Physical Geography and Natural Disasters

PHYSICAL GEOGRAPHY AND NATURAL DISASTERS

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PART I

INTRODUCTION TO GEOGRAPHIC SCIENCE

1.1 SCIENCE AS A WAY OF KNOWING

The Nature of Science

Science can be defined as the systematic examination of the natural world's structure and functioning, including its physical and biological attributes. Science is also a rapidly expanding body of knowledge, whose ultimate goal is to discover the most straightforward general principles that can explain the enormous complexity of nature. These principles can be used to gain insights into the natural world and make predictions about future change.

Science is a relatively new way of learning about natural phenomena, having largely replaced the influences of less objective methods and world views. The primary alternatives to science are **belief systems** that are influential in all cultures, including those based on religion, morality, and aesthetics. These belief systems are primarily directed toward different ends than science, such as finding meaning that transcends mere existence, learning how people ought to behave, and understanding the value of artistic expression. (Environmental Science – Simple Book Publishing, n.d.)

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Modern science evolved from a way of learning called **natural philosophy**, which was developed by classical Greeks and was concerned with the rational investigation of existence, knowledge, and phenomena. Compared with modern science, however, studies in natural philosophy used unsophisticated technologies and methods and were not mainly quantitative, sometimes involving only the application of logic.

Inductive and Deductive Logic

The English philosopher Francis Bacon (1561-1626) was highly influential in the development of modern science. Bacon was not an actual practitioner of science but was a strong proponent of its emerging methodologies. He promoted the application of **inductive logic**, in which conclusions are developed from the accumulating evidence of experience and the results of experiments. Inductive logic can lead to unifying explanations based on large bodies of data and observations of phenomena. Consider the following illustration of inductive logic, applied to an environmental topic:

- Observation 1: Marine mammals off the Atlantic coast have significant DDT residues and other chlorinated hydrocarbons in their fat and other body tissues.
- Observation 2: So do marine mammals off British Columbia.
- Observation 3: As do those in the Arctic Ocean, although in lower concentrations.

Inductive conclusion: There is widespread contamination of marine mammals with chlorinated hydrocarbons. Further research may demonstrate that contamination is a global phenomenon. This suggests a potentially crucial environmental problem. (Environmental Science – Simple Book Publishing, n.d.)

In contrast, **deductive logic** involves making one or more initial assumptions and then drawing logical conclusions from those premises. Consequently, the truth of a deductive conclusion depends on the veracity of the original assumptions. If those assumptions are based on false information or supernatural beliefs, then any deduced conclusions are likely to be wrong. Consider the following illustration of deductive logic:

- Assumption 1: TCDD, an extremely toxic chemical in the dioxin family, is poisonous when present in even the smallest concentrations in food and water – even a single molecule can cause toxicity.
- Assumption 2: Exposure to anything poisonous in even the smallest concentrations is unsafe.
- Assumption 3: No unsafe exposure should be allowed.

Deductive conclusion 1: No exposure to TCDD is safe.
Deductive conclusion 2: No emissions of TCDD should be allowed.

The two conclusions are consistent with the original assumptions. However, there is disagreement among highly qualified scientists about those assumptions. Many toxicologists believe that exposure to TCDD (and any other potentially toxic chemicals) must exceed a threshold of biological tolerance before poisoning results. In contrast, other scientists believe that even the smallest exposure to TCDD carries some degree of toxic risk. Thus, the strength of deductive logic depends on the acceptance and truth of the original assumptions from which its conclusions flow.

In general, inductive logic plays a much stronger role in modern science than does deductive logic. In both cases, however, the usefulness of any conclusions depends significantly on the accuracy of any observations and other data on which they were based. Poor data may lead to an inaccurate conclusion through the application of inductive logic, as will inappropriate assumptions in deductive logic. (Environmental Science – Simple Book Publishing, n.d.)

Understanding Science

Scientists seek to understand the fundamental principles that explain natural patterns and processes. Science is more than just a body of knowledge; *science provides a means to evaluate and create new knowledge without bias.* Scientists use objective evidence over subjective evidence to reach sound and logical conclusions.

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Objective observation is without personal bias and the same by all individuals. Humans are biased by nature, so they cannot be completely objective; the goal is to be unbiased. A subjective observation is based on a person's feelings and beliefs and is unique to that individual.

Another way scientists avoid bias is by using quantitative over qualitative measurements whenever possible. **Quantitative measurement** is expressed with a specific numerical value. Qualitative observations are general or relative descriptions. For example, describing a rock as red or heavy is a qualitative observation. Determining a rock's color by measuring wavelengths of reflected light or its density by measuring the proportions of minerals it contains is quantitative. Numerical values are more precise than general descriptions, and they can be analyzed using statistical calculations. This is why quantitative measurements are much more useful to scientists than qualitative observations.

It is challenging to establish truth in science because all scientific claims are falsifiable, which means any initial hypothesis may be tested and proven false. Only after exhaustively eliminating false results, competing ideas, and possible variations does a hypothesis become regarded as a reliable scientific theory. This meticulous scrutiny reveals weaknesses or flaws in a hypothesis and is the strength that supports all scientific ideas and procedures. Proving current ideas are wrong has been the driving force behind many scientific careers.

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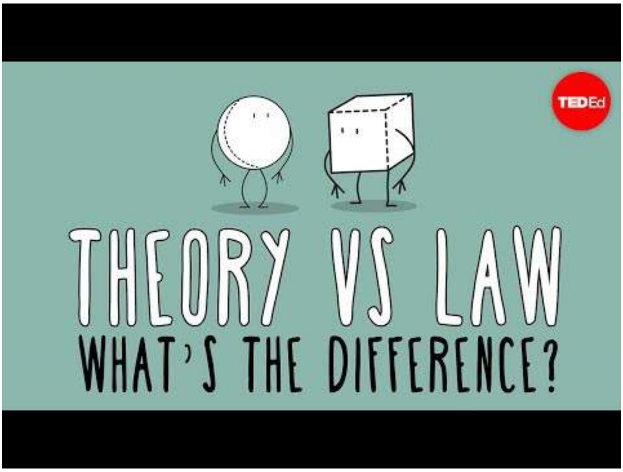
Falsifiability separates science from pseudoscience. Scientists are wary of explanations of natural phenomena that discourage or avoid falsifiability. An explanation that cannot be tested or does not meet scientific standards is not considered science, but pseudoscience. **Pseudoscience** is a collection of ideas that may appear scientific but does not use the scientific method. Astrology is an example of pseudoscience. It is a belief system that attributes the movement of celestial bodies to influencing human behavior. Astrologers rely on celestial observations, but their conclusions are not based on experimental evidence, and their statements are not falsifiable. This is not to be confused with astronomy, which is the scientific study of celestial bodies and the cosmos.

Science is also a social process. Scientists share their ideas with peers at conferences, seeking guidance and feedback. Research papers and data submitted for publication are rigorously reviewed by qualified peers, scientists who are experts in the same field. The scientific review process aims to weed out misinformation, invalid research results, and wild speculation. Thus, it is slow, cautious, and conservative. Scientists tend to wait until a hypothesis is supported by an overwhelming amount of evidence from many independent researchers before accepting it as a scientific theory.

Goals of Science

The broad goals of science are to understand natural phenomena and explain how they may be changing over time. To achieve those goals, scientists undertake investigations based on information, inferences, and conclusions developed through a systematic application of logic, usually of the inductive sort. As such, scientists carefully observe natural phenomena and conduct experiments.

A higher goal of scientific research is to formulate laws that describe the workings of the universe in general terms. Universal laws, along with theories and hypotheses, are used to understand and explain natural phenomena. However, many natural phenomena are incredibly complicated and may never be fully understood in terms of physical laws. This is particularly true of the ways that organisms and ecosystems are organized and function.



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Scientific investigations may be pure or applied. Pure science is driven by intellectual curiosity – it is the unfettered search for knowledge and understanding, without regard for its usefulness in human welfare. Applied science is more goal-oriented and deals with practical difficulties and problems of one sort or another. Applied science might examine how to improve technology, advance the management of natural resources, or reduce pollution or other environmental damages associated with human activities. (Environmental Science – Simple Book Publishing, n.d.)

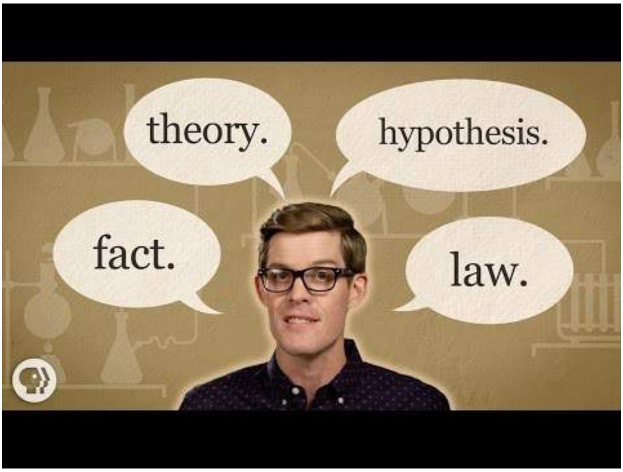
Facts, Hypotheses, and

Experiments

A **fact** is an event or thing known to have happened, to exist, and to be true. Facts are based on experience and scientific evidence. In contrast, a **hypothesis** is a proposed explanation for the occurrence of a phenomenon. Scientists formulate hypotheses as statements and then test them through experiments and other forms of research. Hypotheses are developed using logic, inference, and mathematical arguments in order to explain observed phenomena. However, it must always be possible to refute a scientific hypothesis. Thus, the hypothesis that "cats are so intelligent that they prevent humans from discovering it" cannot be logically refuted, and so it is not a scientific hypothesis.

A **theory** is a broader conception that refers to a set of explanations, rules, and laws. These are supported by a large body of observational and experimental evidence, all leading to robust conclusions. The following are some of the most famous theories in science:

- the theory of gravitation, first proposed by Isaac Newton (1642-1727)
- the theory of evolution by natural selection published simultaneously in 1858 by two English naturalists, Charles Darwin (1809-1882) and Alfred Russel Wallace (1823-1913)
- the theory of relativity, identified by the German-Swiss physicist, Albert Einstein (1879-1955)



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Large bodies of evidence strongly support celebrated theories like these, and they will likely persist for a long time. However, we cannot say that these (or any other) theories are known with certainty to be exact – some future experiments may yet falsify even these famous theories. (Environmental Science – Simple Book Publishing, n.d.)

Scientific Method

The **scientific method** begins with identifying a question involving the structure or function of the natural world, which is usually developed using inductive logic. The question is interpreted in terms of existing theory, and specific hypotheses are formulated to explain the character and causes of the natural phenomenon. The research might involve observations made in nature or carefully controlled experiments, and the results usually give scientists reasons to reject hypotheses rather than accept them. Most hypotheses are rejected because their predictions are not borne out during research. Any viable hypotheses are further examined through additional research, primarily involving experiments designed to disprove their predictions. Once a large body of evidence accumulates in support of a hypothesis, it can corroborate the original theory.

The scientific method is only to investigate questions that can be critically examined through observation and experiment. Consequently, science cannot resolve value-laden questions, such as the meaning of life, good versus evil, or the existence and qualities of God or any other supernatural being or force.

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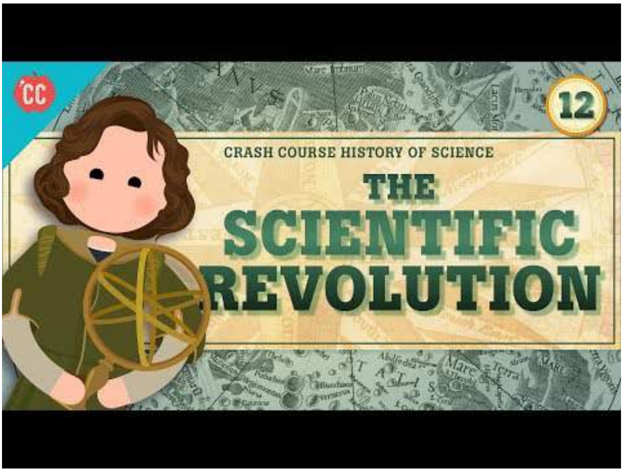
An **experiment** is a test or investigation designed to provide evidence in support of, or preferably against, a hypothesis. A **natural experiment** is conducted by observing actual variations of phenomena in nature, and then developing explanations by analyzing possible causal mechanisms. A **manipulative experiment** involves the deliberate alteration of factors that are hypothesized to influence phenomena. The manipulations are carefully planned and controlled to determine whether predicted responses will occur, thereby uncovering causal relationships.

By far, the most useful working hypotheses in scientific research are designed to disprove rather than support. A **null hypothesis** is a specific testable investigation that denies something implied by the central hypothesis being studied. Unless null hypotheses are eliminated based on contrary evidence, we cannot be confident of the central hypothesis. (Environmental Science – Simple Book Publishing, n.d.)

This is an essential aspect of scientific investigation. For instance, a particular hypothesis might be supported by many confirming experiments or observations. However, this does not serve to "prove" the hypothesis; instead, it only supports its conditional acceptance. As soon as a clearly defined hypothesis is falsified by an appropriately designed and well-conducted experiment, it is disproved for all time. This is why experiments designed to disprove hypotheses are a vital aspect of the scientific method.

Revolutionary advances in understanding may occur when an important hypothesis or theory is rejected through discoveries of science. For instance, once it was discovered that the Earth is not flat, it became possible to sail beyond the visible horizon confidently without fear of falling off the edge of the world. Another example involved the discovery by Copernicus that the planets of our solar system revolve around the Sun. The related concept that the Sun is an ordinary star among many – these revolutionary ideas replaced the previously dominant one that the planets, Sun, and stars all revolved around the Earth.

Thomas Kuhn (1922-1995) was a philosopher of science who emphasized the critical role of "scientific revolutions" in achieving significant advances in our understanding of the natural world. In essence, Kuhn (1996) said that a scientific revolution occurs when a well-established theory is rigorously tested and then collapses under the accumulating weight of new facts and observations that cannot be explained. This renders the original theory obsolete, to be replaced by a new, more informed paradigm (i.e., a set of assumptions, concepts, practices, and values that constitutes a way of viewing reality and is shared by an intellectual community).



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A **variable** is a factor that is believed to influence a natural phenomenon. For example, a scientist might hypothesize that the productivity of a wheat crop is potentially limited by such variables as the availability of water or nutrients such as nitrogen and phosphorus. Some of the most powerful scientific experiments involve manipulating key (or controlling) variables and comparing the results of those treatments with a control that was not manipulated. In the example just described, the specific variable that controls wheat productivity could be identified by conducting an experiment in which test populations are provided with varying amounts of water, nitrogen, and phosphorus, alone and in combination, and then comparing the results with a non-manipulated control.

In some respects, however, the explanation of the scientific method offered above is a bit uncritical. It perhaps suggests a too-orderly progression in terms of logical, objective experimentation and comparison of alternative hypotheses. These are, in fact, essential components of the scientific method. Nevertheless, it is essential to understand that scientists' insights and personal biases are also significant in the conduct and progress of science. In most cases, scientists design research that they think will "work" to yield useful results and contribute to the orderly advancement of knowledge in their field. Karl Popper (1902-1994), a European philosopher, noted that scientists tend to use their "imaginative preconception" of the workings of the natural world to design experiments based on their informed insights. This means that competent scientists must be more than knowledgeable and technically skilled – they should also be capable of a degree of insightful creativity when forming their ideas, hypotheses, and research. (Environmental Science – Simple Book Publishing, n.d.)

Uncertainty

Much scientific investigation involves the collection of observations by measuring phenomena in the natural world. Another essential aspect of science involves making predictions values of variables.

Such projections require a degree of understanding of the relationships among variables, influencing factors, and recent patterns of change. However, many kinds of scientific information and predictions are subject to inaccuracy. This occurs because measured data are often approximations of the true values of phenomena, and predictions are rarely fulfilled precisely. The accuracy of observations and predictions is influenced by various factors, primarily those described in the following sections. (Environmental Science – Simple Book Publishing, n.d.)

Predictability

A few phenomena are considered to have a universal character and are consistent wherever and whenever they are accurately measured. One of the best examples of such a universal constant is the speed of light, which always has a value of 2.998 × 108 meters per second, regardless of where it is measured or of the speed of the body from which the light is emitted. Similarly, certain relationships describing transformations of energy and matter, known as the laws of thermodynamics, always give reliable predictions.

However, most natural phenomena are not consistent – depending on circumstances, there are exceptions to general predictions about them. This circumstance is particularly true of biology and ecology, related fields of science in which almost all general predictions have exceptions. Laws or unifying principles of biology or ecology have not yet been discovered, compared to the several esteemed laws and 11 universal constants of physics. Thus, biologists and ecologists have great difficulties making accurate predictions about the responses of organisms and ecosystems to environmental change.

Variability

Many natural phenomena are highly variable in space and time. This is true of physical and chemical variables as well as biological and ecological ones. Within a forest, the amount of sunlight reaching the ground varies significantly with time, depending on the hour of the day and the season of the year. It varies spatially, depending on the density of foliage over any place where sunlight is being measured. Similarly, the density of a particular species of fish within a river typically varies in response to changes in habitat conditions and other influences. Most fish populations also vary over time, mainly migratory species such as salmon. In environmental science, replicated (or independently repeated) measurements and statistical analyses are used to measure and account for these temporal and spatial variations.

Accuracy and Precision

Accuracy refers to the degree to which a measurement or observation reflects the actual or true value of the subject. For example, the insecticide DDT and the metal mercury are potentially toxic chemicals that occur in trace concentrations in all organisms, but their small residues are challenging to analyze chemically. Some of the analytical methods used to determine the concentrations of DDT and mercury are more accurate than others and provide relatively useful and reliable data compared with less accurate methods. Analytical data are usually approximations of the real values – rigorous accuracy is rarely attainable.

Precision is related to the degree of repeatability of a measurement or observation. For example, suppose that the actual number of caribou in a migrating herd is 10,246 animals. A wildlife ecologist might estimate that there were about 10,000 animals in that herd, which for practical purposes is a reasonably accurate reckoning of the actual number of caribou. If other ecologists also independently estimate the herd's size at about 10,000 caribou, there is a reasonable degree of precision among the values. If, however, some systematic bias existed in the methodology used to count the herd, giving consistent estimates of 15,000 animals (remember, the actual population is 10 246 caribou), these estimates would be considered precise, but not particularly accurate.

Precision is also related to the number of digits with which data are reported. If you were using a flexible tape to measure the lengths of 10 large, wriggly snakes, you would probably measure the reptiles only to the nearest centimeter. The strength and squirminess of the animals make more precise measurements impossible. The reported average length of the ten snakes should reflect the original measurements and might be given 204 cm and not a value such as 203.8759 cm. The latter number might be displayed as a digital average by a calculator or computer, but it is unrealistically precise.

Significant figures are related to accuracy and precision and can be defined as the number of digits used to report data from analyses or calculations. Examples most easily understand significant figures. The number 179 has three significant figures, as does the number of 0.0849 and 0.000794 (the zeros preceding the significant integers do not count). However, the number 195,000,000 has nine significant figures (the zeros following are meaningful), although the number 195 × 106 has only three significant figures.

It is rarely useful to report environmental or ecological data to more than 2-4 significant figures. This is because any more would generally exceed the accuracy and precision of the methodology used in the estimation and would be unrealistic. For example, the United States approximate population in 2020 was 330 million people, (or 330 × 106; both of these notations have three significant figures). However, the population should not be reported as 333,000,000, which implies an unrealistic accuracy and precision of eight significant figures.

A Need for Scepticism

Environmental science is filled with many examples of uncertainty – in present values and future changes of environmental variables and predictions of biological and ecological responses to those changes. To some degree, the difficulties associated with scientific uncertainty can be mitigated by developing improved methods and technologies for analysis and modeling and examining changes occurring in different parts of the world. The latter approach enhances our understanding by providing convergent evidence about the occurrence and causes of natural phenomena.

However, scientific information and understanding will always be subject to some degree of uncertainty. Therefore, predictions will always be inaccurate to some extent, and this uncertainty must be considered when trying to understand and deal with the causes and consequences of environmental changes. As such, all information and predictions in environmental science must be critically interpreted with uncertainty in mind. This should be done whenever one is learning about an environmental issue, whether it involves listening to a speaker in a classroom, at a conference, or on video, or when reading an article in a newspaper, textbook, website, or scientific journal. Because of the uncertainty of many predictions in science, and particularly in the environmental realm, a certain amount of skepticism and critical analysis is always useful.

Environmental issues are acutely important to the welfare of people and other species. Science and its methods allow for a critical and objective identification of crucial issues, the investigation of their causes, and a degree of understanding of the consequences of environmental change. Scientific information influences decision making about environmental issues, including whether to pursue expensive strategies to avoid further, but often uncertain, damage.

However, scientific information is only one consideration for decision-makers, who are also concerned with the economic, cultural, and political contexts of environmental problems. When deciding how to deal with the causes and consequences of environmental changes, decision-makers may give greater weight to non-scientific (social and economic) considerations than scientific ones, especially when there is uncertainty about the latter. The most critical decisions about environmental issues are made by politicians and senior bureaucrats in government, or by private managers, rather than by environmental scientists. Decision-makers typically worry about the short-term implications of their decisions on their chances for re-election or continued employment, and on the economic activity of a company or society at large, as much as they do about environmental damage. (Environmental Science – Simple Book Publishing, n.d.) That is why the United States struggled so much with the COVID-19 pandemic. On one end of the response, was a focus on health science. On the other were economists worried about collapsing the economy. It was ultimately up to politicians to make the decision on how much the nation should "lockdown" and how much the nation needed to stay economically "open."

Science Denial and Evaluating Sources

Introductory science courses usually deal with accepted scientific theory and do not include opposing ideas, even though these alternate ideas may be credible. This makes it easier for students to understand complex material. Advanced students will encounter more controversies as they continue to study their discipline.

Some groups argue that some established scientific theories are wrong, not based on their scientific merit but the group's ideology. This section focuses on how to identify evidence-based information and differentiate it from pseudoscience.

Science Denial

Science denial happens when people argue that established scientific theories are wrong, not based on scientific merit but rather on subjective ideology – such as for social, political, or economic reasons. Organizations and people use science denial as a rhetorical argument against issues or ideas they oppose. Three examples of science denial versus science are:

- Teaching evolution in public schools
- Linking tobacco smoke to cancer
- Linking human activity to climate change.

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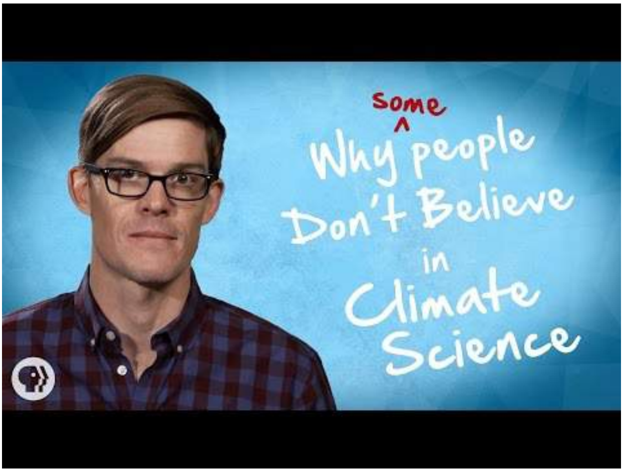
Among these, denial of climate change is strongly connected with geography. A climate denier denies explicitly or doubts the objective conclusions of geologists and climate scientists. Science denial generally uses three false arguments. The first argument tries to undermine the scientific conclusion's credibility by claiming the research methods are flawed, or the theory is not universally accepted—the science is unsettled. The notion that scientific ideas are not absolute creates doubt for non-scientists; however, a lack of universal truths should not be confused with scientific uncertainty. Because science is based on falsifiability, scientists avoid claiming universal truths and use language that conveys uncertainty. This allows scientific ideas to change and evolve as more evidence is uncovered.



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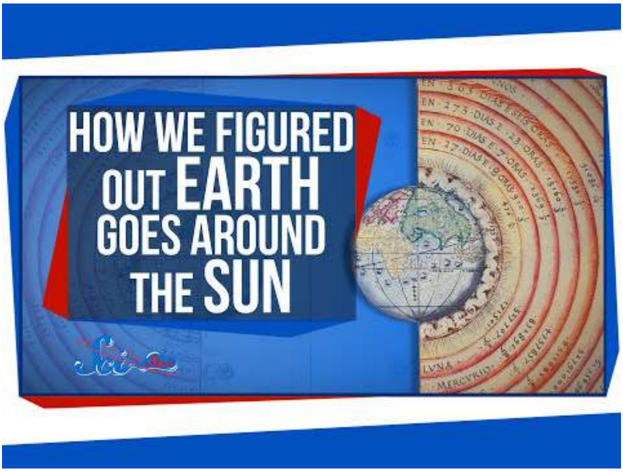
The second argument claims the researchers are not objective and motivated by ideology or economic agenda. This is an *ad hominem* argument in which a person's character is attacked instead of the merit of their argument. They claim results have been manipulated so researchers can justify asking for more funding. They claim that because a federal grant funds the researchers, they are using their results to lobby for expanded government regulation.

The third argument is to demand a balanced view, equal time in media coverage, and educational curricula to engender the false illusion of two equally valid arguments. Science deniers frequently demand equal coverage of their proposals, even when there is little scientific evidence supporting their ideology. For example, science deniers might demand religious explanations to be taught as an alternative to the well-established theory of evolution. Alternatively, all possible causes of climate change are discussed as equally probable, regardless of the body of evidence. Conclusions derived using the scientific method should not be confused with those based on ideologies.

Furthermore, conclusions about nature derived from ideologies have no place in science research and education. For example, it would be inappropriate to teach the flat earth model in modern geography or earth science courses because this idea has been disproved by the scientific method. Unfortunately, widespread scientific illiteracy allows these arguments to be used to suppress scientific knowledge and spread misinformation.



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The formation of new conclusions based on the scientific method is the only way to change scientific conclusions. We would not teach Flat Earth geology and plate tectonics because Flat Earthers do not follow the scientific method. The fact that scientists avoid universal truths and change their ideas as more evidence is uncovered should not be seen as meaning that the science is unsettled. Because of widespread scientific illiteracy, these arguments are used by those who wish to suppress science and misinform the general public.

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In a classic case of science denial, beginning in the 1960s and for the next three decades, the tobacco industry and their scientists used rhetorical arguments to deny a connection between tobacco usage and cancer. Once it became clear scientific studies overwhelmingly found that using tobacco dramatically increased a person's likelihood of getting cancer, their next strategy was to create a sense of doubt about the science. The tobacco industry suggested the results were not yet fully understood, and more study was needed. They used this doubt to lobby for delaying legislative action to warn consumers of the potential health hazards. This tactic is currently employed by those who deny the significance of human involvement in climate change.

Evaluating Sources of Information

In the age of the internet, information is plentiful. Geologists, scientists, or anyone exploring scientific inquiry must discern valid sources of information from pseudoscience and misinformation. This evaluation is especially critical in scientific research because scientific knowledge is respected for its reliability. Textbooks such as this one can aid this complex and crucial task. At its roots, quality information comes from the scientific method, beginning with the empirical thinking of Aristotle. The application of the scientific method helps produce unbiased results. A valid inference or interpretation is based on objective evidence or data. Credible data and inferences are clearly labeled, separated, and differentiated. Anyone looking over the data can understand how the author's conclusion was derived or come to an alternative conclusion.

Scientific procedures are clearly defined, so the investigation can be replicated to confirm the original results or expanded further to produce new results. These measures make a scientific inquiry valid and its use as a source reputable. Of course, substandard work occasionally slips through, and retractions are published from time to time. An infamous article linking the MMR vaccine to autism appeared in the highly reputable journal *Lancet* in 1998. Journalists discovered that the author had multiple conflicts of interest and fabricated data, and the article was retracted in 2010.

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In addition to methodology, data, and results, the authors of a study should be investigated. When looking into any research, the author(s) should be investigated. An author's credibility is based on multiple factors, such as having a degree in a relevant topic or being funded from an unbiased source.

The same rigor should be applied to evaluating the publisher, ensuring the results reported come from an unbiased process. The publisher should be easy to discover. Good publishers will show the latest papers in the journal and make their contact information and identification clear. Reputable journals show their peer review style. Some journals are predatory, where they use unexplained and unnecessary fees to submit and access journals. Reputable journals have recognizable editorial boards. Often, a reputable journal will associate with a trade, association, or recognized open-source initiative.

One of the hallmarks of scientific research is peer review. Research should be transparent to peer review. This allows the scientific community to reproduce experimental results, correct and retract errors, and validate theories. This allows the reproduction of experimental results, corrections of errors, and proper justification of the research to experts.

Citation is imperative to avoid plagiarism, and also allows readers to investigate an author's line of thought and conclusions. When reading scientific works, it is essential to confirm that the citations are from reputable scientific research. Most often, scientific citations are used to reference paraphrasing rather than quotes. The number of times a work is cited is said to measure the investigation has within the scientific community, although this technique is inherently biased. (Environmental Science – Simple Book Publishing, n.d.)

Critical Evaluation of an Overload of Information

More so than any previous society, we live today in a world of accessible and abundant information. It has become remarkably easy for people to communicate with others over vast distances, turning the world into a "global village" (a phrase coined by Marshall McLuhan (1911-1980), a Canadian philosopher, to describe the phenomenon of universal networking). Technologies have facilitated this global connectedness for transferring ideas and knowledge – mainly electronic communication devices, such as radio, television, computers, and their networks. Today, these technologies compress space and time to achieve a virtually instantaneous communication. So much information is now available that the situation is often referred to as an "information overload" that must be analyzed critically. **Critical analysis** is the process of sorting information and making scientific inquiries about data. Involved in all aspects of the scientific process, critical analysis scrutinizes information, and research by posing sensible questions such as the following:

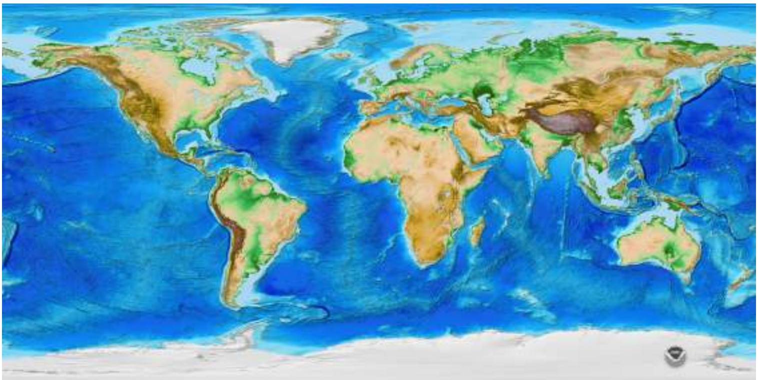
- Is the information derived from a scientific framework consisting of a hypothesis that has been developed and tested within the context of an existing body of knowledge and theory in the field?
- Were the methodologies used likely to provide data that are objective, accurate, and precise? Were the data analyzed using statistical methods appropriate to the data structure and the questions being asked?
- Were the results of the research compared with other pertinent work that has been previously published? Were key similarities and differences discussed and a conclusion deduced about what the new work reveals about the issue being investigated?
- Is the information based on research published in a refereed journal that requires highly qualified reviewers in the subject area to scrutinize the work, followed by an editorial decision about whether it warrants publication?
- If the analysis of an issue was based on incomplete or possibly inaccurate information, was a precautionary approach used to

accommodate the uncertainty inherent in the recommendations? All users of published research have an obligation to critically evaluate what they are reading in these ways in order to decide whether the theory is appropriate, the methodologies reliable, and the conclusions sufficiently robust. Because so many environmental issues are controversial, with data and information presented on both sides of the debate, people need to formulate objectively critical judgments. Thus, people need a high degree of environmental literacy – an informed understanding of the causes and consequences of environmental damage. Being able to analyze information critically is a key personal benefit of studying environmental science.

1.2 GEOGRAPHY AS A SCIENCE

Geography is the spatial study of the earth's physical and cultural environments. Geographers study the earth's physical characteristics, its inhabitants and cultures, phenomena such as climate, and the earth's place within the universe. Geography also examines the spatial relationships between all physical and cultural phenomena in the world. Furthermore, geographers also look at how the earth, its climate, and its landscapes are changing due to cultural intervention. Geography is a much broader field than many people realize. Most people think of area studies as the whole of geography. In reality, geography is the study of the earth, including how human activity has changed it. Geography involves studies that are much broader than merely understanding the shape of the earth's landforms. Physical geography involves all the planet's physical systems. Human geography incorporates studies of human culture, spatial relationships, interactions between humans and the environment, and many other research areas that involve the different subspecialties of geography. Students interested in a career in geography would be well served to learn geospatial techniques and gain skills and experience in GIS and remote sensing, as they are the areas within geography where employment opportunities have grown the most over the past few decades.

Themes of Geography



"Pathemetric Data" by NOAA is licensed under Public Domain.

Geography helps us make sense of the world through four historical traditions. **Spatial analysis** includes many of the concepts tied to geospatial technology: the study and analysis between the interactions and distribution patterns of the physical and human environments using spatial technology such as geographic information systems, satellite imagery, aerial photography and drones, global positioning systems, and more. **Earth science** includes the study of landforms, climates, and the distribution of plants and animals. **Regional studies** focus on a particular region to understand the dynamics of a specific interaction between human activity and the environment. Researchers studying **human-landscape interaction** examine the impact of humans on their landscape and find out how different cultures have used and changed their environments. Geography provides the tools to integrate knowledge from many disciplines into a usable form by providing a sense of place to natural or human events. Geography often explains why or how something occurs in a specific location. World geography utilizes the spatial approach to help understand the components of our global community.

The discipline of geography can be broken down into three fundamental areas of focus: physical geography, human geography, and world regional geography. These fundamental areas are similar in that they use a spatial perspective, and include the study of place and the comparison of one place with another.

Physical Geography

Physical geography is the spatial study of natural phenomena that make up the environment, such as rivers, mountains, landforms, weather, climate, soils, plants, and any other physical aspects of the earth's surface. Physical geography focuses on geography as a form of earth science. It tends to emphasize the main physical parts of the earth – the lithosphere (surface layer), the atmosphere (air), the hydrosphere (water), and the biosphere (living organisms)—and the relationships between these parts.

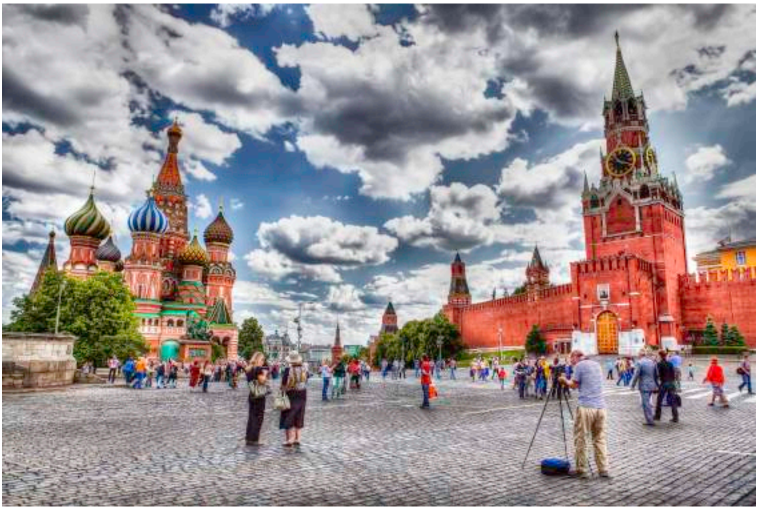
"Merapi in Java, Indonesia" by Brigitte Werner is licensed as Public Domain.

Some researchers are environmental geographers, part of an emerging field that studies the spatial aspects and cultural perceptions of the natural environment. **Environmental geography** requires an understanding of both physical and human geography, as well as an understanding of how humans conceptualize their environment and the physical landscape.

The **physical landscape** is the term used to describe the natural terrain at any one place on the planet. The natural forces of erosion, weather, tectonic plate action, and water have formed the earth's physical features. Many states and national parks in the United States attempt to preserve unique physical landscapes for the public to enjoy, such as Yellowstone, Yosemite, and the Grand Canyon.

Human Geography

Human geography is the study of human activity and its relationship to the earth's surface. Human geographers examine the spatial distribution of human populations, religions, languages, ethnicities, political systems, economics, urban dynamics, and other components of human activity. They study patterns of interaction between human cultures and various environments and focus on the causes and consequences of human settlement and distribution over the landscape. While the economic and cultural aspects of humanity are the primary focus of human geography, these aspects cannot be understood without describing the landscape on which economic and cultural activities occur.



"Red Square, Moscow, Russia" by Valerii Tkachenko is licensed under the Creative Commons Attribution 2.0 Generic license.

The **cultural landscape** is the term used to describe those parts of the earth's surface that have been altered or created by humans. For example, the urban cultural landscape of a city may include buildings, streets, signs, parking lots, or vehicles, while the rural cultural landscape may consist of fields, orchards, fences, barns, or farmsteads. Cultural forces unique to a given place – such as religion, language, ethnicity, customs, or heritage – influence the cultural landscape of that place at a given time. The colors, sizes, and shapes of the cultural landscape usually symbolize some level of significance regarding societal norms. Spatial dynamics assist in identifying and evaluating cultural differences between places.

World Regional Geography

World regional geography studies various world regions as they compare with the rest of the world. Factors for comparison include both the physical and the cultural landscape. The main questions are, Who lives there? What are their lives like? What do they do for a living? Physical factors of significance can include location, climate type, and terrain. Human factors include cultural traditions, ethnicity, language, religion, economics, and politics.

"Big Ben, London" by Pixabay.

World regional geography focuses on regions of various sizes across the earth's landscape and aspires to understand the unique character of regions in terms of their natural and cultural attributes. Spatial studies can play an essential role in regional geography. The scientific approach can focus on the distribution of cultural and natural phenomena within regions as delimited by various natural and cultural factors. The focus is on the spatial relationships within any field of study, such as regional economics, resource management, regional planning, and landscape ecology.

The regions studied in world regional geography can be combined into more substantial portions called realms. **Realms** are large areas of the planet, usually, with multiple regions that share the same general geographic location. Regions are cohesive areas within each realm.

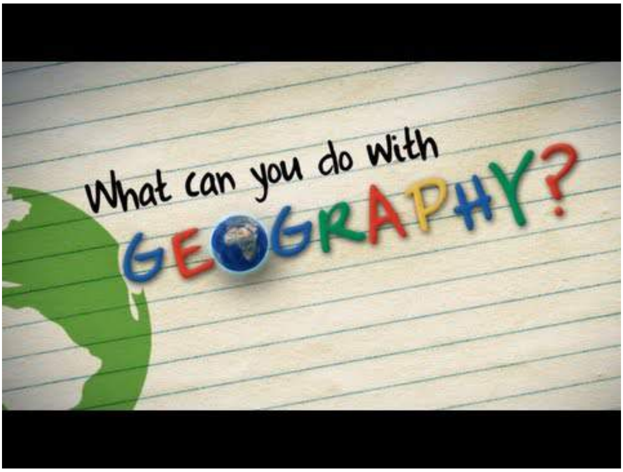
Careers in Geography and GIS

Geography is not a discipline of endlessly memorizing capitals, countries, rivers, mountain ranges, and more. The discipline is about scientifically analyzing the spatial and temporal distribution, connections, and patterns of the physical and cultural environments we live within.

The following information on careers in geography is from the website of the Association of American Geographers (AAG), which is a resource for those interested in pursuing employment in the field of geography.

Many occupations require knowledge of and skills in geography. Geographers work in many different areas, such as environmental management, education, disaster response, city and county planning, community development, and more. Geography is an interdisciplinary field that offers diverse career opportunities.

Many geographers pursue rewarding careers in business; local, state, or federal government agencies, nonprofit organizations; and schools. Geographers with graduate (master's and doctorate) degrees may become educators in higher education (community colleges and universities).



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Because of modern location technology such as GPS, web-based mapping technology, satellite imagery, and now small unmanned aerial systems – also known as drones – careers in geospatial technology are exploding. The U.S. Department of Labor, in partnership with the National Geospatial Technology Center for Excellence, has created the Geospatial Technology Competency Model (GTCM) as a way to have industry help determine what knowledge and skillsets are needed to be successful in this career path. The global leader in GIS, Environmental Systems Research Institute (ESRI), has created a great resource of industries that use geospatial technology.

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1.3 GEOGRAPHIC LITERACY

Spatial Thinking

At no other time in the history of the world has it been easier to create or to acquire a map of nearly anything. Maps and mapping technology are literally and virtually everywhere. Though the modes and means of making and distributing maps have been revolutionized with recent advances in computing like the Internet, the art and science of map-making dates back centuries. This is because humans are inherently spatial organisms, and in order for us to live in the world, we must first somehow relate to it. Enter the mental map.

Mental Maps

Mental or cognitive maps are psychological tools that we all use every day. As the name suggests, **mental maps** are maps of our environment that are stored in our brains. We rely on our mental maps to get from one place to another, to plan our daily activities, or to understand and situate events that we hear about from our friends, family, or the news. Mental maps also reflect the amount and extent of geographic knowledge and spatial awareness that we possess.

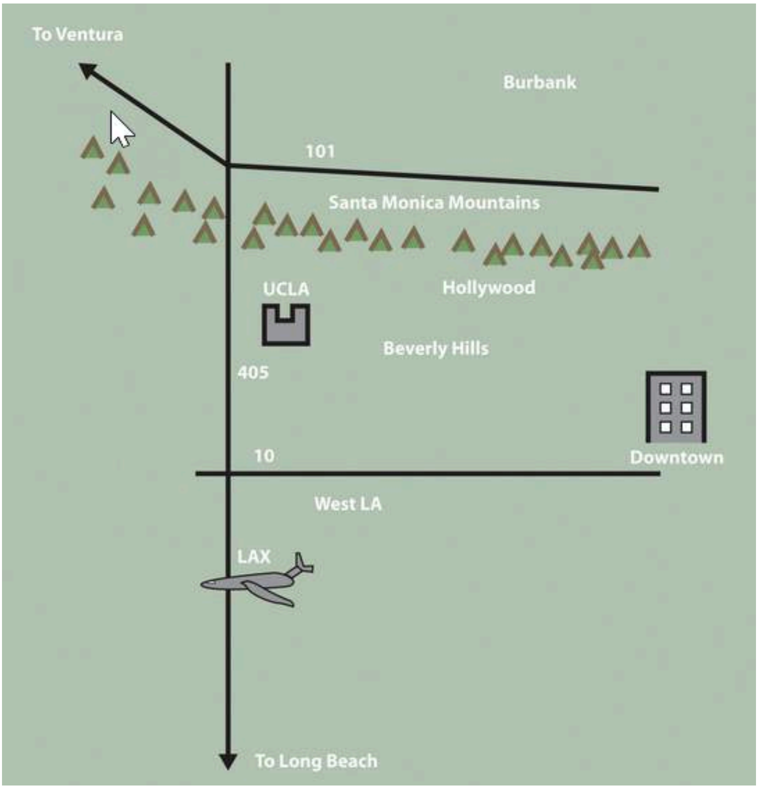
Mental maps tend to have the following characteristics:

- Mental maps illustrate what we know about the places we live. They are rough "sketches" or ideas of our geographic knowledge of an area.
- Mental maps highlight how we relate to our local environment.
- What we choose to include and exclude on our map provides insights about what places we think are important and how we move through our places of residence.
- When we compare our mental maps to someone else's from the same place, certain similarities emerge that shed light upon how we as humans tend to think spatially and organize geographical information in our minds.

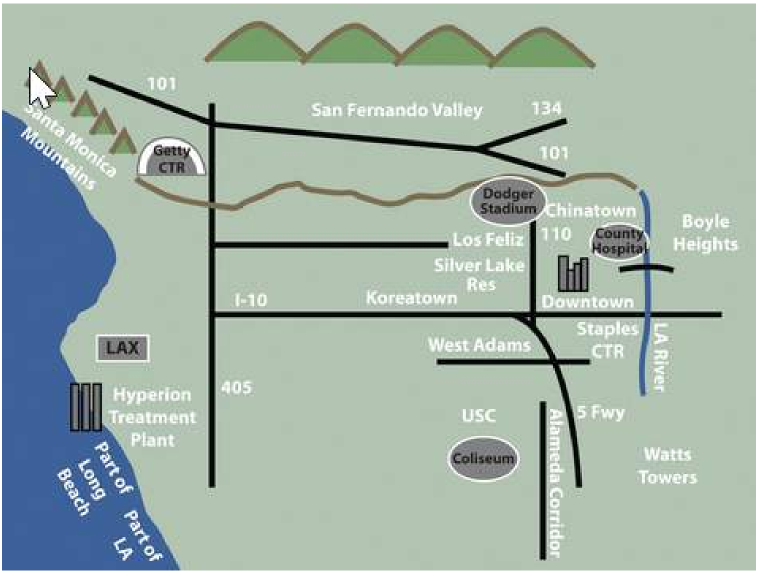
To reinforce these points, consider the series of mental maps of Los Angeles provided below. Take a moment to look at each map and compare the maps with the following questions in mind:

- What similarities are there on each map?
- What are some of the differences?
- Which places or features are illustrated on the map?
- From what you know about Los Angeles, what is included or excluded on the maps?
- What assumptions are made in each map?
- At what scale is the map drawn?

“Mental Map of Los Angeles A” is licensed under a Creative Commons Attribution 4.0 License.



"Mental Map of Los Angeles B" is licensed under a Creative Commons Attribution 4.0 License.



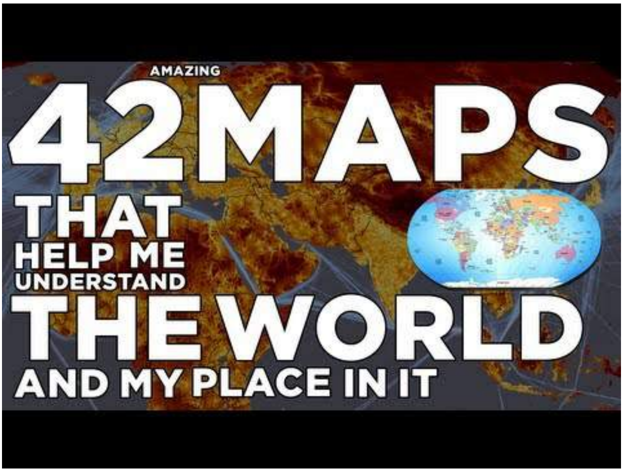
"Mental Map of Los Angeles C" is licensed under a Creative Commons Attribution 4.0 License.

Each map is probably an imperfect representation of one's mental map. However, we can see some similarities and differences that provide insights into how people relate to Los Angeles, maps, and, more generally, the world. First, all maps are oriented so that north is up. Though only one of the maps contains a north arrow that explicitly informs viewers of the geographic orientation of the map, we are accustomed to most maps having north at the top of the page. Second, all but the first map identify some prominent features and landmarks in the Los Angeles area. For instance, Los Angeles International Airport (LAX) appears on two of these maps, as do the Santa Monica Mountains. How the airport is represented or portrayed on the map, for instance, as text, an abbreviation, or symbol, also speaks to our experience using and understanding maps. Third, two of the maps depict a portion of the freeway network in Los Angeles, and one also highlights the Los Angeles River and Ballona Creek. In a city where the "car is king," how can any map omit the freeways?

What we include and omit on our mental maps, by choice or not, speaks volumes about our geographical knowledge and spatial awareness. Recognizing and identifying what we do not know is an essential part of learning. It is only when we identify the unknown that we can ask questions, collect information to answer those questions, develop knowledge through answers, and begin to understand the world where we live.

Asking Geographic Questions

Filling in the gaps in our mental maps and, more generally, the gaps in our geographic knowledge requires us to ask questions about the world where we live and how we relate to it. Such questions can be simple with a local focus (e.g., "Which way is the nearest hospital?") or more complex with a more global perspective (e.g., "How is urbanization impacting biodiversity hotspots around the world?"). The thread that unifies such questions is geography. For instance, the question of "where?" is an essential part of the questions "Where is the nearest hospital?" and "Where are the biodiversity hotspots concerning cities?" Being able to articulate questions clearly and to break them into manageable pieces are valuable skills when using and applying a geographic information system (GIS).



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Though there may be no such thing as a "dumb" question, some questions are indeed better than others. Learning how to ask the right question takes practice and is often more difficult than finding the answer itself. However, when we ask the right question, problems are more easily solved, and our understanding of the world is improved. There are five general types of geographic questions that we can ask and that GIS can help us to answer. Each type of question is listed here and is also followed by a few examples (Nyerges 1991). Nyerges, T. 1991. "Analytical Map Use." Cartography and Geographic Information Systems (formerly The American Cartographer) 18: 11–22.

Questions about *geographic location*:

- Where is it?
- Why is it here or there?
- How much of it is here or there?

Questions about *geographic distribution*:

- Is it distributed locally or globally?
- Is it spatially clustered or dispersed?
- Where are the boundaries?

Questions about *geographic association*:

- What else is near it?
- What else occurs with it?
- What is absent in its presence?

Questions about *geographic interaction*:

- Is it linked to something else?
- What is the nature of this association?
- How much interaction occurs between the locations?

Questions about *geographic change*:

- Has it always been here?
- How has it changed over time and space?
- What causes its diffusion or contraction?

These and related geographic questions are frequently asked by people from various areas of expertise, industries, and professions.

For instance, urban planners, traffic engineers, and demographers may be interested in understanding the commuting patterns between cities and suburbs (geographic interaction). Biologists and botanists may be curious about why one animal or plant species flourish in one place and not another (geographic location/distribution). Epidemiologists and public health officials are undoubtedly interested in where disease outbreaks occur and how, why, and where they spread (geographic change/interaction/location).

A **geographic information system** (GIS) can assist in answering all these questions and many more. Furthermore, GIS often opens up additional avenues of inquiry when searching for answers to geographic questions. Herein is one of the greatest strengths of the GIS. While GIS can be used to answer specific questions or to solve particular problems, it often unearths even more interesting questions. It presents more problems to be solved in the future.

Geographic Inquiry

Geography is the study of the physical and cultural environments of the earth. What makes geography different from other disciplines is that it is focusing on spatial inquiry and analysis. Geographers also try to look for connections between things such as patterns, movement and migration, trends, and so forth. This process is called **a geographic** or **spatial inquiry**.

In order to do this, geographers go through a geographic methodology that is quite similar to the scientific method, but again with a geographic or spatial emphasis. This method can be simplified in a six-step geographic inquiry process.

- **Ask a geographic question.** This means asking questions about spatial relationships in the world around you.
- **Acquire geographic resources.** Identify data and information that you need to answer your question.
- **Explore geographic data.** Turn the data into maps, tables, and graphs, and look for patterns and relationships.
- **Analyze geographic information.** Determine what the patterns and relationships mean concerning your question.

"Knowing where something is, how its location influences its characteristics, and how it influences relationships with other phenomena are the foundation of geographic thinking. This mode of the investigation asks you to see the world and all that is in it in spatial terms. Like other research methods, it also asks you to explore, analyze, and act upon the things you find. It also is important to recognize that this is the same method used by professionals around the world working to address social, economic, political, environmental, and a range of scientific issues" (ESRI).

Geographic Concepts

Before we can learn how to think geographically and apply spatial thinking, it is first necessary to review and reconsider a few key geographic concepts that are often taken for granted. For instance, what is a location, and how can it be defined? At what distance does a location become "nearby"? Or what do we mean when we say that someone has a "good sense of direction"? By answering these and related questions, we establish a framework that will help us to learn and to apply a GIS. This framework will also permit us to share and communicate geographic information with others, which can facilitate collaboration, problem-solving, and decision making.

Scale

When representing the Earth on a manageable-sized map, the actual size of the location is reduced. **Scale** is the ratio between the distance between two locations on a map and the corresponding distance on Earth's surface. A 1:1000 scale map, for example, would mean that 1 meter on the map equals 1000 meters, or 1 kilometer, on Earth's surface. Scale can sometimes be a confusing concept, so it is important to remember that it refers to a *ratio*. It does not refer to the size of the map itself, but rather, how zoomed in or out the map is. A 1:1 scale map of your room would be the same size of your room – plenty of room for significant detail, but hard to fit into a glove compartment.

As with map projections, the "best" scale for a map depends on what it is used for. If you are going on a walking tour of a historic town, a 1:5,000 scale map is commonly used. If you are a geography student looking at a map of the entire world, a 1:50,000,000 scale map would be appropriate. "Large" scale and "small" scale refer to the ratio, not to the size of the landmass on the map. 1 divided by 5,000 is 0.0002, which is a larger number than 1 divided by 50,000,000 (which is 0.00000002). Thus, a 1:5,000 scale map is considered “large” scale while 1:50,000,000 is considered “small” scale.

Location

The one concept that distinguishes geography from other fields is location, which is central to a GIS. **Location** is simply a position on the surface of the earth. What is more, nearly everything can be assigned a geographic location. Once we know the location of something, we can put it on a map, for example, with a GIS.

Generally, we tend to define and describe locations in nominal or absolute terms. In the case of the former, locations are simply defined and described by name. For example, city names such as New York, Tokyo, or London refer to nominal locations. **Toponymy**, or the study of place names and their respective history and meanings, is concerned with such nominal locations.

Though we tend to associate the notion of location with particular points on the surface of the earth, locations can also refer to geographic features (e.g., Rocky Mountains) or large areas (e.g., Siberia). The United States Board on Geographic Names maintains geographic naming standards and keeps track of such names through the Geographic Names Information Systems. The GNIS database also provides information about which state and county the feature is located as well as its geographic coordinates.

