properties of each plate must clearly result in differences in the degree to which such processes are actively driving the plates. One method of dealing with this problem is to consider the relative rate at which each plate is moving and to consider the available 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 (Conrad & Lithgow-Bertelloni 2002). The driving forces of plate motion continue to be active subjects of on-going research within geophysics and tectonophysics.

Historical context - 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 (Hughes 2001a). 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 (Wegener 1966; Hughes 2001b).

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.

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 reverse through time, and, especially important in paleotectonic studies, the relative position of the magnetic north varies through time. Initially, during the first half of the twentieth century, the latter phenomena 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 in was shown with success that these data could show the validity of continental drift in two occasions: 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 (Korgen 1995; Spiess & Kuperman 2003).

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 these evidences, both from the ocean floor and from the continental margins made 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 (Kious & Tilling 1996).

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 (Frankel 1987).

The discovery of radioactivity and its associated heating properties in 1895 prompted a re-examination of the apparent age of the Earth (Joly 1909) since this had previously been estimated by its cooling rate and assumption the Earth's surface radiated like a black body (Thomson 1863).

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 (Wegener 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 due to the fact that 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:

1. During this timespan, continental drift was not accepted.
2. Some of these ideas were discussed in the context of abandoned fixistic ideas of a deforming globe without continental drift or an expanding Earth.

3. They were published during an episode of extreme political and economic instability and scientific communication was obviously hampered by this.
4. 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 (Lippsett 2001; and Lippsett 2006).

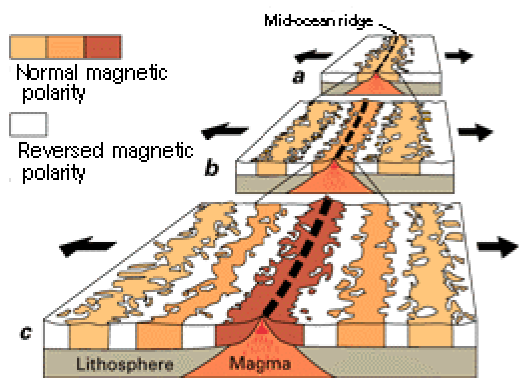
The new data that had been collected on the ocean basins also showed particular characteristics regarding the bathymetry. One of the major outcomes of these datasets was that all along the globe, a system of mid-oceanic ridges was detected. An important conclusion was that along this system, new ocean 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 ocean floor, the pieces of the theory fell quickly at its 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.

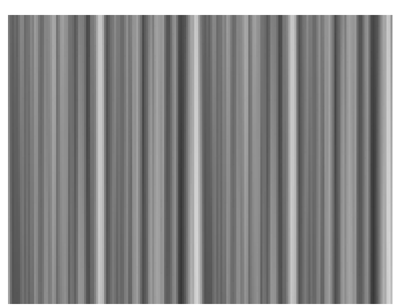
In the same year, Robert R. Coats of the U.S. Geological Survey described the main features of island arc subduction in the Aleutian Islands. His paper, though little–noted (and even ridiculed) at the time, has since been called "seminal" and "prescient". In reality, it actually shows that the work by 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 present e.g. along the rim of the Pacific Ocean basin – were formed. 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 like what 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 (Mason & Raff 1961); (Raff & Mason 1961).

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 (Vine & Matthews 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

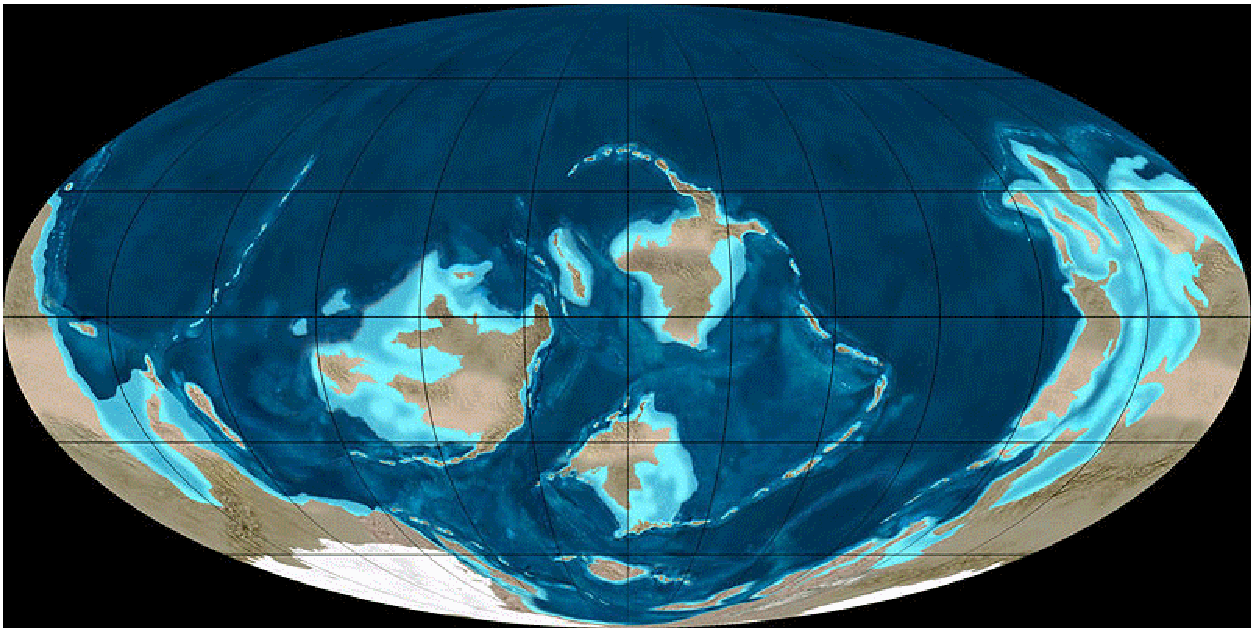
After all these considerations, Plate Tectonics (or, as it was initially called "New Global Tectonics") became quickly accepted in the scientific world, and numerous papers followed that defined the concepts:

- In 1965, Tuzo Wilson who had been a promotor of the sea floor spreading hypothesis and continental drift from the very beginning (e.g. Wilson 1963) 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 (Wilson 1965).
- 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 Tuzo Wilson published the paper that referred to previous plate tectonic reconstructions, introducing the concept of what is now known as the "Wilson Cycle" (Wilson 1966).
- 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 (Morgan 1968).
- Two months later, Xavier Le Pichon published a complete model based on 6 major plates with their relative motions, and we may say that this parks the final acceptance of the scientific community of plate tectonics (Le Pichon 1967).
- 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 (McKenzie & Parker 1967).

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 (Moss & Wilson 1998). 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 (Condie 1997). Past plate boundaries within existing plates are identified from evidence of vanished oceans, such as ophiolites (Lliboutry 2000).

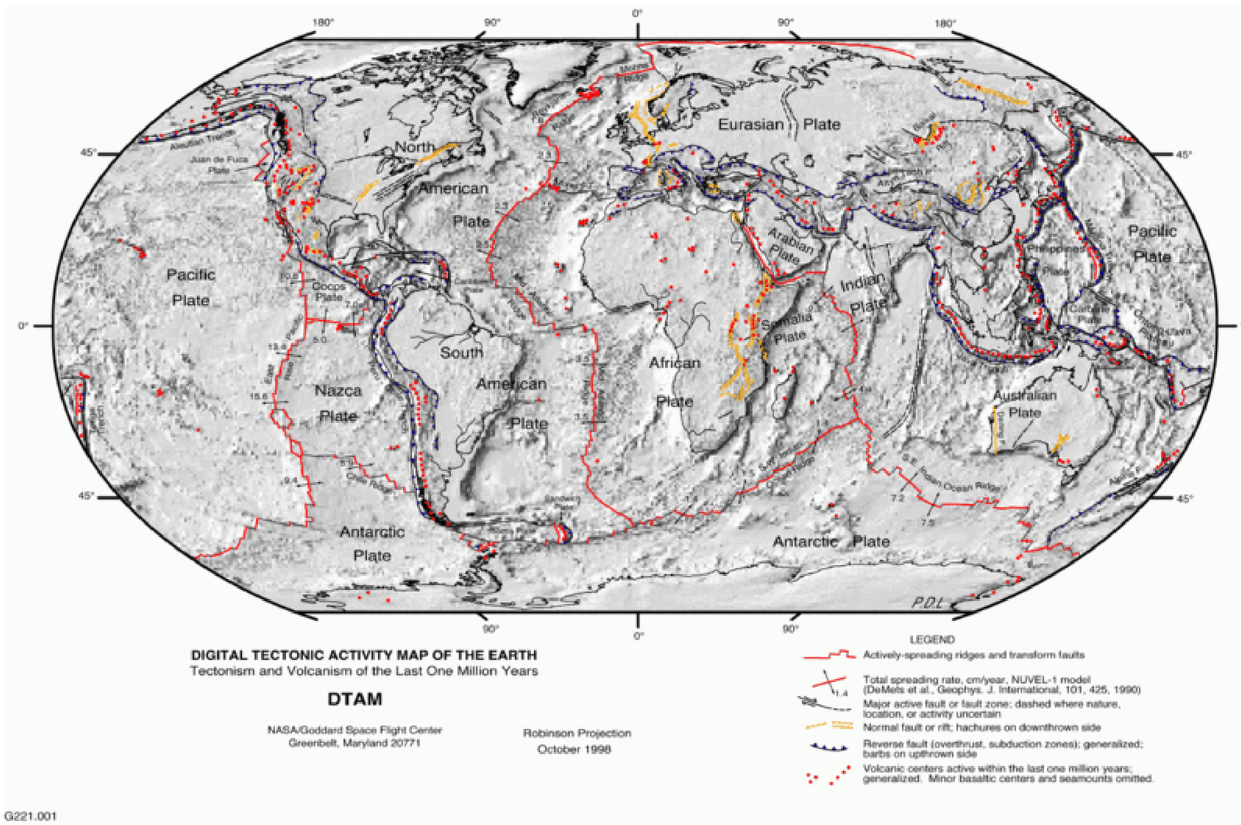
Past plate motions

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

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 (Torsvik 2008).

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 (Butler 1992). Additional evidence comes from the distribution of certain sedimentary rock types, faunal provinces shown by particular fossil groups, and the position of orogenic belts (Torsvik 2008).

Current plates



Major plates

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

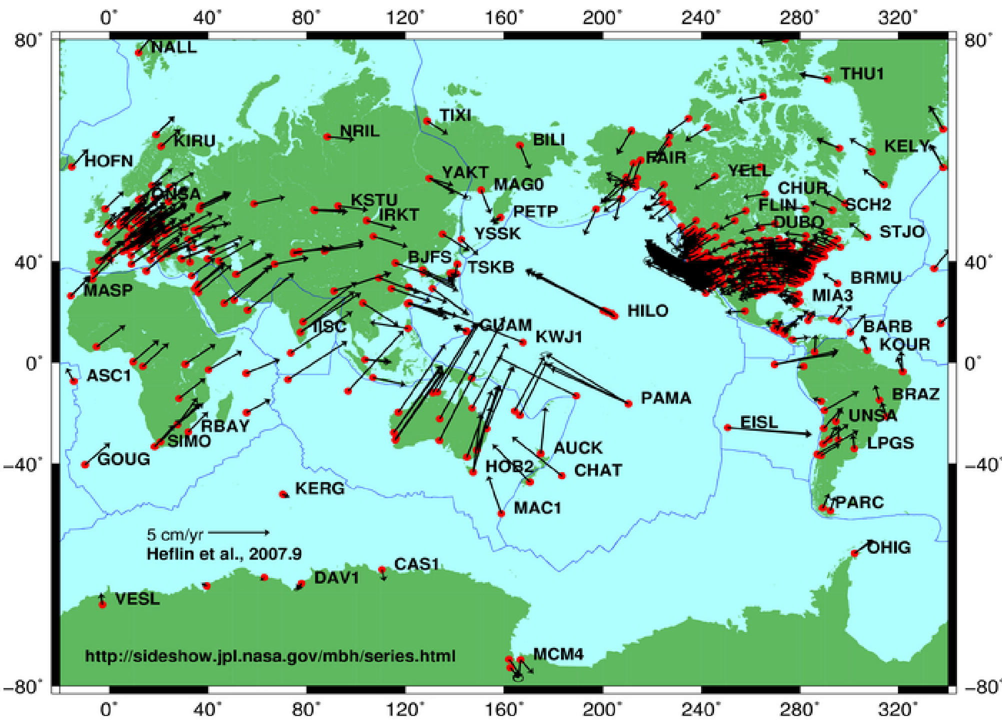


Plate motion based on Global Positioning System (GPS) satellite data from NASA JPL. The vectors show direction and magnitude of motion.

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 (Valencia, O'Connell & Sasselov 2007)

(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 (Kasting 1988). 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 (Sleep 1994). 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 (Zhong & Zuber 2001) or by a giant impact that excavated the Northern Lowlands (Andrews-Hanna, Zuber & Banerdt 2008).

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 (Connerney et al. 1999, Connerney et al. 2005)). 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 (Harrison 2000).

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.

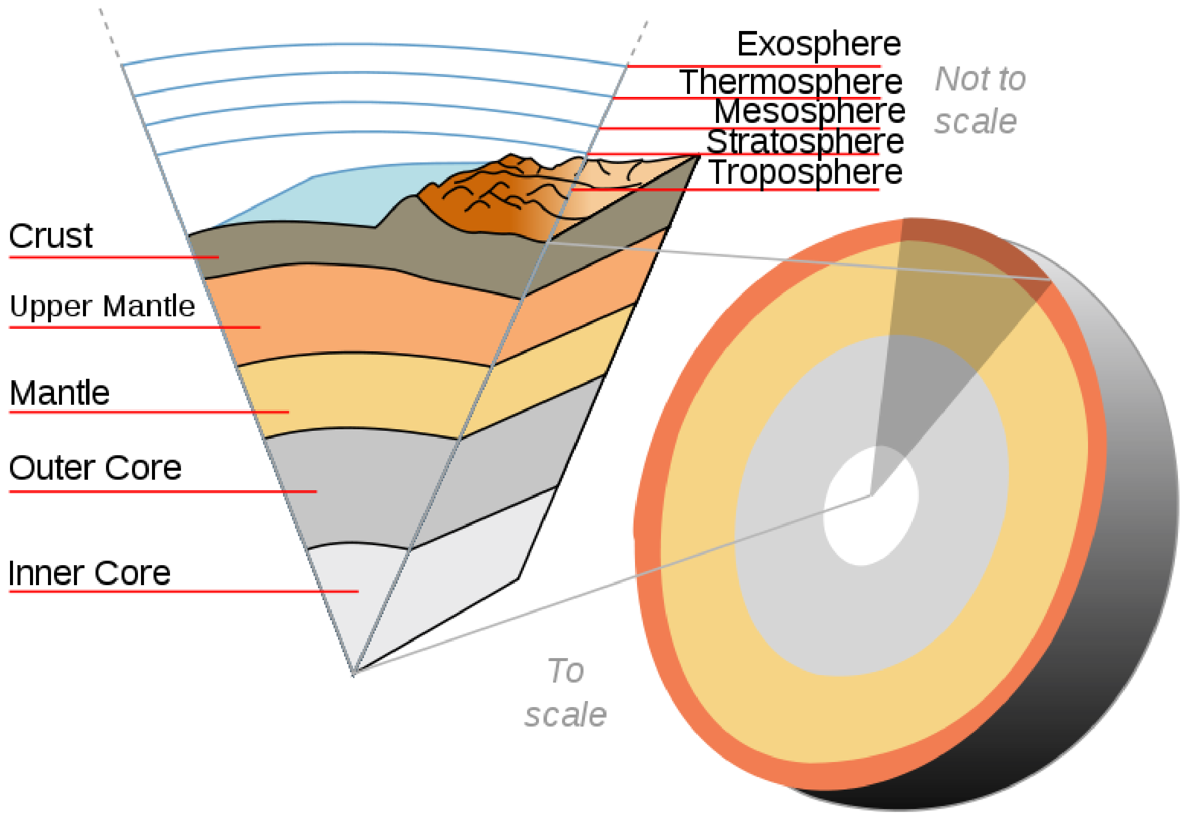
Titan, moon of Saturn

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 (Soderblom et al. 2007).

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 (Valencia, O'Connell & Sasselov 2007).

Structure of the Earth



Earth cutaway from core to exosphere. Left picture is not to scale

The interior **structure of the Earth**, similar to the outer, is layered. These layers can be defined by either their chemical or their rheological properties. The Earth has an outer silicate solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core. Scientific understanding of Earth's internal structure is based on observations of topography and bathymetry, observations of rock in outcrop, samples brought to the surface from greater depths by volcanic activity, analysis of the seismic waves that pass through the Earth, measurements of the gravity field of the Earth, and experiments with crystalline solids at pressures and temperatures characteristic of the Earth's deep interior.

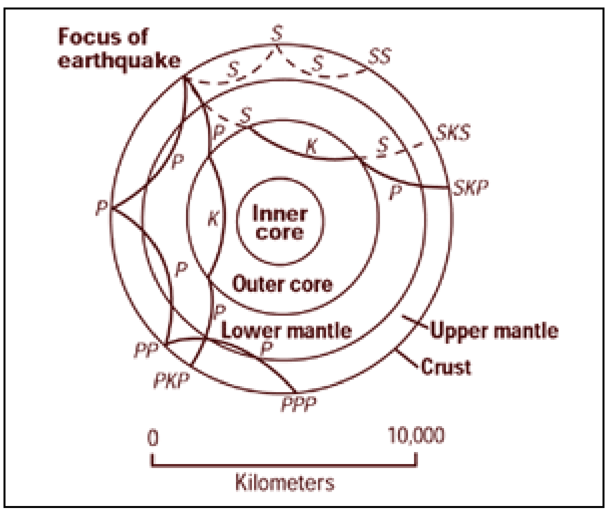
Assumptions

The force exerted by Earth's gravity can be used to calculate its mass, and by estimating the volume of the planet, its average density can be calculated. Astronomers can also calculate Earth's mass from its orbit and effects on nearby planetary bodies. Observations of rocks, bodies of water and atmosphere allow estimation of the mass, volume and density of rocks to a certain depth, so the remaining mass must be in the deeper layers.

