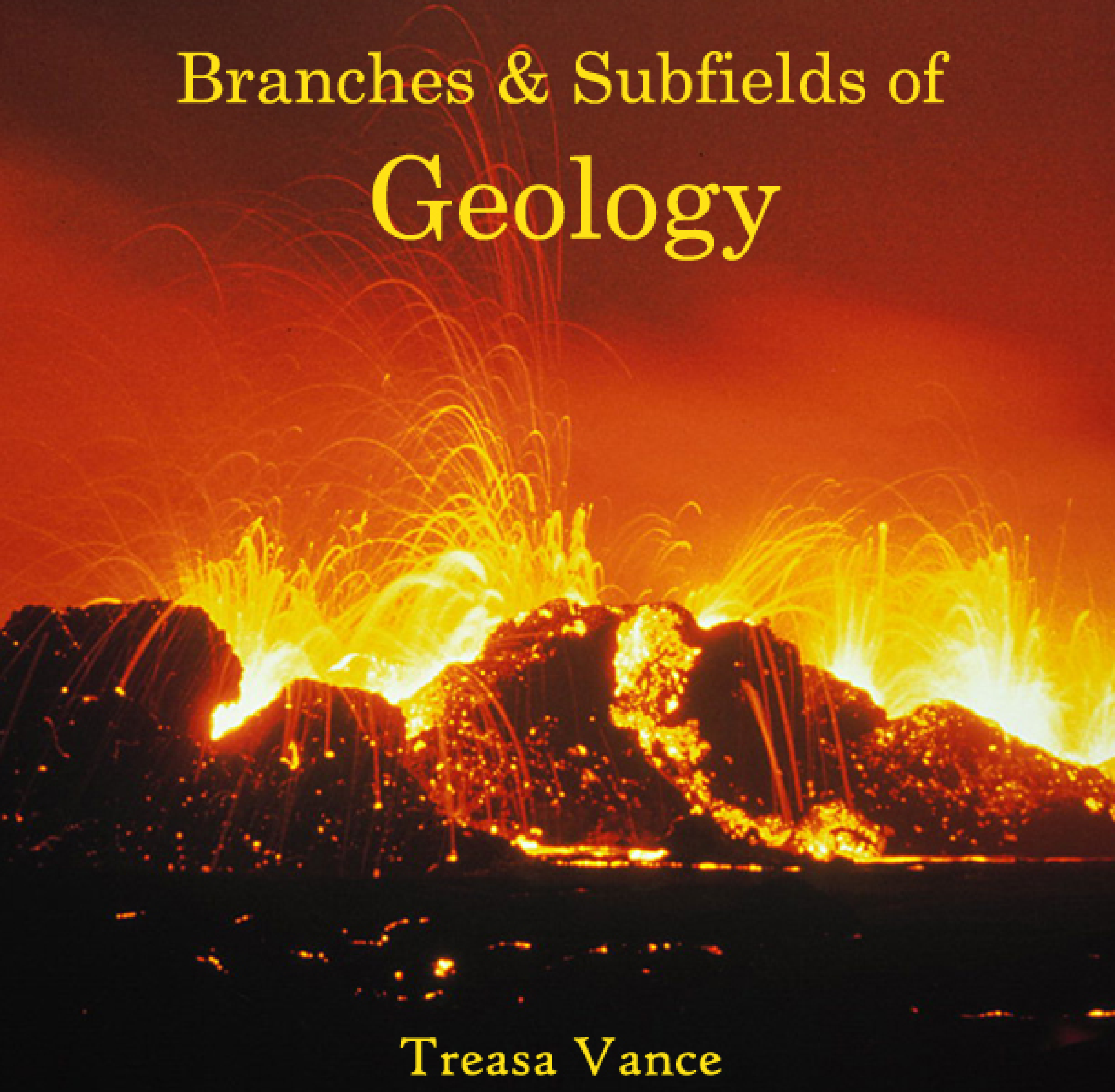
Branches & Subfields of Geology



Treasa Vance

First Edition, 2012

ISBN 978-81-323-1916-0

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

Table of Contents

Chapter- 1

Geochemistry and Geomorphology

Geochemistry

The field of **geochemistry** involves study of the chemical composition of the Earth and other planets, chemical processes and reactions that govern the composition of rocks, water, and soils, and the cycles of matter and energy that transport the Earth's chemical components in time and space, and their interaction with the hydrosphere and the atmosphere.

Some subsets of geochemistry are:

1. Isotope geochemistry:Determination of the relative and absolute concentrations of the elements and their isotopes in the earth and on earth's surface.
2. Examination of the distribution and movements of elements in different parts of the earth (crust, mantle, hydrosphere etc.) and in minerals with the goal to determine the underlying system of distribution and movement.
3. Cosmochemistry: Analysis of the distribution of elements and their isotopes in the cosmos.
4. Biogeochemistry: Field of study focusing on the effect of life on the chemistry of the earth.
5. Organic geochemistry: A study of the role of processes and compounds that are derived from living or once-living organisms.
6. Water Geochemistry: Understanding the role of various elements in watersheds, including Cu, S, Hg, and how elemental fluxes are exchanged through atmospheric-terrestrial-aquatic interactions.
7. Regional, environmental and exploration geochemistry: Applications to environmental, hydrological and mineral exploration studies.

Victor Goldschmidt is considered by most to be the father of modern geochemistry and the ideas of the subject were formed by him in a series of publications from 1922 under the title ‘Geochemische Verteilungsgesetze der Elemente’.

Chemical characteristics

The more common rock constituents are nearly all oxides; chlorine, sulfur and fluorine are the only important exceptions to this and their total amount in any rock is usually much less than 1%. F. W. Clarke has calculated that a little more than 47% of the Earth's crust consists of oxygen. It occurs principally in combination as oxides, of which the chief are silica, alumina, iron oxides, and various carbonates (calcium carbonate, magnesium carbonate, sodium carbonate, and potassium carbonate). The silica functions principally as an acid, forming silicates, and all the commonest minerals of igneous rocks are of this nature. From a computation based on 1672 analyses of numerous kinds of rocks Clarke arrived at the following as the average percentage composition: SiO_2=59.71, Al_2O_3=15.41, Fe_2O_3=2.63, FeO=3.52, MgO=4.36, CaO=4.90, Na_2O=3.55, K_2O=2.80, H_2O=1.52, TiO_2=0.60, P_2O_5=0.22, total 99.22%). All the other constituents occur only in very small quantities, usually much less than 1%.

These oxides combine in a haphazard way. For example, potash (potassium carbonate) and soda (sodium carbonate) combine to produce feldspars. In some cases they may take other forms, such as nepheline, leucite, and muscovite, but in the great majority of instances they are found as feldspar. Phosphoric acid with lime (calcium carbonate) forms apatite. Titanium dioxide with ferrous oxide gives rise to ilmenite. Part of the lime forms lime feldspar. Magnesium carbonate and iron oxides with silica crystallize as olivine or enstatite, or with alumina and lime form the complex ferro-magnesian silicates of which the pyroxenes, amphiboles, and biotites are the chief. Any excess of silica above what is required to neutralize the bases will separate out as quartz; excess of alumina crystallizes as corundum. These must be regarded only as general tendencies. It is possible, by rock analysis, to say approximately what minerals the rock contains, but there are numerous exceptions to any rule.

Mineral constitution

Hence we may say that except in acid or siliceous rocks containing 66% of silica and over, quartz will not be abundant. In basic rocks (containing 20% of silica or less) it is rare and accidental. If magnesia and iron be above the average while silica is low, olivine may be expected; where silica is present in greater quantity over ferro-magnesian minerals, such as augite, hornblende, enstatite or biotite, occur rather than olivine. Unless potash is high and silica relatively low, leucite will not be present, for leucite does not occur with free quartz. Nepheline, likewise, is usually found in rocks with much soda and comparatively little silica. With high alcalis, soda-bearing pyroxenes and amphiboles may be present. The lower the percentage of silica and the alkalis, the greater is the prevalence of t lime felspar as contracted with soda or potash felspar. Clarke has calculated the relative abundance of the principal rock-forming minerals with the following results: Apatite=0.6, titanium minerals=1.5, quartz=12.0, felspars=59.5, biotite=3.8, hornblende and pyroxene=16.8, total=94.2%. This, however, can only be a rough approximation.

The other determining factor, namely the physical conditions attending consolidation, plays on the whole a smaller part, yet is by no means negligible, as a few instances will prove. Certain minerals are practically confined to deep-seated intrusive rocks, e.g., microcline, muscovite, diallage. Leucite is very rare in plutonic masses; many minerals have special peculiarities in microscopic character according to whether they crystallized in depth or near the surface, e.g., hypersthene, orthoclase, quartz. There are some curious instances of rocks having the same chemical composition, but consisting of entirely different minerals, e.g., the hornblendite of Gran, in Norway, which contains only hornblende, has the same composition as some of the camptonites of the same locality that contain felspar and hornblende of a different variety. In this connection we may repeat what has been said above about the corrosion of porphyritic minerals in igneous rocks. In rhyolites and trachytes, early crystals of hornblende and biotite may be found in great numbers partially converted into augite and magnetite. Hornblende and biotite were stable under the pressures and other conditions below the surface, but unstable at higher levels. In the ground-mass of these rocks, augite is almost universally present. But the plutonic representatives of the same magma, granite and syenite contain biotite and hornblende far more commonly than augite.

Acid, intermediate and basic igneous rocks

Those rocks that contain the most silica, and on crystallizing yield free quartz, form a group generally designated the "acid" rocks. Those again that contain least silica and most magnesia and iron, so that quartz is absent while olivine is usually abundant, form the "basic" group. The "intermediate" rocks include those characterized by the general absence of both quartz and olivine. An important subdivision of these contains a very high percentage of alkalis, especially soda, and consequently has minerals such as nepheline and leucite not common in other rocks. It is often separated from the others as the "alkali" or "soda" rocks, and there is a corresponding series of basic rocks. Lastly a small sub-group rich in olivine and without felspar has been called the "ultrabasic" rocks. They have very low percentages of silica but much iron and magnesia.

Except these last, practically all rocks contain felspars or felspathoid minerals. In the acid rocks the common felspars are orthoclase, perthite, microcline, and oligoclase—all having much silica and alkalis. In the basic rocks labradorite, anorthite and bytownite prevail, being rich in lime and poor in silica, potash and soda. Augite is the commonest ferro-magnesian of the basic rocks, but biotite and hornblende are on the whole more frequent in the acid.

	Acid	**Intermediate**		**Mafic**	**Ultramafic**
Commonest Minerals	**Quartz Orthoclase (and Oligoclase), Mica, Hornblende, Augite**	**Little or no Quartz: Orthoclase hornblende, Augite, Biotite**	**Little or no Quartz: Plagioclase Hornblende, Augite, Biotite**	**No Quartz Plagioclase Augite, Olivine**	**No Felspar Augite, Hornblende, Olivine**
Plutonic or Abyssal type	Granite	Syenite	Diorite	Gabbro	Peridotite
Intrusive or Hypabyssal type	Quartz-porphyry	Orthoclase-porphyry	Porphyrite	Dolerite	Picrite
Lavas or Effusive type	Rhyolite, Obsidian	Trachyte	Andesite	Basalt	Limburgite

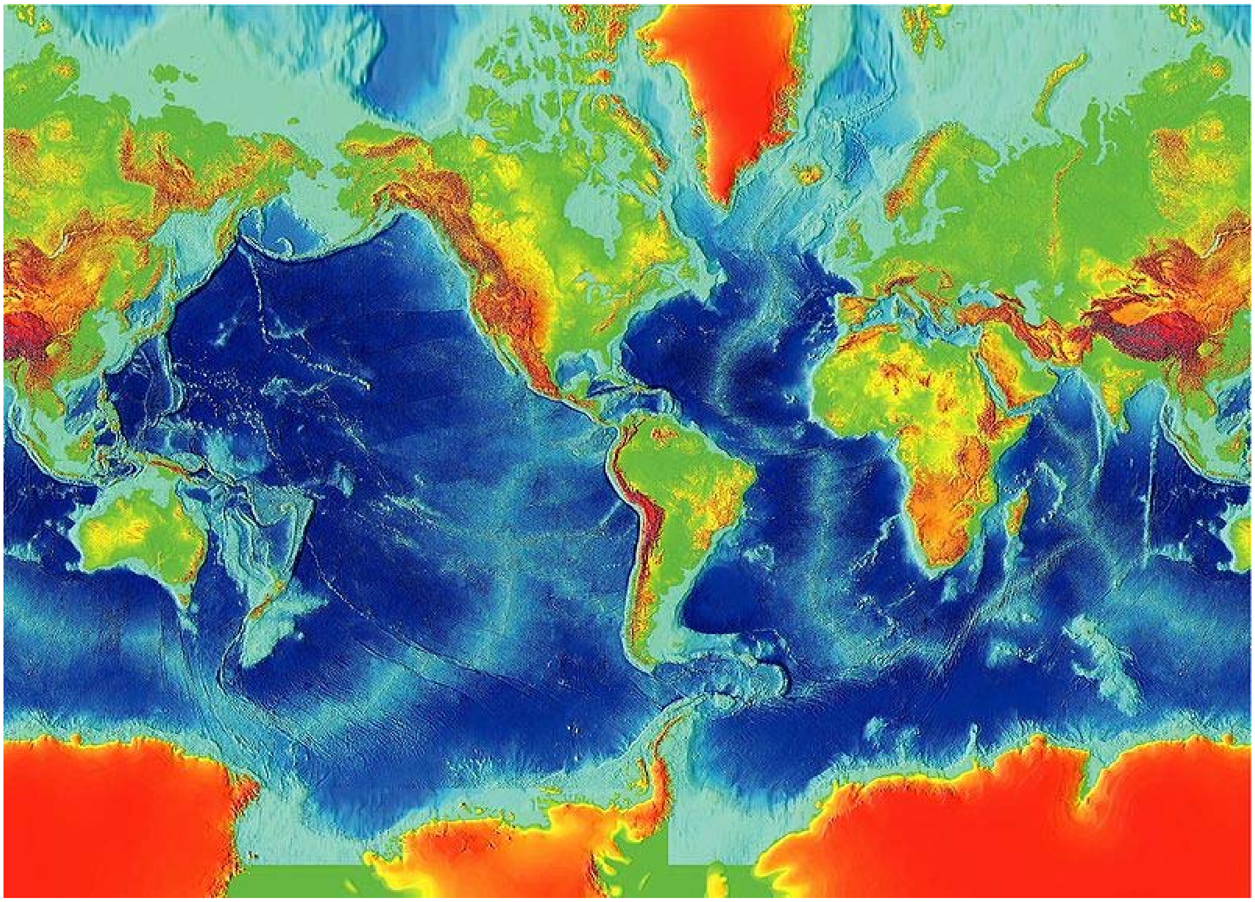
Rocks that contain leucite or nepheline, either partly or wholly replacing felspar, are not included in this table. They are essentially of intermediate or of basic character. We might in consequence regard them as varieties of syenite, diorite, gabbro, etc., in which felspathoid minerals occur, and indeed there are many transitions between syenites of ordinary type and nepheline — or leucite — syenite, and between gabbro or dolerite and theralite or essexite. But, as many minerals develop in these "alcali" rocks that are uncommon elsewhere, it is convenient in a purely formal classification like that outlined here to treat the whole assemblage as a distinct series.

Nepheline and Leucite-bearing Rocks

Commonest Minerals	**Alkali Felspar, Nepheline or Leucite, Augite, Hornblend, Biotite**	**Soda Lime Felspar, Nepheline or Leucite, Augite, Hornblende (Olivine)**	**Nepheline or Leucite, Augite, Hornblende, Olivine**
Plutonic type	Nepheline-syenite, Leucite-syenite, Nepheline-porphyry	Essexite and Theralite	Ijolite and Missourite
Effusive type or Lavas	Phonolite, Leucitophyre	Tephrite and Basanite	Nepheline-basalt, Leucite-basalt

This classification is based essentially on the mineralogical constitution of the igneous rocks. Any chemical distinctions between the different groups, though implied, are relegated to a subordinate position. It is admittedly artificial by it has grown up with the grown of the science and is still adopted as the basis on which more minute subdivisions are erected. The subdivisions are by no means of equal value. The syenites, for example, and the peridotites, are far less important than the granites, diorites and gabbros. Moreover, the effusive andesites do not always correspond to the plutonic diorites but partly also to the gabbros. As the different kinds of rock, regarded as aggregates of minerals, pass gradually into one another, transitional types are very common and are often so important as to receive special names. The quartz-syenites and nordmarkites may be interposed between granite and syenite, the tonalites and adamellites between granite and diorite, the monzoaites between syenite and diorite, norites and hyperites between diorite and gabbro, and so on.

Geomorphology



Surface of the Earth

Geomorphology (from Greek: γῆ, *ge*, "earth"; μορφή, *morfé*, "form"; and λόγος, *logos*, "study") is the scientific study of landforms and the processes that shape them, and more broadly, the evolution of processes controlling the topography of any planet. Geomorphologists seek to understand why landscapes look the way they do, to understand landform history and dynamics, and to predict future changes through a combination of field observation, physical experiment, and numerical modeling. Geomorphology is practiced within geography, geology, geodesy, engineering geology, archaeology, and geotechnical engineering, and this broad base of interest contributes to a wide variety of research styles and interests within the field.

The form of the Earth's surface evolves in response to a combination of natural and anthropogenic processes, and responds to the balance between processes that add material and those that remove it. Such processes may act across very many lengthscales and timescales. On the broadest scales, the landscape is built up through tectonic uplift and volcanism. Denudation occurs by erosion and mass wasting, which produces sediment that is transported and deposited elsewhere within the landscape or off the coast. On progressively smaller scales, similar ideas apply, where individual landforms evolve in response to the balance of additive (tectonic or sedimentary) and subtractive (erosive) processes. Modern geomorphology can be thought of as the study of the divergence of flux of material on a planetary surface, and as such is closely allied with sedimentology, which can equally be seen as the convergence of that flux.

Geomorphic processes are influenced by tectonics, climate, ecology, and human activity, and equally, many of these drivers can be affected by the ongoing evolution of the Earth's surface, for example, via isostasy or orographic precipitation. Many geomorphologists are particularly interested in the potential for feedbacks between climate and tectonics mediated by geomorphic processes.

Practical applications of geomorphology include hazard assessment including landslide prediction and mitigation, river control and restoration, and coastal protection.

History

With some notable exceptions (see below), geomorphology is a relatively young science, growing along with interest in other aspects of the Earth Sciences in the mid 19th century. This section provides a very brief outline of some of the major figures and events in its development.

Ancient geomorphology

Perhaps the earliest one to devise a theory of geomorphology was the polymath Chinese scientist and statesman Shen Kuo (1031-1095 AD). This was based on his observation of marine fossil shells in a geological stratum of a mountain hundreds of miles from the Pacific Ocean. Noticing bivalve shells running in a horizontal span along the cut section of a cliffside, he theorized that the cliff was once the pre-historic location of a seashore that had shifted hundreds of miles over the centuries. He inferred that the land was reshaped and formed by soil erosion of the mountains and by deposition of silt, after observing strange natural erosions of the Taihang Mountains and the Yandang Mountain near Wenzhou. Furthermore, he promoted the theory of gradual climate change over centuries of time once ancient petrified bamboos were found to be preserved underground in the dry, northern climate zone of *Yanzhou*, which is now modern day Yan'an, Shaanxi province.

Early modern geomorphology

The first use of the word geomorphology was likely to be in the German language when it appeared in Laumann's 1858 work. Keith Tinkler has suggested that the word came into general use in English, German and French after John Wesley Powell and W. J. McGee used it in the International Geological Conference of 1891.

An early popular geomorphic model was the *geographical cycle* or the *cycle of erosion*, developed by William Morris Davis between 1884 and 1899. The cycle was inspired by theories of uniformitarianism first formulated by James Hutton (1726–1797). Concerning valley forms, uniformitarianism depicted the cycle as a sequence in which a river cuts a valley more and more deeply, but then erosion of side valleys eventually flatten the terrain again, to a lower elevation. uplift could start the cycle over. Many studies in geomorphology in the decades following Davis' development of his theories sought to fit their ideas into this framework for broad scale landscape evolution, and are often today termed "Davisian". Davis' ideas have largely been superseded today, mainly due to their lack of predictive power and qualitative nature, but he remains an extremely important figure in the history of the subject.