Contrasting nominal locations are **absolute locations** that use some type of reference system to define positions on the earth’s surface. For instance, defining a location on the surface of the earth using latitude and longitude is an example of absolute location. Postal codes and street addresses are other examples of absolute location that usually follow some form of local logic. Though there is no global standard when it comes to street addresses, we can determine the geographic coordinates (i.e., latitude and longitude) of particular street addresses, zip codes, place names, and other geographic data through a process called **geocoding**. There are several free online geocoders that return the latitude and longitude for various locations and addresses around the world.

With the advent of the global positioning system (GPS), determining the location of nearly any object on the surface of the earth is a relatively simple and straightforward exercise. GPS technology consists of a constellation of twenty-four satellites that are orbiting the earth and continuously transmitting time signals. To determine a position, earth-based GPS units (e.g., handheld devices, car navigation systems, mobile phones) receive the signals from at least three of these satellites and use this information to triangulate a location. All GPS units use the geographic coordinate system (GCS) to report location. Initially developed by the United States Department of Defense for military purposes, there is now a wide range of commercial and scientific uses of a GPS.

Location can also be defined in relative terms. **Relative location** refers to defining and describing places in relation to other known locations. For instance, Cairo, Egypt, is north of Johannesburg, South Africa; New Zealand is southeast of Australia; and Kabul, Afghanistan, is northwest of Lahore, Pakistan. Unlike nominal or absolute locations that define single points, relative locations provide a bit more information and situate one place in relation to another.

Direction

Like location, the concept of direction is central to geography and GIS. **Direction** refers to the position of something relative to something else, usually along a line. In order to determine direction, a reference point or benchmark from which direction will be measured needs to be established. One of the most common benchmarks used to determine direction is ourselves. Egocentric direction refers to when we use ourselves as a directional benchmark. Describing something as “to my left,” “behind me,” or “next to me” are examples of egocentric direction.

As the name suggests, landmark direction uses a known landmark or geographic feature as a benchmark to determine direction. Such landmarks may be a busy intersection of a city, a prominent point of interest like the Colosseum in Rome, or some other feature like a mountain range or river. The critical thing to remember about landmark direction, especially when providing directions, is that the landmark should be relatively well-known.

In geography and GIS, three more standard benchmarks are used to define the directions of true north, magnetic north, and grid north. True north is based on the point at which the axis of the earth’s rotation intersects the earth’s surface. In this respect, the North and South Poles serve as the geographic benchmarks for determining direction. Magnetic north (and south) refers to the point on the surface of the earth where the earth’s magnetic fields converge. This is also the point to which magnetic compasses point. Note that magnetic north falls somewhere in northern Canada and is not geographically coincident with true north or the North Pole. Grid north simply refers to the northward direction that the grid lines of latitude and longitude on a map, called a **graticule**, point to.

Distance

Complementing the concepts of location and direction is distance. **Distance** refers to the degree or amount of separation between locations and can be measured in nominal or absolute terms with various units. We can describe the distances between locations nominally as “large” or “small,” or we can describe two or more locations as “near” or “far apart.”

Calculating the distance between two locations on the surface of the earth can be quite involving because we are dealing with a three-dimensional object. Moving from the three-dimensional earth to two-dimensional maps on paper, computer screens, and mobile devices is not a trivial matter and is discussed in greater detail in a later chapter.

We also use a variety of units to measure distance. For instance, the distance between London and Singapore can be measured in miles, kilometers, flight time on a jumbo jet, or days on a cargo ship. Whether or not such distances make London and Singapore “near” or “far” from each other is a matter of opinion, experience, and patience. Hence the use of absolute distance metrics, such as that derived from the distance formula, provide a standardized method to measure how far away or how near locations are from each other.

Space

Where distance suggests a measurable quantity in terms of how far apart locations are situated, space is a more abstract concept that is more commonly described rather than measured. For example, space can be described as “empty,” “public,” or “private.”

Within the scope of a digital mapping or GIS, we are interested in space, and in particular, we are interested in what fills particular spaces and how and why things are distributed across space. In this sense, **space** is a somewhat ambiguous and generic term that is used to denote the general geographic area of interest.

One kind of space that is of particular relevance to a GIS is **topological space**. Simply put, topological space is concerned with the nature of relationships and the connectivity of locations within a given space. What is essential within topological space are (1) how locations are (or are not) related or connected, and (2) the rules that govern such geographic relationships.

Transportation maps such as those for subways provide some of the best illustrations of topological spaces. When using maps, we are primarily concerned with how to get from one stop to another along a transportation network. Specific rules also govern how we can travel along the network (e.g., transferring lines is possible only at a few key stops; we can travel only one direction on a particular line). Such maps may be of little use when traveling around a city by car or foot. However, they show the local transportation network and how locations are linked together effectively and efficiently.

Navigation

Transportation maps, like those discussed previously, illustrate how we move through the environments where we live, work, and play. This movement and, in particular, destination-oriented travel are generally referred to as **navigation**. How we navigate through space is a complex process that blends our various motor skills; technology, mental maps, and awareness of locations, distances, directions, and the space where we live. What is more, our geographical knowledge and spatial awareness are continuously updated and changed as we move from one location to another.

Photo by Suzy Brooks on Unsplash.

The acquisition of geographic knowledge is a lifelong endeavor. Though several factors influence the nature of such knowledge, we tend to rely on the three following types of geographic knowledge when navigating through space:

- Landmark knowledge refers to our ability to locate and identify unique points, patterns, or features (e.g., landmarks) in space.
- Route knowledge permits us to connect and travel between landmarks by moving through space.
- Survey knowledge enables us to understand where landmarks are concerning each other and to take shortcuts.

Each type of geographic knowledge is acquired in stages, one after the other. For instance, when we find ourselves in a new or unfamiliar location, we usually identify a few unique points of interest (e.g., hotel, building, fountain) to orient ourselves. We are, in essence, building up our landmark knowledge. Using and traveling between these landmarks develops our route knowledge and reinforces our landmark knowledge and our overall geographical awareness. Survey knowledge develops once we begin to understand how routes connect landmarks and how various locations are situated in space. It is at this point, when we are somewhat comfortable with our survey knowledge, that we can take shortcuts from one location to another. Though there is no guarantee that a shortcut will be successful, if we get lost, we are at least expanding our local geographic knowledge.

Landmark, route, and survey knowledge are the cornerstones of having a sense of direction and frame our geographical learning and awareness. While some would argue that they are born with a good sense of direction, others admit to always getting lost. The popularity of personal navigation devices and online mapping services speaks to the overwhelming desire to know and to situate where we are in the world. Though developing and maintaining a keen sense of direction presumably matters less and less as such devices and services continue to develop and spread, it can also be argued that the more we know about where we are in the world, the more we will want to learn about it.

This section covers concepts essential to geography, GIS, and many other fields of interest. Understanding how location, direction, and distance can be defined and described provides an essential foundation for the successful use and implementation of a GIS. Thinking about space and how we navigate through, it also serves to improve and own geographic knowledge and spatial awareness.

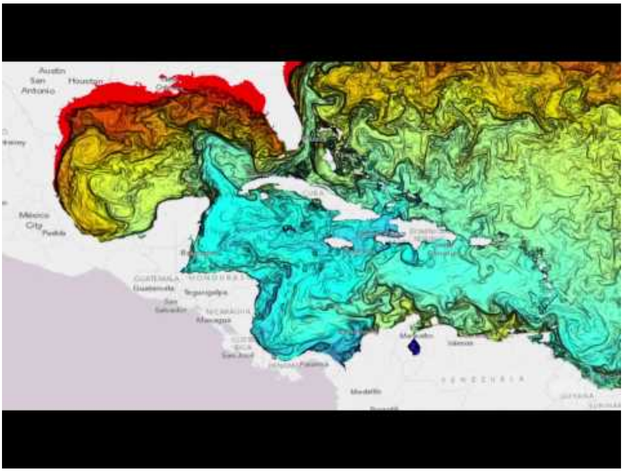
Understanding Maps

A **map** can be defined as a graphic representation of the real world. Because of the infinite nature of our Universe, it is impossible to capture all of the complexity found in the real world. For example, topographic maps abstract the three-dimensional real world at a reduced scale on a two-dimensional plane of paper. **Cartography** is the art and science of making maps, and a **cartographer** is professional who creates maps.

Maps are among the most compelling forms of information for several reasons. Maps are artistic. Maps are scientific. Maps preserve history. Maps clarify. Maps reveal the invisible. Maps inform the future. Regardless of the reason, maps capture the imagination of people around the world. As one of the most trusted forms of information, map makers, and geographic information system (GIS) practitioners hold a considerable amount of power and influence. Therefore, understanding and appreciating maps and how maps convey information are essential aspects of GIS. The appreciation of maps begins with exploring various map types.

So what exactly is a map? Like GIS, there are probably just as many definitions of maps as there are people who use and make them. We can define a map simply as a representation of the world. Such maps can be stored in our brain (i.e., mental maps), they can be printed on paper, or they can appear online. Notwithstanding the actual medium of the map (e.g., our fleeting thoughts, paper, or digital display), maps represent and describe various aspects of the world. For purposes of clarity, the three types of maps are the reference map, the thematic map, and the dynamic map.

Most maps allow us to specify the location of points on the Earth's surface using a coordinate system. For a two-dimensional map, this coordinate system can use simple geometric relationships between the perpendicular axes on a grid system to define spatial location. Two types of coordinate systems are currently in general use in geography: the *geographical coordinate system* and the *rectangular* (also called *Cartesian*) *coordinate system*.



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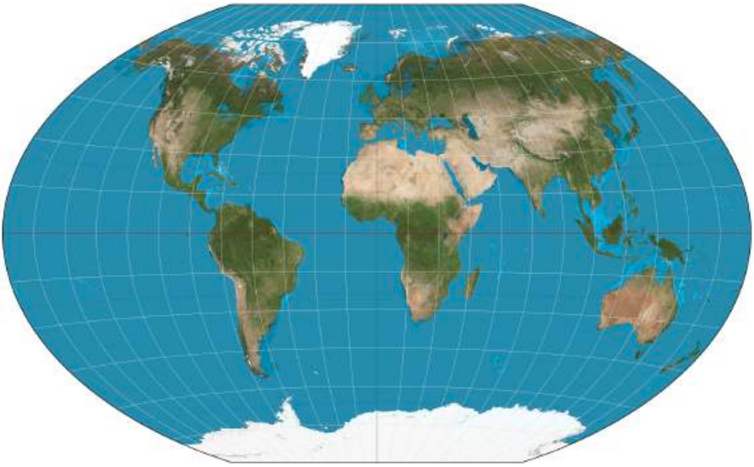
Geographic Information Science (GIScience)

Reference Maps

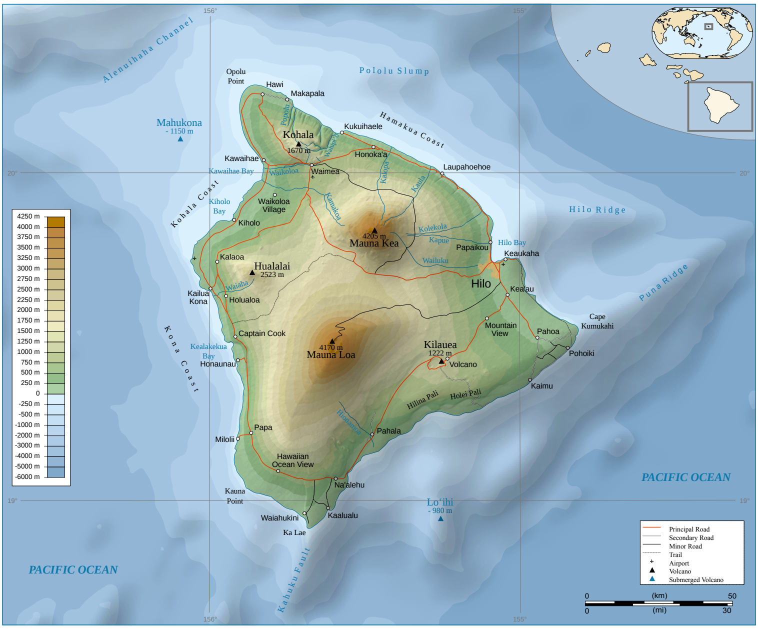
The primary purpose of a **reference map** is to deliver location information to the map user. Geographic features and map elements on a reference map tend to be treated and represented equally. In other words, no single aspect of a reference map takes precedence over any other aspect. Moreover, reference maps generally represent geographic reality accurately. Examples of some common types of reference maps include topographic maps such as those created by the United States Geological Survey (USGS) and image maps obtained from satellites or aircraft that are available through online mapping services.



"Winkel Triple" by Daniel R. Strebe is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported.

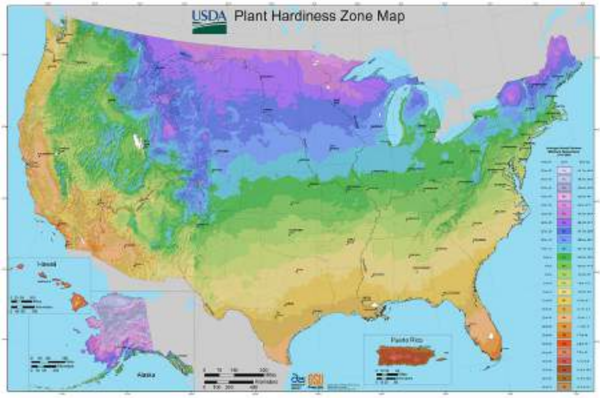
The accuracy of a given reference map is indeed critical to many users. For instance, local governments need accurate reference maps for land use, zoning, and tax purposes. National governments need accurate reference maps for political, infrastructure, and military purposes. People who depend on navigation devices like global positioning systems (GPS) units also need accurate, and up-to-date reference maps to arrive at their desired destinations.

Thematic Maps



“Hawaii Island Topographic Map” licensed as Creative Commons Attribution-ShareAlike 3.0 Unported.

Contrasting the reference map are thematic maps. As the name suggests, **thematic maps** are concerned with a particular theme or topic of interest. While reference maps emphasize the location of geographic features, thematic maps are more concerned with how things are distributed across space. Such things are often abstract concepts such as life expectancy around the world, per capita gross domestic product (GDP) in Europe, or literacy rates across India. One of the strengths of mapping, and in particular of thematic mapping, is that it can make such abstract and invisible concepts visible and comparable on a map.



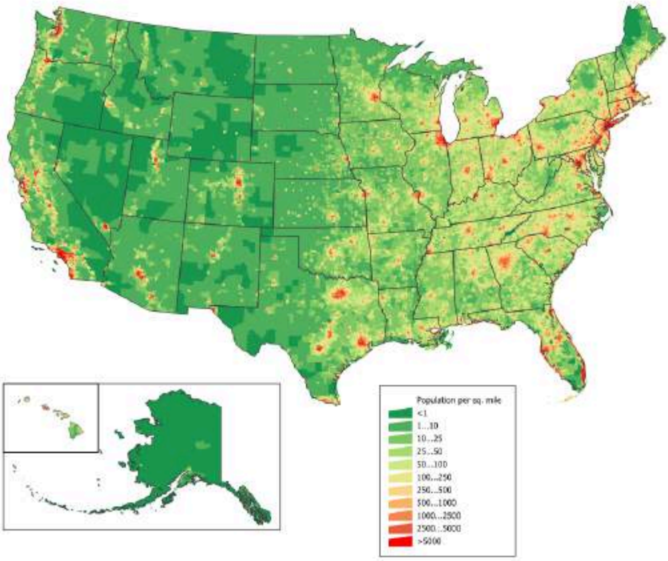
"2012 USDA Plant Hardiness Zone Map (USA)" by USDA-ARS and Oregon State University (OSU) is licensed under Public Domain.

It is important to note that reference and thematic maps are not mutually exclusive. In other words, thematic maps often contain and combine geographical reference information, and conversely, reference maps may contain thematic information. What is more, when used in conjunction, thematic and reference maps often complement each other.

For example, public health officials in a city may be interested in providing equal access to emergency rooms to the city's residents. Insights into this and related questions can be obtained through visual comparisons of a reference map that shows the locations of emergency rooms across the city to thematic maps of various segments of the population (e.g., households below poverty, percent elderly, underrepresented groups).

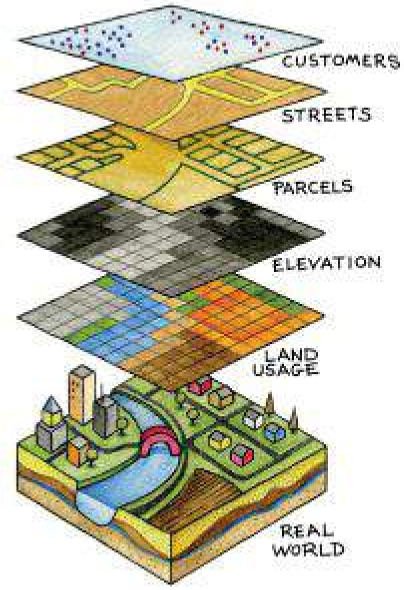
Thematic maps are generally are more abstract, involving more processing and interpretation of data, and often depict concepts that are not directly visible; examples include maps of income, health, climate, or ecological diversity. There is no clear-cut line between reference and thematic maps, but the categories are useful to recognize because they relate directly to how the maps are intended to be used and to decisions that their cartographers have made in the process of shrinking and abstracting aspects of the world to generate the map. Different types of thematic maps include:

- **choropleth** – a thematic map that uses tones or colors to represent spatial data as average values per unit area
- **proportional symbol** – uses symbols of different sizes to represent data associated with different areas or locations within the map
- **isopleth**– also known as contour maps or isopleth maps depict smooth continuous phenomena such as precipitation or elevation
- **dot density** – uses a dot symbol to show the presence of a feature or phenomenon – dot maps rely on a visual scatter to show a spatial pattern
- **dasymetric** – an alternative to a choropleth map but instead of mapping the data so that the region appears uniform, ancillary information is used to model the internal distribution of the data



"United States population density map based on Census 2010 data" by Jim Irwin and licensed under the Creative Commons Attribution-Share Alike 3.0 Unported.

Within the context of a GIS, we can **overlay** the reference map of emergency rooms directly on top of the population maps to see whether or not access is uniform across neighborhood types. There are other factors to consider when looking at emergency room access (e.g., access to transport), but through such map overlays, underserved neighborhoods can be identified.

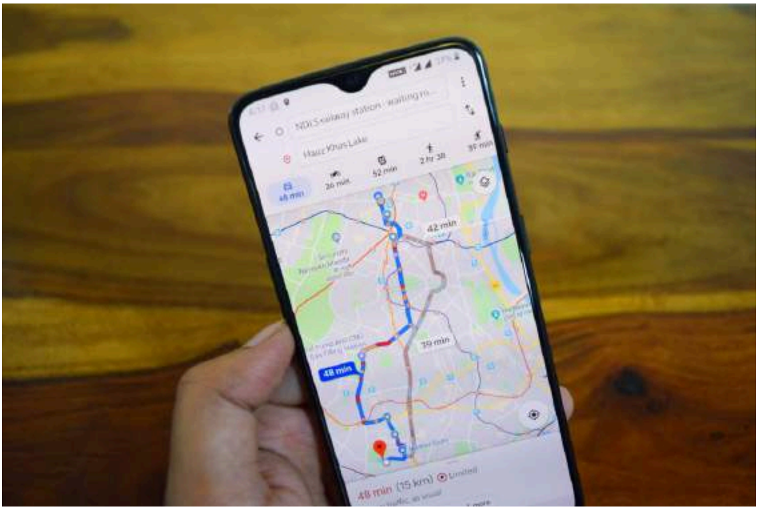


"GIS Overlay Process" is licensed under a Creative Commons Attribution 4.0 License.

When presented in hardcopy format, both reference and thematic maps are static or fixed representations of reality. Such permanence on the page suggests that geography and the things that we map are also in many ways, fixed or constant. This is far from reality. The integration of GIS with other forms of information technology like the Internet and mobile telecommunications is rapidly changing this view of maps and mapping, as well as geography at large.

Dynamic Maps

The diffusion of GIS and the popularity of online mapping tools and applications speak to this shift in thinking about maps and map use. In this regard, it is worthwhile to discuss the diffusion of dynamic maps. **Dynamic maps** are simply changeable or interactive representations of the earth. Dynamic mapping refers more to how maps are used and delivered to the map user today (e.g., online, via mobile phone) than to the content of the map itself. Both reference and thematic maps can be dynamic, and such maps are an integral component of any GIS. The critical point about dynamic maps is that more and more people, not just GIS professionals, have access to such maps.



"Google Maps" by Deepanker Verma is licensed under no copyright.

Unlike a hardcopy map that has features and elements, users cannot modify or change, dynamic maps encourage and sometimes require user interaction. Such interaction can include changing the scale or visible area by zooming in or zooming out, selecting which features or layers to include or to remove from a map (e.g., roads, imagery), or even starting and stopping a map animation.

Just as dynamic maps will continue to evolve and require more user interaction in the future, map users will demand more interactive map features and controls. As this democratization of maps and mapping continues, the geographic awareness and map appreciation of map users will also increase. Therefore, it is of critical importance to understand the nature, form, and content of maps to support the changing needs, demands, and expectations of map users in the future.

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Topographic Maps

Maps are used to display both the cultural and physical features of the environment. Standard **topographic maps** show a variety of information including roads, land-use classification, elevation, rivers and other water bodies, political boundaries, and the identification of houses and other types of buildings. Some maps are created with particular goals in mind, with an intended purpose.

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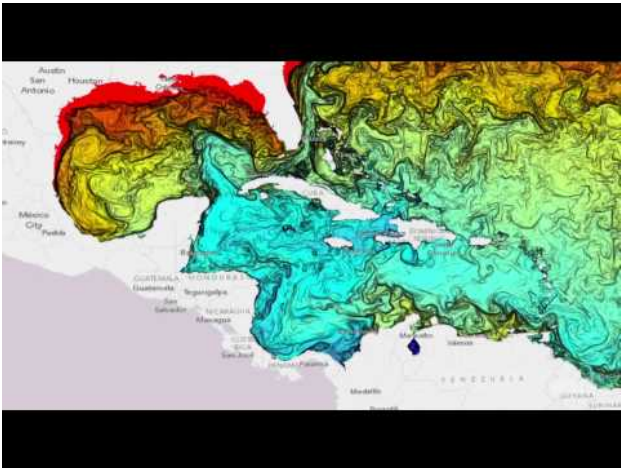
Most maps allow us to specify the location of points on the Earth's surface using a coordinate system. For a two-dimensional map, this coordinate system can use simple geometric relationships between the perpendicular axes on a grid system to define spatial location. Two types of coordinate systems are currently in general use in geography: the *geographical coordinate system* and the *rectangular* (also called *Cartesian*) *coordinate system*.

Have you ever found driving directions and maps online, used a smartphone to 'check-in' to your favorite restaurant, or entered a town name or zip code to retrieve the local weather forecast? Every time you and millions of other users perform these tasks, you are making use of Geographic Information Science (GIScience) and related spatial technologies. Many of these technologies, such as Global Positioning Systems (GPS) and in-vehicle navigation units, are very well-known, and you can probably recall the last time you have used them.



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Geographic Information Science (GIScience)

Other applications and services that are the products of GIScience are a little less obvious, but they are every bit as common. If you are connected to the Internet, you are making use of geospatial technologies right now. Every time your browser requests a web page from a Content Delivery Network (CDN), a geographic lookup occurs and the server you are connected to contacts other servers that are closest to it and retrieves the information. This happens so that the delay between your request to view the data and the data being sent to you is as short as possible.

GIScience and the related technologies are everywhere, and we use them every day. When it comes to information, "spatial is special." Reliance on spatial attributes is what separates geographic information from other types of information. There are several distinguishing properties of geographic information. Understanding them, and their implications for the practice of geographic information science is a key utilizing geographic data.

- Geographic data represent spatial locations and non-spatial attributes measured at certain times.
- Geographic space is continuous.
- Geographic space is nearly spherical.
- Geographic data tend to be spatially dependent.

Spatial attributes tell us where things are, or where things were at the time the data were collected. By merely including spatial attributes, geographic data allow us to ask a plethora of geographic questions. For example, we might ask, "are gas prices in Puyallup high?" The interactive map from GasBuddy.com can help us with such a question while enabling us to generate many other spatial inquiries related to the geographic variation in fuel prices.

Another essential characteristic of geographic space is that it is "**continuous**." Although the Earth has valleys, canyons, caves, oceans, and more, there are no places on Earth without a location, and connections exist from one place to another. Outside of science fiction, there are no tears in the fabric of space-time. Modern technology can measure location very precisely, making it possible to generate incredibly detailed depictions of geographic feature location (e.g., of the coastline of the eastern U.S). It is often possible to measure so precisely that we collect more location data than we can store and much more than is useful for practical applications. How much information is useful to store or to display in a map will depend on the map scale (how much of the world we represent within a fixed display such as the size of your computer screen) as well as on the map's purpose. The map below is a digital elevation model (DEM), that is considered continuous because elevation always exits on the planet.

"Global DEM using GEBCO 08 Elevation Dataset" by Kevin Gill, licensed under Attribution 2.0 Generic (CC BY 2.0).

In addition to being continuous, geographic data also tend to be spatially dependent. More simply, "everything is related to everything else, but near things are more related than distant things" (which leads to an expectation that things that are near to one another tend to be more alike than things that are far apart). How alike things are in relation to their proximity to other things can be measured by a statistical calculation known as spatial autocorrelation. Without this fundamental property, geographic information science as we know it today would not be possible.

Geographic data comes in many types, from many different sources and captured using many techniques; they are collected, sold, and distributed by a wide array of public and private entities. In general, we can divide the collection of geographic data into two main types:

- Directly collected data
- Remotely sensed data

Directly collected data are generated at the source of the phenomena being measured. Examples of directly collected data include measurements such as temperature readings at specific weather stations, elevations recorded by visiting the location of interest, or the position of a grizzly bear equipped with a GPS-enabled collar. Also, included here are data derived from surveys (e.g., the census) or observation (e.g., Audubon Christmas bird count).

Remotely sensed data are measured from remote distances without any direct contact with the phenomena or need to visit the locations of interest. Satellite images, sonar readings, and radar are all forms of remotely sensed data.

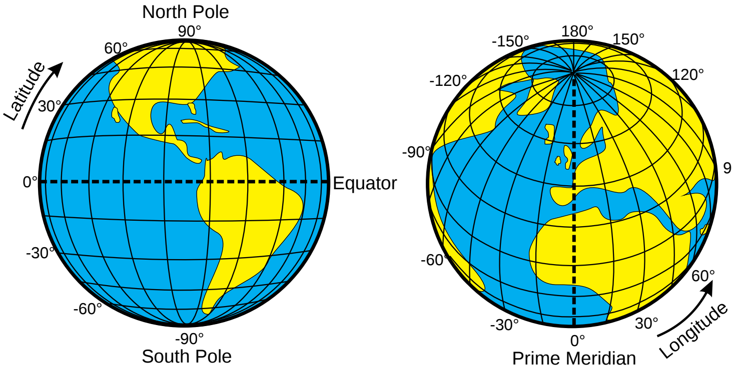
Maps are both the raw material and the product of geographic information systems (GIS). All maps represent features and characteristics of locations, and that representation depends upon data relevant at a particular time. All maps are also selective; they do not show us everything about the place depicted; they show only the particular features and characteristics that their maker decided to include. Maps are often categorized into reference or thematic maps based upon the producer's decision about what to include and the expectations about how the map will be used. The prototypical reference map depicts the location of "things" that are usually visible in the world; examples include road maps and topographic maps depicting terrain.

1.4 MAPPING TECHNOLOGY

Geographic Grid Systems

The earth has 360 degrees, and they are measured using a grid pattern called the **graticule**. Lines of latitude and longitude allow any absolute location on the planet to have an identifiable address of degrees north or south and east or west, which will enable geographers to locate, measure, and study spatial activity accurately.

Geographers and cartographers organize locations on the earth using a series of imaginary lines that encircle the globe. The two primary lines are the equator and the prime meridian. The systems of longitude and latitude are formed from these lines, allowing users to locate themselves anywhere on the planet. The line is the longest when one travels along in an east-west direction. At the equator, the sun is directly overhead at noon on the two equinoxes, which occur in March and September.



"Latitude and Longitude of the Earth" (author unknown) licensed under the Creative Commons CC0 1.0 Universal Public Domain Dedication.

Latitude and Parallels

The **equator** is the largest circle of latitude on Earth. The equator divides the earth into the Northern and Southern Hemispheres and is called 0 degrees latitude. The other lines of latitude are numbered from 0 to 90 degrees, going toward each of the poles. The lines north of the equator toward the North Pole are north latitude, and each of the numbers is followed by the letter "N." The lines south of the equator toward the South Pole are south latitude, and the letter "S follows each of the numbers." The equator (0 latitude) is the only line of latitude without any letter following the number. Notice that all lines of latitude are parallel to the equator (they are often called parallels) and that the North Pole equals 90 degrees N, and the South Pole equals 90 degrees S. Noted parallels include both the Tropic of Cancer and the Tropic of Capricorn, which are 23.5 degrees from the equator. At 66.5 degrees from the equator are the Arctic Circle and the Antarctic Circle near the North and South Pole, respectively. The following are the essential parallel lines:

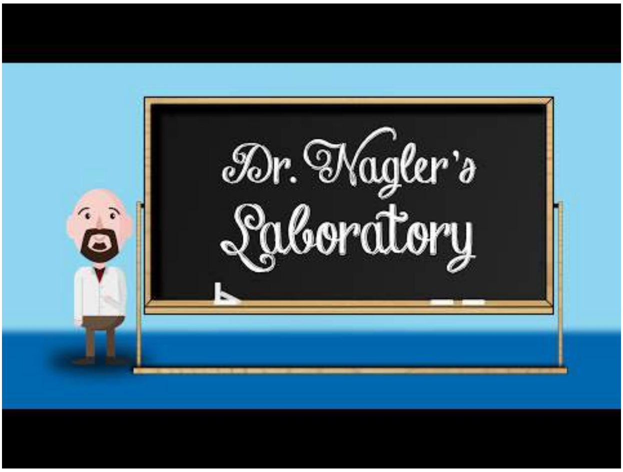
- Equator, 0 degrees
- Tropic of Cancer, 23.5 degrees north
- Tropic of Capricorn, 23.5 degrees south
- Arctic Circle, 66.5 degrees north
- Antarctic Circle, 66.5 degrees south
- North Pole, 90 degrees north (infinitely small circle)
- South Pole, 90 degrees south (infinitely small circle)

Longitude and Meridians

The **prime meridian** sits at 0 degrees longitude and divides the earth into the Eastern and Western Hemispheres. The prime meridian is defined as an imaginary line that runs through the Royal Observatory in Greenwich, England, a suburb of London. The Eastern Hemisphere includes the continents of Europe, Asia, and Australia, while the Western Hemisphere includes North and South America. All meridians (lines of longitude) east of the prime meridian (0 and 180) are numbered from 1 to 180 degrees east (E); the lines west of the prime meridian (0 and 180) are numbered from 1 to 180 degrees west (W). The 0 and 180 lines do not have a letter attached to them. The meridian at 180 degrees is called the **International Date Line**. The International Date Line (180 degrees longitude) is opposite the prime meridian and indicates the start of each day (Monday, Tuesday, etc.). Each day officially starts at 12:01 a.m., at the International Date Line. Do not confuse the

International Date Line with the prime meridian (0 longitude). The actual International Date Line does not follow the 180-degree meridian exactly. Several alterations have been made to the International Date Line to accommodate political agreements to include an island or country on one side of the line or another. Latitude is also sometimes described as **zones of latitude**. Some of these zones of latitude include:

- Low latitude – generally between the equator and 30 degrees north
- Midlatitude – between 30 degrees and 60 degrees north and south
- High latitude – latitudes greater than about 60 degrees north and south
- Equatorial – within a few degrees of the equator
- Tropical – within the tropics (between 23.5 degrees north and 23.5 degrees south
- Subtropical – slightly pole-ward of the tropics, generally around 25-30 degrees north and south
- Polar – within a few degrees of the North Pole or South Pole



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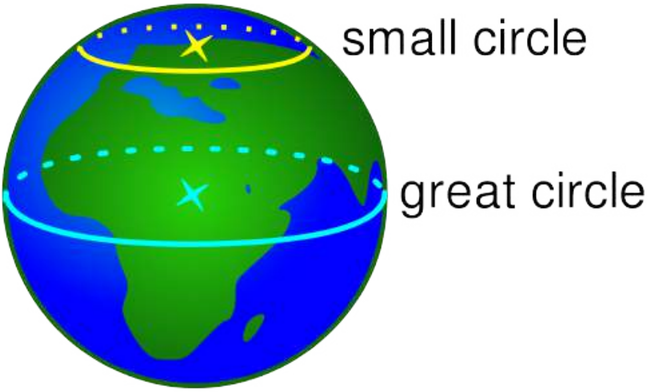
Great and Small Circles



"Illustration of the concept of a great circle on a sphere" by Brian Brondel licensed under the Creative Commons Attribution-Share Alike 2.5 Generic.

Much of Earth's grid system is based on the location of the North Pole, South Pole, and the Equator. The poles are an imaginary line running from the axis of Earth's rotation. The **plane of the equator** is an imaginary horizontal line that cuts the earth into two halves. This brings up the topic of great and small circles. A **great circle** is any circle that divides the earth into a circumference of two halves. It is also the largest circle that can be drawn on a sphere. The line connecting any points along a great circle is also the shortest distance between those two points. Examples of great circles include the Equator, all lines of longitude, the line that divides the earth into day and night called the **circle of illumination**, and the **ecliptic** plane, which divides the earth into equal halves along the equator. **Small circles** are circles that cut the earth, but not into equal halves. Examples of small circles include all latitude lines except the equator, the Tropical of Cancer, Tropic of Capricorn, the Arctic Circle, and Antarctic Circle.

Climate and Latitude

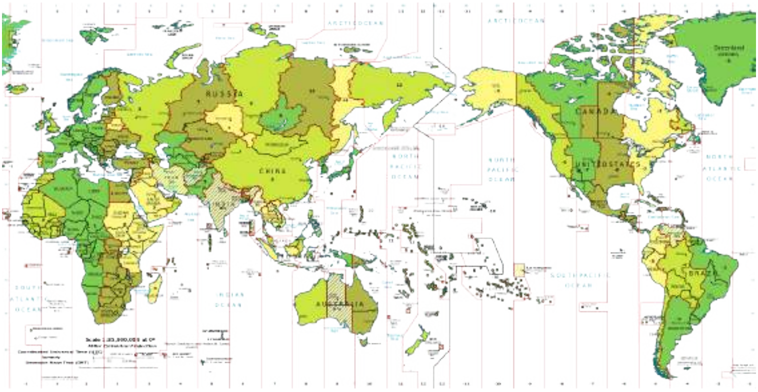
"Satellite Map of the World: Physical: Geographic Projection" by Newport Geography licensed under Creative Commons Attribution 2.0 Generic.

The earth is tilted on its axis 23.5 degrees. As it rotates around the sun, the tilt of the earth's axis provides different climatic seasons because of the variations in the angle of direct sunlight on the planet. Places receiving more direct sunlight experience a warmer climate. Elsewhere, the increased angle of incoming solar radiation near the earth's poles results in more reflected sunlight and a colder climate. The Northern Hemisphere experiences winter when sunlight is reflected off the earth's surface, and less of the sun's energy is absorbed from the sun's sharper angle.

Time Zones

Universal Time (UT), **Coordinated Universal Time (UTC)**, **Greenwich Mean Time (GMT)**, or **Zulu Time (Z)**: all four terms can be defined as the local time at 0 degrees longitude, which is the prime meridian (location of Greenwich, England). This is the same time under which many military operations, international radio broadcasts, and air traffic control systems operate worldwide. UTC is set in zero- to twenty-four-hour time periods, as opposed to two twelve-hour periods (a.m. and p.m.). The designations of a.m. and p.m. are relative to the central meridian: a.m. refers to ante meridiem, or "before noon," and p.m. refers to post meridiem, or "after-noon." UT, UTC, GMT, and Z all refer to the same twenty-four-hour time system that assists in unifying a standard time regarding global operations. For example, all air flights use the twenty-four-hour time system so the pilots can coordinate flights across time zones and around the world.

The earth rotates on its axis once every twenty-four hours at the rate of 15 degrees per hour (15 × 24 = 360). **Time zones** are established roughly every 15 degrees longitude so that local times correspond to similar hours of day and night. With this system, the sun is generally overhead at noon in every time zone that follows the 15-degree-wide system. The twenty-four times zones are based on the prime meridian regarding Universal Coordinated Time (UTC), Greenwich Mean Time (GMT), or Zulu Time (Z), which all operate on the twenty-four-hour time clock. Local time zones are either plus or minus determined by the distance from the prime meridian.



"Standard Time Zones of the World" by Poulpy is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported.

The 15-degree time zone problem is that the zones do not necessarily follow state, regional, or local boundaries. The result is that time zones are seldom precisely 15 degrees wide and usually have various boundary lines. In the United States, the boundaries between the different time zones are inconsistent with the lines of longitude; in some cases, time zones zigzag to follow state lines or to keep cities within a single time zone. Other countries address the problem differently. China, for example, is a significant inland area as the United States yet operates on only one time zone for the entire country.

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Coordinate Systems

Just as all maps have a map scale, all maps have locations, too. **Coordinate systems** are frameworks that are used to define unique positions. For instance, in geometry, we use *x* (horizontal) and *y* (vertical) coordinates to define points on a two-dimensional plane. The coordinate system that is most commonly used to define locations on the three-dimensional earth is called the **geographic coordinate system (GCS)**, and it is based on a sphere or spheroid. A spheroid (a.k.a. ellipsoid) is simply a sphere that is slightly wider than it is tall and approximates more closely the actual shape of the earth. Spheres are commonly used as models of the earth for simplicity.

The unit of measure in the GCS is degrees, and their respective latitude and longitude define locations within the GCS. Latitude is measured relative to the equator at zero degrees, with maxima of either ninety degrees north at the North Pole or ninety degrees south at the South Pole. Longitude is measured relative to the prime meridian at zero degrees, with maxima of 180 degrees west or 180 degrees east.

Note that latitude and longitude can be expressed in degrees-minutes-seconds (DMS) or decimal degrees (DD). When using decimal degrees, latitudes above the equator and longitudes east of the prime meridian are positive, and latitudes below the equator and longitudes west of the prime meridian are negative (see the following table for examples).

Converting from DMS to DD is a relatively straightforward exercise. For example, since there are sixty minutes in one degree, we can convert 118° 15 minutes to 118.25 (118 + 15/60). Note that an online search of the term "coordinate conversion" will return several coordinate conversion tools.

When we want to map things like mountains, rivers, streets, and buildings, we need to define how the lines of latitude and longitude will be oriented and positioned on the sphere. A datum serves this purpose and specifies precisely the orientation and origins of the lines of latitude and longitude relative to the center of the earth or spheroid.

Depending on the need, situation, and location, there are several datums to choose from. For instance, local datums try to match the spheroid closely to the earth's surface in a local area and return accurate local coordinates. A typical local datum used in the United States is called NAD83 (i.e., North American Datum of 1983). For locations in the United States and Canada, NAD83 returns relatively accurate positions, but positional accuracy deteriorates when outside of North America.

The global WGS84 datum (i.e., World Geodetic System of 1984) uses the center of the earth as the origin of the GCS and is used for defining locations across the globe. Because the datum uses the center of the earth as its origin, locational measurements tend to be more consistent regardless of where they are obtained on the earth. However, they may be less accurate than those returned by a local datum. Note that switching between datums will alter the coordinates (i.e., latitude and longitude) for all locations of interest.

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Introducing Coordinate Systems and Map Projections

Melita Kennedy
Bojan Šavrič

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Map Projections

The Earth is not flat or round, but a spherical shape, called a **spheroid**. A globe is an excellent representation of the three-dimensional, spheroid earth. One of the problems with globes, however, is that they are not very portable (i.e., you cannot fold a globe and put in it in your pocket), and their small scale makes them of limited practical use (i.e., geographic detail is sacrificed). To overcome these issues, it is necessary to transform the three-dimensional shape of the earth to a two-dimensional surface like a flat piece of paper, computer screen, or mobile device display in order to obtain more useful map forms and map scales. Enter the map projection.

Map projections refer to the methods and procedures that are used to transform the spherical three-dimensional earth into two-dimensional planar surfaces. Specifically, map projections are mathematical formulas that are used to translate latitude and longitude on the surface of the earth to x and y coordinates on a plane. Since there is an infinite number of ways this translation can be performed, there is an infinite number of map projections. The mathematics behind map projections are beyond the scope of this introductory overview for simplicity, the following discussion focuses on describing types of map projections, the distortions inherent to map projections, and the selection of appropriate map projections.

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To illustrate the concept of a map projection, imagine that we place a light bulb in the center of a translucent globe. On the globe are outlines of the continents and the lines of longitude and latitude called the graticule. When we turn the light bulb on, the outline of the continents and the graticule will be "projected" as shadows on the wall, ceiling, or any other nearby surface. This is what is meant by map "projection."

Within the realm of maps and mapping, there are three surfaces used for map projections (i.e., surfaces on which we project the shadows of the graticule). These surfaces are the plane, the cylinder, and the cone. Referring again to the previous example of a light bulb in the center of a globe, note that during the projection process, we can situate each surface in any number of ways. For example, surfaces can be tangential to the globe along the equator or poles, they can pass through or intersect the surface, and they can be oriented at any number of angles.

Naming conventions for many map projections include the surface as well as its orientation. For example, as the name suggests, "planar" projections use the plane, "cylindrical" projections use cylinders, and "conic" projections use the cone. For cylindrical projections, the "normal" or "standard" aspect refers to when the cylinder is tangential to the equator (i.e., the axis of the cylinder is oriented north-south). When the axis of the cylinder is perfectly oriented east-west, the aspect is called “transverse,” and all other orientations are referred to as “oblique.” Regardless of the orientation or the surface on which a projection is based, a number of distortions will be introduced that will influence the choice of map projection.

When moving from the three-dimensional surface of the earth to a two-dimensional plane, distortions are not only introduced but also inevitable. Generally, map projections introduce distortions in distance, angles, and areas. Depending on the purpose of the map, a series of trade-offs will need to be made concerning such distortions.

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Map projections that accurately represent distances are referred to as equidistant projections. Note that distances are only correct in one direction, usually running north-south, and are not correct everywhere across the map. Equidistant maps are frequently used for small-scale maps that cover large areas because they do an excellent job of preserving the shape of geographic features such as continents.

Maps that represent angles between locations also referred to as bearings, are called conformal. Conformal map projections are used for navigational purposes due to the importance of maintaining a bearing or heading when traveling great distances. The cost of preserving bearings is that areas tend to be quite distorted in conformal map projections. Though shapes are more or less preserved over small areas, at small scales areas become wildly distorted. The Mercator projection is an example of a conformal projection and is famous for distorting Greenland.

As the name indicates, equal area or equivalent projections preserve the quality of the area. Such projections are of particular use when accurate measures or comparisons of geographical distributions are necessary (e.g., deforestation, wetlands). To maintain true proportions in the surface of the earth, features sometimes become compressed or stretched depending on the orientation of the projection. Moreover, such projections distort distances as well as angular relationships.

As noted earlier, there is theoretically an infinite number of map projections to choose from. One of the key considerations behind the choice of map projection is to reduce the amount of distortion. The geographical object being mapped and the respective scale at which the map will be constructed are also essential factors to think about. For instance, maps of the North and South Poles usually use planar or azimuthal projections, and conical projections are best suited for the middle latitude areas of the earth. Features that stretch east-west, such as the country of Russia, are represented well with the standard cylindrical projection, while countries oriented north-south (e.g., Chile, Norway) are better represented using a transverse projection.

If a map projection is unknown, sometimes it can be identified by working backward and carefully examining the nature and orientation of the graticule (i.e., grid of latitude and longitude), as well as the varying degrees of distortion. There are trade-offs made concerning distortion on every map. There are no hard-and-fast rules as to which distortions are more preferred over others. Therefore, the selection of map projection largely depends on the purpose of the map.

Within the scope of GIS, knowing, and understanding map projections are critical. For instance, in order to perform an overlay analysis as the one described earlier, all map layers need to be in the same projection. If they are not, geographical features will not be appropriately aligned, and any analyses performed will be inaccurate and incorrect. Most GIS includes functions to assist in the identification of map projections, as well as to transform between projections in order to synchronize spatial data. Despite the capabilities of technology, an awareness of the potential and pitfalls that surround map projections is essential.

Geospatial Technology

Traditionally, the field of **cartography**, or mapmaking, has been a vital discipline for geographers. While cartography is an essential part of geography, geographers also look at **spatial** (space) and **temporal** (time) relationships between various types of data, including physical landscape types, economies, and human activity. Geography also examines the relationships between and the processes of humans and their physical and cultural environments. Because maps are powerful visual graphics tools that illustrate relationships and processes at work in the world, cartography and geographic information systems have become prominent in modern science. Maps are the most common method of illustrating different spatial qualities, and geographers create and use maps to communicate spatial data about the earth's surface.

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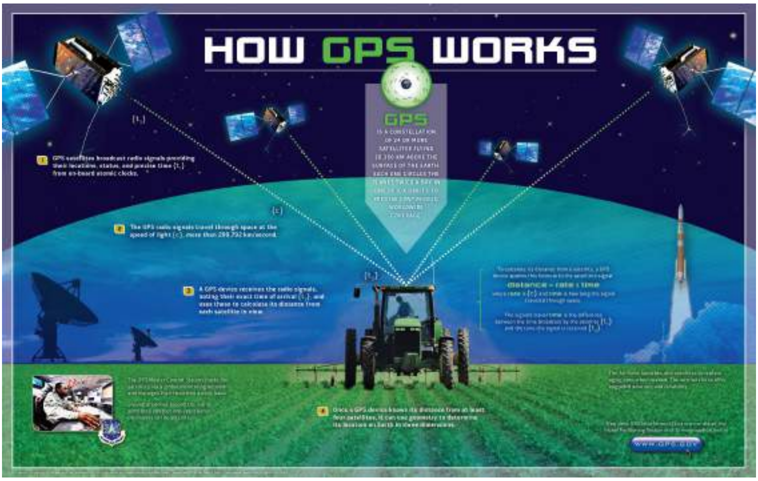
Geospatial techniques are tools used by geographers to illustrate, manage, and manipulate spatial data. Cartography is the art and science of making maps, which illustrate data in a spatial form and are invaluable in understanding what is going on at a given place at a given time.

Global Positioning Systems



"How GPS Works" from The Defense Department is licensed under CC0 1.0 Universal Public Domain Dedication.

Making maps and verifying a location has become more exact with the development of the **global positioning system (GPS)**. A GPS unit can receive signals from orbiting satellites and calculate an exact location in latitude and longitude, which helps determine where one is located on the earth or for verifying a point on a map. GPS units are standard equipment for many transportation systems and have found their way into products such as cell phones, handheld computers, fish finders, and other mobile equipment. GPS technology is widely implemented in the transport of people, goods, and services around the world.

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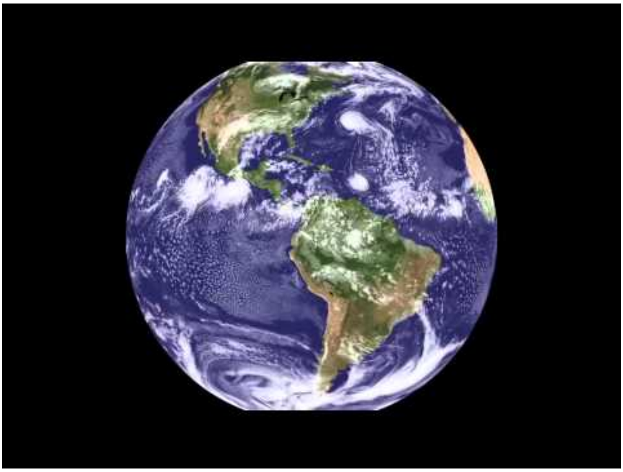
Remote Sensing

Remote sensing technology acquires data about the earth's surface through aerial photographs taken from airplanes or images created from satellites orbiting the earth. Remotely sensed images allow geographers to identify, understand, or explain a particular landscape or determine the land use of a place. These images can serve as essential components in the cartographic (mapmaking) process. These technologies provide the means to examine and analyze changes on the earth's surface caused by natural or human forces. Google Earth is an excellent example of a computer tool that illustrates remotely sensed images of locations on the earth.



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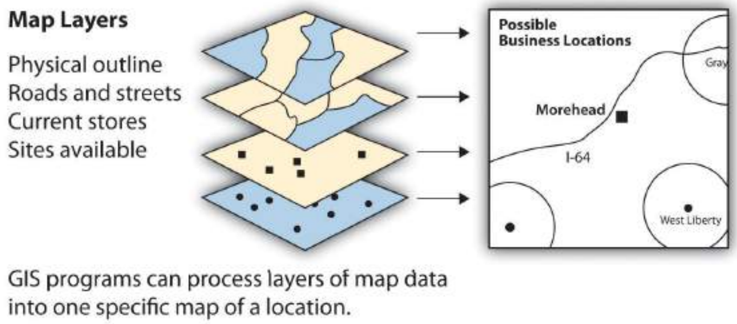
Geographic Information Systems

Geographic information systems (GIS), uses a computer program to assimilate and manage many layers of map data, which then provide specific information about a given place. GIS data are usually in digital form and arranged in layers. The GIS computer program can sort or analyze layers of data to illustrate a specific feature or activity. GIS programs are used in a wide range of applications, from determining the habitat range of a bird species to mapping the hometowns of university students.



"Illustration of Layers in a GIS Process" by the University of Minnesota is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. Click on the image to view the source.

GIS specialists often create and analyze geographical information for government agencies or private businesses. They use computer programs to take raw data to develop the information these organizations need to make vital decisions. For example, in business applications, GIS can be used to determine a desirable location for a retail store based on the analysis of spatial data layers such as population distribution, highway or street arrangements, and the locations of similar stores or competitive establishments. GIS can integrate several maps into one to help analysts understand a place concerning their own specific needs.

GIS also focuses on storing information about the earth (both cultural and natural) in computer databases that can be retrieved and displayed in the form of specialized maps for specific purposes or analyses. GIS specialists require knowledge about computer and database systems. Over the last two decades, GIS has revolutionized the field of cartography: nearly all cartography is now done with the assistance of GIS software. Additionally, the analysis of various cultural and natural phenomena through the use of GIS software and specialized maps is an integral part of urban planning and other social and physical sciences. GIS can also refer to techniques used to represent, analyze, and predict spatial relationships between different phenomena.

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1.5 UNDERSTANDING NATURAL DISASTERS

Science of Natural Disasters

Because of the scientific method, we now understand *where* and *why* most natural disasters occur. For example, because of the theory of plate tectonics, we understand why nearly 90 percent of all earthquakes and volcanoes occur along the Pacific Ocean's outer edges, called the **Ring of Fire**. The theory of plate tectonics has also helped to explain why some volcanoes are more explosive and active than others. We also understand that different tectonic plate boundaries produce different fault lines and, thus, different types of earthquakes.

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Many natural hazards have seasons, especially those controlled by external forces. The United States has more tornadoes than the rest of the world combined, yet it most only occurs in the spring and early fall. Landslides are more prone in the spring when snow begins to melt, and the saturated ground causes unstable slopes to slide. Wildfires are frequent in the middle of the summer and early fall when the land is dry, and afternoon thunderstorms in arid climates produce lightning without any precipitation. Furthermore, hurricane season in the Northern Hemisphere peaks between August and September when the Atlantic Ocean is warmest.

Since hazards are statistically predictable in some manner, it becomes essential to develop a warning system. **Predictions**, such as weather predictions, state that it will occur at a specified time, date, and intensity. It is like saying, "a major snowstorm will reach Salt Lake City at 4:30 PM for the commute home." A **forecast** states a probability of something occurring, such as "40 percent of showers today." Forecasts are much broader than predictions.

When a natural disaster event is about to happen or has occurred, a system has been set up to alert the public. A **watch** is issued when the conditions for an event are right. If a severe thunderstorm is strong enough and rotating, a tornado may form. Alternatively, if an earthquake with a magnitude of 7.5 strikes somewhere in the ocean, a tsunami watch may be issued because it was strong enough to generate one. However, a watch does not necessarily mean that it will occur. A **warning** is sent out to the areas that could be impacted if a tornado is spotted on the ground or an ocean sensor records an approaching tsunami.

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Determining Risk

To understand how to prepare for a natural hazard, a risk assessment must be conducted for a specific geographic area. The **risk** of a potential hazard is defined as the probability of a disaster *multiplied by* the consequence to the human environment.

- *Risk = Probability of Disaster x Consequence of Disaster*

It is essential to determine the potential risk a location has for any particular disaster to know how to prepare for one. Referring to Salt Lake City again, the probability of an earthquake occurring anytime soon is small, but the consequences to human lives and destruction are very high. There is a moderately high risk of an earthquake striking Salt Lake City. One of the limiting factors of risk is knowing the probability of a disaster. Too often, scientific data is lacking enough information to determine how often a disaster occurs for a particular location. This is particularly true with geologic hazards, where geologic time is vastly more extensive than the age of scientific reasoning.

Hazards, Disasters, and Catastrophes

What is the difference between a natural hazard, a disaster, or a catastrophe? A **hazard** is any natural process, or even that poses a direct threat to the human environment. The event itself is not a hazard; instead, a process or event becomes a hazard when it threatens human interests. A **disaster** is the effect of a hazard on society, usually as an event that occurs over a limited time in a defined geographic area. The term disaster is used when the interaction between humans and a natural process results in significant property damage, injuries, or loss of life. Finally, a **catastrophe** is a massive disaster that significantly impacted the human environment and requiring a significant expenditure of time, money, and resources for response and recovery.