Structure

The structure of Earth can be defined in two ways: by mechanical properties such as rheology, or chemically. Mechanically, it can be divided into lithosphere, asthenosphere, mesosphere, outer core, and the inner core. The interior of the earth is divided into 5 important layers. Chemically, Earth can be divided into the crust, upper mantle, lower mantle, outer core, and inner core. The geologic component layers of Earth are at the following depths below the surface:

Depth		
Kilometers	**Miles**	**Layer**
0–60	0–37	Lithosphere (locally varies between 5 and 200 km)
0–35	0–22	… Crust (locally varies between 5 and 70 km)
35–60	22–37	… Uppermost part of mantle
35–2,890	22–1,790	Mantle
100–200	62–125	… Asthenosphere
35–660	22–410	… Upper mantle
660–2,890	410–1,790	… Lower mantle
2,890–5,150	1,790–3,160	Outer core
5,150–6,360	3,160–3,954	Inner core



Mapping the interior of the Earth with earthquake waves

The layering of Earth has been inferred indirectly using the time of travel of refracted and reflected seismic waves created by earthquakes. The core does not allow shear waves to pass through it, while the speed of travel (seismic velocity) is different in other layers. The changes in seismic velocity between different layers causes refraction owing to Snell's law. Reflections are caused by a large increase in seismic velocity and are similar to light reflecting from a mirror.

Core

The average density of Earth is 5,515 kg/m^3. Since the average density of surface material is only around 3,000 kg/m^3, we must conclude that denser materials exist within Earth's core. Further evidence for the high density core comes from the study of seismology.

Seismic measurements show that the core is divided into two parts, a solid inner core with a radius of ~1,220 km and a liquid outer core extending beyond it to a radius of ~3,400 km. The solid inner core was discovered in 1936 by Inge Lehmann and is generally believed to be composed primarily of iron and some nickel.

In early stages of Earth's formation about 4.5 billion (4.5×10^9) years ago, melting would have caused denser substances to sink toward the center in a process called planetary differentiation, while less-dense materials would have migrated to the crust. The core is thus believed to largely be composed of iron (80%), along with nickel and one or more light elements, whereas other dense elements, such as lead and uranium, either are too rare to be significant or tend to bind to lighter elements and thus remain in the crust. Some have argued that the inner core may be in the form of a single iron crystal.

The liquid outer core surrounds the inner core and is believed to be composed of iron mixed with nickel and trace amounts of lighter elements.

Recent speculation suggests that the innermost part of the core is enriched in gold, platinum and other iron-loving (siderophile) elements.

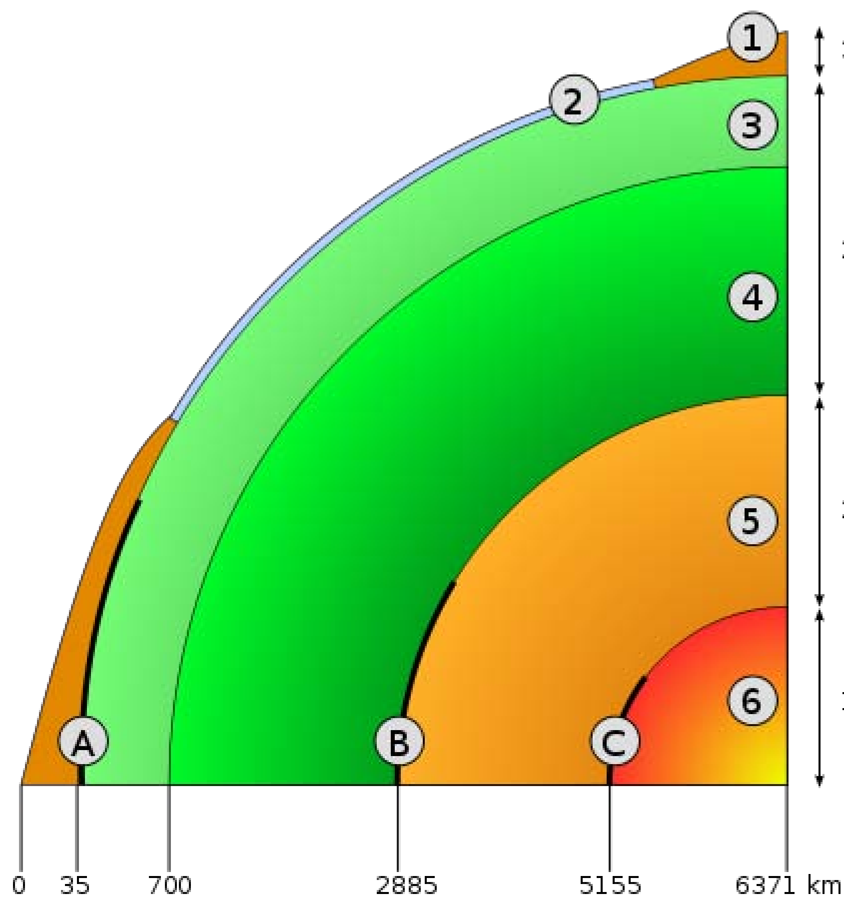
The matter that comprises Earth is connected in fundamental ways to matter of certain chondrite meteorites, and to matter of outer portion of the Sun. There is good reason to believe that Earth is, in the main, like a chondrite meteorite. Beginning as early as 1940, scientists, including Francis Birch, built geophysics upon the premise that Earth is like ordinary chondrites, the most common type of meteorite observed impacting Earth, while totally ignoring another, albeit less abundant type, called enstatite chondrites. The principal difference between the two meteorite types is that enstatite chondrites formed under circumstances of extremely limited available oxygen, leading to certain normally oxyphile elements existing either partially or wholly in the alloy portion that corresponds to the core of Earth.

Dynamo theory suggests that convection in the outer core, combined with the Coriolis effect, gives rise to Earth's magnetic field. The solid inner core is too hot to hold a permanent magnetic field but probably acts to stabilize the magnetic field generated by the liquid outer core.

Recent evidence has suggested that the inner core of Earth may rotate slightly faster than the rest of the planet. In August 2005 a team of geophysicists announced in the journal *Science* that, according to their estimates, Earth's inner core rotates approximately 0.3 to 0.5 degrees per year relative to the rotation of the surface.

The current scientific explanation for the Earth's temperature gradient is a combination of heat left over from the planet's initial formation, decay of radioactive elements, and freezing of the inner core.

Mantle



Schematic view of the interior of Earth. 1. continental crust - 2. oceanic crust - 3. upper mantle - 4. lower mantle - 5. outer core - 6. inner core - A: Mohorovičić discontinuity - B: Gutenberg Discontinuity - C: Lehmann discontinuity

Earth's mantle extends to a depth of 2,890 km, making it the thickest layer of the Earth. The pressure, at the bottom of the mantle, is ~140 GPa (1.4 Matm). The mantle is composed of silicate rocks that are rich in iron and magnesium relative to the overlying crust. Although solid, the high temperatures within the mantle cause the silicate material to be sufficiently ductile that it can flow on very long timescales. Convection of the mantle is expressed at the surface through the motions of tectonic plates. The melting point and viscosity of a substance depends on the pressure it is under. As there is intense and increasing pressure as one travels deeper into the mantle, the lower part of the mantle flows less easily than does the upper mantle (chemical changes within the mantle may also be important). The viscosity of the mantle ranges between 10^{21} and 10^{24} Pa·s, depending on depth. In comparison, the viscosity of water is approximately 10^{-3} Pa·s and that of pitch is 10^{7} Pa·s.

Crust

The crust ranges from 5–70 km in depth and is the outermost layer. The thin parts are the oceanic crust, which underlie the ocean basins(5–10 km) and are composed of dense (mafic) iron magnesium silicate rocks, like basalt. The thicker crust is continental crust, which is less dense and composed of (felsic) sodium potassium aluminium silicate rocks, like granite. The rocks of the crust fall into two major categories - sial and sima (Suess,1831–1914). As the main mineral constituents of the continental mass are silica and alumina, it is thus called sial (si-silica, 65–75% and al-alumina). The oceanic crust mainly consists of silica and magnesium; it is therefore called sima (si-silica and ma-magnesium). It is estimated that sima starts about 11 km below the Conrad discontinuity, a second order discontinuity. The uppermost mantle together with the crust constitutes the lithosphere. The crust-mantle boundary occurs as two physically different events. First, there is a discontinuity in the seismic velocity, which is known as the Mohorovičić discontinuity or Moho. The cause of the Moho is thought to be a change in rock composition from rocks containing plagioclase feldspar (above) to rocks that contain no feldspars (below). Second, in oceanic crust, there is a chemical discontinuity between ultramafic cumulates and tectonized harzburgites, which has been observed from deep parts of the oceanic crust that have been obducted onto the continental crust and preserved as ophiolite sequences.

Many rocks now making up Earth's crust formed less than 100 million (1×10^{8}) years ago; however the oldest known mineral grains are 4.4 billion (4.4×10^{9}) years old, indicating that Earth has had a solid crust for at least that long.

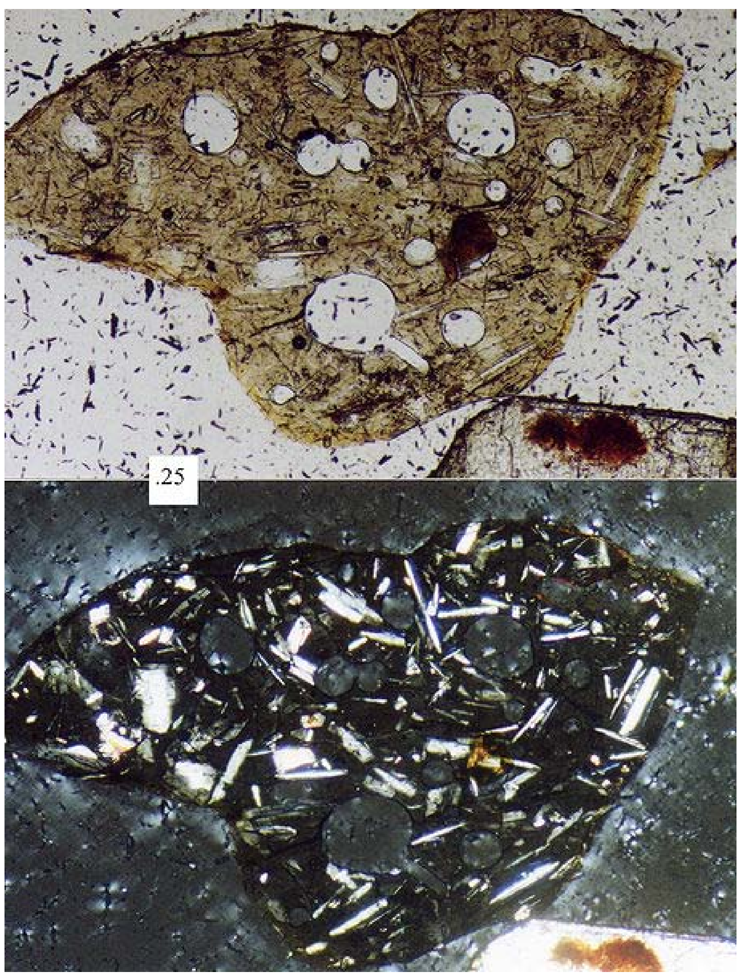
Historical development of alternative conceptions

In 1692 Edmund Halley (in a paper printed in *Philosophical Transactions of Royal Society of London*) put forth the idea of Earth consisting of a hollow shell about 500 miles thick, with two inner concentric shells around an innermost core, corresponding to the diameters of the planets Venus, Mars, and Mercury respectively. Halley's construct was a method of accounting for the (flawed) values of the relative density of Earth and the Moon that had been given by Sir Isaac Newton, in *Principia* (1687). "Sir Isaac Newton has demonstrated the Moon to be more solid than our Earth, as 9 to 5," Halley remarked; "why may we not then suppose four ninths of our globe to be cavity?"

Chapter- 7

Branches & Methods in Geology

1. Petrology



A volcanic sand grain seen under the microscope, with plane-polarized light in the upper picture, and cross polarized light in the lower picture. Scale box is 0.25 mm.

Petrology (from Greek: πέτρα, *petra*, rock; and λόγος, *logos*, knowledge) is the branch of geology that studies rocks, and the conditions in which rocks form.

Lithology once was approximately synonymous with petrography, but in current usage, lithology is a subdivision of petrology focusing on macroscopic hand-sample or outcrop-scale description of rocks, while petrography is the speciality that deals with microscopic details.

In the oil industry, lithology, or more specifically mud logging, is the graphic representation of geological formations being drilled through, and drawn on a log called a mud log. As the cuttings are circulated out of the borehole they are sampled, examined (typically under a 10x microscope) and tested chemically when needed.

Methodology

Petrology utilizes the classical fields of mineralogy, petrography, optical mineralogy, and chemical analyses to describe the composition and texture of rocks. Modern petrologists also include the principles of geochemistry and geophysics through the studies of geochemical trends and cycles and the use of thermodynamic data and experiments to better understand the origins of rocks.

Branches

There are three branches of petrology, corresponding to the three types of rocks: igneous, metamorphic, and sedimentary, and another dealing with experimental techniques:

- Igneous petrology focuses on the composition and texture of igneous rocks (rocks such as granite or basalt which have crystallized from molten rock or magma). Igneous rocks include volcanic and plutonic rocks.
- Sedimentary petrology focuses on the composition and texture of sedimentary rocks (rocks such as sandstone, shale, or limestone which consist of pieces or particles derived from other rocks or biological or chemical deposits, and are usually bound together in a matrix of finer material).
- Metamorphic petrology focuses on the composition and texture of metamorphic rocks (rocks such as slate, marble, gneiss, or schist which started out as sedimentary or igneous rocks but which have undergone chemical, mineralogical or textural changes due to extremes of pressure, temperature or both)
- Experimental petrology employs high-pressure, high-temperature apparatus to investigate the geochemistry and phase relations of natural or synthetic materials at elevated pressures and temperatures. Experiments are particularly useful for investigating rocks of the lower crust and upper mantle that rarely survive the journey to the surface in pristine condition. The work of experimental petrologists has laid a foundation on which modern understanding of igneous and metamorphic processes has been built.

2. Structural geology

Structural geology is the study of the three-dimensional distribution of rock units with respect to their deformational histories. The primary goal of structural geology is to use measurements of present-day rock geometries to uncover information about the history of deformation (strain) in the rocks, and ultimately, to understand the stress field that resulted in the observed strain and geometries. This understanding of the dynamics of the stress field can be linked to important events in the regional geologic past; a common goal is to understand the structural evolution of a particular area with respect to regionally widespread patterns of rock deformation (e.g., mountain building, rifting) due to plate tectonics.

Use and importance

The study of geologic structures has been of prime importance in economic geology, both petroleum geology and mining geology. Folded and faulted rock strata commonly form traps for the accumulation and concentration of fluids such as petroleum and natural gas. Faulted and structurally complex areas are notable as permeable zones for hydrothermal fluids and the resulting concentration areas for base and precious metal ore deposits. Veins of minerals containing various metals commonly occupy faults and fractures in structurally complex areas. These structurally fractured and faulted zones often occur in association with intrusive igneous rocks. They often also occur around geologic reef complexes and collapse features such as ancient sinkholes. Deposits of gold, silver, copper, lead, zinc, and other metals, are commonly located in structurally complex areas.

Structural geology is a critical part of engineering geology, which is concerned with the physical and mechanical properties of natural rocks. Structural fabrics and defects such as faults, folds, foliations and joints are internal weaknesses of rocks which may affect the stability of human engineered structures such as dams, road cuts, open pit mines and underground mines or road tunnels.

Geotechnical risk, including earthquake risk can only be investigated by inspecting a combination of structural geology and geomorphology. In addition areas of karst landscapes which are underlain by underground caverns and potential sinkholes or collapse features are of importance for these scientists. In addition, areas of steep slopes are potential collapse or landslide hazards.

Environmental geologists and hydrogeologists or hydrologists need to understand structural geology because structures are sites of groundwater flow and penetration, which may affect, for instance, seepage of toxic substances from waste dumps, or seepage of salty water into aquifers.

Plate tectonics is a theory developed during the 1960s which describes the movement of continents by way of the separation and collision of crustal plates. It is in a sense structural geology on a planet scale, and is used throughout structural geology as a framework to analyze and understand global, regional, and local scale features.

Methods

Structural geologists use a variety of methods to (first) measure rock geometries, (second) reconstruct their deformational histories, and (third) calculate the stress field that resulted in that deformation.

Geometries

Primary data sets for structural geology are collected in the field. Structural geologists measure a variety of planar features (bedding planes, foliation planes, fold axial planes, fault planes, and joints), and linear features (stretching lineations, in which minerals are ductily extended; fold axes; and intersection lineations, the trace of a planar feature on another planar surface).