In the 1920s, Walther Penck developed an alternative model to Davis', believing that landform evolution was better described as a balance between ongoing processes of uplift and denudation, rather than Davis' single uplift followed by decay. However, due to his relatively young death, disputes with Davis and a lack of English translation of his work his ideas were not widely recognised for many years.

These authors were both attempting to place the study of the evolution of the Earth's surface on a more generalized, globally relevant footing than had existed before. In the earlier parts of the 19th century, authors - especially in Europe - had tended to attribute the form of landscape to local climate, and in particular to the specific effects of glaciation and periglacial processes. In contrast, both Davis and Penck were seeking to emphasize the importance of evolution of landscapes through time and the generality of Earth surface processes across different landscapes under different conditions.

Quantitative geomorphology

While Penck and Davis and their followers were writing and studying primarily in Western Europe, another, largely separate, school of geomorphology was developed in the United States in the middle years of the 20th century. Following the early trailblazing work of Grove Karl Gilbert around the turn of the 20th century, a group of natural scientists, geologists and hydraulic engineers including Ralph Alger Bagnold, John Hack, Luna Leopold, Thomas Maddock and Arthur Strahler began to research the form of landscape elements such as rivers and hillslopes by taking systematic, direct, quantitative measurements of aspects of them and investigating the scaling of these measurements. These methods began to allow prediction of the past and future behavior of landscapes from present observations, and were later to develop into what today is known as the subdiscipline of *Quantitative Geomorphology*, or *Geomorphometry*.

Contemporary geomorphology

Today, the field of geomorphology encompasses a very wide range of different approaches and interests. Modern researchers aim to draw out quantitative "laws" that govern Earth surface processes, but equally, recognize the uniqueness of each landscape and environment in which these processes operate. Particularly important realizations in contemporary geomorphology include:

1) that not all landscapes can be considered as either "stable" or "perturbed", where this perturbed state is a temporary displacement away from some ideal target form. Instead, dynamic changes of the landscape are now seen as an essential part of their nature.

2) that many geomorphic systems are best understood in terms of the stochasticity of the processes occurring in them, that is, the probability distributions of event magnitudes and return

times. This in turn has indicated the importance of chaotic determinism to landscapes, and that landscape properties are best considered statistically. The same processes in the same landscapes does not always lead to the same end results.

Processes

Grand Canyon, Arizona

Modern geomorphology focuses on the quantitative analysis of interconnected processes. Modern advances in geochemistry, in particular cosmochemistry, isotope geochemistry and fission track dating, have enabled us for the first time to measure the rates at which geomorphic processes occur at geologically relevant timescales. At the same time, the use of more precise physical measurement techniques, including differential GPS, remotely sensed digital terrain models and laser scanning techniques, have allowed quantification and study of these processes as they happen. Computer simulation and modeling may then be used to test our understanding of how these processes work together and through time.

Most geomorphically relevant processes can be thought of as either erosive, transportive, or some combination thereof. Depositional processes are mostly thought of as within the field of sedimentology, but also frequently considered as part of geomorphology. Weathering is the chemical and physical disruption of earth materials in place on exposure to atmospheric or near surface agents. The products of these near surface changes can subsequently be transported away by various agents of erosion.

The nature of the processes investigated by geomorphologists is strongly dependent on the landscape or landform under investigation and the time and length scales of interest. However, the following non-exhaustive list provides a flavor of the landscape elements associated with some of these.

Primary surface processes responsible for most topographic features include wind, waves, chemical dissolution, mass wasting, groundwater movement, surface water flow, glacial action, tectonism, and volcanism. Other more exotic geomorphic processes might include periglacial (freeze-thaw) processes, salt-mediated action, or extraterrestrial impact.

Fluvial processes

Rivers and streams are not only conduits of water, but also of sediment. The water, as it flows over the channel bed, is able to mobilize sediment and transport it downstream, either as bed load, suspended load or dissolved load. The rate of sediment transport depends on the availability of sediment itself and on the river's discharge.

Rivers are also capable of eroding into rock and creating new sediment, both from their own beds and also by coupling to the surrounding hillslopes. In this way, rivers are thought of as setting the base level for large scale landscape evolution in nonglacial environments. Rivers are key links in the connectivity of different landscape elements.

As rivers flow across the landscape, they generally increase in size, merging with other rivers. The network of rivers thus formed is a drainage system and is often dendritic, but may adopt other patterns depending on the regional topography and underlying geology.

Aeolian processes

Wind-eroded alcove near Moab, Utah

Aeolian processes pertain to the activity of the winds and more specifically, to the winds' ability to shape the surface of the Earth. Winds may erode, transport, and deposit materials, and are effective agents in regions with sparse vegetation and a large supply of unconsolidated sediments. Although water and mass flow tend to mobilize more material than wind in most environments, aeolian processes are important in arid environments such as deserts.

Mesquite Flat Dunes in Death Valley looking toward the Cottonwood Mountains from the north west arm of Star Dune (2003)

Hillslope processes

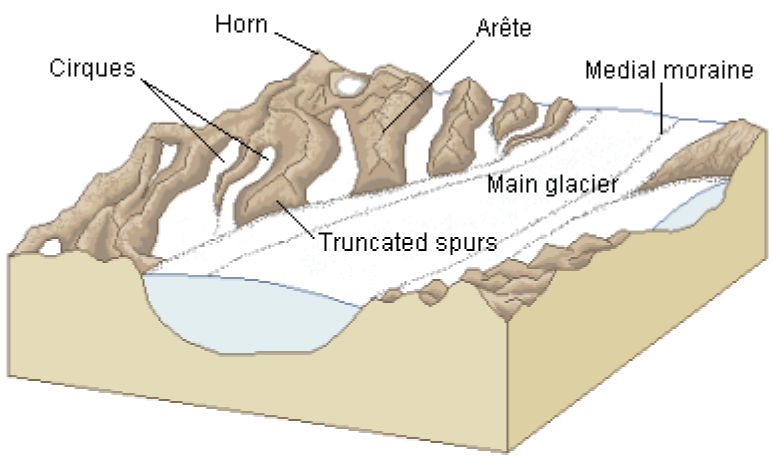
Example of mass wasting at Palo Duro Canyon, Texas

Soil, regolith, and rock move downslope under the force of gravity via creep, slides, flows, topples, and falls. Such mass wasting occurs on both terrestrial and submarine slopes, and has been observed on Earth, Mars, Venus, Titan and Iapetus.

Ongoing hillslope processes can change the topology of the hillslope surface, which in turn can change the rates of those processes. Hillslopes that steepen up to certain critical thresholds are capable of shedding extremely large volumes of material very quickly, making hillslope processes an extremely important element of landscapes in tectonically active areas.

On Earth, biological processes such as burrowing or tree throw may play important roles in setting the rates of some hillslope processes.

Glacial processes



Features of a glacial landscape

Glaciers, while geographically restricted, are effective agents of landscape change. The gradual movement of ice down a valley causes abrasion and plucking of the underlying rock. Abrasion produces fine sediment, termed glacial flour. The debris transported by the glacier, when the glacier recedes, is termed a moraine. Glacial erosion is responsible for U-shaped valleys, as opposed to the V-shaped valleys of fluvial origin.

The way glacial processes interact with other landscape elements, particularly hillslope and fluvial processes, is an important aspect of Plio-Pleistocene landscape evolution and its sedimentary record in many high mountain environments. Environments that have been relatively recently glaciated but are no longer may still show elevated landscape change rates compared to those that have never been glaciated. Nonglacial geomorphic processes which nevertheless have been conditioned by past glaciation are termed paraglacial processes. This concept contrasts with periglacial processes, which are directly driven by formation or melting of ice or frost.

Tectonic processes

Tectonic effects on geomorphology can range from scales of millions of years to minutes or less. The effects of tectonics on landscape are heavily dependent on the nature of the underlying bedrock fabric that more less controls what kind of local morphology tectonics can shape. Earthquakes can, in terms of minutes, submerge large extensions creating new wetlands. Isostatic rebound can account for significant changes over thousand or hundreds of years, and allows erosion of a mountain belt to promote further erosion as mass is removed from the chain and the belt uplifts. Long-term plate tectonic dynamics give rise to orogenic belts, large mountain chains with typical lifetimes of many tens of millions of years, which form focal points for high rates of fluvial and hillslope processes and thus long-term sediment production.

Features of deeper mantle dynamics such as plumes and delamination of the lower lithosphere have also been hypothesised to play important roles in the long term (> million year), large scale (thousands of km) evolution of the Earth's topography. Both can promote surface uplift through isostasy as hotter, less dense, mantle rocks displace cooler, denser, mantle rocks at depth in the Earth.

Igneous processes

Both volcanic (eruptive) and plutonic (intrusive) igneous processes can have important impacts on geomorphology. The action of volcanoes tends to rejuvenize landscapes, covering the old land surface with lava and tephra, releasing pyroclastic material and forcing rivers through new paths. The cones built by eruptions also build substantial new topography, which can be acted upon by other surface processes.

Subsurface movement of magma also plays a role in geomorphology. Migrating melts beneath the surface can cause the inflation and deflation of the land surface, and a partially molten crustal layer beneath Tibet has even been implicated in controlling the geomorphology of the Tibetan plateau across many thousands of kilometres.

Biological processes

The interaction of living organisms with landforms, or biogeomorphologic processes, can be of many different forms, and is probably of profound importance for the terrestrial geomorphic system as a whole. Biology can influence very many geomorphic processes, ranging from biogeochemical processes controlling chemical weathering, to the influence of mechanical processes like burrowing and tree throw on soil development, to even controlling global erosion rates through modulation of climate through carbon dioxide balance. Terrestrial landscapes in which the role of biology in mediating surface processes can be definitively excluded, are extremely rare, but may hold important information for understanding the geomorphology of other planets, such as Mars.

Scales in geomorphology

Different geomorphological processes dominate at different spatial and temporal scales. Moreover, scales on which processes occur may determine the reactivity or otherwise of landscapes to changes in driving forces such as climate or tectonics. These ideas are key to the study of geomorphology today.

Chapter- 2

Geophysics

Geophysics is the physics of the Earth and its environment in space. Its subjects include the shape of the Earth, its gravitational and magnetic fields, the dynamics of the Earth as a whole and of its component parts, the Earth's internal structure, composition and tectonics, the generation of magmas, volcanism and rock formation, the hydrological cycle including snow and ice, all aspects of the oceans, the atmosphere, ionosphere, magnetosphere and solar-terrestrial relations, and analogous problems associated with the Moon and other planets.

Geophysics is also applied to societal needs, such as mineral resources, mitigation of natural hazards and environmental protection. Geophysical survey data are used to analyze potential petroleum reservoirs and mineral deposits, to locate groundwater, to locate archaeological finds, to find the thicknesses of glaciers and soils, and for environmental remediation.

History

Ancient and classical eras

The magnetic compass existed in China back as far as the fourth century BC. It was used as much for feng shui as for navigation on land. It was not until good steel needles could be forged that compasses were used for navigation at sea; before that, they could not retain their magnetism for long. The first mention of a compass in Europe was in 1190.

In circa 240 BC, Erastothenes of Cyrene deduced that the Earth was round and measured the circumference of the Earth, using trigonometry and the angle of the Sun at more than one latitude in Egypt. He developed a system of latitude and longitude and measured the tilt of the Earth's axis.

Perhaps the earliest contribution to seismology was the invention of a seismoscope by the prolific inventor Zhang Heng in 132 CE. This instrument was designed to drop a bronze ball from the mouth of a dragon into the mouth of a toad. By looking at which of eight toads had the ball, one could determine the direction of the earthquake. It was 1571 years before the first design for a seismoscope was published in Europe, by Jean de la Hautefeuille. It was never built.

Replica of Zhang Heng's seismoscope

Beginnings of modern science

One of the publications that marked the beginning of modern science was William Gilbert's *De Magnete* (1600), a report of a series of meticulous experiments in magnetism. Gilbert deduced that compasses point north because the Earth itself is magnetic.

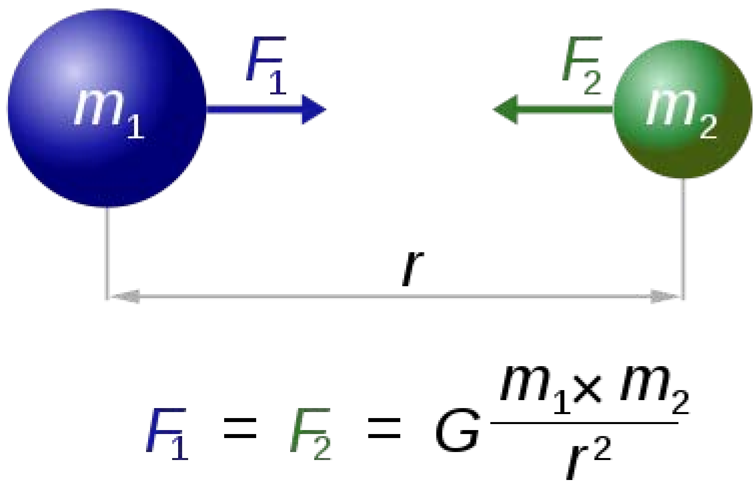
In 1687 Isaac Newton published his *Principia*, which not only laid the foundations for classical mechanics and gravitation but also explained a variety of geophysical phenomena such as the tides and the precession of the equinox.

The first seismometer, an instrument capable of keeping a continuous record of seismic activity, was built by James Forbes in 1844.

Physical phenomena

Geophysics is a highly interdisciplinary subject and geophysicists contribute to every area of the Earth sciences. To provide a clearer idea of what constitutes geophysics, this section describes phenomena that are studied in physics and how they relate to the Earth and its surroundings.

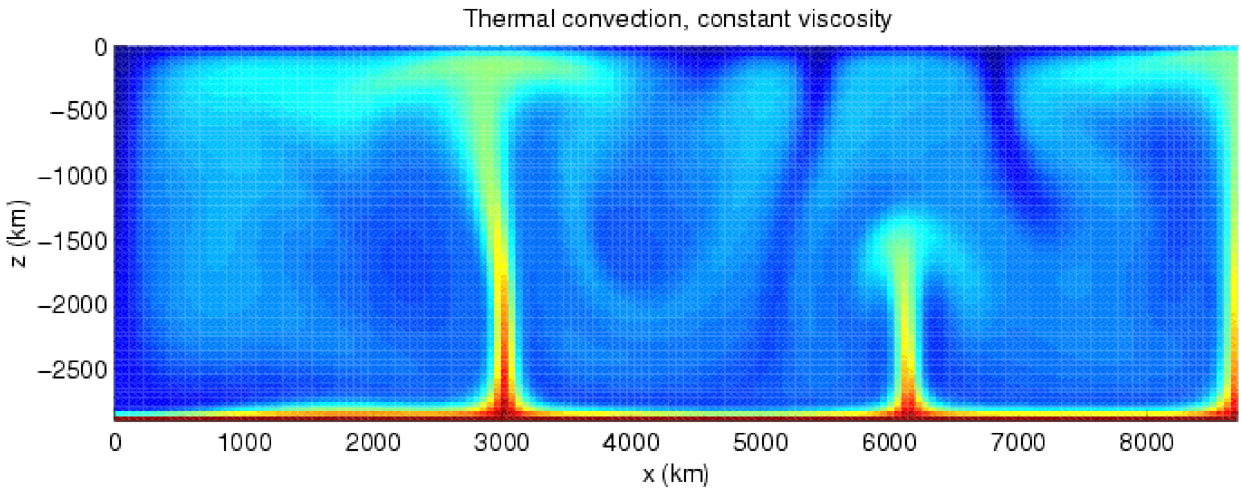
Gravity



The mechanism of Newton's law of universal gravitation

The gravitational attraction of the Moon and Sun give rise to two high tides and two low tides a day. Gravitational forces cause rocks to press down on deeper rocks, making them increase in density as the depth increases. Measurements of gravitational acceleration and gravitational potential at the Earth's surface and above it can provide information on mineral deposits and the dynamics of plates. A particular geopotential surface called the geoid is one definition of the shape of the Earth: it would be the global mean sea level if the oceans were in equilibrium and could be extended through the continents (such as with very narrow canals).

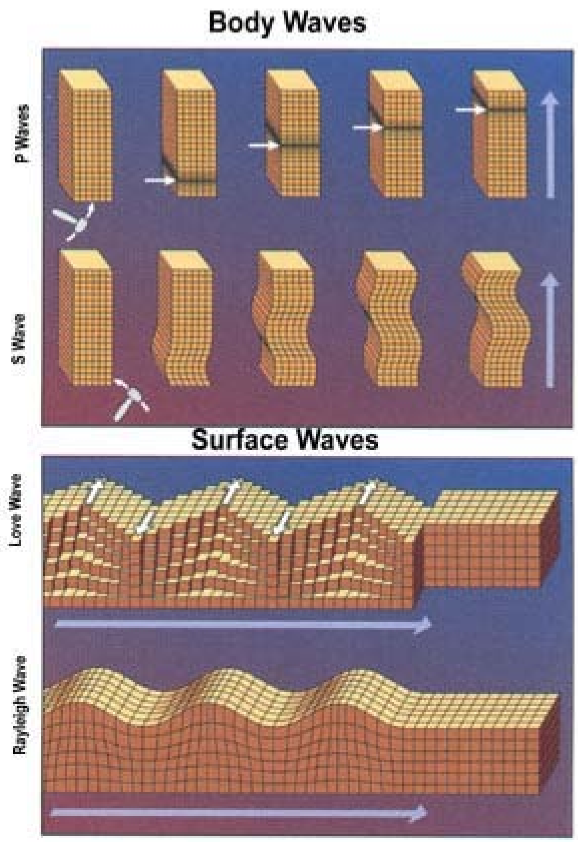
Heat flow



A model of thermal convection in the Earth's mantle

The Earth is cooling, and the resulting heat flow generates the Earth's magnetic field through the geodynamo and plate tectonics through mantle convection. The main sources of heat are the primordial heat and radioactivity, although there are also contributions from phase transitions. Heat is mostly carried to the surface by thermal convection, although there are two thermal boundary layers - the core-mantle boundary and the lithosphere - in which heat is transported by conduction. Some heat is carried up from the bottom of the mantle by mantle plumes. The heat flow at the Earth's surface is about 4.2×10^{13} watts, and it is a potential source of geothermal energy.

Vibrations

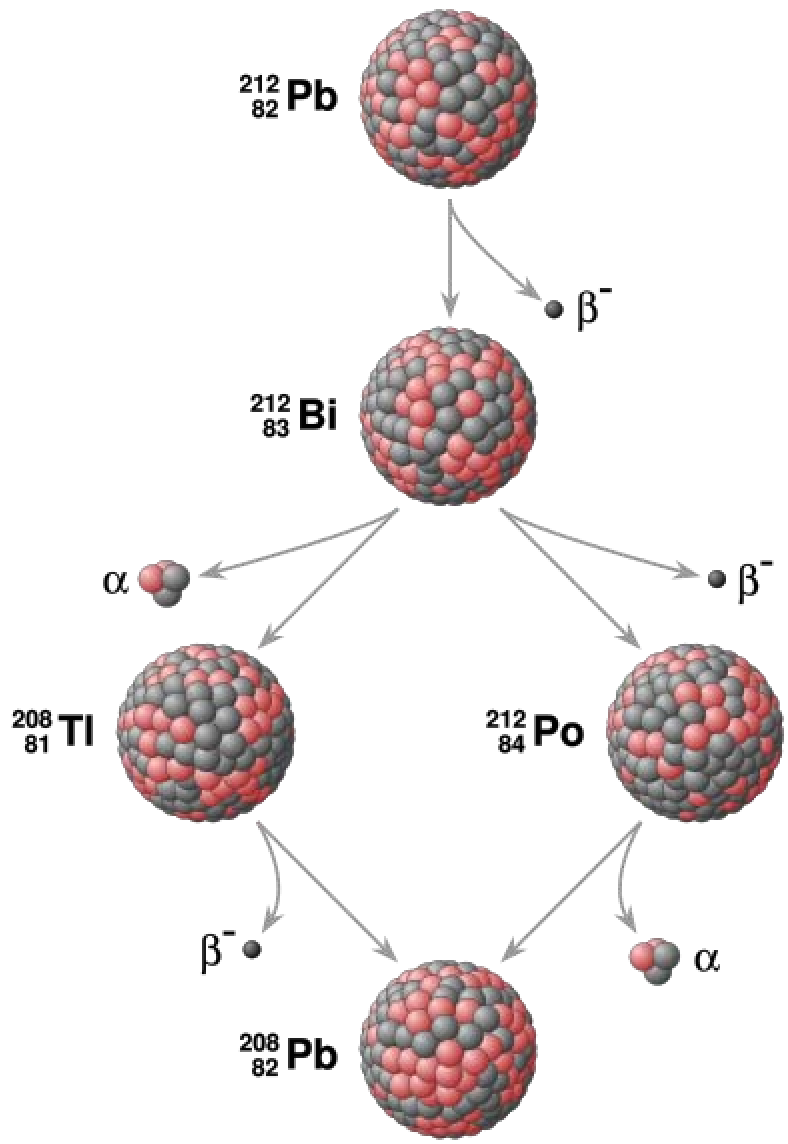


Body waves and surface waves

Vibrations of the Earth can take the form of seismic waves, which travel through the Earth's interior or along its surface, and normal modes or free oscillations. Seismic waves that are caused by localized sources such as earthquakes or explosions can be received at a distance by seismographs and the observed motion can provide information on the source as well as the Earth in between. Seismic reflections can provide information on near-surface structure while seismic refraction can be used to infer the deep structure of the Earth. The locations of earthquakes provide information on plate tectonics and mantle convection.