Currently, the earthquake that is expected to strike Salt Lake City is just a hazard, a natural process that poses a potential threat to the human environment, because it has not occurred yet. If that earthquake turns out to be a moderate 5.0 magnitude earthquake, it will likely be considered a disaster. However, if the expected 7.0 to 7.5 magnitude earthquake were to occur, it would be considered a catastrophe because thousands of people will likely perish, tens of thousands will be injured, and the economic cost will be in the billions of dollars. An article by NASA titled The Rising Costs of Natural Hazards talks about how the financial and human cost of natural disasters is rising. To help prepare for these disasters, better **mitigation** efforts will be required, such as proper building and zoning codes, first responder preparedness, and public education.

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In the summer of 2008, China was rocked by a magnitude 8.0 earthquake that killed over 80,000 people. A week earlier, a cyclone struck Burma killing 130,000. On January 12, 2010, a magnitude 7.0 earthquake killed nearly 300,000 people and leveled the capital city of Port-a-Prince in Haiti. On March 11, 2011, a magnitude 9.0 earthquake generated a tsunami off the coast of eastern Japan, killing 30,000 people. Are natural disasters getting worse? Not really. Humans are over-populating the earth and living in more hazard-prone areas. Over the last 70 years, the world's population has tripled to 6.7 billion. World population projections suggest that the human population will reach 9 billion by 2050. by exponentially grow, and by 2050 the world's population will reach

9 billion. **Exponential growth** means the world's population will not grow linearly (in a straight line), but rather as a percent. Our increased population size has caused air quality to suffer, reduced the availability of clean drinking water, increased the world's extreme poverty rate, and has made us more prone to natural hazards.

There is also a relationship between the **magnitude** of an event (energy released) and its **frequency** (intervals between episodes). The more earthquakes that occur for a particular location, the weaker they tend to be. That is because built-up energy is slowly being released at a relatively constant rate. However, if there are long intervals between one earthquake and the next, the energy can build and can ultimately produce a stronger earthquake. That is the problem with earthquakes along the Wasatch Front of Utah. The interval or frequency between earthquakes tends to be 1,500 years, so the magnitude tends to be high because of the built-up energy. At some point, we are going to want to get this earthquake over with because the longer it waits, the worse it will be.

Primary and Secondary Effects

There are two types of effects caused by natural disasters: *direct* and *indirect*. **Direct** effects, also called **primary effects**, include destroyed infrastructure and buildings, injuries, separated families, and even death. **Indirect**, sometimes called **secondary effects**, are things like contaminated water, disease, and financial losses. In other words, indirect effects are things that happen *after* the disaster has occurred.

How we chose to build our cities will significantly determine how many lives are saved in a disaster. For example, we should not be building homes in areas that are prone to landslides, liquefaction, or flash floods. Instead, these places should be left as open-space such as parks, golf courses, or nature preserves. This is a matter of proper zoning laws which are controlled by the local government. Another way we can reduce the impact of natural disasters is by having evacuation routes, disaster preparedness and education, and building codes so that our building does not collapse on people.

Internal and External Forces

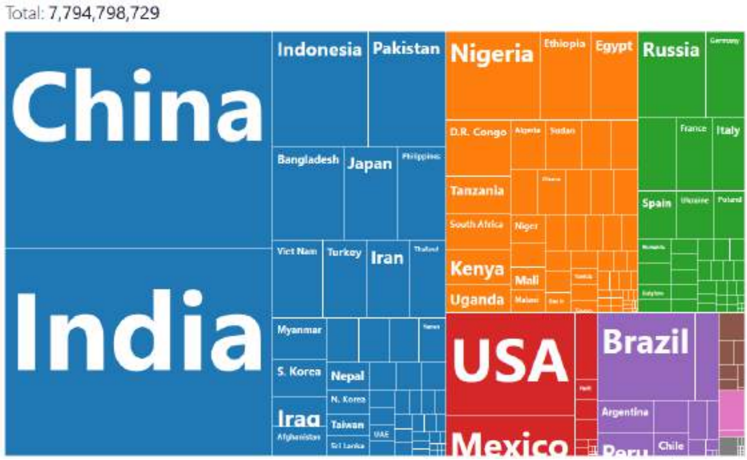
Two forces generate natural hazards: *internal forces* and *external forces*. The first is **internal forces** generated by the internal heat of the earth and creates geologic hazards like earthquakes, volcanoes, and tsunamis. The theory of **plate tectonics** proposes that internal heating from the earth's core causes large tectonic plates that make up the planet's continents and oceans and move around like bumper cars, where they either slam into each other or pull apart.

External forces influence weather, climate, and landslides. Heating from the Sun causes differential heating on the surface, ultimately creating our weather and all the hazards associated with it. These external forces create flash floods, tornadoes, hurricanes, supercells, and climatic disasters such as droughts and famines.

Human Population

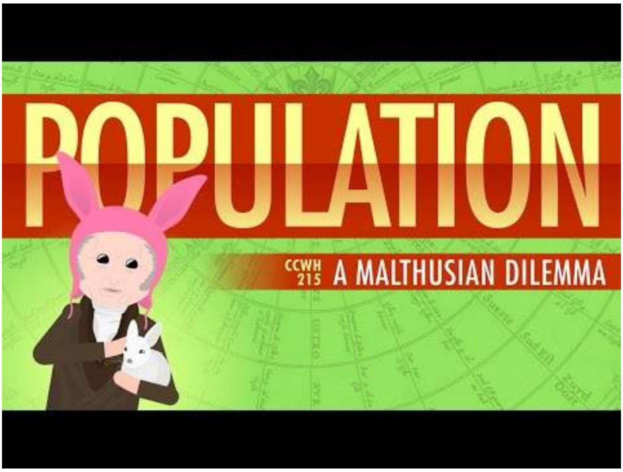
Sometimes people will ask if natural disasters are getting worse. This apocalyptic concern has only increased over time because of climate change or COVID-19. From a geologic perspective, and what the data suggests, is that natural events are not continuing to get worse. That does not mean that issues such as climate change should be discounted, far from it. But one variable that is consistent is that human population growth is causing humans to be more in the way of natural events.

Demography is the study of how human populations change over time and space. It is a branch of human geography related to **population geography**, which is the examination of the spatial distribution of human populations. Geographers study how populations grow and migrate, how people are distributed around the world, and how these distributions change over time.



"List of Countries Ordered by their Population Size" by PopulationPyramid.net is under licensed under Creative Commons 3.0 IGO.

For most of human history, relatively few people lived on Earth, and the world population grew slowly. Only about five hundred million people lived on the entire planet in 1650 (that is less than half India's population in 2000). Things changed dramatically during Europe's Industrial Revolution in the late 1700s and into the 1800s, when declining death rates due to improved nutrition and sanitation allowed more people to survive to adulthood and reproduce. The population of Europe grew rapidly. However, by the middle of the twentieth century, birth rates in developed countries declined, as children had become a financial liability rather than an economic asset to families. Fewer families worked in agriculture, more families lived in urban areas, and women delayed the age of marriage to pursue education, resulting in a decline in family size and a slowing of population growth. In some countries (e.g., Russia and Japan), the population is actually in decline, and the average age in developed countries has been rising for decades. The process just described is called the **demographic transition**.



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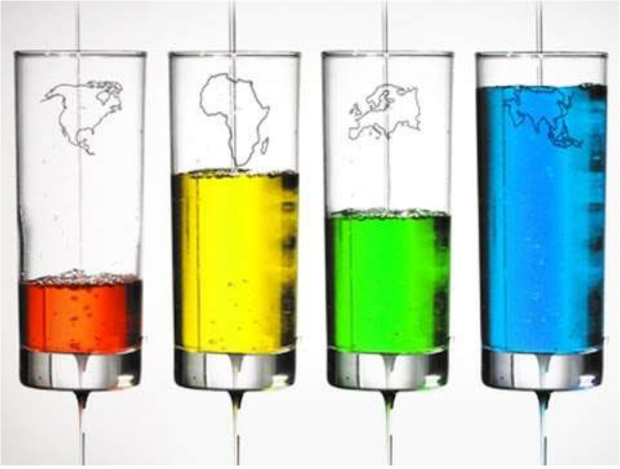
At the beginning of the twentieth century, the world's population was about 1.6 billion. One hundred years later, there were roughly six billion people worldwide, and as of 2011, the number was approaching seven billion. This rapid growth occurred as the demographic transition spread from developed countries to the rest of the world. During the twentieth century, death rates due to disease and malnutrition decreased in nearly every corner of the globe. In developing countries with agricultural societies, however, birth rates remained high. Low death rates and high birth rates resulted in rapid population growth.

Meanwhile, birth rates and family sizes have also been declining in most developing countries as people leave agricultural professions and move to urban areas. This means that population growth rates, while still higher in the developing world than in the developed world, are declining. Although the exact figures are unknown, demographers expect the world's population to stabilize by 2100 and decline somewhat.



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The world's population growth rate has been mostly occurring in developing countries, whereas populations are stable or in decline in places such as Europe and North America. World population increase is pronounced on the continent of Asia: China and India are the most populous countries in the world, each with more than a billion people, and Pakistan is an emerging population giant with a high rate of population growth. The continent of Africa has the highest fertility rates in the world. The most striking paradox within population studies is that while there has been a decline in fertility (a declining family size) in developing countries, the world's population will grow substantially by 2030 because of the compounding effect of a large number of people already in the world. Even though population growth rates are in decline in many countries, the population is still growing. A small growth rate on a broad base population still results in the birth of many millions of people.

As of May 2020, the United States Census Bureau estimates that the world population is nearly 7.65 billion, with a growth rate of roughly 1.07 percent, or roughly 82 million people per year. The world population reached 6 billion in 1999 and 7 billion in 2011. If the current growth rate continues, the human population will reach 8 billion by 2023 and hopefully level off at roughly 10 billion by 2055. Between 2010 and 2050, world population growth will be generated exclusively in developing countries.

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The three most significant population clusters in the world are the regions of eastern China, South Asia, and Europe. Southeast Asia also has large population clusters. Additional large population centers exist in various countries with high urbanization. An example is the urbanized region between Boston and Washington, DC, which includes New York City, Philadelphia, Baltimore, and neighboring metropolitan areas, which is often called a megalopolis. The coastal country of Nigeria in West Africa or the island of Java in Indonesia are good examples of large population clusters centered in the tropics.

Social dynamics and geography will determine where the new additions to the human family will live. Providing food, energy, and materials for these additional humans will tax many countries of the world, and poverty, malnutrition, and disease are expected to increase in regions with poor sanitation, limited clean water, and lack of economic resources. In 2010, more than two billion people (one-third of the planet's population) lived in abject poverty and earned less than the equivalent of two US dollars per day. The carrying capacity of the planet is not and cannot be known. How many humans can the earth sustain indefinitely? There is the possibility that we have already reached the threshold of its **carrying capacity**.

The human population will continue to grow until it either crashes due to the depletion of resources or stabilizes at a sustainable carrying capacity. Population growth exacts a toll on the earth as more people use more environmental resources. The areas most immediately affected by increased populations include forests (a fuel resource and a source of building material), freshwater supplies, and agricultural soils. These systems get overtaxed, and their depletion has serious consequences. Type C climates, which are moderate and temperate, are usually the most productive and are already vulnerable to severe deforestation, water pollution, and soil erosion. Maintaining adequate food supplies will be critical to supporting a sustainable carrying capacity. The ability to transport food supplies quickly and safely is a significant component of managing the conservation of resources. Deforestation by humans using wood for cooking fuel is already a serious concern in the arid and dry type B climates.

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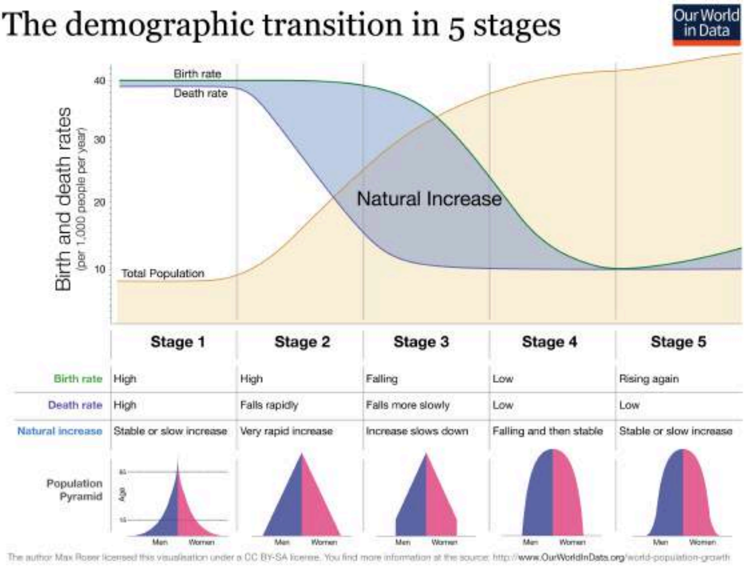
Population Demographics

The Industrial Revolution, which prompted the shift in population from rural to urban, also encouraged market economies, which have evolved into modern consumer societies. Various theories and models have been developed over the years to help explain these changes. For example, in 1929, the American demographer Warren Thompson developed the **Demographic Transition Model (DTM)** to explain population growth based on an interpretation of demographic history. A revised version of Thomson's model outlines five stages of demographic transition, from traditional rural societies to modern urban societies.



"The Demographic Transition in 5 Stages" by Max Roser is licensed under Creative Commons Attribution-Share Alike 4.0 International.

Stage 1: Low Growth Rate

Humans have lived in the first stage of the DTM for most of our existence. In this first stage, CBRs and CDRs fluctuated greatly regionally, globally, and overtime because of living conditions, food output, environmental conditions, war, and disease. Ultimately, the natural increase of the world was stable because CBRs and CDRs were about equal. However, around 8,000 BC, the world's population began to grow dramatically due to the agricultural revolution. During this time, humans learn to domesticate plants and animals for personal use and became less reliant on hunting and gathering for sustenance. This allowed for more stable food production and allowed village populations to grow. War and disease prevented population growth from occurring on a global scale.

Stage 2: High Growth Rate

Around the mid-1700s, global populations began to grow ten times faster than in the past because of the Industrial Revolution. The Industrial Revolution brought with it a variety of technological improvements in agricultural production and food supply. Increased wealth in Europe and later North America, because the Industrial Revolution meant that more money and resources could be devoted to medicine, medical technology, water sanitation, and personal hygiene. Sewer systems were installed in cities; thus, public health improved. All of this dramatically caused CDRs to drop around the world. At first, CBRs stayed high as CDRs dropped, causing populations to increase in Europe and North America. Over time, this would change.

Africa, Asia, and Latin America moved into Stage 2 of the demographic transition model 200 years later for different reasons than their European and North American counterparts. The medicine created in Europe and North America was brought into these developing nations creating what is now called the medical revolution. This revolution or diffusion of medicine to this region caused death rates to drop quickly. While the medical revolution reduced death rates, it did not bring with it the wealth and improved living conditions, and development that the Industrial Revolution created. Global population growth is most significant in the regions that are still in Stage 2.

Stage 3: Moderate Growth Rate

Today, Europe and North America have moved to Stage 3 of the demographic transition model. A nation moves from Stage 2 to Stage 3 when CBRs begin to drop while CDRs remain low or even continue to fall. It should be noted that the natural rate of increase in nations within Stage 3 is moderate because CBRs are somewhat higher than CDRs. The United States, Canada, and nations in Europe entered this stage in the early 20th century. Latin American nations entered this stage later in the century.

Advances in technology and medicine cause a decrease in IMR and overall CDR during Stage 2. Social and economic changes bring about a decrease in CBR during Stage 3. Countries that begin to acquire wealth tend to have fewer children as they move away from rural-based development structures toward urban-based structures because more children survive childhood, and the need for large families for agricultural work decreases. Additionally, women gained more legal rights and chose to enter the workforce, own property, and have fewer children as nations move into Stage 3.

Stage 4: Return to Low Growth Rate

A country enters Stage 4 of the demographic transition model when CBRs equal to or become less than CDRs. When CBRs are equal to CDRs, a nation will experience zero population growth (ZPG). This occurs in many countries where girls do not live as long as they reach their childbearing age due to gender inequality.

A country in the first two stages of the transition model will have a broad base of young people and a smaller proportion of older people. A country in Stage 4 will have a much smaller base of young people (fewer children), but a much larger population of elderly (decreased CDR). A country with a large youth population is more likely to be rural with high birthrates and possibly high death rates, helping geographers analyze a nation's health care system. Moreover, a country in Stage 4 with a large elderly population will have much fewer young people supporting the economy. These two examples represent the **dependency ratio**, mentioned earlier in this chapter. This ratio is the number of people, young and old, dependent on the working force.

Human geographers like to focus on the following demographic groups: 0-14 years old, 15-64 years old, and 65 and older. Individuals who are 0-14 and over 65 are considered dependents (though this is changing in older generations). One-third of all young people live in developing nations. Moreover, this places considerable strain on those nations' infrastructure, such as schools, hospitals, and day-care. Older individuals in more developed nations (MDL) benefit from health care services, but require more help and resources from the government and economy.

Another ratio geographers look at is the number of males compared to females, called the **sex ratio**. Globally, more males are born than females, but males have a higher death rate than females. However, understanding a country's sex ratio and its dependency ratio helps human geographers analyze fertility rates and natural increase.

As noted earlier, population growth has increased dramatically in the last century. No country is still in Stage 1, and very few have moved into Stage 4. The majority of the world is either in Stage 2 or

3, which both have higher CBRs than CDRs, creating a human population of over 7.5 billion today.

Stage 5: Population Decline

Many demographers believe a new stage in the DTM should be added to address issues starting to develop in countries within Europe and Japan. In this final stage, CBR would be extremely low and an increasing CDR. This would cause the area's NIR to become negative, leading to declining population growth. This may create an enormous strain on the social safety net programs of a country as is tries to support older citizens who are no longer working and contributing to the economy.

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Unnatural Disasters

Former UN Security General Kofi Annan has said, “The term natural disaster has become a misnomer increasingly. Human behavior transforms natural hazards into unnatural disasters.” Most deaths from natural disasters occur in less developed countries. According to the United Nations, a **less developed country** (LDC) is a country that exhibits the lowest indicators of socioeconomic development and ranked among the lowest on the Human Development Index. Those who live in low-income environments tend to have the following characteristics:

- Live in areas that are at a higher risk to geologic, weather, and climate-related disasters
- Live in areas that lack the economics and resources to provide a safe living infrastructure for its people
- Tend to have few social and economic assets and a weak social safety net
- Lack the technological infrastructure to provide early warning systems

As human populations have grown and expanded, and technology has allowed us to manipulate the environment, natural disasters have become more complex and arguable more “unnatural.” There are a variety of ways humans have not only influenced but magnified the impacts of disasters on society. For simplification, this book will narrow it down to four: human population growth, poverty and inequality, environmental degradation, and climate change.

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PART II

UNIVERSE AND SOLAR SYSTEM

2.1 THE UNIVERSE

The Expanding Universe

The ancient Greeks believed that the universe contained Earth at the center and that the sun, moon, and stars were connected around the planet. This idea held for many centuries until Galileo's telescope helped allow people to realize that Earth is not the center of the universe. They also found out that there are many more stars than were visible to the naked eye. All of those stars were in the Milky Way Galaxy.

In the early 20th century, an astronomer named Edwin Hubble discovered that what scientists called the Andromeda Nebula was over 2 million light-years away, many times farther than the farthest distances that had ever been measured. Hubble realized that many of the objects that astronomers called nebulas were not clouds of gas, but were collections of millions or billions of stars that we now call galaxies.

Hubble showed that the universe was much larger than our galaxy. Today, we know that the universe contains about a hundred billion galaxies, about the same number of galaxies as there are stars in the Milky Way Galaxy. Edwin Hubble went on to measure the distance to hundreds of other galaxies after discovering that there are galaxies beyond the Milky Way. His data would eventually show how the universe is changing, and would even yield clues as to how the universe formed. Today we now know that the universe in nearly 14 billion years old.

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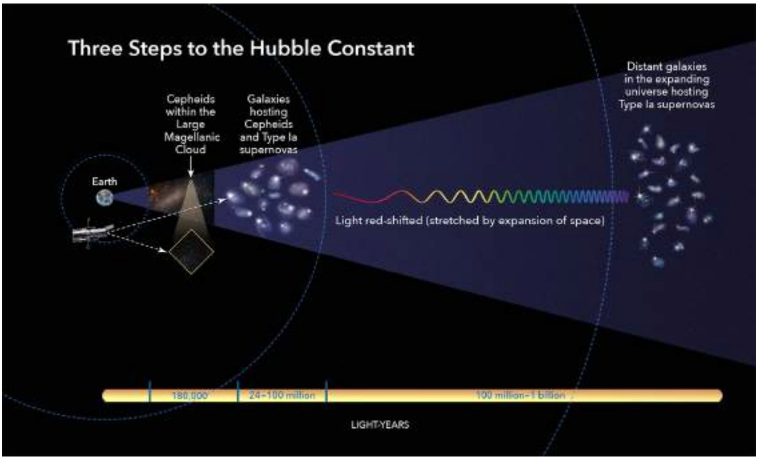
Redshift

If we look at a star through a prism, we will see a spectrum or a range of colors through the rainbow. The spectrum will have specific dark bands where elements in the star absorb light of particular energies. By examining the arrangement of these dark absorption lines, astronomers can determine the composition of elements that make up a distant star. The element helium was first discovered in our Sun, not on Earth, by analyzing the absorption lines in the spectrum of the Sun.

While studying the spectrum of light from distant galaxies, astronomers noticed something strange. The dark lines in the spectrum were in the patterns they expected, but they were shifted toward the red end of the spectrum. This shift of absorption bands toward the red end of the spectrum is known as redshift.



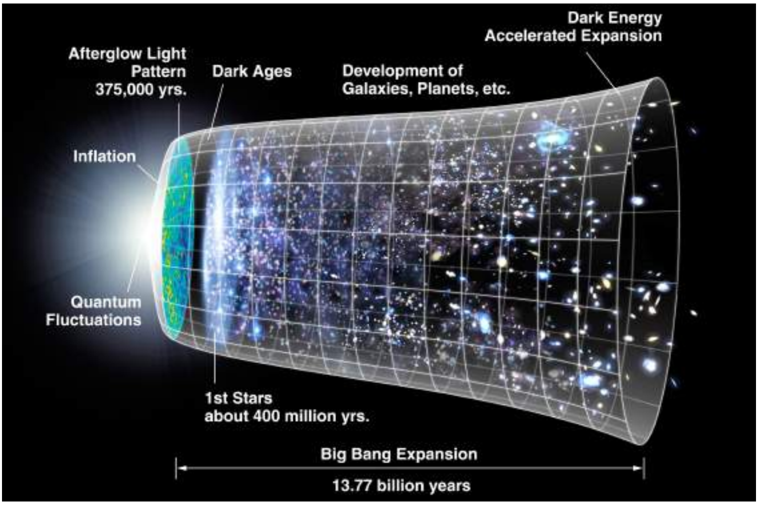
"Three Steps to the Hubble Constant" by NASA is licensed as Public Domain.

Redshift occurs when the light source is moving away from the observer or when the space between the observer and the source is stretched. What does it mean that stars and galaxies are redshifted? When astronomers see redshift in the light from a galaxy, they know that the galaxy is moving away from Earth. What astronomers are noticing is that all the galaxies have a redshift, strongly indicating that all galaxies are moving away from each other, causing the Universe to expand.

Redshift can occur with other types of waves, too, called the **Doppler Effect**. An analogy to redshift is the noise a siren makes as it passes. As it passes by, the ambulance will seem to lower the pitch of its siren. This is because the sound waves shift towards a lower pitch when the ambulance speeds away. Though redshift involves light instead of sound, a similar principle operates in both situations.

The Expanding Universe

Edwin Hubble combined his measurements of the distances to galaxies with other astronomers' measurements of redshift. From this data, he noticed a relationship, called **Hubble's Law,** that states that the farther away a galaxy is, the faster it is moving away from us. What this leads to is the hypothesis that the universe is expanding.



"Timeline of the Expanding Universe" by NASA is licensed as Public Domain.

The figure above by NASA shows a simplified diagram of the expansion of the universe. If we look closely at the diagram, the formation of the universe and the energy is relatively high. Over the 13.7 billion years, the energy begins to cool enough to create trillions of stars and, over time, develop into galaxies. Over time, the galaxies continue to cool and expand farther apart from each other.

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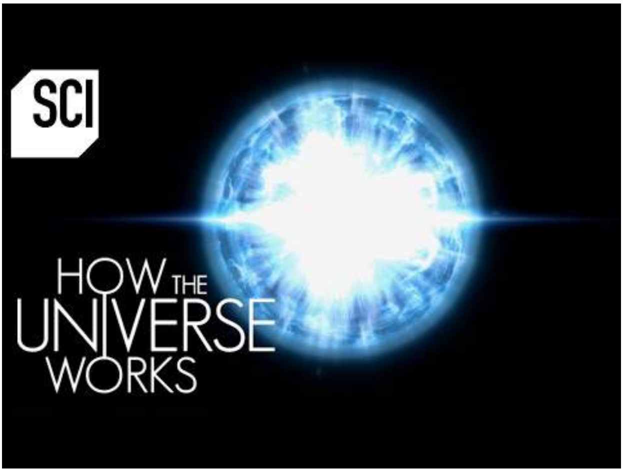
Formation of the Universe

Before Hubble, most astronomers thought that the universe did not change. However, if the universe is expanding, what does that say about where it was in the past? If the universe is expanding, the next logical thought is that it had to have been smaller in the past.



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The Big Bang Theory

The **Big Bang Theory** is the most widely accepted cosmological explanation of how the universe formed. According to the Big Bang theory, the universe began about 13.7 billion years ago. Everything that is now in the universe was squeezed into a tiny volume of hot, chaotic mass. An enormous explosion, a big bang – caused the universe to start expanding rapidly. All the matter and energy in the universe and even space itself came out of this explosion. Currently, there is not a way for scientists to know since there is no remaining evidence.

After the Big Bang

In the first few moments after the Big Bang, the universe was unimaginably hot and dense. As the universe expanded, it became less dense and began to cool. After only a few seconds, protons, neutrons, and electrons formed. After a few minutes, those subatomic particles came together to create hydrogen. The energy in the universe was significant enough to initiate nuclear fusion, and hydrogen nuclei were fused into helium nuclei. The first neutral atoms that included electrons did not form until about 380,000 years later.

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The matter in the early universe was not smoothly distributed across space. Dense clumps of matter held close together by gravity were spread around. Eventually, these clumps formed countless trillions of stars, billions of galaxies, and other structures that now form most of the universe's visible mass. If we look at an image of galaxies at the far edge of what we can see, we are looking at great distances. However, we are also looking across a different type of distance. Because it takes so long for light from so far away to reach us, we are also looking back in time.

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Dark Matter and Dark Energy

The Big Bang Theory is still the best scientific model we have for explaining the formation of the universe, and many lines of evidence support it. However, recent discoveries continue to shake up our understanding of the universe. Astronomers and other scientists are now wrestling with some unanswered questions about what the universe is made of and why it is expanding. Many cosmologists create mathematical models and computer simulations to account for these unknown phenomena, such as **dark energy** and **dark matter**.

The things we observe in space are objects that emit electromagnetic radiation. However, scientists think that matter that emits light makes up only a small part of the matter in the universe. The rest of the matter, about 80 percent, is dark matter. Dark matter emits no electromagnetic radiation, so we cannot observe it directly. However, astronomers know that dark matter exists because its gravity affects the motion of objects around it. When astronomers measure how spiral galaxies rotate, they find that the outside edges of a galaxy rotate at the same speed as parts closer to the center. This can only be explained if there is a lot more matter in the galaxy than they can see.

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Gravitational lensing occurs when light is bent from a very distant bright source around a supermassive object. To explain strong gravitational lensing, more matter than is observed must be present. With so little to go on, astronomers do not know much about the nature of dark matter. One possibility is that it could just be ordinary matter that does not emit radiation in objects such as black holes, neutron stars, and brown dwarfs, objects more massive than Jupiter but smaller than the smallest stars. However, astronomers cannot find enough of these types of objects, which they have named MACHOS (massive astrophysical compact halo object), to account for all the dark matter, so they are thought to be only a small part of the total.

Another possibility is that the dark matter is thought to be much different from the ordinary matter we see. Some appear to be particles that have gravity, but do not otherwise appear to interact with other particles. Scientists call these theoretical particles WIMPs, which stands for Weakly Interactive Massive Particles. Most scientists who study dark matter think that the dark matter in the universe is a combination of massive astrophysical compact halo objects (MACHOS) and some exotic matter such as weakly-interacting massive particles (WIMPs). Researching dark matter is an active area of scientific research, and astronomers' knowledge about dark matter is changing rapidly.

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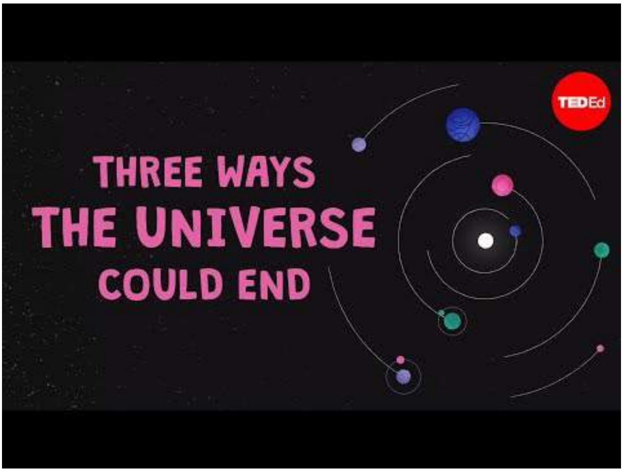
Astronomers who study the expansion of the universe are interested in knowing the rate of that expansion. Is the rate fast enough to overcome the attractive pull of gravity? If yes, then the universe will expand forever, although the expansion will slow down over time. If no, then the universe would someday start to contract, and eventually get squeezed together in a big crunch, the opposite of the Big Bang. Observations of the universe show that it is expanding faster now than ever before, and in the future, it will expand even faster. So now, astronomers think that the universe will keep expanding forever. However, it also proposes a problematic new question: What is causing the expansion of the universe to accelerate? One possible hypothesis involves a new, hypothetical form of energy called dark energy. Some scientists think that dark energy makes up as much as 72 percent of the total energy content of the universe.



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Star Systems

"**Stars** are the most widely recognized astronomical objects, and represent the most fundamental building blocks of galaxies. The age, distribution, and composition of the stars in a galaxy trace the history, dynamics, and evolution of that galaxy. Moreover, stars are responsible for the manufacture and distribution of heavy elements such as carbon, nitrogen, and oxygen, and their characteristics are intimately tied to the characteristics of the planetary systems that may coalesce about them. Consequently, the study of the birth, life, and death of stars is central to the field of astronomy." (Stars | Science Mission Directorate, n.d.)

Although constellations have stars that usually only appear to be close together, stars may be found in the same portion of space. Stars that are grouped tightly together are called **star systems**. Larger groups of hundreds or thousands of stars are called **star clusters**. The image shown here is a famous star cluster known as Pleiades, which can be seen with the naked autumn sky.

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Although the star humans know best is a single star, many stars – in fact, more than half of the bright stars in our galaxy – are star systems. A system of two stars orbiting each other is a binary star. A system with more than two stars orbiting each other is a multiple star system. The stars in a binary or multiple star system are often so close together that they appear as only through a telescope can the pair be distinguished.

Star clusters are divided into two main types, open clusters and globular clusters. **Open clusters** are groups of up to a few thousand stars that are loosely held together by gravity. Pleiades is an open cluster that is also called the Seven Sisters. Open clusters tend to be blue and often contain glowing gas and dust and are made of young stars formed from the same nebula. The stars may eventually be pulled apart by gravitational attraction to other objects.

Globular clusters are groups of tens to hundreds of thousands of stars held tightly together by gravity. Globular clusters have a definite, spherical shape and contain mostly reddish stars. The stars are closer together, closer to the center of the cluster. Globular clusters do not have much dust in them — the dust has already formed into stars.

2.2 GALAXIES AND STARS

Types of Galaxies

Galaxies are the most prominent groups of stars and can contain anywhere from a few million stars to many billions of stars. Every star that is visible in the night sky is part of the Milky Way Galaxy. To the naked eye, the closest major galaxy, the Andromeda Galaxy, looks like only a dim, fuzzy spot, but that fuzzy spot contains one trillion stars.

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Spiral and Elliptical Galaxies

Spiral galaxies spin, so they appear as a rotating disk of stars and dust, with a bulge in the middle, like the Sombrero Galaxy. Several arms spiral outward in the Pinwheel Galaxy and are appropriately called spiral arms. Spiral galaxies have lots of gas and dust and lots of young stars.

Other galaxies are egg-shaped and called an **elliptical galaxy**. The smallest elliptical galaxies are as small as some **globular clusters**. Giant elliptical galaxies, on the other hand, can contain over a trillion stars. Elliptical galaxies are reddish to yellowish because they contain mostly old stars. Most elliptical galaxies contain very little gas and dust because they had already formed. However, some elliptical galaxies contain lots of dust. Why might some elliptical galaxies contain dust?

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Irregular and Dwarf Galaxies

Galaxies that are not elliptical galaxies or spiral galaxies are **irregular galaxies**. Most irregular galaxies were once spiral or elliptical galaxies that were then deformed either by gravitational attraction to a more massive galaxy or by a collision with another galaxy.

Dwarf galaxies are small galaxies containing only a few million to a few billion stars. Dwarf galaxies are the most common type in the universe. However, because they are relatively small and dim, we do not see as many dwarf galaxies from Earth. Most dwarf galaxies are irregular in shape. However, there are also dwarf elliptical galaxies and dwarf spiral galaxies.

Look back at the picture of the spiral galaxy, Andromeda. Next to our closest galaxy neighbor are two dwarf elliptical galaxies that are companions to the Andromeda Galaxy. One is a bright sphere to the left of center, and the other is a long ellipse below and to the center's right. Dwarf galaxies are often found near more massive galaxies. They sometimes collide with and merge into their larger neighbors.

Milky Way Galaxy

On a dark, clear night, a milky band of light will stretch across the sky. This band is the disk of a galaxy, the **Milky Way Galaxy** is our galaxy and is made up of millions of stars along with a lot of gas and dust. Although it is difficult to know what the shape of the Milky

Way Galaxy is because we are inside of it, astronomers have identified it as a typical spiral galaxy containing about 100 billion to 400 billion stars.

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Like other spiral galaxies, our galaxy has a disk, a central bulge, and spiral arms. The disk is about 100,000 light-years across and 3,000 light-years thick. Most of the Galaxy's gas, dust, young stars, and open clusters are in the disk. Scientists know that the Milky Way is a spiral galaxy because of the shape of the galaxy as from Earth's perspective, the velocities of stars and gas in the galaxy show a rotational motion, and the gases, color, and dust are typical of spiral galaxies.

The central bulge is about 12,000 to 16,000 light-years wide and 6,000 to 10,000 light-years thick. The central bulge contains mostly older stars and globular clusters. Some recent evidence suggests the bulge might not be spherical, but is instead shaped like a bar. The bar might be as long as 27,000 light-years long. The disk and bulge are surrounded by a faint, spherical halo, which also includes old stars and globular clusters. Astronomers have discovered that there is a gigantic black hole at the center of the galaxy.

The Milky Way Galaxy is a significant place. Our solar system, including the Sun, Earth, and all the other planets, is within one of the spiral arms in the disk of the Milky Way Galaxy. Most of the stars we see in the sky are relatively nearby stars that are also in this spiral arm. Earth is about 26,000 light-years from the center of the galaxy, a little more than halfway out from the center of the galaxy to the edge.

Just as Earth orbits the Sun, the Sun and solar system orbit the center of the Milky Way Galaxy. One orbit of the solar system takes about 225 to 250 million years. The solar system has orbited 20 to 25 times since it formed 4.6 billion years ago. Astronomers have recently found that at the center of the Milky Way, and most other galaxies, is a supermassive black hole, though a black hole cannot be seen.

https://youtu.be/O37DrGZxDyw

Nuclear Fusion within Stars

The Sun is Earth's primary source of energy, yet the planet only receives a small portion of its energy, and the Sun is just an ordinary star. Many stars produce much more energy than the Sun. The energy source for all stars is **nuclear fusion**.

Stars are made mostly of hydrogen and helium, which are packed so densely in a star that is the star's center. The pressure is enormous enough to initiate nuclear fusion reactions. In a nuclear fusion reaction, the nuclei of two atoms combine to create a new atom. Most commonly, two hydrogen atoms fuse to become a helium atom in the core of a star. Although nuclear fusion reactions require much energy to get started, they produce enormous amounts of energy once they are going.

In a star, the energy from fusion reactions in the core pushes outward to balance the inward pull of the star's gravity. This energy moves outward through the star's layers until it finally reaches the star's outer surface. The star's outer layer glows brightly, sending the energy into space as **electromagnetic radiation**, including visible light, heat, ultraviolet light, and radio waves.

In particle accelerators, subatomic particles are propelled until they have attained almost the same amount of energy as found in the core of a star. When these particles collide head-on, new particles are created. This process simulates the nuclear fusion that takes place in the cores of stars. The process also mimics the conditions that allowed for the first helium atom to be produced from the collision of two hydrogen atoms in the first few minutes of the universe.

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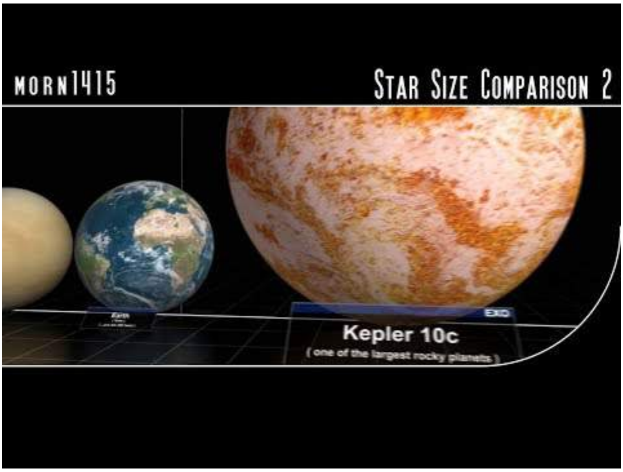
Star Classification

Think about how the color of a piece of metal changes with temperature. A coil of an electric stove will start black, but with added heat will start to glow a dull red. With more heat, the coil turns a brighter red, then orange. At extremely high temperatures, the coil will turn yellow-white or even blue-white. A star's color is also determined by the temperature of the star's surface. Relatively cool stars are red, warmer stars are orange or yellow, and extremely hot stars are blue or blue-white.

Color is the most common way to classify stars. A star's class is given by a letter, where each letter corresponds to a color and temperature range. Note that these letters do not match the color names; they are leftover from an older system that is no longer used. For most stars, the surface temperature is also related to size. Bigger, bluish-white stars produce more energy and have hotter surfaces than smaller, yellow stars that produce less energy, so their surfaces are hotter than smaller stars. These stars tend toward bluish-white.

Stars have a life cycle that is expressed similarly to the life cycle of a living creature: they are born, grow, change over time, and eventually die. Most stars vary in size, color, and class at least once in their lifetime. What astronomers know about the life cycles of stars is because of data gathered from visual, radio, and X-ray telescopes.



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Main Sequence Stars

For most of a star's life, nuclear fusion in the core produces helium from hydrogen, a stage called a **main-sequence star**. This term comes from the **Hertzsprung-Russell diagram** shown below. For stars on the main sequence, the temperature is directly related to brightness. A star is on the main sequence as long as it can balance the inward force of gravity with the outward force of nuclear fusion in its core. The more massive a star, the more it must burn hydrogen fuel to prevent internal gravitational collapse. Because they burn more fuel, massive stars have higher temperatures, but run out of hydrogen sooner than smaller stars.

Our Sun, a yellow star, has been a main-sequence star for about 5 billion years and will continue on the main sequence for about 5 billion more years. Massive stars may be on the main sequence for only 10 million years. Tiny stars may last tens to hundreds of billions of years.

Red Giants and White Dwarfs

As a star begins to use up its hydrogen, it fuses helium atoms into heavier atoms such as carbon. A blue giant star has exhausted its hydrogen fuel and is a transitional phase. When the light elements are mostly used up, the star can no longer resist gravity, and it starts to collapse inward. The outer layers of the star grow outward and cool. The larger, cooler star turns red, and so is called a **red giant**.

Eventually, a red giant burns up all of the helium in its core. What happens next depends on how massive the star is. A typical star, such as the Sun, stops fusion completely. Gravitational collapse shrinks the star's core to a white, glowing object about Earth's size, called a **white dwarf**, which will ultimately fade out.

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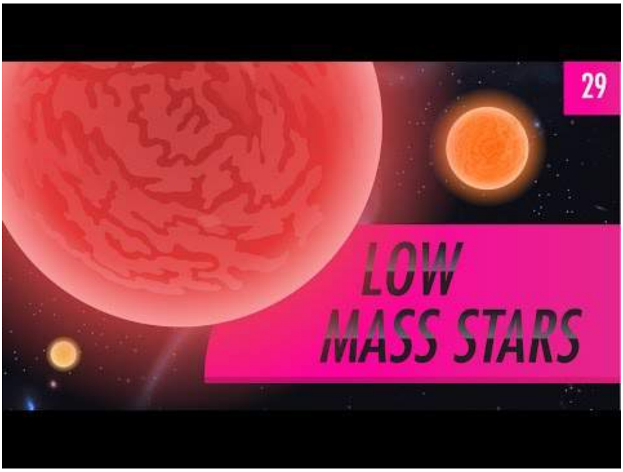
Low Mass Stars



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High Mass Stars

A star that runs out of helium will end its life much more dramatically. When very massive stars leave the main sequence, they become **red supergiants**. Unlike a red giant, when all the helium in a red supergiant is gone, fusion continues. Lighter atoms fuse into heavier atoms up to iron atoms. Creating elements heavier than iron through fusion uses more energy than it produces, so stars do not ordinarily form any heavier elements. When there are no more elements for the star to fuse, the core succumbs to gravity and collapses, creating an explosion called a **supernova**.

A supernova explosion contains so much energy that atoms can fuse to produce heavier elements such as gold, silver, and uranium. A supernova can shine as brightly as an entire galaxy for a short time. Nuclear fusion in stars created all elements with an atomic number more significant than that of lithium.

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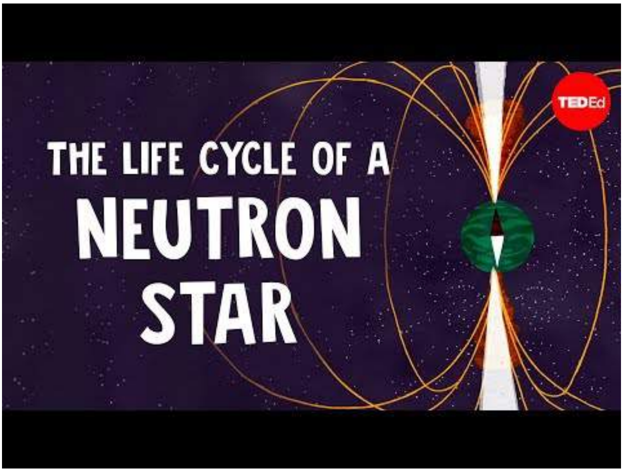
Neutron Stars and Black Holes

After a supernova explosion, the leftover material in the core is incredibly dense. If the core is less than about four times the mass of the Sun, the star becomes a **neutron star**. A neutron star is made almost entirely of neutrons, relatively large particles that have no electrical charge.



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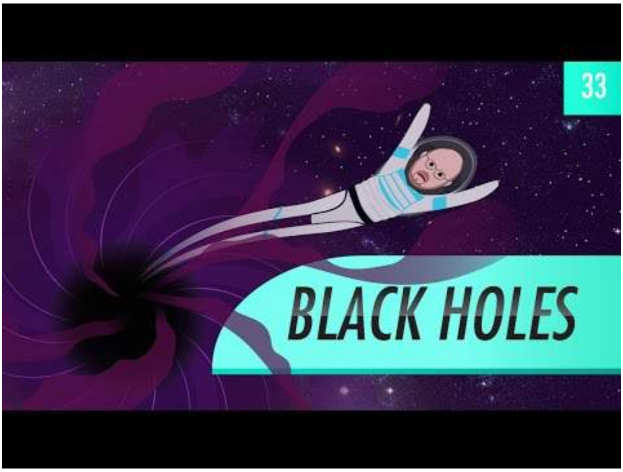
If the core remaining after a supernova is more than about five times the mass of the Sun, the core collapses into a black hole. **Black holes** are so dense that not even light can escape their gravity. With no light, a black hole cannot be observed directly. However, a black hole can be identified by the effect that it has on objects around it, and by radiation that leaks out around its edges.



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Observing and Measuring Stars

Astronomical Observations

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Telescopes

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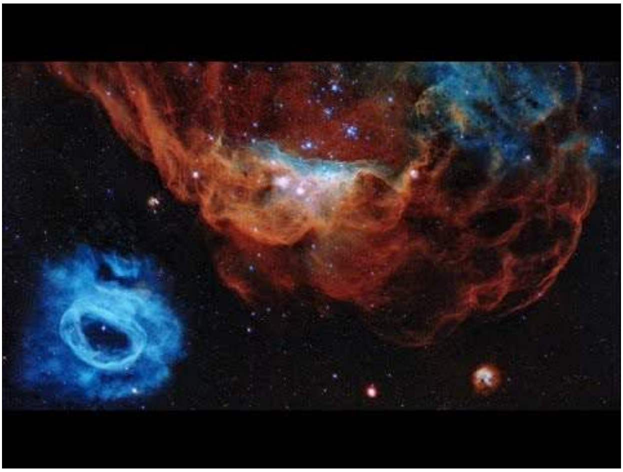

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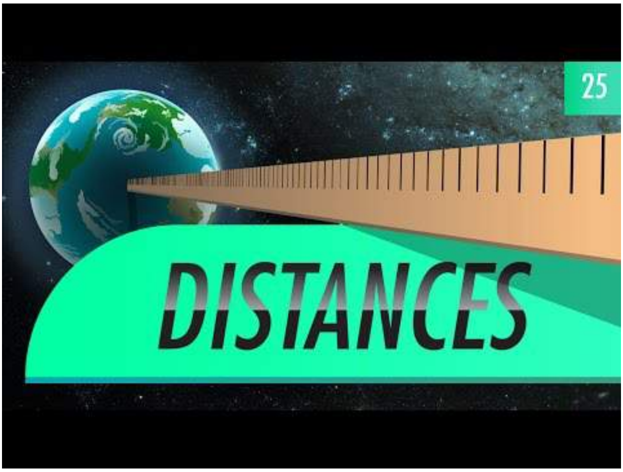
Parallax

Parallax is an apparent shift in position that takes place when the position of the observer changes. To see an example of parallax, try holding your finger about 30 cm (1 foot) in front of your eyes. Now, while focusing on your finger, close one eye and then the other. Alternate back and forth between eyes, and pay attention to how your finger appears to move. The shift in the position of your finger is an example of parallax. Now try moving your finger closer to your eyes, and repeat the experiment and notice any differences. The closer your finger is to your eyes, the more significant the position changes because of parallax.

Astronomers use this same principle to measure the distance to stars. Instead of a finger, they focus on a star, and instead of switching back and forth between eyes, they switch between the most significant possible differences in observing position. To do this, an astronomer first looks at the star from one position and notes where the star is relative to more distant stars. Now, where will the astronomer go to observe the most significant distance from the first observation? In six months, after Earth moves from one side of its orbit around the Sun to the other side, the astronomer looks at the star again. This time parallax causes the star to appear in a different position relative to more distant stars. From the size of this shift, astronomers can calculate the distance to the star.



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Using NASA's Hubble Space Telescope, astronomers now can precisely measure the distance of stars up to 10,000 light-years away, ten times farther than previously possible. Astronomers have developed yet another novel way to use the 24-year-old space telescope by employing a technique called spatial scanning, which dramatically improves Hubble's accuracy for making angular measurements. The technique, when applied to the age-old method for gauging distances called astronomical parallax, extends Hubble's tape measure ten times farther into space. "This new capability is expected to yield new insight into the nature of dark energy, a mysterious component of space that is pushing the universe apart at an ever-faster rate," said Noble laureate Adam Riess of the Space Telescope Science Institute (STScI) in Baltimore, Md.

Parallax, a trigonometric technique, is the most reliable method for making astronomical distance measurements, and a practice long employed by land surveyors here on Earth. Earth's orbit's diameter is the base of a triangle, and the star is the apex where the triangle's sides meet. The lengths of the sides are calculated by accurately measuring the three angles of the resulting triangle. Astronomical parallax works reliably well for stars within a few hundred light-years of Earth. (Northon, 2014)

For example, measurements of the distance to Alpha Centauri, the star system closest to our sun, vary only by one arc second. This variance in distance is equal to the apparent width of a dime seen from two miles away. Stars farther out have much smaller angles of apparent back-and-forth motion that are extremely difficult to measure. (Northon, 2014)

Astronomers have pushed to extend the parallax yardstick ever deeper into our galaxy by measuring smaller angles more accurately. This new long-range precision was proven when scientists successfully used Hubble to measure the distance of a particular class of bright stars called Cepheid variables, approximately 7,500 light-years away in the northern constellation Auriga. The technique worked so well; they are now using Hubble to measure the distances of other far-flung Cepheids. Such measurements will be used to provide a firmer footing for the so-called cosmic "distance ladder." This ladder's "bottom rung" is built on measurements to Cepheid variable stars that, because of their known brightness, have been used for more than a century to gauge the size of the observable universe. They are the first step in calibrating far more distant extra-galactic milepost markers such as Type Ia supernovae.

Riess and the Johns Hopkins University in Baltimore, Md., in collaboration with Stefano Casertano of STScI, developed a technique to use Hubble to make measurements as small as five-billionths of a degree. To make a distance measurement, two exposures of the target Cepheid star were taken six months apart, when Earth was on opposite sides of the sun. A very subtle shift in the star's position was measured to an accuracy of 1/1,000 the width of a single image pixel in Hubble's Wide Field Camera 3, which has 16.8 megapixels total. A third exposure was taken after another six months to allow for the team to subtract the effects of the subtle space motion of stars, with additional exposures used to remove other sources of error.

Riess shares the 2011 Nobel Peace Prize in Physics with another team for his leadership in the 1998 discovery the universe's expansion rate is accelerating — a phenomenon widely attributed to a mysterious, unexplained dark energy filling the universe. This new high-precision distance measurement technique is enabling Riess to gauge just how much the universe is stretching. His goal is to refine estimates of the universe's expansion rate to the point where dark energy can be better characterized. (Northon, 2014)

2.3 THE SOLAR SYSTEM

Geocentric Model

Humans' view of the **solar system** has evolved as technology and scientific knowledge has increased. The ancient Greeks identified five of the planets, and they were the only planets known for many centuries. Since then, scientists have discovered two more planets, many other solar-system objects, and even planets found outside our solar system. (Introduction to the Solar System | Earth Science, n.d.)

The ancient Greeks believed that Earth was at the center of the universe. This view is called the **geocentric “**Earth-centered” **model**. In the geocentric model, the sky, or heavens, are a set of spheres layered on top of one another. Each object in the sky is attached to a sphere and moves around Earth as that sphere rotates. From Earth outward, these spheres contain the Moon, Mercury, Venus, the Sun, Mars, Jupiter, and Saturn. An outer sphere holds all the stars. Since the planets appear to move much faster than the stars, the Greeks placed them closer to Earth.

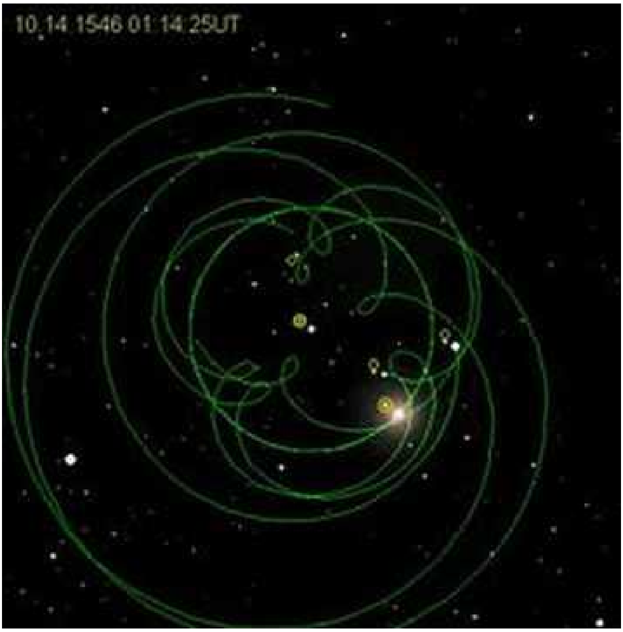
The geocentric model worked well by explaining why all the stars appear to rotate around Earth once per day. The model also explained why the planets move differently from the stars and each other. One problem with the geocentric model is that some planets seem to move backward, in retrograde, instead of in their usual forward motion around Earth.

Around 150 A.D., the astronomer Ptolemy resolved this problem by using a system of circles to describe the motion of planets. In Ptolemy's system, a planet moves in a small circle, called an **epicycle**. This circle moves around Earth in a larger circle, called a **deferent**. Ptolemy's version of the geocentric model worked so well that it remained the accepted model of the universe for more than a thousand years.