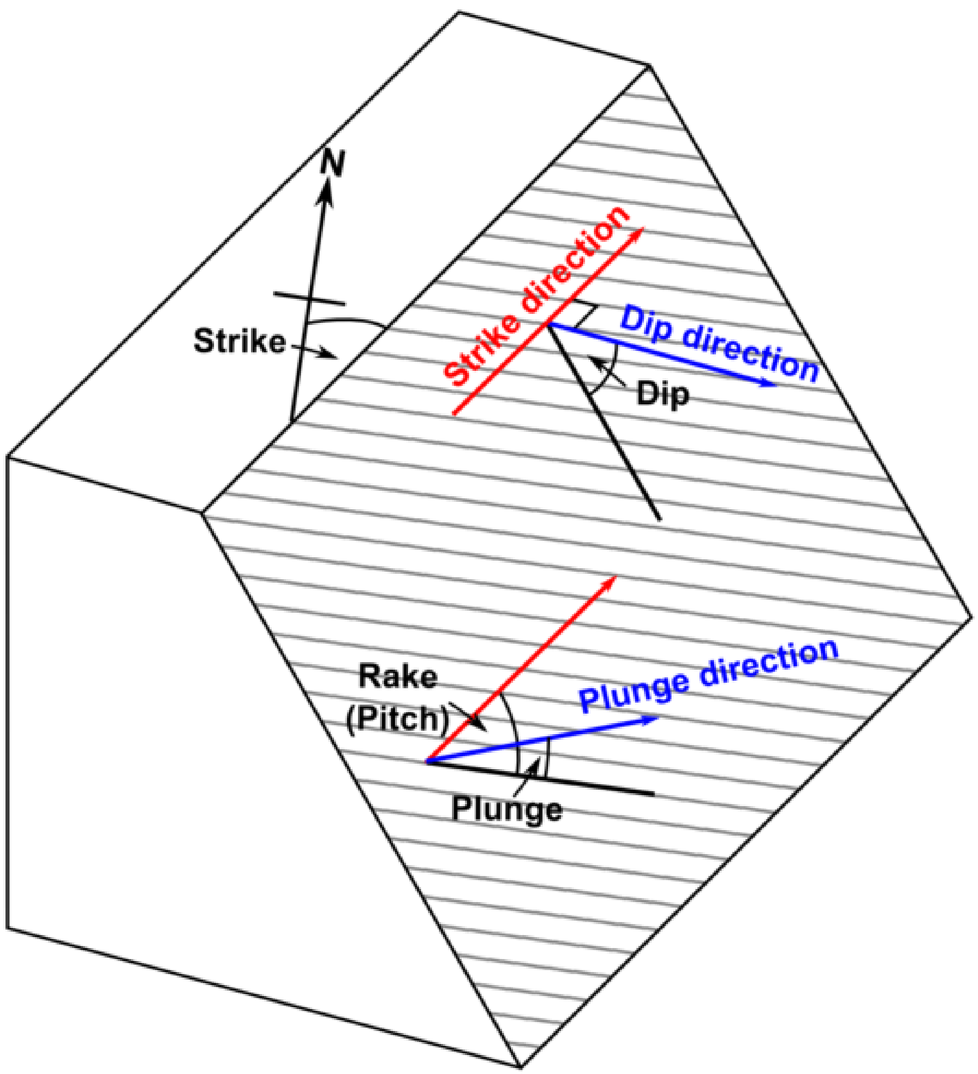


Illustration of measurement conventions for planar and linear structures

Measurement conventions

The inclination of a planar structure in geology is measured by *strike and dip*. The strike is the line of intersection between the planar feature and a horizontal plane, taken according to the right hand convention, and the dip is the magnitude of the inclination, below horizontal, at right angles to strike. For example; striking 25 degrees East of North, dipping 45 degrees Southeast, recorded as N25E,45SE.
Alternatively, dip and dip direction may be used as this is absolute. Dip direction is measured in 360 degrees, generally clockwise from North. For example, a dip of 45 degrees towards 115 degrees azimuth, recorded as 45/115. Note that this is the same as above.

The term *hade* is occasionally used and is the deviation of a plane from vertical i.e. (90°-dip).

Fold axis plunge is measured in dip and dip direction (strictly, plunge and azimuth of plunge). The orientation of a fold axial plane is measured in strike and dip or dip and dip direction.

Lineations are measured in terms of dip and dip direction, if possible. Often lineations occur expressed on a planar surface and can be difficult to measure directly. In this case, the lineation may be measured from the horizontal as a *rake* or *pitch* upon the surface.

Rake is measured by placing a protractor flat on the planar surface, with the flat edge horizontal and measuring the angle of the lineation clockwise from horizontal. The orientation of the lineation can then be calculated from the rake and strike-dip information of the plane it was measured from, using a stereographic projection.

If a fault has lineations formed by movement on the plane, eg; slickensides, this is recorded as a lineation, with a rake, and annotated as to the indication of throw on the fault.

Generally it is easier to record strike and dip information of planar structures in dip/dip direction format as this will match all the other structural information you may be recording about folds, lineations, etc., although there is an advantage to using different formats that discriminate between planar and linear data.

Plane, fabric, fold and deformation conventions

The convention for analysing structural geology is to identify the **planar structures**, often called *planar fabrics* because this implies a textural formation, the **linear structures** and, from analysis of these, unravel **deformations**.

Planar structures are named according to their order of formation, with original sedimentary layering the lowest at S0. Often it is impossible to identify S0 in highly deformed rocks, so numbering may be started at an arbitrary number or given a letter (S_A, for instance). In cases where there is a bedding-plane foliation caused by burial metamorphism or diagenesis this may be enumerated as S0a.

If there are folds, these are numbered as F_1, F_2, etc. Generally the axial plane foliation or cleavage of a fold is created during folding, and the number convention should match. For example, an F_2 fold should have an S_2 axial foliation.

Deformations are numbered according to their order of formation with the letter D denoting a deformation event. For example D_1, D_2, D_3. Folds and foliations, because they are formed by deformation events, should correlate with these events. For example an F_2 fold, with an S_2 axial plane foliation would be the result of a D_2 deformation.

Metamorphic events may span multiple deformations. Sometimes it is useful to identify them similarly to the structural features for which they are responsible, eg; M_2. This may be possible by observing porphyroblast formation in cleavages of known deformation age, by identifying metamorphic mineral assemblages created by different events, or via geochronology.

Intersection lineations in rocks, as they are the product of the intersection of two planar structures, are named according to the two planar structures from which they are formed. For instance, the intersection lineation of a S_1 cleavage and bedding is the L_{1-0} intersection lineation (also known as the cleavage-bedding lineation).

Stretching lineations may be difficult to quantify, especially in highly stretched ductile rocks where minimal foliation information is preserved. Where possible, when correlated with deformations (as few are formed in folds, and many are not strictly associated with planar foliations), they may be identified similar to planar surfaces and folds, eg; L_1, L_2. For convenience some geologists prefer to annotate them with a subscript S, for example L_{s1} to differentiate them from intersection lineations, though this is generally redundant.

Stereographic projections

Stereographic projection of structural strike and dip measurements is a powerful method for analyzing the nature and orientation of deformation stresses, lithological units and penetrative fabrics.

Rock macro-structures

On a large scale, structural geology is the study of the three dimensional relationships of stratigraphic units to one another within terranes of rock or within geological regions.

This branch of structural geology deals mainly with the orientation, deformation and relationships of stratigraphy (bedding), which may have been faulted, folded or given a foliation by some tectonic event. This is mainly a geometric science, from which *cross sections* and three dimensional *block models* of rocks, regions, terranes and parts of the Earth's crust can be generated.

Study of regional structure is important in understanding orogeny, plate tectonics and more specifically in the oil, gas and mineral exploration industries as structures such as faults, folds and unconformities are primary controls on ore mineralisation and oil traps.

Modern regional structure is being investigated using seismic tomography and seismic reflection in three dimensions, providing unrivaled images of the Earth's interior, its faults and the deep crust.

Rock microstructures

Rock microstructure or *texture* of rocks is studied by structural geologists on a small scale to provide detailed information mainly about metamorphic rocks and some features of sedimentary rocks, most often if they have been folded.
Textural study involves measurement and characterisation of foliations, crenulations, metamorphic minerals, and timing relationships between these structural features and mineralogical features.
Usually this involves collection of hand specimens, which may be cut to provide petrographic thin sections which are analysed under a petrographic microscope.

Kinematics

Geologists use their measurements of rock geometries to understand histories of strain in the rocks. Strain can take the form of brittle faulting and ductile folding and shearing. Brittle deformation takes place in the shallow crust, and ductile deformation takes place in the deeper crust, where temperatures and pressures are higher.

Stress Fields

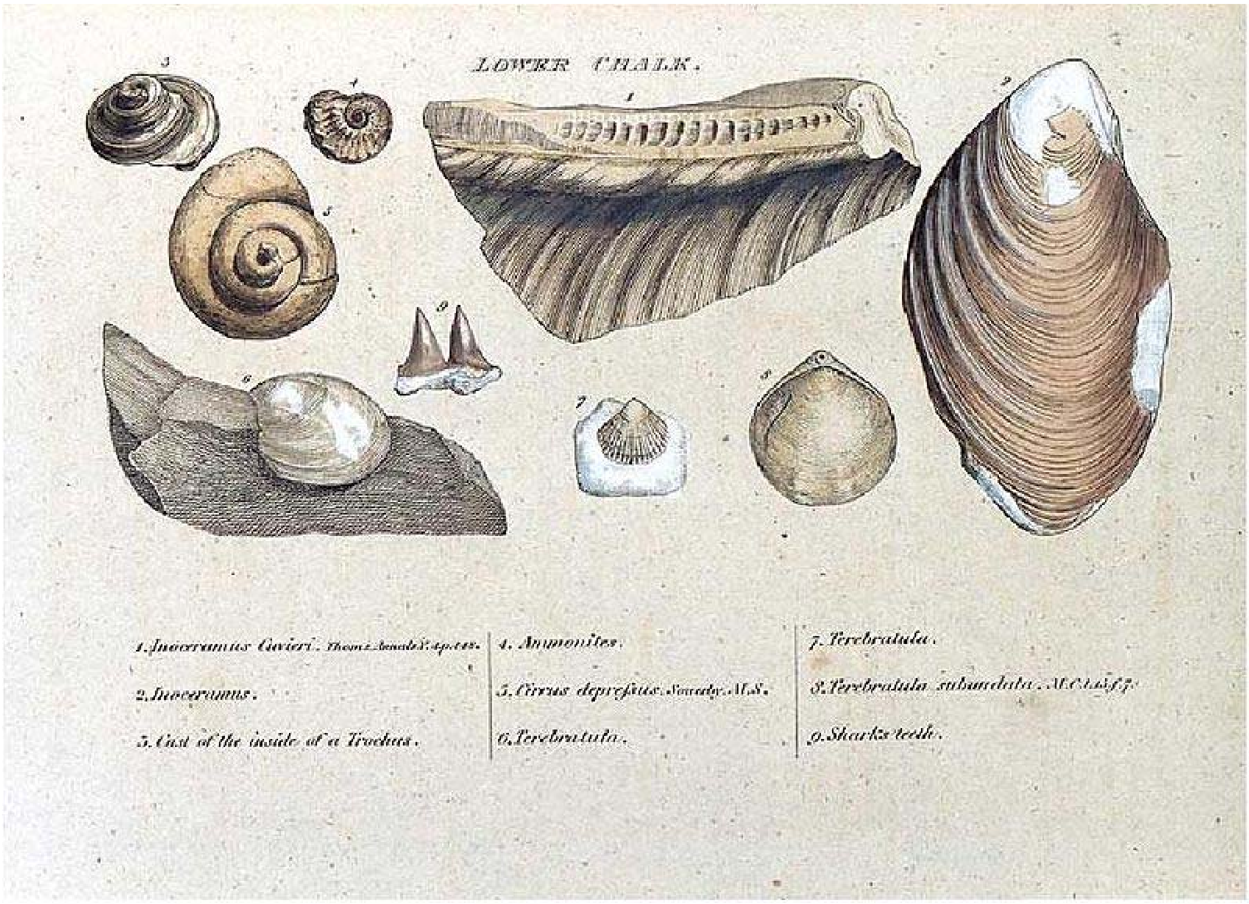
By understanding the constitutive relationships between stress and strain in rocks, geologists can translate the observed patterns of rock deformation into a stress field during the geologic past. The following list of features are typically used to determine stress fields from deformational structures.

- In perfectly brittle rocks, faulting occurs at 30° to the greatest compressional stress. (Byerlee's Law)
- The greatest compressive stress is normal to fold axial planes.

3. Stratigraphy

Stratigraphy, a branch of geology, studies rock layers and layering (stratification). It is primarily used in the study of sedimentary and layered volcanic rocks. Stratigraphy includes two related subfields: lithologic or lithostratigraphy and biologic stratigraphy or biostratigraphy.

Historical development

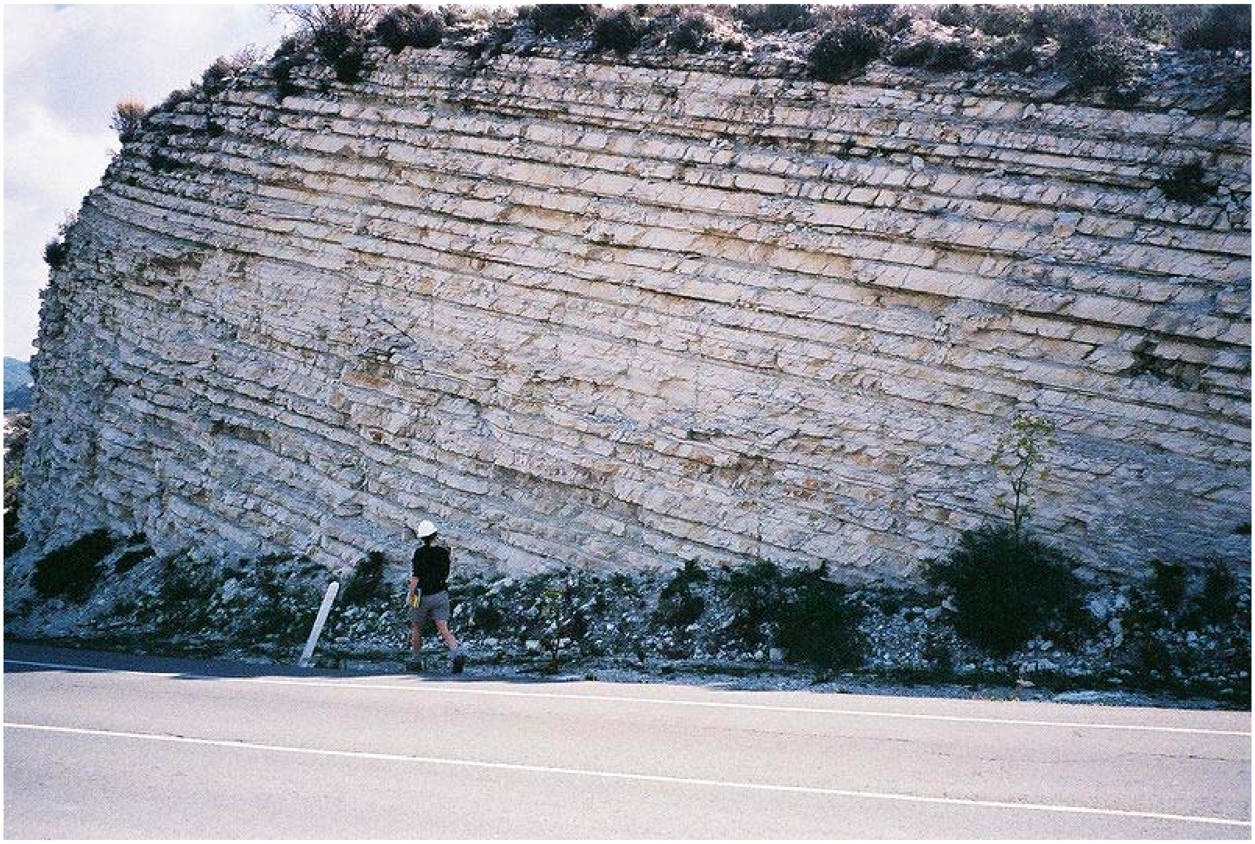


Engraving from William Smith's monograph on identifying strata based on fossils

The theoretical basis for the subject was established by Nicholas Steno who re-introduced the law of superposition and introduced the principle of original horizontality and principle of lateral continuity in a 1669 work on the fossilization of organic remains in layers of sediment.

The first practical large scale application of stratigraphy was by William Smith in the 1790s and early 19th century. Smith, known as the *Father of English Geology*, created the first geologic map of England, and first recognized the significance of strata or rock layering, and the importance of fossil markers for correlating strata. Another influential application of stratigraphy in the early 19th century was a study by Georges Cuvier and Alexandre Brongniart of the geology of the region around Paris.

Lithologic stratigraphy



Chalk Layers in Cyprus - showing sedimentary layering

Lithostratigraphy, or lithologic stratigraphy, is the most obvious. It deals with the physical lithologic, or rock type, change both vertically in layering or bedding of varying rock type and laterally reflecting changing environments of deposition, known as facies change. Key elements of stratigraphy involve understanding *how* certain geometric relationships between rock layers arise and *what* these geometries mean in terms of depositional environment. One of stratigraphy's basic concepts is codified in the Law of Superposition, which simply states that, in an undeformed stratigraphic sequence, the oldest strata occur at the base of the sequence.

Chemostratigraphy is based on the changes in the relative proportions of trace elements and isotopes within and between lithologic units. Carbon and oxygen isotope ratios vary with time and are used to map subtle changes in the paleoenvironment. This has led to the specialized field of *isotopic stratigraphy*.

Cyclostratigraphy documents the often cyclic changes in the relative proportions of minerals, particularly carbonates, and fossil diversity with time, related to changes in palaeoclimates.

Biostratigraphy

Biostratigraphy or paleontologic stratigraphy is based on fossil evidence in the rock layers. Strata from widespread locations containing the same fossil fauna and flora are correlatable in time. Biologic stratigraphy was based on William Smith's *principle of faunal succession*, which predated, and was one of the first and most powerful lines of evidence for, biological evolution. It provides strong evidence for formation (speciation) of and the extinction of species. The geologic time scale was developed during the 19th century based on the evidence of biologic stratigraphy and faunal succession. This timescale remained a relative scale until the development of radiometric dating, which gave it and the stratigraphy it was based on an absolute time framework, leading to the development of *chronostratigraphy*.

One important development is the Vail curve, which attempts to define a global historical sea-level curve according to inferences from world-wide stratigraphic patterns. Stratigraphy is also commonly used to delineate the nature and extent of hydrocarbon-bearing reservoir rocks, seals and traps in petroleum geology.