Earthquakes pose a risk to humans. Understanding their mechanisms (which depend on the type of earthquake, e.g., intraplate or deep focus can lead to better assessments of earthquake risk and improvements in earthquake engineering.

Radioactivity



Example of a radioactive decay chain

Radioactive decay, in addition to being the main source of heat in the Earth, is an invaluable tool for geochronology. Unstable isotopes decay at predictable rates, and the decay rates of different isotopes cover several orders of magnitude, so radioactive decay can be used to accurately date both recent events and events in past geologic eras.

Electricity

Although we mainly notice electricity during thunderstorms, there is always a downward electric field near the surface that averages 120V m^{-1}. Relative to the solid Earth, the atmosphere has a net positive charge due to bombardment by cosmic rays. A current of about 1800A flows in the global circuit. It flows downward from the ionosphere over most of the Earth and back upwards through thunderstorms. The flow is manifested by lightning below the clouds and sprites above.

A variety of electric methods are used in geophysical survey. Some measure spontaneous potential a potential that arises in the ground because of man-made or natural disturbances. Telluric currents flow in Earth and the Oceans. They have two causes: electromagnetic induction by the time-varying, external-origin geomagnetic field and motion of conducting bodies (such as seawater) across the Earth's permanent magnetic field. The distribution of telluric current density can be used to detect variations in electrical resistivity of underground structures. Geophysicists can also provide the electric current themselves.

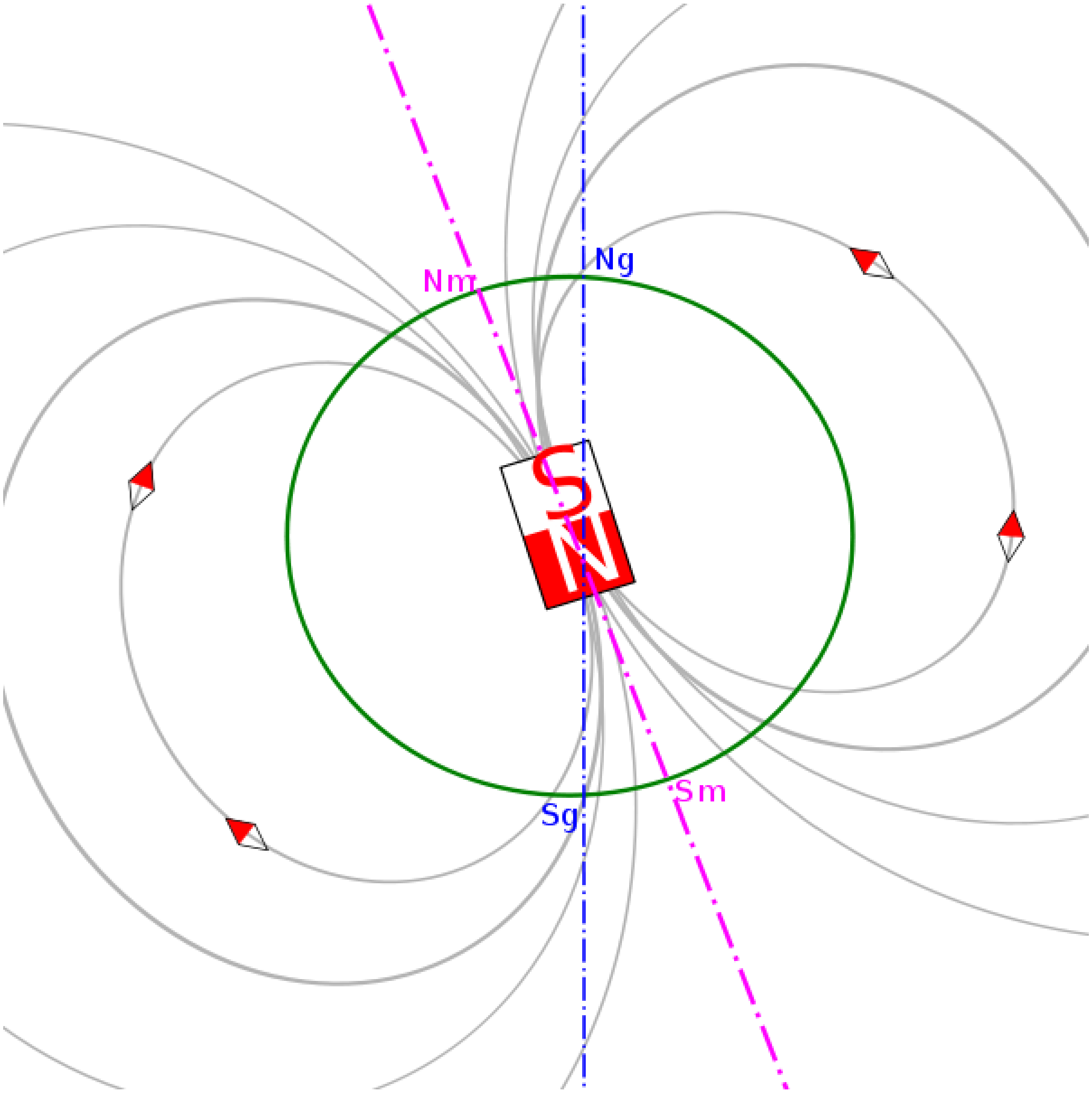
Electromagnetic waves

Electromagnetic waves occur in the ionosphere and magnetosphere as well as the Earth's outer core. they have a variety of others. dawn chorus is caused by high-energy electrons that get caught in the Van Allen radiation belt. Whistlers are produced by lightning strikes. Hiss may be generated by both. Electromagnetic waves may also be generated by earthquakes.

In the Earth's outer core, electric currents in the highly conductive liquid iron create magnetic fields by magnetic induction. Alfvén waves are magnetohydrodynamic waves in the magnetosphere or the Earth's core. In the core, they probably have little observable effect on the geomagnetic field, but slower waves such as magnetic Rossby waves may be one source of secular variation.

Electromagnetic methods that are used for geophysical survey include transient electromagnetics and magnetotellurics.

Magnetism



The variation between magnetic north and "true" north

The Earth's magnetic field protects the Earth from the deadly Solar wind and has long been used for navigation. It originates in the fluid motions of the Earth's core. The magnetic field in the upper atmosphere gives rise to the auroras.

The Earth's field is roughly like a tilted dipole, but it changes over time (a phenomenon called secular variation). Mostly the geomagnetic pole stays near the geographic pole, but at random intervals averaging a million years or so, the polarity of the Earth's field reverses. These geomagnetic reversals are recorded in rocks and their signature can be seen in striped magnetic anomalies on the seafloor. These stripes provide quantitative information on seafloor spreading, a part of plate tectonics. In addition, the magnetization in rocks can be used to measure the motion of continents.

Fluid dynamics

Fluid motions occur in the magnetosphere, atmosphere, ocean, mantle and core. Even the mantle, though it has an enormous viscosity, flows like a fluid over long time intervals. This flow is reflected in phenomena such as isostasy and post-glacial rebound. The mantle flow drives plate tectonics and the flow in the Earth's core drives the geodynamo.

Geophysical fluid dynamics is a primary tool in physical oceanography and meteorology. The rotation of the Earth has profound effects on the Earth's fluid dynamics, often due to the Coriolis effect. In the atmosphere it gives rise to large-scale patterns like Rossby waves and determines the basic circulation patterns of storms. In the ocean they drive large-scale circulation patterns as well as Kelvin waves and Ekman spirals at the ocean surface. In the Earth's core, the circulation of the molten iron is structured by Taylor columns.

Waves and other phenomena in the magnetosphere can be modeled using magnetohydrodynamics.

Condensed matter physics

The physical properties of minerals must be understood to infer the composition of the Earths' interior from seismology, the geothermal gradient and other sources of information. Mineral physicists study the elastic properties of minerals as well as their high-pressure phase diagrams, melting points and equations of state at high pressure. Studies of creep determine how rocks that are brittle at the surface can flow deep down. These properties determine the rheology that determines the geodynamics.

Water is a very complex substance and its unique properties are essential for life. Its physical properties shape the hydrosphere and are an essential part of the water cycle and climate. Its thermodynamic properties determine evaporation and the thermal gradient in the atmosphere. The many types of precipitation involve a complex mixture of processes such as coalescence, supercooling and supersaturation. Some of the precipitated water becomes groundwater, and groundwater flow includes phenomena such as percolation, while the conductivity of water makes electrical and electromagnetic methods useful for tracking groundwater flow. Physical properties of water such as salinity have a large effect on its motion in the oceans.

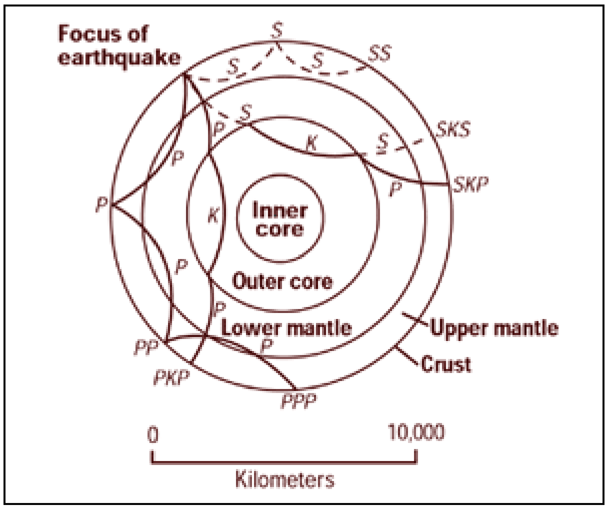
The many phases of ice form the cryosphere and come in forms like ice sheets, glaciers, sea ice, freshwater ice, snow, and frozen ground (or permafrost).

Regions of the Earth

Size and form of the Earth

The Earth is roughly spherical, but it bulges towards the Equator, so it is roughly in the shape of an ellipsoid. This bulge is due to its rotation and is nearly consistent with an Earth in hydrostatic equilibrium. The detailed shape of the Earth, however, is also affected by the distribution of continents and ocean basins, and to some extent by the dynamics of the plates.

Structure of the Earth



Mapping the interior of the Earth with earthquake waves

Evidence from seismology, heat flow at the surface, and mineral physics is combined with the Earth's mass and moment of inertia to infer models of the Earth's interior - its composition, density, temperature, pressure. The Earth's mass is $M = 5.975 \times 10^{24}\,\mathrm{kg}$ and its mean radius is $R = 6371\,\mathrm{km}$, so its mean specific gravity is $\overline{\rho} = 5.515$. This is substantially higher than the typical specific gravity (2.7 − 3.3) of rocks at the surface. Its moment of inertia is $0.33MR^2$, whereas it would be $0.4MR^2$ if the earth was a sphere of constant density. Both lines of evidence point to a concentration of mass near the center. However, the density of the rock will increase with depth because of the increasing pressure. To determine how large this effect is, the Adams–Williamson equation is used to determine how density increases with pressure. The conclusion is that pressure alone cannot account for the increase in density. Instead, we know that the Earth's core is composed of an alloy of iron and other minerals.

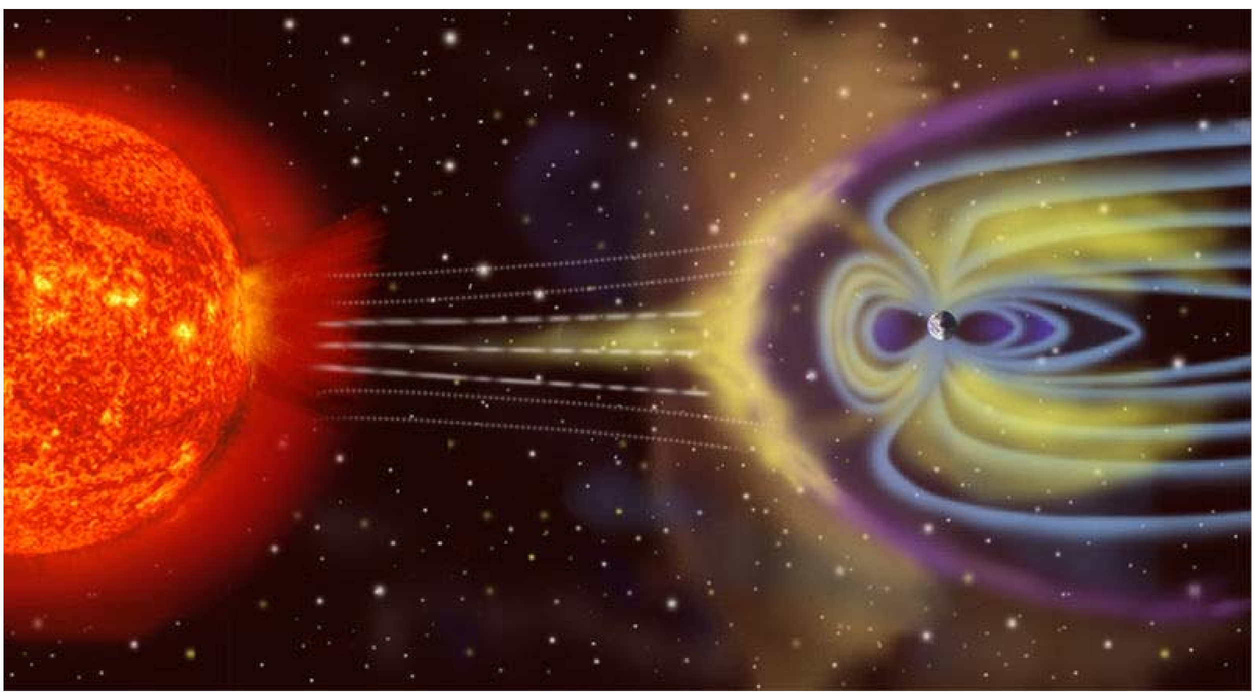
Reconstructions of seismic waves in the deep interior of the Earth show that there are no S-waves in the outer core. This indicates that the outer core is liquid, because liquids cannot support shear. The outer core is liquid, and the motion of this highly conductive fluid generates the Earth's field. The inner core, however, is solid because of the enormous pressure.

Reconstruction of seismic reflections in the deep interior indicate some major discontinuities in seismic velocities that demarcate the major zones of the Earth: inner core, outer core, mantle, lithosphere and crust. The mantle itself is divided into the upper mantle, transition zone, lower mantle and D'' layer. Between the crust and the mantle is the Mohorovičić discontinuity.

The seismic model of the Earth does not by itself determine the composition of the layers. For a complete model of the Earth, mineral physics is needed to interpret seismic velocities in terms of composition. The mineral properties are temperature-dependent, so the geotherm must also be determined. This requires physical theory for thermal conduction and convection and the heat contribution of radioactive elements. The main model for the radial structure of the interior of the Earth is the Preliminary Reference Earth Model (PREM). Some parts of this model have been updated by recent findings in mineral physics and supplemented by seismic tomography. The mantle is mainly composed of silicates, and the boundaries between layers of the mantle are probably due to phase transitions.

The mantle acts as a solid for seismic waves, but under high pressures and temperatures it deforms so that over millions of years it acts like a liquid. This makes plate tectonics possible. Geodynamics is the study of the fluid flow in the mantle and core.

The magnetosphere



The solar wind is deflected by the magnetosphere (not to scale)

If a planet's magnetic field is sufficiently strong, its interaction with the solar wind forms a magnetosphere around a planet. Early space probes discovered the gross dimensions of the terrestrial magnetic field, which extends about 10 Earth radiii towards the Sun. The solar wind, a stream of charged particles, streams out and around the terrestrial magnetic field, and continues behind the magnetic tail, hundreds of Earth radii downstream. Inside the magnetosphere, there are relatively dense regions of solar wind particles, the Van Allen radiation belts.

Other fields and related disciplines

Fields

- Geodesy, measurement of the Earth: GPS, vertical and horizontal motions of the Earth's surface, navigation, the study of the Earth's gravitational field, and the size and form of the Earth
- The study of large-scale motions of the Earth's surface and interior, including:
    - Tectonophysics, the study of the physical processes that cause and result from plate tectonics
    - Geodynamics, the study of modes of transport deformation within the Earth: rock deformation, mantle flow and convection, heat flow, lithosphere dynamics
    - Shallow seismology is used in exploration geophysics (to find oil and gas) and for environmental characterization of the subsurface
- Geomagnetism, the study of the Earth's magnetic field, including its origin, telluric currents driven by the magnetic field, the Van Allen belts, and the interaction between the magnetosphere and the solar wind. This field is associated with paleomagnetism, or the measurement of the orientation of the Earth's magnetic field over the geologic past.
- Mathematical geophysics, The development and applications of mathematical methods and techniques for the solution of geophysical problems.
- Geophysical surveying:
    - Exploration and engineering geophysics, using surface methods to detect or infer the presence and position of concentrations of ore minerals and hydrocarbons
    - Archaeological geophysics, for archaeological imaging or mapping
    - Environmental and Engineering Geophysics, for locating underground storage tanks (USTs) or utilities, Unexploded ordnance (UXO), delineating landfills, locating voids or potential subsidence, finding depth to, P-wave or S-wave velocity of, or rippability of bedrock, or the pathway of groundwater movement

Related disciplines

- Volcanology, the study of volcanoes, volcanic features (hot springs, geysers, fumaroles), volcanic rock, and heat flow related to volcanoes
- Atmospheric sciences, which includes:
    - Atmospheric electricity and the ionosphere
    - Aeronomy, the study of the physical structure and chemistry of the atmosphere.
    - Meteorology and Climatology, which both involve studies of the weather.

- The study of water on the Earth, hydrology, physical oceanography and glaciology
- Geological and geophysical engineering and Engineering geology, applying geophysics to the engineering design of facilities including roads, tunnels, and mines
- The study of the rocks and minerals, including petrophysics and aspects of mineralogy such as physical mineralogy and crystal structure

Methods of geophysics

Space probes

Space probes made it possible to collect data not only the visible light region, but in other areas of the electromagnetic spectrum. The planets can be characterized by their force fields: gravity and their magnetic fields, which are studied through geophysics and space physics.

Measuring the changes in acceleration experienced by spacecraft as they orbit has allowed fine details of the gravity fields of the planets to be mapped. For example, in the 1970s, the gravity field disturbances above lunar maria were measured through lunar orbiters, which lead to the discovery of concentrations of mass, mascons, beneath the Imbrium, Serenitatis, Crisium, Nectaris and Humorum basins.

In 2002, NASA launched the Gravity Recovery and Climate Experiment, wherein two twin satellites map variations in Earth's gravity field by making measurements of the distance between the two satellites using GPS and a microwave ranging system. Gravity variations detected by GRACE include those caused by changes in ocean currents; runoff and ground water depletion; melting ice sheets and glaciers.