Heliocentric Model

Ptolemy's geocentric model worked, but it was not only complicated, it occasionally made errors in predicting the movement of planets. At the beginning of the 16th century A.D., Nicolaus Copernicus proposed that Earth and all the other planets orbit the Sun. With the Sun at the center, this model is called the heliocentric or "sun-centered" model of the universe. Copernicus' model explained the motion of the planets, as well as Ptolemy's model, did, but it did not require complicated additions like epicycles and deferents.

Although Copernicus' model worked more simply than Ptolemy's, it still did not entirely describe the motion of the planets because, like Ptolemy, Copernicus thought planets moved in perfect circles. Not long after Copernicus, Johannes Kepler refined the heliocentric model so that the planets moved around the Sun in ellipses (ovals), not circles. Kepler's model matched observations perfectly.



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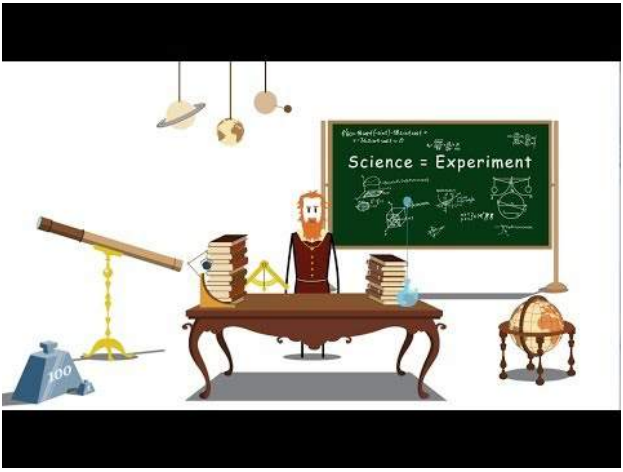
Because people were so used to thinking of Earth at the center of the universe, the heliocentric model was not widely accepted at first. However, when Galileo Galilei first turned a telescope to the heavens in 1610, he made several striking discoveries. Galileo discovered that the planet Jupiter has moons orbiting around it. This provided the first evidence that objects could orbit something besides Earth. Galileo also discovered that Venus has phases like the Moon, which provides direct proof that Venus orbits the Sun.

Galileo's discoveries caused many more people to accept the heliocentric model of the universe, although Galileo himself was found guilty of heresy for his ideas. The shift from an Earth-centered view to a Sun-centered view of the universe is referred to as the Copernican Revolution.



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Watch this animation of the Ptolemaic and Copernican models of the solar system. Ptolemy made the best model he could with the assumption that Earth was the center of the universe, but by letting that assumption go, Copernicus came up with a much simpler model. Before people would accept that Copernicus was right, they needed to accept that the Sun was the center of the solar system.

Today we know that just as Earth orbits the Sun, the Sun and solar system orbit the center of the Milky Way galaxy. The center of the Milky way may likely be a massive black hole. One orbit of the solar system takes about 225 to 250 million years. It is believed that the solar system has orbited 20 to 25 times since it formed 4.6 billion years ago.

Modern Solar System

Today, we know that our **solar system** is just one tiny part of the universe. Neither Earth nor the Sun is at the center of the universe. However, the heliocentric model accurately describes the solar system. In our modern view of the solar system, the Sun is at the center, with the planets moving in elliptical orbits around the Sun. The planets do not emit their light, but instead, reflect light from the Sun.

Esri has created an excellent story map called the Solar System Atlas. NASA has created a great website called Solar System Exploration, and National Geographic has created a great resource called Solar System. Both websites are splendid sources to introduce yourself to our solar system.

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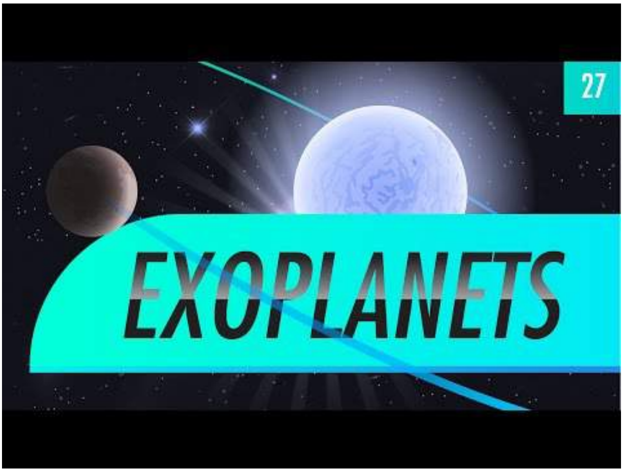
Exoplanets

Since the early 1990s, astronomers have discovered other solar systems, with planets orbiting stars other than our own Sun, called **extrasolar planets** or simply, **exoplanets**. Some extrasolar planets have been directly observed, but indirect methods have discovered most. One technique involves detecting a star's very slight motion periodically moving toward and away from us along our line-of-sight, known as a star's **radial velocity**. This periodic motion can be attributed to the gravitational pull of a planet or, sometimes, another star orbiting the star.

A planet may also be identified by measuring a star's brightness over time. A temporary, periodic decrease in light emitted from a star can occur when a planet crosses in front of the star it is orbiting, called a **transit**, momentarily blocking out some of the starlight. More than 3,600 extrasolar planets have been identified, and the rate of discovery is increasing rapidly.



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Planets and Their Motions

Since the time of Copernicus, Kepler, and Galileo, we have learned a lot more about our solar system. Astronomers have discovered two more planets (Uranus and Neptune), four dwarf planets

(Ceres, Pluto, Makemake, Haumea, and Eris), more than 150 moons, and many, many asteroids and other small objects.

Although the Sun is just an average star compared to other stars, it is by far the most massive object in the solar system. The Sun is more than 500 times the mass of everything else in the solar system combined. The table below gives data on the sizes of the Sun and planets relative to Earth. (Introduction to the Solar System | Earth Science, n.d.)

Object	**Mass (Relative to Earth**	**Diameter of Planet (Relative to Earth)**
Sun	333,000 Earth's mass	109.2 Earth's diameter
Mercury	0.06 Earth's mass	0.39 Earth's diameter
Venus	0.82 Earth's mass	0.95 Earth's diameter
Earth	1.00 Earth's mass	1.00 Earth's diameter
Mars	0.11 Earth's mass	0.53 Earth's diameter

Jupiter	317.8 Earth’s mass	11.21 Earth’s diameter
Saturn	95.2 Earth’s mass	9.41 Earth’s diameter
Uranus	4.6 Earth’s mass	3.98 Earth’s diameter
Neptune	7.2 Earth’s mass	.81 Earth’s diameter

Size and Shape of Planetary Orbits

The figure below shows the relative sizes of the orbits of the major planets within our solar system. In general, the farther away from the Sun, the higher the distance from one planet's orbit to the next. The orbits of the planets are not circular but slightly elliptical with the Sun located at one of the foci.

While studying the solar system, Johannes Kepler discovered the relationship between the time it takes a planet to make one complete orbit around the Sun, its "orbital period," and the distance from the Sun to the planet. If the orbital period of a planet is known, it is possible to determine the planet's distance from the Sun. This is how astronomers without modern telescopes could determine the distances to other planets within the solar system.

Distances in the solar system are often measured in astronomical units (AU). One astronomical unit is defined as the distance from Earth to the Sun. 1 AU equals about 150 million kilometers or 93 million miles. The table below shows the distances to the planets (the average radius of orbits) in AU. The table also indicates how long it takes each planet to spin on its axis (the length of a day) and how long it takes each planet to complete an orbit (the length of a year); in particular, notice how slowly Venus rotates relative to Earth.

Planet	**Average Distance from Sun**	**Length of Day**	**Length of Year**
Mercury	0.39 Astronomical Units (AU)	56.84 (In Earth Days)	0.24 (In Earth Years)
Venus	0.72	243.02	0.62
Earth	1.00	1.00	1.00
Mars	1.52	1.03	1.88
Jupiter	5.2	0.41	11.86
Saturn	9.54	0.43	29.46
Uranus	19.22	0.72	84.01
Neptune	30.06	0.67	164.8

The Role of Gravity

Isaac Newton was one of the first scientists to explore gravity. He understood that the Moon circles the Earth because a force is pulling the Moon toward Earth's center. Without that force, the Moon would continue moving in a straight line off into space. Newton also came to understand that the same force that keeps the Moon in its orbit is the same force that causes objects on Earth to fall to the ground.

Newton defined the **Universal Law of Gravitation**, which states that a force of attraction, called **gravity**, exists between all objects in the universe. The strength of the gravitational force depends on how much mass the objects have and how far apart they are from each other. The greater the objects' mass, the higher the force of attraction; also, the greater the distance between the objects, the smaller the force of attraction.

The distance between the Sun and each of its planets is substantial, but the Sun and each of the planets are also gigantic. Gravity keeps each planet orbiting the Sun because the star and its planets are enormous objects. The force of gravity also holds moons in orbit around planets. There are two additional key features of the solar system that helps us understand how it formed: 1) All the planets lie in nearly the same plane, or flat disk-like region, 2) All the planets orbit in the same direction around the Sun.

Formation of the Solar System

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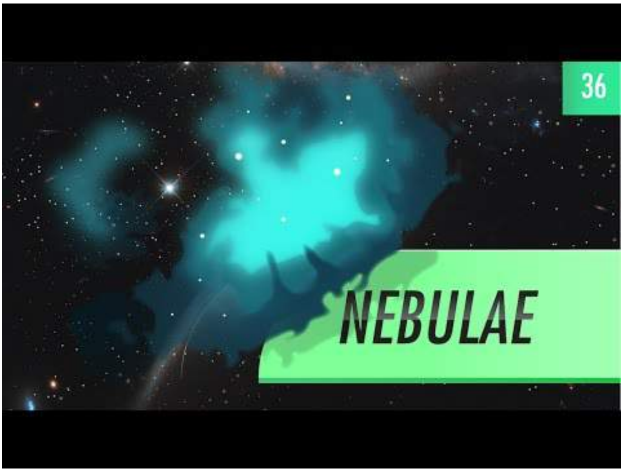
The most widely accepted explanation of how the solar system formed is called the **nebular hypothesis**. According to this hypothesis, the Sun and the planets of our solar system formed about 4.6 billion years ago from the collapse of a giant cloud of gas and dust, called a **nebula**.



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The nebula was drawn together by gravity, which released gravitational potential energy. As small particles of dust and gas smashed together to create larger ones, they released kinetic energy. As the nebula collapsed, the gravity at the center increased, and the cloud started to spin because of its angular momentum. As it collapsed further, the spinning got faster, much as an ice skater spins faster when he pulls his arms to his sides during a spin.

Much of the cloud's mass migrated to its center, but the rest of the material flattened out in an enormous disk. The disk contained hydrogen and helium, along with heavier elements and even simple organic molecules.

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Formation of the Sun and Planets

As gravity pulled matter into the center of the disk, the density and pressure at the center became intense. When the pressure in the center of the disk was high enough, nuclear fusion within our star began, and the blazing star stopped the disk from collapsing further.

Meanwhile, the outer parts of the disk were cooling off. Matter condensed from the cloud, and small pieces of dust started clumping together to create ever bigger clumps of matter. Larger clumps, called **planetesimals**, attracted smaller clumps with their gravity. Gravity at the center of the disk attracted more massive particles, such as rock and metal, and lighter particles remained further out in the disk. Eventually, the planetesimals formed **protoplanets**, which grew to become the planets and moons that we find in our solar system today.

The gravitational sorting of material with the inner planets, Mercury, Venus, Earth, and Mars, dense rock and metal formed. The outer planets, Jupiter, Saturn, Uranus, and Neptune, condensed farther from the Sun from lighter materials such as hydrogen, helium, water, ammonia, and methane. Out by Jupiter and beyond, where it is frigid, these materials formed solid particles.

The nebular hypothesis was designed to explain some of the essential features of the solar system:

- Orbits of the planets lie in nearly the same plane with the Sun at the center
- Planets revolve in the same direction
- Planets mostly rotate in the same direction
- Axes of rotation of the planets are mostly nearly perpendicular to the orbital plane
- Oldest moon rocks are 4.5 billion years

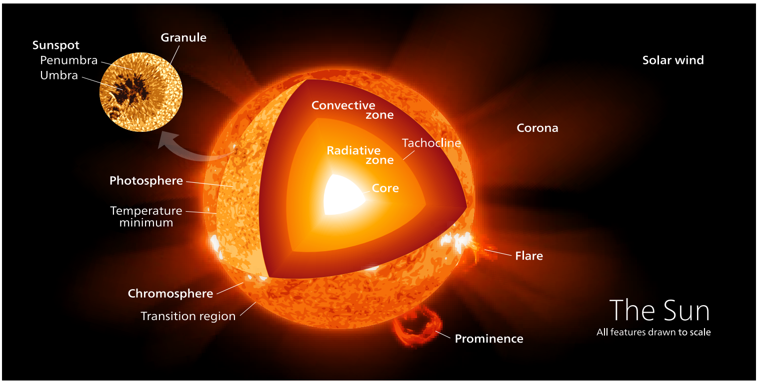
The two videos below, from the European Space Agency (ESA), discusses the Sun, planets, and other bodies in the Solar System and how they formed. The first part of the video explores the evolution of our view of the solar system, starting with the early Greeks, who reasoned that since some points of light, which they called planets, moved faster than the stars, they must be closer.

https://www.youtube.com/watch?time_continue=4&v=-NxfBOhQ1CY

https://www.youtube.com/watch?v=nw5ZOVOzOJs

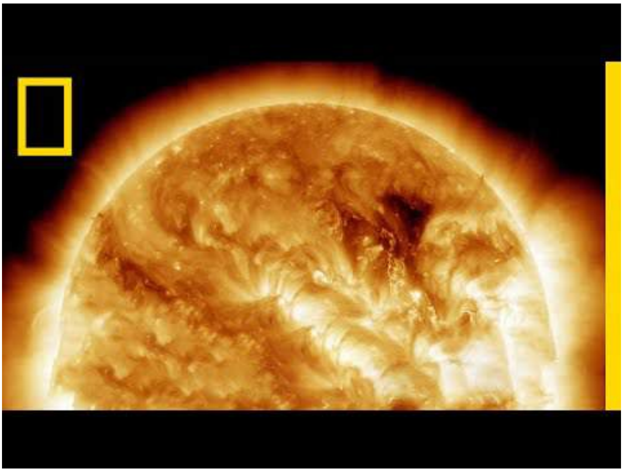
2.4 THE SUN

Consider Earth, the Moon, and all the other planets and satellites in the solar system. The mass of all of those objects together accounts for only 0.2 percent of the total mass of the solar system. The remaining 99.8 percent of the solar system's mass is within the Sun. The **Sun** is the center of the solar system and the most massive object in the solar system. This nearby star provides light and heat and supports almost all life on Earth.



"The Sun" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

The Sun is a sphere, composed almost entirely of the elements hydrogen and helium. The Sun is not solid or typical gas. Most atoms in the Sun exist as plasma, the fourth state of matter made up of superheated gas with a positive electrical charge. (The Sun | Earth Science, n.d.)



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Internal Structure

Because the Sun is not solid, it does not have a defined outer boundary. It does, however, have a definite internal structure with identifiable layers.

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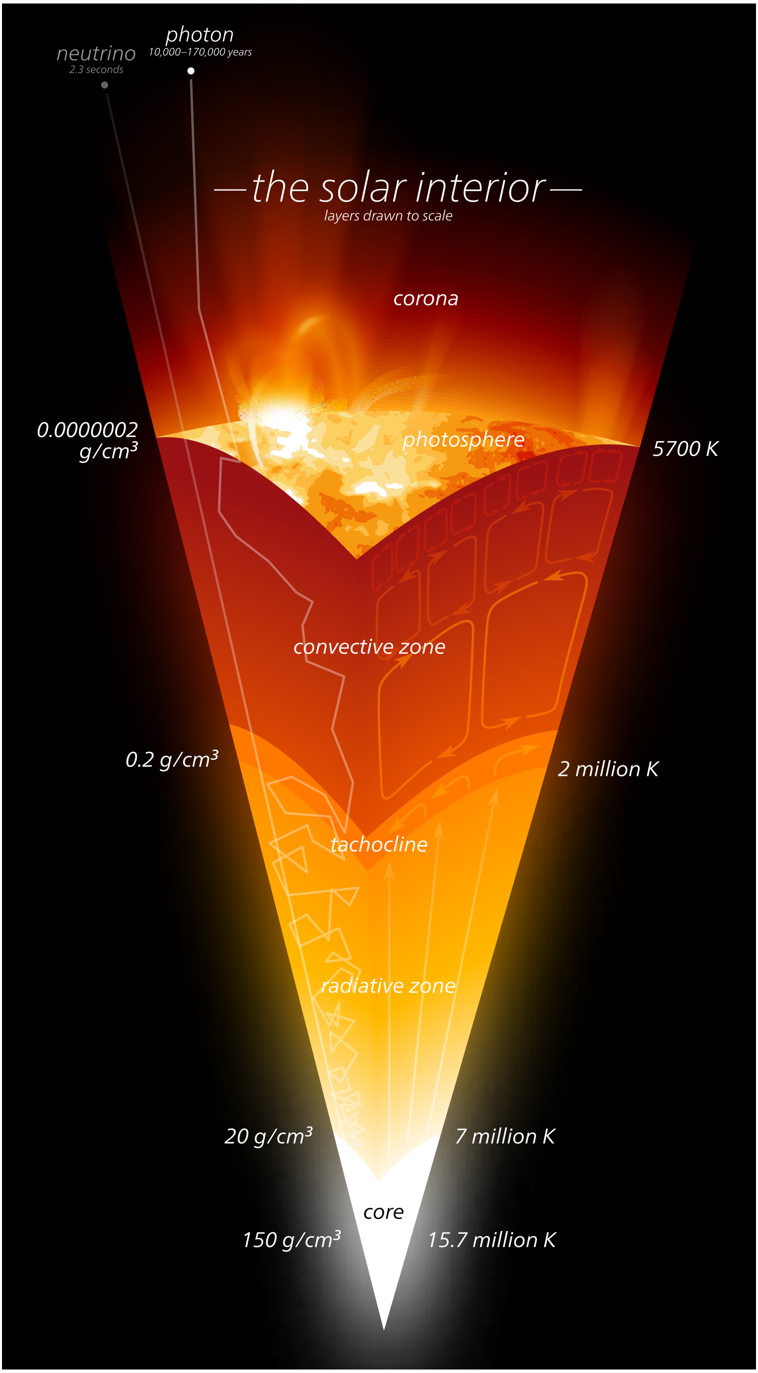
The Sun's **central core** is plasma with a temperature of around 27 million degrees Celsius. At such high temperatures, hydrogen combines to form helium by nuclear fusion, a process that releases vast amounts of energy. This energy moves outward towards the outer layers of the Sun.

The **radiative zone**, just outside the core, has a temperature of about 7 million degrees Celsius. The energy released in the core travels exceptionally slow through the radiative zone. A particle of light, called a photon, travels only a few millimeters before it hits another particle. The photon is absorbed and then released again. A photon may take as long as 50 million years to travel through the radiative zone.

In the **convection zone**, hot material from near the radiative zone rises, cools at the Sun's surface, and then plunges back downward to the radiative zone. Convective movement helps to create solar flares and sunspots.


neutrino
2.3 seconds
photon
10,000–170,000 years
—the solar interior—
layers drawn to scale
corona
0.0000002 g/cm³
photosphere
5700 K
convective zone
0.2 g/cm³
2 million K
tachocline
radiative zone
20 g/cm³
7 million K
core
150 g/cm³
15.7 million K

“Cross-section Diagram of the Solar Interior” is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

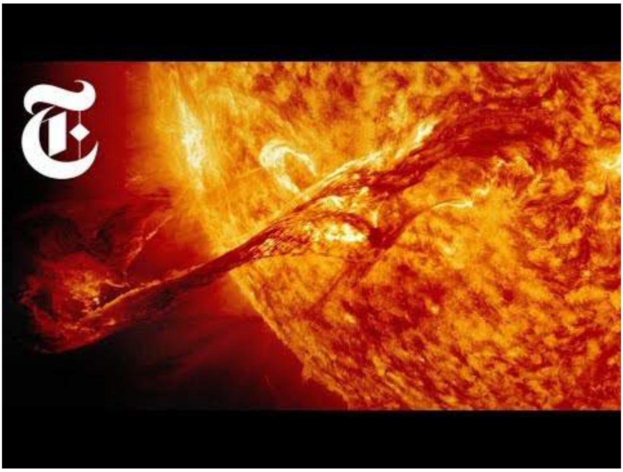
The Outer Layers

The next three layers make up the Sun’s atmosphere. Since there are no solid layers to any part of the Sun, these boundaries are fuzzy and indistinct.

The **photosphere** is the visible surface of the Sun, the region that emits sunlight. The photosphere is relatively cool, only about 6,700 degrees Celsius. The photosphere has several different colors; oranges, yellows, and reds, giving it a grainy appearance.

The **chromosphere** is a thin zone, about 2,000 km thick, that glows red as energy heats it from the photosphere. Temperatures in the chromosphere range from about 4,000-10,000 degrees Celsius. Jets of gas fire up through the chromosphere at speeds up to 72,000 km per hour, reaching heights as high as 10,000 km.

The **corona** is the outermost plasma layer and is called the Sun’s halo or crown. The corona’s temperature of 2 to 5 million degrees Celsius is much hotter than the photosphere.



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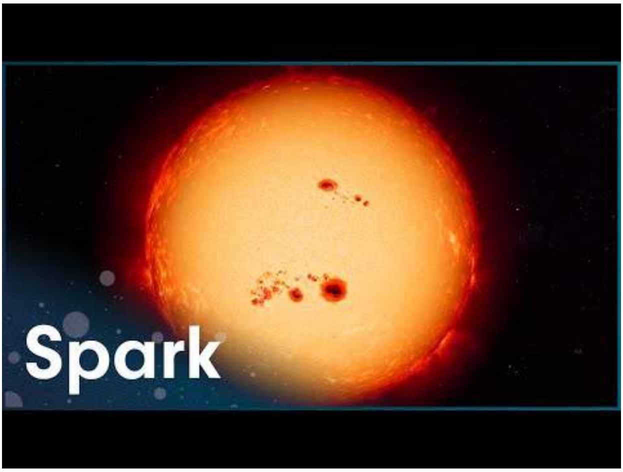
Surface Features

The Sun's surface features are quite visible for humans to observe, but only with specialized equipment. The most noticeable surface feature of the Sun are cooler, darker areas known as sunspots. **Sunspots** are located where loops of the Sun's magnetic field break through the surface and disrupt the smooth transfer of heat from lower layers of the Sun, making them cooler and darker and marked by intense magnetic activity. Sunspots usually occur in pairs. When a loop of the Sun's magnetic field breaks through the surface, a sunspot is created where the loop comes out and where it goes back in again.



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There are other types of interruptions of the Sun's magnetic energy. If a loop of the sun's magnetic field snaps and breaks, it creates solar flares, which are explosions that release vast amounts of energy. A strong solar flare can turn into a **coronal mass ejection**.

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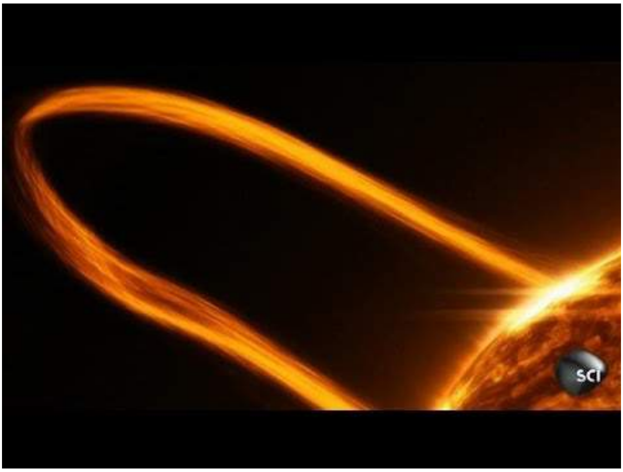
A solar flare or coronal mass ejection release streams of highly energetic particles that make up the **solar wind**. The solar wind can be dangerous to spacecraft and astronauts because it sends massive amounts of radiation that can harm the human body. Solar flares have knocked out entire power grids and disturbing radio, satellite, and cell phone communications.



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Another highly visible feature on the Sun is **solar prominences**. If plasma flows along a loop of the Sun's magnetic field from sunspot to sunspot, it forms a glowing arch that reaches thousands of kilometers into the Sun's atmosphere. Prominences can last for a day to several months. Prominences are also visible during a total **solar eclipse**.

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2.5 TERRESTRIAL PLANETS

On Earth, scientists can collect and analyze the chemistry of samples, do radiometric dating to determine their ages, and look at satellite images to see large-scale features. Rovers have landed on Mars and sent back enormous amounts of information, but much of the rest of what is known about the inner planets are from satellite images.

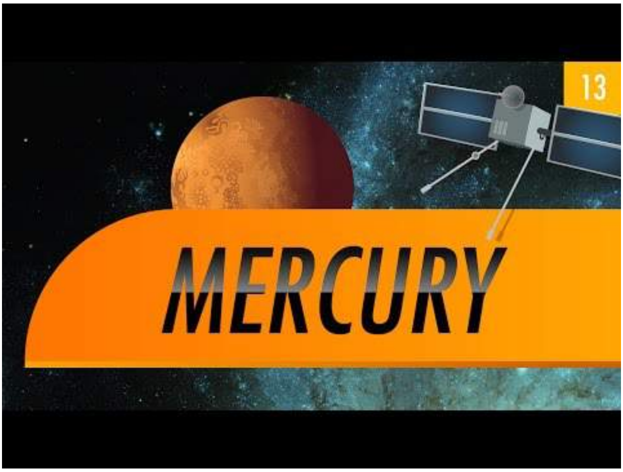
The inner planets, or **terrestrial planets**, are the four planets closest to the Sun: Mercury, Venus, Earth, and Mars. Unlike the outer planets, which have many satellites, Mercury and Venus do not have moons, Earth has one, and Mars has two. Of course, the inner planets have shorter orbits around the Sun, and they all spin more slowly. Geologically, the inner planets are all made of cooled igneous rock with iron cores, and all have been geologically active, at least early in their history. None of the inner planets has rings. (Inner Planets | Earth Science, n.d.)

Terrestrial planets are substantially different from gas giants, which might not have solid surfaces and are composed mostly of hydrogen, helium, and water existing in various physical states. Terrestrial planets all have roughly the same structure: a central metallic core, mostly iron, with a surrounding silicate mantle. Terrestrial planets have canyons, craters, mountains, volcanoes, and secondary atmospheres.

Mercury

The smallest planet, **Mercury**, is the planet closest to the Sun. Because of Mercury's proximity to the Sun, it is difficult to observe from Earth, even with a telescope. However, the Mariner 10 spacecraft visited Mercury from 1974 to 1975. The MESSENGER spacecraft, which stands for Mercury Surface, Space Environment, Geochemistry, and Ranging, has been studying Mercury in detail since 2005. The craft is currently in orbit around the planet, where it is creating detailed maps. MESSENGER stands for Mercury Surface, Space Environment, Geochemistry, and Ranging.

The surface of Mercury is covered with craters. Ancient impact craters mean that for billions of years, Mercury has not changed much geologically. Also, with minimal atmosphere, the processes of weathering and erosion do not wear down structures on the planet. Mercury is one of the solar system's densest planets. It is relatively large, liquid core, made mostly of melted iron, takes up about 42 percent of the planet's volume.



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Mercury is named for the Roman messenger god, who could run extremely quickly, just as the planet moves very quickly in its orbit around the Sun. A year on Mercury, the length of time it takes to orbit the Sun is just 88 Earth days.

Despite its short years, Mercury has very long days. A day is defined as the time it takes a planet to turn on its axis. Mercury rotates slowly on its axis, turning precisely three times for every two times it orbits the Sun. Therefore, each day on Mercury is 57 Earth days long. In other words, on Mercury, a year is only a Mercury day and a half long!

Mercury is close to the Sun so that it can get scorching. However, Mercury has virtually no atmosphere, no water to insulate the surface, and rotates very slowly. For these reasons, temperatures on the surface of Mercury vary widely. Indirect sunlight, the surface can be as hot as 427 degrees Celsius (801 degrees Fahrenheit). On the dark side, or in the shadows inside craters, the surface can be as cold as -183 degrees Celsius (-297 degrees Fahrenheit). Although most of Mercury is extremely dry, scientists think there may be a small amount of water in the form of ice at the poles of Mercury, in areas that never receive direct sunlight.

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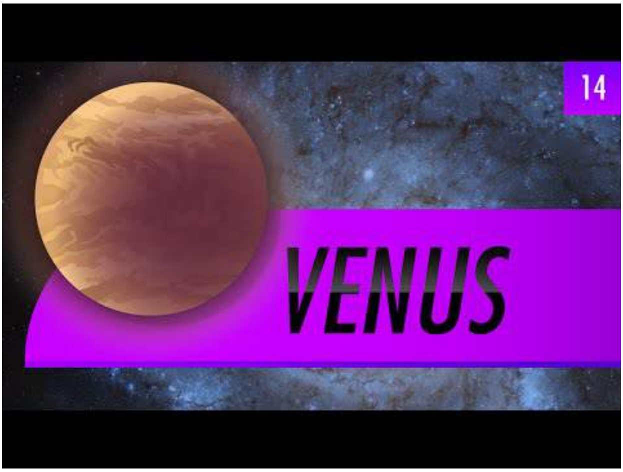
Venus

Named after the Roman goddess of love, **Venus** is the only planet named after a female. Venus' thick clouds reflect sunlight well, so Venus is very bright, making it the brightest object in the sky beside the Sun and the Moon. Because the orbit of Venus is inside Earth's orbit, Venus always appears close to the Sun. When Venus rises just before the Sun rises, the bright object is called the morning star. When it sets just after the Sun sets, it is the evening star.

Of the planets, Venus is most similar to Earth in size and density. Venus is also our nearest neighbor. The planet's interior structure is similar to Earth's with a large iron core and a silicate mantle. However, the resemblance between the two inner planets ends there.

Venus rotates in a direction opposite the other planets and opposite to the direction it orbits the Sun. This rotation is extremely slow, only one turn every 243 days. This is longer than a year on Venus, where it only takes Venus 224 days to orbit the Sun.



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A thick layer of clouds covers Venus. Venus' clouds are not made of water vapor like Earth's clouds. Clouds on Venus are made mostly of carbon dioxide with a bit of sulfur dioxide and corrosive sulfuric acid. Because carbon dioxide is a greenhouse gas, the atmosphere traps heat from the Sun and creates a powerful greenhouse effect. Even though Venus is further from the Sun than Mercury, the greenhouse effect makes Venus the hottest planet. Temperatures at the surface reach 465 degrees Celsius (860 degrees Fahrenheit), which is hot enough to melt lead.

The atmosphere of Venus is so thick that the atmospheric pressure on the planet's surface is 90 times greater than the atmospheric pressure on Earth's surface. The dense atmosphere obscures the surface of Venus, even from spacecraft orbiting the planet.

Since spacecraft cannot see through the thick atmosphere, radar is used to map Venus' surface. Many features found on the surface are similar to Earth and yet are very different. Orbiting spacecraft have used radar to reveal mountains, valleys, and canyons. Most of the surface has large areas of volcanoes surrounded by plains of lava. Venus has many more volcanoes than any other planet in the solar system, and some of those volcanoes are very large. Most of the volcanoes are no longer active, but scientists have found that there is some active volcanism.

It is difficult for scientists to figure out the geological history of Venus. The environment is too harsh for a rover to go there. It is even more difficult for students to figure out the geological history of a distant planet based on the information given here. Scientists can still piece information together to begin t understand Venus's past.

On Earth, volcanism is generated because the planet's interior is hot. Much of the volcanic activity is caused by plate tectonic activity. However, on Venus, there is no evidence of plate boundaries, and volcanic features do not line up the way they do at plate boundaries.

Because the density of impact craters can be used to determine how old a planet's surface is, the small number of impact craters means that Venus' surface is still relatively young. Scientists think that there is frequent, planet-wide resurfacing of Venus with volcanism taking place in many locations. The cause is the heat that builds up below the surface that has no es-cape until finally it destroys the crust and results in volcanoes.

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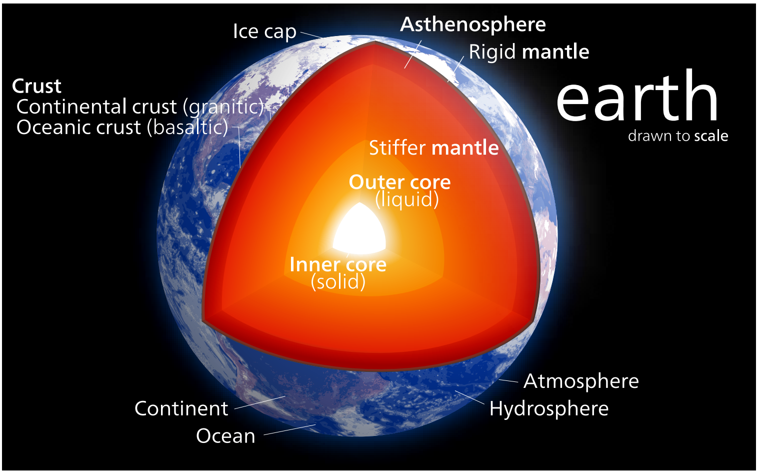
Earth

Earth has vast oceans of liquid water, large masses of exposed land, and a dynamic atmosphere with clouds of water vapor. Earth also has ice covering its polar regions. Earth's average surface temperature is 14 degrees Celsius (57 degrees Fahrenheit). Water is a liquid at this temperature, but the planet also has water in its other two states, solid and gas. The oceans and the atmosphere help keep Earth's surface temperatures reasonably steady.



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Earth is the only planet known to have known life. The presence of liquid water, the atmosphere's ability to filter out harmful radiation, and many other features make the planet uniquely suited to harbor life. Life and Earth now affect each other; for example, the evolution of plants allowed oxygen to enter the atmosphere in large enough quantities for animals to evolve. Although life has not been found elsewhere in the solar system, other planets or satellites may harbor primitive life forms. Life may also be found elsewhere in the universe.

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The heat that remained from the planet's accretion, gravitational compression, and radioactive decay allowed the Earth to melt, probably more than once. As it subsequently cooled, gravity pulled metal into the center to create the core. Heavier rocks formed the mantle, and lighter rocks formed the crust.

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Earth's crust is divided into tectonic plates, which move around on the surface because of the convecting mantle below. The plates' movement causes other geological activity, such as earthquakes, volcanoes, and mountains. The locations of these features are mostly related to current or former plate boundaries. Earth is the only planet known to have plate tectonics.

Earth rotates on its axis once per day, by definition. Earth orbits the Sun once every 365.24 days, which is defined as a year. Earth has one large moon, which orbits Earth once every 29.5 days, a period known as a month.

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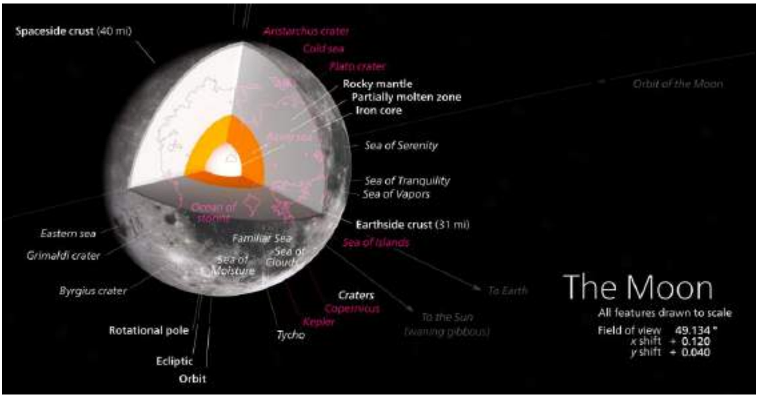
The Moon

Earth's moon is the only large moon orbiting a terrestrial planet in the solar system. The moon is covered with craters; it also has vast plains of lava. The considerable number of craters suggests that the moon's surface is ancient. There is evidence that the moon formed when a large object, perhaps as large as the planet Mars, struck Earth in the distant past.



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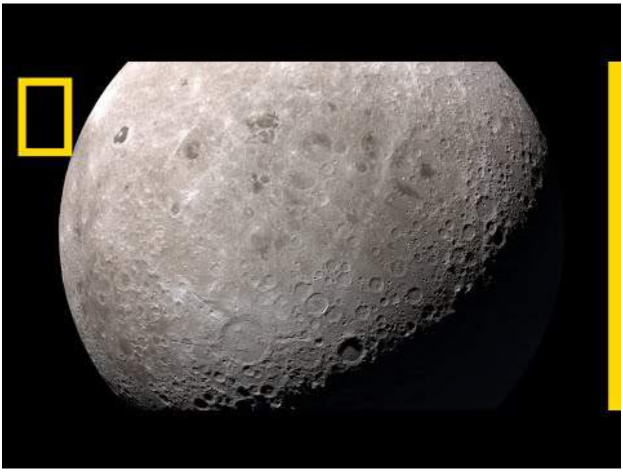

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Lunar Eclipses

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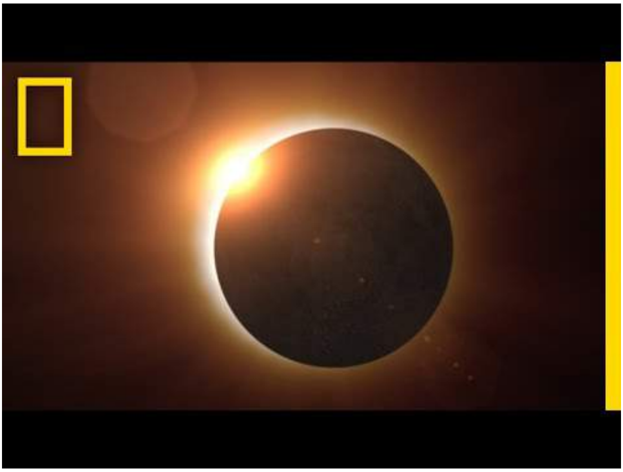
Solar Eclipses



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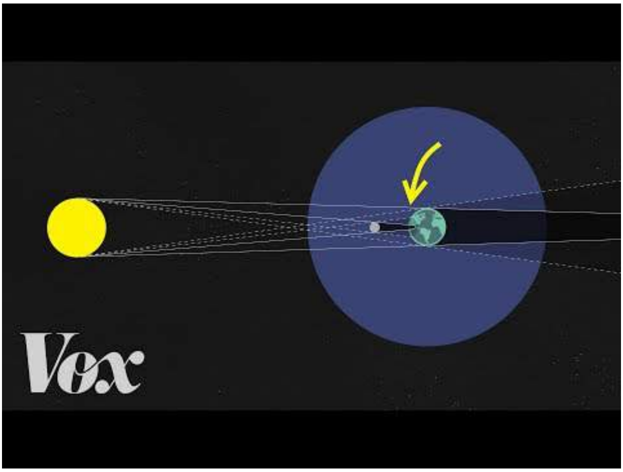

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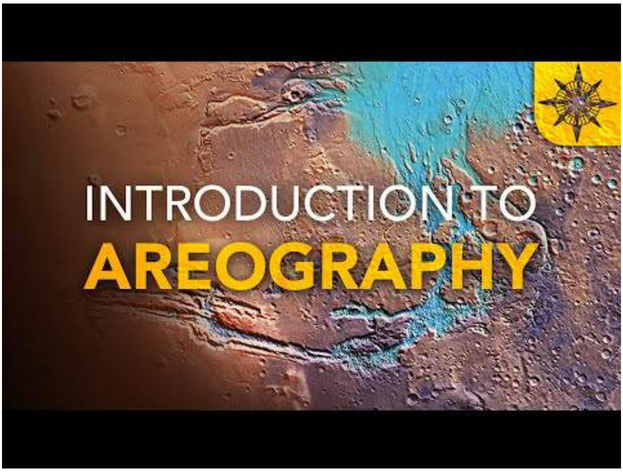
Mars

Mars is the fourth planet from the Sun and the first planet beyond Earth's orbit. Mars is quite different from Earth and yet more similar than any other planet. Mars is smaller, colder, drier, and appears to have no life, but volcanoes are common to both planets, and Mars has many.

Mars is easy to observe, so the planet has been studied more thoroughly than any other extraterrestrial planet in our solar system. Space probes, rovers, and orbiting satellites have all yielded information to planetary geologists. Although no humans have ever set foot on Mars, both NASA and the European Space Agency have set goals of sending people to Mars sometime between 2030 and 2040.



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Viewed from Earth, Mars is reddish. The ancient Greeks and Romans named the planet after the god of war. However, the surface is not red from blood but significant amounts of iron oxide in the soil. The Martian atmosphere is very thin relative to Earth's and has much lower atmospheric pressure. Although the atmosphere is made up mostly of carbon dioxide, the planet has only a weak greenhouse effect, so temperatures are only slightly higher than if the planet had no atmosphere.

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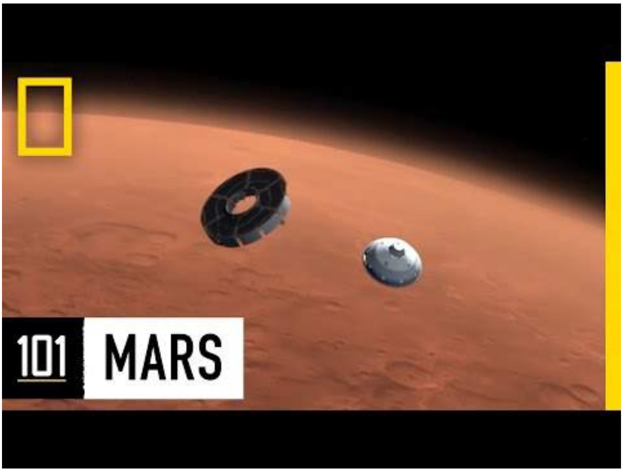
Mars has mountains, canyons, and other features similar to Earth, and some of these surface features are exceptional for their size. Olympus Mons is a shield volcano, similar to the volcanoes that make up the Hawaiian Islands. However, Olympus Mons is also the largest mountain in the solar system. Mars also has the largest canyon in the solar system, Valles Marineris.

Mars has more impact craters than Earth, though fewer than the moon. Water cannot stay in liquid form on Mars because the atmospheric pressure is too low. However, there is much water in the form of ice and even prominent ice caps. Scientists also think that there is a lot of water ice present just under the Martian surface. This ice can melt when volcanoes erupt, and water can flow across the surface temporarily.



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Scientists think that water once flowed over the Martian surface because surface features look like water-eroded canyons. The presence of water on Mars, even though it is now frozen as ice, suggests that it might have been possible for life to exist on Mars in the past.

Mars has two tiny moons that are irregular rocky bodies. **Phobos** and **Deimos** are named after characters in Greek mythology; the two sons of Ares followed their father into war. Ares is equivalent to the Roman god Mars.

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2.6 GAS GIANTS

The Outer Planets

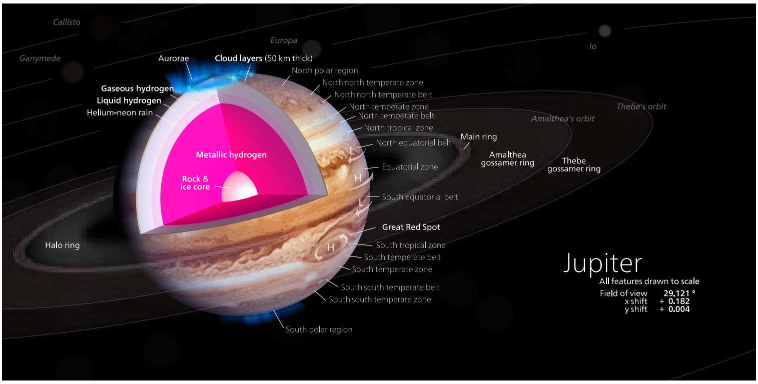
The four planets farthest from the Sun are the **outer planets**. These planets are much larger than the inner planets and are made primarily of gases and liquids, so they are also called gas giants or Jovian planets.

The **gas giants** are made up primarily of hydrogen and helium, the same elements that make up most of the Sun. Astronomers think that hydrogen and helium gases comprised much of the solar system when it first formed. Since the inner planets did not have enough mass to hold on to these light gases, their hydrogen and helium floated away into space. The Sun and the massive outer planets had enough gravity to keep hydrogen and helium from drifting away. (Outer Planets | Earth Science, n.d.)

All of the outer planets have numerous moons. They all also have planetary rings, composed of dust and other small particles that encircle the planet in a thin plane.

Jupiter

Because **Jupiter** is so massive, it reflects much sunlight and appears bright in the night sky; only the Moon and Venus are brighter. This brightness is all the more impressive because Jupiter is quite far from the Earth, 5.20 AUs away. It takes Jupiter about 12 Earth years to orbit once around the Sun.



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Jupiter is named for the king of the gods in Roman mythology. The planet is enormous, the most massive object in the solar system besides the Sun. Although Jupiter is over 1,300 times Earth’s volume, it has only 318 times the mass of Earth. Like the other gas giants, it is less dense than Earth. Hypothetically, astronauts trying to land a spaceship on the surface of Jupiter would find that there is no solid surface. Jupiter is made mostly of hydrogen, with some helium, and small amounts of other elements.

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The upper layer of Jupiter's atmosphere contains clouds of ammonia (NH3) in bands of different colors. These bands rotate around the planet, but also swirl around in violent storms. The **Great Red Spot** is an enormous, oval-shaped storm found south of Jupiter's equator. This storm is more than three times as wide as the entire Earth. Clouds in the storm rotate in a counterclockwise direction, making one complete turn every six days. The Great Red Spot has been on Jupiter for at least 300 years since astronomers could first see the storm through telescopes.

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Jupiter's Moons

Jupiter has 63 moons orbiting it that we are aware of so far. Four are big enough and bright enough to be seen from Earth, using no more than a pair of binoculars. These four moons, **Io**, **Europa**, **Ganymede**, and **Callisto**, were first discovered by Galileo in 1610 and are referred to as the Galilean moons. The Galilean moons are more significant than the dwarf planets Pluto, Ceres, and Eris. Ganymede is not only the biggest moon in the solar system, but it is also even larger than the planet Mercury.

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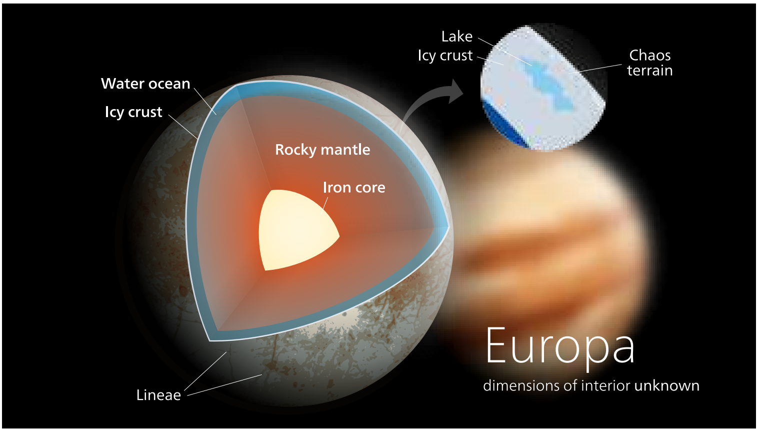
Scientists are particularly interested in Europa because it may be a place to find extraterrestrial life. Although the surface of Europa is a smooth layer of ice, there is evidence that there is an ocean of liquid water underneath. Europa also has a continual source of energy; it is heated as it is stretched and squashed by tidal forces from Jupiter. Numerous missions have been planned to explore Europa, including plans to drill through the ice and send a probe into the ocean. However, no such mission has yet been attempted.



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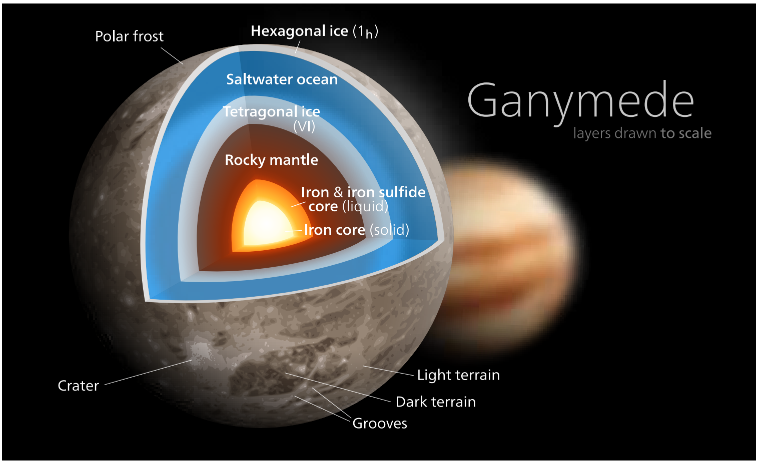

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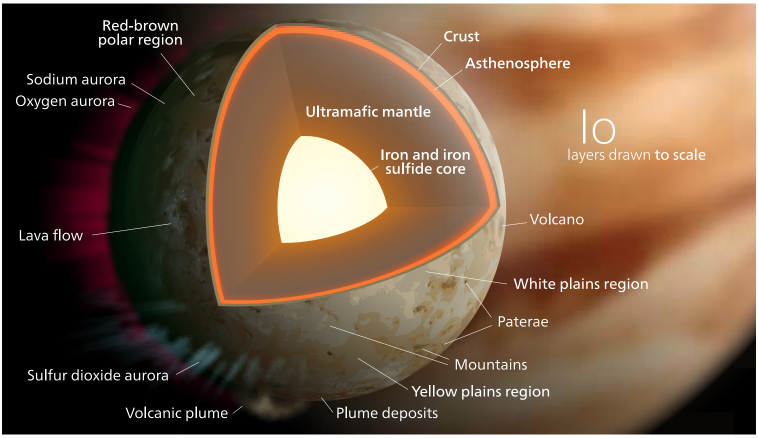

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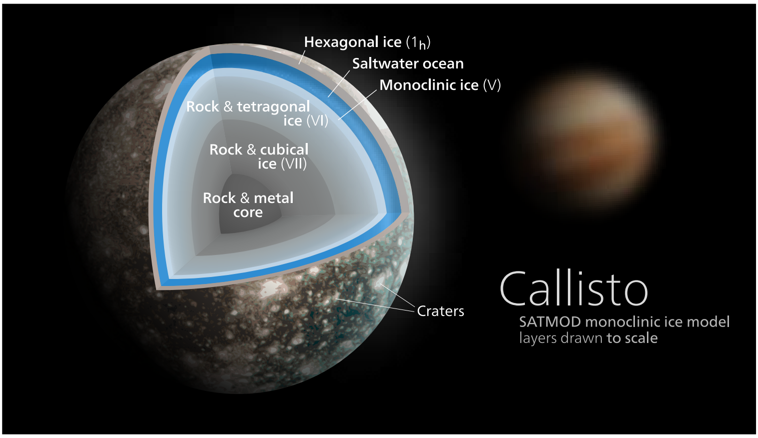

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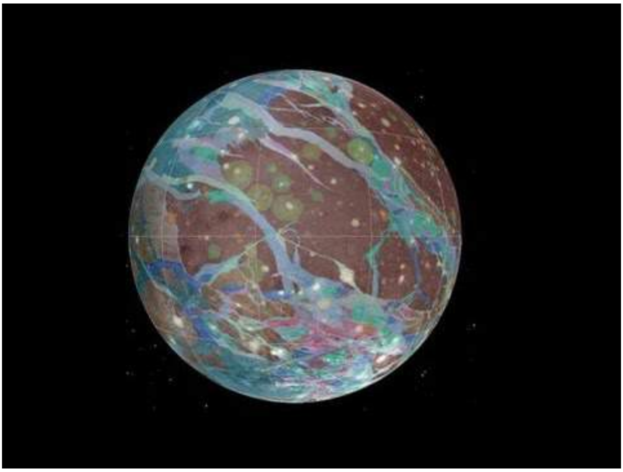
In 1979, two spacecraft, Voyager 1 and Voyager 2 visited Jupiter and its moons. Photos from the Voyager missions showed that Jupiter has a faint ring system. This ring system is very faint, so it is difficult to observe from Earth. Recently, NASA launched the Juno satellite to study Jupiter.



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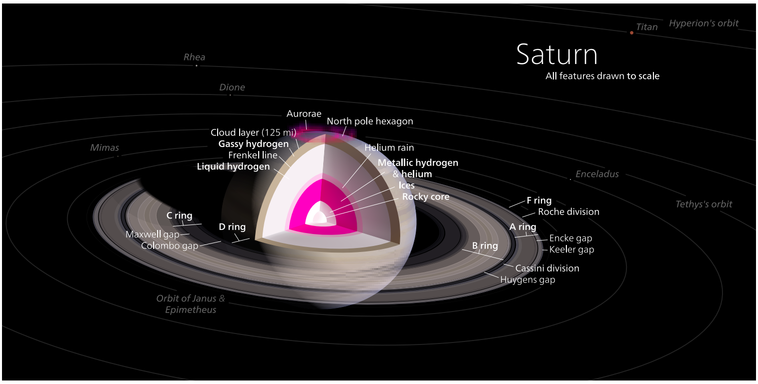
Saturn

Saturn is famous for its beautiful rings. Although all the gas giants have rings, only Saturn's can be easily seen from Earth. In Roman mythology, Saturn was the father of Jupiter. Saturn's mass is about 95 times the mass of Earth, and its volume is 755 times Earth's volume, making it the second-largest planet in the solar system. Saturn is also the least dense planet in the solar system. It is less dense than water, meaning that Saturn would float on water. Saturn orbits the Sun once about every 30 Earth years.