Chronostratigraphy

Chronostratigraphy is the branch of stratigraphy that studies the relative, not absolute, age of rock strata.

Chronostratigraphy is based upon deriving geochronological data for rock units, both directly and by inference, so that a sequence of time relative events of rocks within a region can be derived. In essence, chronostratigraphy seeks to understand the geologic history of rocks and regions.

The ultimate aim of chronostratigraphy is to arrange the sequence of deposition and the time of deposition of all rocks within a geological region, and eventually, the entire geologic record of the Earth.

Magnetostratigraphy

Magnetostratigraphy is a chronostratigraphic technique used to date sedimentary and volcanic sequences. The method works by collecting oriented samples at measured intervals throughout the section. The samples are analyzed to determine their detrital remnant magnetism (DRM), that is, the polarity of Earth's magnetic field at the time a stratum was deposited. This is possible because when very fine-grained magnetic minerals (< 17 micrometres) fall through the water column, they orient themselves with Earth's magnetic field. Upon burial, that orientation is preserved. The minerals, in effect, behave like tiny compasses.

Oriented paleomagnetic core samples are collected in the field; mudstones, siltstones, and very fine-grained sandstones are the preferred lithologies because the magnetic grains are finer and more likely to orient with the ambient field during deposition. If the ancient magnetic field was oriented similar to today's field (North Magnetic Pole near the North Rotational Pole) the strata retain a normal polarity. If the data indicate that the North Magnetic Pole was near the South Rotational Pole, the strata exhibit reversed polarity.

Results of the individual samples are analysed by removing the natural remanent magnetization (NRM) to reveal the DRM. Following statistical analysis the results are used to generate a local magnetostratigraphic column that can then be compared against the Global Magnetic Polarity Time Scale.

This technique is used to date sequences that generally lack fossils or interbedded igneous rocks. The continuous nature of the sampling means that it is also a powerful technique for the estimation of sediment accumulation rates.

Archaeological stratigraphy

In the field of archaeology, soil stratigraphy is used to better understand the processes that form and protect archaeological sites. The law of superposition holds true, and this can help date finds or features from each context, as they can be placed in sequence and the dates interpolated. Phases of activity can also often be seen through stratigraphy, especially when a trench or feature is viewed in section (profile). As pits and other features can be dug down into earlier levels, not all material at the same absolute depth is necessarily of the same age, but close attention has to be paid to the archeological layers. The Harris-matrix is a tool to depict complex stratigraphic relations, as they are found, for example, in the contexts of urban archaeology.

Chapter- 8

Applied Geology

1. Economic geology

Economic geology is concerned with earth materials that can be used for economic and/or industrial purposes. These materials include precious and base metals, nonmetallic minerals, construction-grade stone, petroleum minerals, coal, and water. The term commonly refers to metallic mineral deposits and mineral resources. The techniques employed by other earth science disciplines (such as geochemistry, mineralogy, geophysics, and structural geology) might all be used to understand, describe, and exploit an ore deposit.

Economic geology is studied and practiced by geologists. However it is of prime interest to investment bankers, stock analysts and other professions such as engineers, environmental scientists, and conservationists because of the far-reaching impact that extractive industries have on society, the economy, and the environment.

Mineral resources

Mineral resources are concentrations of minerals significant for current and future societal needs. Ore is classified as mineralization economically and technically feasible for extraction. Not all mineralization meets these criteria for various reasons. The specific categories of mineralization in an economic sense are:

- *Mineral occurrences* or prospects of geological interest but not necessarily economic interest
- *Mineral resources* include those potentially economically and technically feasible and those that are not
- *Ore reserves*, which must be economically and technically feasible to extract

Ore geology

Geologists are involved in the study of ore deposits, which includes the study of ore genesis and the processes within the Earth's crust that form and concentrate ore minerals into economically viable quantities.

Study of metallic ore deposits involves the use of structural geology, geochemistry, the study of metamorphism and its processes, as well as understanding metasomatism and other processes related to ore genesis.

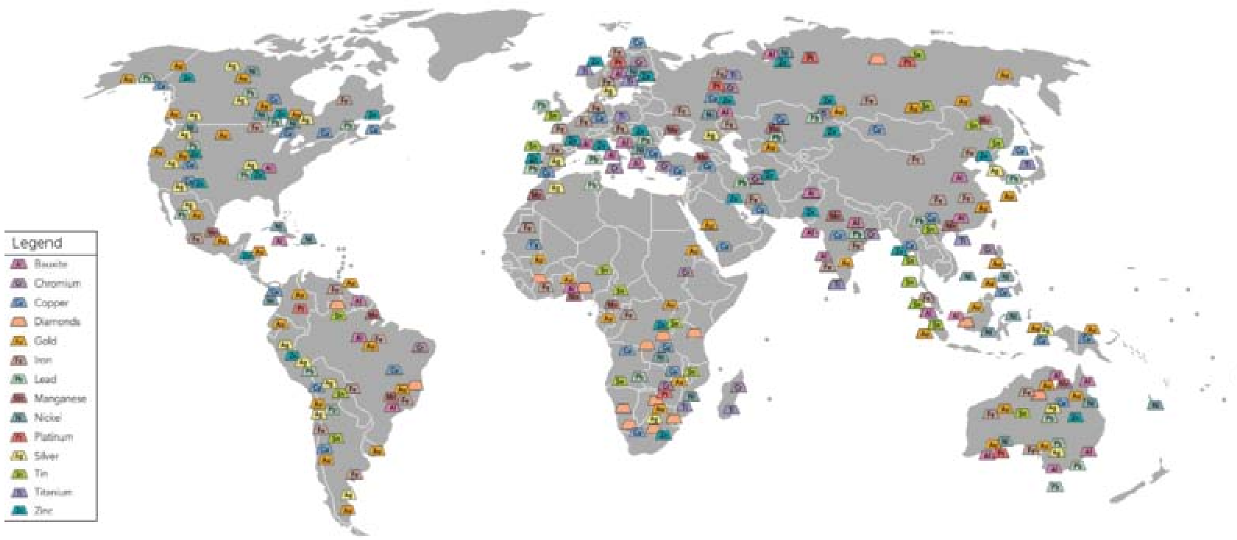
Ore deposits are delineated by mineral exploration, which uses geochemical prospecting, drilling and resource estimation via geostatistics to quantify economic ore bodies. The ultimate aim of this process is mining.

Coal and petroleum geology

The study of sedimentology is of prime importance to the delineation of economic reserves of petroleum and coal energy resources.

2. Mining

Chuquicamata, Chile, site of the largest circumference and second deepest open pit copper mine in the world.



Simplified world mining map

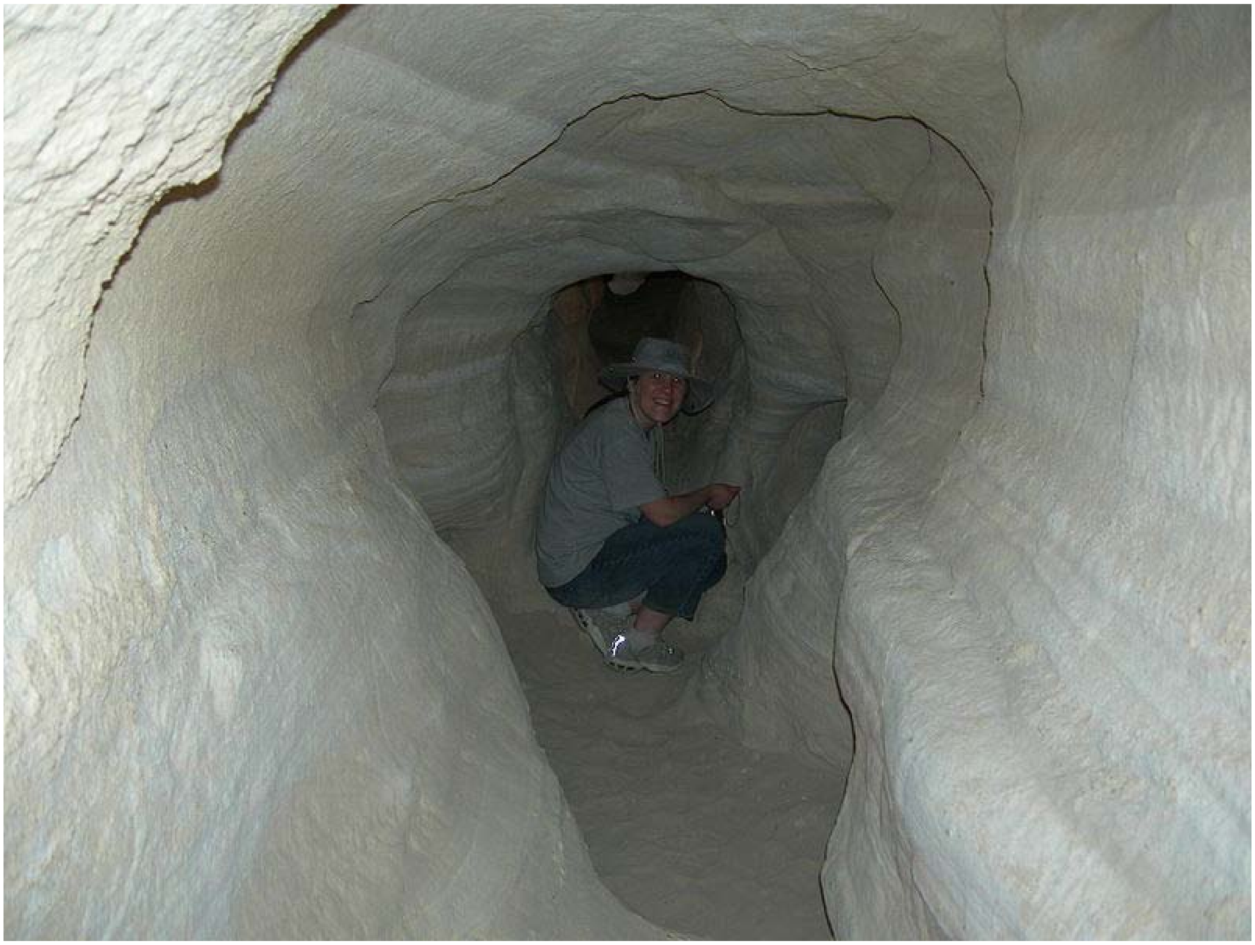
Mining is the extraction of valuable minerals or other geological materials from the earth, usually from an ore body, vein or (coal) seam. Materials recovered by mining include base metals, precious metals, iron, uranium, coal, diamonds, limestone, oil shale, rock salt and potash. Any material that cannot be grown through agricultural processes, or created artificially in a laboratory or factory, is usually mined. Mining in a wider sense comprises extraction of any non-renewable resource (e.g., petroleum, natural gas, or even water).

Mining of stone and metal has been done since pre-historic times. Modern mining processes involve prospecting for ore bodies, analysis of the profit potential of a proposed mine, extraction of the desired materials and finally reclamation of the land to prepare it for other uses once the mine is closed.

The nature of mining processes creates a potential negative impact on the environment both during the mining operations and for years after the mine is closed. This impact has led to most of the world's nations adopting regulations to moderate the negative effects of mining operations. Safety has long been a concern as well, though modern practices have improved safety in mines significantly.

History

Prehistoric mining



Chalcolithic copper mine in Timna Valley, Negev Desert, Israel

Since the beginning of civilization, people have used stone, ceramics and, later, metals found on or close to the Earth's surface. These were used to manufacture early tools and weapons, for example, high quality flint found in northern France and southern England were used to create flint tools. Flint mines have been found in chalk areas where seams of the stone were followed underground by shafts and galleries. The mines at Grimes Graves are especially famous, and like most other flint mines, are Neolithic in origin (ca 4000 BC-ca 3000 BC). Other hard rocks mined or collected for axes included the greenstone of the Langdale axe industry based in the English Lake District.

The oldest known mine on archaeological record is the "Lion Cave" in Swaziland. At this site, which by radiocarbon dating proves the mine to be about 43,000 years old, paleolithic humans mined mineral hematite, which contained iron and was ground to produce the red pigment ochre.

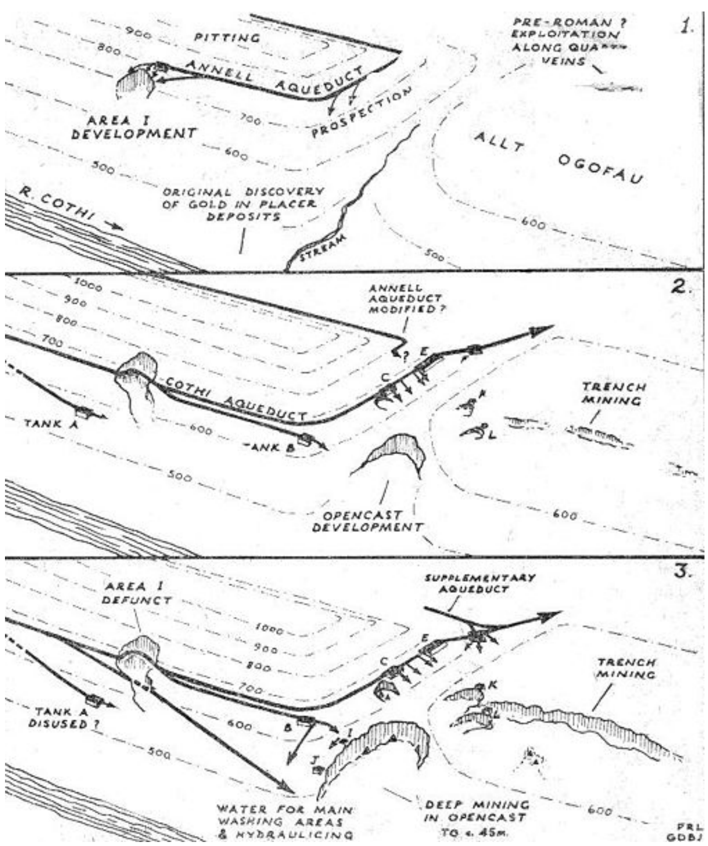
Mines of a similar age in Hungary are believed to be sites where Neanderthals may have mined flint for weapons and tools.

Ancient Egypt

Ancient Egyptians mined malachite at Maadi. At first, Egyptians used the bright green malachite stones for ornamentations and pottery. Later, between 2,613 and 2,494 BC, large building projects required expeditions abroad to the area of Wadi Maghara in order "to secure minerals and other resources not available in Egypt itself." Quarries for turquoise and copper were also found at "Wadi Hamamat, Tura, Aswan and various other Nubian sites" on the Sinai Peninsula and at Timna.

Mining in Egypt occurred in the earliest dynasties, and the gold mines of Nubia were among the largest and most extensive of any in Ancient Egypt, and are described by the Greek author Diodorus Siculus. He mentions that fire-setting was one method used to break down the hard rock holding the gold. One of the complexes is shown in one of earliest known maps. They crushed the ore and ground it to a fine powder before washing the powder for the gold dust.

Ancient Greece and Rome



Ancient Roman development of the Dolaucothi Gold Mines, Wales

Mining in Europe has a very long history, examples including the silver mines of Laurium, which helped support the Greek city state of Athens. However, it is the Romans who developed large scale mining methods, especially the use of large volumes of water brought to the minehead by numerous aqueducts. The water was used for a variety of purposes, including using it to remove overburden and rock debris, called hydraulic mining, as well as washing comminuted or crushed ores, and driving simple machinery.

The Romans used hydraulic mining methods on a large scale to prospect for the veins of ore, especially a now obsolete form of mining known as hushing. It involved building numerous aqueducts to supply water to the minehead where it was stored in large reservoirs and tanks. When a full tank was opened, the wave of water sluiced away the overburden to expose the bedrock underneath and any gold veins. The rock was then attacked by fire-setting to heat the rock, which would be quenched with a stream of water. The thermal shock cracked the rock, enabling it to be removed, aided by further streams of water from the overhead tanks. They used similar methods to work cassiterite deposits in Cornwall and lead ore in the Pennines.

The methods had been developed by the Romans in Spain in 25 AD to exploit large alluvial gold deposits, the largest site being at Las Medulas, where seven long aqueducts were built to tap local rivers and to sluice the deposits. Spain was one of the most important mining regions, but all regions of the Roman Empire were exploited. They used reverse overshot water-wheels for dewatering their deep mines such as those at Rio Tinto. In Great Britain the natives had mined minerals for millennia, but when the Romans came, the scale of the operations changed dramatically.

The Romans needed what Britain possessed, especially gold, silver, tin and lead. Roman techniques were not limited to surface mining. They followed the ore veins underground once opencast mining was no longer feasible. At Dolaucothi they stoped out the veins, and drove adits through barren rock to drain the stopes. The same adits were also used to ventilate the workings, especially important when fire-setting was used. At other parts of the site, they penetrated the water table and dewatered the mines using several kinds of machine, especially reverse overshot water-wheels. These were used extensively in the copper mines at Rio Tinto in Spain, where one sequence comprised 16 such wheels arranged in pairs, and lifting water about 80 feet (24 m). They were worked as treadmills with miners standing on the top slats. Many examples of such devices have been found in old Roman mines and some examples are now preserved in the British Museum and the National Museum of Wales.

Medieval Europe

Agricola, author of *De Re Metallica*

Mining as an industry underwent dramatic changes in medieval Europe. The mining industry in the early Middle Ages was mainly focused on the extraction of copper and iron. Other precious metals were also used mainly for gilding or coinage. Initially, many metals were obtained through open-pit mining, and ore was primarily extracted from shallow depths, rather than though the digging of deep mine shafts. Around the 14th century, the demand for weapons, armor, stirrups, and horseshoes greatly increased the demand for iron. Medieval knights for example were often laden with up to 100 pounds of plate or chain link armor in addition to swords, lances and other weapons. The overwhelming dependency on iron for military purposes helped to spur increased iron production and extraction processes.