Chapter- 3

Mineralogy

Mineralogy is the study of chemistry, crystal structure, and physical (including optical) properties of minerals. Specific studies within mineralogy include the processes of mineral origin and formation, classification of minerals, their geographical distribution, as well as their utilization.

History

Early writing on mineralogy, especially on gemstones, comes from ancient Babylonia, the ancient Greco-Roman world, ancient and medieval China, and Sanskrit texts from ancient India and the ancient Islamic World. Books on the subject included the Naturalis Historia of Pliny the Elder, which not only described many different minerals but also explained many of their properties, and Kitab al Jawahir (Book of Precious Stones) by Muslim scientist Al Biruni. The German Renaissance specialist Georgius Agricola wrote works such as *De re metallica* (*On Metals*, 1556) and *De Natura Fossilium* (*On the Nature of Rocks*, 1546) which begin the scientific approach to the subject. Systematic scientific studies of minerals and rocks developed in post-Renaissance Europe. The modern study of mineralogy was founded on the principles of crystallography (the origins of geometric crystallography, itself, can be traced back to the mineralogy practiced in the eighteenth and nineteenth centuries) and to the microscopic study of rock sections with the invention of the microscope in the 17th century.

Modern mineralogy

Chalcocite, a copper ore mineral

Historically, mineralogy was heavily concerned with taxonomy of the rock-forming minerals; to this end, the International Mineralogical Association is an organization whose members represent mineralogists in individual countries. Its activities include managing the naming of minerals (via the Commission of New Minerals and Mineral Names), location of known minerals, etc. As of 2004 there are over 4,000 species of mineral recognized by the IMA. Of these, perhaps 150 can be called "common," another 50 are "occasional," and the rest are "rare" to "extremely rare."

More recently, driven by advances in experimental technique (such as neutron diffraction) and available computational power, the latter of which has enabled extremely accurate atomic-scale simulations of the behaviour of crystals, the science has branched out to consider more general problems in the fields of inorganic chemistry and solid-state physics. It, however, retains a focus on the crystal structures commonly encountered in rock-forming minerals (such as the perovskites, clay minerals and framework silicates). In particular, the field has made great advances in the understanding of the relationship between the atomic-scale structure of minerals and their function; in nature, prominent examples would be accurate measurement and prediction of the elastic properties of minerals, which has led to new insight into seismological behaviour of rocks and depth-related discontinuities in seismograms of the Earth's mantle. To this end, in their focus on the connection between atomic-scale phenomena and macroscopic properties, the **mineral sciences** (as they are now commonly known) display perhaps more of an overlap with materials science than any other discipline.

Physical mineralogy

Physical mineralogy is the specific focus on physical attributes of minerals. Description of physical attributes is the simplest way to identify, classify, and categorize minerals, and they include:

- crystal structure
- crystal habit
- twinning
- cleavage
- luster
- color
- streak
- hardness
- specific gravity

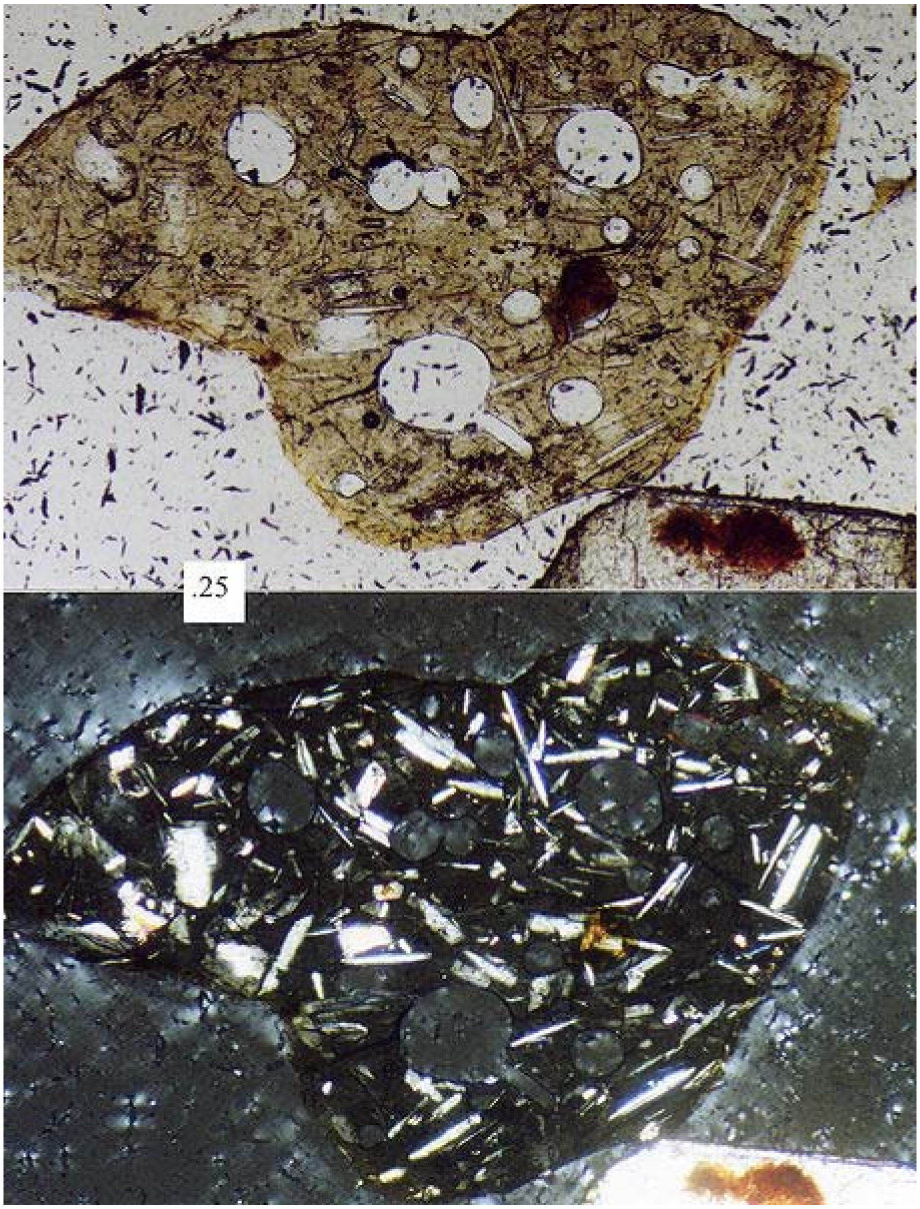
Chemical mineralogy

Chemical mineralogy focuses on the chemical composition of minerals in order to identify, classify, and categorize them, as well as a means to find beneficial uses from them. There are a few minerals which are classified as whole elements, including sulfur, copper, silver, and gold, yet the vast majority of minerals are chemical compounds, some more complex than others. In terms of major chemical divisions of minerals, most are placed within the isomorphous groups, which are based on analogous chemical composition and similar crystal forms. A good example of isomorphism classification would be the calcite group, containing the minerals calcite, magnesite, siderite, rhodochrosite, and smithsonite.

Biomineralogy

Biomineralogy is a cross-over field between mineralogy, paleontology and biology. It is the study of how plants and animals stabilize minerals under biological control, and the sequencing of mineral replacement of those minerals after deposition. It uses techniques from chemical mineralogy, especially isotopic studies, to determine such things as growth forms in living plants and animals as well as things like the original mineral content of fossils.

Optical mineralogy



Photomicrograph of a volcanic lithic fragment (sand grain); upper picture is plane-polarized light, bottom picture is cross-polarized light, scale box at left-center is 0.25 millimeter.

Optical mineralogy is a specific focus of mineralogy that applies sources of light as a means to identify and classify minerals. All minerals which are not part of the cubic system are double refracting, where ordinary light passing through them is broken up into two plane polarized rays that travel at different velocities and refracted at different angles. Mineral substances belonging to the cubic system pertain only one index of refraction. Hexagonal and tetragonal mineral substances have two indices, while orthorhombic, monoclinic, and triclinic substances have three indices of refraction. With opaque ore minerals, reflected light from a microscope is needed for identification.

Crystal structure

X-rays are used to determine the atomic arrangements of minerals and so to identify and classify them. The arrangements of atoms define the crystal structures of the minerals. Some very fine-grained minerals, such as clays, commonly can be identified most readily by their crystal structures. The structure of a mineral also offers a precise way of establishing isomorphism. With knowledge of atomic arrangements and compositions, one may deduce why minerals have specific physical properties and one may calculate how those properties change with pressure and temperature.

Formation environments

The environments of mineral formation and growth are highly varied, ranging from slow crystallization at the high temperature and pressures of igneous melts deep within the Earth's crust to the low temperature precipitation from a saline brine at the Earth's surface.

Various possible methods of formation include:

- sublimation from volcanic gases
- deposition from aqueous solutions and hydrothermal brines
- crystallization from an igneous magma or lava
- recrystallization due to metamorphic processes and metasomatism
- crystallization during diagenesis of sediments
- formation by oxidation and weathering of rocks exposed to the atmosphere or within the soil environment.

Descriptive mineralogy

Descriptive mineralogy summarizes results of studies performed on mineral substances. It is the scholarly and scientific method of recording the identification, classification, and categorization of minerals, their properties, and their uses. Classifications for descriptive mineralogy includes:

- native elements
- sulfides
- oxides and hydroxides
- halides
- carbonates, nitrates and borates
- sulfates, chromates, molybdates and tungstates
- phosphates, arsenates and vanadates
- silicates
- organic minerals

Determinative mineralogy

Determinative mineralogy is the actual scientific process of identifying minerals, through data gathering and conclusion. When new minerals are discovered, a standard procedure of scientific analysis is followed, including measures to identify a mineral's formula, its crystallographic data, its optical data, as well as the general physical attributes determined and listed.

Uses

Minerals are essential to various needs within human society, such as minerals used as ores for essential components of metal products used in various commodities and machinery, essential components to building materials such as limestone, marble, granite, gravel, glass, plaster, cement, etc. Minerals are also used in fertilizers to enrich the growth of agricultural crops.

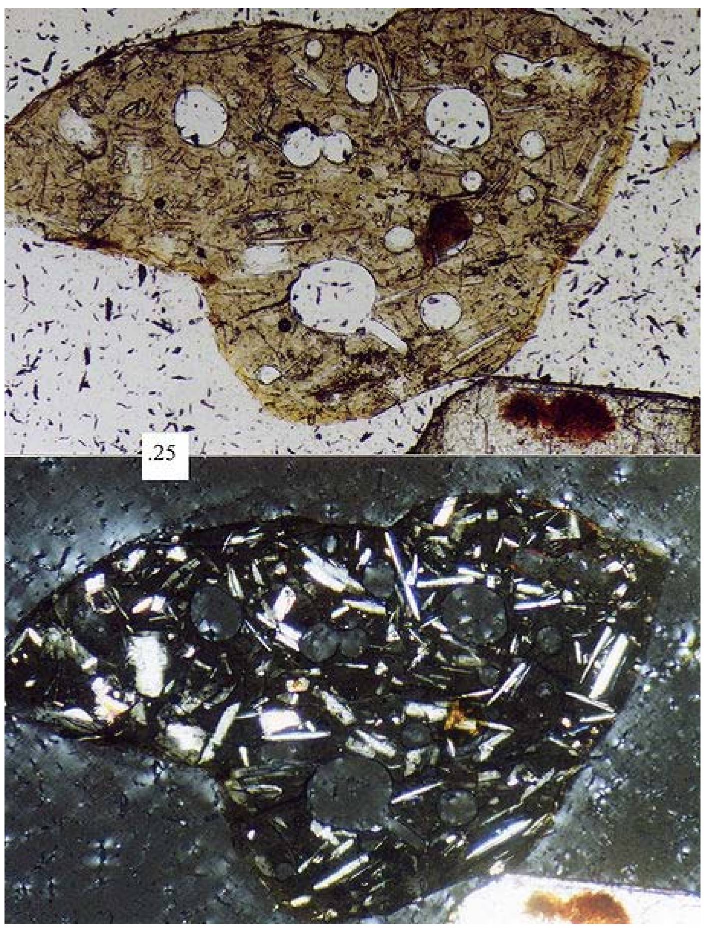
Collecting

Mineral collecting is also a recreational study and collection hobby, with clubs and societies representing the field. Museums, such as the Smithsonian National Museum of Natural History Hall of Geology, Gems, and Minerals and the Natural History Museum of Los Angeles County, have popular collections of mineral specimens on permanent display.

Chapter- 4

Petrology and Hydrogeology

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.

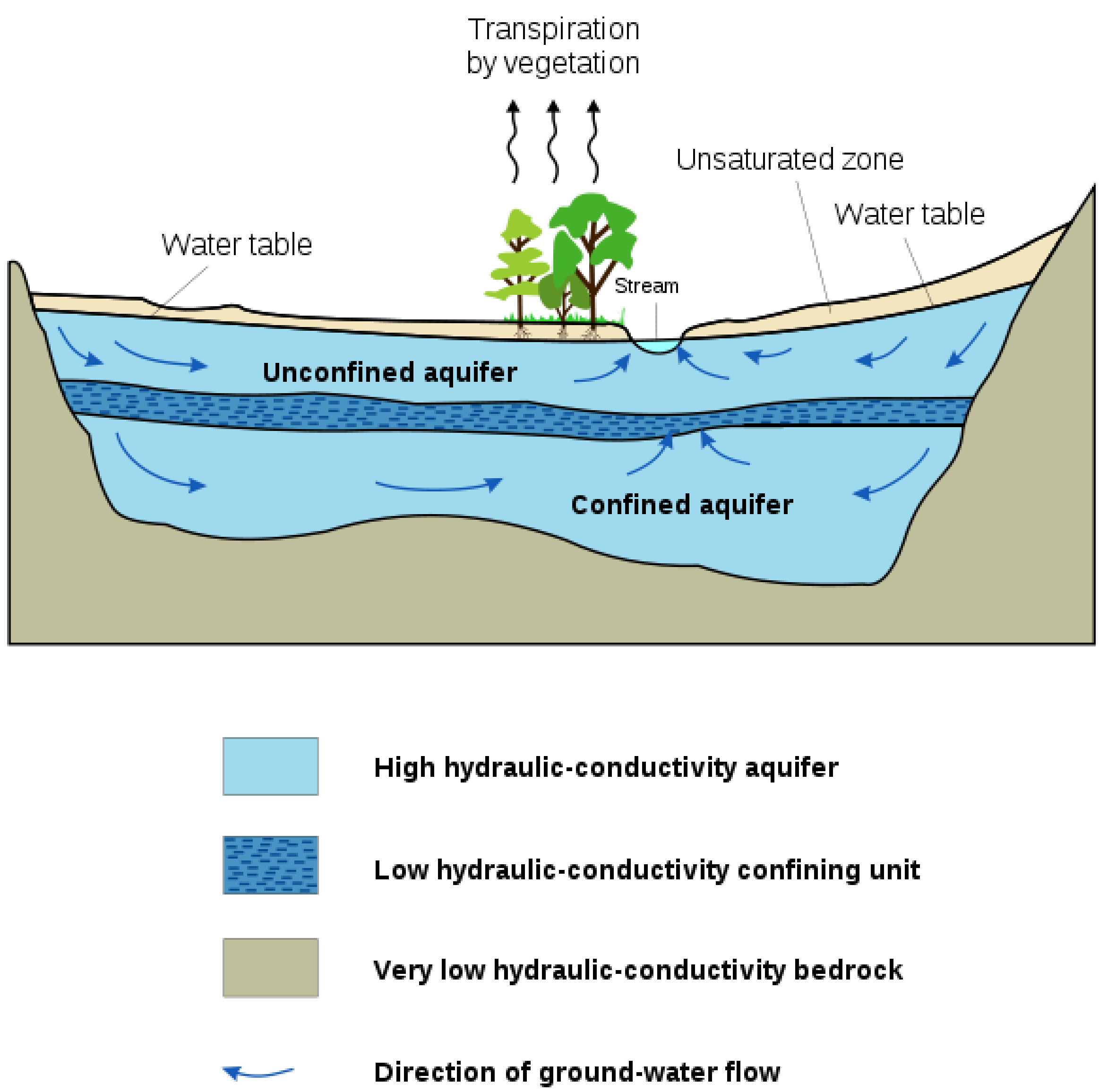
Branches

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.

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 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

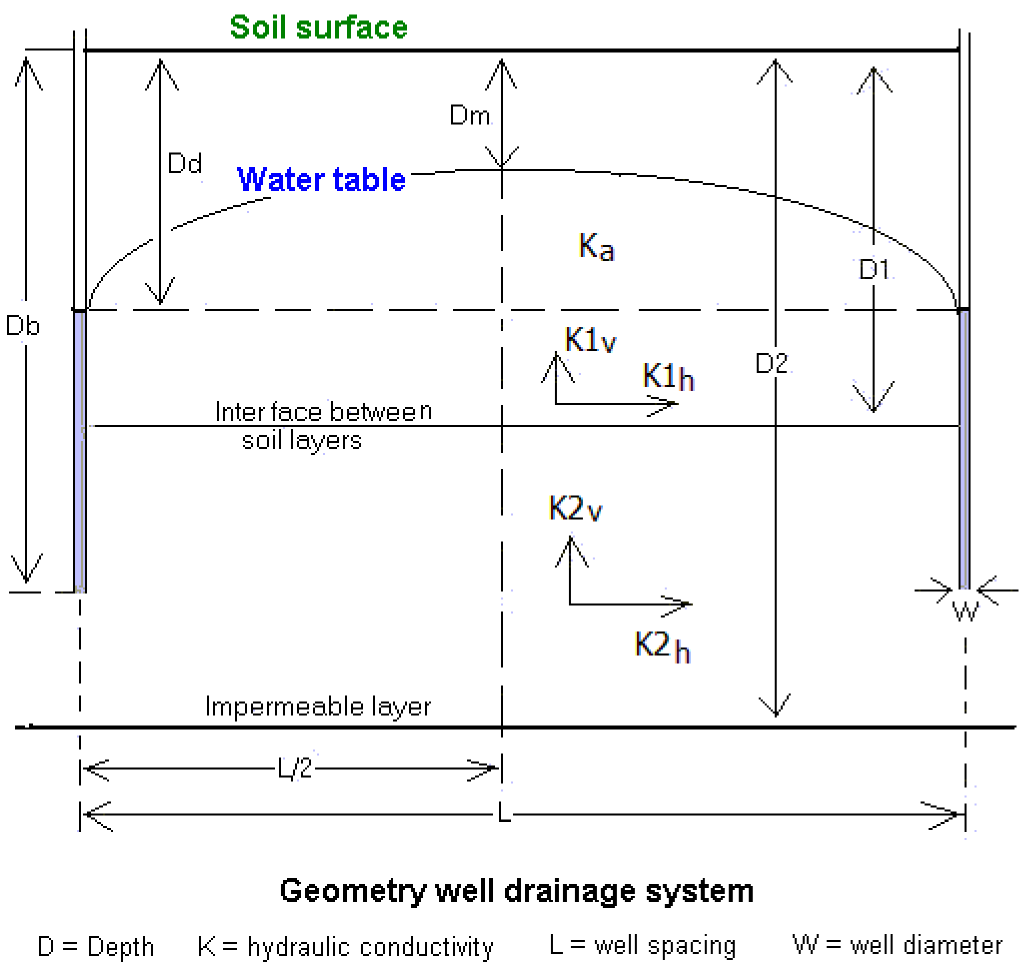
The retardation factor is another very important feature that make the motion of the contaminant to deviate from the average groundwater motion. It is analogous to the retardation factor of chromatography. Unlike diffusion and dispersion, which simply spread the contaminant, the retardation factor changes 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.