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Like Jupiter, Saturn is made mostly of hydrogen and helium gases in the outer layers and liquids at greater depths. The upper atmosphere has clouds in bands of different colors. These rotate rapidly around the planet, but there seems to be less turbulence and fewer storms on Saturn than on Jupiter. One interesting phenomenon that has been observed in the storms on Saturn is the presence of thunder and lightning. The planet likely has a small rocky and metallic core.

In 1610 Galileo first observed Saturn's rings with his telescope, but he thought they might be two large moons, one on either side of the planet. In 1659, the Dutch astronomer Christian Huygens realized that the features were rings. Saturn's rings circle the planet's equator and appear tilted because Saturn itself is tilted about 27 degrees. The rings do not touch the planet.

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The Voyager 1 and 2 spacecraft in 1980 and 1981 sent back detailed pictures of Saturn, its rings, and some of its moons. Saturn's rings are made of particles of water and ice, with some dust and rocks. There are several gaps in the rings that scientists think have originated because 1) the material was cleared out by the gravitational pull within the rings or, 2) by the gravitational forces of Saturn and of moons outside the rings. The rings were likely formed by the breakup of Saturn's moons or a material that never accreted into the planet when Saturn formed initially.

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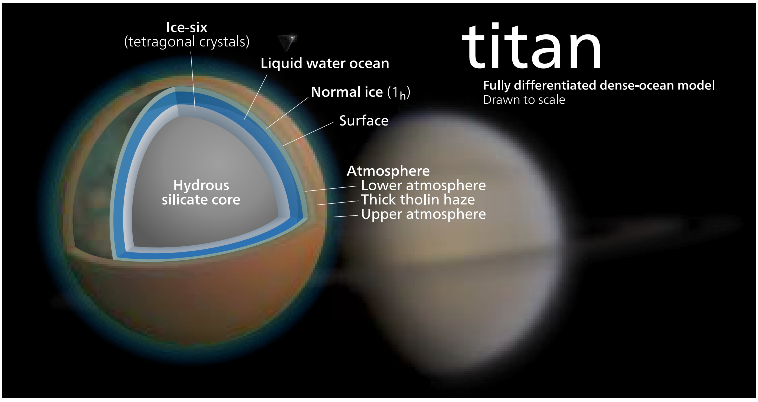
Saturn's Moons

Most of Saturn's moons are very small, and only seven are large enough for gravity to have made them spherical. Only Titan is more massive than Earth's Moon at about 1.5 times its size. Titan is even more massive than the planet Mercury. Scientists are interested in Titan because its atmosphere is similar to what Earth's was like before life developed. Nitrogen is dominant, and methane is the second most abundant gas. **Titan** may have a layer of liquid water and ammonia under a layer of surface ice. Lakes of liquid methane (CH4) and ethane (C2H6) are found on Titan's surface. Although conditions are similar enough to those of early Earth for scientists to speculate that extremely primitive life may exist on Titan, the extreme cold and lack of carbon dioxide make it unlikely.



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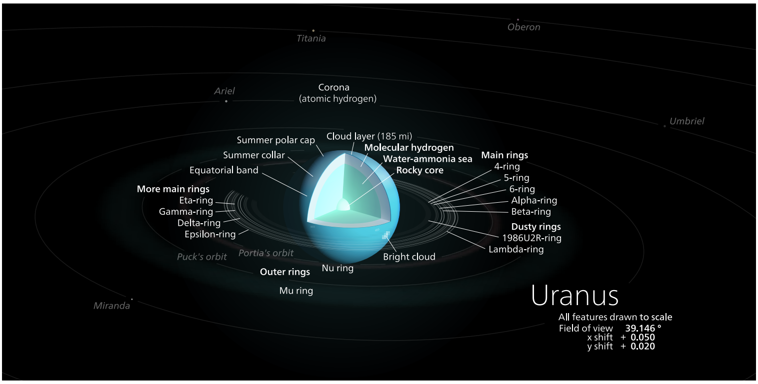
Uranus

Uranus (YOOR-uh-nuhs) is named after the Greek god of the sky. From Earth, Uranus is so faint that it was unnoticed by ancient observers. William Herschel first discovered the planet in 1781. Although Uranus is enormous, it is incredibly far away, about 2.8 billion km (1.8 billion mi) from the Sun. Light from the Sun takes about 2 hours and 40 minutes to reach Uranus, and the planet orbits the Sun once about every 84 Earth years. Uranus has a mass of about 14 times the mass of Earth, but it is much less dense than Earth. Gravity at the surface of Uranus is weaker than on Earth's surface, so if a human were at the top of the clouds on Uranus, they would weigh about 10 percent less than what they would weigh on Earth.



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Like Jupiter and Saturn, Uranus is composed mainly of hydrogen and helium, with an outer gas layer that gives way to liquid on the inside. Uranus has a higher percentage of icy materials, including water, ammonia (NH3), and methane (CH4) than Jupiter and Saturn. When sunlight reflects off Uranus, clouds of methane filter out red light, giving the planet a blue-green color. There are bands of clouds in Uranus’ atmosphere, but they are hard to see in normal light, so the planet looks like a plain blue ball.

Most of the solar system planets rotate on their axes in the same direction as they move around the Sun. Uranus is tilted on its side, so its axis is almost identical to its orbit. It rotates like a top that was turned so that it was spinning parallel to the floor. Scientists think that Uranus was probably knocked over by a collision with another planet-sized object billions of years ago.

Uranus's Moons

Uranus has a faint system of rings. The rings circle the planet's equator, but because Uranus is tilted on its side, the rings are almost perpendicular to the planet's orbit. Uranus has 27 known moons, and all but a few of them are named after characters from the plays of William Shakespeare. The five biggest moons are Miranda, Ariel, Umbriel, Titania, and Ober-on.

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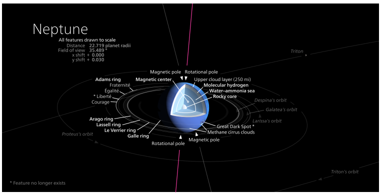
Neptune

Neptune is the only major planet that cannot be seen from Earth without a telescope. Scientists predicted Neptune's existence before it was discovered because Uranus did not always appear exactly where it should appear. They knew that the gravitational pull of another planet beyond Uranus must be affecting Uranus' orbit.



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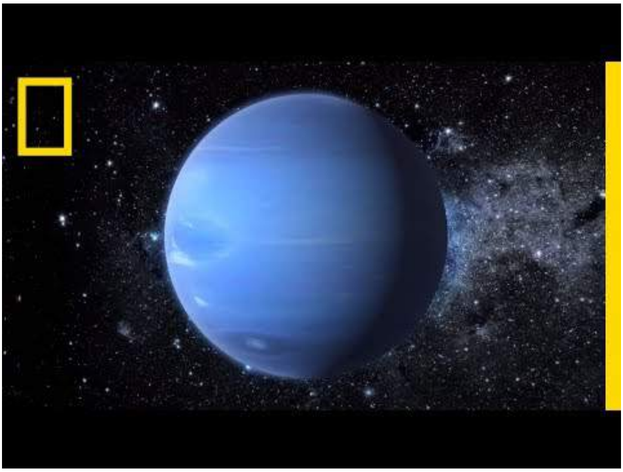
Neptune was discovered in 1846, in the position that had been predicted, and it was named Neptune for the Roman god of the sea because of its bluish color. In many respects, Neptune is similar to Uranus. Neptune has slightly more mass than Uranus, but it is somewhat smaller in size. Neptune is much farther from the Sun at nearly 4.5 billion km (2.8 billion mi) than Uranus. The planet's slow orbit means that it takes 165 Earth years to go once around the Sun.



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Neptune's blue color is mostly because of frozen methane. When Voyager 2 visited Neptune in 1986, there was a sizeable dark-blue spot that scientists named the Great Dark Spot, south of the equator. When the Hubble Space Telescope took pictures of Neptune in 1994, the Great Dark Spot had disappeared, but another dark spot had appeared north of the equator. Astronomers think that both of these spots represent gaps in the methane clouds on Neptune.

The changing appearance of Neptune is caused by its turbulent atmosphere. The winds on Neptune are more substantial than on any other planet in the solar system, reaching speeds of 1,100 km/h (700 mi/h) close to the sound speed. This extreme weather surprised astronomers since the planet receives little energy from the Sun to power weather systems. Neptune is also one of the coldest places in the solar system. Temperatures at the top of the clouds are about -218 degrees Celsius (-360 degrees Fahrenheit). Neptune has faint rings of ice and dust that may change or disappear in reasonably short time frames.

Neptune's Moons

Neptune has 13 known moons. Triton is the only one of them that has enough mass to be spherical. Triton orbits in the direction opposite to the orbit of Neptune. Scientists think Triton did not form around Neptune, but instead was captured by Neptune's gravity as it passed by.

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2.7 OTHER OBJECTS IN THE SOLAR SYSTEM

When the solar system formed, most of the matter ended up in the Sun. Material spinning in a disk around the Sun clumped together into larger pieces to form the eight planets. However, some of the smaller pieces of matter never joined one of these larger bodies and are still out there in space. (Other Objects in the Solar System | Earth Science, n.d.)

Asteroids

Asteroids are tiny, rocky bodies that orbit the Sun. “Asteroid” means “star-like,” and in a telescope, asteroids look like points of light, just like stars. Asteroids are irregularly shaped because they do not have enough gravity to become round. They are also too small to maintain an atmosphere, and without internal heat, they are not geologically active. Collisions with other bodies may break up the asteroid or create craters on its surface.

Asteroid impacts have had dramatic impacts on the shaping of the planets, including Earth. Early impacts caused the planets to grow as they cleared their portions of space. An impact with an asteroid about the size of Mars caused Earth’s fragments to fly into space and ultimately create the moon. Asteroid impacts are linked to mass extinctions throughout Earth history.

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The Asteroid Belt

Hundreds of thousands of asteroids have been discovered in our solar system. They are still being discovered at a rate of about 5,000 new asteroids per month. The majority of the asteroids are found in between the orbits of Mars and Jupiter in a region called the **asteroid belt**. Although there are many thousands of asteroids in the asteroid belt, their total mass adds up to only about 4 percent of Earth's moon.

Scientists think that the bodies in the asteroid belt formed during the formation of the solar system. The asteroids might have come together to make a single planet, but they were pulled apart by Jupiter's intense gravity.

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Near-Earth Asteroids

More than 4,500 asteroids cross Earth's orbit; they are near-Earth asteroids. Between 500 and 1,000 of these are over 1 km in diameter. Any object whose orbit crosses Earth's can collide with Earth, and many asteroids do. On average, each year, a rock about 5–10 m in diameter hits Earth. Since past asteroid impacts have been implicated in mass extinctions, astronomers are always on the lookout for new asteroids and follow the known near-Earth asteroids closely to predict a possible collision as early as possible.

Scientists are interested in asteroids because they are representatives of the earliest solar system. Eventually, asteroids could be mined for rare minerals or construction projects in space. A few missions have studied asteroids directly. NASA's DAWN mission orbited asteroid Vesta from July 2011 to September 2012 and is on its way to meet dwarf planet Ceres in 2015.

Thousands of objects, including comets and asteroids, are zooming around our solar system; some could be on a collision course with Earth. A meteor is a streak of light across the sky. People call them shooting stars, but small pieces of matter are burning up as they enter Earth's atmosphere from space.

Meteors are called meteoroids before they reach Earth's atmosphere. Meteoroids are smaller than asteroids and range from the size of boulders down to the size of tiny sand grains. Still, smaller objects are called interplanetary dust. When Earth passes through a cluster of meteoroids, there is a meteor shower. These clusters are often remnants left behind by comet tails.

Meteorites

Although most meteors burn up in the atmosphere, larger **meteoroids** may strike the Earth's surface to create a meteorite. Meteorites are valuable to scientists because they provide clues about our solar system. Many meteorites are from asteroids that formed when the solar system formed. A few meteorites are made of rocky material that is thought to have come from Mars when an asteroid impact shot material off the Martian surface and into space.

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Comets

Comets are small, icy objects that have very elliptical orbits around the Sun. Their orbits carry them from the outer solar system to the inner solar system, close to the Sun. Early in Earth's history, comets may have brought water and other substances to Earth during collisions.

Comet tails form the outer layers of ice melt and evaporate as the comet flies close to the Sun. The ice from the comet vaporizes and forms a glowing coma, which reflects light from the Sun. Radiation and particles streaming from the Sun push this gas and dust into a long tail that always points away from the Sun. Comets appear for only a short time when they are near the Sun; they seem to disappear again as they move back to the outer solar system.

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The time between one appearance of a comet and the next is called the comet's period. Halley's comet, with a period of 75 years, will next be seen in 2061. The first mention of the comet in historical records may go back as much as two millennia. Short-period comets, with periods of about 200 years or less, come from a region beyond Neptune's orbit. The Kui-per belt (pronounced "KI-per") contains not only comets, but asteroids, and at least two dwarf planets.

Comets, with periods as long as thousands or even millions of years, come from a distant region of the solar system called the **Oort cloud**, about 50,000–100,000 AU from the Sun (50,000–100,000 times the distance from the Sun to Earth).

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Dwarf Planets

The dwarf planets of our solar system are exciting proof of how much we are learning about our solar system. With the discovery of many new objects in our solar system, in 2006, astronomers refined the definition of a planet. Their subsequent reclassification of Pluto to the new category dwarf planet stirred up a great deal of controversy. How the classification of Pluto has evolved is an interesting story in science.

Pluto

From the time it was discovered in 1930 until the early 2000s, **Pluto** was considered the ninth planet. When astronomers first located Pluto, the telescopes were not as good as they are today. Back then, astronomers believe Pluto and its moon, **Charon**, were one large object. With better telescopes, astronomers realized that Pluto was much smaller than they had initially been thought. Better technology also allowed astronomers to discover many smaller objects like Pluto that orbit the Sun. One of them, Eris, discovered in 2005, is even larger than Pluto.

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Even when it was considered a planet, Pluto was an oddball. Unlike the other outer planets in the solar system, which are all gas giants, it is small, icy, and rocky. With a diameter of about 2,400 km, it is only about one-fifth the mass of Earth's Moon. Pluto's orbit is tilted relative to the other planets and is shaped like a long, narrow ellipse. Pluto's orbit sometimes even passes inside Neptune's orbit.

In 1992 Pluto's orbit was recognized to be part of the **Kuiper Belt**. With more than 200 million Kuiper belt objects, Pluto has failed the test of clearing other bodies out its orbit. In 2006, the International Astronomical Union decided that there were too many questions surrounding what could be called a planet and so refined its definition.

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According to the new definition, a planet must:

- Orbit a star
- Be big enough that its gravity causes it to be shaped like a sphere.
- Be small enough that it is not a star itself.
- Have cleared the area of its orbit of smaller objects.
- A dwarf planet is an object that meets items the first three items in the list above, but not the fourth. Pluto is now called a dwarf planet, along with the objects Ceres, Make-make, and Eris.

According to the IAU, a dwarf planet must:

- Orbit a star
- Have enough mass to be nearly spherical
- Not have cleared the area around its orbit of smaller objects.
- Not be a moon

Pluto has three moons of its own. The largest, Charon, is big enough that the Pluto-Charon system is sometimes considered to be a double dwarf planet. Two smaller moons, Nix and Hydra, were discovered in 2005. However, having moons is not enough to make an object a planet.

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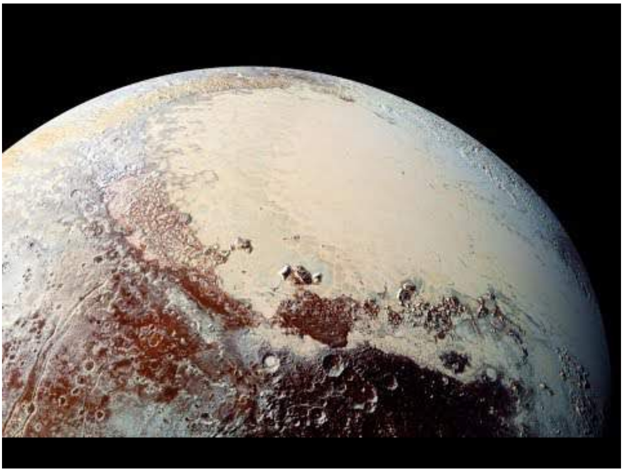

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Ceres

Ceres is the most massive object in the asteroid belt. Before 2006, Ceres was considered the largest of the asteroids, with only about 1.3 percent of the mass of the Earth's Moon. However, unlike the asteroids, Ceres has enough mass that its gravity causes it to be shaped like a sphere. Like Pluto, Ceres is rocky. Ceres orbits the Sun, is round, and is not a moon. As part of the asteroid belt, its orbit is full of other smaller bodies, so Ceres fails the fourth criterion for being a planet.

Makemake

Makemake is the third largest and second brightest dwarf planet we have discovered so far. With a diameter estimated to be between 1,300 and 1,900 km, it is about three-quarters the size of Pluto. Makemake orbits the Sun in 310 years at a distance between 38.5 to 53 AU. It is thought to be made of methane, ethane, and nitrogen ices.

Eris

Eris is the most widely-known dwarf planet in the solar system, which is roughly 27 percent more massive than Pluto. The object was not discovered until 2003 because it is about three times farther from the Sun than Pluto, and almost 100 times farther from the Sun than Earth is. For a short time, Eris was considered the "tenth planet" in the solar system, but its discovery helped to prompt astronomers to better define planets and dwarf planets in 2006. Eris also has a small moon, Dysnomia, that orbits it once about every 16 days.

Astronomers know there may be other dwarf planets in the outer reaches of the solar system. Haumea was made a dwarf planet in 2008, and so now the total is five. Quaoar, Varuna, and Orcus may be added to the list of dwarf planets in the future. We still have a lot to discover and explore.

Extent of the Solar System

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PART III

PLANET EARTH

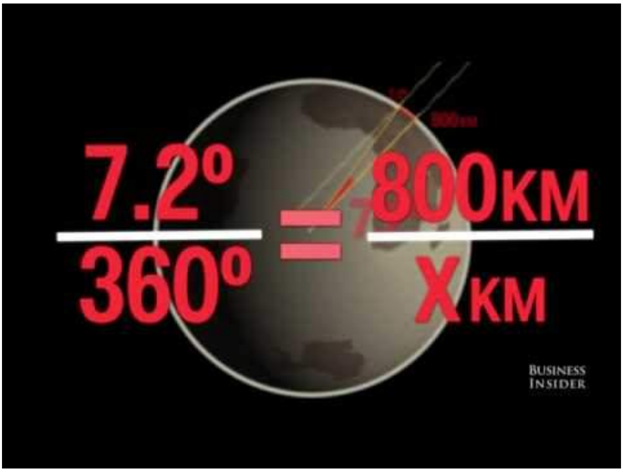
3.1 EARTH AS A PLANETARY BODY

Earth as a Planetary Body

Earth is a terrestrial planet in the solar system, and it is like the other inner planets, at least in its size, shape, and composition. However, many features make Earth vastly different from the planets and any other planet that we know of so far.

Earth is a sphere or, more correctly, an **oblate spheroid**, which is a sphere that is a bit squished down at the poles and bulges a bit at the equator. Alternatively, to be more technical, the minor axis (the diameter through the poles) is smaller than the major axis (the diameter through the equator). When the earth is cut into equal halves, each half is called a **hemisphere**. North of the equator in the northern hemisphere and south of the equator in the southern hemisphere. Eastern and western hemispheres are also designated.

Even the ancient Greeks knew that Earth was round by observing the arc shape of the shadow on the Moon during a lunar eclipse. The Sun and the other planets of the solar system are also spherical. Larger satellites, those that have enough mass for their gravitational attraction to have made them round, are as well.



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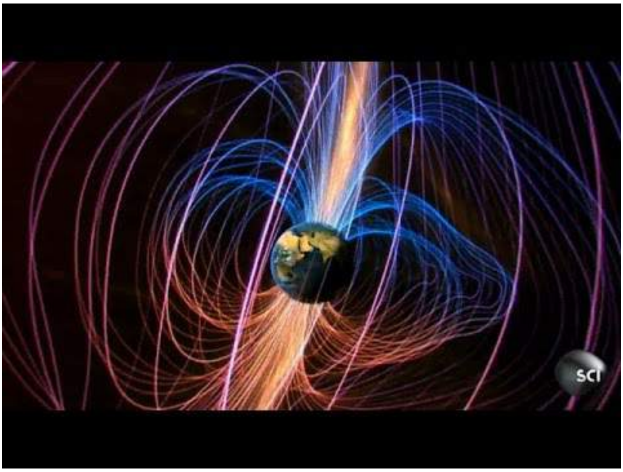
Earth has a **magnetic field** that behaves as if the planet had a gigantic bar magnet inside of it. Earth's magnetic field also has a north and south pole and a magnetic field that surrounds it. The magnetic field arises from the convection of molten iron and nickel metal in Earth's outer liquid iron core. Earth's magnetic field extends several thousand kilometers into space. The magnetic field shields the planet from harmful radiation from the Sun.



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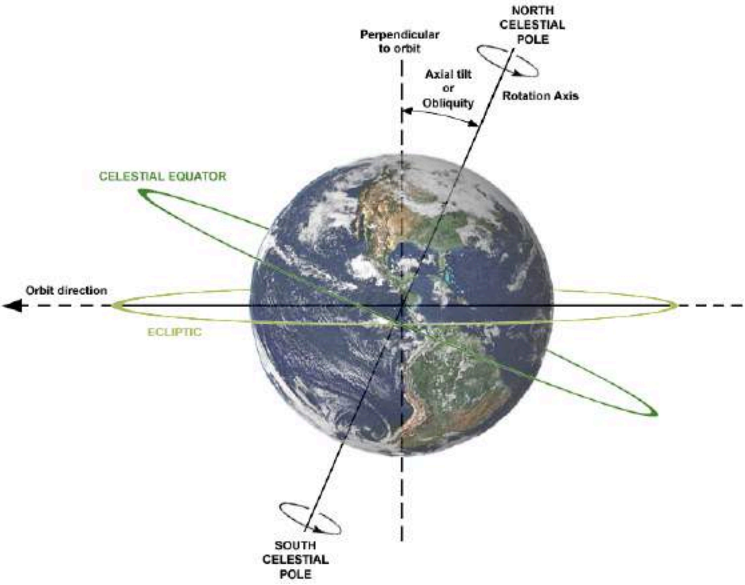
Earth's Rotation

Imagine a line passing through the center of Earth that goes through both the North Pole and the South Pole. This imaginary line is called an **axis**. Earth spins around its axis, just as a top spins around its spindle. This spinning movement is called the Earth's **rotation**. While the Earth spins on its axis, it also orbits or revolves around the Sun, called a **revolution**.

A pendulum set in motion will not change its motion, and so the direction of its swinging should not change. However, Foucault observed that his pendulum did seem to change direction. Since he knew that the pendulum could not change its motion, he concluded that the Earth, underneath the pendulum, was moving. An observer in space will see that Earth requires 23 hours, 56 minutes, and 4 seconds to make one complete rotation on its axis. However, because Earth moves around the Sun at the same time as rotating, the planet must turn just a bit more to reach the same place relative to the Sun. Hence the length of a day on Earth is 24 hours. At the equator, the Earth rotates at a speed of about 1,700 km per hour, but at the poles, the movement speed is nearly nothing.



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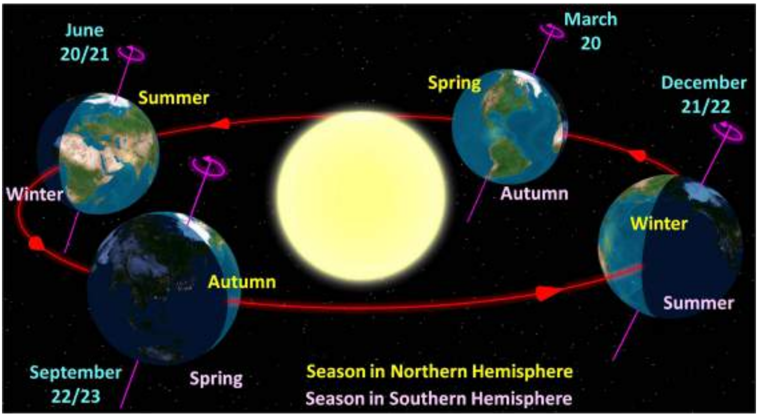
Earth's Revolution

For Earth to make one complete **revolution** around the Sun takes 365.24 days. This amount of time is the definition of one year. The gravitational pull of the Sun keeps Earth and the other planets in orbit around the star. Like the other planets, Earth's orbital path is an ellipse, so the planet is sometimes farther away from the Sun than at other times. The closest Earth gets to the Sun each year is at **perihelion** (147 million km) on about January 3, and the furthest is at **aphelion** (152 million km) on July 4. Earth's elliptical orbit has nothing to do with Earth's seasons.

During one revolution around the Sun, Earth travels at an average distance of about 150 million km. Earth revolves around the Sun at an average speed of about 27 km (17 mi) per second, but the speed is not constant. The planet moves slower when it is at aphelion and faster when it is at perihelion.

Seasons

The reason the Earth has seasons is that Earth is tilted 23.5 degrees on its axis, along with Earth's daily rotation and annual revolution around the sun. During the Northern Hemisphere summer, the North Pole points toward the Sun, and in the Northern Hemisphere winter, the North Pole has tilted away from the Sun.



"North Season" by Tauʻolunga is licensed under the Creative Commons CC0 1.0 Universal Public Domain Dedication.

The **Tropic of Cancer** is the parallel at 23.5 degrees north of the equator, which is the most northerly place on Earth, receiving direct sunlight during the Northern Hemisphere's summer. Remember that the earth is tilted 23.5 degrees, which accounts for seasonal variations in climate. The **Tropic of Capricorn** is the parallel at 23.5 degrees south of the equator and is the most southerly location on Earth, receiving direct sunlight during the Southern Hemisphere's summer.

The tropics (Cancer and Capricorn) are the two imaginary lines directly above which the sun shines on the two **solstices**, which occur on or near June 20 or 21 (summer solstice in the Northern Hemisphere) and December 21 or 22 (winter solstice in the Northern Hemisphere). The sun is directly above the Tropic of Cancer at noon on June 20 or 21, marking the beginning of summer in the Northern Hemisphere and the beginning of winter in the Southern Hemisphere. The sun is directly above the Tropic of Capricorn at noon on December 21 or 22, marking the beginning of winter in the Northern Hemisphere and the beginning of summer in the Southern Hemisphere. Solstices are the extreme ends of the seasons, when the line of direct sunlight is either the farthest north or the farthest south that it ever goes. The region between the Tropics of Cancer and Capricorn is known as the tropics. This area does not experience dramatic seasonal changes because the amount of direct sunlight received does not vary widely. The higher latitudes (north of the Tropic of Cancer and south of the Tropic of Capricorn) experience significant seasonal variation in climate.

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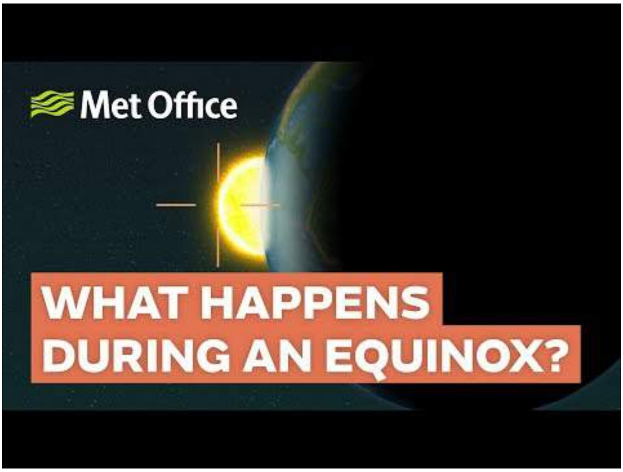
The **Arctic Circle** is a line of latitude at 66.5 degrees north. It is the farthest point north that receives sunlight during its winter season (90 N – 23.5 = 66.5 N). During winter, the North Pole is away from the sun and does not receive much sunlight. At times, it is dark for most of the twenty-four-hour day. During the Northern Hemisphere's summer, the North Pole faces more toward the sun and may receive sunlight for more extended portions of the 24-hour day. The **Antarctic Circle** is the corresponding line of latitude at 66.5 degrees south. It is the farthest location south that receives sunlight during the winter season in the Southern Hemisphere (90 S – 23.5 = 66.5 S). When it is winter in the north, it is summer in the south.

The Arctic and Antarctic Circles mark the extremities (southern and northern, respectively) of the polar day (twenty-four-hour sunlit day) and the polar night (24-hour sunless night). North of the Arctic Circle, the sun is above the horizon for twenty-four continuous hours at least once per year and below the horizon for twenty-four continuous hours per year. This is true also near the Antarctic Circle, but it occurs south of the Antarctic Circle, toward the South Pole. **Equinoxes**, when the line of direct sunlight hits the equator and days and nights are of equal length, occur in the spring and fall on or around March 20 or 21 and September 22 or 23.



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Geologic Time and Deep Time

In 1788, after many years of geological study, James Hutton, one of the early pioneers of geology, wrote the following about the age of the Earth: "The result, therefore, of our present inquiry is, that we find no vestige of a beginning, — no prospect of an end." Although he was not precisely correct (there was a beginning and an end to planet Earth), he was trying to express the vastness of geological time that humans have a hard time perceiving. Although Hutton did not assign an age to the Earth, he was the first to suggest that the planet was incredibly old. Today we know Earth is approximately

4.6 billion years old, an age first calculated by Caltech professor Clair Patterson in 1956 by radiometrically dating meteorites with uranium-lead dating. (Earle, 2015)

“Geologic Time Spiral” by the United States Geologic Survey (USGS) is licensed under Public Domain.

On a **geologic scale**, the lifespan of a human is truly short, and we struggle to comprehend the depth of geologic time and slow geologic processes. Studying **geologic time**, also known as **deep time**, can help us overcome our limited view of Earth during our lifetime. For example, the science of earthquakes only goes back about 100 years; however, geologic evidence shows that large earthquakes have occurred in the past and will continue to occur in the future. Thus, the human perspective of time does not always overlap with geologic timescales.

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A diagram above is of geological time. The largest division of time is the **Eon**—Hadean, Archean, Proterozoic (sometimes combined as the Precambrian), and Phanerozoic. Although life appeared more than 3,800 million years ago (Ma), during most of Earth's history, from 3,500 Ma to 542 Ma (88 percent of geologic time), life forms consisted mainly of simple single-celled organisms such as bacteria. Only in more recent geologic time have more biologically complex organisms appeared in the geologic record.

The Phanerozoic Eon, the last 542 million years, is only 12 percent of geological time and is named for the time during which visible (phaneros-) life (-zoic), i.e., abundant fossils, appeared in the geological record. Although simple life forms had been around for billions of years, the Phanerozoic marks the beginning of abundant multicellular animals having preservable hard parts such as shells. Animals have been on land for only 360 million years, or 8 percent of geological time. Mammals have dominated since the demise of the dinosaurs around 65 Ma, or 1.5 percent of geological time, and the genus Homo has existed since approximately 2.2 Ma, or 0.05 percent of geological time. (1 Understanding Science – An Introduction to Geology, n.d.)

Additionally, the Phanerozoic is divided into three **Eras**: Paleozoic, Mesozoic, and Cenozoic. Life of the Paleozoic (meaning "ancient life") consisted of invertebrate animals, fish, amphibians, and reptiles. The Mesozoic (meaning "middle life") is known as the Age of Rep-tiles popularized by the dominance of dinosaurs, which evolved into birds, and Cenozoic (meaning "new life") is the Age of Mammals in which mammals evolved to be the dominant form of animal life on land following the mass extinction of the dinosaurs and other apex predator reptiles at the end of the Mesozoic. Early humans (hominids) appear in the rock record only during the last few million years of the Cenozoic.

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Evolution of Life on Earth

Scientists believe that life on earth started relatively early, within the first few billion years. During that time, simple life formed and evolved into more complex lifeforms. During the Paleozoic era, a mass extinction event called The Great Dying occurred. However, following that dramatic event, life became more diversified, including the evolution of the dinosaurs.

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3.2 IMPACTS AND EXTINCTIONS

Coming soon…

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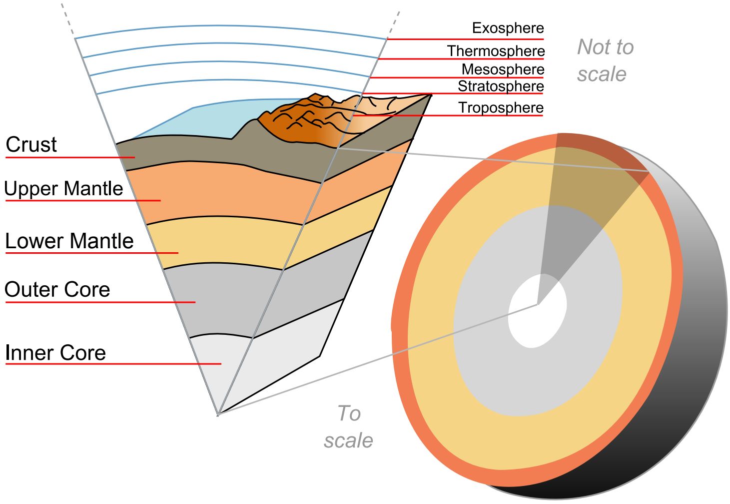
3.3 INTERNAL STRUCTURE OF EARTH

Layers of the Earth

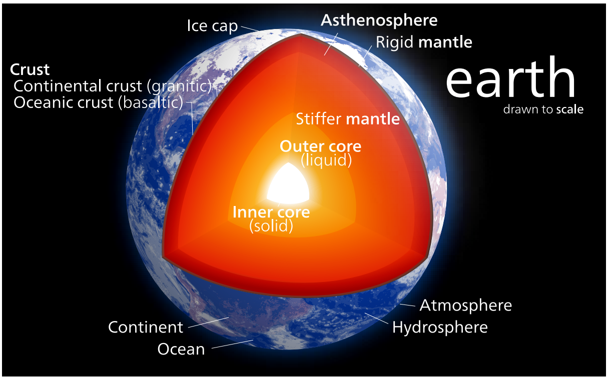
To understand the details of plate tectonics, one must first understand the layers of the Earth. Humankind has insufficient first-hand information regarding what is below; most of what we know is pieced together from models, seismic waves, and assumptions based on meteorite material. In general, the Earth can be divided into layers based on chemical composition and physical characteristics. (2 Plate Tectonics – An Introduction to Geology, n.d.)



"Earth and Atmosphere Cutaway" by the USGS is licensed under Public Domain.

Chemical Layers

The Earth has three main divisions based on their chemical composition, which means chemical makeup. Indeed, there are countless variations in composition throughout the Earth, but only two significant changes take place, leading to three distinct chemical layers.



"Diagram of Earth" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

Crust

The outermost chemical layer and the layer humans currently reside on is known as the **crust**. The crust has two types: **continental crust**, which is relatively low density and has a composition similar to granite, and **oceanic crust**, which is relatively high density (especially when it is cold and old) and has a composition similar to basalt. In the lower part of the crust, rocks start to be more ductile and less brittle, because of added heat. Earthquakes, therefore, generally occur in the upper crust.

At the base of the crust is a substantial change in seismic velocity called the **Mohorovičić Discontinuity**, or **Moho** for short, discovered by Andrija Mohorovičić (pronounced mo-ho-ro-vee-cheech) in 1909 by studying earthquake wave paths in his native Croatia. It is caused by the dramatic change in composition that occurs between the mantle and the crust. Underneath the oceans, the Moho is about 5 km down. Under continents, the average is about 30-40 km, except near a sizeable mountain-building event, known as an **orogeny**, where that thickness is about doubled.

Mantle

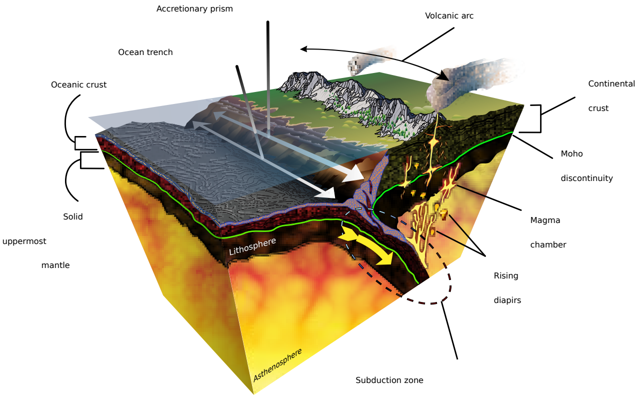
The **mantle** is the layer below the crust and above the core. It is the most substantial layer by volume, extending from the base of the crust to a depth of about 2900 km. Most of what we know about the mantle comes from seismic waves, though some direct information can be gathered from parts of the ocean floor that are brought to the surface, known as ophiolites. Also, carried within magma are xenoliths, which are small chunks of lower rock carried to the surface by eruptions. These xenoliths are made of the rock peridotite, which on the scale of igneous rocks is ultramafic. We assume the majority of the mantle is made of peridotite.

Core

The **core** of the Earth, which has both liquid and solid components, is made mostly of iron, nickel, and oxygen. First discovered in 1906 by looking into seismic data, it took the union of modeling, astronomical insight, and seismic data to arrive at the idea that the core is mostly metallic iron. Meteorites contain much more iron than typical surface rocks, and if meteoric material is what made the Earth, the core would have formed as dense material (including iron and nickel) sank to the center of the Earth via its weight as the planet formed, heating the Earth intensely.

Physical Layers

The Earth can also be broken down into five distinct physical layers based on how each layer responds to stress. While there is some overlap in the chemical and physical designations of layers, precisely the core-mantle boundary, there are significant differences between the two systems. (2 Plate Tectonics – An Introduction to Geology, n.d.)



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Lithosphere

The **lithosphere**, with ‘litho’ meaning rock, is the outermost physical layer of the Earth. Including the crust, it has both an oceanic component and a continental component. **Oceanic lithosphere**, ranging from a thickness of zero (at the forming of new plates on the mid-ocean ridge) to 140 km, is thin and rigid. **The continental lithosphere** is more plastic (especially with depth) and is overall thicker, from 40 to 280 km thick. Most importantly, the lithosphere is not continuous. It is broken into several segments that geologists call plates. A plate boundary is where two plates meet and move relative to each other. It is at and near plate boundaries where plate tectonics' real action is seen, including mountain building, earthquakes, and volcanism.

Asthenosphere

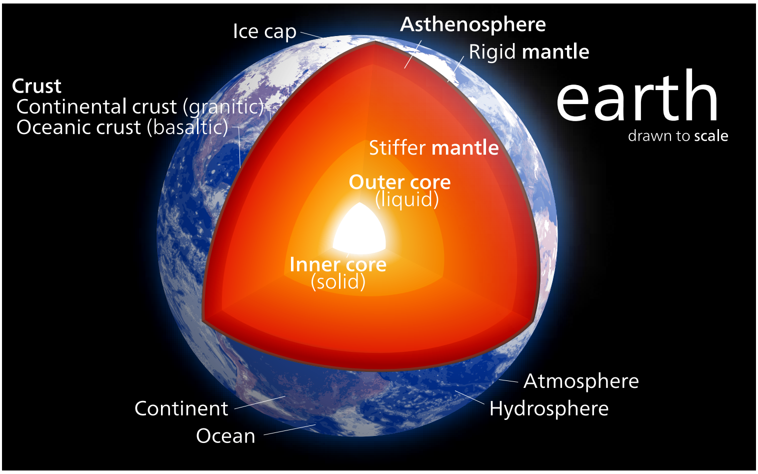
The **asthenosphere**, with 'astheno' meaning weak, is the layer below the lithosphere. The most distinctive property of the asthenosphere is movement. While still solid, over geologic time scales, it will flow and move because it is mechanically weak. In this layer, partly driven by convection of intense interior heat, movement allows the lithospheric plates to move. Since certain types of seismic waves pass through the asthenosphere, we know that it is solid, at least at the short time scales of the passage of seismic waves. The depth and occurrence of the asthenosphere are dependent on heat and can be very shallow at mid-ocean ridges and very deep in plate interiors and beneath mountains.

Mesosphere

The **mesosphere**, or **lower mantle** as it is sometimes called, is more rigid and immobile than the asthenosphere, though still hot. This can be attributed to increased pressure with depth. Between approximately 410 and 660 km depth, the mantle is in a state of transition, as minerals with the same composition are changed to various forms, dictated by increasing pressure conditions. Changes in seismic velocity show this, and this zone also can be a physical barrier to movement. Below this zone, the mantle is uniform and homogeneous, as no significant changes occur until the core is reached.

The **outer core** is the only liquid layer found within Earth. It starts at 2,890 km (1,795 mi) depth and extends to 5,150 km (3,200 mi). Inge Lehmann, a Danish geophysicist, in 1936, was the first to prove that there was an inner core that was solid within the liquid outer core based on analyzing seismic data. The solid inner core is about 1,220 km (758 mi) thick, and the outer core is about 2,300 km (1,429 mi) thick.

It seems like a contradiction that the hottest part of the Earth is substantial, as hot temperatures usually lead to melting or boiling. The solid **inner core** can be explained by understanding that the immense pressure inhibits melting, though as the Earth cools by heat flowing outward, the inner core grows slightly larger over time. As the liquid iron and nickel in the outer core moves and convects, it becomes the most likely source for Earth's magnetic field. This is critically important to maintaining the atmosphere and conditions on Earth that make it favor-able to life. Loss of outer core convection and the Earth's magnetic field could strip the atmosphere of most of the gases essential to life and dry out the planet, much like what has happened to Mars.



"Structure of Earth" is licensed under Creative Commons Attribution-ShareAlike 3.0 Unported.

Structure of Earth's Crust

The fundamental unifying principle of geology and the rock cycle is the theory of **Plate Tectonics**. Plate tectonics describes how the layers of the Earth move relative to each other. Specifically, the outer layer divided into tectonic or lithospheric plates. As the tectonic plates float on a mobile layer beneath called the asthenosphere, they collide, slide past each other, and split apart. Significant landforms are created at these plate boundaries, and rocks making up the tectonic plates move through the rock cycle.

The following is a summary of the Earth's layers based on chemical composition (or the chemical makeup of the layers). Earth has three main geological layers based on chemical composition – crust, mantle, and core. The outermost layer is the **crust** and is composed of mostly silicon, oxygen, aluminum, iron, and magnesium. There are two types of crust, continental and oceanic crust. **Continental crust** is about 50 kilometers (30 miles) thick, represents most of the continents, and is composed of low-density igneous and sedimentary rocks. Oceanic crust is approximately 10 kilometers (6 miles) thick, makes up most of the ocean floor, and covers about 70 percent of the planet. **Oceanic crust** is high-density igneous basalt-type rocks. The moving tectonic plates are made of crust, and some of the next layers within the earth called the **mantle**. The crust and this portion of the upper mantle are rigid and called the **lithosphere** and make up the tectonic plates.

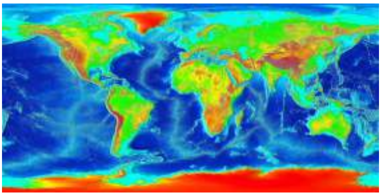
Continents

The oldest continental rocks are billions of years old, so the continents have had much time to happen to them. **Constructive forces** cause physical features on Earth's surface known as landforms to grow. **Crustal deformation** – when crust compresses, pulls apart, or slides past other crust – results in hills, valleys, and other landforms. Mountains rise when continents collide when one slab of ocean crust plunges beneath another or a slab of continental crust to create a chain of volcanoes. Sediments are deposited to form landforms, such as deltas. Volcanic eruptions can also be destructive forces that blow landforms apart. The **destructive forces** of weathering and erosion modify landforms. Water, wind, ice, and gravity are essential forces of erosion.

Oceanic Basins

The ocean basins are all younger than 180 million years. Although the ocean basins begin where the ocean meets the land, the continent extends downward to the seafloor, so the continental margin is made of continental crust.

The ocean floor itself is not flat. The most distinctive feature is the mountain range that runs through much of the ocean basin, known as the mid-ocean ridge. The ocean trenches are the deepest places of the ocean, many of which are found around the edge of the Pacific Ocean. Chains of volcanoes are also found in the center of the oceans, such as around Hawaii. Flat plains are found on the ocean floor with their features covered by mud.



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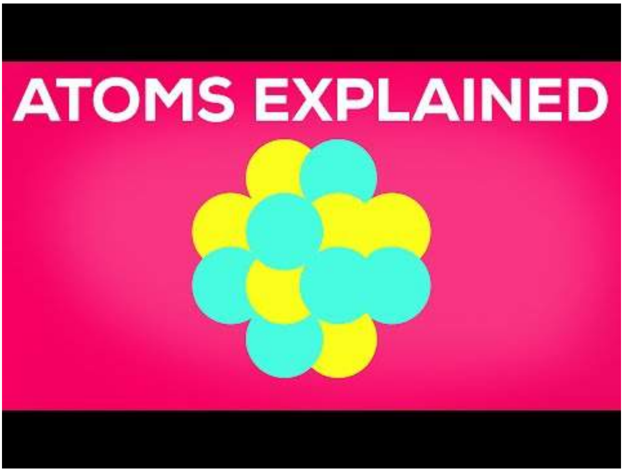
3.4 MINERALS

Atoms and Isotopes

A **chemical element** is a substance that cannot be made into a more straightforward form by ordinary chemical means the smallest unit of a chemical element is an atom. An **atom** has all the properties of that element. At the center of an atom is a nucleus made up of subatomic particles called protons and neutrons. **Protons** have a positive electrical charge. The number of protons in the nucleus determines what element the atom is. **Neutrons** are about the size of protons but have no charge. **Electrons**, each having a negative electrical charge, orbit the nucleus at varying energy levels in a region known as the **electron cloud**.



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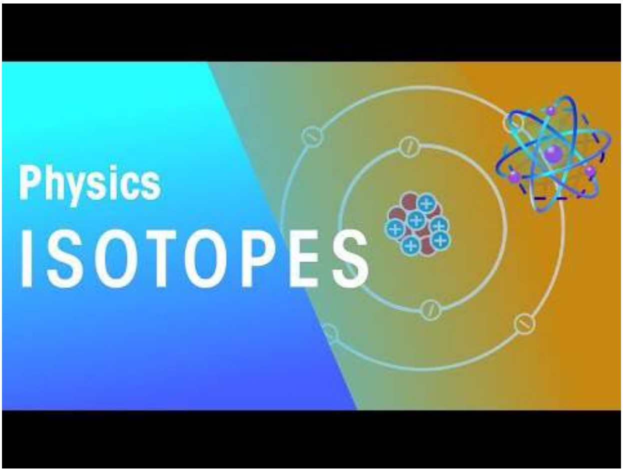
Because electrons are minuscule compared with protons and neutrons, the number of protons plus neutrons gives the atom its atomic mass. All atoms of a given element always have the same number of protons but may differ in the number of neutrons found in its nucleus. Atoms of an element with differing numbers of neutrons are called **isotopes**. (Matter Matters | Earth Science, n.d.)



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Ions and Molecules

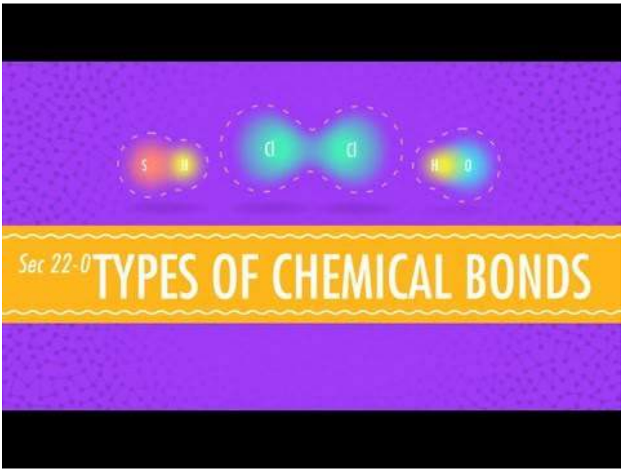
Atoms are stable when they have a full outermost electron valence shell. For an atom to fill its outermost shell, it will give, take, or share electrons. When an atom either gains or loses electrons, this creates an ion. Ions have either a positive or a negative electrical charge. What is the charge of an ion if the atom loses an electron? An atom with the same number of protons and electrons has no overall charge, so if an atom loses the negatively charged electron, it has a positive charge. What is the charge of an ion if the atom gains an electron? If the atom gains an electron, it has a negative charge.

When atoms chemically bond, they form **compounds**. The smallest unit of a compound with all the properties of that compound is a **molecule**. When two or more atoms share electrons to form a chemical bond, they form a molecule. The molecular mass is the sum of the masses of all the atoms in the molecule.

Chemical Bonding

Ions come together to create a molecule so that electrical charges are balanced; the positive charges balance the negative charges, and the molecule has no electrical charge. An atom will balance its electrical charge by sharing an electron with another atom, giving it away, or receive an electron from another atom.

The joining of ions to make molecules is chemical bonding. There are three main types of chemical bonds. **Ionic bonds** occur when electrons are transferred between atoms. **Covalent bonds** occur when an atom shares one or more electrons with another atom. The sharing of electrons is not always evenly distributed within a molecule. If one atom has the electrons more often than another atom in the molecule, it has a positive and a negative side. It is a polar molecule because it acts a little bit as if it had poles, like a magnet. Finally, **hydrogen bonds** are weak intermolecular bonds that form when the positive side of one polar molecule is attracted to another polar molecule's negative side.



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Minerals

Minerals are categorized based on their chemical composition. Owing to similarities in composition, minerals within the same group may have similar characteristics. Geologists have a precise definition of minerals. A material is characterized as a mineral if it meets all the following traits:

- Inorganic, crystalline solid.
- Formed through natural processes and has a definite chemical composition.

- Identified by their characteristic physical properties such as crystalline structure, hardness, density, flammability, and color.

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Crystalline Solid

Minerals are crystalline solids. A **crystal** is a solid in which the atoms are arranged in a regular, repeating pattern. The pattern of atoms in different samples of the same mineral is the same. Is glass a mineral? Without a crystalline structure, even natural glass is not a mineral. (Minerals and Mineral Groups | Earth Science, n.d.)

Organic and Inorganic Substances

Organic substances are the carbon-based compounds made by living creatures and include proteins, carbohydrates, and oils. **Inorganic substances** have a structure that is not characteristic of living bodies. Coal is made of plant and animal remains. Is it a mineral? Coal is classified as a sedimentary rock but is not a mineral. (Minerals and Mineral Groups | Earth Science, n.d.)

Natural Processes

Minerals are made by natural processes, those that occur in or on Earth. A diamond created deep in Earth's crust is a mineral. Is a diamond created in a laboratory by placing carbon under high pressures a mineral? No. Do not buy a laboratory-made "diamond" for jewelry without realizing it is not technically a mineral.

Chemical Composition

Nearly all (98.5 percent) of Earth's crust is made up of only eight elements – oxygen, silicon, aluminum, iron, calcium, sodium, potassium, and magnesium – and these are the elements that make up most minerals.

All minerals have a specific chemical composition. The mineral silver is made up of only silver atoms and diamond is made only of carbon atoms, but most minerals are made up of chemical compounds. Each mineral has its chemical formula. Halite is NaCl (sodium chloride). Quartz is always made of two oxygen atoms bonded to a silicon atom, SiO2. If a mineral contains any other elements in its crystal structure, it is not quartz.

A hard mineral with covalently bonded carbon is diamond, but a softer mineral containing calcium and oxygen along with carbon is calcite. Some minerals have a range of chemical composition. Olivine always has silicon and oxygen, as well as iron or magnesium or both. (Minerals and Mineral Groups | Earth Science, n.d.)

Mineral Identification

Their physical characteristics can identify minerals. The physical properties of minerals are related to their chemical composition and bonding. Some characteristics, such as a mineral's hardness, are more useful for mineral identification. Color is readily observable and undoubtedly visible, but it is usually less reliable than other physical properties. (Reading: Physical Characteristics of Minerals | Geology, n.d.)

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Color

Diamonds are popular gemstones because the way they reflect light makes them very sparkly. Turquoise is prized for its striking greenish-blue color. Notice that specific terms are being used to describe the appearance of minerals. Color is rarely useful for identifying a mineral.

Streak

Streak is the color of a mineral's powder. Streak is a more reliable property than color because streak does not vary. Minerals that are the same color may have a different colored streak. Many minerals, such as the quartz, do not have a streak. To check streak, scrape the mineral across an unglazed porcelain plate. Yellow-gold pyrite has a blackish streak, another indicator that pyrite is not gold, with a golden yellow streak.

Luster

Luster describes the reflection of light off a mineral's surface. Mineralogists have specific terms to describe luster. One straightforward way to classify luster is based on whether the mineral is metallic or non-metallic. Minerals that are opaque and shiny, such as pyrite, have a metallic luster. Minerals such as quartz have a non-metallic luster.

Specific Gravity

Density describes how much matter is in a certain amount of space: density = mass/volume. Mass is a measure of the amount of matter in an object. Its volume describes the amount of space an object takes up. The density of an object depends on its mass and its volume. For example, the water in a drinking glass has the same density as the water in the same volume of a swimming pool. Gold has a density of about 19 g/cm3; pyrite has a density of about 5 g/cm3 – that is another way to tell pyrite from gold. Quartz is even less dense than pyrite and has a density of 2.7 g/cm3. The specific gravity of a substance compares its density to that of water. Denser substances have higher specific gravity.