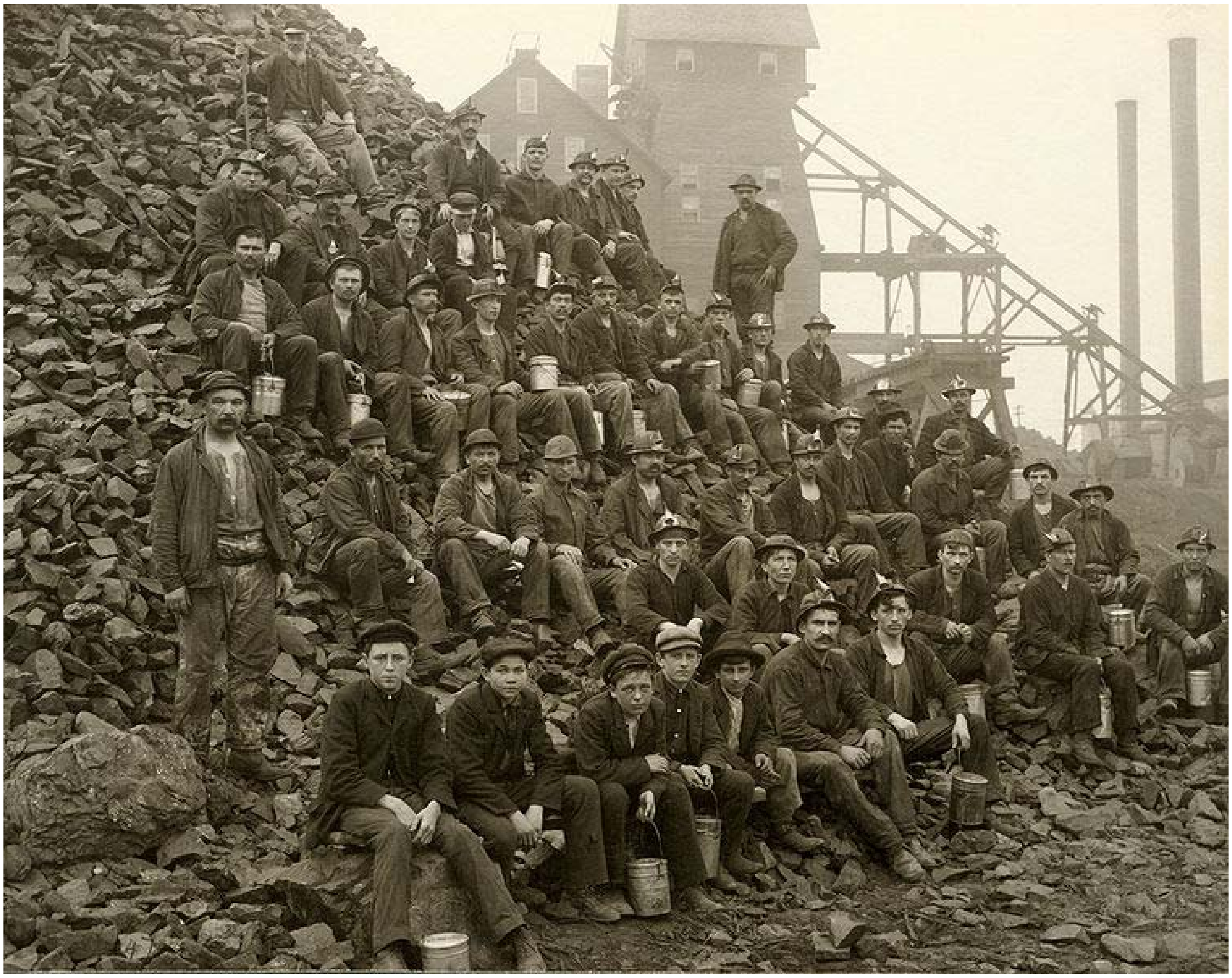
These new military applications coincided with a population explosion throughout Europe in the 11th-14th centuries which enriched the demand for precious metals in order to fill a currency shortage. The silver crisis of 1465 occurred when the mines had all reached depths at which the shafts could no longer be pumped dry with the available technology. Although the increased use of bank notes and the use of credit during this period did decrease the dependence and value of precious metals, these forms of currency still remained vital to the story of medieval mining. Use of water power in the form of water mills was extensive; they were employed in crushing ore, raising ore from shafts and ventilating galleries by powering giant bellows. Black powder was first used in mining in Selmecbánya, Kingdom of Hungary (present-day Banská Štiavnica, Slovakia) in 1627. Black powder allowed blasting of rock and earth to loosen and reveal ore veins, which was much faster than fire-setting, in which rock was exposed to heat and then doused with cold water. Black powder allowed the mining of previously impenetrable metals and ores. In 1762, the world's first mining academy was established in the same town.

The widespread adoption of agricultural innovations such as the iron plowshare, as well as the growing use of metal as a building material, was also a driving force in the tremendous growth of the iron industry during this period. Inventions like the arrastra were often used by the Spanish to pulverize ore after being mined. This device employed animal power and utilized mechanical principles similar to that of the ancient Middle Eastern technology of grain threshing.

Much of our knowledge of Medieval mining techniques comes from books such as Biringuccio's *De la pirotechnia* and probably most importantly from Georg Agricola's *De re metallica* (1556). These books detail many different mining methods used in German and Saxon mines. One of the prime issues confronting medieval miners (and one which Agricola explains in detail) was the removal of water from mining shafts. As miners dug deeper to access new veins, flooding became a very real obstacle. As a result the mining industry became dramatically more efficient and prosperous as the use of various mechanical and animal driven pump systems were implemented.

North and South America

Lead mining in the upper Mississippi River region of the U.S., 1865



Miners at the Tamarack Mine in Copper Country, Michigan, U.S. in 1905

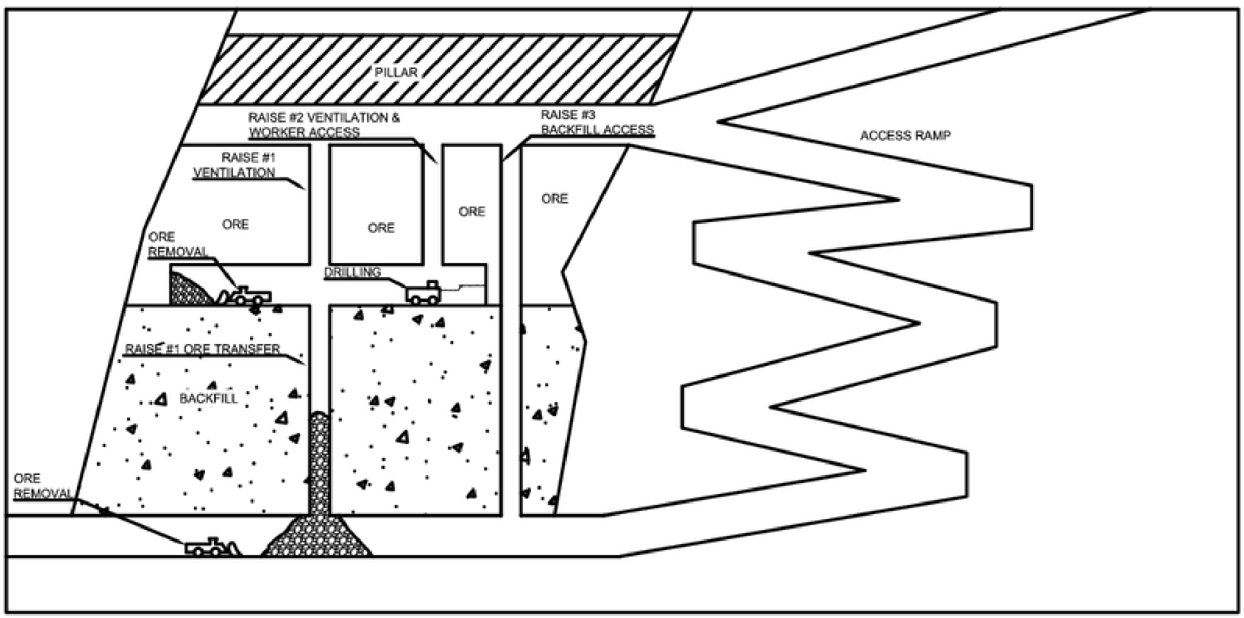
In North America there are ancient, prehistoric copper mines along Lake Superior. "Indians availed themselves of this copper starting at least 5000 years ago," and copper tools, arrowheads, and other artifacts that were part of an extensive native trade network have been discovered. In addition, obsidian, flint, and other minerals were mined, worked, and traded. While the early French explorers that encountered the sites made no use of the metals due to the difficulties in transporting it, the copper was eventually traded throughout the continent along major river routes. In Manitoba, Canada, there also are ancient quartz mines near Waddy Lake and surrounding regions.

In the early colonial history of the Americas, "native gold and silver was quickly expropriated and sent back to Spain in fleets of gold- and silver-laden galleons" mostly from mines in Central and South America. Turquoise dated at 700 A.D. was mined in pre-Columbian America; in the Cerillos Mining District in New Mexico, estimates are that "about 15,000 tons of rock had been removed from Mt Chalchihuitl using stone tools before 1700."

Mining in the United States became prevalent in the 19th century, and the General Mining Act of 1872 was passed to encourage mining of federal lands. As with the California Gold Rush in the mid 19th century, mining for minerals and precious metals, along with ranching, was a driving factor in the Westward Expansion to the Pacific coast. With the exploration of the West, mining camps were established and "expressed a distinctive spirit, an enduring legacy to the new nation;" Gold Rushers would experience the same problems as the Land Rushers of the transient West that preceded them. Aided by railroads, many traveled West for work opportunities in mining. Western cities such as Denver and Sacramento originated as mining towns.

Mining methods and procedures

Steps of mine development



Schematic of a cut and fill mining operation in hard rock

The process of mining from discovery of an ore body through extraction of minerals and finally to returning the land to its natural state consists of several distinct steps. The first is discovery of the ore body, which is carried out through prospecting or exploration to find and then define the extent, location and value of the ore body. This leads to a mathematical resource estimation to estimate the size and grade of the deposit.

This estimation is used to conduct a pre-feasibility study to determine the theoretical economics of the ore deposit. This identifies, early on, whether further investment in estimation and engineering studies is warranted and identifies key risks and areas for further work. The next step is to conduct a feasibility study to evaluate the financial viability, technical and financial risks and robustness of the project.

This is when the mining company makes the decision to develop the mine or to walk away from the project. This includes mine planning to evaluate the economically recoverable portion of the deposit, the metallurgy and ore recoverability, marketability and payability of the ore concentrates, engineering concerns, milling and infrastructure costs, finance and equity requirements and an analysis of the proposed mine from the initial excavation all the way through to reclamation.

Once the analysis determines a given ore body is worth recovering, development begins to create access to the ore body. The mine buildings and processing plants are built and any necessary equipment is obtained. The operation of the mine to recover the ore begins and continues as long as the company operating the mine finds it economical to do so. Once all the ore that the mine can produce profitably is recovered, reclamation begins to make the land used by the mine suitable for future use.

Mining techniques

Underground Longwall mining

Mining techniques can be divided into two common excavation types: surface mining and sub-surface (underground) mining. Surface mining is much more common, and produces, for example, 85% of minerals (excluding petroleum and natural gas) in the United States, including 98% of metallic ores. Targets are divided into two general categories of materials: *placer deposits*, consisting of valuable minerals contained within river gravels, beach sands, and other unconsolidated materials; and *lode deposits*, where valuable minerals are found in veins, in layers, or in mineral grains generally distributed throughout a mass of actual rock. Both types of ore deposit, placer or lode, are mined by both surface and underground methods.

Processing of placer ore material consists of gravity-dependent methods of separation, such as sluice boxes. Only minor shaking or washing may be necessary to disaggregate (unclump) the sands or gravels before processing. Processing of ore from a lode mine, whether it is a surface or subsurface mine, requires that the rock ore be crushed and pulverized before extraction of the valuable minerals begins. After lode ore is crushed, recovery of the valuable minerals is done by one, or a combination of several, mechanical and chemical techniques.

Uranium mine near Moab, Utah

Some mining, including much of the rare earth elements and uranium mining, is done by less-common methods, such as in-situ leaching: this technique involves digging neither at the surface nor underground. The extraction of target minerals by this technique requires that they be soluble, e.g., potash, potassium chloride, sodium chloride, sodium sulfate, which dissolve in water. Some minerals, such as copper minerals and uranium oxide, require acid or carbonate solutions to dissolve.

Surface mining is done by removing (stripping) surface vegetation, dirt, and if necessary, layers of bedrock in order to reach buried ore deposits. Techniques of surface mining include; Open-pit mining which consists of recovery of materials from an open pit in the ground, quarrying or gathering building materials from an open pit mine, strip mining which consists of stripping surface layers off to reveal ore/seams underneath, and mountaintop removal, commonly associated with coal mining, which involves taking the top of a mountain off to reach ore deposits at depth. Most (but not all) placer deposits, because of their shallowly buried nature, are mined by surface methods. Landfill mining, finally, involves sites where landfills are excavated and processed.

Sub-surface mining consists of digging tunnels or shafts into the earth to reach buried ore deposits. Ore, for processing, and waste rock, for disposal, are brought to the surface through the tunnels and shafts. Sub-surface mining can be classified by the type of access shafts used, the extraction method or the technique used to reach the mineral deposit. Drift mining utilizes horizontal access tunnels, slope mining uses diagonally sloping access shafts and shaft mining consists of vertical access shafts.

Other methods include shrinkage stope mining which is mining upward creating a sloping underground room, long wall mining which is grinding a long ore surface underground and room and pillar which is removing ore from rooms while leaving pillars in place to support the roof of the room. Room and pillar mining often leads to retreat mining which is removing the pillars which support rooms, allowing the room to cave in, loosening more ore. Additional sub-surface mining methods include hard rock mining which is mining of hard materials, bore hole mining, drift and fill mining, long hole slope mining, sub level caving and block caving

Garzweiler open-pit mine, Germany

Machinery

The Bagger 288 is a bucket-wheel excavator used in strip mining

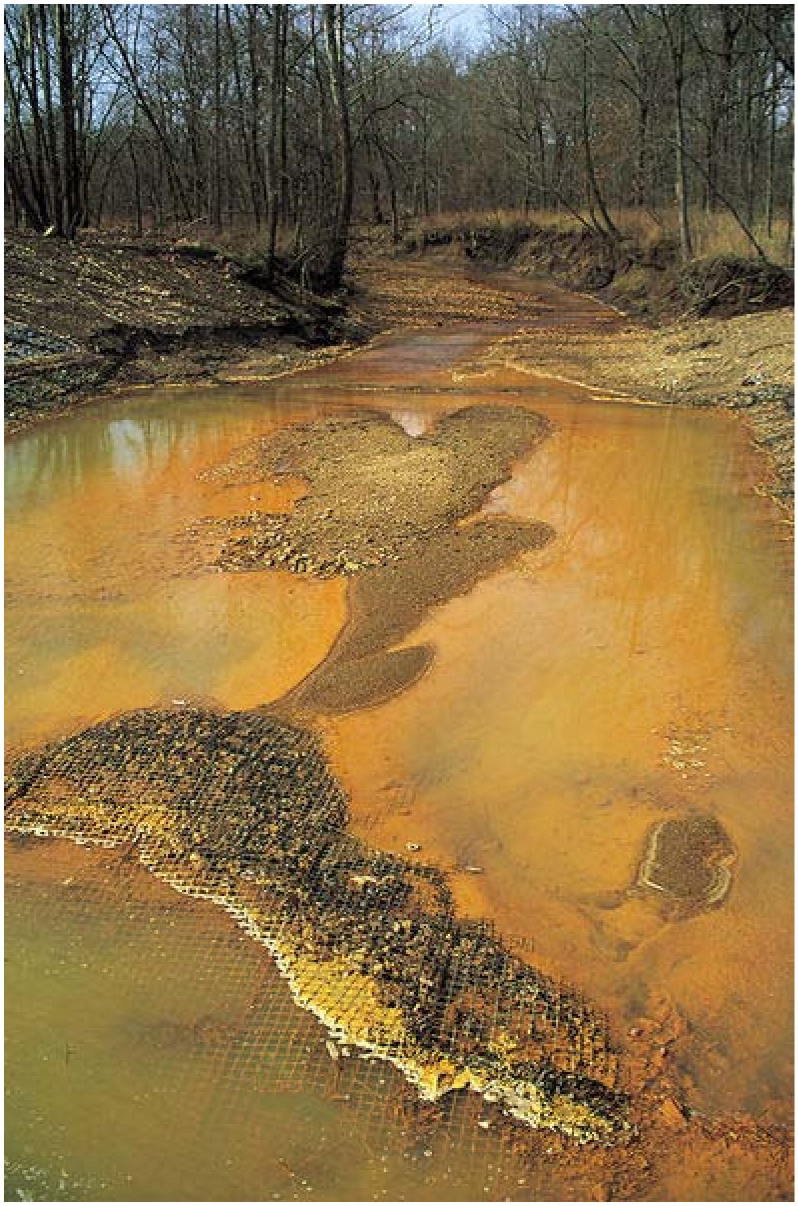
Heavy machinery is needed in mining for exploration and development, to remove and stockpile overburden, to break and remove rocks of various hardness and toughness, to process the ore and for reclamation efforts after the mine is closed. Bulldozers, drills, explosives and trucks are all necessary for excavating the land. In the case of placer mining, unconsolidated gravel, or alluvium, is fed into machinery consisting of a hopper and a shaking screen or trommel which frees the desired minerals from the waste gravel. The minerals are then concentrated using sluices or jigs.

Large drills are used to sink shafts, excavate stopes and obtain samples for analysis. Trams are used to transport miners, minerals and waste. Lifts carry miners into and out of mines, as well as moving rock and ore out, and machinery in and out of underground mines. Huge trucks, shovels and cranes are employed in surface mining to move large quantities of overburden and ore. Processing plants can utilize large crushers, mills, reactors, roasters and other equipment to consolidate the mineral-rich material and extract the desired compounds and metals from the ore.