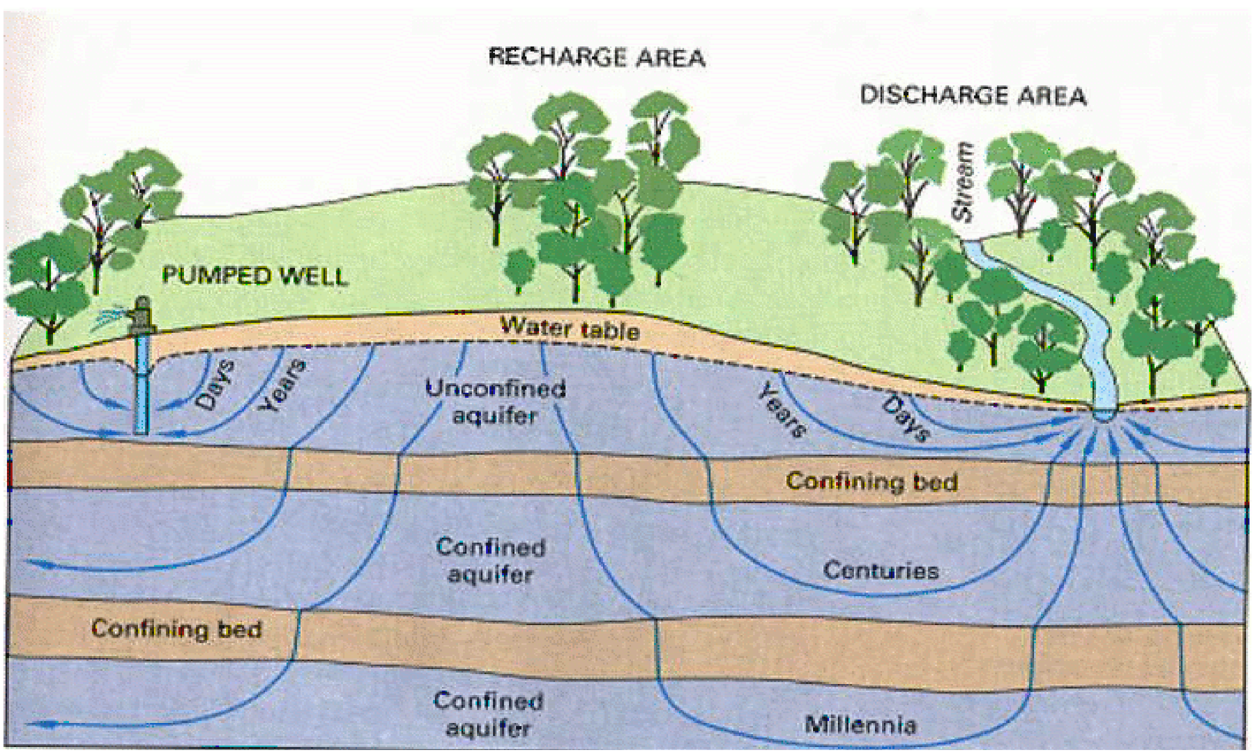
The Theis equation is one of the most commonly used and fundamental solutions to the groundwater flow equation; it can be used to predict the transient evolution of head due to the effects of pumping one or a number of pumping wells.

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.

Chapter- 5

Volcanology

Volcanology (also spelled **vulcanology**) is the study of volcanoes, lava, magma, and related geological, geophysical and geochemical phenomena. The term *volcanology* is derived from the Latin word *vulcan*. Vulcan was the ancient Roman god of fire.

A volcanologist sampling lava using a rock hammer and a bucket of water

A **volcanologist** is a person who studies the formation of volcanoes, and their current and historic eruptions. Volcanologists frequently visit volcanoes, especially active ones, to observe volcanic eruptions, collect eruptive products including tephra (such as ash or pumice), rock and lava samples. One major focus of enquiry is the prediction of eruptions; there is currently no accurate way to do this, but predicting eruptions, like predicting earthquakes, could save many lives.

History of volcanology

Volcanology has an extensive history. The earliest known recording of a volcanic eruption may be on a wall painting dated to about 7000 B.C.E. found at the Neolithic site at Çatal Höyük (now known as Çatalhöyük), in Anatolia, Turkey. This painting has been interpreted as a depiction of an erupting volcano, with a cluster of houses below shows a twin peaked volcano in eruption, with a town at its base (though archaeologists now question this interpretation). The volcano may be either Hasan Dağ, or its smaller neighbour, Melendiz Dağ.

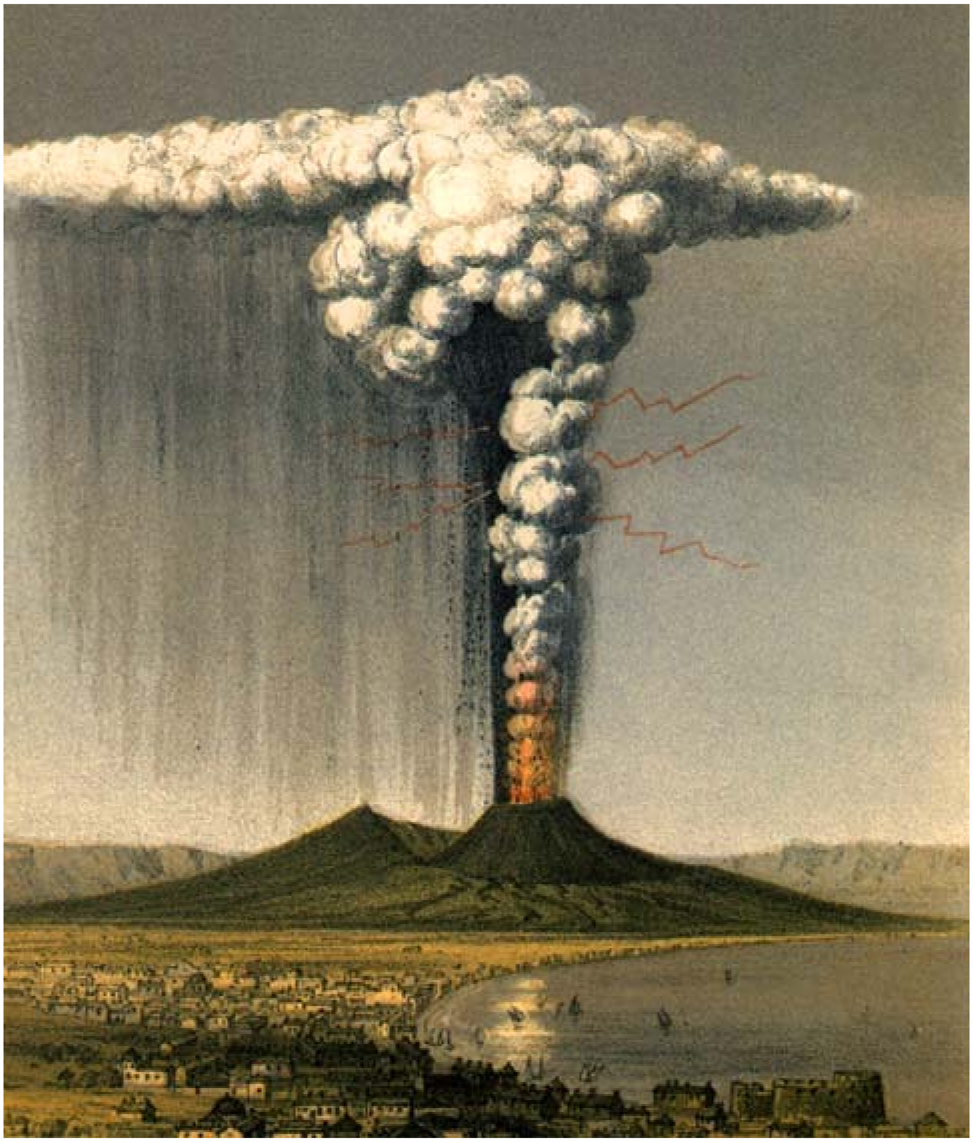
Mythical explanations

The classical world of Greece and the early Roman Empire explained volcanoes as the work of the gods as science and alchemy had no explanation for their existence. Grecian myths and tales tell of Atlantis, a fabled island that sank into the sea. Plato (428-348 B.C.) told of the disappearance of a vast island and its powerful civilization, the Atlanteans, in two of his dialogues, *Critias* and *Timaeus*. It is now considered that the island of Thera, now Santorini, in the Aegean Sea, was destroyed by a tremendous series of volcanic explosions around 1620 B.C., with ash falls of up to a foot deep recorded in Turkey. The explosion of Thera sent colossal tsunamis, estimated at 100 feet height, racing across the Aegean, and the southern coast of Crete. Other recordings of the Thera eruption spawned Greek myths, namely the *Deucalion*, in which Poseidon, god of the sea, took revenge upon Zeus by inundating Attica, Argolis, Salonika, Rhodes and the coast of Lycia (Turkey) to Sicily.

Greeks also considered that Hephaestus, the god of fire, sat below the volcano Etna, forging the weapons of Zeus. His minions, the cyclops with their single staring eye, may be an allegory to the round craters and cones of a volcano. Indeed, the Greek word used to describe volcanoes was *etna*, or *hiera*, after Heracles, the son of Zeus. The Roman poet Virgil, in interpreting the Greek mythos, held that the hero Enceladus was buried beneath Etna by the goddess Athena as punishment for disobeying the gods; the mountain's rumblings were his tormented cries, the flames his breath and the tremors his railing against the bars of his prison. Enceladus' brother Mimas was buried beneath Vesuvius by Hephaestus, and the blood of other defeated giants welled up in the Phlegrean Fields surrounding Vesuvius.

Tribal legends of volcanoes abound from the Pacific Ring of Fire and the Americas, usually invoking the forces of the supernatural or the divine to explain the violent outbursts of volcanoes. Taranaki and Tongariro, according to Māori mythology, were lovers who fell in love with Pihanga, and a spiteful jealous fight ensued. Māori will not to this day live between Tongariro and Taranaki for fear of the dispute flaring up again.

Greco-Roman science



Eruption of Vesuvius in 1822. The eruption of AD 79 would have appeared very similar

The first attempt at a scientific explanation of volcanoes was undertaken by the Greek philosopher Empedocles (c. 490-430 B.C.), who saw the world divided into four elemental forces, of Earth, Air, Fire and Water. Volcanoes, Empedocles maintained, were the manifestation of Elemental Fire. Plato contended that channels of hot and cold waters flow in inexhaustible quantities through subterranean rivers. In the depths of the earth snakes a vast river of fire, the *Pyriphlegethon*, which feeds all the world's volcanoes. Aristotle considered underground fire as the result of "the...friction of the wind when it plunges into narrow passages."

Wind played a key role in volcano explanations until the 16th century. Lucretius, a Roman philosopher, claimed Etna was completely hollow and the fires of the underground driven by a fierce wind circulating near sea level. Ovid believed that the flame was fed from "fatty foods" and eruptions stopped when the food ran out. Vitruvius contended that sulfur, alum and bitumen fed the deep fires. Observations by Pliny the Elder noted the presence of earthquakes preceded an eruption; he died in the eruption of Vesuvius in 79 AD while investigating it at Stabiae. His nephew, Pliny the Younger gave detailed descriptions of the eruption in which his uncle died, attributing his death to the effects of toxic gases. Such eruptions have been named Plinian in honour of the two authors.

Christian mythology

The study of volcanology was not advanced much between the days of Plato and Hutton. The Christian world explained volcanoes by a multitude of prescientific notions, but it was also thought they were the work of Satan or the wrath of God, and only saintly miracles could avert their wrath. For this reason the relics of Saint Agatha were paraded in front of lava advancing on Catania in 253 A.D., and miraculously the lava clove in two (down two valleys) and spared the town. Unfortunately the relics of St. Agatha proved ineffective in 1669, with the loss of much of Catania to Etna's lava.

In 1660 the eruption of Vesuvius rained twinned pyroxene crystals and ash upon the nearby villages. The twinned pyroxene crystals resembled the crucifix and this was interpreted as the work of Saint Januarius. In Naples, the relics of St Januarius are paraded through town at every major eructation of Vesuvius. The register of these processions allowed British diplomat and amateur naturalist Sir William Hamilton to document Vesuvius' eruptions, one of the first few 'scientific' studies of the eruptive history of a volcano.

An aerial photo of Vesuvius

Renaissance observations

Renaissance descriptions of volcanoes vastly improved the state of knowledge, despite the resistance of the Church to scientific explorations of the natural world, especially those at odds with Biblical teachings. Nevertheless, *nuées ardentes* were described from the Azores in 1580. Georgius Agricola argued the rays of the sun, as later proposed by Descartes had nothing to do with volcanoes. Agricola believed vapor under pressure caused eruptions of 'mointain oil' and basalt.

Jesuit Athanasius Kircher (1602–1680) witnessed eruptions of Mount Etna and Stromboli, then visited the crater of Vesuvius and published his view of an Earth with a central fire connected to numerous others caused by the burning of sulfur, bitumen and coal.

Johannes Kepler considered volcanoes as conduits for the tears and excrement of the Earth, voiding bitumen, tar and sulfur. Descartes, pronouncing that God had created the Earth in an instant, declared he had done so in three layers; the fiery depths, a layer of water, and the air. Volcanoes, he said, were formed where the rays of the sun pierced the earth.

Science wrestled with the ideas of the combustion of pyrite with water, that rock was solidified bitumen, and with notions of rock being formed from water (Neptunism). Of the volcanoes then known, all were near the water, hence the action of the sea upon the land was used to explain volcanism.

Modern volcanology

Volcanologist examining tephra horizons in south-central Iceland

Seismic observations are made using seismographs deployed near volcanic areas, watching out for increased seismicity during volcanic events, in particular looking for long period harmonic tremors, which signal magma movement through volcanic conduits.

Surface deformation monitoring includes the use of geodetic techniques such as leveling, tilt, strain, angle and distance measurements through tiltmeters, total stations and EDMs. This also includes GNSS observations and InSAR.Surface deformation indicates magma upwelling: increased magma supply produces bulges in the volcanic center's surface.

Gas emissions may be monitored with equipment including portable ultra-violet spectrometers (COSPEC, now superseded by the miniDOAS), which analyzes the presence of volcanic gases such as sulfur dioxide; or by infra-red spectroscopy (FTIR). Increased gas emissions, and more particularly changes in gas compositions, may signal an impending volcanic eruption.

Temperature changes are monitored using thermometers and observing changes in thermal properties of volcanic lakes and vents, which may indicate upcoming activity.

Satellites are widely used to monitor volcanoes, as they allow a large area to be monitored easily. They can measure the spread of an ash plume, such as the one from Eyjafjallajokull's 2010 eruption, as well as SO_2 emissions. InSAR and thermal imaging can monitor large, scarcely populated areas where it would be too expensive to maintain instruments on the ground.

Other geophysical techniques (electrical, gravity and magnetic observations) include monitoring fluctuations and sudden change in resistivity, gravity anomalies or magnetic anomaly patterns that may indicate volcano-induced faulting and magma upwelling.

Stratigraphic analyses includes analyzing tephra and lava deposits and dating these to give volcano eruption patterns, with estimated cycles of intense activity and size of eruptions.

Lava

10 m (33 ft) high fountain of Pāhoehoe lava, Hawaii, United States

Lava flow during a rift eruption at Krafla, Iceland in 1984

Lava is molten rock expelled by a volcano during an eruption. This molten rock is formed in the interior of some planets, including Earth, and some of their satellites. When first erupted from a volcanic vent, lava is a liquid at temperatures from 700 °C to 1,200 °C (1,300 °F to 2,200 °F). Up to 100,000 times as viscous as water, lava can flow great distances before cooling and solidifying because of its thixotropic and shear thinning properties.

A *lava flow* is a moving outpouring of lava, which is created during a non-explosive effusive eruption. When it has stopped moving, lava solidifies to form igneous rock. The term *lava flow* is commonly shortened to *lava*. Explosive eruptions produce a mixture of volcanic ash and other fragments called tephra, rather than lava flows. The word "lava" comes from Italian, and is probably derived from the Latin word *labes* which means a fall or slide. The first use in connection with extruded magma (molten rock below the Earth's surface) was apparently in a short account written by Francesco Serao on the eruption of Vesuvius between May 14 and June 4, 1737. Serao described "a flow of fiery lava" as an analogy to the flow of water and mud down the flanks of the volcano following heavy rain.

Lava composition and behavior

Pāhoehoe and ʻAʻā lava flows side by side at the Big Island of Hawaii in September, 2007

In general, the composition of a lava determines its behavior more than the temperature of its eruption.

Composition

Igneous rocks, which form lava flows when erupted, can be classified into three chemical types; *felsic*, *intermediate*, and *mafic* (four if one includes the super-heated *ultramafic*). These classes are primarily chemical; however, the chemistry of lava also tends to correlate with the magma temperature, its viscosity and its mode of eruption.

Felsic lava

Felsic (or silicic) lavas such as rhyolite and dacite typically form lava spines, lava domes or "coulees" (which are thick, short lavas) and are associated with pyroclastic (fragmental) deposits. Most Silicic lava flows are extremely viscous, and typically fragment as they extrude, producing blocky autobreccias. The high viscosity and strength are the result of their chemistry, which is high in silica, aluminium, potassium, sodium, and calcium, forming a polymerized liquid rich in feldspar and quartz, which thus has a higher viscosity than other magma types. Felsic magmas can erupt at temperatures as low as 650 to 750 °C. Unusually hot (>950 °C) rhyolite lavas, however, may flow for distances of many tens of kilometres, such as in the Snake River Plain of the northwestern United States.

Intermediate lava

Intermediate or andesitic lavas are lower in aluminium and silica, and usually somewhat richer in magnesium and iron. Intermediate lavas form andesite domes and block lavas, and may occur on steep composite volcanoes, such as in the Andes. Poorer in aluminium and silica than felsic lavas, and also commonly hotter (in the range of 750 to 950 °C), they tend to be less viscous. Greater temperatures tend to destroy polymerized bonds within the magma, promoting more fluid behaviour and also a greater tendency to form phenocrysts. Higher iron and magnesium tends to manifest as a darker groundmass, and also occasionally amphibole or pyroxene phenocrysts.

Mafic lava

Mafic or basaltic lavas are typified by their high ferromagnesian content, and generally erupt at temperatures in excess of 950 °C. Basaltic magma is high in iron and magnesium, and has relatively lower aluminium and silica, which taken together reduces the degree of polymerization within the melt. Owing to the higher temperatures, viscosities can be relatively low, although still thousands of times more viscous than water. The low degree of polymerization and high temperature favors chemical diffusion, so it is common to see large, well-formed phenocrysts within mafic lavas. Basalt lavas tend to produce low-profile shield volcanoes or "flood basalt fields", because the fluidal lava flows for long distances from the vent. The thickness of a basalt lava, particularly on a low slope, may be much greater than the thickness of the moving lava flow at any one time, because basalt lavas may "inflate" by supply of lava beneath a solidified crust. Most basalt lavas are of *ʻAʻā* or *pāhoehoe* types, rather than block lavas. Underwater they can form "pillow lavas", which are rather similar to entrail-type pahoehoe lavas on land.

Ultramafic lava

Ultramafic lavas such as komatiite and highly magnesian magmas which form boninite take the composition and temperatures of eruptions to the extreme. Komatiites contain over 18% magnesium oxide, and are thought to have erupted at temperatures of 1600 °C. At this temperature there is no polymerization of the mineral compounds, creating a highly mobile liquid with viscosity as low as that of water. Most if not all ultramafic lavas are no younger than the Proterozoic, with a few ultramafic magmas known from the Phanerozoic. No modern komatiite lavas are known, as the Earth's mantle has cooled too much to produce highly magnesian magmas.

Lava behavior

Toes of a pāhoehoe advance across a road in Kalapana on the east rift zone of Kīlauea Volcano in Hawaii,United States.

The viscosity of lava is important because it determines how the lava will behave. Lavas with high viscosity are rhyolite, dacite, andesite and trachyte, with cooled basaltic lava also quite viscous; those with low viscosities are freshly erupted basalt, carbonatite and occasionally andesite.

Highly viscous lava shows the following behaviors:

- tends to flow slowly, clog, and form semi-solid blocks which resist flow

- tends to entrap gas, which form vesicles (bubbles) within the rock as they rise to the surface
- correlates with explosive or phreatic eruptions and is associated with tuff and pyroclastic flows

Highly viscous lavas do not usually flow as liquid, and usually form explosive fragmental ash or tephra deposits. However, a degassed viscous lava or one which erupts somewhat hotter than usual may form a lava flow.

Lava with low viscosity shows the following behaviors:

- tends to flow easily, forming puddles, channels, and rivers of molten rock
- tends to easily release bubbling gases as they are formed
- eruptions are rarely pyroclastic and are usually quiescent
- volcanoes tend to form broad shields rather than steep cones

Lavas also may contain many other components, sometimes including solid crystals of various minerals, fragments of exotic rocks known as xenoliths and fragments of previously solidified lava.