Hardness

Hardness is a measure of whether a mineral will scratch or be scratched. **Mohs Hardness Scale** is a reference for mineral hardness. With a Mohs scale, anyone can evaluate an unknown mineral for its hardness. Imagine you have an unknown mineral. You find that it can scratch fluorite or even apatite, but feldspar scratches it. This examination of the mineral informs you that the mineral's hardness is between 5 and 6. Note that no other mineral can scratch diamond. Breaking a mineral breaks its chemical bonds. Since some bonds are weaker than other bonds, each type of mineral is likely to break where the bonds between the atoms are weakest. For that reason, minerals break apart in distinctive ways. (Mineral Identification | Earth Science, n.d.)

Cleavage

Cleavage is the tendency of a mineral to break along specific planes to make smooth surfaces. Halite breaks between layers of sodium and chlorine to form cubes with smooth surfaces. One reason gemstone is beautiful is that the cleavage planes make an attractive crystal shape with smooth faces. (Mineral Identification | Earth Science, n.d.)

Fracture

Fracture is a break in a mineral that is not along a cleavage plane. Fracture is not always the same in the same mineral because its structure does not determine fracture. Minerals may have natural fractures. Metals usually fracture into jagged edges. If a mineral splinter like wood, it may be fibrous. Some minerals, such as quartz, form smooth curved surfaces when they fracture. (Reading: Physical Characteristics of Minerals | Geology, n.d.)

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Other Identifying Characteristics

Mineral Formation

Minerals form under an enormous range of geologic conditions. There are more ways to form minerals than there are types of minerals themselves. Minerals can form from volcanic gases, sediment formation, oxidation, crystallization from magma, or deposition from a saline fluid. (Reading: Physical Characteristics of Minerals | Geology, n.d.)

Formation from Hot Material

A rock is a collection of minerals. Imagine a rock that becomes so hot it melts. Many minerals start in liquids that are hot enough to melt rocks. Magma is melted rock inside Earth, a molten mixture of substances that can be hotter than 1,000oC. Magma cools slowly inside Earth, which gives mineral crystals time to grow large enough to be seen clearly. When magma erupts onto Earth's surface, it is called lava. Lava cools much more rapidly than magma when it is below the surface. In cooling lava, mineral crystals do not have time to form and are exceedingly small. The chemical composition will be the same as if the magma cooled slowly. Existing rocks may be heated enough to release the molecules from their structure and move around. The molecules may match up with different molecules to form new minerals as the rock cools, a process called metamorphism. (Matter Matters | Earth Science, n.d.)

Formation from Solutions

Water on Earth, such as the water in the oceans, contains chemical elements mixed into a solution. Various processes can cause these elements to combine to form solid mineral deposits.

Minerals from Salt Water

When water evaporates, it leaves behind a solid precipitate of minerals. Water can only hold a certain amount of dissolved minerals and salts. When the amount is too vast to stay dissolved in the water, the particles come together to form mineral solids, which sink. Halite readily precipitates out of the water, as does calcite. Some lakes, such as Mono Lake in California or The Great Salt Lake in Utah, contain many mineral precipitates.

Minerals from Hot Underground Water

Magma heats nearby underground water, which reacts with the rocks around it to pick up dissolved particles. As the water flows through open spaces in the rock and cools, it deposits solid minerals. The mineral deposits form when a mineral fills cracks in rocks are called veins when minerals are deposited in open spaces and large crystal forms.

Mining and Mineral Use

Some minerals are beneficial. An ore is a rock that contains minerals with useful elements. Aluminum in bauxite ore is extracted from the ground and refined to be used in aluminum foil and many other products. The cost of creating a product from a mineral depends on how abundant the mineral is and how much the extraction and refining processes cost. Environmental damage from these processes is often not figured into a product's cost. It is crucial to use mineral resources wisely.

Finding and Mining Minerals

Geologic processes create and concentrate minerals that are valuable natural resources. Geologists study geological formations and test the physical and chemical properties of soil and rocks to locate possible ores and determine their size and concentration. A mineral deposit will only be mined if it is profitable. A concentration of minerals is only called an ore deposit if it is profitable to mine. There are many ways to mine ores. (Reading: Mining and Mineral Use | Geology, n.d.)

Surface mining allows the extraction of ores that are close to Earth's surface. Overlying rock is blasted, and the rock that contains the valuable minerals is placed in a truck and taken to a refinery. Surface mining includes open-pit mining and mountaintop removal. Other methods of surface mining include strip mining, placer mining, and dredging. Strip mining is like open-pit mining but with material removed along a strip.

Placers are valuable minerals found in stream gravels. California's nickname, the Golden State, can be traced to the discovery of placer deposits of gold in 1848. The gold weathered out of hard metamorphic rock in the western Sierra Nevada, which also contains deposits of copper, lead, zinc, silver, chromite, and other valuable minerals. The gold traveled down rivers and then settled in gravel deposits. Currently, California has active mines for gold and silver and for non-metal minerals such as sand and gravel, which are used for construction. (Reading: Mining and Mineral Use | Geology, n.d.)

"Bingham Copper Mine" by David Guthrie is licensed under Creative Commons Attribution 2.0 Generic.

Underground mining is used to recover ores that are deeper into Earth's surface. Miners blast and tunnel into the rock to gain access to the ores. How underground mining is approached depends on the placement of the ore body, its depth, concentration of ore, and the surrounding rock's strength. Underground mining is costly and dangerous. Fresh air and lights must also be brought into the tunnels for the miners, and accidents are far too frequent.

The ore's journey to becoming a useable material is only just beginning when the ore leaves the mine. Rocks are crushed so that the valuable minerals can be separated from the waste rock. Then the minerals are separated from the ore. A few methods for extracting ore are:

- **Heap leaching**: the addition of chemicals, such as cyanide or acid, to remove ore.
- **Flotation**: the addition of a compound that attaches to the valuable mineral and floats.
- **Smelting**: roasting rock, causing it to segregate into layers so the mineral can be extracted.

To extract the metal from the ore, the rock is melted at a temperature higher than 900 degrees Celsius, which requires much energy. Extracting a metal from the rock is so energy-intensive that recycling just 40 aluminum cans will save the energy equivalent of one gallon of gasoline. (Mining and Mineral Use | Earth Science, n.d.)

Although mining provides people with many necessary resources, environmental costs can be high. Surface mining clears the landscape of trees and soil, and nearby streams and lakes are inundated with sediment. Pollutants from the mined rock, such as heavy metals, enter the sediment and water system. Acids flow from some mine sites, changing the composition of nearby waterways.

U.S. law has changed so that in recent decades a mine region must be restored to its natural state, a process called reclamation. This is not true of older mines. Pits may be refilled or reshaped, and vegetation planted. Pits may be allowed to fill with water and become lakes or maybe turned into landfills. Underground mines may be sealed off or left open as homes for bats.

Some minerals are valuable because they are beautiful. Jade has been used for thousands of years in China. Diamonds sparkle on many engagement rings. Minerals like jade, turquoise, diamonds, and emeralds are gemstones. A gemstone, or gem, is a material that is cut and polished for jewelry. Gemstones are usually rare and do not break or scratch easily. Most are cut along cleavage faces and then polished so that light bounces back off the cleavage planes. Light does not pass through opaque gemstones, such as turquoise. Gemstones are not just used in jewelry. Diamonds are used to cut and polish other materials, such as glass and metals because they are so hard. The mineral corundum, of which ruby and sapphire are varieties, is used in sandpaper products.

Minerals are used in much less obvious places. The mineral gypsum is used for the sheetrock in homes. Window glass is made from sand, which is mostly quartz. Halite is mined for rock salt. Copper is used in electrical wiring, and bauxite is the source of the aluminum used in soda cans. (Reading: Mining and Mineral Use | Geology, n.d.)

Conflict Resouces

Blood Diamonds

Blood diamonds, also called **conflict diamonds**, are diamonds mined in conflict areas and sold to finance warlords or invading armies in a geographic region. The term "blood" diamonds are used to highlight the negative impacts and consequences of diamonds mined for these ends. Often, women and children are enslaved to mine blood diamonds, and other conflict resources, to fund these local and regional wars. The Kimberley Process was created to help combat and regulate the flow of diamonds mined around the world to ensure that people were not purchasing blood diamonds. Blood diamonds have been mined from Angola, Ivory Coast, Sierra Leone, Liberia, Guinea, and Guinea Bissau.

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Cobalt

A new form of conflict mineral has developed in recent years. With the advancement of technology (i.e. laptops, smartphones, tablets), the need and demand for the mineral cobalt have grown rapidly. It is believed that Subsaharan Africa, specifically Central Africa, has roughly two-thirds of the world's cobalt. To meet the demand, women and children have been imprisoned to extract cobalt from the mines. Currently, there is not a formalized process to track and monitor where cobalt comes from. Technology companies like Apple, Samsung, Dell, and others are looking at creating their own supply chain for cobalt so that where the cobalt comes from can be monitored.

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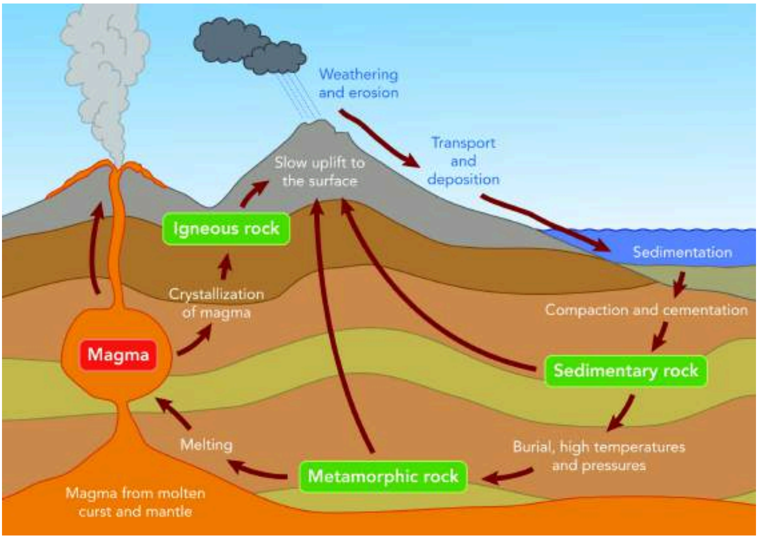
3.5 THE ROCK CYCLE

The most fundamental view of Earth materials is the **rock cycle**, which presents the primary materials that comprise the Earth and describes the processes by which they form and relate to each other. The rock cycle is usually said to begin with a hot molten liquid rock called magma or lava. **Magma** forms under the Earth's surface in the crust or mantle and erupts on Earth's surface as **lava**. When magma or lava cools, it solidifies by **crystallization** in which minerals grow within the magma or lava. The rock that results from this is an igneous rock from the Latin word ignis, meaning "fire."

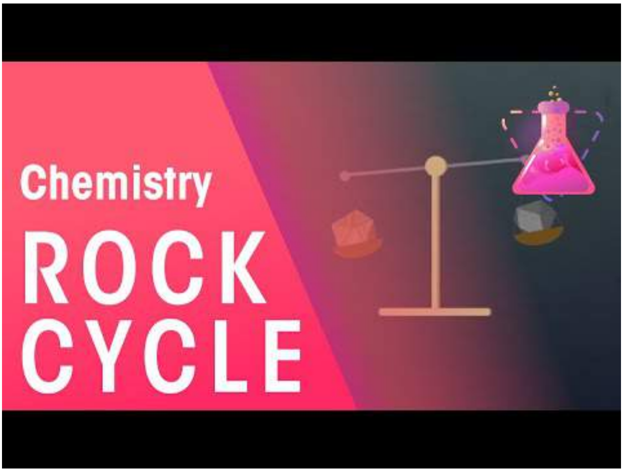


"Rock Cycle" by Siyavula Education is licensed under Creative Commons Attribution 2.0 Generic.

Igneous rocks, as well as other types of rocks on Earth's surface, are exposed to weathering and erosion processes to produce sediments. **Weathering** is the physical and chemical breakdown of rocks into smaller fragments, and erosion is the removal of those fragments from their original location. Once igneous rocks are broken down and transported, these fragments or grains are considered sediments. Sediments such as gravel, sand, silt, and clay can be transported by water in the form of streams, ice in the form of glaciers, and air in the form of wind. Sediments ultimately come to rest in a process known as **deposition**. The deposited sediments accumulate in place, often underwater such as a shallow marine environment, get buried.

Within the burial process, the sediments go through compaction by the weight of overlying sediments and cementation as minerals in groundwater glue the sediments together. The process of compacting and cementing sediments together is lithification, and lithified sediments are considered a **sedimentary rock**, such as sandstone and shale. Other sedimentary rocks, known as **chemical sedimentary rocks**, are not made of weathered and eroded sedimentary fragments. The direct chemical precipitation instead makes them of minerals.

Pre-existing rocks may be metamorphosed into a **metamorphic rock**, meta- means "change", -morphos means "form" or "shape." When rocks are subjected to extreme increases in temperatures or pressures, the minerals alter into enlarged crystals, or entirely new minerals with a similar chemical make up. These elevated temperatures and pressures can occur when rocks are buried deep within the Earth's crust, or they encounter hot magma or lava. In some cases, the temperature and pressure conditions can allow rocks to melt and create magma and lava, showing the cyclical nature of the rock cycle as new rocks are born. Click here to learn more about various igneous, sedimentary, and metamorphic rocks from the Utah Geologic Survey (UGS).



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Igneous Rocks

Igneous rocks form from the cooling and hardening of molten magma in many different environments. Their composition and texture identify these rocks. More than 700 distinct types of igneous rocks are known.

“Sarychev Peak Eruption, Kuril Islands” by NASA’s Earth Observatory is licensed under Public Domain.

Magma Composition

The rock beneath the Earth’s surface is sometimes heated to high enough temperatures that it melts to create magma. Different magmas have a different composition and contain whatever elements were in the rock that melted. Magma also contains gases. (Reading: Types of Rocks | Geology, n.d.) The main elements are the same as the elements found in the crust. Whether rock melts to create magma depends on:

- **Temperature**: Temperature increases with depth, so melting is more likely to occur at greater depths.
- **Pressure**: Pressure increases with depth, but increased pressure raises the melting temperature, so melting is less likely to occur at higher pressures.

- **Water**: The addition of water changes the melting point of rock. As the number of water molecules increases, the melting point decreases.
- **Rock composition**: Minerals melt at different temperatures, so the temperature must be high enough to melt some minerals in the rock. The first mineral to melt from a rock will be quartz (if present), and the last will be olivine (if present).

As a rock heats up, the minerals that melt at the lowest temperatures will melt first. Partial melting occurs when the temperature on a rock is high enough to melt only some of the minerals in the rock. The minerals that will melt will be those that melt at lower temperatures. Fractional crystallization is the opposite of partial melting. This process describes the crystallization of different minerals as magma cools. (Igneous Rocks | Geology, n.d.)

Bowen's Reaction Series indicates the temperatures at which minerals melt or crystallize. An understanding of the way atoms joins to form minerals leads to an understanding of how different igneous rocks form. Bowen's Reaction Series also explains why some minerals are always found together, and some are never found together.

If the liquid separates from the solids at any time in partial melting or fractional crystallization, the liquid and solid chemical composition will be different. When that liquid crystallizes, the resulting igneous rock will have a different composition from the parent rock. (Reading: Types of Rocks | Geology, n.d.)

Intrusive Igneous Rock

Igneous rocks are called **intrusive** when they cool and solidify beneath the surface. Intrusive igneous rocks form **plutons**, and so are also called **plutonic**. A pluton is an igneous intrusive rock body that has cooled in the crust. When magma cools within the Earth, the cooling proceeds slowly. Intrusive igneous rocks cool slower than extrusive igneous rocks, which allows for more massive crystal structure to develop.

Igneous rocks make up most of the rocks on Earth. Most igneous rocks are buried below the surface and covered with sedimentary rocks or are buried beneath the ocean water. In some places, geological processes have brought igneous rocks to the surface. Yosemite is a classic example of intrusive igneous rock. The molten magma never reached Earth's surface, so the molten material had millions of years to cool down slowly to form granite. Later, geologic forces and erosion have caused those granite plutons to surface as they are today.

Extrusive Igneous Rock

Igneous rocks are called **extrusive** when they cool and solidify above the surface. These rocks usually form from a volcano, so they are also called volcanic rocks. Extrusive igneous rocks cool much more rapidly than intrusive rocks, reducing the time for crystal structure to form within the rocks.

Cooling rate and gas content create a variety of rock textures. Lavas that cool exceptionally rapidly may have a glassy texture. Those with many holes from gas bubbles have a vesicular texture. (Igneous Rocks | Geology, n.d.)

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Human Uses of Igneous Rock

Igneous rocks have a wide variety of uses, including to create buildings and statues, kitchen countertops, abrasive material for household products, or for smoothing skin. Ground-up pumice stone is sometimes added to toothpaste to function as an abrasive material to scrub teeth. Peridotite is sometimes mined for peridot, a type of olivine that is used in jewelry. Diorite was used extensively by ancient civilizations for vases and other decorative artwork and is still used for art today.

Sedimentary Rock

Sandstone is one of the common types of **sedimentary rocks** that form from **sediments**. There are many other types. Sediments may include:

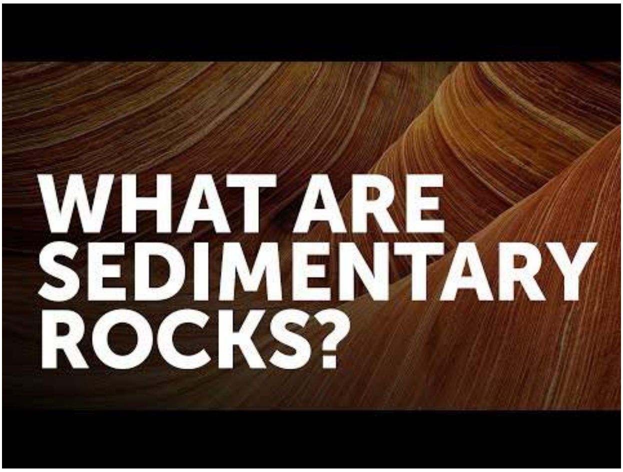
- Fragments of other rocks that often have been worn down into small pieces, such as sand, silt, or clay.
- Organic materials, or the remains of once-living organisms.
- Chemical precipitates, which are materials that get left behind after the water evaporates from a solution.

Rocks at the surface undergo mechanical and chemical weathering. These physical and chemical processes break the rock into smaller pieces. **Physical weathering** breaks the rocks apart, while **chemical weathering** dissolves the less stable minerals. These original elements of the minerals end up in solution, and new minerals may form. Sediments are removed and transported by water, wind, ice, or gravity in a process called **erosion**.

"Bryce Canyon at Sunset" by R. Adam Dastrup is copywritten.

Streams carry vast amounts of sediment. The more energy the water has, the larger the particle it can carry. A rushing river on a steep slope might be able to carry boulders. As this stream slows down, it no longer has the energy to carry large sediments and will drop them. A slower moving stream will only carry smaller particles.

Sediments are deposited on beaches and deserts, at the bottom of oceans, and in lakes, ponds, rivers, marshes, and swamps. Fast-moving avalanches and slow-moving glaciers can drop large piles of sediment. Wind can only transport sand and smaller particles. The type of sediment that is deposited will determine the type of sedimentary rock that can form. Distinct colors of sedimentary rock are determined by the environment where they are deposited. Red rocks form where oxygen is present, while darker sediments form when the environment is oxygen-poor. (Reading: Mining and Mineral Use | Geology, n.d.)



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Sedimentary Rock Formation

Accumulated sediments harden into a rock by a process called **lithification**. Two essential steps are needed for sediments to lithify. Sediments are squeezed together by the weight of overlying sediments on top of them, called **compaction**. Cemented, non-organic sediments become **clastic rocks**. If organic material is included, they are **bioclastic rocks**.

Fluids fill in the spaces between the loose particles of sediment and crystallize to create a rock by **cementation**. When sediments settle out of calmer water, they form horizontal layers. One layer is deposited first, and another layer is deposited on top of it. So, each layer is younger than the layer beneath it. When the sediments harden, the layers are preserved. Sedimentary rocks formed by the crystallization of chemical precipitates are called **chemical sedimentary rocks**.

Biochemical sedimentary rocks form in the ocean or a salt lake. Living creatures remove ions, such as calcium, magnesium, and potassium, from the water to make shells or soft tissue. When the organism dies, it sinks to the ocean floor to become biochemical sediment, which may become compacted and cemented into solid rock. (Reading: Mining and Mineral Use | Geology, n.d.)

Human Use of Sedimentary Rock

Sedimentary rocks are used as building stones, although they are not as hard as igneous or metamorphic rocks. Sedimentary rocks are used in construction. Sand and gravel are used to make concrete; they are also used in asphalt. Many economically valuable resources come from sedimentary rocks. Iron ore and aluminum are two examples. (Reading: Mining and Mineral Use | Geology, n.d.)

Metamorphic Rock

Metamorphism is the addition of heat and/or pressure to existing rocks, which causes them to change physically and/or chemically so that they become a new rock. **Metamorphic rocks** may change so much that they may not resemble the original rock.

Any type of rock – igneous, sedimentary, or metamorphic – can become a metamorphic rock. All that is needed is enough heat and/or pressure to alter the existing rock's physical or chemical makeup without melting the rock entirely. Rocks change during metamorphism be-cause the minerals need to be stable under the new temperature and pressure conditions. The need for stability may cause the structure of minerals to rearrange and form new minerals. Ions may move between minerals to create minerals of the different chemical compositions. Hornfels, with its alternating bands of dark and light crystals, is an excellent example of how minerals rearrange themselves during metamorphism.

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Extreme pressure may also lead to foliation, the flat layers that form in rocks as pressure squeezes the rocks. **Foliation** forms typically when pressure is exerted in only one direction. Metamorphic rocks may also be **non-foliated**. Quartzite and limestone are non-foliated. The two main types of metamorphism are both related to heat within Earth:

- **Regional metamorphism**: Changes in enormous quantities of rock over a wide area caused by extreme pressure from overlying rock or compression caused by geologic processes. Deep burial exposes the rock to hot temperatures.
- **Contact metamorphism**: Changes in a rock that is in contact with magma because of the magma's extreme heat.

The Utah Geologic Survey has several resources related to landforms in Utah. They have also created a fun story map called GeoSights of popular geologic sights within the State of Utah.

3.6 THEORY OF PLATE TECTONICS

Continental Drift Hypothesis

Alfred Wegener (1880-1930) was a German scientist who specialized in meteorology and climatology. He had a knack for questioning accepted ideas, and this started in 1910 when he disagreed with isostasy (vertical land movement due to the weight being removed or added) as the explanation for the Bering Land Bridge. After literary reviews, he published a hypothesis stating the continents had moved in the past. While he did not have the precise mechanism worked out, he had an extensive list of evidence that backed up his hypothesis of **continental drift**.

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Early Evidence for Continental Drift

The first piece of evidence is that the shape of the coastlines of some continents fit together like pieces of a jigsaw puzzle. Since the first world map, people have noticed the similarities in the coastlines of South America and Africa, and the continents being ripped apart had even been mentioned as an explanation. Antonio Snider-Pellegrini even did preliminary work on continental separation and matching fossils in 1858.

What Wegener did differently than others was synthesized a significant amount of data in one place, as well as use the shape of the continental shelf, the actual edge of the continent, instead of the current coastline, which fit even better than previous efforts. Wegener also compiled and added to evidence of similar rocks, fossils, and glacial formations across the oceans.

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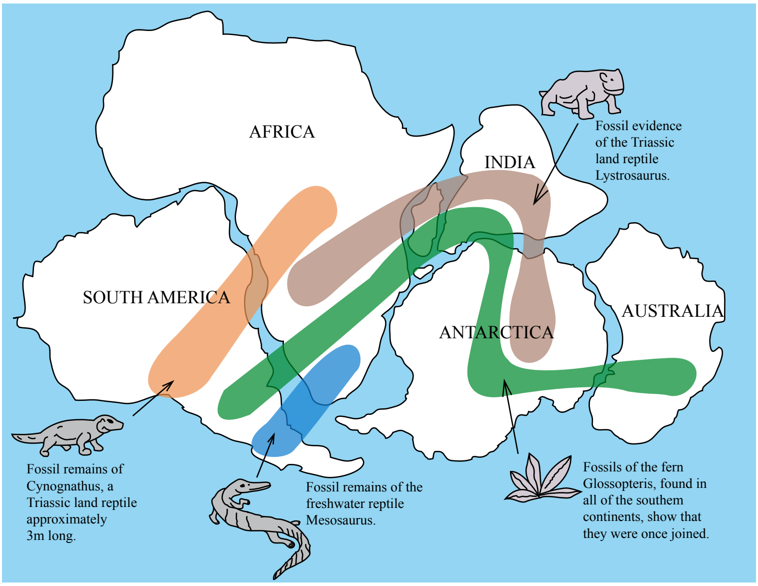
Fossil Evidence

For example, the primitive aquatic reptile Mesosaurus was found on the separate coastlines of the continents of Africa and South America, and the reptile Lystrosaurus was found on Africa, India, and Antarctica. These were land-dwelling creatures that could not have swam across an entire ocean; thus, this was explained away by opponents of continental drift by land bridges. The land bridges had eroded, allowed animals and plants to move between the continents. However, some of the presumed land bridges would have had to have stretched across broad, deep oceans.



"Snider-Pellegrini Wegener Fossil Map" is licensed under Public Domain.

Geologic Evidence

Mountain ranges with the same rock types, structures, and ages are now on opposite sides of the Atlantic Ocean. The Appalachians of the eastern United States and Canada, for example, are just like mountain ranges in eastern Greenland, Ireland, Great Britain, and Norway. Wegener concluded that they formed a single mountain range that was separated as the continents drifted. (Dastrup, 2014)

Climatic Evidence

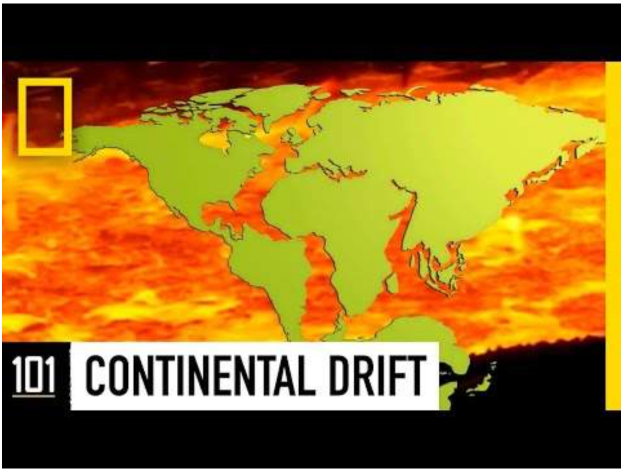
Another significant piece of evidence was climate anomalies. Late Paleozoic glacial evidence was found in widespread, warm areas like southern Africa, India, Australia, and the Arabian subcontinent. Wegener himself had found evidence of tropical plant fossils in areas north of the Arctic Circle. According to Wegener, the more straightforward explanation that fits all the climate, rock, and fossil observations, mainly as more data were collected, involved moving continents.

Grooves and rock deposits left by ancient glaciers are found today on different continents close to the equator. This would indicate that the glaciers either formed in the middle of the ocean or covered most of the Earth. Today glaciers only form on land and nearer the poles. Wegener thought that the glaciers were centered over the southern landmass close to the South Pole, and the continents later moved to their present positions.

Proposed Mechanism for Continental Drift

Wegener's work was considered a fringe theory for his entire life. One of the most significant flaws and easiest dismissals of Wegener's hypothesis was a mechanism for the movement of the continents. The continents did not appear to move, and extraordinary evidence would need to be provided to change the establishment's minds, including a mechanism for movement. Other pro-continental drift followers had used expansion, contraction, or even the origin of the

Moon as ideas to how the continents moved. Wegener used centrifugal forces and precession to explain the movement, but that was proven wrong. He had some speculation about **seafloor spreading**, with hints of convection within the earth, but these were unsubstantiated. As it turns out, convection within the mantle has been revealed as a significant force in driving plate movements, according to current knowledge.



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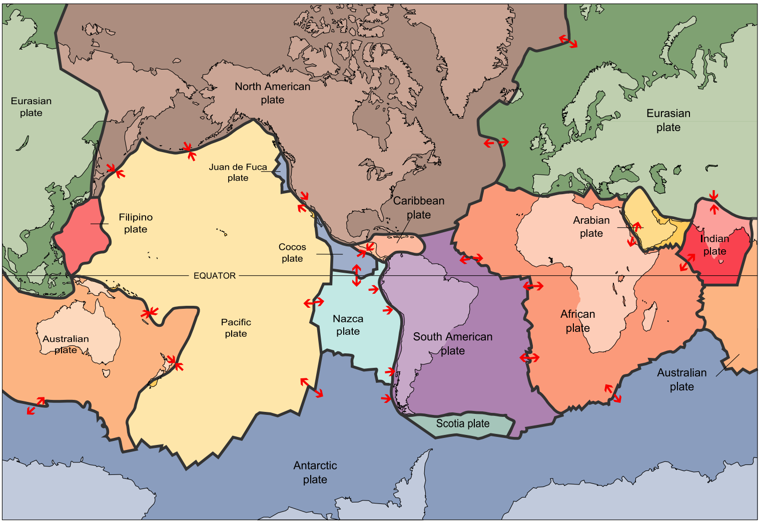
Theory of Plate Tectonics

Wegener died in 1930 on an expedition in Greenland. He was poorly respected in his lifetime, and his ideas of moving continents seemed destined to be lost to history as a fringe idea. However, starting in the 1950s, evidence started to trickle in that made continental drift more viable. By the 1960s, there was enough evidence supporting Wegener's missing mechanism, seafloor spreading, allowing continental drift's hypothesis to develop into the **Theory of Plate Tectonics**. Widespread acceptance among scientists has transformed Wegener's hypothesis to a Theory. Today, GPS and earthquake data continue to back up the theory. Below are the pieces of evidence that allowed the transformation.



"Tectonic Plates" by the United States Geologic Survey (USGS) is licensed under Public Domain.

Mapping the Ocean Floors

Starting in 1947 and using an adaptation of sonar, researchers began to map a poorly understood topographic and thermal high in the mid-Atlantic. Bruce Heezen and Marie Tharp were the first to make a detailed map of the ocean floor, and this map revealed the **mid-Atlantic Ridge**, a basaltic feature, unlike the continents. Initially, this was thought to be part of an expanding Earth or a mechanism for the ocean's growth. Transform faults were also added to explain movements more completely. When it was later realized that earthquake epicenters were also found within this feature, the idea that this was part of the continental movement took hold.

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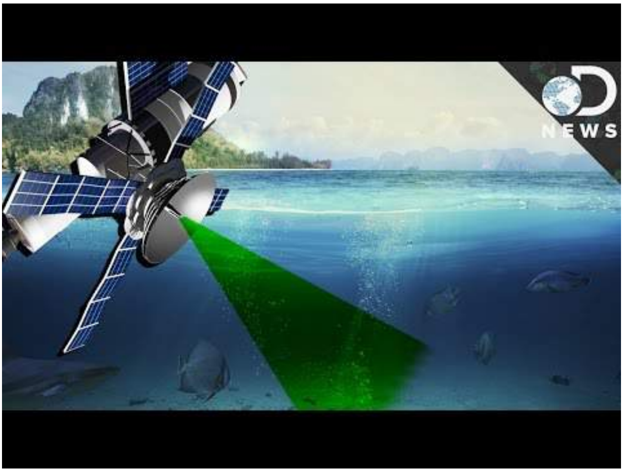
Another way the seafloor was mapped was **magnetical**. Scientists had long known of strange magnetic anomalies (magnetic values that differ from expected values) associated with the ocean floor. This tool was adapted by geologists later for further study of the ocean depths, including strange alternating symmetrical stripes on both sides of a feature (which would be discovered later as the mid-ocean ridge) showing reversing magnetic pole directions. By 1963, these magnetic stripes would be explained in concordance with Hess's spreading model and others.

Seafloor sediment was also an important feature that was measured in the oceans, both with dredging and with drilling. Sediment was believed to have been piling up on ocean floors for an exceptionally long time in a static model of accumulation. Initial studies showed less sediment than expected, and initial results were even used to argue against the continental movement. With more time, researchers discovered thinner sediment close to ridges, indicating a younger age.



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Wadati-Benioff Zones

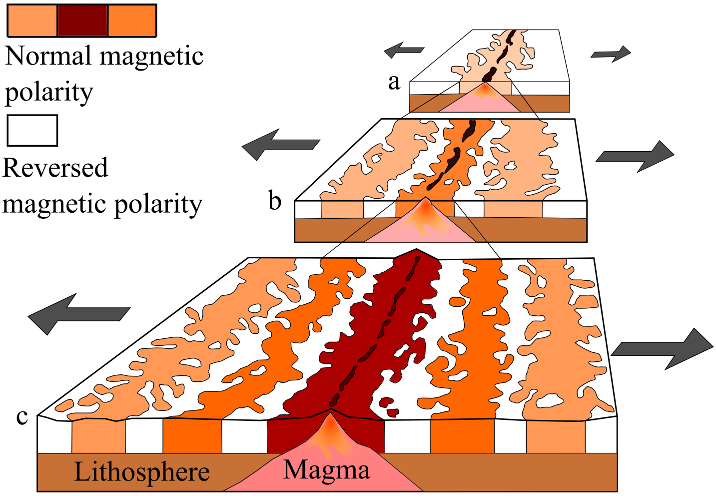
Around the same time that mid-ocean ridges were being investigated, ocean trenches and island arcs were also being linked to seismic action, explaining the opposite sides of the plates. A zone of deep earthquakes that lay along a plane, trending from the surface near the trenches to inside the Earth beneath the continents and island arcs, were recognized independently by several scientists. Today called the **Wadati-Benioff zone**; it was an essential piece of the puzzle.

Paleomagnetism

Magnetic field mapping, as mentioned above, was not the only way magnetism was used in the development of plate tectonics. The first new hard evidence that supported plate motion came from paleomagnetism. **Paleomagnetism** is the study of magnetic fields frozen within rocks, basically a fossil compass. This is typically most useful with igneous rocks where magnetic minerals like magnetite crystallizing in the magma align with the Earth's magnetic field and in the solid rock point to the paleo-magnetic north. The earth's magnetic field creates flux lines surrounding the magnetic north and south poles (like a bar magnet), which are both close to the

Earth's rotational north and south poles. In igneous rocks, magnetic minerals align parallel with these flux lines. Thus, both magnetic inclination, related to latitude, and declination related to magnetic north are preserved in the rocks.

Scientists had noticed that, for some time, the magnetic north, to which many rocks pointed, was nowhere close to the current magnetic north. This was explained by implying the magnetic north pole moved over time. Eventually, scientists started to realize that moving continents explained the data better than moving the pole around alone.

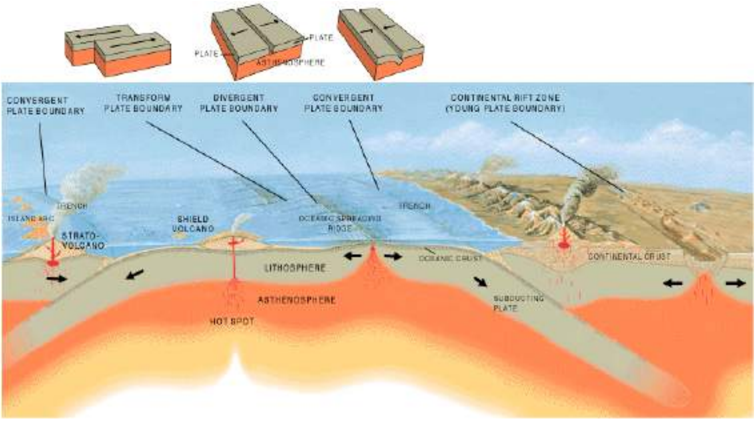


"Oceanic Stripe Magnetic Anomalies Scheme" by the United States Geologic Survey (USGS) is licensed under Public Domain.

Seafloor Spreading

World War II gave scientists the tools to find the mechanism for continental drift that had eluded Wegener. Maps and other data gathered during the war allowed scientists to develop the **seafloor spreading hypothesis**. This hypothesis traces oceanic crust from its origin at a mid-ocean ridge to its destruction at a deep-sea trench and is the mechanism for continental drift. (Seafloor Spreading | Earth Science, n.d.)

During World War II, battleships and submarines carried echo sounders to locate enemy submarines. Echo sounders produce sound waves that travel outward in all directions, bounce off the nearest object, and then return to the ship. By knowing the sound speed in seawater, scientists calculate the distance to the object based on the time it takes for the wave to make a round trip. During the war, most of the sound waves ricocheted off the ocean bottom. This animation shows how sound waves are used to create pictures of the seafloor and ocean crust.

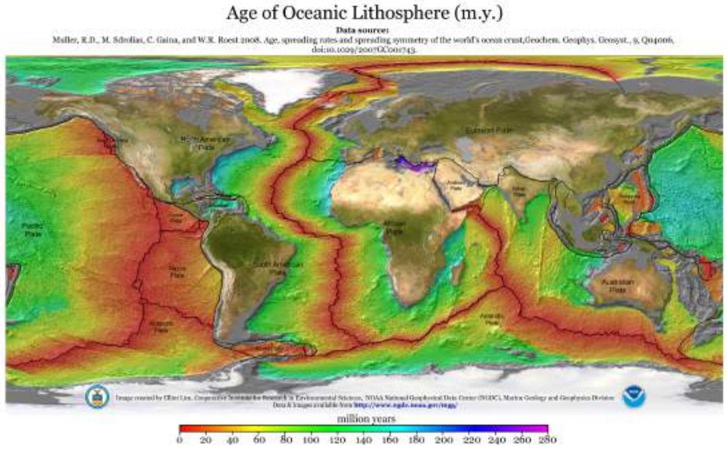


"Tectonic Plate Boundaries" by the United States Geologic Survey (USGS) is licensed under Public Domain.

After the war, scientists pieced together the ocean depths to produce bathymetric maps, which revealed the ocean floor features as if the water were taken away. Even scientists were amazed that the seafloor was not completely flat. What was discovered was a large chain of mountains along the deep seafloor, called mid-ocean ridges. Scientists also discovered deep-sea trenches along the edges of continents or in the sea near active volcanic chains. Finally, large, flat areas called abyssal plains we found. When they first observed these bathymetric maps, scientists wondered what had formed these features.

Scientists brought these observations together in the early 1960s to create the **seafloor spreading hypothesis**. In this hypothesis, a hot, buoyant mantle creates a mid-ocean ridge, causing the ridge to rise upward. The hot magma at the ridge erupts as lava that forms new seafloor. When the lava cools, the magnetite crystals take on the current magnetic polarity, and as more lava erupts, it pushes the seafloor horizontally away from the ridge axis. (Seafloor Spreading | Earth Science, n.d.)

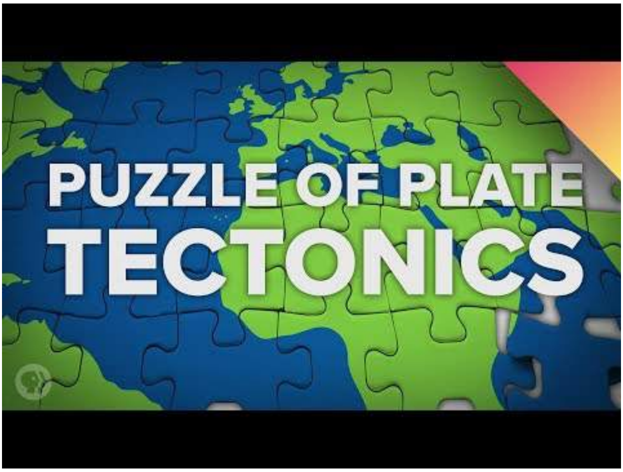
The magnetic stripes continue across the seafloor. As oceanic crust forms and spreads, moving away from the ridge crest, it pushes the continent away from the ridge axis. If the oceanic crust reaches a deep-sea trench, it sinks into the trench and is lost into the mantle. Scientists now know that the oldest crust is coldest and lies deepest in the ocean because it is less buoyant than the hot new crust.



“Age of Oceanic Lithosphere” by the National Oceanic and Atmospheric Administration (NOAA) is licensed under Public Domain.

Unifying Theory of Plate Tectonics

Using all the evidence mentioned, the theory of plate tectonics took shape. In 1966, J. Tuzo Wilson was the first scientist to put the entire picture together of an opening and closing ocean. Before long, models were proposed showing the plates moving concerning each other with clear boundaries between them, and scientists had also started to piece together complicated tectonic histories. The plate tectonic revolution had taken hold.



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Seafloor and continents move around on Earth's surface, but what is moving? What part of the Earth makes up the "plates" in plate tectonics? This question was also answered because of technology developed during the Cold War. The **tectonic plates** are made up of the lithosphere. During the 1950s and early 1960s, scientists set up seismograph networks to see if enemy nations were testing atomic bombs. These seismographs also recorded all the earthquakes around the planet. The seismic records could be used to locate an earthquake's epicenter, the point on Earth's surface directly above the earthquake's place. Earthquake epicenters outline these tectonic plates. Mid-ocean ridges, trenches, and significant faults mark the edges of these plates along with where earthquakes occur. (Reading: Theory of Plate Tectonics | Geology (Modification for Lehman College, CUNY), n.d.)

The lithosphere is divided into a dozen major and several minor tectonic plates. The plates' edges can be drawn by connecting the dots that mark earthquakes' epicenters. A single tectonic plate can be made of all oceanic lithosphere or all continental lithosphere, but nearly all plates are made of a combination of both. Movement of the plates over Earth's surface is termed **plate tectonics**. Plates move at a rate of a few centimeters a year, about the same rate fingernails grow. (Theory of Plate Tectonics | Earth Science, n.d.)

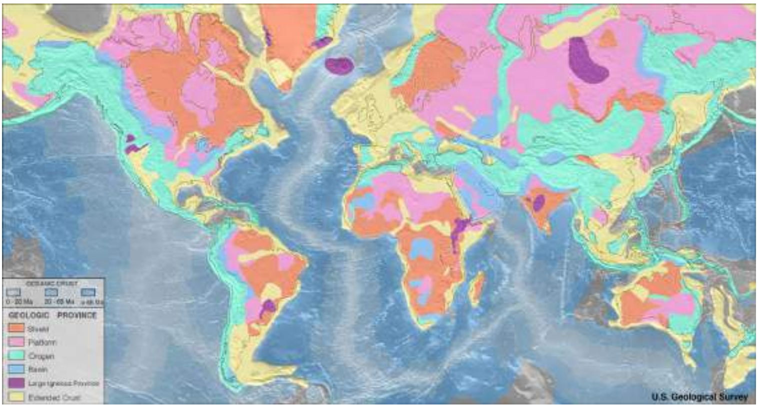
3.7 TECTONIC PLATE BOUNDARIES

Places, where oceanic and continental lithospheric tectonic plates meet and move relative to each other, are called **active margins** (e.g., the western coasts of North and South America). A location where continental lithosphere transitions into the oceanic lithosphere without movement is known as a **passive margin** (e.g., the eastern coasts of North and South Ameri-ca). Therefore, tectonic plates may be made of both oceanic and continental lithosphere. In the process of plate tectonics, the movement of the lithospheric plates is the primary force that causes the majority of features and activity on the Earth's surface that can be attributed to plate tectonics. This movement occurs (at least partially) via the drag of motion within the asthenosphere and because of density. (2 Plate Tectonics – An Introduction to Geology, n.d.)

As they move, the tectonic plates interact with each other at the boundaries between the tectonic plates. These interactions are the primary drivers of mountain building, earthquakes, and volcanism on the planet. In a simplified plate tectonic model, plate interaction can be placed in one of three categories. In places where plates move toward each other, the boundary is known as *convergent*. In places where plates move apart, the boundary is known as *divergent*. In places where the plates slide past each other, the boundary is known as a *transform* boundary. The next three subchapters will explain the details of the movement at each type of boundary.

Convergent Boundaries

Convergent boundaries, sometimes called **destructive boundaries**, are places where two or more tectonic plates have a net movement toward each other. Convergent boundaries, more than any other, are known for **orogenesis**, the process of building mountains and mountain chains. The key to convergent boundaries is understanding the density of each plate involved in the movement. The continental lithosphere is always lower in density and is buoyant when compared to the asthenosphere. On the other hand, the oceanic lithosphere is denser than the continental lithosphere and, when old and cold, may even be denser than the asthenosphere. When plates of different density converge, the denser plate sinks beneath, the less dense plate, a process called **subduction**. (2 Plate Tectonics – An Introduction to Geology, n.d.)



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Subduction is when the oceanic lithosphere descends into the mantle due to its density. The average rate of subduction of oceanic crust worldwide is 25 miles per million years, about a half-inch per year. Continental lithosphere can partially subduct if attached to the sinking oceanic lithosphere, but its buoyancy does not allow it to subduct fully. As the tectonic plate descends, it also pulls the ocean floor down in a **trench feature**. On average, the ocean floor is around 3-4 km deep. In trenches, the ocean can be more than twice as deep, with the Mariana Trench approaching a staggering 11 km.

Within the trench is a feature called the **accretionary wedge**, sometimes known as **melange** or **accretionary prism**, which is a mix of ocean floor sediments that are scraped and compressed at the boundary between the subducting plate and the overriding plate. Sometimes pieces of continental material, like microcontinents, riding with the subducting plate will become sutured to the accretionary wedge, forming a **terrane**. Substantial portions of California are comprised of accreted terranes.

When the subducting plate, known as a **slab**, submerges into the depths of the mantle, the heat and pressure are so immense that lighter materials, known as **volatiles**, like water and carbon dioxide, are pushed out of the subducting plate into an area called the **mantle wedge**. The volatiles is released mostly via hydrated minerals that revert to non-hydrated forms in these conditions. When mixed with asthenospheric material above the tectonic plate, these volatiles lower the melting point of the material. At the temperature of that depth, the material melts to form **magma**. This process of magma generation is called **flux melting**. Magma, because of its lower density, migrates toward the surface, creating **volcanism**. This forms a curved chain of volcanoes, due to many boundaries being curved on a spherical Earth, a feature called an **arc**. The overriding plate, which contains the arc, can be either oceanic or continental, where some features are different, but the general architecture remains the same.

How subduction initiates are still a matter of some debate. This would start at passive margins where oceanic and continental crust meet. At the current time, there is oceanic lithosphere that is denser than the underlying asthenosphere on either side of the Atlantic Ocean that is not currently subducting. Why has it not turned into an active margin? Firstly, there is strength in the connection between the dense oceanic lithosphere and the less dense continental lithosphere it is connected to, which needs to be overcome. Gravity could cause the denser oceanic plate to force itself down, or the plate can start to flow ductility at a low angle.

There is evidence that new subduction is starting off the coast of Portugal. Massive earthquakes, like the 1755 Lisbon Earthquake, may even have something to do with this process of creating a subduction zone, though it is not definitive. Transform boundaries that have brought areas of different densities together are also thought to start subduction. (2 Plate Tectonics – An Introduction to Geology, n.d.)

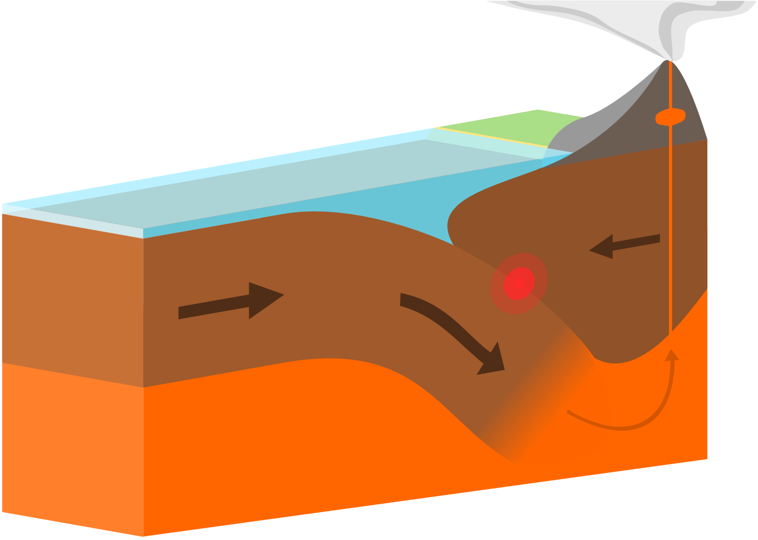
Besides volcanism, subduction zones are also known for the most massive earthquakes in the world. In places, the entire subducting slab can become stuck, and when the energy has built up too high, the entire subduction zone can slide at once along a zone extending for hundreds of kilometers along the trench, creating enormous earthquakes and tsunamis. The earthquakes can not only be significant, but they can be deep, outlining the subducting slab as it descends. Sub-duction zones are the only places on Earth with fault surfaces large enough to create 9.0 magnitude earthquakes. Also, because the faulting occurs beneath seawater, subduction can create giant tsunamis, such as the 2004 Indian Ocean Earthquake and the 2011 Tōhoku Earthquake in Japan.

Subduction, which is a convergent motion, can have varying degrees of convergence. In places with a high rate of convergence, mostly due to young, buoyant oceanic crust sub-ducting, the subduction zone can create faulting behind the arc area itself, known as back-arc faulting. This faulting can be tensional, or this area is subject to compressional forces. A modern example of this occurs in the two 'spines' of the Andes Mountains. In the west, the mountains are formed from the volcanic arc itself; in the east, thrust faults have pushed up another, non-volcanic mountain range still part of the Andes. This type of thrusting can typically occur in two styles: thin-skinned, which only faults surficial rocks, and thick-skinned, which thrusts deeper crustal rocks. Thin-skinned deformation notably occurred in the western US during the Cretaceous Sevier Orogeny. Near the end of the Sevier Orogeny, thick-skinned deformation also occurred in the Laramide Orogeny.

The **Laramide Orogeny** is also known for another subduction feature: **flat-slab subduction**. When the slab subducts at such a low angle, there is an interaction between the slab and the overlying continental plate. Magmatic activity can give rise to mineral deposits, and deformation can occur well into the interior of the overriding plate. All subduction zones have a **forearc basin**, which is an area between the arc and the trench. This is an area of a high degree of thrust faulting and deformation, seen mostly within the accretionary wedge. There are also places where the convergence shows the results of tensional forces. A variety of causes have been proposed for this, including slab roll-back due to density or ridge migration. This causes extension behind the volcanic or island arc, known as a **back-arc basin**. These can have so much extension that rifting and divergence can develop, though they can be more asymmetric than their mid-ocean ridge counterparts. (2 Plate Tectonics – An Introduction to Geology, n.d.)

Oceanic-Continental Subduction

Oceanic-continental subduction occurs when an oceanic plate dives below a continental plate. These regions can have powerful earthquakes along the subduction zones, with the potential of generating tsunamis. This boundary has a trench and mantle wedge, but the volcanoes are expressed in a feature known as a volcanic arc. A **volcanic arc** is a chain of mountain volcanoes, with famous examples including the Cascade Range of the Pacific Northwest and the Andes Mountains of South America.



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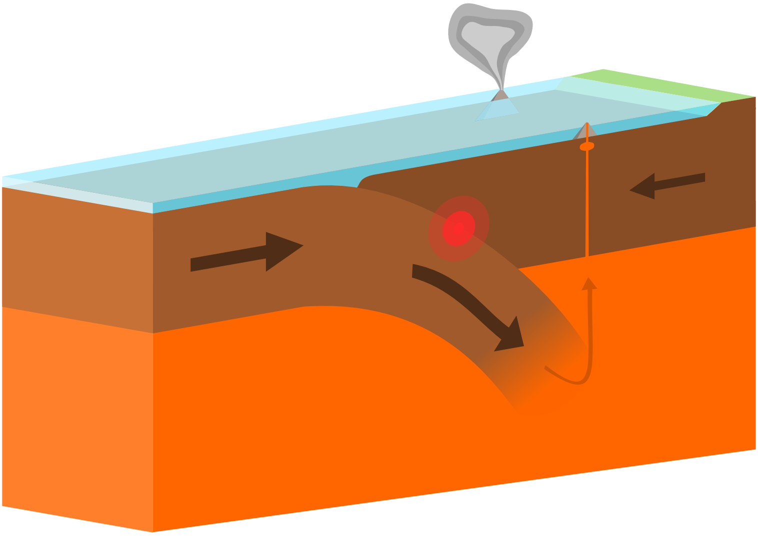
Oceanic-Oceanic Subduction

Oceanic-oceanic subduction zones have two significant differences from boundaries that have continental lithosphere. Firstly, each plate in an ocean-ocean plate boundary is capable of subduction. Therefore, it is typical that the denser, older, and colder of the two plates is the one that subducts. Secondly, since both plates are oceanic, volcanism creates **volcanic islands** instead of **continental volcanic mountain ranges**. This chain of active volcanoes is known as an island arc. There are many examples of this on Earth, including the Aleutian Islands off of Alaska, the Lesser Antilles in the Caribbean, and several island arcs in the western Pacific.