Extractive metallurgy

The science of extractive metallurgy is a specialized area in the science of metallurgy that studies the extraction of valuable metals from their ores, especially through chemical or mechanical means. Mineral processing (or mineral dressing) is a specialized area in the science of metallurgy that studies the mechanical means of crushing, grinding, and washing that enable the separation (extractive metallurgy) of valuable metals or minerals from their gangue (waste material). Since most metals are present in ores as oxides or sulfides, the metal needs to be reduced to its metallic form. This can be accomplished through chemical means such as smelting or through electrolytic reduction, as in the case of aluminum. Geometallurgy combines the geologic sciences with extractive metallurgy and mining.

Environmental effects



Iron hydroxide precipitate stains a stream receiving acid drainage from surface coal mining

Environmental issues can include erosion, formation of sinkholes, loss of biodiversity, and contamination of soil, groundwater and surface water by chemicals from mining processes. In some cases, additional forest logging is done in the vicinity of mines to increase the available room for the storage of the created debris and soil. Contamination resulting from leakage of chemicals can also affect the health of the local population if not properly controlled.

Mining companies in most countries are required to follow stringent environmental and rehabilitation codes in order to minimize environmental impact and avoid impacts on human health. These codes and regulations all require the common steps of Environmental impact assessment, development of Environmental management plans, Mine closure planning (which must be done before the start of mining operations), and Environmental monitoring during operation and after closure. However, in some areas, particularly in the developing world, regulation may not be well enforced by governments.

For major mining companies, and any company seeking international financing, there are however a number of other mechanisms to enforce good environmental standards. These generally relate to financing standards such as Equator Principles, IFC environmental standards, and criteria for Socially responsible investing. Mining companies have used this financial industry oversight to argue for some level of self-policing. In 1992 a Draft Code of Conduct for Transnational Corporations was proposed at the Rio Earth Summit by the UN Centre for Transnational Corporations (UNCTC), but the Business Council for Sustainable Development (BCSD) together with the International Chamber of Commerce (ICC) argued successfully for self-regulation instead.

This was followed up by the Global Mining Initiative which was initiated by nine of the largest metals and mining companies, and led to the formation of the International Council on Mining and Metals to "act as a catalyst" for social and environmental performance improvement in the mining and metals industry internationally. The mining industry has provided funding to various conservation groups, some of which have been working with conservation agendas that are at odds with emerging acceptance of the rights of indigenous people - particularly rights to make land-use decisions.

Ore mills generate large amounts of waste, called tailings. For example, 99 tons of waste are generated per ton of copper, with even higher ratios in gold mining. These tailings can be toxic. Tailings, which are usually produced as a slurry, are most commonly dumped into ponds made from naturally existing valleys. These ponds are secured by impoundments (dams or embankment dams). In 2000 it was estimated that 3,500 tailings impoundments existed, and that every year, 2 to 5 major failures and 35 minor failures occurred ; for example, in the Marcopper mining disaster at least 2 million tons of tailings were released into a local river. Subaqueous tailings disposal is another option. The mining industry has argued that submarine tailings disposal (STD), which disposes of tailings in the sea, is ideal because it avoids the risks of tailings ponds; although the practice is illegal in the United States and Canada, it is used in the developing world.

Certification of mines with good practices occurs through the International Organization for Standardization (ISO) such as ISO 9000 and ISO 14001, which certifies an 'auditable environmental management system'; this certification involves short inspections, although it has been accused of lacking rigor. Certification is also available through Ceres' Global Reporting Initiative, but these reports are voluntary and unverified. Miscellaneous other certification programs exist for various projects, typically through nonprofit groups.

Regulations and World Bank relationship

The World Bank has been involved in mining since 1955, mainly through grants from its International Bank for Reconstruction and Development, with the Bank's Multilateral Investment Guarantee Agency offering political risk insurance. Between 1955 and 1990 it provided about $2 billion to fifty mining projects, broadly categorized as reform and rehabilitation, greenfield mine construction, mineral processing, technical assistance, and engineering. These projects have been criticized, particularly the Ferro Carajas project of Brazil, begun in 1981. The bank established mining codes intended to increase foreign investment, in 1988 solicited feedback from 45 mining companies on how to increase their involvement.

In 1992 the bank began to push for privatization of government-owned mining companies with a new set of codes, beginning with its report *The Strategy for African Mining*. In 1997, Latin America's largest miner Companhia Vale do Rio Doce (CVRD) was privatized. These and other movements such as the Philippines 1995 Mining Act led the World Bank to publish a third report (*Assistance for Minerals Sector Development and Reform in Member Countries*) which endorsed mandatory environment impact assessments and attention to the locals. The codes based on this report are influential in the legislation of developing nations. The new codes are intended to encourage development through tax holidays, zero custom duties, reduced income taxes, and related measures. The results of these codes were analyzed by a group from the University of Quebec, which concluded that the codes promote foreign investment but "fall very short of permitting sustainable development". The observed negative correlation between natural resources and economic development is known as the resource curse.

Mining industry

Mining exists in many countries but Australia and Canada have a reputation for domestic mining expertise, and London is known as the capital of global "mining houses" such as Rio Tinto, BHP Billiton, and Anglo American PLC. The US mining industry is also large but it is dominated by the coal and nonmetal minerals, and the various regulations have worked to reduce the significance of mining in the United States. In 2007 the total market cap of mining companies was reported at US$962 billion, which compares to a total global market cap of publicly traded companies of about US$50 trillion in 2007.

While exploration and mining can sometimes be conducted by individual entrepreneurs or small business, most modern-day mines are large enterprises requiring large amounts of capital to establish. Consequently, the mining sector of the industry is dominated by large, often multinational companies, most of them publicly listed. It can be argued that what is referred to as the 'mining industry' is actually two sectors, one specializing in exploration for new resources, the other specializing in mining those resources. The exploration sector is typically made up of individuals and small mineral resource companies ("juniors") dependent on venture capital. The mining sector is typically large and multi-national companies sustained by mineral production from their mining operations. In addition to these two sectors, various other industries such as equipment manufacture, environmental testing and metallurgy analysis also rely on and support the mining industry throughout the world. Canadian stock exchanges have a particular focus on mining companies, particularly junior exploration companies through the TSX Venture Exchange; Canadian companies raise capital on these exchanges and then invest the money in exploration globally. Some have argued that below juniors there exists a substantial sector of illegitimate companies primarily focused on manipulating stock prices.

Mining operations can be grouped into five major categories in terms of their respective resources. These are, oil and gas extraction, coal mining, metal ore mining, nonmetallic mineral mining and quarrying, and support activities for mining. Out of all these categories, oil and gas extraction remains one of the largest in terms of its global economic importance. Prospecting potential mining sites, a vital area of concern for the mining industry is now done using sophisticated new technologies such as seismic prospecting and remote-sensing satellites.

Corporate classifications

Mining companies can be classified based on their size and financial capabilities:

- **Major** companies are considered to have an adjusted annual mining-related revenue of more than US$500 million, with the financial capability to develop a major mine on its own.

- **Intermediate** companies have at least $50 million in annual revenue but less than $500 million.

- **Junior** companies rely on equity financing as their principal means of funding exploration. Juniors are mainly pure exploration companies, but may also produce minimally, and do not have a revenue of US$50 million.

Safety

Danger sign at an old Arizona mine

Abandoned mine entrance in Yorkshire, England, United Kingdom

Safety has long been a controversial issue in the mining business especially with sub-surface mining. While mining today is substantially safer than it was in the previous decades, mining accidents are often very high profile, such as the Quecreek Mine Rescue saving 9 trapped Pennsylvania coal miners in 2002. The Courrières mine disaster, Europe's worst mining accident, caused the death of 1,099 miners (including many children) in Northern France on 10 March 1906. It seems that this disaster was surpassed only by the Benxihu Colliery accident in China on April 26, 1942, which killed 1,549 miners. Government figures indicate that 5.000 Chinese miners die in accidents each year, while other reports have suggested a figure as high as 20.000. Mining ventilation is a significant safety concern for many miners. Poor ventilation of the mines causes exposure to harmful gases, heat and dust inside sub-surface mines. These can cause harmful physiological effects, including death. The concentration of methane and other airborne contaminants underground can generally be controlled by dilution (ventilation), capture before entering the host air stream (methane drainage), or isolation (seals and stoppings).

Ignited methane gas is a common source of explosions in coal mines, or, the more violent coal dust explosions. Gases in mines can also poison the workers or displace the oxygen in the mine, causing asphyxiation. For this reason, the MHSA requires that workers have gas detection equipment in groups of miners. It must be able to detect common gases, such as CO, O2, H2S, and % Lower Explosive Limit. Additionally, further regulation is being requested for more gas detection as newer technology such as nanotechnology is introduced.

High temperatures and humidity may result in heat-related illnesses, including heat stroke which can be fatal. Dusts can cause lung problems, including silicosis, asbestosis and pneumoconiosis (also known as miners lung or black lung disease). A ventilation system is set up to force a stream of air through the working areas of the mine. The air circulation necessary for the effective ventilation of a mine is generated by one or more large mine fans, usually located above ground. Air flows in one direction only, making circuits through the mine such that each main work area constantly receives a supply of fresh air.

Miners utilize equipment strong enough to break through extremely hard layers of the Earth's crust. This equipment, combined with the closed workspace that underground miners work in, can cause hearing loss. For example, a roof bolter (commonly used by mine roof bolter operators) can reach sound power levels of up to 115 dB. Combined with the reverberant effects of underground mines, a miner without proper hearing protection is at a high risk for hearing loss.

Since mining entails removing dirt and rock from its natural location creating large empty pits, rooms and tunnels, cave-ins are a major concern within mines. Modern techniques for timbering and bracing walls and ceilings within sub-surface mines have reduced the number of fatalities due to cave-ins, but accidents still occur. The presence of heavy equipment in confined spaces also poses a risk to miners, and despite modern improvements to safety practices, mining remains dangerous throughout the world.

Abandoned mines

Abandoned mine in Nevada

Warning sign near Jerome, Arizona

There are upwards of 560,000 abandoned mines on public and privately owned lands in the United States alone. Abandoned mines pose a threat to anyone who may attempt to explore them without proper knowledge and safety training. Old mines are often dangerous and can contain deadly gases. Standing water in mines from seepage or infiltration poses a significant hazard as the water can hide deep pits and trap gases below the water. Additionally, since weather may have eroded the earth and rock surrounding it, the entrance to an old mine in particular can be very dangerous. Old mine workings, caves, etc. are commonly hazardous simply due to the lack of oxygen in the air, a condition in mines known as blackdamp.

Records

As of 2008, the deepest mine in the world is TauTona in Carletonville, South Africa at 3.9 kilometers, replacing Savuka Mine in the North West Province of South Africa at 3,774 meters. East Rand Mine in Boksburg, South Africa briefly held the record at 3,585 meters, and the first mine declared the deepest in the world was also TauTona when it was at 3,581 meters. The deepest mine in Europe is Pyhäsalmi Mine in Pyhäjärvi, Finland at 1,444 meters. The second deepest mine in Europe is Boulby Mine England at 1,400 meters (shaft depth 1,100 meters).

The deepest open pit mine in the world is Bingham Canyon Mine in Bingham Canyon, Utah, United States at over 1,200 meters. The largest and second deepest open pit copper mine in the world is Chuquicamata in Chuquicamata, Chile at 900 meters, 940,600 tons of copper and 17,700 tons of molybdenum produced annually.

The deepest open pit mine with respect to sea level is Tagebau Hambach in Germany, where the ground of the pit is 293 meters below sea level.

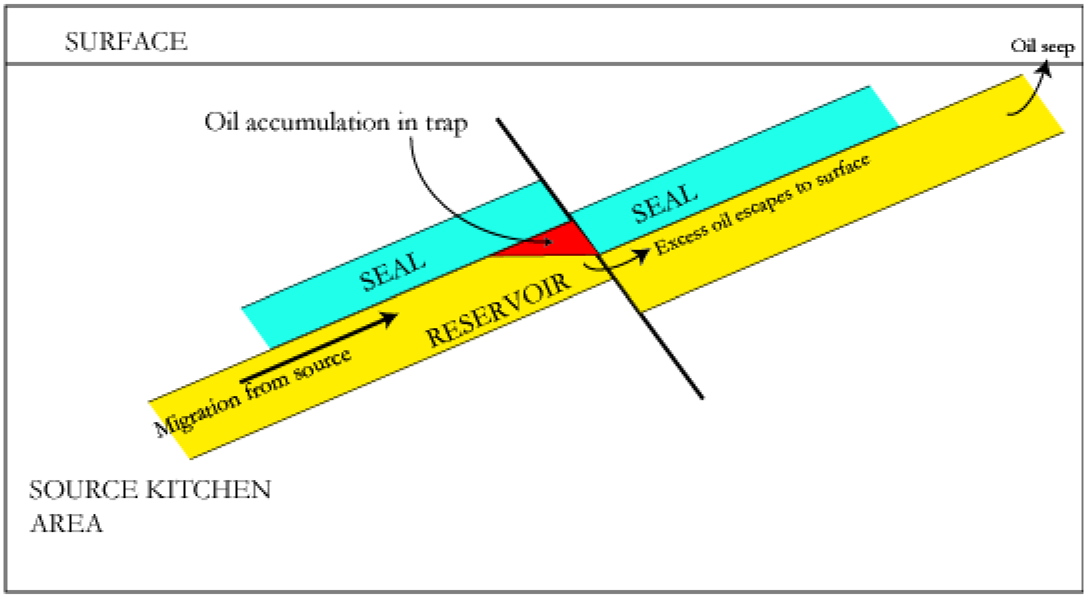
The largest underground mine: El Teniente, in Rancagua, Chile, 2,400 kilometers of underground drifts, 418,000 tons of copper yearly. The deepest borehole in the world is Kola Superdeep Borehole at 12,262 meters. This, however, is not a matter of mining but rather related to scientific drilling.

3. Petroleum geology

Petroleum geology refers to the specific set of geological disciplines that are applied to the search for hydrocarbons (oil exploration).

Sedimentary basin analysis

Petroleum geology is principally concerned with the evaluation of seven key elements in sedimentary basins:



A structural trap, where a fault has juxtaposed a porous and permeable reservoir against an impermeable seal. Oil (shown in red) accumulates against the seal, to the depth of the base of the seal. Any further oil migrating in from the source will escape to the surface and seep.

- Source
- Reservoir
- Seal
- Trap
- Timing
- Maturation
- Migration

In general, all these elements must be assessed via a limited 'window' into the subsurface world, provided by one (or possibly more) exploration wells. These wells present only a 1-dimensional segment through the Earth and the skill of inferring 3-dimensional characteristics from them is one of the most fundamental in petroleum geology. Recently, the availability of cheap and high quality 3D seismic data (from reflection seismology) has greatly aided the accuracy of such interpretation. The following section discusses these elements in brief.

Evaluation of the **source** uses the methods of geochemistry to quantify the nature of organic-rich rocks which contain the precursors to hydrocarbons, such that the type and quality of expelled hydrocarbon can be assessed.

The **reservoir** is a porous and permeable lithological unit or set of units that holds the hydrocarbon reserves. Analysis of reservoirs at the simplest level requires an assessment of their porosity (to calculate the volume of *in situ* hydrocarbons) and their permeability (to calculate how easily hydrocarbons will flow out of them). Some of the key disciplines used in reservoir analysis are the fields of stratigraphy, sedimentology, and reservoir engineering.

The **seal**, or *cap* rock, is a unit with low permeability that impedes the escape of hydrocarbons from the reservoir rock. Common seals include evaporites, chalks and shales. Analysis of seals involves assessment of their thickness and extent, such that their effectiveness can be quantified.

The **trap** is the stratigraphic or structural feature that ensures the juxtaposition of reservoir and seal such that hydrocarbons remain trapped in the subsurface, rather than escaping (due to their natural buoyancy) and being lost.

Analysis of **maturation** involves assessing the thermal history of the source rock in order to make predictions of the amount and timing of hydrocarbon generation and expulsion.

Finally, careful studies of **migration** reveal information on how hydrocarbons move from source to reservoir and help quantify the source (or *kitchen*) of hydrocarbons in a particular area.

Mud log in process, a common way to study the lithology when drilling oil wells

Major subdisciplines in petroleum geology

Several major subdisciplines exist in petroleum geology specifically to study the seven key elements discussed above.

Analysis of source rocks

In terms of source rock analysis, several facts need to be established. Firstly, the question of whether there actually *is* any source rock in the area must be answered. Delineation and identification of potential source rocks depends on studies of the local stratigraphy, palaeogeography and sedimentology to determine the likelihood of organic-rich sediments having been deposited in the past.

If the likelihood of there being a source rock is thought to be high, the next matter to address is the state of thermal maturity of the source, and the timing of maturation. Maturation of source rocks depends strongly on temperature, such that the majority of oil generation occurs in the 60° to 120°C range. Gas generation starts at similar temperatures, but may continue up beyond this range, perhaps as high as 200°C. In order to determine the likelihood of oil/gas generation, therefore, the thermal history of the source rock must be calculated. This is performed with a combination of geochemical analysis of the source rock (to determine the type of kerogens present and their maturation characteristics) and basin modelling methods, such as back-stripping, to model the thermal gradient in the sedimentary column.

Analysis of reservoir

The existence of a reservoir rock (typically, sandstones and fractured limestones) is determined through a combination of regional studies (i.e. analysis of other wells in the area), stratigraphy and sedimentology (to quantify the pattern and extent of sedimentation) and seismic interpretation. Once a possible hydrocarbon reservoir is identified, the key physical characteristics of a reservoir that are of interest to a hydrocarbon explorationist are its bulk rock volume, net-to-gross ratio, porosity and permeability.