Volcanic morphologies

Lava entering the sea to expand the big island of Hawaii, Hawaii Volcanoes National Park

The physical behavior of lava creates the physical forms of a lava flow or volcano. More fluid basaltic lava flows tend to form flat sheet-like bodies, whereas viscous rhyolite lava flows forms knobbly, blocky masses of rock.

General features of volcanology can be used to classify volcanic edifices and provide information on the eruptions which formed the lava flow, even if the sequence of lavas have been buried or metamorphosed.

Lava enters the Pacific at the Big Island of Hawaii

The ideal lava flow will have a brecciated top, either as pillow lava development, autobreccia and rubble typical of *ʻaʻā* and viscous flows, or a vesicular or frothy carapace such as scoria or pumice. The top of the lava will tend to be glassy, having been flash frozen in contact with the air or water.

The centre of a lava flow is commonly massive and crystalline, flow banded or layered, with microscopic groundmass crystals. The more viscous lava forms tend to show sheeted flow features, and blocks or breccia entrained within the sticky lava. The crystal size at the centre of a lava will in general be greater than at the margins, as the crystals have more time to grow.

The base of a lava flow may show evidence of hydrothermal activity if the lava flowed across moist or wet substrates. The lower part of the lava may have vesicles, perhaps filled with minerals (amygdules). The substrate upon which the lava has flowed may show signs of scouring, it may be broken or disturbed by the boiling of trapped water, and in the case of soil profiles, may be baked into a brick-red terracotta.

Discriminating between an intrusive sill and a lava flow in ancient rock sequences can be difficult. However, some sills do not usually have brecciated margins, and may show a weak metamorphic aureole on both the upper and lower surface, whereas a lava will only bake the substrate beneath it. However, it is often difficult in practise to identify these metamorphic phenomenon because they are usually weak and restricted in size. Peperitic sills intruded into wet sedimentary rocks, commonly do not bake upper margins and have upper and lower autobreccias, closely similar to lavas.

ʻAʻā

ʻA ʻā is one of three basic types of flow lava. ʻAʻā is basaltic lava characterized by a rough or rubbly surface composed of broken lava blocks called clinker. The Hawaiian word was introduced as a technical term in geology by Clarence Dutton.

Glowing ʻaʻā flow front advancing over pāhoehoe on the coastal plain of Kīlauea in Hawaiʻi, United States.

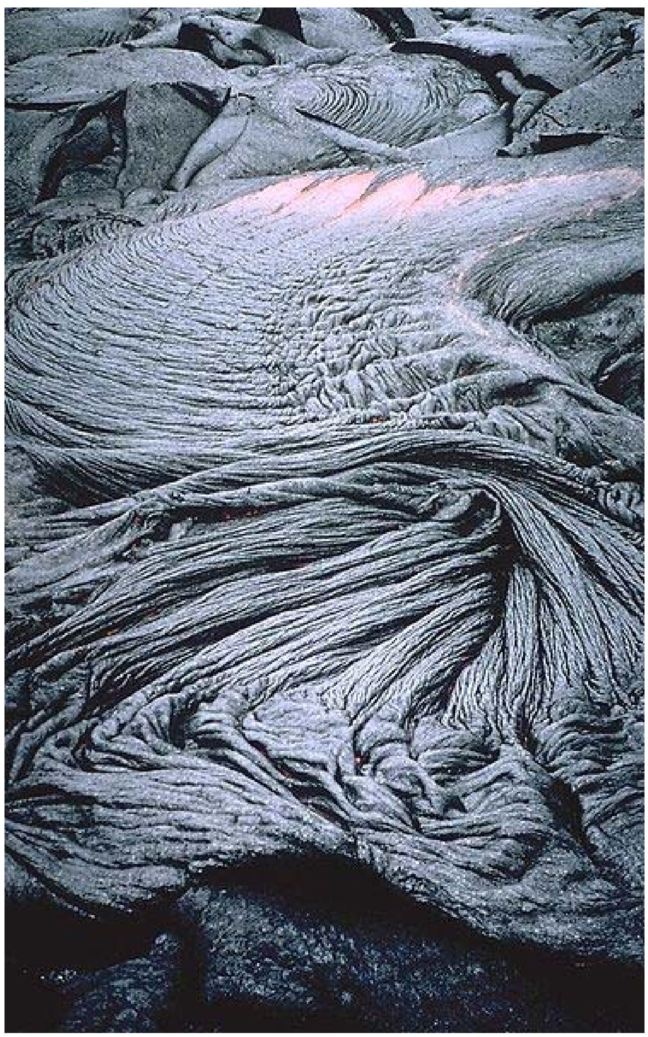
The loose, broken, and sharp, spiny surface of an ʻaʻā flow makes hiking difficult and slow. The clinkery surface actually covers a massive dense core, which is the most active part of the flow. As pasty lava in the core travels downslope, the clinkers are carried along at the surface. At the leading edge of an ʻaʻā flow, however, these cooled fragments tumble down the steep front and are buried by the advancing flow. This produces a layer of lava fragments both at the bottom and top of an ʻaʻā flow.

Accretionary lava balls as large as 3 metres (10 feet) are common on ʻaʻā flows. ʻAʻā is usually of higher viscosity than pāhoehoe. Pāhoehoe can turn into ʻaʻā if it becomes turbulent from meeting impediments or steep slopes.

The sharp, angled texture makes ʻaʻā a strong radar reflector, and can easily be seen from an orbiting satellite (bright on Magellan pictures).

ʻAʻā lavas typically erupt at temperatures of 1000 to 1100 °C

Pāhoehoe



Pāhoehoe lava from Kīlauea volcano, Hawaii, United States

Pāhoehoe is basaltic lava that has a smooth, billowy, undulating, or ropy surface. These surface features are due to the movement of very fluid lava under a congealing surface crust. The Hawaiian word was introduced as a technical term in geology by Clarence Dutton.

A pāhoehoe flow typically advances as a series of small lobes and toes that continually break out from a cooled crust. It also forms lava tubes where the minimal heat loss maintains low viscosity. The surface texture of pāhoehoe flows varies widely, displaying all kinds of bizarre shapes often referred to as lava sculpture. With increasing distance from the source, pāhoehoe flows may change into ʻaʻā flows in response to heat loss and consequent increase in viscosity. Pahoehoe lavas typically have a temperature of 1100 to 1200 °C.

The rounded texture makes pāhoehoe a poor radar reflector, and is difficult to see from an orbiting satellite (dark on Magellan picture).

Pillow lava

Pillow lava (NOAA)

Pillow lava is the lava structure typically formed when lava emerges from an underwater volcanic vent or subglacial volcano or a lava flow enters the ocean. However, pillow lava can also form when lava is erupted beneath thick glacial ice. The viscous lava gains a solid crust on contact with the water, and this crust cracks and oozes additional large blobs or "pillows" as more lava emerges from the advancing flow. Since water covers the majority of Earth's surface and most volcanoes are situated near or under bodies of water, pillow lava is very common.

Lava landforms

Because it is formed from viscous molten rock, lava flows and eruptions create distinctive formations, landforms and topographical features from the macroscopic to the microscopic.

Volcanoes

Arenal Volcano, Costa Rica, is a stratovolcano

Volcanoes are the primary landforms built by repeated eruptions of lava and ash over time. They range in shape from shield volcanoes with broad, shallow slopes formed from predominantly effusive eruptions of relatively fluid basaltic lava flows, to steeply-sided stratovolcanoes (also known as composite volcanoes) made of alternating layers of ash and more viscous lava flows typical of intermediate and felsic lavas.

A caldera, which is a large subsidence crater, can form in a stratovolcano, if the magma chamber is partially or wholly emptied by large explosive eruptions; the summit cone no longer supports itself and thus collapses in on itself afterwards. Such features may include volcanic crater lakes and lava domes after the event. However, calderas can also form by non-explosive means such as gradual magma subsidence. This is typical of many shield volcanoes.

Cinder and spatter cones

Cinder cones and spatter cones are small-scale features formed by lava accumulation around a small vent on a volcanic edifice. Cinder cones are formed from tephra or ash and tuff which is thrown from an explosive vent. Spatter cones are formed by accumulation of molten volcanic slag and cinders ejected in a more liquid form.

Kīpukas

Another Hawaiian English term derived from the Hawaiian language, a kīpuka denotes an elevated area such as a hill, ridge or old lava dome inside or downslope from an area of active volcanism. New lava flows will cover the surrounding land, isolating the kīpuka so that it appears as a (usually) forested island in a barren lava flow.

Lava domes

A forested lava dome in the midst of the Valle Grande, the largest meadow in the Valles Caldera National Preserve, New Mexico, United States.

Lava domes are formed by the extrusion of viscous felsic magma. They can form prominent rounded protuberances, such as at Valles Caldera. As a volcano extrudes silicic lava, it can form an *inflation dome*, gradually building up a large, pillow-like structure which cracks, fissures, and may release cooled chunks of rock and rubble. The top and side margins of an inflating lava dome tend to be covered in fragments of rock, breccia and ash.

Examples of lava dome eruptions include the Novarupta dome, and successive lava domes of Mount St Helens.

Lava tubes

Lava tubes are formed when a flow of relatively fluid lava cools on the upper surface sufficiently to form a crust. Beneath this crust, which being made of rock is an excellent insulator, the lava can continue to flow as a liquid. When this flow occurs over a prolonged period of time the lava conduit can form a tunnel-like aperture or *lava tube*, which can conduct molten rock many kilometres from the vent without cooling appreciably. Often these lava tubes drain out once the supply of fresh lava has stopped, leaving a considerable length of open tunnel within the lava flow.

Lava tubes are known from the modern day eruptions of Kīlauea, and significant, extensive and open lava tubes of Tertiary age are known from North Queensland, Australia, some extending for 15 kilometres.

Lava cascades and fountains

Lava fountain within Villarrica's crater

The eruptions of lava are sometimes attended by peculiarities which impart to them much additional grandeur. Instances have occurred in which the molten stream has plunged over a sheer precipice of immense height, so as to produce a glowing cascade exceeding (in breadth and perpendicular descent) the celebrated Niagara Falls. In other cases, the lava, instead of at once flowing down the sides of the mountain, has been first thrown up into the air as a lava fountain up to several hundred metres in height.

Lava lakes

Rarely, a volcanic cone may fill with lava but not erupt. Lava which pools within the caldera is known as a lava lake. Lava lakes do not usually persist for long, either draining back into the magma chamber once pressure is relieved (usually by venting of gases through the caldera), or by draining via eruption of lava flows or pyroclastic explosion.

There are only a few sites in the world where permanent lakes of lava exist. These include:

- Mount Erebus, Antarctica
- Pu'u 'Ō'ō and formerly Kīlauea volcanoes, Hawaiʻi
- Erta Ale, Ethiopia
- Nyiragongo, Democratic Republic of Congo
- Ambrym, Vanuatu.

Shiprock, New Mexico, United States: a volcanic neck in the distance, with radiating dike on its south side. Photo credit: USGS Digital Data Series

Lava delta

Lava deltas form wherever sub-aerial flows of lava enter standing bodies of water. The lava cools and breaks up as it encounters the water, with the resulting fragments filling in the seabed topography such that the sub-aerial flow can move further offshore. Lava deltas are generally associated with large-scale, effusive type basaltic volcanism.

Unusual lavas

Four types of unusual volcanic rocks have been recognised as erupting onto the surface of the Earth:

- Carbonatite and natrocarbonatite lavas are known from Ol Doinyo Lengai volcano in Tanzania, which is the sole example of an active carbonatite volcano.
- Copper sulfide bearing lavas have been recognised from Chile and Bolivia
- Iron oxide lavas are thought to be the source of the iron ore at Kiruna, Sweden, erupted in the Proterozoic, and in Chile associated with highly alkaline igneous rocks
- Olivine nephelinite lavas are a unique type of lava that is thought to have come from much deeper in the mantle of the Earth.

The term "lava" can also be used to refer to molten "ice mixtures" in eruptions on the icy satellites of the Solar system's gas giants.

Hazards

Lava flows are enormously destructive to property in their path but generally move slowly enough for people to get out of their way, though this is dependent on the viscosity of the lava; casualties caused directly by active lava flows are rare. Nevertheless injuries and deaths have occurred, either because people had their escape route cut off, because they got too close to the flow or, more rarely, if the lava flow front travelled too quickly. This notably happened during the eruption of Nyiragongo in Zaire (now Democratic Republic of Congo) on 10 January 1977 when the crater wall was breached during the night and the fluid lava lake in it drained out in less than an hour. Flowing down the steep slopes of the volcano at up to 100 km/h, the lava swiftly overwhelmed several villages whilst their residents were asleep. As a result of this disaster, the mountain was designated a Decade Volcano in 1991.

Deaths attributed to volcanoes frequently have a different cause, for example volcanic ejecta, pyroclastic flow from a collapsing lava dome, lahars, poisonous gases that travel ahead of lava, or explosions caused when the flow comes into contact with water.

Magma

Lava flow on Hawaii. Lava is the extrusive equivalent of magma

Magma (from Greek μάγμα "paste") is a mixture of molten rock, volatiles and solids that is found beneath the surface of the Earth, and may also exist on other terrestrial planets. Besides molten rock, magma may also contain suspended crystals and gas bubbles. Magma often collects in magma chambers that may feed a volcano or turn into a pluton. Magma is capable of intrusion into adjacent rocks, extrusion onto the surface as lava, and explosive ejection as tephra to form pyroclastic rock.

Magma is a complex high-temperature fluid substance. Temperatures of most magmas are in the range 700 °C to 1300 °C (or 1300 °F to 2400 °F), but very rare carbonatite melts may be as cool as 600 °C, and komatiite melts may have been as hot as 1600 °C. Most are silicate mixtures.

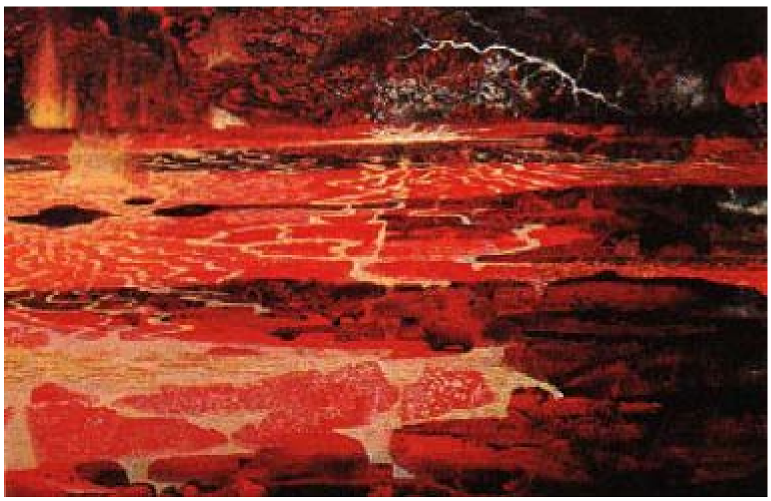
Environments of magma formation and compositions are commonly correlated. Environments include subduction zones, continental rift zones, mid-oceanic ridges, and hotspots, some of which are interpreted as mantle plumes. Despite being found in such widespread locales, the bulk of the Earth's crust and mantle is not molten. Rather, most of the Earth takes the form of a rheid, a form of solid that can move or deform under pressure. Magma, as liquid, preferentially forms in high temperature, low pressure environments within several kilometers of the Earth's surface.

Magma compositions may evolve after formation by fractional crystallization, contamination, and magma mixing. By definition, all igneous rock is formed from magma.

While the study of magma has historically relied on observing magma in the form of lava outflows, magma has been encountered in situ three times during drilling projects—twice in Iceland, and once in Hawaii.

Source

Partial melting



An artist's impression of a magma ocean on the early Earth

Melting of solid rock to form magma is controlled by three physical parameters: its temperature, pressure, and composition. Mechanisms are discussed in the entry for igneous rock.

When rocks melt they do so incrementally and gradually; most rocks are made of several minerals, all of which have different melting points, and the phase diagrams that control melting are often complex. As a rock melts, its volume changes. When enough rock is melted, the small globules of melt (generally occurring in between mineral grains) link up and soften the rock. Under pressure within the earth, as little as a fraction of a percent partial melting may be sufficient to cause melt to be squeezed from its source.

Melts can stay in place long enough to melt to 20% or even 35%, but rocks are rarely melted in excess of 50%, because eventually the melted rock mass becomes a crystal and melt mush that can then ascend *en masse* as a diapir, which may then cause further decompression melting.

Geochemical implications of partial melting

The degree of partial melting is critical for determining what type of magma is produced. The degree of partial melting required to form a melt can be estimated by considering the relative enrichment of incompatible elements versus compatible elements. Incompatible elements commonly include potassium, barium, caesium, rubidium.

Rock types produced by small degrees of partial melting in the Earth's mantle are typically alkaline (Ca, Na), potassic (K) and/or peralkaline (high aluminium to silica ratio). Typically, primitive melts of this composition form lamprophyre, lamproite, kimberlite and sometimes nepheline-bearing mafic rocks such as alkali basalts and essexite gabbros or even carbonatite.

Pegmatite may be produced by low degrees of partial melting of the crust. Some granite-composition magmas are eutectic (or cotectic) melts, and they may be produced by low to high degrees of partial melting of the crust, as well as by fractional crystallization. At high degrees of partial melting of the crust, granitoids such as tonalite, granodiorite and monzonite can be produced, but other mechanisms are typically important in producing them.

Evolution of magmas

Primary melts

When a rock melts, the liquid as a *primary melt*. Primary melts have not undergone any differentiation and represent the starting composition of a magma. In nature it is rare to find primary melts. The leucosomes of migmatites are examples of primary melts. Primary melts derived from the mantle are especially important, and are known as *primitive melts* or primitive magmas. By finding the primitive magma composition of a magma series it is possible to model the composition of the mantle from which a melt was formed, which is important in understanding evolution of the mantle.

Parental melts

Where it is impossible to find the primitive or primary magma composition, it is often useful to attempt to identify a parental melt. A parental melt is a magma composition from which the observed range of magma chemistries has been derived by the processes of igneous differentiation. It need not be a primitive melt.

For instance, a series of basalt flows are assumed to be related to one another. A composition from which they could reasonably be produced by fractional crystallization is termed a *parental melt*. Fractional crystallization models would be produced to test the hypothesis that they share a common parental melt.

At high degrees of partial melting of the mantle, komatiite and picrite are produced.

Migration

Magma exists and has existed in earth's interior since the formation of the earth. Magma rises toward the Earth's surface as long as it is less dense than the surrounding rock. Once magma stops rising, it can collect in areas called magma chambers. Magma can remain in a chamber until it cools, forming igneous rock, it erupts or moves on to another magma chamber.

Porous rock

When rock is first melted the liquid forms pores in the source rock. Magma in this kind of porous media is very primitive. As the host rock compacts the magma is expelled forming a network that collects magma into magma chambers.

Dikes

Dikes are temporary vertical passages trough which magma moves.

Cooling of magmas

Although now covered by forest the mountains around Panguipulli Lake in Chile were once magma that crystallized deep in earth's crust, now these magmatic bodies form the Panguipulli Batholith.

There are two known processes by which magma ceases to exist, by volcanic eruption or by plutonism. In both cases the bulk of the magma eventually cools and form igneous rocks.

When magma cools it begins to form solid mineral phases, some of them settles at the bottom of the magma chamber forming cumulates that might form mafic layered intrusions. Magma that cools down slowly in a magma chamber usually ends up as forming bodies of plutonic rocks like gabbro, diorite and granite depending on the comoposition of the magma, while if the magma is erupted it forms volcanic rocks such as basalt, andesite and rhyolite (the extrusive equivalents of gabbro, diorite and granite respectively).

Volcanism

During a volcanic eruption the magma that leaves the underground is called lava (an old word for magma is "subterranean lava"). Lava cools down and solidifies relatively quickly compared to underground bodies of magma. This fast cooling does not allow new crystals to grow large, and a part of the melt does not crystallize at all, becoming glass (obsidian).