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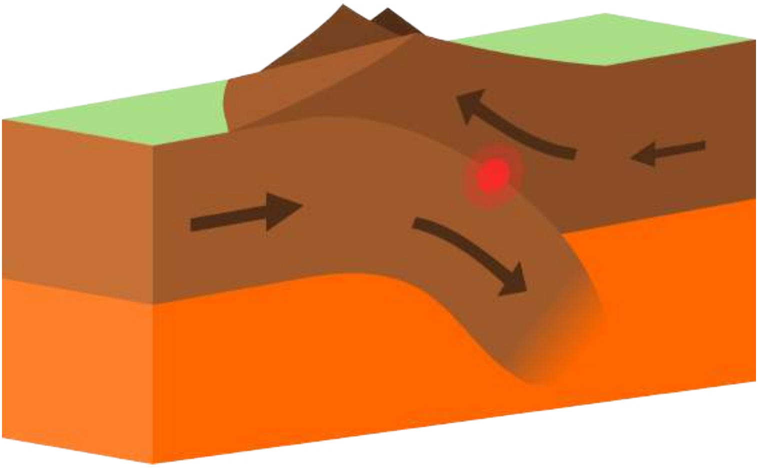
Continental-Continental Convergence

In places where two continental plates converge toward each other, subduction is not possible. This occurs when an ocean basin closes, and a passive margin is attempted to drive down with the subducting slab. Instead of subducting beneath the continent, the two masses of continental lithosphere slam into each other, in a process known as a collision. **Collision zones** are known for tall mountains and frequent, massive earthquakes, with little to no volcanism. With subduction ceasing with the collision, there is not a process to create the magma for volcanism.

Continental plates are too low density to subduct, which is why the process of collision occurs instead of subduction. Unlike the dense subducting slabs that form from oceanic plates, any attempt to subduct continental plates is short-lived. An occasional exception to this is **obduction**, in which a part of a continental plate is caught beneath an oceanic plate, formed in collision zones or with small plates caught in subduction zones. This imbalance in density is solved by the continental material buoying upward, bringing oceanic floor and mantle material to the surface, and is the primary source of ophiolites. An **ophiolite** consists of rocks of the ocean floor that are moved onto the continent, which can also expose parts of the mantle on the surface.



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Foreland basins can also develop near the mountain belt, as the lithosphere is depressed due to the mass of the mountains themselves. While subduction mountain ranges can cause this, collisions have many examples, with possibly the best modern example being the Persian Gulf, a feature only there due to the weight of the nearby Zagros Mountains. The subducting oceanic lithosphere powers collisions, and eventually stop as the continental plates combine into a more substantial mass. In truth, a small portion of the continental crust can be driven down into the subduction zone, though due to its buoyancy, it returns to the surface over time. Because of the relative plastic nature of the continental lithosphere, the **zone of deformation** is much broader. Instead of earthquakes found along a narrow boundary, collision earthquakes can be found hundreds of miles from the suture between the landmasses.

The best modern example of this process occurs concurrently in many locations across the Eurasian continent. It includes mountain building in the Pyrenees (the Iberian Peninsula converging with France), Alps (Italy converging into central Europe), Zagros (Arabia converging into Iran), and Himalayan (India converging into Asia) ranges. Eventually, as ocean basins close, continents join together to form a massive accumulation of continents called a **supercontinent**, which has taken place in hundreds of million-year cycles over earth's history. (2 Plate Tectonics – An Introduction to Geology, n.d.)

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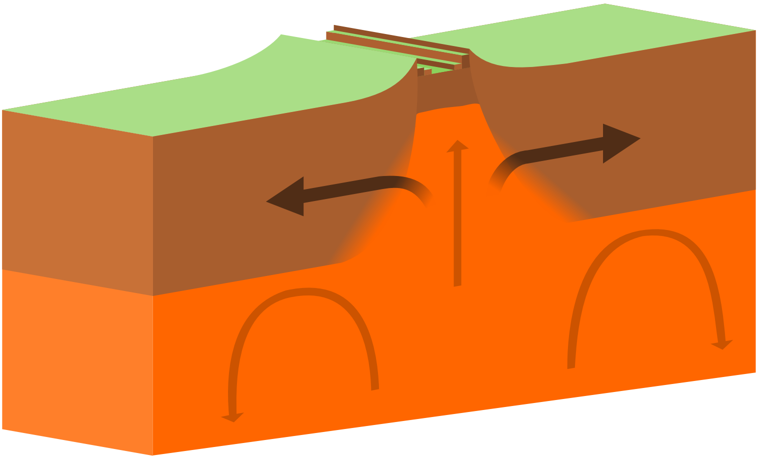
Divergent Boundaries

Divergent boundaries, sometimes called **constructive boundaries**, are places where two or more plates have a net movement away from each other. They can occur within a continental plate or an oceanic plate, though the typical pattern is for divergence to begin within the continental lithosphere in a process known as "rift to drift," described below.

Continental Rifting

Because of the thickness of continental plates, heat flow from the interior is suppressed. The shielding that supercontinents provide is even stronger, eventually causing an upwelling of hot mantle material. This material uplift weakens overlying continental crust, and as convection beneath naturally starts pulling the material away from the area, the area starts to be de-formed by tensional stress forming a valley feature known as a **rift valley**. These features are bounded by normal faults and include tall shoulders called horsts, and deep basins called **grabens**. When rifts form, they can eventually create **linear lakes**, **linear seas**, and even **oceans** to form as divergent forces continue.



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This breakup via rifting, while initially seeming random, has two influences that dictate the shape and location of rifting. First, the stable interiors of some continents, called a **craton**, are too strong to be broken apart by rifting. Where cratons are not a factor, rifting typically occurs along with the patterns of a **truncated icosahedron**, or "soccer ball" pattern. This is the geometric pattern of fractures that requires the least amount of energy when expanding a sphere equally in all directions. Taking into account the radius of the Earth, this includes 110 km segments of deformation and volcanism, which have 120-degree turns, forming something known as **failed rift arms**. Even if the motion stops, a minor basin can develop in this weak spot called an **aulacogen**, which can form long-lived basins well after tectonic processes stop. These are places where extension started but did not continue. One famous example is the Mississippi Valley Embayment, which forms a depression through which the upper end of the Mississippi River flows. In places where the rift arms do not fail, for example, the Afar Triangle, three divergent boundaries can develop near each other, forming a triple junction. (2 Plate Tectonics – An Introduction to Geology, n.d.)

"Albertine Rift, East African Rift" by Christoph Hormann is licensed under Creative Commons Attribution-ShareAlike 3.0 Unported.

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Rifts come in two types: narrow and broad. **Narrow rifts** contain concentrated stress or divergent action. The best example is the East African Rift Zone, where the Horn of Africa near Somalia is breaking away from mainland Africa. Lake Baikal in Russia is also an active rift. **Broad rifts** distribute the deformation over a wide area of many fault-bounded locations, like in the western United States in a region known as the **Basin and Range**. The **Wasatch Fault**, which created the Wasatch Range in Utah, marks the eastern edge of the Basin and Range.

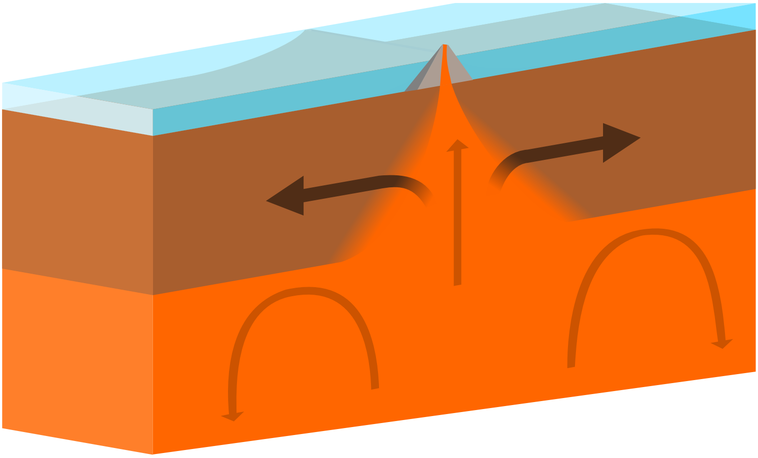
"Great Basin Map" is licensed under Creative Commons Attribution-ShareAlike 3.0 Unported.

Of course, earthquakes do occur at rifts, though not at the severity and frequency of some other boundaries. Volcanism is also frequent in the extended, faulted, and thin lithosphere found at rift zones due to decompression melting and faults acting as conduits for the lava reaching the surface. Many relatively young volcanoes dot the Basin and Range, and bizarre volcanoes occur in East Africa like Ol

Doinyo Lengai in Tanzania, which erupts carbonatite lavas, relatively cold liquid carbonate.

Mid-Oceanic Ridges

As rifting and volcanic activity progress, the continental lithosphere becomes more mafic and thinner, with the eventual result transforming the plate under the rifting area into the oceanic lithosphere. This is the process that gives birth to a new ocean, much like the narrow Red Sea (map) that emerged with the movement of Arabia away from Africa. As the oceanic litho-sphere continues to diverge, a mid-ocean ridge is formed. (2 Plate Tectonics – An Introduction to Geology, n.d.)



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A **mid-ocean ridge**, also known as a **spreading center**, has many distinctive features. They are the only places on Earth where the new oceanic lithosphere is being created via slow oozing volcanism. As the oceanic lithosphere spreads apart, rising asthenosphere melts due to decreasing pressure and fills in the void, making the new lithosphere and crust. These volcanoes produce more lava than all the other volcanoes on Earth combined, and yet are not usually listed on maps of volcanoes due to the vast majority of mid-ocean ridges being underwater. Only rare locations, such as Iceland, are the volcanism and divergent characteristics seen on land. Technically, these places are not mid-ocean ridges because they are above the surface of the seafloor.

Alfred Wegener even hypothesized this concept of mid-ocean ridges. Because the lithosphere is extremely hot at the ridge, it has a lower density. This lower density allows it to isostatically 'float' higher on the asthenosphere. As the lithosphere moves away from the ridge by continued spreading, the plate cools and starts to sink isostatically lower, creating the surrounding abyssal plains with lower topography. Age patterns match this idea, with younger rocks near the ridge and older rocks away from the ridge. Sediment patterns also thin toward the ridge, since the steady accumulation of dust and biologic material takes time to accumulate.

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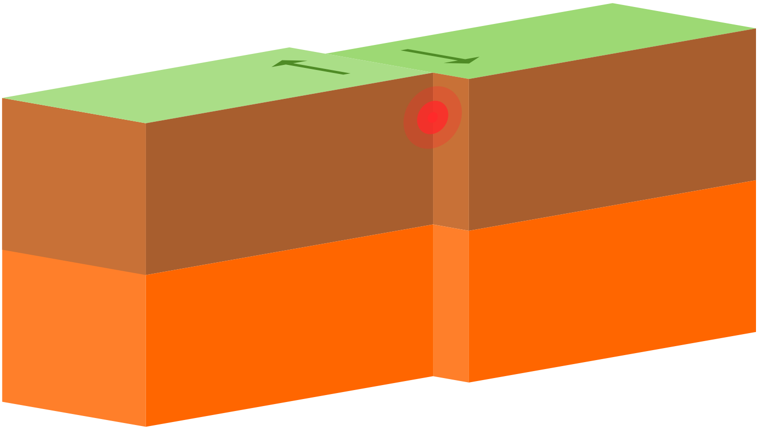
Another distinctive feature around mid-ocean ridges is **magnetic striping**. Called the **Vine-Matthews-Morley Hypothesis**, it states that as the material moves away from the ridge, it cools below the **Curie Point**, the temperature at which the magnetic field is imprinted on the rock as the rock freezes. Over time, the Earth's magnetic field has flipped back and forth, and it is this change in the field causes the stripes. This pattern is an excellent record of past ocean-floor movements and can be used to reconstruct past tectonics and determine rates of spreading at the ridges.

Mid-ocean ridges also are home to some of the unique ecosystems discovered, found around hydrothermal vents that circulate ocean water through the shallow oceanic crust, and send it back out to rich chemical compounds and heat. While it was known for some time that hot fluids could be found on the ocean floor, it was only in 1977 when a team of scientists using the Diving Support Vehicle Alvin discovered a thriving community of organisms, including tubeworms bigger than people. This group of organisms is dependent on the sun and photosynthesis but instead relies on chemical reactions with sulfur compounds and heat from within the Earth, a process known as **chemosynthesis**. Before this discovery, the thought in biology was that the sun was the ultimate source of energy in ecosystems; now, we know this to be false. Not only that, but some have also suggested it is from this that life could have started on Earth, and it now has become a target for extraterrestrial life (e.g., Jupiter's moon Europa).

Transform Boundaries

A **transform boundary** sometimes called a **strike-slip** or **a conservative boundary**, is where the motion is of the plates sliding past each other. They can move in either **dextral fashion** with the side opposite moving toward the right, or a **sinistral fashion** with the side opposite moving toward the left. Most transform boundaries can be viewed as a single fault or as a series of faults. As stress builds on adjacent plates attempting to slide them past each other, eventually, a fault occurs and releases stress with an earthquake. **Transform faults** have a shearing motion and are prevalent in places where tectonic stresses are transferred. In general, transform boundaries are known for only earthquakes, with little to no mountain building and volcanism.



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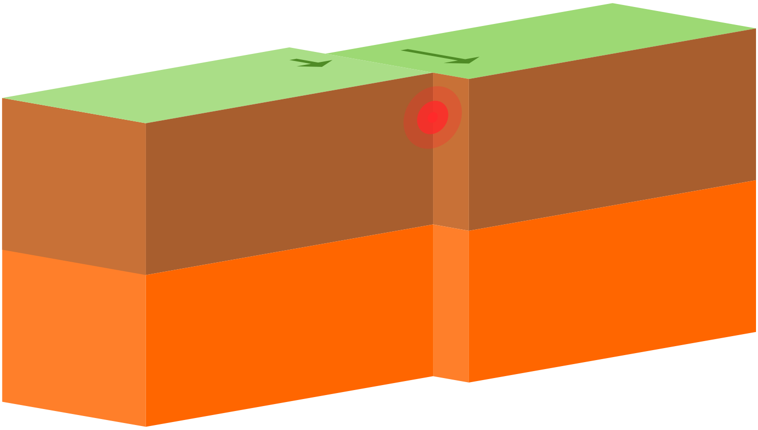
Most transform boundaries are associated with mid-ocean ridges. As spreading centers progress, these aseismic fracture zone transform faults accommodate different amounts of spreading due to Eulerian geometry that a sphere rotates faster in the middle (Equator) than at the top (Poles) than along the ridge. However, in the eyes of humanity, the more significant trans-form faults are where the motion occurs within continental plates with a shearing motion. These transform faults produce frequent moderate to large earthquakes. Famous examples include California's San Andreas Fault, the Northern and Eastern Anatolian Faults in Turkey, the Altyn Tagh Fault in central Asia, and the Alpine Fault in New Zealand. (2 Plate Tectonics – An Introduction to Geology, n.d.)



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Transpression and Transtension

In places where transform faults are not straight, they can create **secondary faulting**. **Transpression** is defined as places where there is an extra component of compression with shearing. In these restraining bends, mountains can be built up along the fault. The southern part of the San Andreas Fault has a large area of transpression known as the "big bend" and has built, moved, and rotated many mountain ranges in southern California.

Transtension is defined as places where there is an extra component of extension with shearing. In these releasing bends, depressions and sometimes volcanism are formed along the fault. The Dead Sea and California's Salton Sea are examples of basins formed by transtensional forces.

Piercing Points

A **piercing point** is a feature that is cut by a fault and can be used to recreate past movements along the fault. While this can be used on all faults, transform faults are most adapted for this technique. Normal and reverse faulting and divergent and convergent boundaries tend to obscure, bury, or destroy these features; transform faults generally do not. Piercing points usually consist of unique lithologic, structural, or geographic patterns that can be matched by removing the movement along the fault. Detailed studies of piercing points along the San Andreas Fault has shown over 225 km of movement in the last 20 million years along three different active traces of the fault.

"Aerial San Andreas Carrizo Plain" by John Wiley is licensed under Creative Commons Attribution 3.0 Unported.

Wilson Cycle

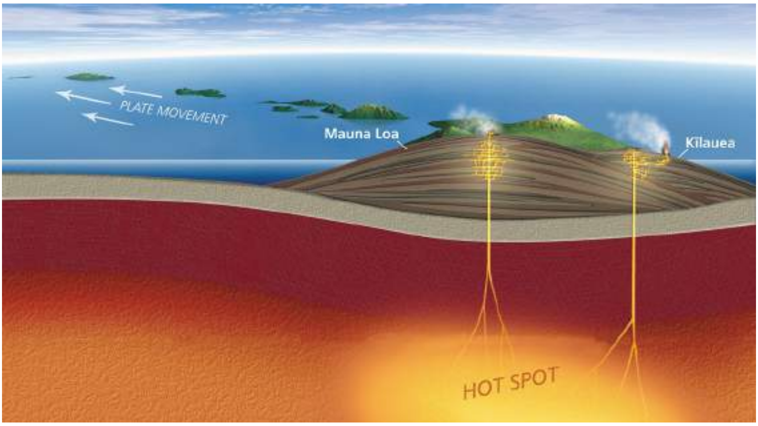
The **Wilson Cycle**, named for J. Tuzo Wilson, who first described it in 1966, outlines the origin and subsequent breakup of supercontinents. This cycle has been operating for the last billion years with supercontinents **Pangaea** and **Rodinia**, and possibly billions of years before that. The driving force of this is two-fold. The more straightforward mechanism arises from the fact that continents hold the Earth's internal heat much better than the ocean basins. When continents congregate together, they hold more heat in which more vigorous convection can occur, which can start the rifting process. Mantle plumes are inferred to be the legacy of this increased heat and may record the history of the start of rifting. The second mechanism for the Wilson Cycle involves the destruction of plates. While rifting eventually leads to drifting continents, a few unanswered questions emerge:

- Does their continued movement result from a continuation of the ridge spreading and under-lying convection, known as ridge push?
- Do the tectonic plates move because of the weight of the subducting slab sinking via its density, known as slab pull?
- Alternatively, does the height of the ridge pushing down, known as gravitational sliding?

To be sure, these are all factors in plate movement and the Wilson Cycle. It does appear, in the current best hypothesis, that there is a more significant component of slab pull than ridge push. Plate tectonic models are beginning to detail the next supercontinent, called Pangea Proxima, that will form 250 million years.

Hotspots

While the Wilson Cycle can give a general overview of plate motions in the past, another process can give a more precise, but recent, plate movement. A **hot spot** is an area of rising magma, causing a series of volcanic centers that form volcanic islands in the ocean or craters/mountains on land. There is no plate tectonic process, like subduction or rifting, which causes this volcanic activity; it seems disconnected to plate tectonics processes. Also first postulated by J. Tuzo Wilson, in 1963, hot spots have a continual source of magma with no earthquakes, besides those associated with volcanism. The classic idea is that hot spots do not move, though some evidence has been suggested that the hot spots do move as well. Even though hotspots and plate tectonics seem independent, there are some relationships between them, and they have two components: Firstly, there are several hot spots currently and several others in the past that are believed to have begun at the time of rifting. Secondly, as plate tectonics moves the plates around, the assumed stationary nature of hot spots creates a track of volcanism that can measure past plate movement. By using the age of the eruptions from hot spots and the direction of the chain of events, one can identify a specific rate and direction of movement of a plate over the time the hot spot was active.



"Hawaiian Hot Spot" by the National Park Service is licensed under Public Domain.

Hot spots are still very mysterious in their exact mechanism of magma generation. The main camps on hotspot mechanics are opposed. Some claim deep sources of heat, from as deep as the core, bring heat up to the surface in a structure called a **mantle plume**. Some have argued that not all hot spots are sourced from deep within the planet, and are sourced from shallower parts of the mantle. Others have mentioned how difficult it has been to imagine these deep features. The idea of how hot spots start is also controversial. Usually, divergent boundaries are tabbed as the start, especially during supercontinent break up, though some question whether extensional or tectonic forces alone can explain the volcanism. Subducting slabs have also been named as a cause for hotspot volcanism. Even impacts of objects from space have been used to explain plumes. However, they are formed; there are dozens found throughout the Earth. Famous examples include the Tahiti, Afar Triangle, Easter Island, Iceland, the Galapagos Islands, and Samoa. The United States has two of the most extensive and best-studied examples: Hawai'i and Yellowstone.

Hawaiian Hot Spot

The big island of Hawaii is the active end of the **Hawaiian-Emperor seamount chain**, which stretches across the Pacific for almost 6000 km. The evidence for this hot spot goes back at least 80 million years, and presumably, the hot spot was around before then, but rocks older than that in the Pacific Plate had already subducted. The most striking feature of the chain is a significant bend that occurs about halfway through the chain that occurred about 50 million years ago. The change in direction has been more often linked to a plate re-configuration, but also other things like plume migration. While some scientists often assume that mantle plumes do not move, much like the plumes themselves, this idea is under dispute.

Three-dimensional seismic imaging, called **tomography**, has mapped the Hawaiian mantle plume at depths, including the lower mantle. Within the Hawaiian Islands, there is unmistakable evidence of the age of volcanism decreasing, including island size, rock age, and even vegetation. Hawai'i is one of the most active hotspots on Earth. Kilauea, the central active vent of the hot spot eruption, has continually erupted since 1983.

A YouTube element has been excluded from this version of the text. You can view it online here: https://slcc.pressbooks.pub/physicalgeography/?p=288

Yellowstone Supervolcano

The **Yellowstone Hot Spot** is formed from rising magma, much like Hawai'i. The significant difference is that Hawaii sits on a thin oceanic plate, which makes the magma easily come to the surface. Yellowstone, however, is on a continental plate. The thickness of the plate causes the generally much more violent and less frequent eruptions that have carved a curved path in the western United States for over 15 million years. Some have speculated an earlier start to the hotspot, tying it to the Columbia River flood basalts and even 70 million-year-old volcanism in Canada's Yukon.

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The most recent significant eruption formed the current caldera and the Lava Creek Tuff. This eruption threw into the atmosphere about 1000 cubic kilometers of magma erupted 631,000 years ago. Ash from the eruption has been found as far away as Mississippi. The next eruption, when it occurs, should be of equivalent size, causing a massive calamity to not only the western United States but also the world. These so-called "supervolcanic" eruptions have the potential for volcanic winters lasting years. With so much gas and ash filling the atmosphere, sunlight is blocked and unable to reach Earth's surface as well as usual, which could drastically alter global environments and send worldwide food production into a tailspin.

A YouTube element has been excluded from this version of the text. You can view it online here: https://slcc.pressbooks.pub/physicalgeography/?p=288

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PART IV

TECTONIC FORCES

4.1 GEOLOGIC STRUCTURES AND LANDFORMS

Stress and Strain

Stress is the force exerted per unit area, and strain is a material's response to that force. **Strain** is deformation caused by stress. Strain in rocks can be represented as a change in rock volume and rock shape, as well as fracturing the rock. There are three types of stress: tensional, compressional, and shear. **Tensional stress** involves pulling something apart in opposite directions, stretching and thinning the material. **Compressional stress** involves things coming together and pushing on each other, thickening the material. **Shear stress** involves transverse movement of the material moving past each other, like a scissor. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Deformation

When rocks are stressed, the resulting strain can be elastic, ductile, or brittle, called **deformation**. **Elastic deformation** is strain that is reversible after the stress is released. For example, when compressing a spring, it elastically returns to its original shape after releasing it.

Ductile deformation occurs when enough stress is applied to a material that the changes are permanent, and the material is no longer able to revert to its original shape. For example, if a spring is stretched too far, it can be permanently bent out of shape. Note that concepts related to ductile deformation apply at the visible (macro) scale, and deformation is more complicated at a microscopic scale. Research of plastic deformation, which touches on the atomic scale, is beyond the scope of introductory texts. The yield point is the amount of strain at which elastic deformation is surpassed, and permanent deformation is measurable. Brittle deformation is when the material undergoes another critical point of no return. When sufficient stress to pass that point occurs, it fails and fractures. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

"Deformation" by NASA's Earth Observatory is licensed under Public Domain.

Important factors that influence how a rock will undergo elastic, ductile, or brittle deformation is the intensity of the applied stress, time, temperature, confining pressure, pore pressure, strain rate, and rock strength. **Pore pressure** is the pressure exerted by fluids inside of the open spaces (pores) inside of a rock or sediment. **Strain rate** is how quickly material is deformed. **Rock strength** is a measure of how readily a rock will respond to stress. Shale has low strength, and granite has high strength.

Removing heat, such as decreasing temperature, makes the material more rigid. Likewise, heating materials make them more ductile. Heating glass makes it capable of bending and stretching. Regarding strain response, it is easier to bend a piece of wood slowly without breaking it.

Sedimentary rocks are essential for deciphering the geologic history of a region because they follow specific rules. First, sedimentary rocks are formed with the oldest layers on the bottom and the youngest on top. Second, sediments are deposited horizontally, so sedimentary rock layers are originally horizontal, as are some volcanic rocks, such as ash falls. Finally, sedimentary rock layers that are not horizontal are deformed in some manner – often looking like they are tiling into the earth. Scientists can trace the deformation a rock has experienced by seeing how it differs from its original horizontal, oldest-on-bottom position. This deformation produces geologic structures such as folds, joints, and faults that are caused by stresses.

Stress and Mountain Building

The sheer power and strength of two or more converging continental plates smash upwards that create mountain ranges. Stresses from geologic uplift cause folds, reverse faults, and thrust faults, which allow the crust to rise upwards. The subduction of oceanic lithosphere at convergent plate boundaries also builds mountain ranges. When tensional stresses pull crust apart, it breaks into blocks that slide up and drop down along normal faults. The result is alternating mountains and valleys, known as a basin-and-range.

Folds

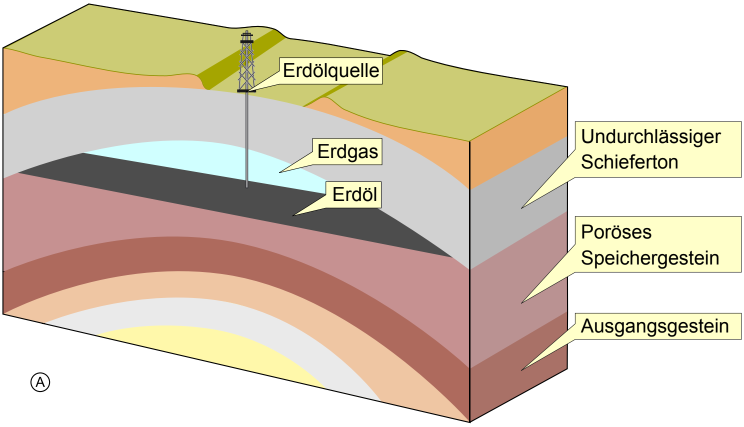
Geologic folds are layers of rock that are curved or bent by **ductile deformation**. Terms involved with folds include axis, which is the line along which the bending occurred, and limbs, which are the dipping beds that make up the sides of the folds. Compressional forces most commonly form folds at depth, where hotter temperatures and higher confining pressures allow ductile deformation to occur.

Folds are described by the orientation of their axes, axial planes, and limbs. They are made up of two or more dipping beds, dipping in opposite directions, which come together along a line, called the axis. Each set of dipping beds is known as a **fold limb**. The plane that splits the fold into two halves is known as the **axial plane**. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Symmetrical folds have mirrored limbs across their axial planes. The limbs of a symmetrical fold are inclined at the same, but opposite, angle indicating equal compression on both sides of the fold. **Asymmetrical folds** have dipping, non-vertical axial planes, where limbs dip into the ground at different angles. **Recumbent folds** are very tight folds with limbs compressed near the axial planes and are generally horizontal, and overturned folds are where the angles on both limbs dip in the same direction. The fold axis is where the axial plane intersects the strata involved in the fold. A horizontal fold has a horizontal fold axis. When the axis of the fold plunges into the ground, the fold is called a **plunging fold**.

Anticline

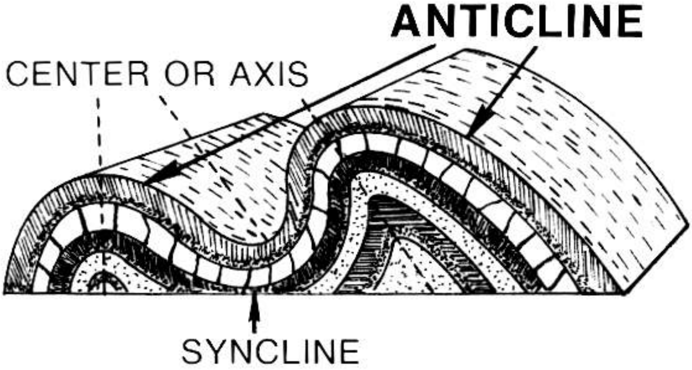
Anticlines are arch-like ("A"-shaped) folds, with downward curving limbs that have beds that dip away from the central axis of the fold. They are convex-upward in shape. In anticlines, the oldest rock strata are in the center of the fold along the axis, and the younger beds are on the outside. An antiform has the same shape as an anticline, but in antiforms, the relative ages of the beds in the fold cannot be determined. Oil geologists have an interest in anticlines because they can form oil traps, where oil migrates up along the limbs of the fold and accumulates in the high point along the axis of the fold. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)



"Anticline Trap" is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported.

Syncline

Synclines are trough-like ("U" shaped), upward-curving folds that have beds that dip in towards the fold's central axis. They are concave-upward in shape. In synclines, the older rock is on the outside of the fold, and the youngest rock is on the inside of the fold along the axis. A synform has the shape of a syncline but, like an antiform, does not distinguish between the ages of the units.



"Anticline" by Pearson Scott Foresman is licensed under Public Domain.

Monocline

Monoclines are step-like folds, in which flat rocks are upwarped or downwarped, then continue flat. They are relatively common on the Colorado Plateau, where they form "reefs," ridges that act as topographic barriers and should not be confused with ocean reefs. Capitol Reef National Park is an example of a monocline in Utah. Monoclines can be caused by bending of shallower sedimentary strata as faults grow below them. These faults are commonly called "blind faults" because they end before reaching the surface and can be either normal or reverse faults. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Dome

A **dome** is a symmetrical to semi-symmetrical upwarping of rock beds, like in Utah's San Rafael Swell. Domes have a shape like an inverted bowl, similar to domes on buildings, like the Capitol Building. Some domes are formed from compressional forces, while other domes are formed from underlying igneous intrusions, by salt diapirs, or even impacts, like upheaval dome in Canyonlands National Park. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Basin

A **basin** is the inverse of a dome. The basin is when rock forms a bowl-shaped depression. The Uinta Basin is an example of a basin in Utah. Technically, geologists refer to rocks folded into a bowl-shape as structural basins. Sometimes structural basins can also be sedimentary basins in which large quantities of sediment accumulate over time. Sedimentary basins can form as a result of folding but are much more commonly produced in mountain building, between mountain blocks or via faulting. Regardless of the cause, as the basin sinks, called **subsidence**, it can accumulate even more sediment as the sediment's weight causes more subsidence in a positive-feedback loop. There are active sedimentary basins all over the world.

4.2 EARTHQUAKES

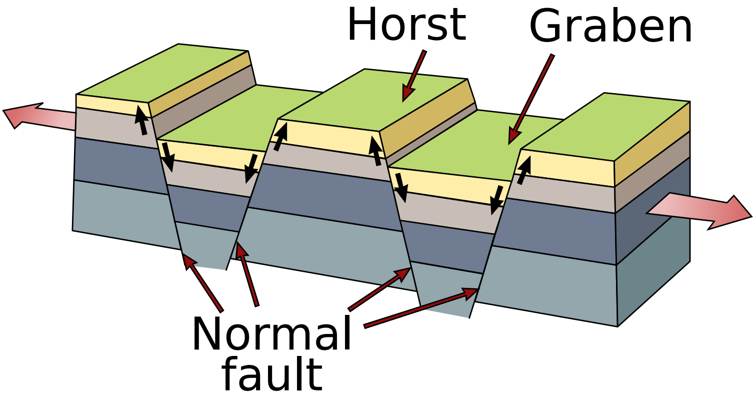
Types of Faults

Faults are the places in the crust where brittle deformation occurs as two blocks of rocks move relative to one another. There are three major fault types: normal, reverse, and strike-slip. Normal and reverse faults display vertical, also known as dip-slip, motion. **Dip-slip motion** consists of relative up and down movement along a dipping fault between two blocks, the hanging wall and the footwall. In a dip-slip system, the **footwall** is below the **fault plane**, and the **hanging-wall** is above the fault plane. An excellent way to remember this is to imagine a mine tunnel through a fault; the hanging wall would be where a miner would hang a lantern, and the footwall would be at the miner's feet. Faults are more prevalent near and related to plate boundaries but can occur in plate interiors as well. Faults can show evidence of movement along the fault plane. **Slickensides** are polished, often grooved surfaces along the fault plane created by friction during the movement. A **joint** or **fracture** is a plane of breakage in a rock that does not show movement or offset. Joints can result from many processes, such as cooling, depressurizing, or folding. Joint systems may be regional affecting many square miles. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

“Moab Fault” by Andrew Wilson” is licensed under Public Domain.

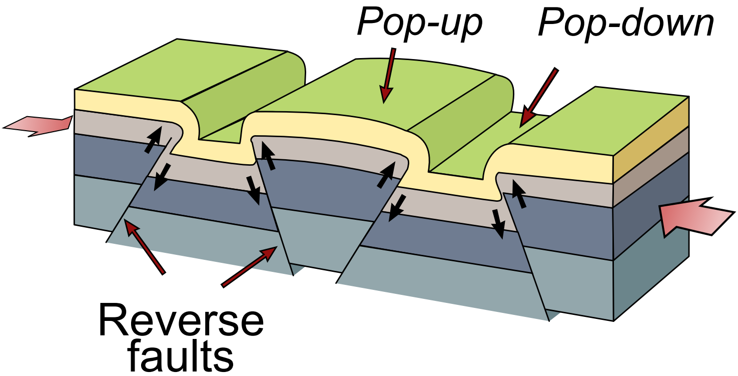
Normal faults move by a vertical motion where the hanging-wall moves downward relative to the footwall along the dip of the fault. Tensional forces create normal faults in the crust. Normal faults and tensional forces are commonly caused at divergent plate boundaries and where tensional stresses are stretching the crust. An example of a normal fault is the Wasatch Fault along the Wasatch Range.

Grabens, **horsts**, and **half-grabens** are all blocks of crust or rock bounded by normal faults. Grabens drop down relative to adjacent blocks and create valleys. Horsts go up relative to adjacent down-dropped blocks and become areas of high topography. Where together, horsts and grabens create a symmetrical pattern of valleys surrounded by normal faults on both sides and mountains. Half-grabens are a one-sided version of a horst and graben, where blocks are tilted by a normal fault on one side, creating an asymmetrical valley-mountain arrangement. The mountain-valleys of the Basin and Range Province of Western Utah and Nevada consist of a series of full and half-grabens from the Salt Lake Valley to the Sierra Nevada Mountains. When the dip of a normal fault decreases with depth (i.e., the fault becomes more horizontal as it goes deeper), the fault is **listric**. Extreme versions of listric faulting occur when substantial amounts of extension occur along very low-angle normal faults, known as detachment faults. The normal faults of the Basin and Range appear to be-come detachment faults at depth. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)



"Horst and Graben" by the United States Geologic Survey is licensed under Public Domain.

Reverse faults, caused by compressional forces, are when the hanging wall moves up relative to the footwall. A thrust fault is a reverse fault where the fault plane has a low dip angle (generally less than 45 degrees). Thrust faults bring older rocks on top of younger rocks and can cause repetition of rock units in the stratigraphic record. Convergent plate boundaries with subduction zones create a particular type of "reverse" fault called a **megathrust fault**. Megathrust faults cause the most significant magnitude earthquakes and commonly cause tsunamis.

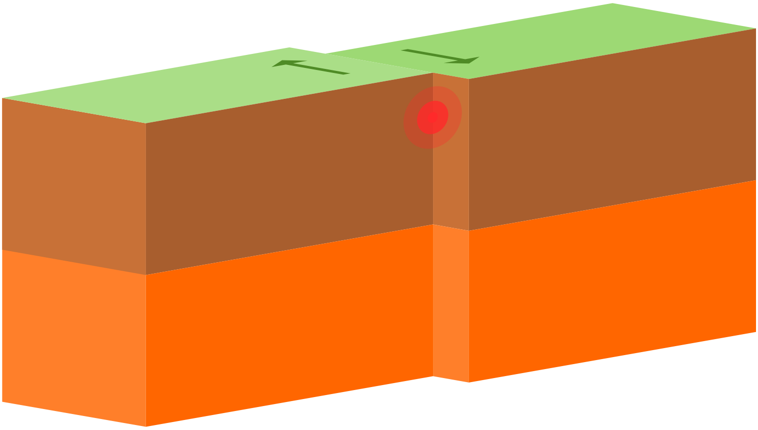


"Reverse Faults" by the United States Geologic Survey is licensed under Public Domain.

Strike-slip faults have a side to side motion. In the pure strike-slip motion, crustal blocks on either side of the fault do not move up or down relative to each other. There is left-lateral, called **sinistral**, and right-lateral, called **dextral**, strike-slip motion. In left-lateral or sinistral strike-slip motion, the opposite block moves left relative to the block that the observer is standing on. In right-lateral or dextral strike-slip motion, the opposite block moves right relative to the observer's block. Strike-slip faults are most associated with transform boundaries and are prevalent in fracture zones adjacent to mid-ocean ridges.

Bends in strike-slip faults can create areas where the sliding blocks create compression or tension. Tensional stresses will create **transtensional** features with normal faults and basins like California's Salton Sea, and compressional stresses will create transpressional features with reverse faults and small-scale mountain building, like California's San Gabriel Mountains. The faults that play off transpression or transtension features are known as **flower structures**.

An example of a **right-lateral strike-slip fault** is the San Andreas Fault, which denotes a transform boundary between the North American and Pacific plates. An example of a left-lateral strike-slip fault is the Dead Sea fault in Jordan and Israel. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)



"Strike-slip Fault" is licensed under Creative Commons Attribution 4.0 International.

Causes of Earthquakes

People feel approximately 1 million earthquakes a year. Few are noticed far from the source. Even fewer are significant earthquakes. Earthquakes are usually felt only when they are greater than a magnitude 2.5 or greater. The USGS Earthquakes Hazards Program has a real-time map showing the most recent earthquakes. Most earthquakes occur along active plate boundaries. Intraplate earthquakes (not along plate boundaries) are still poorly understood. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Earthquake energy is known as **seismic energy**, and it travels through the earth in the form of seismic waves. To understand some of the basics of earthquakes and how they are measured, consider some of the fundamental properties of waves. **Waves** describe a motion that repeats itself in a medium such as rock or unconsolidated sediments. The **magnitude** refers to the height, called **amplitude**, of a wave. **Wavelength** is the distance between two successive peaks of the wave. The number of repetitions of the motion over time, called **cycles per time**, is the **frequency**. The inverse of frequency, which is the amount of time for a wave to travel one wavelength, is the period. When multiple waves combine, they can interfere with each other. When the waves are in sync with each other, they will have constructive interference, where the influence of one wave will add to and magnify the other. If the waves are out of sync with each other, they will have destructive interference. If two waves have the same amplitude and frequency and are ½ wavelength out of sync, the destructive interference between them can eliminate each wave.

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The elastic rebound theory explains the release of seismic energy. When the rock is strained to the point that it undergoes brittle deformation, built-up elastic energy is released during displacement, which radiates away as seismic waves. When the brittle deformation occurs, it creates an offset between the fault blocks at a starting point called the focus. This offset propagates along the surface of rupture, which is known as the fault plane.

The fault blocks of persistent faults like the Wasatch Fault of Utah are locked together by friction. Over hundreds to thousands of years, stress builds up along the fault. Eventually, stress along the fault overcomes the frictional resistance, and slip initiates as the rocks break. The deformed rocks "snap back" toward their original position in a process called elastic rebound. Bending of the rocks near the fault may reflect this buildup of stress, and in earth-quake-prone areas like California, strain gauges that measure this bending are set up in an attempt to understand more about predicting an earthquake. In some locations where the fault is not locked, seismic stress causes a continuous movement along the fault called fault creep, where displacement occurs gradually. Fault creep occurs along some parts of the San Andreas Fault.

The release of seismic energy occurs in a series of steps. After a seismic energy release, energy begins to build again during a period of inactivity along the fault. The accumulated elastic strain may produce small earthquakes (on or near the main fault). These are called fore-shocks and can occur hours or days before a massive earthquake, but they may not occur at all. The main release of energy occurs during the major earthquake, known as the mainshock. Aftershocks may then occur to adjust strain that built up from the movement of the fault. They generally decrease over time. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Earthquake Zones

Nearly 95 percent of all earthquakes occur along with one of the three types of tectonic plate boundaries, but earthquakes do occur along all three types of plate boundaries. About 80 percent of all earthquakes strike around the Pacific Ocean basin because it is lined with convergent and transform boundaries. Called the **Ring of Fire**, this is also the location of most volcanoes around the planet.

About 15 percent take place in the Mediterranean-Asiatic Belt, where convergence is causing the Indian Plate to run into the Eurasian Plate, creating the largest mountain ranges in the world. The remaining 5 percent are scattered around other plate boundaries or are intraplate earthquakes. (Reading: The Nature of Earthquakes | Geology, n.d.)

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Transform Plate Boundaries

Transform plate boundaries occur when two tectonic plates grind parallel to each other rather than colliding or subducting. Deadly earthquakes occur at transform plate boundaries, creating **strike-slip faults** because they tend to have shallow focuses where the rupture occurs. The faults along the San Andreas Fault zone produce around 10,000 earthquakes a year. Most are tiny, but occasionally one is massive. In the San Francisco Bay Area, the Hayward Fault was the site of a magnitude 7.0 earthquake in 1868. The 1906 quake on the San Andreas Fault had a magnitude estimated at 7.9.

During the 1989 World Series, a magnitude 7.1 earthquake struck Loma Prieta, near Santa Cruz, California, killing 63 people, injuring 3,756, and cost $6 billion. A few years later, in Northridge, California, a magnitude 6.7 earthquake killed 72 people, injured 12,000 people, and caused $12.5 billion in damage. This earthquake occurred on an unknown fault because it was a blind thrust fault near Los Angeles, California.

Although California is prone to many natural hazards, including volcanic eruptions at Mt. Shasta or Mt. Lassen, and landslides on coastal cliffs, the natural hazard the state is linked with is earthquakes. New Zealand also has strike-slip earthquakes, about 20,000 a year, but only a small percentage of those are large enough to be felt. A 6.3 quake in Christchurch in February 2011 killed about 180 people. (Reading: The Nature of Earthquakes | Geology, n.d.)

Convergent Plate Boundaries

Earthquakes at convergent plate boundaries mark the motions of the subducting lithosphere as it plunges through the mantle, creating reverse and thrust faults. Convergent plate boundaries produce earthquakes all around the Pacific Ocean basin. The

Philippine Plate and the Pacific Plate subduct beneath Japan, creating a chain of volcanoes and produces as many as 1,500 earthquakes annually.

In March 2011, an enormous 9.0 earthquake struck off Sendai in northeastern Japan. This quake, called the 2011 Tōhoku earthquake, was the most powerful ever to strike Japan and one of the top five known worldwide. Damage from the earthquake was over-shadowed by the tsunami it generated, which wiped out coastal cities and towns. Two months after the earthquake, about 25,000 people died or were missing, and 125,000 buildings were damaged or destroyed. Aftershocks, some as large as major earthquakes, have continued to rock the region. A map of aftershocks is seen here. Recently, the New York Times created an interactive website of the Japan earthquake and tsunami.

The Pacific Northwest of the United States is at risk from a potentially massive earthquake that could strike any time. Subduction of the Juan de Fuca plate beneath North America produces active volcanoes, but large earthquakes only hit every 300 to 600 years. The last was in 1700, with an estimated magnitude of around 9.0. The elastic rebound theory, as applied to subduction zones, can be viewed here.

Massive earthquakes are the hallmark of the thrust faulting and folding when two continental plates converge. The 2001 Gujarat earthquake in India was responsible for about 20,000 deaths, and many more people became injured or homeless. In Understanding Earthquakes: From Research to Resilience, scientists try to understand the mechanisms that cause earthquakes and tsunamis and how society can deal with them. (Reading: The Nature of Earthquakes | Geology, n.d.)

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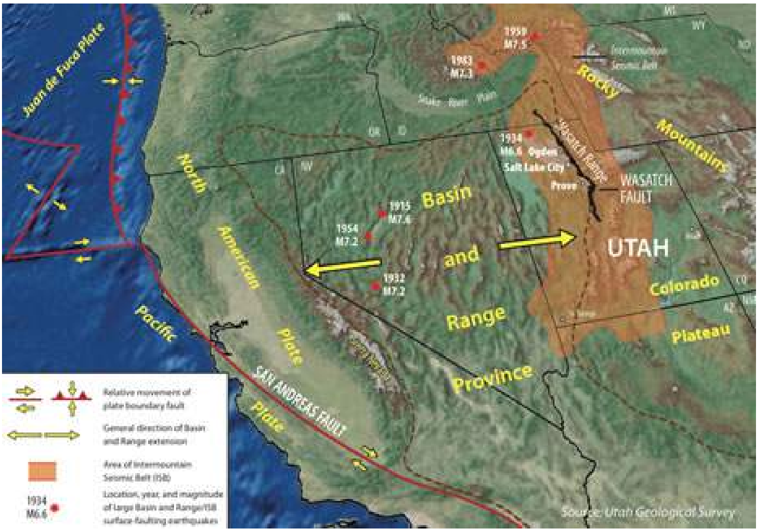
Divergent Plate Boundaries

Many earthquakes occur where tectonic plates are moving apart or where a tectonic plate is tearing itself apart. Earthquakes at mid-ocean ridges are small and shallow because the plates are young, thin, and hot. On land where continents split apart, earthquakes are larger and stronger. A classic example of normal faulting along divergent boundaries is the Wasatch Front in Utah and the entire Basin and Range through Nevada.



"Wasatch Fault" by the United States Geologic Survey is licensed under Public Domain.

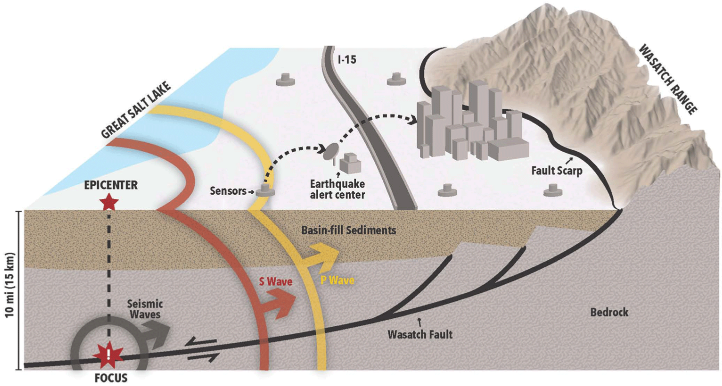
Intraplate Boundaries

Intraplate earthquakes are the result of stresses caused by plate motions acting in solid slabs of the lithosphere. In 1812, a magnitude 7.5 earthquake struck near New Madrid, Missouri. The earthquake was strongly felt over approximately 50,000 square miles and altered the course of the Mississippi River. Because very few people lived there at the time, only 20 people died. Many more people live there today. A similar earthquake today would undoubtedly kill many people and cause a great deal of property damage. (Reading: The Nature of Earthquakes | Geology, n.d.)

4.3 MEASURING AND LOCATING EARTHQUAKES

Focus and Epicenter

The **focus**, also called a **hypocenter** of an earthquake, is the point of initial breaking or rupturing where the displacement of rocks occurs. The focus is always at some depth below the ground surface in the crust, and not at the surface. From the focus, the displacement propagates up, down, and laterally along the fault plane. The displacement produces shock waves, creates seismic waves. The larger the displacement and the further it propagates, the more significant the seismic waves and ground shaking. More shaking is usually the result of more seismic energy released. The **epicenter** is the location on the Earth's surface vertically above the point of rupture (focus). The epicenter is also the location that most news reports give because it is the center of the area where people are affected. The focus is the point along the fault plane from which the seismic waves spread outward. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

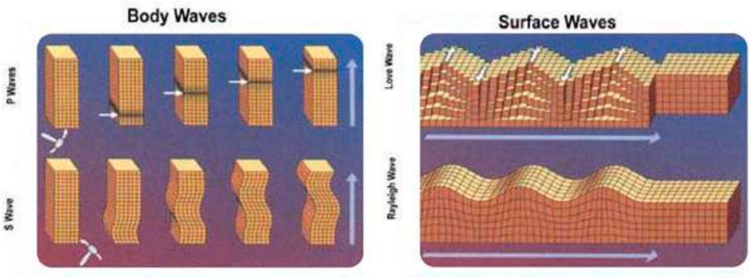


"Focus and Epicenter" by the Utah Geologic Survey is licensed under Public Domain.

Seismic Waves

Seismic waves are an expression of the energy released after an earthquake in the form of **body waves** and **surface waves**. When seismic energy is released, the first waves to propagate out are body waves that pass through the planet's body. Body waves include primary waves (P waves) and secondary waves (S waves). **Primary waves** are the fastest seismic waves. They move through the rock via compression, very much like sound waves move through the air. Particles of rock move forward and back during the passage of the P waves. Primary waves can travel through both fluids and solids. **Secondary waves** travel slower and follow primary waves, propagating as shear waves. Particles of rock move from side to side during the passage of S waves. Because of this, secondary waves cannot travel through liquids, plasma, or gas.

When an earthquake occurs at a location in the earth, the body waves radiate outward, passing through the earth and into the rock of the mantle. A point on this spreading wave-front travels along a specific path that reaches a seismograph located at one of the thousands of seismic stations scattered over the earth. That specific travel path is a line called a **seismic ray**. Since the density (and seismic velocity) of the mantle increases with depth, a process called **refraction** causes earthquake rays to curve away from the vertical and bend back toward the surface, passing through bodies of rock along the way.



"Seismic Waves" by the United States Geologic Survey is licensed under Public Domain.

Surface waves are produced when P and S body waves strike the earth's surface and travel along the Earth's surface, radiating outward from the epicenter. Surface waves travel more slowly than body waves. They have complex horizontal and vertical ground movements that create a rolling motion. Because they propagate at the surface and have complex motions, surface waves are responsible for most of the damage. Two types of surface waves are Love waves and Rayleigh waves. **Love waves** produce horizontal ground shaking and, ironically from their name, are the most destructive. **Rayleigh waves** produce an elliptical motion of points on the surface, with longitudinal dilation and compression, like ocean waves. How-ever, with Raleigh waves, rock particles move in a direction opposite to that of water particles in ocean waves. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Earth is like a bell, and an earthquake is a way to ring it. Like other waves, seismic waves bend and bounce when passing from one material to another, like moving from a dense rock to rock with even higher density. When a wave bends as it moves into a different substance, it is known as refraction, and when waves bounce back, it is known as **reflection**. Because S waves cannot move through a liquid, they are blocked by the liquid outer core, creating a shadow zone on the opposite side of the planet to the earthquake source.

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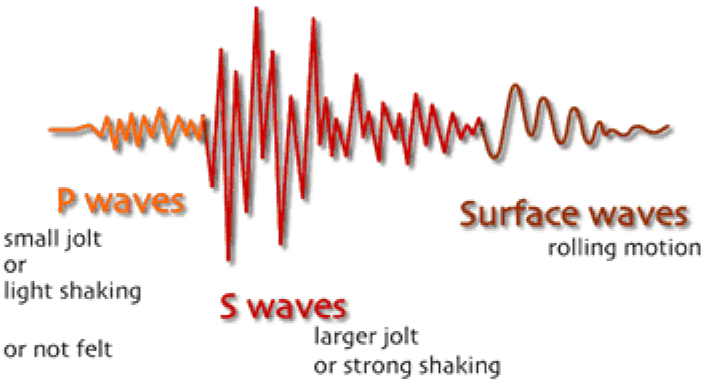
Seismographs

Seismographs are instruments used to measure seismic waves. They measure the vibration of the ground using pendulums or springs. The seismograph principle involves mounting a recording device solidly to the earth and suspending a pen or writing instrument above it on a spring or pendulum. As the ground shakes, the suspended pen records the shaking on the recording device. The graph resulting from measurements of a seismograph is a **seismogram**. Seismographs of the early 20th century were mostly springs or pendulums with pens on them that wrote on a rotating drum of paper. Digital ones now use magnets and wire coils to measure ground motion. Typical seismograph arrays measure vibrations in three directions: north-south (x), east-west (y), and up-down (z).

"Seismograph Recording" is licensed under Creative Commons Attribution 4.0 International.

To determine the distance of the seismograph from the epicenter, **seismologists** use the difference between when the first P waves and S waves arrive. After an earthquake, P waves will appear first on the seismogram, followed by S waves, and finally, body waves, which have the largest amplitude on the seismogram. Surface waves do lose energy quickly, so they are not measured at great distances from the focus. Seismograph technology across the globe record the arrival of seismic waves from each earthquake at many station sites. The distance to the epicenter can be determined by comparing arrival times of the P and S waves. Electronic communication among seismic stations and connected computers used to make calculations mean that locations of earthquakes and news reports about them are generated quickly in the modern world. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

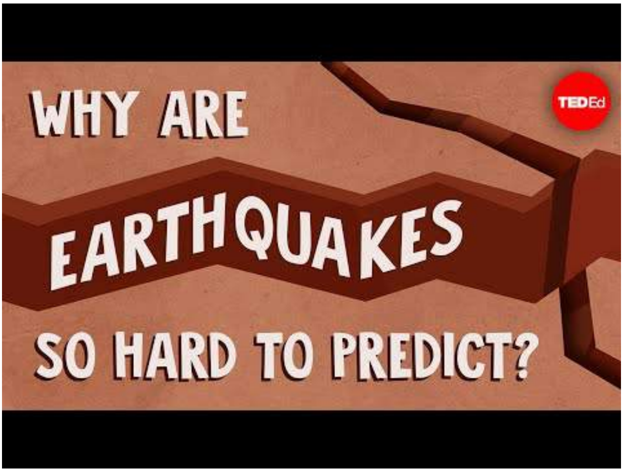


Locating Earthquakes

Each seismograph gives the distance from that station to the earthquake epicenter. Three or more seismograph stations are needed to locate the epicenter of an earthquake through triangulation. Using the arrival-time difference from the first P wave to the first S wave, one can determine the distance from the epicenter, but not the direction. The distance from the epicenter to each station can be plotted as a circle, the distance being equal to the circle's radius. The place where the circles intersect demarks the epicenter. This method also works in three dimensions with spheres and multi-axis seismographs to locate not only the epicenter but also the depth of the earthquake's focus.