Bulk rock volume, or the gross rock volume of rock above any hydrocarbon-water contact, is determined by mapping and correlating sedimentary packages. The net-to-gross ratio, typically estimated from analogues and wireline logs, is used to calculate the proportion of the sedimentary packages that contains reservoir rocks. The bulk rock volume multiplied by the net-to-gross ratio gives the net rock volume of the reservoir. The net rock volume multiplied by porosity gives the total hydrocarbon pore volume i.e. the volume within the sedimentary package that fluids (importantly, hydrocarbons and water) can occupy. The summation of these volumes for a given exploration prospect will allow explorers and commercial analysts to determine whether a prospect is financially viable.

Traditionally, porosity and permeability were determined through the study of hand specimens, contiguous parts of the reservoir that outcrop at the surface and by the technique of formation evaluation using wireline tools passed down the well itself. Modern advances in seismic data acquisition and processing have meant that seismic attributes of subsurface rocks are readily available and can be used to infer physical/sedimentary properties of the rocks themselves.

4. Engineering geology

Engineering Geology is the application of the geologic sciences to engineering practice for the purpose of assuring that the geologic factors affecting the location, design, construction, operation and maintenance of engineering works are recognized and adequately provided for. Engineering geologists investigate and provide geologic and geotechnical recommendations, analysis, and design associated with human development. The realm of the engineering geologist is essentially in the area of earth-structure interactions, or investigation of how the earth or earth processes impact human made structures and human activities.

Engineering geologic studies may be performed during the planning, environmental impact analysis, civil or structural engineering design, value engineering and construction phases of public and private works projects, and during post-construction and forensic phases of projects. Works completed by engineering geologists include; geologic hazards, geotechnical, material properties, landslide and slope stability, erosion, flooding, dewatering, and seismic investigations, etc. Engineering geologic studies are performed by a geologist or engineering geologist that is educated, trained and has obtained experience related to the recognition and interpretation of natural processes, the understanding of how these processes impact man-made structures (and vice versa), and knowledge of methods by which to mitigate for hazards resulting from adverse natural or man-made conditions. The principal objective of the engineering geologist is the protection of life and property against damage caused by geologic conditions.

Engineering geologic practice is also closely related to the practice of geological engineering, geotechnical engineering, soils engineering, environmental geology and economic geology. If there is a difference in the content of the disciplines described, it mainly lies in the training or experience of the practitioner.

History

Although the science of geology has been around since the 18th century, at least in its modern form, the science and practice of engineering geology didn't begin as a recognized discipline until the late 19th and early 20th centuries. The first book entitled Engineering Geology was published in 1880 by William Penning. In the early 20th century Charles Berkey, an American trained geologist who was considered the first American engineering geologist, worked on a number of water supply projects for New York City, then later worked on the Hoover dam and a multitude of other engineering projects. The first American engineering geology text book was written in 1914 by Ries and Watson. In 1925, Karl Terzaghi, an Austrian trained engineer and geologist, published the first text in Soil Mechanics (in German). Terzaghi is known as the father of soil mechanics, but also had great interest in geology; Terzaghi considered soil mechanics to be a sub-discipline of engineering geology. In 1929, Terzaghi, along with Redlich and Kampe, published their own Engineering Geology text (also in German).

The need for geologist on engineering works gained world wide attention in 1928 with the failure of the St. Francis dam in California and the loss of 426 lives. More engineering failures which occurred the following years also prompted the requirement for engineering geologists to work on large engineering projects.

In 1951, one of the earliest definitions of the "Engineering geologist" or "Professional Engineering Geologist" was provided by the Executive Committee of the Division on Engineering Geology of the Geological Society of America.

The Practice

One of the most important roles of the engineering geologist is the interpretation of landforms and earth processes to identify potential geologic and related man-made hazards that may impact civil structures and human development. Nearly all engineering geologists are initially trained and educated in geology, primarily during their undergraduate education. This background in geology provides the engineering geologist with an understanding of how the earth works, which is crucial in mitigating for earth related hazards. Most engineering geologists also have graduate degrees where they have gained specialized education and training in soil mechanics, rock mechanics, geotechnics, groundwater, hydrology, and civil design. These two aspects of the engineering geologists' education provides them with a unique ability to understand and mitigate for hazards associated with earth-structure interactions.

Scope of Studies

Engineering geologic studies may be performed:

- for residential, commercial and industrial developments;
- for governmental and military installations;
- for public works such as a power plant, wind turbine, transmission line, sewage treatment plant, water treatment plant, pipeline (aqueduct, sewer, outfall), tunnel, trenchless construction, canal, dam, reservoir, building, railroad, transit, highway, bridge, seismic retrofit, airport and park;
- for mine and quarry excavations, mine tailing dam, mine reclamation and mine tunneling;
- for wetland and habitat restoration programs;
- for coastal engineering, sand replenishment, bluff or sea cliff stability, harbor, pier and waterfront development;
- for offshore outfall, drilling platform and sub-sea pipeline, sub-sea cable; and
- for other types of facilities.

Geohazards and adverse geo-conditions

Typical geologic hazards or other adverse conditions evaluated and mitigated by an engineering geologist include:

- fault rupture on seismically active faults ;
- seismic and earthquake hazards (ground shaking, liquefaction, lurching, lateral spreading, tsunami and seiche events);
- landslide, mudflow, rockfall, debris flow, and avalanche hazards ;
- unstable slopes and slope stability;
- erosion;
- slaking and heave of geologic formations;
- ground subsidence (such as due to ground water withdrawal, sinkhole collapse, cave collapse, decomposition of organic soils, and tectonic movement);
- volcanic hazards (volcanic eruptions, hot springs, pyroclastic flows, debris flow, debris avalanche, gas emissions, volcanic earthquakes);
- non-rippable or marginally rippable rock requiring heavy ripping or blasting;
- weak and collapsible soils, foundation bearing failures;
- shallow ground water/seepage; and
- other types of geologic constraints.

An engineering geologist or geophysicist may be called upon to evaluate the excavatability (i.e. rippability) of earth (rock) materials to assess the need for pre-blasting during earthwork construction, as well as associated impacts due to vibration during blasting on projects.

Soil and Rock Mechanics

Soil mechanics is a discipline that applies principles of engineering mechanics, e.g. kinematics, dynamics, fluid mechanics, and mechanics of material, to predict the mechanical behavior of soils. Rock mechanics is the theoretical and applied science of the mechanical behaviour of rock and rock masses; it is that branch of mechanics concerned with the response of rock and rock masses to the force fields of their physical environment. The fundamental processes are all related to the behaviour of porous media. Together, soil and rock mechanics are the basis for solving many engineering geologic problems.

Methods and reporting

The methods used by engineering geologists in their studies include

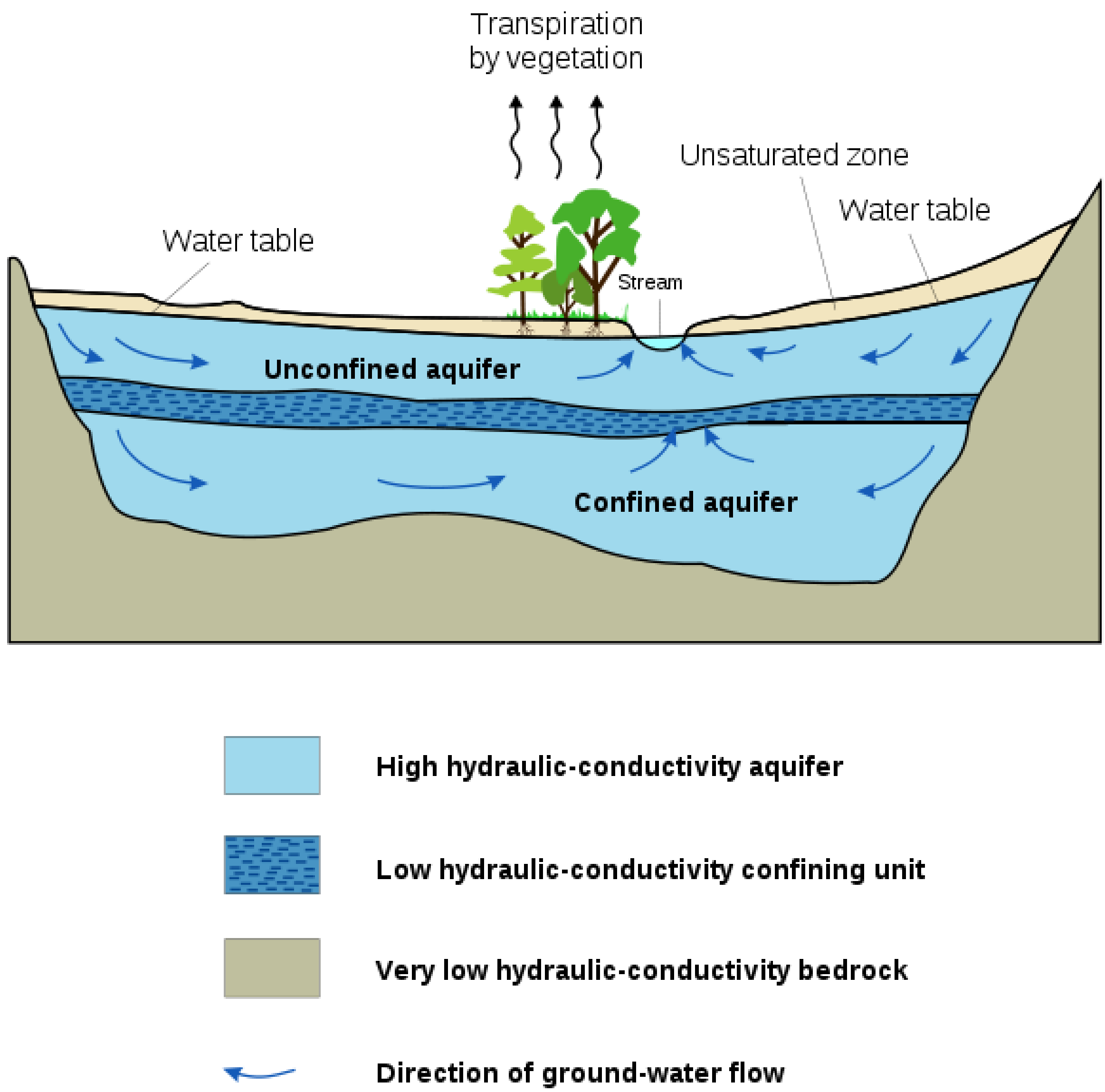
- geologic field mapping of geologic structures, geologic formations, soil units and hazards;
- the review of geologic literature, geologic maps, geotechnical reports, engineering plans, environmental reports, stereoscopic aerial photographs, remote sensing data, Global Positioning System (GPS) data, topographic maps and satellite imagery;

- the excavation, sampling and logging of earth/rock materials in drilled borings, backhoe test pits and trenches, fault trenching, and bulldozer pits;
- geophysical surveys (such as seismic refraction traverses, resistivity surveys, ground penetrating radar (GPR) surveys, magnetometer surveys, electromagnetic surveys, high-resolution sub-bottom profiling, and other geophysical methods);
- deformation monitoring as the systematic measurement and tracking of the alteration in the shape or dimensions of an object as a result of the application of stress to it manually or with an automatic deformation monitoring system; and
- other methods.

The field work is typically culminated in analysis of the data and the preparation of an engineering geologic report, geotechnical report, fault hazard or seismic hazard report, geophysical report, ground water resource report or hydrogeologic report. The engineering geologic report is often prepared in conjunction with a geotechnical report, but commonly provide geotechnical analysis and design recommendations independent of a geotechnical report. An engineering geologic report describes the objectives, methodology, references cited, tests performed, findings and recommendations for development. Engineering geologists also provide geologic data on topograpic maps, aerial photographs, geologic maps, Geographic Information System (GIS) maps, or other map bases.

5. Hydrogeology

Hydrogeology (*hydro-* meaning water, and *-geology* meaning the study of the Earth) is the area of geology that deals with the distribution and movement of groundwater in the soil and rocks of the Earth's crust, (commonly in aquifers). The term **geohydrology** is often used interchangeably. Some make the minor distinction between a hydrologist or engineer applying themselves to geology (geohydrology), and a geologist applying themselves to hydrology (hydrogeology).



Typical aquifer cross-section

Introduction

Hydrogeology is an interdisciplinary subject; it can be difficult to account fully for the chemical, physical, biological and even legal interactions between soil, water, nature and society. The study of the interaction between groundwater movement and geology can be quite complex. Groundwater does not always flow in the subsurface down-hill following the surface topography; groundwater follows pressure gradients (flow from high pressure to low) often following fractures and conduits in circuitous paths. Taking into account the interplay of the different facets of a multi-component system often requires knowledge in several diverse fields at both the experimental and theoretical levels. The following is a more traditional introduction to the methods and nomenclature of saturated subsurface hydrology, or simply hydrogeology.

Hydrogeology in relation to other fields

Hydrogeology, as stated above, is a branch of the earth sciences dealing with the flow of water through aquifers and other shallow porous media (typically less than 450 m or 1,500 ft below the land surface.) The very shallow flow of water in the subsurface (the upper 3 m or 10 ft) is pertinent to the fields of soil science, agriculture and civil engineering, as well as to hydrogeology. The general flow of fluids (water, hydrocarbons, geothermal fluids, etc.) in deeper formations is also a concern of geologists, geophysicists and petroleum geologists. Groundwater is a slow-moving, viscous fluid (with a Reynolds number less than unity); many of the empirically derived laws of groundwater flow can be alternately derived in fluid mechanics from the special case of Stokes flow (viscosity and pressure terms, but no inertial term).

The mathematical relationships used to describe the flow of water through porous media are the diffusion and Laplace equations, which have applications in many diverse fields. Steady groundwater flow (Laplace equation) has been simulated using electrical, elastic and heat conduction analogies. Transient groundwater flow is analogous to the diffusion of heat in a solid, therefore some solutions to hydrological problems have been adapted from heat transfer literature.

Traditionally, the movement of groundwater has been studied separately from surface water, climatology, and even the chemical and microbiological aspects of hydrogeology (the processes are uncoupled). As the field of hydrogeology matures, the strong interactions between groundwater, surface water, water chemistry, soil moisture and even climate are becoming more clear.

Definitions and material properties

One of the main tasks a hydrogeologist typically performs is the prediction of future behavior of an aquifer system, based on analysis of past and present observations. Some hypothetical, but characteristic questions asked would be:

- Can the aquifer support another subdivision?
- Will the river dry up if the farmer doubles his irrigation?
- Did the chemicals from the dry cleaning facility travel through the aquifer to my well and make me sick?
- Will the plume of effluent leaving my neighbor's septic system flow to my drinking water well?

Most of these questions can be addressed through simulation of the hydrologic system (using numerical models or analytic equations). Accurate simulation of the aquifer system requires knowledge of the aquifer properties and boundary conditions. Therefore a common task of the hydrogeologist is determining aquifer properties using aquifer tests.

In order to further characterize aquifers and aquitards some primary and derived physical properties are introduced below. Aquifers are broadly classified as being either confined or unconfined (water table aquifers), and either saturated or unsaturated; the type of aquifer affects what properties control the flow of water in that medium (e.g., the release of water from storage for confined aquifers is related to the storativity, while it is related to the specific yield for unconfined aquifers).

Hydraulic head

Changes in hydraulic head (h) are the driving force which causes water to move from one place to another. It is composed of pressure head (ψ) and elevation head (z). The head gradient is the change in hydraulic head per length of flowpath, and appears in Darcy's law as being proportional to the discharge.

Hydraulic head is a directly measurable property that can take on any value (because of the arbitrary datum involved in the z term); ψ can be measured with a pressure transducer (this value can be negative, e.g., suction, but is positive in saturated aquifers), and z can be measured relative to a surveyed datum (typically the top of the well casing). Commonly, in wells tapping unconfined aquifers the water level in a well is used as a proxy for hydraulic head, assuming there is no vertical gradient of pressure. Often only *changes* in hydraulic head through time are needed, so the constant elevation head term can be left out ($\Delta h = \Delta\psi$).

A record of hydraulic head through time at a well is a hydrograph or, the changes in hydraulic head recorded during the pumping of a well in a test are called drawdown.

Porosity

Porosity (n) is a directly measurable aquifer property; it is a fraction between 0 and 1 indicating the amount of pore space between unconsolidated soil particles or within a fractured rock. Typically, the majority of groundwater (and anything dissolved in it) moves through the porosity available to flow (sometimes called effective porosity). **Permeability** is an expression of the connectedness of the pores. For instance, an unfractured rock unit may have a high *porosity* (it has lots of *holes* between its constituent grains), but a low *permeability* (none of the pores are connected). An example of this phenomenon is pumice, which, when in its unfractured state, can make a poor aquifer.

Porosity does not directly affect the distribution of hydraulic head in an aquifer, but it has a very strong effect on the migration of dissolved contaminants, since it affects groundwater flow velocities through an inversely proportional relationship.

Water content

Water content (θ) is also a directly measurable property; it is the fraction of the total rock which is filled with liquid water. This is also a fraction between 0 and 1, but it must also be less than or equal to the total porosity.

The water content is very important in vadose zone hydrology, where the hydraulic conductivity is a strongly nonlinear function of water content; this complicates the solution of the unsaturated groundwater flow equation.

Hydraulic conductivity

Hydraulic conductivity (K) and transmissivity (T) are indirect aquifer properties (they cannot be measured directly). T is the K integrated over the vertical thickness (b) of the aquifer ($T=Kb$ when K is constant over the entire thickness). These properties are measures of an aquifer's ability to transmit water. Intrinsic permeability (κ) is a secondary medium property which does not depend on the viscosity and density of the fluid (K and T are specific to water); it is used more in the petroleum industry.

Specific storage and specific yield

Specific storage (S_s) and its depth-integrated equivalent, storativity ($S=S_sb$), are indirect aquifer properties (they cannot be measured directly); they indicate the amount of groundwater released from storage due to a unit depressurization of a confined aquifer. They are fractions between 0 and 1.