Before and during volcanic eruptions, fluids like CO_2 and H_2O partially leave the melt through a process known as exsolution. Magma with low water content becomes increasingly viscous. If massive exsolution occurs when magma heads upwards during a volcanic eruption, the resulting eruption is usually explosive (at least in its initial phases).

Composition, melt structure and properties

Silicate melts are composed mainly of silicon, oxygen, aluminium, alkalis (sodium, potassium, calcium), magnesium and iron. Silicon atoms are in tetrahedral coordination with oxygen, as in almost all silicate minerals, but in melts atomic order is preserved only over short distances. The physical behaviours of melts depend upon their atomic structures as well as upon temperature and pressure and composition.

Viscosity is a key melt property in understanding the behaviour of magmas. More silica-rich melts are typically more polymerized, with more linkage of silica tetrahedra, and so are more viscous. Dissolution of water drastically reduces melt viscosity. Higher-temperature melts are less viscous.

Generally speaking, more mafic magmas, such as those that form basalt, are hotter and less viscous than more silica-rich magmas, such as those that form rhyolite. Low viscosity leads to gentler, less explosive eruptions.

Characteristics of several different magma types are as follows:

Ultramafic (picritic)
SiO_2 < 45%
Fe-Mg >8% up to 32%MgO
Temperature: up to 1500°C
Viscosity: Very Low

Eruptive behavior: gentle or very explosive (kimberilites)
Distribution: divergent plate boundaries, hot spots, convergent plate boundaries; komatiite and other ultramafic lavas are mostly Archean and were formed from a higher geothermal gradient and are unknown in the present
Mafic (basaltic)
$SiO_2 < 50\%$
FeO and MgO typically < 10 wt%
Temperature: up to ~1300°C
Viscosity: Low
Eruptive behavior: gentle
Distribution: divergent plate boundaries, hot spots, convergent plate boundaries
Intermediate (andesitic)
$SiO_2 \sim 60\%$
Fe-Mg: ~ 3%
Temperature: ~1000°C
Viscosity: Intermediate
Eruptive behavior: explosive or effusive
Distribution: convergent plate boundaries, island arcs
Felsic (rhyolitic)
$SiO_2 > 70\%$
Fe-Mg: ~ 2%
Temp: < 900°C
Viscosity: High
Eruptive behavior: explosive or effusive
Distribution: hot spots in continental crust (Yellowstone National Park), continental rifts

Temperature

At any given pressure and for any given composition of rock, a rise in temperature past the solidus will cause melting. Within the solid earth, the temperature of a rock is controlled by the geothermal gradient and the radioactive decay within the rock. The geothermal gradient averages about 25 °C/km with a wide range from a low of 5-10 °C/km within oceanic trenches and subduction zones to 30-80 °C/km under mid-ocean ridges and volcanic arc environments.

Pressure

As magma buoyantly rises it will cross the solidus-liquidus and its temperature will reduce by adiabatic cooling. At this point it will liquefy and if erupted onto the surface will form lava. Melting can also occur due to a reduction in pressure by a process known as decompression melting.

Composition

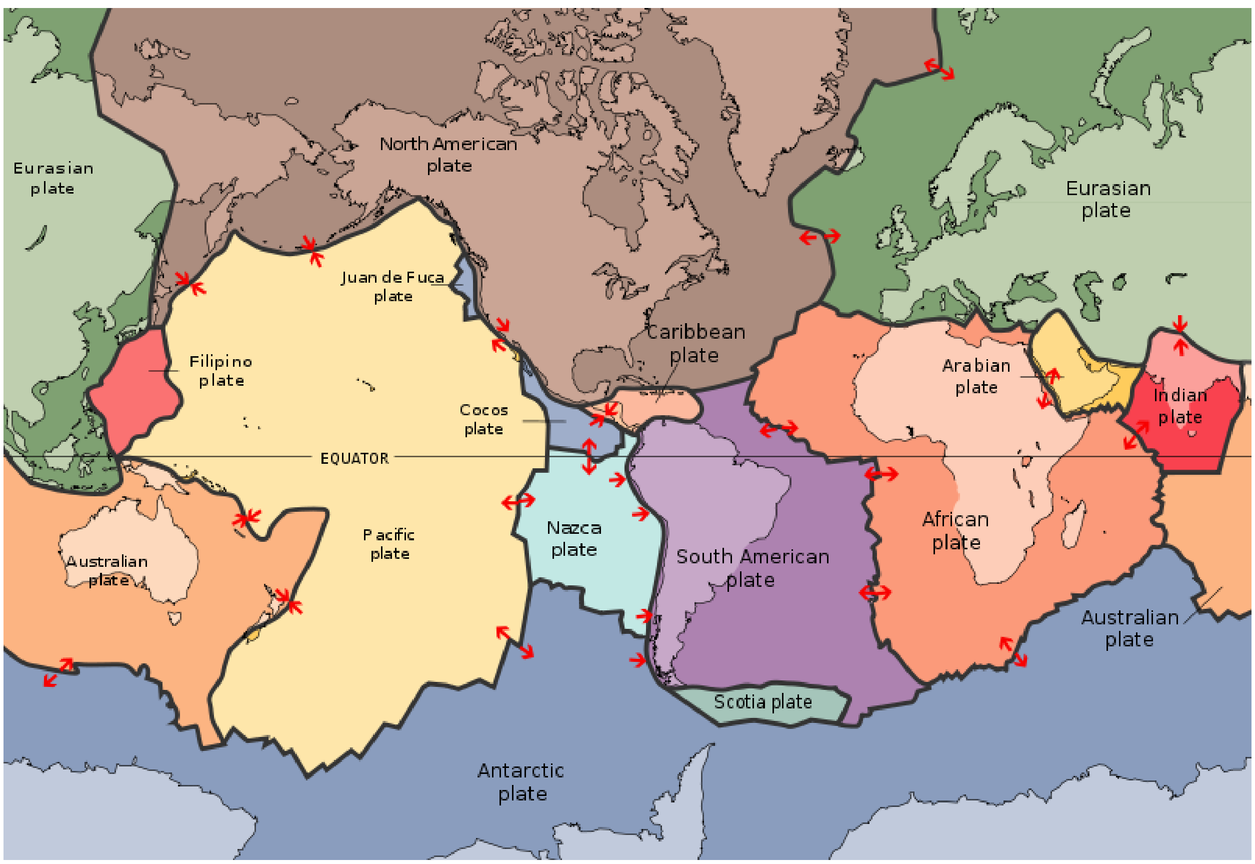
It is usually very difficult to change the bulk composition of a large mass of rock, so composition is the basic control on whether a rock will melt at any given temperature and pressure. The composition of a rock may also be considered to include *volatile* phases such as water and carbon dioxide.

The presence of volatile phases in a rock under pressure can stabilize a melt fraction. The presence of even 0.8% water may reduce the temperature of melting by as much as 100 °C. Conversely, the loss of water and volatiles from a magma may cause it to essentially freeze or solidify.

Also a major portion of all magma is silica, which is a compound of silicon and oxygen. Magma also contains gases, which expand as the magma rises. Magma that is high in silica resists flowing, so expanding gases are trapped in it. Pressure builds up until the gases blast out in a violent, dangerous explosion. Magma that is relatively poor in silica flows easily, so gas bubbles move up through it and escape fairly gently. Though an eruption of silica-poor magma can throw lava high into the air, forming lava fountains, visitors can usually watch safely nearby.

Chapter- 6

Plate Tectonics



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

Plate tectonics (from the Late Latin *tectonicus*, from the Greek: *τεκτονικός* "pertaining to building") is a scientific theory which describes the large scale motions of Earth's lithosphere. The theory builds on the older concepts of continental drift, developed during the first decades of the 20th century (one of the most famous advocates was Alfred Wegener), and was accepted by the majority of the geoscientific community when the concepts of seafloor spreading were developed in the late 1950s and early 1960s. The lithosphere is broken up into what are called "tectonic plates". In the case of the Earth, there are currently seven to eight major (depending on how they are defined) and many minor plates. The lithospheric plates ride on the asthenosphere. These plates move in relation to one another at one of three types of plate boundaries: convergent, or collisional boundaries; divergent boundaries, also called spreading centers; and conservative transform boundaries. Earthquakes, volcanic activity, mountain-building, and oceanic trench formation occur along these plate boundaries. The lateral relative movement of the plates varies, though it is typically 0–100 mm annually.

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

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

Key principles

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

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

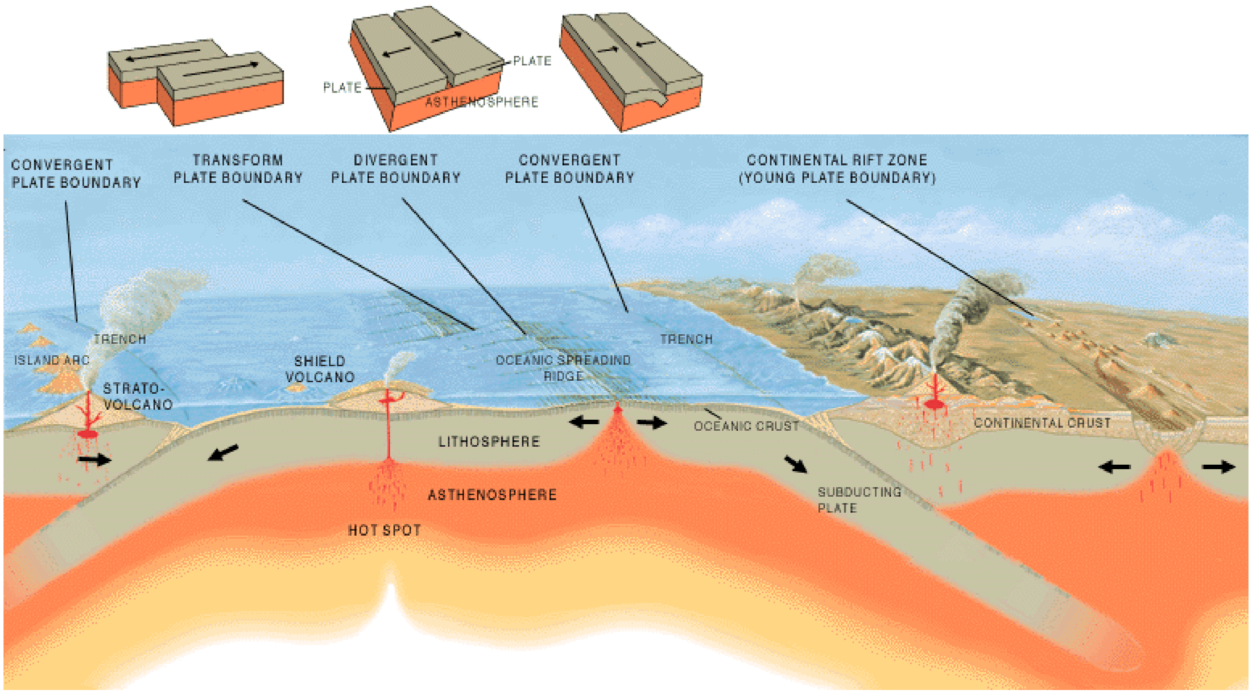
(Nazca Plate; about as fast as hair grows). The driving mechanism behind this movement is described separately below.

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

The location where two plates meet is called a *plate boundary*, and plate boundaries are commonly associated with geological events such as earthquakes and the creation of topographic features such as mountains, volcanoes, mid-ocean ridges, and oceanic trenches. The majority of the world's active volcanoes occur along plate boundaries, with the Pacific Plate's Ring of Fire being most active and most widely known. These boundaries are discussed in further detail below. Some volcanoes occur in the interiors of plates, and these have been variously attributed to internal plate deformation and to mantle plumes.

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

Types of plate boundaries



Three types of plate boundary

Basically, three types of plate boundaries exist, with a fourth, mixed type, characterized by the way the plates move relative to each other. They are associated with different types of surface phenomena. The different types of plate boundaries are:

1. *Transform boundaries (Conservative)* occur where plates slide or, perhaps more accurately, grind past each other along transform faults. The relative motion of the two plates is either sinistral (left side toward the observer) or dextral (right side toward the observer). The San Andreas Fault in California is an example of a transform boundary exhibiting dextral motion.
2. *Divergent boundaries (Constructive)* occur where two plates slide apart from each other. Mid-ocean ridges (e.g., Mid-Atlantic Ridge) and active zones of rifting (such as Africa's Great Rift Valley) are both examples of divergent boundaries.
3. *Convergent boundaries (Destructive)* (or *active margins*) occur where two plates slide towards each other commonly forming either a subduction zone (if one plate moves underneath the other) or a continental collision (if the two plates contain continental crust). Deep marine trenches are typically associated with subduction zones, and the basins that develop along the active boundary are often called "foreland basins". The subducting slab contains many hydrous minerals, which release their water on heating; this water then causes the mantle to melt, producing volcanism. Examples of this are the Andes mountain range in South America and the Japanese island arc.
4. *Plate boundary zones* occur where the effects of the interactions are unclear and the boundaries, usually occurring along a broad belt, are not well defined, and may show various types of movements in different episodes.

Driving forces of plate motion

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

Generally, it is accepted that tectonic plates are able to move because of the relative density of oceanic lithosphere and the relative weakness of the asthenosphere. Dissipation of heat from the mantle is acknowledged to be the original source of energy driving plate tectonics, through convection or large scale upwelling and doming. As a consequence, in the current view, although it is still a matter of some debate, because of the excess density of the oceanic lithosphere sinking in subduction zones a powerful source of plate motion is generated. When the new crust forms at mid-ocean ridges, this oceanic lithosphere is initially less dense than the underlying asthenosphere, but it becomes denser with age, as it conductively cools and thickens. The greater density of old lithosphere relative to the underlying asthenosphere allows it to sink into the deep mantle at subduction zones, providing most of the driving force for plate motions. The weakness of the asthenosphere allows the tectonic plates to move easily towards a subduction zone. Although subduction is believed to be the strongest force driving plate motions, it cannot be the only force since there are plates such as the North American Plate which are moving, yet are nowhere being subducted. The same is true for the enormous Eurasian Plate. The sources of plate motion are a matter of intensive research and discussion among earth scientists. One of the main points is that the kinematic pattern of the movements itself should be separated clearly from the possible geodynamic mechanism that is invoked as the driving force of the observed movements, as some patterns may be explained by more than one mechanism. Basically, the driving forces that are advocated at the moment, can be divided in three categories: mantle dynamics related, gravity related (mostly secondary forces), and Earth rotation related.

Mantle dynamics related driving forces

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

Two– and three–dimensional imaging of the Earth's interior (seismic tomography) shows that there is a laterally varying density distribution throughout the mantle. Such density variations can be material (from rock chemistry), mineral (from variations in mineral structures), or thermal (through thermal expansion and contraction from heat energy). The manifestation of this varying lateral density is mantle convection from buoyancy forces.

How mantle convection relates directly and indirectly to the motion of the plates is a matter of ongoing study and discussion in geodynamics. Somehow, this energy must be transferred to the lithosphere in order for tectonic plates to move. There are essentially two types of forces that are thought to influence plate motion: friction and gravity.

- **Basal drag** (friction): The plate motion is in this way driven by friction between the convection currents in the asthenosphere and the more rigid overlying floating lithosphere.
- **Slab suction** (gravity): Local convection currents exert a downward frictional pull on plates in subduction zones at ocean trenches. Slab suction may occur in a geodynamic setting wherein basal tractions continue to act on the plate as it dives into the mantle (although perhaps to a greater extent acting on both the under and upper side of the slab).

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

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

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

Gravity related driving forces

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

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

This force is regarded as a secondary force often referred to as "ridge push". This is a misnomer as nothing is "pushing" horizontally and tensional features are dominant along ridges. It is more accurate to refer to this mechanism as gravitational sliding as variable topography across the totality of the plate can vary considerably and the topography of spreading ridges is only the most prominent feature. Other mechanisms generating this gravitational secondary force include flexural bulging of the lithosphere before it dives underneath an adjacent plate, which produces a clear topographical feature that can offset or at least affect the influence of topographical ocean ridges, and mantle plumes and hot spots, which are postulated to impinge on the underside of tectonic plates.

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

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

Earth rotation related driving forces

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

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

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

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

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

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

In 1973 George W. Moore of the USGS and R. C. Bostrom presented evidence for a general westward drift of the Earth's lithosphere with respect to the mantle, and, therefore, tidal forces or tidal lag or "friction" due to the Earth's rotation and the forces acting upon it by the Moon being a driving force for plate tectonics: as the Earth spins eastward beneath the moon, the moon's gravity ever so slightly pulls the Earth's surface layer back westward, just like proposed by Alfred Wegener (see above). In a more recent 2006 study, scientists rediscussed and advocated these earlier proposed ideas. It has also been suggested recently in Lovett (2006) that this observation may also explain why Venus and Mars have no plate tectonics, since Venus has no moon and Mars' moons are too small to have significant tidal effects on Mars. In a recent paper it was suggested that, on the other hand, it can easily be observed that many plates are moving north and eastward, and that the dominantly westward motion of the Pacific ocean basins derives simply from the eastward bias of the Pacific spreading center (which is not a predicted manifestation of such lunar forces). In the same paper the authors admit, however, that relative to the lower mantle, there is a slight westward component in the motions of all the plates. They demonstrated though that the westward drift, seen only for the past 30 Ma, is attributed to the increased dominance of the steadily growing and accelerating Pacific plate. The debate is still open.

Relative significance of each driving force mechanism

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

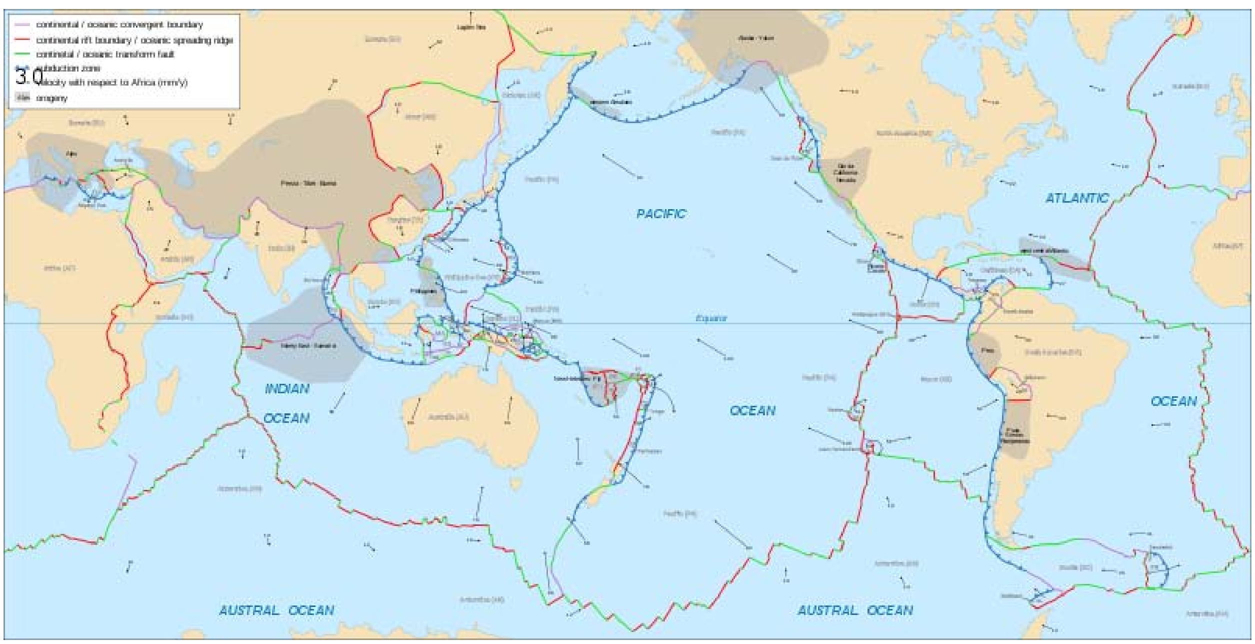
The diversity of geodynamic settings and properties of each plate must clearly result in differences in the degree to which such processes are actively driving the plates. One method of dealing with this problem is to consider the relative rate at which each plate is moving and to consider the available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

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

Development of the theory

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

Summary



Detailed map showing the tectonic plates with their movement vectors

In line with other previous and contemporaneous proposals, in 1912 the meteorologist Alfred Wegener amply described what he called continental drift, expanded in his 1915 book *The Origin of Continents and Oceans* and the scientific debate started that would end up fifty years later in the theory of plate tectonics. Starting from the idea (also expressed by his forerunners) that the present continents once formed a single land mass (which was called Pangea later on) that drifted apart, thus releasing the continents from the Earth's mantle and likening them to "icebergs" of low density granite floating on a sea of denser basalt. Supporting evidence for the idea came from the dove-tailing outlines of South America's east coast and Africa's west coast, and from the matching of the rock formations along these edges. Confirmation of their previous contiguous nature also came from the fossil plants *Glossopteris* and *Gangamopteris*, and the therapsid or mammal-like reptile *Lystrosaurus*, all widely distributed over South America, Africa, Antarctica, India and Australia. The evidence for such an erstwhile joining of these continents was patent to field geologists working in the southern hemisphere. The South African Alex du Toit put together a mass of such information in his 1937 publication *Our Wandering Continents*, and went further than Wegener in recognising the strong links between the Gondwana fragments.

But without detailed evidence and a force sufficient to drive the movement, the theory was not generally accepted: the Earth might have a solid crust and mantle and a liquid core, but there seemed to be no way that portions of the crust could move around. Distinguished scientists, such as Harold Jeffreys and Charles Schuchert, were outspoken critics of continental drift.

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

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

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

Simultaneous advances in early seismic imaging techniques in and around Wadati-Benioff zones along the trenches bounding many continental margins, together with many other geophysical (e.g. gravimetric) and geological observations, showed how the oceanic crust could disappear into the mantle, providing the mechanism to balance the extension of the ocean basins with shortening along its margins.

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

Continental drift

In the late 19th and early 20th centuries, geologists assumed that the Earth's major features were fixed, and that most geologic features such as basin development and mountain ranges could be explained by vertical crustal movement, described in what is called the geosynclinal theory. Generally, this was placed in the context of a contracting planet Earth due to heat loss in the course of a relatively short geological time.

It was observed as early as 1596 that the opposite coasts of the Atlantic Ocean—or, more precisely, the edges of the continental shelves—have similar shapes and seem to have once fitted together.

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

The discovery of radioactivity and its associated heating properties in 1895 prompted a re-examination of the apparent age of the Earth. since this had previously been estimated by its cooling rate and assumption the Earth's surface radiated like a black body. Those calculations had implied that, even if it started at red heat, the Earth would have dropped to its present temperature in a few tens of millions of years. Armed with the knowledge of a new heat source, scientists realized that the Earth would be much older, and that its core was still sufficiently hot to be liquid.

By 1915, after having published a first article in 1912, Alfred Wegener was making serious arguments for the idea of continental drift in the first edition of *The Origin of Continents and Oceans*. In that book (re-issued in four successive editions up to the final one in 1936), he noted how the east coast of South America and the west coast of Africa looked as if they were once attached. Wegener wasn't the first to note this (Abraham Ortelius, Snider-Pellegrini, Roberto Mantovani and Frank Bursley Taylor preceded him just to mention a few), but he was the first to marshal significant fossil and paleo-topographical and climatological evidence to support this simple observation (and was supported in this by researchers such as Alex du Toit). Furthermore, when the rock strata of the margins of separate continents are very similar it suggests that these rocks were formed in the same way, implying that they were joined initially. For instance, some parts of Scotland and Ireland contain rocks very similar to those found in Newfoundland and

New Brunswick. Furthermore, the Caledonian Mountains of Europe and parts of the Appalachian Mountains of North America are very similar in structure and lithology.

However, his ideas were not taken seriously by many geologists, who pointed out that there was no apparent mechanism for continental drift. Specifically, they did not see how continental rock could plow through the much denser rock that makes up oceanic crust. Wegener could not explain the force that drove continental drift, and his vindication did not come until after his death in 1930.

Floating continents - paleomagnetism - seismicity zones

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

However, based upon abnormalities in plumb line deflection by the Andes in Peru, Pierre Bouguer had deduced that less-dense mountains must have a downward projection into the denser layer underneath. The concept that mountains had "roots" was confirmed by George B. Airy a hundred years later during study of Himalayan gravitation, and seismic studies detected corresponding density variations. Therefore, by the mid–1950s the question remained unresolved of whether mountain roots were clenched in surrounding basalt or were floating upon it like an iceberg.

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

Meanwhile, debates developed around the phenomena of polar wander. Since the early debates of continental drift, scientists had discussed and used evidence that polar drift had occurred because continents seemed to have moved through different climatic zones during the past. Furthermore, paleomagnetic data had shown that the magnetic pole had also shifted during time. Reasoning in an opposite way, the continents might have shifted and rotated, while the pole remained relatively fixed. The first time the evidence of magnetic polar wander was used to support the movements of continents was in a paper by Keith Runcorn in 1956, and successive papers by him and his students Ted Irving (who was actually the first to be convinced of the fact that paleomagnetism supported continental drift) and Ken Creer.

This was immediately followed by a symposium in Tasmania in March 1956. In this symposium, the evidence was used in the theory of an expansion of the global crust. In this hypothesis the shifting of the continents can be simply explained by a large increase in size of the Earth since its formation. However, this was unsatisfactory because its supporters could offer no convincing mechanism to produce a significant expansion of the Earth. Certainly there is no evidence that the moon has expanded in the past 3 billion years; other work would soon show that the evidence was equally in support of continental drift on a globe with a stable radius.

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

Often, all these milestones are forgotten for various reasons:

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

Mid oceanic ridge spreading and convection

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

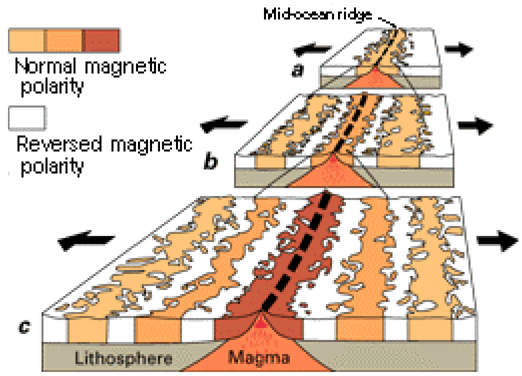
The new data that had been collected on the ocean basins also showed particular characteristics regarding the bathymetry. One of the major outcomes of these datasets was that all along the globe, a system of mid-oceanic ridges was detected. An important conclusion was that along this system, new ocean floor was being created, which led to the concept of the "Great Global Rift". This was described in the crucial paper of Bruce Heezen (1960) which would trigger a real revolution in thinking. A profound consequence of seafloor spreading is that new crust was, and is now, being continually created along the oceanic ridges. Therefore, Heezen advocated the so-called "expanding Earth" hypothesis of S. Warren Carey (see above). So, still the question remained: how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth? In reality, this question had been solved already by numerous scientists during the forties and the fifties, like Arthur Holmes, Vening-Meinesz, Coates and many others: The crust in excess disappeared along what were called the oceanic trenches where so-called "subduction" occurred. Therefore, when various scientists during the early sixties started to reason on the data at their disposal regarding the ocean floor, the pieces of the theory fell quickly into place.

The question particularly intrigued Harry Hammond Hess, a Princeton University geologist and a Naval Reserve Rear Admiral, and Robert S. Dietz, a scientist with the U.S. Coast and Geodetic Survey who first coined the term *seafloor spreading*. Dietz and Hess (the former published the same idea one year earlier in *Nature*, but priority belongs to Hess who had already distributed an unpublished manuscript of his 1962 article by 1960) were among the small handful who really understood the broad implications of sea floor spreading and how it would eventually agree with the, at that time, unconventional and unaccepted ideas of continental drift and the elegant and mobilistic models proposed by previous workers like Holmes.

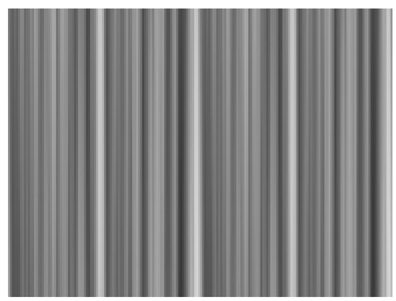
In the same year, Robert R. Coats of the U.S. Geological Survey described the main features of island arc subduction in the Aleutian Islands. His paper, though little–noted (and even ridiculed) at the time, has since been called "seminal" and "prescient". In reality, it actually shows that the work by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

If the Earth's crust was expanding along the oceanic ridges, Hess and Dietz reasoned like Holmes and others before them, it must be shrinking elsewhere. Hess followed Heezen suggesting that new oceanic crust continuously spreads away from the ridges in a conveyor belt–like motion. And, using the mobilistic concepts developed before, he correctly concluded that many millions of years later, the oceanic crust eventually descends along the continental margins where oceanic trenches – very deep, narrow canyons – are formed, e.g. along the rim of the Pacific Ocean basin. The important step Hess made was that convection currents would be the driving force in this process, arriving at the same conclusions as Holmes had decades before with the only difference that the thinning of the ocean crust was performed using the mechanism of Heezen of spreading along the ridges. Hess therefore concluded that the Atlantic Ocean was expanding while the Pacific Ocean was shrinking. As old oceanic crust is "consumed" in the trenches, (like Holmes and others, he believed this was done by thickening of the continental lithosphere, not, as nowadays believed, by underthrusting at a larger scale of the oceanic crust itself into the mantle) new magma rises and erupts along the spreading ridges to form new crust. In effect, the ocean basins are perpetually being "recycled," with the creation of new crust and the destruction of old oceanic lithosphere occurring simultaneously, in a way that later would be called the Wilson cycle (see below). Thus, the new mobilistic concepts neatly explained why the Earth does not get bigger with sea floor spreading, why there is so little sediment accumulation on the ocean floor, and why oceanic rocks are much younger than continental rocks.

The final proof: magnetic striping



Seafloor magnetic striping



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

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

As more and more of the seafloor was mapped during the 1950s, the magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns. When these magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern: one stripe with normal polarity and the adjoining stripe with reversed polarity. The overall pattern, defined by these alternating bands of normally and reversely polarized rock, became known as magnetic striping, and was published by Ron G. Mason and co-workers in 1961, who didn't find, though, an explanation for these data in terms of sea floor spreading, like Vine, Matthews and Morley a few years later.

The discovery of magnetic striping called for an explanation. In the early 1960s scientists such as Heezen, Hess and Dietz had begun to theorise that mid-ocean ridges mark structurally weak zones where the ocean floor was being ripped in two lengthwise along the ridge crest. New magma from deep within the Earth rises easily through these weak zones and eventually erupts along the crest of the ridges to create new oceanic crust. This process, at first denominated the "conveyer belt hypothesis" and later called seafloor spreading, operating over many millions of years continues to form new ocean floor all across the 50,000 km-long system of mid–ocean ridges.

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

1. the stripes are symmetrical around the crests of the mid-ocean ridges; at or near the crest of the ridge, the rocks are very young, and they become progressively older away from the ridge crest;
2. the youngest rocks at the ridge crest always have present-day (normal) polarity;
3. stripes of rock parallel to the ridge crest alternate in magnetic polarity (normal-reversed-normal, etc.), suggesting that they were formed during different epochs documenting the (already known from independent studies) normal and reversal episodes of the Earth's magnetic field.

By explaining both the zebra-like magnetic striping and the construction of the mid-ocean ridge system, the seafloor spreading hypothesis (SFS) quickly gained converts and represented another major advance in the development of the plate-tectonics theory. Furthermore, the oceanic crust now came to be appreciated as a natural "tape recording" of the history of the geomagnetic field reversals (GMFR) of the Earth's magnetic field. Nowadays, extensive studies are dedicated to the calibration of the normal-reversal patterns in the oceanic crust on one hand and known timescales derived from the dating of basalt layers in sedimentary sequences (magnetostratigraphy) on the other, to arrive at estimates of past spreading rates and plate reconstructions.

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

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

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

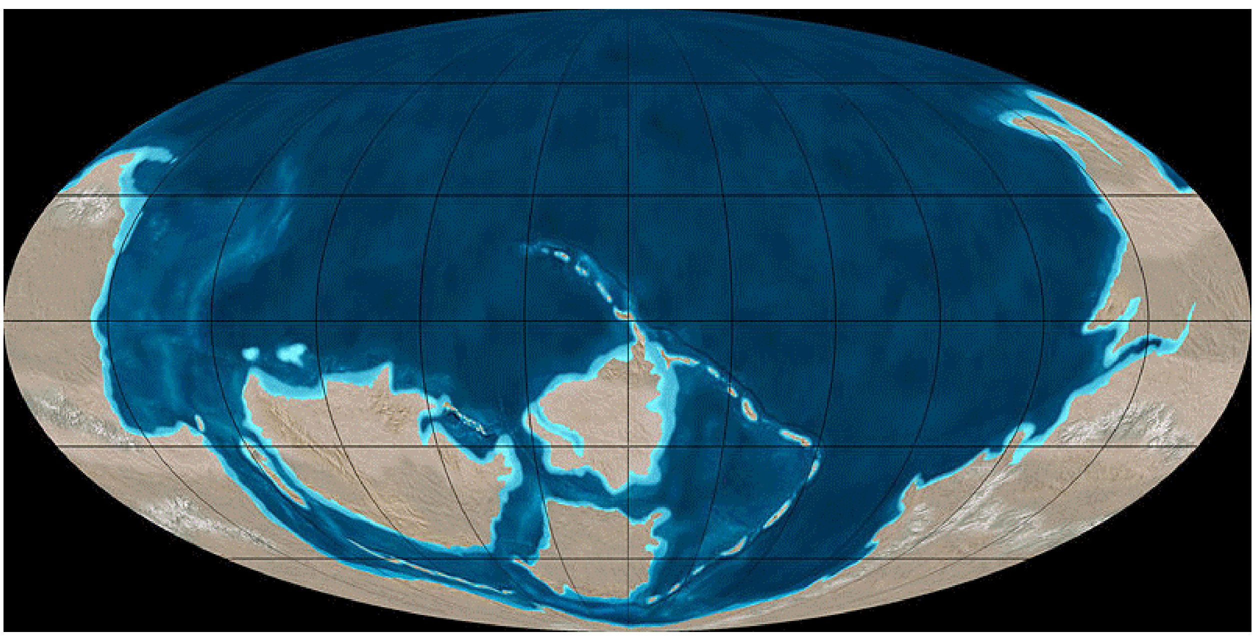
sides of the Atlantic would best fit to close the ocean, which became known as the famous "Bullard's Fit".

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

Implications for biogeography

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

Plate reconstruction



Reconstruction of plate configurations for the whole Phanerozoic

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

Defining plate boundaries

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

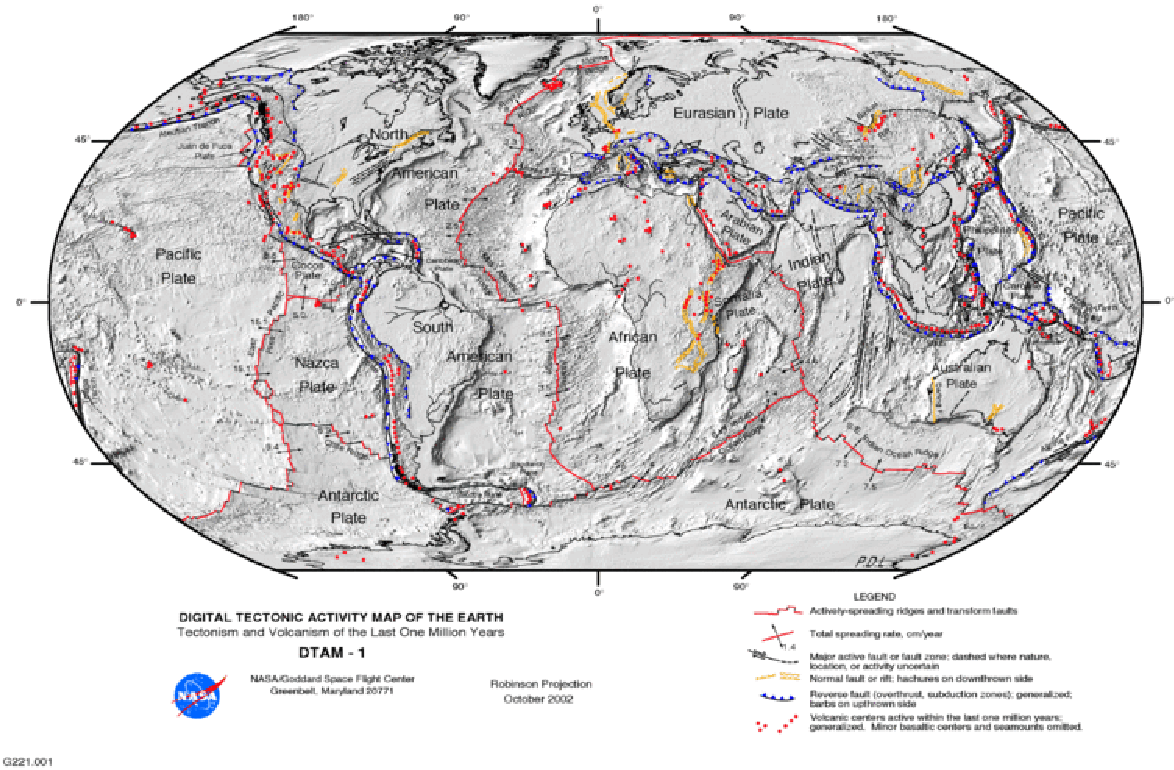
Past plate motions

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

Formation and break-up of continents

The movement of plates has caused the formation and break-up of continents over time, including occasional formation of a supercontinent that contains most or all of the continents. The supercontinent Columbia or Nuna formed during a period of 2.0–1.8 billion years and broke up about 1.5–1.3 billion years ago. The supercontinent Rodinia is thought to have formed about 1 billion years ago and to have embodied most or all of Earth's continents, and broken up into eight continents around 600 million years ago. The eight continents later re-assembled into another supercontinent called Pangaea; Pangaea broke up into Laurasia (which became North America and Eurasia) and Gondwana (which became the remaining continents).

Current plates



Major plates

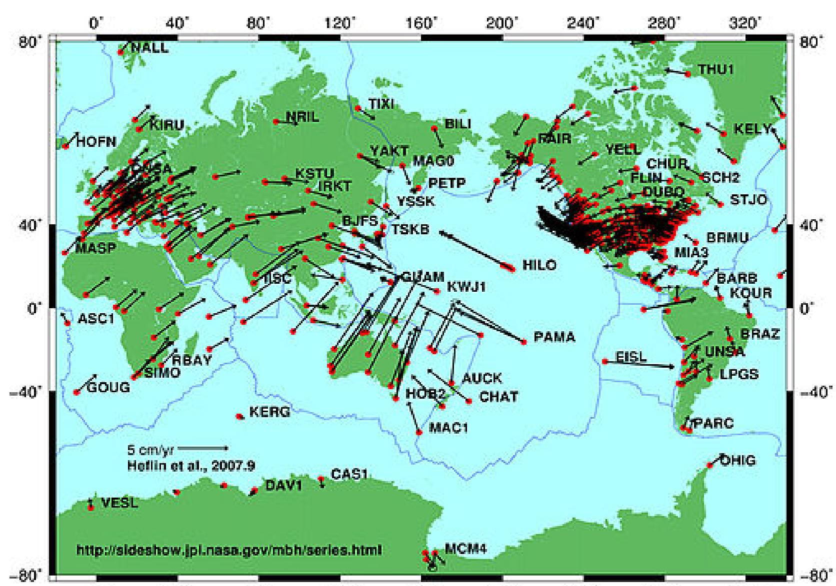


Plate motion based on Global Positioning System (GPS) satellite data from NASA JPL. The vectors show direction and magnitude of motion.

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

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

Minor plates

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

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

Current motion

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

Plate tectonics on other celestial bodies (planets, moons)

The appearance of plate tectonics on terrestrial planets is related to planetary mass, with more massive planets than Earth expected to exhibit plate tectonics. Earth may be a borderline case, owing its tectonic activity to abundant water (Silica and water form a deep eutectic.)

Venus

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

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

Mars

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

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

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

Galilean satellites of Jupiter

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

Titan, moon of Saturn

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

Exoplanets

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