Specific yield (S_y) is also a ratio between 0 and 1 ($S_y \leq$ porosity) and indicates the amount of water released due to drainage from lowering the water table in an unconfined aquifer. The value for specific yield is less than the value for porosity because some water will remain in the medium even after drainage due to molecular forces. Often the porosity or effective porosity is used as an upper bound to the specific yield. Typically S_y is orders of magnitude larger than S_s.

Contaminant transport properties

Often we are interested in how the moving groundwater water will move dissolved contaminants around (the sub-field of contaminant hydrogeology). The contaminants can be man-made (e.g., petroleum products, nitrate or Chromium) or naturally occurring (e.g., arsenic, salinity). Besides needing to understand where the groundwater is flowing, based on the other hydrologic properties discussed above, there are additional aquifer properties which affect how dissolved contaminants move with groundwater.

Hydrodynamic dispersion

Hydrodynamic dispersivity (α_L, α_T) is an empirical factor which quantifies how much contaminants stray away from the path of the groundwater which is carrying it. Some of the contaminants will be "behind" or "ahead" the mean groundwater, giving rise to a longitudinal dispersivity (α_L), and some will be "to the sides of" the pure advective groundwater flow, leading to a transverse dispersivity (α_T). Dispersion in groundwater is due to the fact that each water "particle", passing beyond a soil particle, must choose where to go, whether left or right or up or down, so that the water "particles" (and their solute) are gradually spread in all directions around the mean path. This is the "microscopic" mechanism, on the scale of soil particles. More important, on long distances, can be the macroscopic inhomogeneities of the aquifer, which can have regions of larger or smaller permeability, so that some water can find a preferential path in one direction, some other in a different direction, so that the contaminant can be spread in a completely irregular way, like in a (three-dimensional) delta of a river.

Dispersivity is actually a factor which represents our *lack of information* about the system we are simulating. There are many small details about the aquifer which are being averaged when using a macroscopic approach (e.g., tiny beds of gravel and clay in sand aquifers), they manifest themselves as an *apparent* dispersivity. Because of this, α is often claimed to be dependent on the length scale of the problem — the dispersivity found for transport through 1 m^3 of aquifer is different than that for transport through 1 cm^3 of the same aquifer material.

Molecular Diffusion

Diffusion is a fundamental physical phenomenon, by which Einstein explained Brownian motion, which describes the random thermal movement of molecules and small particles in gases and liquids. It is an important phenomenon for small distances (it is essential for the achievement of thermodinamic equilibria), but, as the time necessary to cover a distance by diffusion is proportional to the square of the distance itself, it is ineffective for spreading a solute over macroscopic distances. The diffusion coefficient, D, is typically quite small, and its effect can often be considered negligible (unless groundwater flow velocities are extremely low, as they are in clay aquitards).

It is important not to confuse diffusion with dispersion, as the former is a physical phenomenon and the latter is an empirical factor which is cast into a similar form as diffusion, because we already know how to solve that problem.

Retardation by adsorption

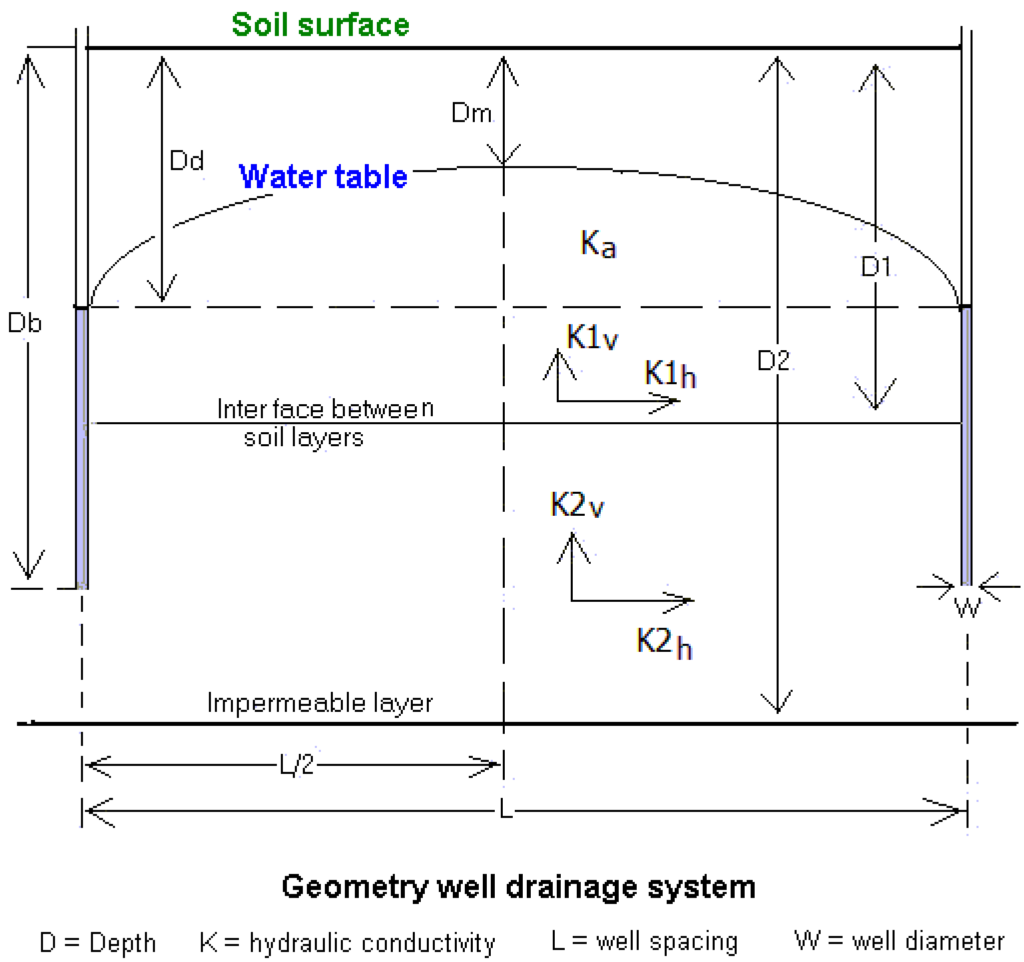
The retardation factor is another very important feature that make the motion of the contaminant to deviate from the average groundwater motion. It is analogous to the retardation factor of chromatography. Unlike diffusion and dispersion, which simply spread the contaminant, the retardation factor changes its *global average velocity*, so that it can be much slower than that of water. This is due to a chemico-physical effect: the adsorption to the soil, which holds the contaminant back and does not allow it to progress until the quantity corresponding to the chemical adsorption equilibrium has been adsorbed. This effect is particularly important for less soluble contaminants, which thus can move even hundreds or thousands times slower than water. The effect of this phenomenon is that only more soluble species can cover long distances. The retardation factor depends on the chemical nature of both the contaminant and the aquifer.

Governing equations

Darcy's Law

Darcy's law is a Constitutive equation (empirically derived by Henri Darcy, in 1856) that states the amount of groundwater discharging through a given portion of aquifer is proportional to the cross-sectional area of flow, the hydraulic head gradient, and the hydraulic conductivity.

Groundwater flow equation



Geometry of a partially penetrating well drainage system in an anisotropic layered aquifer

The groundwater flow equation, in its most general form, describes the movement of groundwater in a porous medium (aquifers and aquitards). It is known in mathematics as the diffusion equation, and has many analogs in other fields. Many solutions for groundwater flow problems were borrowed or adapted from existing heat transfer solutions.

It is often derived from a physical basis using Darcy's law and a conservation of mass for a small control volume. The equation is often used to predict flow to wells, which have radial symmetry, so the flow equation is commonly solved in polar or cylindrical coordinates.

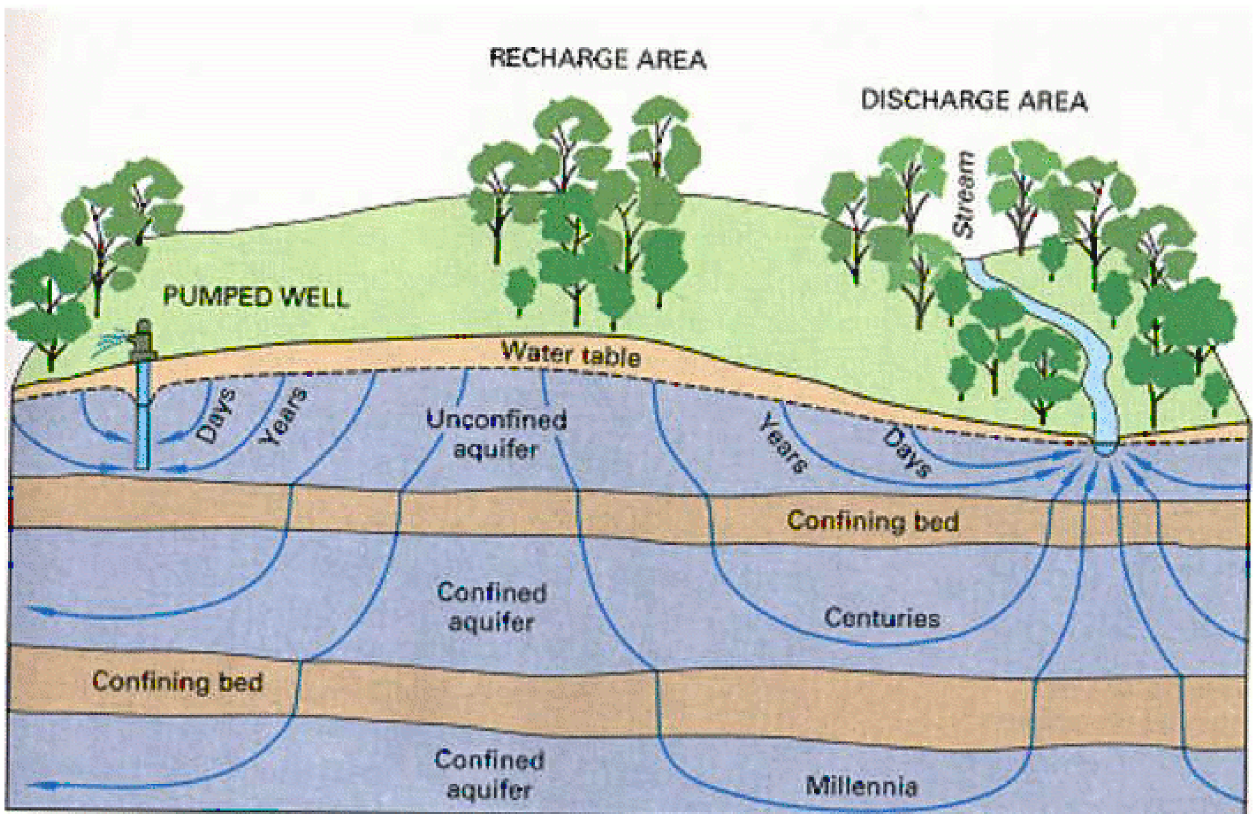
The Theis equation is one of the most commonly used and fundamental solutions to the groundwater flow equation; it can be used to predict the transient evolution of head due to the effects of pumping one or a number of pumping wells.

The Thiem equation is a solution to the steady state groundwater flow equation (Laplace's Equation) for flow to a well. Unless there are large sources of water nearby (a river or lake), true steady-state is rarely achieved in reality.

Both above equations are used in aquifer tests (pump tests).

The Hooghoudt equation is a groundwater flow equation applied to subsurface drainage by pipes, tile drains or ditches. An alternative subsurface drainage method is drainage by wells for which groundwater flow equations are also available.

Calculation of groundwater flow



Relative groundwater travel times

To use the groundwater flow equation to estimate the distribution of hydraulic heads, or the direction and rate of groundwater flow, this partial differential equation (PDE) must be solved. The most common means of analytically solving the diffusion equation in the hydrogeology literature are:

- Laplace, Hankel and Fourier transforms (to reduce the number of dimensions of the PDE),
- similarity transform (also called the Boltzmann transform) is commonly how the Theis solution is derived,

- separation of variables, which is more useful for non-Cartesian coordinates, and
- Green's functions, which is another common method for deriving the Theis solution — from the fundamental solution to the diffusion equation in free space.

No matter which method we use to solve the groundwater flow equation, we need both initial conditions (heads at time (t) = 0) and boundary conditions (representing either the physical boundaries of the domain, or an approximation of the domain beyond that point). Often the initial conditions are supplied to a transient simulation, by a corresponding steady-state simulation (where the time derivative in the groundwater flow equation is set equal to 0).

There are two broad categories of how the (PDE) would be solved; either analytical methods, numerical methods, or something possibly in between. Typically, analytic methods solve the groundwater flow equation under a simplified set of conditions *exactly*, while numerical methods solve it under more general conditions to an *approximation*.

Analytic methods

Analytic methods typically use the structure of mathematics to arrive at a simple, elegant solution, but the required derivation for all but the simplest domain geometries can be quite complex (involving non-standard coordinates, conformal mapping, etc.). Analytic solutions typically are also simply an equation that can give a quick answer based on a few basic parameters. The Theis equation is a very simple (yet still very useful) analytic solution to the groundwater flow equation, typically used to analyze the results of an aquifer test or slug test.

Numerical methods

The topic of numerical methods is quite large, obviously being of use to most fields of engineering and science in general. Numerical methods have been around much longer than computers have (In the 1920s Richardson developed some of the finite difference schemes still in use today, but they were calculated by hand, using paper and pencil, by human "calculators"), but they have become very important through the availability of fast and cheap personal computers.

There are two broad categories of numerical methods: gridded or discretized methods and non-gridded or mesh-free methods. In the common finite difference method and finite element method (FEM) the domain is completely gridded ("cut" into a grid or mesh of small elements). The analytic element method (AEM) and the boundary integral equation method (BIEM — sometimes also called BEM, or Boundary Element Method) are only discretized at boundaries or along flow elements (line sinks, area sources, etc.), the majority of the domain is mesh-free.

General properties of gridded methods

Gridded Methods like finite difference and finite element methods solve the groundwater flow equation by breaking the problem area (domain) into many small elements (squares, rectangles, triangles, blocks, tetrahedra, etc.) and solving the flow equation for each element (all material properties are assumed constant or possibly linearly variable within an element), then linking together all the elements using conservation of mass across the boundaries between the elements (similar to the divergence theorem). This results in a system which overall approximates the groundwater flow equation, but exactly matches the boundary conditions (the head or flux is specified in the elements which intersect the boundaries).

Finite differences are a way of representing continuous differential operators using discrete intervals (Δx and Δt), and the finite difference methods are based on these (they are derived from a Taylor series). For example the first-order time derivative is often approximated using the following forward finite difference, where the subscripts indicate a discrete time location,

$$\frac{\partial h}{\partial t} = h'(t_i) \approx \frac{h_i - h_{i-1}}{\Delta t}.$$

The forward finite difference approximation is unconditionally stable, but leads to an implicit set of equations (that must be solved using matrix methods, e.g. LU or Cholesky decomposition). The similar backwards difference is only conditionally stable, but it is explicit and can be used to "march" forward in the time direction, solving one grid node at a time (or possibly in parallel, since one node depends only on its immediate neighbors). Rather than the finite difference method, sometimes the Galerkin FEM approximation is used in space (this is different from the type of FEM often used in structural engineering) with finite differences still used in time.

Application of finite difference models

MODFLOW is a well-known example of a general finite difference groundwater flow model. It is developed by the US Geological Survey as a modular and extensible simulation tool for modeling groundwater flow. It is free software developed, documented and distributed by the USGS. Many commercial products have grown up around it, providing graphical user interfaces to its input file based interface, and typically incorporating pre- and post-processing of user data. Many other models have been developed to work with MODFLOW input and output, making linked models which simulate several hydrologic processes possible (flow and transport models, surface water and groundwater models and chemical reaction models), because of the simple, well documented nature of MODFLOW.

Application of finite element models

Finite Element programs are more flexible in design (triangular elements vs. the block elements most finite difference models use) and there are some programs available (SUTRA, a 2D or 3D density-dependent flow model by the USGS; Hydrus, a commercial unsaturated flow model; FEFLOW, a commercial modeling environment for subsurface flow, solute and heat transport processes; and COMSOL Multiphysics (FEMLAB) a commercial general modeling environment), but unless they are gaining in importance they are still not as popular in with practicing hydrogeologists as MODFLOW is. Finite element models are more popular in university and laboratory environments, where specialized models solve non-standard forms of the flow equation (unsaturated flow, density dependent flow, coupled heat and groundwater flow, etc.)

Application of finite volume models

The finite volume method is a method for representing and evaluating partial differential equations as algebraic equations [LeVeque, 2002; Toro, 1999]. Similar to the finite difference method, values are calculated at discrete places on a meshed geometry. "Finite volume" refers to the small volume surrounding each node point on a mesh. In the finite volume method, volume integrals in a partial differential equation that contain a divergence term are converted to surface integrals, using the divergence theorem. These terms are then evaluated as fluxes at the surfaces of each finite volume. Because the flux entering a given volume is identical to that leaving the adjacent volume, these methods are conservative. Another advantage of the finite volume method is that it is easily formulated to allow for unstructured meshes. The method is used in many computational fluid dynamics packages.

PORFLOW software package is a comprehensive mathematical model for simulation of Ground Water Flow and Nuclear Waste Management developed by Analytic & Computational Research, Inc., ACRi]ACRi

The **FEHM** software package is available free from Los Alamos National Laboratory and can be accessed at the FEHM Website. This versatile porous flow simulator includes capabilities to model multiphase, thermal, stress, and multicomponent reactive chemistry. Current work using this code includes simulation of methane hydrate formation, CO_2 sequestration, oil shale extraction, migration of both nuclear and chemical contaminants, environmental isotope migration in the unsaturated zone, and karst formation.

Other methods

These include mesh-free methods like the Analytic Element Method (AEM) and the Boundary Element Method (BEM), which are closer to analytic solutions, but they do approximate the groundwater flow equation in some way. The BEM and AEM exactly solve the groundwater flow equation (perfect mass balance), while approximating the boundary conditions. These methods are more exact and can be much more elegant solutions (like analytic methods are), but have not seen as widespread use outside academic and research groups yet.