Seismograph Network

The International Registry of Seismograph Stations lists more than 20,000 seismographs on the planet. Seismologists can use and compare data from sets of multiple seismometers dispersed over a wide area, a seismograph network. By collaborating, scientists can map the inside of the earth's properties, detect large explosive devices, and predict tsunamis. The Global Seismograph Network, a set of worldwide linked seismographs that distribute real-time data electronically, consists of more than 150 stations that meet specific design and precision standards. The Global Seismograph Network helps the Comprehensive Nuclear-Test-Ban Treaty Organization monitor for nuclear tests. The USArray is a network of hundreds of permanent and transportable seismographs within the United States. The USArray is being used to map the subsurface through a passive collection of seismic waves created by earthquakes. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)



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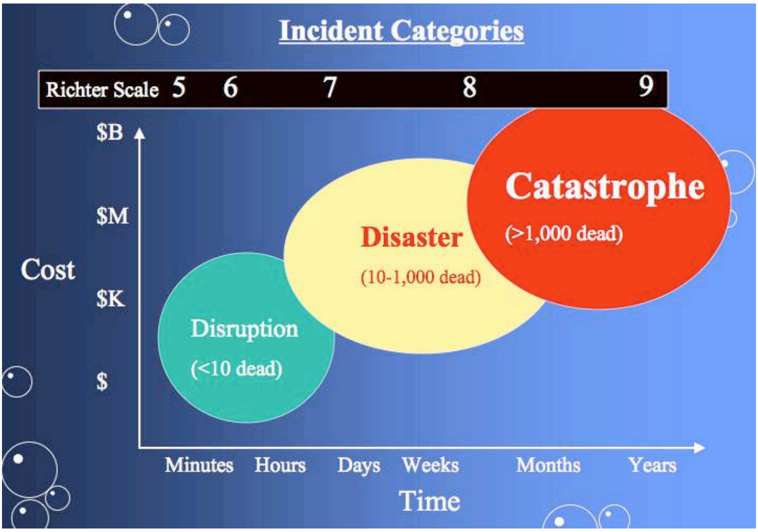
Determining Earthquake Magnitudes

Richter Scale

Magnitude is the measure of the intensity of an earthquake. The **Richter scale** is the most well-known magnitude scale devised for an earthquake and was the first one developed by Charles Richter at CalTech. This was the magnitude scale used historically by early seismologists. The Richter scale magnitude is determined from measurements on a seismogram. Magnitudes on the Richter scale are based on measurements of the maximum amplitude of the needle trace measured on the seismogram and the arrival time difference of S and P waves, which gives the distance to the earthquake. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

The Richter scale is a logarithmic scale, based on powers of 10. The amplitude of the seismic wave recorded on the seismogram is ten times greater for each increase of 1 unit on the Richter scale. That means a magnitude six earthquake shakes the ground ten times more than a magnitude 5. However, the actual energy released for each 1-unit magnitude increase is 32 times greater. That means energy released for a magnitude six earthquake is 32 times greater than a magnitude 5 earthquake. The Richter scale was developed for distances appropriate for earthquakes in Southern California and on seismograph machines in use there. Its applications to more considerable distances and massive earthquakes are limited. Therefore, most agencies no longer use Richter's methods to determine the magnitude but generate a quantity called the **Moment Magnitude**, which is more accurate for large earthquakes measured at the seismic array across the earth. As numbers, the moment magnitudes are comparable to the magnitudes of the Richter Scale. The media still often give magnitudes as Richter Magnitude even though the actual calculation was of moment magnitude.



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Moment Magnitude Scale

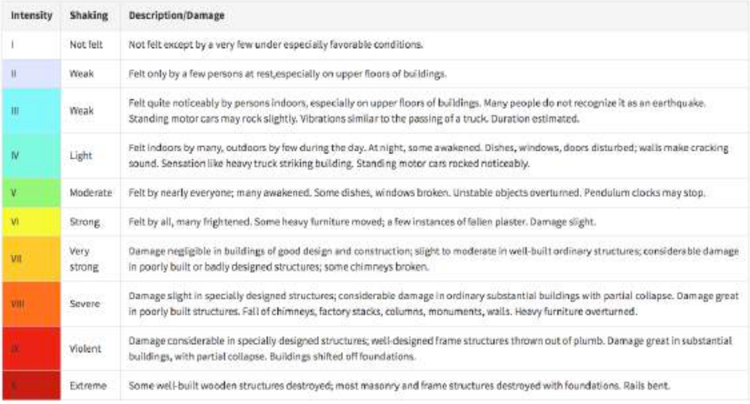
The **Moment Magnitude Scale** depicts the absolute size of earthquakes, comparing information from multiple locations and using a measurement of actual energy released calculated from the cross-sectional area of rupture, amount of slippage, and the rigidity of the rocks. Because of the unique geologic setting of each earthquake and because the rupture area is often hard to measure, estimates of moment magnitude can take days to months to calculate. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Like the Richter magnitude, the moment magnitude scale is logarithmic. Both scales are used in tandem because the estimates of magnitude may change after a quake. The Richter scale is used as a quick determination immediately following the quake (and is usually reported in news accounts), and the moment magnitude is calculated days to months later. The magnitude values of the two magnitudes are approximately equal except for massive earthquakes.

Modified Mercalli-Intensity Scale

The **Modified Mercalli Intensity Scale** is a qualitative scale (I-XII) of the intensity of ground shaking based on damage to structures and people's perceptions. This scale can vary depending on the location and population density (urban vs. rural). It was also used for historical earthquakes, which occurred before quantitative measurements of magnitude could be made. The Modified Mercalli Intensity maps show where the damage is most severe based on questionnaires sent to residents, newspaper articles, and reports from assessment teams. Recently, USGS has used the internet to help gather data more quickly.

Shakemaps (written ShakeMaps by the USGS) use high-quality seismograph data from seismic networks to show areas of intense shaking. They are the result of rapid, computer-interpolated seismograph data. They are useful in crucial minutes after an earthquake, as they can show emergency personnel where the most significant damage likely occurred and locate areas of possible damaged gas lines and other utilities.



Intensity	Shaking	Description/Damage
I	Not felt	Not felt except by a very few under especially favorable conditions.
II	Weak	Felt only by a few persons at rest,especially on upper floors of buildings.
III	Weak	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV	Light	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V	Moderate	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI	Strong	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII	Very strong	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII	Severe	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX	Violent	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X	Extreme	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

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4.4 EARTHQUAKE RISK

Ground Shaking, Location, and Direction

In general, the larger the magnitude, the stronger the shaking, and the longer the shaking will last. However, other factors influence the level of shaking. Closer earthquakes will inherently cause more shaking than those farther away. The location of the epicenter and direction of rupture will influence how much shaking is felt. The direction that the rupture propagates along the fault influences the shaking. The path of most significant rupture can intensify shaking in effect known as **directivity**.

The nature of the ground materials affects the properties of the seismic waves. Varied materials respond differently to an earthquake. Think of shaking jello versus shaking a meatloaf; one will jiggle much more to the same amount of shaking. The response to shaking depends on their degree of consolidation; lithified sedimentary rocks, and crystalline rocks shake less than unconsolidated sediments and landfill. This is because seismic waves move faster through consolidated bedrock, move slower through unconsolidated sediment, and move slowest through unconsolidated materials with high water content. Since the energy is carried by both velocity and amplitude, when a seismic wave slows down, its amplitude increases, which in turn increases seismic shaking. Energy is transferred to the vertical motion of the surface waves.

Depth of Focus

The focus is the place within the Earth where the earthquake starts, and the depth of earthquakes influences the amount of shaking. Deeper earthquakes cause less shaking at the surface because they lose much of their energy before reaching the surface. Recall that most of the destruction is caused by surface waves, caused by the body waves reaching the surface.

What Determines Destruction? Building Materials

Building material choices can influence the amount of damage caused by earthquake shaking. The flexibility of building materials relates to their resistance to damage by earthquake waves. Unreinforced Masonry (URM) is the most devastated by ground shaking. Wood framing held together with nails that can bend and flex with wave passage are more likely to survive earthquakes. Steel also can deform elastically before brittle failure. The Salt Lake City campaign “Fix the Bricks” has useful information on URMs and earthquake safety.

Shaking Intensity and Duration

More significant shaking and duration of shaking will cause more destruction than less shaking and shorter shaking. **Resonance** is when the frequency of seismic energy matches a building's natural frequency of shaking, determined by properties of the building, and intensifies the shaking's amplitude. This famously happened in the 1985 Mexico City Earthquake, where buildings of heights between 6 and 15 stories were especially vulnerable to earthquake damage. Skyscrapers designed with earthquake resilience have dampers, and base isolation features to reduce resonance. Changes in the structural integrity of a structure could alter its resonance. Conversely, changes in measured resonance can indicate potential changes in structural integrity. (9 Crustal Deformation and Earthquakes – An Introduction to Geology, n.d.)

Earthquake Recurrence

Geologists dig earthquake trenches across some faults to measure ground deformation and estimate the frequency of occurrence of past earthquakes. Trenches are useful for faults with prolonged recurrence intervals (100s to 10,000s of years), which is the period be-tween significant earthquakes. In areas with more frequent earthquakes and more measured earthquake data, trenches are less necessary. A long hiatus in earthquake activity could indicate the buildup of stress on a specific segment of a fault with strain held in place by friction, which would indicate a higher probability of an earthquake along that segment. This hiatus of seismic activity along a length of a fault (i.e., a fault that is locked and not having any earthquakes) is known as a seismic gap.

Secondary Hazards Caused by

Earthquakes Liquefaction

Liquefaction is when saturated unconsolidated sediments (usually silt or sand) is liquefied from shaking. Shaking causes loss of cohesion between grains of sediment, reducing the effective stress resistance of the sediment. The sediment flows very much like the quicksand presented in movies. Liquefaction creates sand volcanoes, which is when liquefied sand is squirted through an overlying (usually finer-grained) layer, creating cone-shaped sand features. It may also cause buildings to settle or tilt.

Earthquake-induced tsunamis have caused many of the more recent devastating natural disasters. Tsunamis form when earthquakes offset the seafloor in the ocean subsurface. This offset can be caused by fault movement or underwater landslides and lifts a volume of ocean water generating the tsunami wave. Tsunami waves travel fast with low amplitude in deep ocean water but are significantly amplified as the water shallows as they approach the shore. When a tsunami is about to strike land, the water in front of the wave along the shore will recede significantly, tragically causing curious people to wander out. This receding water is the drawback of the trough in front of the tsunami wave, which then crashes onshore as a wall of water upwards of a hundred feet high. Warning systems have been established to help mitigate the loss of life caused by tsunamis.

Landslides

Shaking can trigger landslides (see landslide section for more information). One example is the 1992 magnitude 5.9 earthquake in St. George, Utah. This earthquake caused the Spring-dale landslide, having a scarp that offset and destroyed several structures in the Balanced Rock Hills subdivision.

Seiches

Seiches are waves on lakes generated by earthquakes, which cause sloshing of water back and forth and, sometimes, even changes in elevation of the lake. A seich in Hebgen Lake during the 1959 earthquake caused significant destruction to structures and roads around the lake.

Land Elevation Changes

Significant subsidence and upheaval of the land can occur about the slippage that causes earthquakes. Land elevation changes are the result of the relaxation of stress and subsequent movement along the fault plane. The 1964 Alaska earthquake is an excellent example of this. Where the fault cuts the surface, the elevation of one side causes a fault scarp that maybe a few feet to 20 or 30 feet in height. The Wasatch Mountains represent an accumulation of fault scarps of a couple of dozen feet at a time over a few million years.

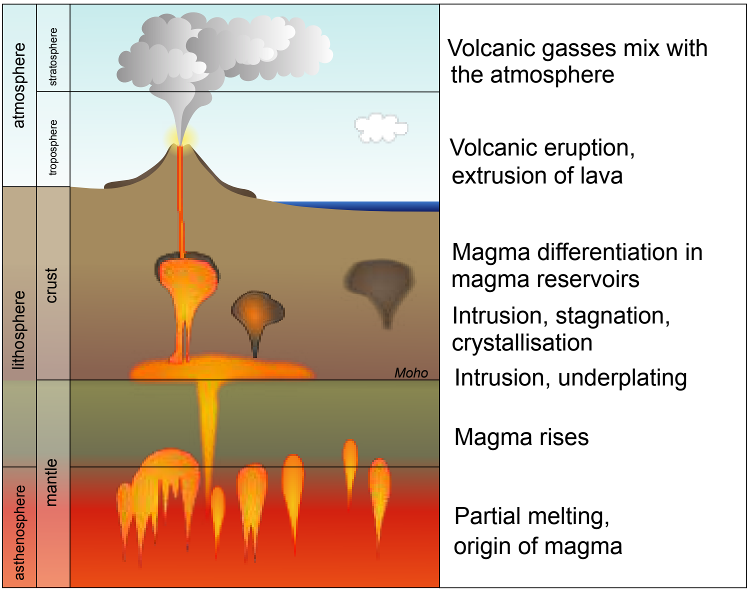
Human-Induced Earthquakes

Can humans create earthquakes? Not intentionally, but the answer is yes, and here is why. If a water reservoir is built on top of an active fault line, the water may lubricate the fault and weaken the stress built up within it. This may either create a series of small earthquakes or potentially create a massive earthquake. Also, the sheer weight of the reservoir r's water can weaken the bedrock causing it to fracture. Then the obvious concern is if the dam fails. Earthquakes can also be generated if humans inject other fluids into a fault, such as sew-age or chemical waste. Finally, nuclear explosions can trigger earthquakes. One way to determine if a nation has tested a nuclear bomb is by monitoring the earthquakes and energy released by the explosion.

4.5 VOLCANISM

Magma Generation

Magma and **lava** contain three components – melt, solids, and volatiles (dissolved gases). The liquid part, called **melt**, is made of ions from minerals that have already melted. The solid part, called **solids**, are crystals of minerals that have not melted (higher melting temperature) and are floating in the melt. Volatiles are gaseous components dissolved in the magma, such as water vapor, carbon dioxide, sulfur, and chlorine. The presence and amount of these three components affect the physical behavior of the magma. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)



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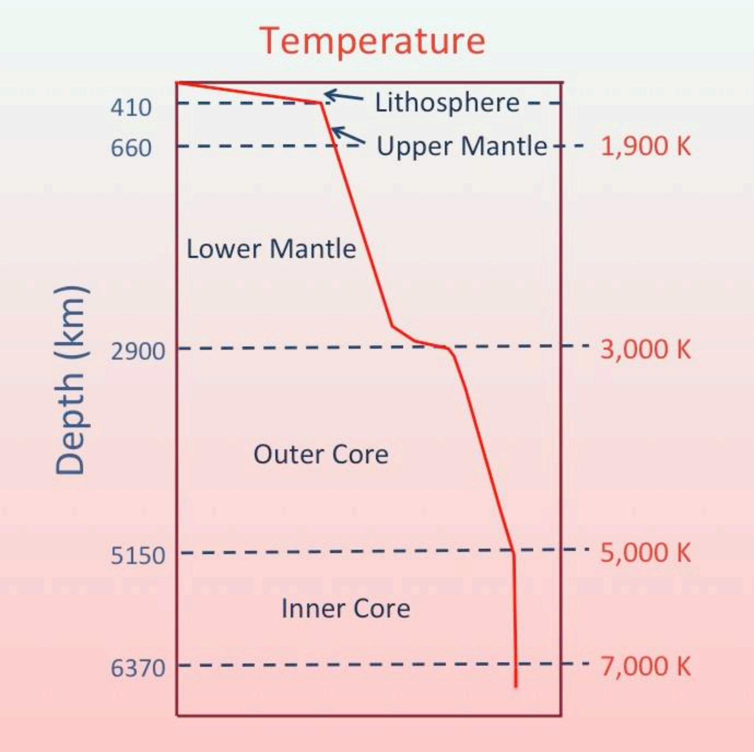
Geothermal Gradient

Although it is scorching under the Earth's surface, the crust and mantle are mostly solid. This heat inside the Earth is caused by residual heat left over from the original formation of Earth and radioactive decay. The rate at which temperature increases with depth is called the **geothermal gradient**. The average geothermal gradient in the upper 100 kilometers of the crust is generally about 25 degrees Celsius per kilometer (km). So, for every kilometer of depth, the temperature increases by about 25 degrees Celsius. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)



“Geothermal Gradient” is licensed under Creative Commons Attribution-ShareAlike 3.0 Unported.

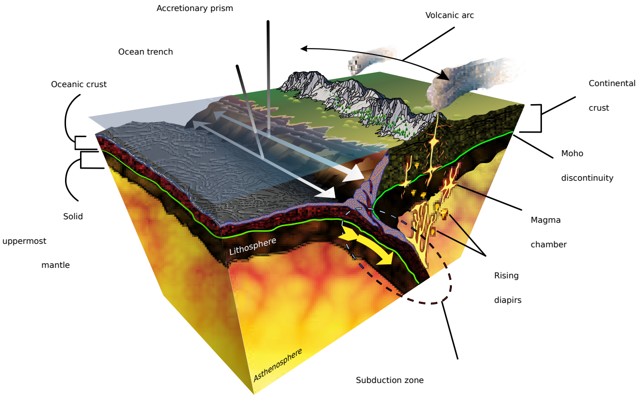
Decompression Melting

Magma is created at the mid-ocean ridge by decompression melting. The mantle is solid but is slowly flowing under enormous pressure and temperatures due to convection. Rock is not a good conductor of heat, so as mantle rock rises, the pressure is reduced along with the melting point (the green line), but the rock temperature remains about the same, and the rising rock begins to melt. Pressure changes instantaneously as the rock rises, but temperature changes slowly because of the low heat conductivity of rock. In the figure above, setting B: mid-ocean ridge shows a mass of mantle rock at a pressure-temperature X on the P-T diagram and its geographical location on the cross-section under a mid-ocean ridge. At this location, the P-T diagram shows the red arrow increasing to the right. Thus, hotter rock is now shallower, at a lower pressure, and the new geothermal gradient (red line) shifts past the solidus (green line) and melting starts. As this magma continues to rise at divergent boundaries and encounters seawater, it cools and crystallizes to form new lithospheric crust. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

Flux Melting

Another way that rocks melt is when volatile gases (e.g., water vapor) are added to mantle rock from a descending subducting slab in a process called flux melting (or fluid-induced melting). The subducting slab contains oceanic lithosphere and hydrated minerals. As the slab descends and slowly increases in temperature, volatiles are expelled from these hydrated minerals, like squeezing water out of a sponge. The volatiles then rises into the overlying asthenospheric mantle, which lowers the melting point of the peridotite minerals (olivine and pyroxene). The pressure and temperature of the overlying mantle rock do not change, but the addition of volatiles lowers the melting temperature. This is analogous to adding salt to an icy roadway. The salt lowers the melting/crystallization temperature of the solid water (ice) so that it melts. Another example is welders adding flux to lower the melting point of their welding materials.

Flux melting is illustrated in setting D: island arc (subduction zone) of the P-T diagram above. Volatiles added to mantle rock at location "Z" act as a flux to lower the melting temperature. This is shown in the P-T diagram by the solidus (green line) shifting to the left. The solidus line moves past the geothermal gradient (red line), and melting begins. Magmas producing the volcanoes of the Ring of Fire, associated with the circum-Pacific subduction zones, are a result of flux melting. As introduced in the minerals chapter, water ions can bond with other ions in the crystal structures of amphibole (and other silicates), which is essential in considering how magmas form in subduction zones by "flux melting." Such hydrated minerals in subducting slabs contribute water to the flux melting process. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)



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Magma Composition

In 1980, Mount St. Helens blew up in the costliest and deadliest volcanic eruption in United States history. The eruption killed 57 people, destroyed 250 homes, and swept away 47 bridges. Mount St. Helens today still has minor earthquakes and eruptions, and now has a horseshoe-shaped crater with a lava dome inside. The dome is formed of viscous lava that oozes into place.

It should first be noted that **magma** is molten material inside the earth, while **lava** is molten on the earth's surface. The reason for the distinction is because lava can cool quickly from the air and solidify into rock rapidly, while magma may never reach the earth's surface. Volcanoes do not always erupt in the same way. Each volcanic eruption is unique, differing in size, style, and composition of the erupted material. One key to what makes the eruption unique is the chemical composition of the magma that feeds a volcano, which determines (1) the eruption style, (2) the type of volcanic cone that forms, and (3) the composition of rocks that are found at the volcano.

Different minerals within rocks melt at different temperatures, and the amount of partial melting and the composition of the original rock determine the magma's composition. Magma collects in magma chambers in the crust at 160 kilometers (100 miles) beneath the surface of a volcano.

The words that describe the composition of igneous rocks also describe magma composition. Mafic magmas are low in silica and have darker magnesium, and iron-rich mafic minerals, such as olivine and pyroxene. Felsic magmas are higher in silica and have lighter colored minerals such as quartz and orthoclase feldspar. The higher the amount of silica in the magma, the higher is its viscosity. **Viscosity** is a liquid's resistance to flow.

Viscosity determines what the magma will do. **Mafic magma** is not viscous and will flow smoothly to the surface. **Felsic magma** is viscous and does not flow smoothly. Most felsic magma will stay deeper in the crust and will cool to form intrusive igneous rocks such as granite and granodiorite. If felsic magma rises into a magma chamber, it may be too viscous to move, and so it gets stuck. Dissolved gases become trapped by thick magma, and the magma chamber begins to build pressure.

Explosive Eruptions

The type of magma in the chamber determines the type of volcanic eruption. A massive explosive eruption creates even more devastation than the force of the atom bomb dropped on Nagasaki at the end of World War II, in which more than 40,000 people died. A massive explosive volcanic eruption is 10,000 times as powerful. Felsic magmas erupt explosively because of hot, gas-rich magma churning within its chamber. The pressure becomes so great that the magma eventually breaks the seal and explodes, just like when a cork is released from a champagne bottle. Magma, rock, and ash burst upward in an enormous explosion creating volcanic ash called **tephra**. It should be noted that when looked under a microscope, the volcanic "ash" is actual microscopic shards of glass. That is why it is so dangerous to inhale the air following an eruption.

"Volcanic Ash Dunes" is licensed under Creative Commons Attribution 4.0 International.

Scorching hot tephra, ash, and gas may speed down the volcano's slopes at 700 km/h (450 mph) as a pyroclastic flow. Pyroclastic flows knock down everything in their path. The temperature inside a pyroclastic flow may be as high as 1,000 degrees Celsius (1,800 degrees Fahrenheit). Before the Mount St. Helens eruption in 1980, the Lassen Peak eruption on May 22, 1915, was the most recent Cascade eruption. A column of ash and gas shot 30,000 feet into the air. This triggered a high-speed pyroclastic flow, which melted snow and created a volcanic mudflow known as a lahar. Lassen Peak currently has geothermal activity and could erupt explosively again. Mt. Shasta, the other active volcano in California, erupts every 600 to 800 years. An eruption would create a large pyroclastic flow, and probably a lahar. Of course, Mt. Shasta could explode and collapse like Mt. Mazama in Oregon.

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Volcanic gases can form toxic and invisible clouds in the atmosphere that could contribute to environmental problems such as acid rain and ozone destruction. Particles of dust and ash may stay in the atmosphere for years, disrupting weather patterns and blocking sunlight.

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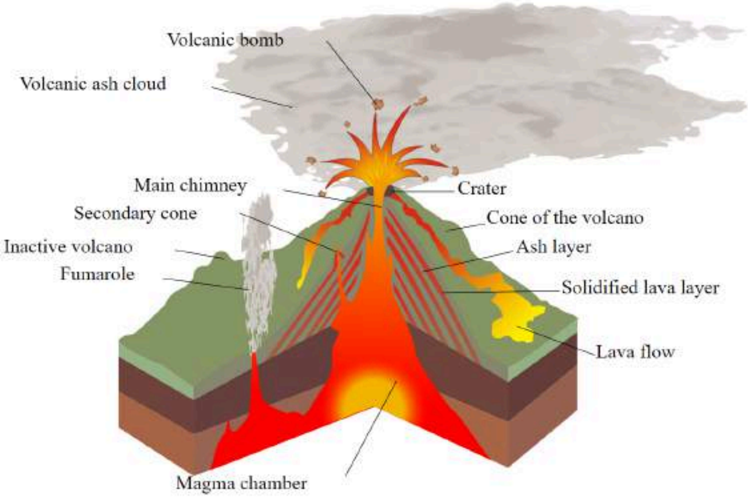
Effusive Eruptions

Mafic magma creates gentler effusive eruptions. Although the pressure builds enough for the magma to erupt, it does not erupt with the same explosive force as felsic magma. People can usually be evacuated before an effusive eruption, so they are much less deadly. Magma pushes toward the surface through fissures and reaches the surface through volcanic vents. Click here to view a lava stream within the vent of a Hawaiian volcano using a thermal camera.

Low-viscosity lava flows down mountainsides. Differences in composition and where the lavas erupt result in lava types like a ropy form **pahoehoe** and a chunky form called **aa**. Although effusive eruptions rarely kill anyone, they can be destructive. Even when people know that a lava flow is approaching, there is not much anyone can do to stop it from destroying a building, road, or infrastructure.

"Pahoehoe Lava" is licensed under Creative Commons Attribution-ShareAlike 4.0 International.

Volcano Features and Types



"Volcano Structure" is licensed under Creative Commons Attribution-ShareAlike 4.0 International.

A **volcano** occurs where lava erupts at the surface and solidifies into rock. There are several types of volcanoes based on their shape, eruption style, magmatic composition, and other aspects. The most massive craters are called a caldera, such as the Crater Lake Caldera in Oregon. Many volcanic features are produced by viscosity, a fundamental property of lava. Viscosity is the resistance to flowing by a fluid. Low viscosity magma flows easily more like syrup, the basaltic volcanism that occurs in Hawaii on shield volcanoes. High viscosity means a sticky magma, typically felsic or intermediate, that flows slowly, like toothpaste. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

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Shield Volcanoes

The largest volcano is a **shield volcano** and is characterized by broad, low-angle flanks, a small vent, or groups of vents at the top, and basaltic magma. The name "shield" comes from the side view resembling a medieval warrior's shield. They are typically associated with hotspots, midocean ridges, or continental rifts where upper mantle material rises, and build up slowly from many low-viscosity basaltic lava flows that can travel long distances, hence making the low-angle flanks. Because the magma is basaltic and low viscosity, the eruption style is not explosive but rather effusive, meaning that volcanic eruptions are small, localized, and predictable. Therefore, this eruption style is not typically much of a hazard.

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Mauna Loa (info) and the more active Kilauea (info) in Hawaii are good examples of vents on a shield volcano. The eruption of Kilauea from fissures in Hawaii in 2018, while not explosive, produced viscous lavas that did considerable damage to roads and structures. Shield volcanoes are also found in Iceland, the Galapagos Islands, Northern California, Oregon, and the East African Rift (USGS, 2011).

"Hawaiian Islands" by NASA's Earth Observatory is licensed under Public Domain.

Basaltic magma can form several rock types and unique landforms. Based on magma temperature, composition, and content of dissolved gases and water vapor, there are two main types of basaltic volcanic rocks with Hawaiian names – pahoehoe and aa. Pahoehoe is a basaltic magma that flows smoothly into a "ropey" appearance. In contrast, aa (sometimes spelled a'a or ʻaʻā and pronounced "ah-ah") has a crumbly blocky appearance. (Peterson and Tilling 1980). Felsic silica-rich lavas also form aa flows.

In **basaltic lava flows**, the low viscosity lava can smoothly flow, and it tends to harden on the outside but continue to flow internally within a tube. Once the interior flowing lava subsides, the tube may be left as an empty lava tube. Lava tubes famously make caves (with or without collapsed roofs) in Hawaii, Northern California, the Columbia River Basalt Plateau of Washington and Oregon, El Malpais National Monument in New Mexico, and Craters of the Moon National Monument in Idaho. Fissures, cracks that originate from shield-style eruptions, are also common. Magmas from fissures are typically very fluid and mafic. The volcanic activity itself causes some fissures, and some can be influenced by tectonics, such as the common fissures parallel to the divergent boundary in Iceland. See above for fissure flows from Kilauea in 2018.

Since basalt flows are thick accumulations of lava with a homogeneous composition that flows quickly when the lava begins to cool, it can contract into columns with a hexagonal cross-section called columnar jointing. This feature is common in basaltic lava flows but can be found in more felsic lavas and tuffs. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

Cinder Cones

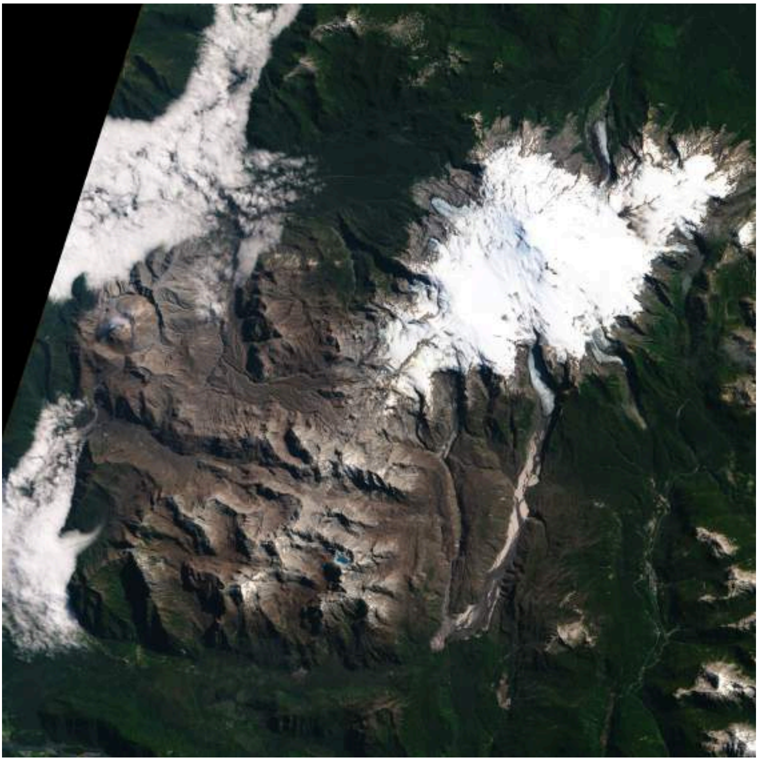
Cinder cones are small volcanoes with steep sides, made of cinders and volcanic bombs ejected from a clear central vent. Typically, they come from mafic lavas that have high volatile content. Cinders form when hot lava is ejected into the air, cooling and solidifying before they reach the flank of the volcano. The largest cinders are called volcanic bombs. Cinder cones form in short-lived eruption events that are common in the western United States.

A recent and striking example of a short-lived cinder cone is the 1943 eruption near Parícutin, Mexico. The cinder cone started with an explosive eruption shooting cinders out of a vent in the middle of a farmer's field. Quickly, volcanism continued building the cone to a height of over 300 feet in a week and 1,200 feet in the first eight months. After the initial explosive gases and cinders were released, growing the cone, basaltic lava poured out around the base of the cone. This order of events is typical for cinder cones: first violent eruption, then the formation of cone and crater, followed by a low-viscosity lava flow from the base (the cone of cinders is not strong enough to support a column of lava rising to the top of the crater). The Parícutin cinder cone was built over nine years and covered about 100-square miles with ashes and destroyed the town of San Juan.

"Groundhog Cinder Cone" by the United States Department of Agriculture is licensed under Public Domain.

Lava Domes

Lava domes are a relatively small accumulation of silica-rich volcanic rocks, such as rhyolite and obsidian, that is too viscous to flow, and therefore, pile high close to the vent. The domes often form within the collapsed crater of a stratovolcano near the vent and grow by expansion from within. As it grows, its outer surface cools and hardens, then shatters, spilling loose fragments down its sides. An excellent example of a lava dome is inside of a collapsed stratovolcano crater is Mount Saint Helens. Examples of a stand-alone lava dome are Chaiten in Chile and the Mammoth Mountain in California. (Volcanoes: Principal Types of Volcanoes, n.d.)



"Chaiten Volcano Lava Dome, Chile" by NASA's Earth Observatory is licensed under Public Domain.

Composite Volcanoes

Composite volcanoes, also called **stratovolcanos**, has steep flanks, a symmetrical cone shape, a distinct crater, and rises prominently above the surrounding landscape. The figure at the beginning of this section shows a stratovolcano. Examples include Mount Rainier in the Cascade Range in Washington and Mount Fuji in Japan. Stratovolcanoes can have magma with felsic to mafic composition. However, felsic to intermediate magmas are most common. The term "composite" refers to the alternating layers of pyroclastic materials (like ash) and lava flows. The viscous nature of the intermediate and felsic magmas in subduction zones results in steep flanks and explosive eruption styles. Stratovolcanoes are made of alternating lava flows and ash. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

"Mount Rainier and the Emmons Glacier" by the National Park Service is licensed under Public Domain.

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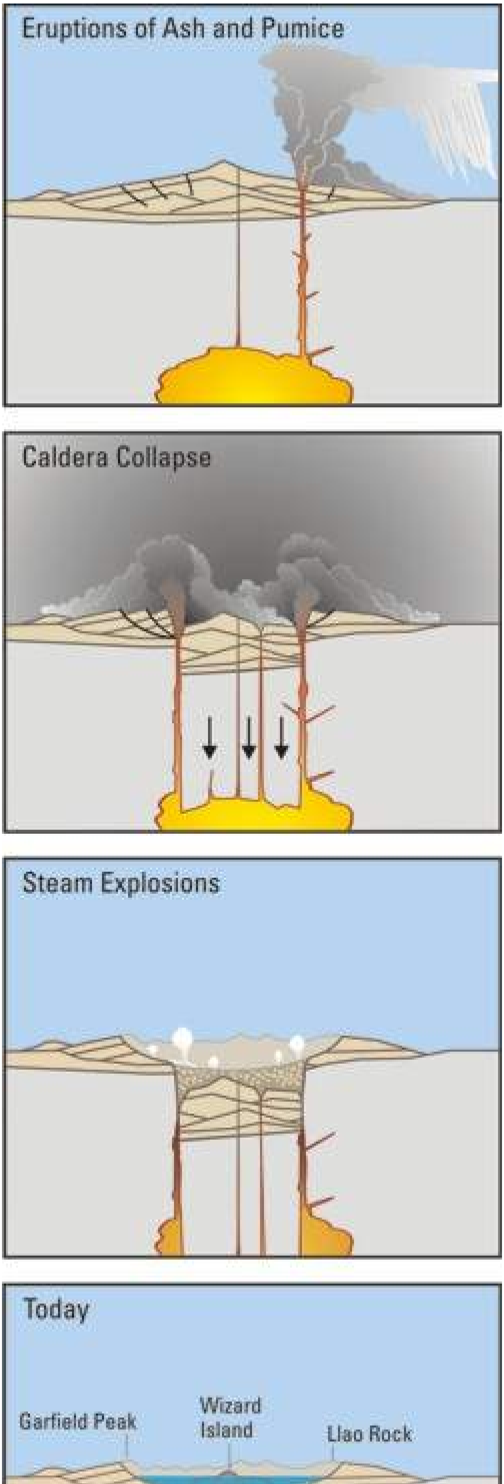
Calderas

Calderas are generally large (some up to 15 miles in diameter), steep-walled, basin-shaped depressions formed by the collapse of a volcanic edifice into an emptying magma chamber and although the word caldera only refers to the vent, many use calderas as a volcano type, typically formed by high-viscosity felsic volcanism with high volatile content. Crater Lake, Yellowstone, and Long Valley Caldera are good examples. At Crater Lake National Park in Oregon, about 6,800 years ago, Mount Mazama was a composite volcano that erupted in a sizeable explosive blast, ejecting massive volcanic ash. The eruption rapidly drained the underlying magma chamber causing the top to collapse into it, forming a significant depression that later filled with water. Today a resurgent dome is found rising through the lake as a cinder cone, called Wizard Island.


Eruptions of Ash and Pumice
Caldera Collapse
Steam Explosions
Today
Garfield Peak
Wizard Island
Llao Rock

"Mount Mazama Eruption" by the United States Geologic Survey is licensed under Public Domain.

"Crater Lake" is licensed under Creative Commons Attribution-ShareAlike 3.0 Unported.

Flood Basalts

A rare volcanic eruption type, unobserved in modern times, is the flood basalt. **Flood basalts** are some of the largest and lowest viscosity types of eruptions known. They are not known from any eruption in human history, so the exact mechanisms of eruption are still debatable. Some famous examples include the Columbia River Flood Basalts in Washington, Oregon, and Idaho, the Deccan Traps, which cover about 1/3 of the country of India, and the Siberian Traps, which may have been involved in the Earth's most massive mass extinction at the end of the Permian. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

Supervolcanoes

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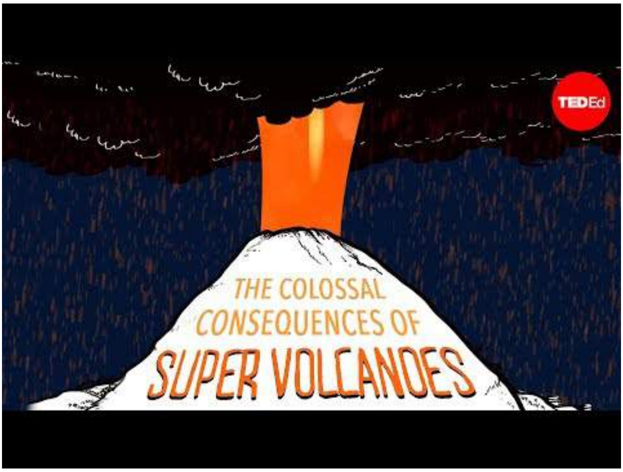
The Yellowstone caldera erupted three times in the recent past, at 2.1, 1.3, and 0.64 million years ago. Each eruption created large rhyolite flows and pyroclastic clouds of ash that solidified into tuff. These extra-large eruptions rapidly emptied the magma chamber causing the roof to collapse and form a caldera. Three calderas are still preserved from these eruptions, and most of the roads and hotels of Yellowstone National Park are located within the caldera. Two resurgent domes are located within the last caldera.



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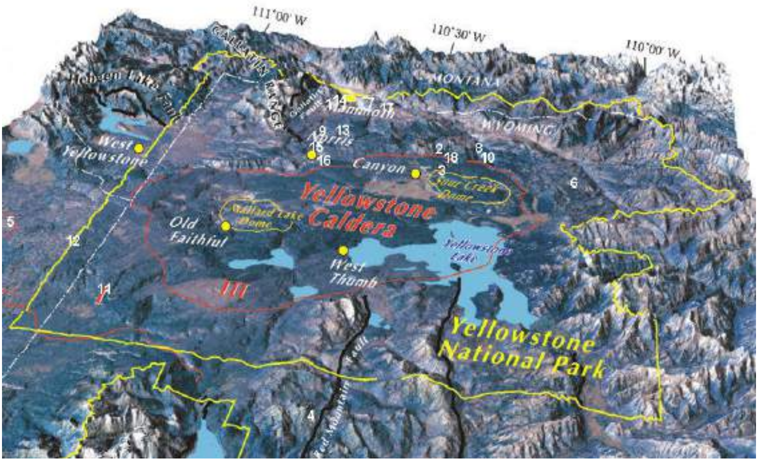
Yellowstone volcanism started as a hot spot under the North American lithosphere about 17-million years ago near the Oregon/Nevada border. As the North American plate slid southwestward over the stationary hotspot, surface volcanism followed and helped form Idaho's Snake River Plain, eventually arriving at its current location in northwestern Wyoming. As the plate moved to the southwest over the stationary hotspot, it left a track of past volcanic activities.



"Yellowstone Relief Map" by the United States Geologic Survey is licensed under Public Domain.

The Long Valley Caldera near Mammoth California is a massive explosive volcano that erupted 760,000 years ago and dumped a significant amount of ash throughout the United States, similar to the Yellowstone eruptions. This ash formed the large Bishop Tuff deposit. Like the Yellowstone caldera, the Long Valley Caldera contains the town of Mammoth Lakes, a major ski resort, an airport, and a major highway. Further, there is a resurgent dome in the middle and active hot springs. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

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Distribution of Volcanic Activity

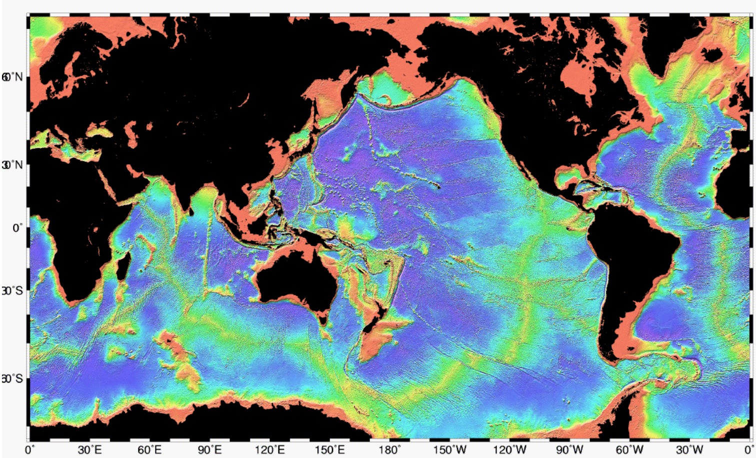
Most volcanoes are located at active plate boundaries called **interplate volcanism**. The prefix "inter-" means "between." In contrast, some volcanoes are not associated with plate boundaries but are found within the plate far from plate boundaries. These are called intraplate volcanoes, and hotspots and fissure eruptions form many. The prefix "intra-" means "within." The following discusses volcanism's location in more detail with mid-ocean ridges, subduction zones, continental rifts representing interplate volcanism, and hot spots representing intraplate volcanism.

Volcanoes along Mid-Oceanic Ridges

Although most volcanism occurs on the ocean floor along the mid-ocean ridge (a type of divergent plate boundary), they are the least observed since most are under 10,000 to 15,000 feet of ocean, an exception being Iceland. As the oceanic plates diverge and thin, hot mantle rock is allowed to rise, pressure from depth is released, which causes the ultramafic mantle rock (peridotite) to melt partially. The resulting magma is basaltic in composition based on the concept of partial melting discussed earlier. Because most volcanoes on the ocean floor are basaltic, most of the oceanic lithosphere is also basaltic near the surface with phaneritic gabbro and ultramafic peridotite forming underneath. Icelandic volcanism is an example of this, but lying above sea level.

An underwater volcanic eruption occurs when basaltic magma erupts underwater, forming **pillow basalts** or in small explosive eruptions. Lava erupting into seawater forms pillow-shaped structures, hence the name. In association with these seafloor eruptions, an entire underwater ecosystem thrives in parts of the mid-ocean ridge. This ecosystem exists around tall vents emitting black, hot mineral-rich water called **deep-sea hydrothermal vents** (also known as **black smokers**).

This hot water, up to 380 degrees Celsius (716 degrees Fahrenheit), is heated by the magma and dissolves many elements that support the ecosystem. Deep underwater where the sun cannot reach, this ecosystem of organisms depends on the heat of the vent for energy and vent chemicals as its foundation of life called **chemosynthesis**. The foundation of the ecosystem is hydrogen sulfide-oxidizing bacteria that live symbiotically with the larger organisms. Hydrogen sulfide (H2S, the gas that smells like rotten eggs) needed by these bacteria is contained in the volcanic gases emitted from the hydrothermal vents. The source of most of this sulfur and other elements is the Earth's interior. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)



"Mid-Ocean Ridge System" by the National Oceanic and Atmospheric Administration is licensed under Public Domain.

Volcanoes along Convergent Boundaries

Volcanoes are a vibrant manifestation of plate tectonics processes. Volcanoes are common along convergent and divergent plate boundaries but are also found within lithospheric plates away from plate boundaries. Wherever mantle can melt, volcanoes may be the result. Volcanoes erupt because mantle rock melts. The first stage in creating a volcano is when mantle rock begins to melt because of scorching temperatures, lithospheric pressure lowers, or water is added.

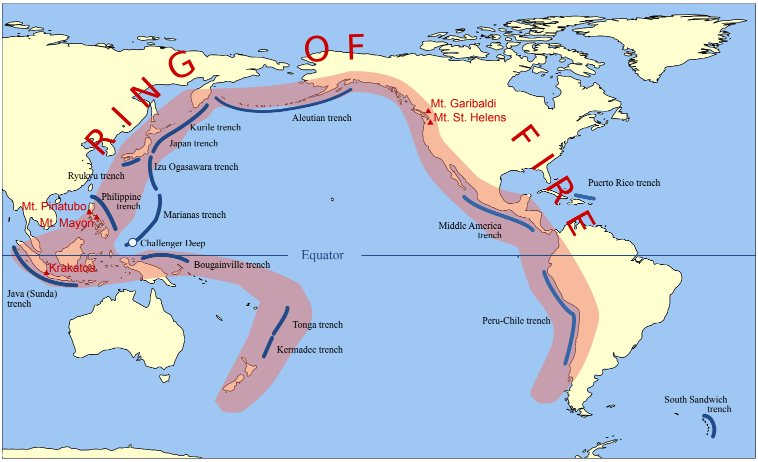
Subduction Zones

During the process of **subduction**, water is expelled from the hydrated minerals causing partial melting by flux melting in the overlying mantle rock. This creates a mafic magma that rises through the lithosphere and can change the composition by interacting with surrounding continental crust as well as by magma differentiation. These changes then evolve basaltic magma into a more silica-rich rock in volcanoes and plutons. These silica-rich rocks are felsic to intermediate rocks such as andesite, rhyolite, pumice, and tuff. The **Ring of Fire** surrounding the Pacific Ocean is dominated by subduction and contains volcanoes with silica-rich magma. These volcanoes are discussed in more detail in the stratovolcano section.

Large earthquakes are prevalent along convergent plate boundaries. Since the Pacific Ocean is rimmed by convergent and transform boundaries, 80 percent of all earthquakes occur around the Pacific Ocean basin, called the Ring of Fire. A description of the Pacific Ring of Fire along western North America is below:

- Subduction at the Middle American Trench creates volcanoes in Central America.
- The San Andreas Fault is a transform boundary.
- Subduction of the Juan de Fuca plate beneath the North American plate creates the Cascade volcanoes like Mount St. Helens, Mount Rainer, Mount Hood, and more.

- Subduction of the Pacific plate beneath the North American plate in the north creates the long chain of the Aleutian Islands volcanoes near Alaska.



"Pacific Ring of Fire" is licensed under Public Domain.

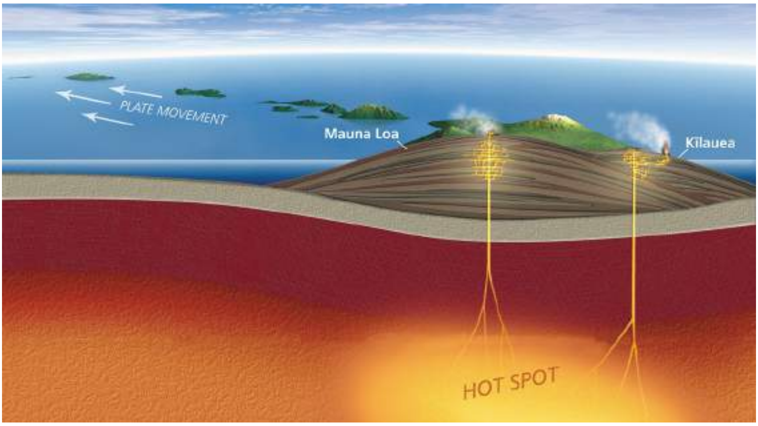
Continental Rifts

In addition to volcanoes at the mid-ocean ridge and subduction zones, some volcanoes are at **continental rifts**, where the lithosphere is diverging and thinning, such as in the Basin and Range Province in North America and the East African Rift Basin in Africa. The thinning allows for some of the lower crustal rocks or upper mantle rocks to rise, releasing some pressure and causing partial melting. The magma generated is less dense than the surrounding rock and rises through the crust to the surface, erupting as basalt. These basaltic eruptions are usually in the form of flood basalts, cinder cones, and basaltic lava flows. For example, young cinder cones are found in south-central Utah, the Black

Rock Desert Volcanic Field, which is part of the Basin and Range crustal extension. The 1-minute video (below) illustrates volcanism in the Basin and Range Province. These Utah cinder cones and lava flows started erupting 6 million years ago with the last volcanic eruption 720 years ago. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

Hotspots

The primary source of intraplate volcanism is hotspots. **Hotspots** occur when lithospheric plates glide over a hot mantle plume, an ascending column of hot rock (solid, not magma) originating from deep within the mantle. A chain of ancient volcanoes formerly active but now inactive for millions of years can be seen on the seafloor or on continents, which leads to an active intraplate volcano, indicating hotspot volcanism. The Pacific oceanic plate overrode a hotspot mantle plume producing a long volcanic island chain beginning with the Emperor Seamounts in the northwest Pacific and terminating at the Hawaiian Islands with currently active volcanoes. When the North American continental plate overrode a mantle plume hotspot, a chain of ancient volcanic calderas formed extending from Southwestern Idaho to the Yellowstone caldera. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)



"Hawaiian Hot Spot" by the National Park Service is licensed under Public Domain.

Once the ascending magma reaches the lithosphere, it spreads out into a mushroom-shaped head that is tens to hundreds of kilometers across. Think of the Bowen's Reaction Series and the temperatures of the magmas that contain the respective minerals. If hot mafic magma rises beneath felsic continental crust spreads into a head below the felsic boundary, the higher heat of the mafic magma may cause the felsic rock above it to melt. There may be mixing of the mafic material from below with the felsic above to form intermediate magmas, or the felsic magma may melt and rise higher, forming granitic batholiths or even emerging as a felsic volcano. Such felsic (granitic) batholiths lie at the core of the Sierra Nevada Mountains and comprise Yosemite's dramatic features. Since most mantle plumes are beneath the oceanic lithosphere, volcanism's initial stages typically take place on the seafloor. Over time, basaltic volcanoes may form islands like those in Hawaii. If the hotspot is under the continental lithosphere, magma of more felsic to intermediate (silica-rich) composition rises into an explosive volcano like Mt. St. Helens or the Yellowstone caldera.

4.6 PREDICTING ERUPTIONS AND RISK

Predicting Volcanic Eruptions

Volcanologists try to forecast volcanic eruptions, but this has proven to be as difficult as predicting an earthquake. Many pieces of evidence can mean that a volcano is about to erupt, but the time and magnitude of the eruption are challenging to pin down. This evidence includes the history of previous volcanic activity, earthquakes, slope deformation, and gas emissions. (Volcanic Eruptions | Earth Science, n.d.)

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History of Volcanic Activity

A volcano's history, how long since its last eruption and the period between its previous eruptions, is an excellent first step to predicting eruptions. If the volcano is considered active, it is currently erupting or shows signs of erupting soon. A dormant volcano means there is no current activity, but it has erupted recently. Finally, an extinct volcano means there is no activity and will probably not erupt again. Active and dormant volcanoes are heavily monitored, especially in populated areas. (Volcanic Eruptions | Earth Science, n.d.)

Earthquakes

Moving magma shakes the ground, so the number and size of earthquakes increase before an eruption. A volcano that is about to erupt may produce a sequence of earthquakes. Scientists use seismographs that record each earthquake's length and strength to determine if an eruption is imminent.

Magma and gas can push the volcano's slope upward. Most ground deformation is subtle and can only be detected by tiltmeters, which are instruments that measure the angle of a volcano's slope. However, ground swelling may sometimes create considerable changes in the shape of a volcano. Mount St. Helens grew a bulge on its north side before its 1980 eruption. Ground swelling may also increase rockfalls and landslides. (Volcanoes | Earth Science, n.d.)

Gas Emissions

Gases may be able to escape a volcano before magma reaches the surface. Scientists measure gas emissions in vents on or around the volcano. Gases, such as sulfur dioxide (SO2), carbon dioxide (CO2), hydrochloric acid (HCl), and even water vapor, can be measured at the site or, in some cases, from a distance using satellites. The amounts of gases and their ratios are calculated to help predict eruptions. (Volcanoes | Earth Science, n.d.)

Remote Monitoring

Some aspects of volcanic monitoring can be monitored using satellite technology. Satellites also monitor temperature readings and deformation. As technology improves, scientists are better able to detect changes in a volcano accurately and safely. Since volcanologists are usually uncertain about an eruption, officials may not know whether to require evacuation. If people are evacuated, and the eruption does not happen, the people will be displeased and less likely to evacuate the next time there is a threat of an eruption. The costs of disrupting business are high. However, scientists continue to work to improve the accuracy of their predictions.

Volcanic Hazards

Volcanoes are responsible for a large number of deaths. Volcanic hazards have been famous for centuries, but recent eruptions are better documented. The most apparent hazard is the lava itself within a lava flow, but volcanic hazards go far beyond a lava flow. For example, on May 18, 1980, Mount Saint Helens erupted with an explosion and landslide that removed the upper 1,300 feet (400 m) of the mountain. This explosion was immediately followed by a lateral blast and pyroclastic flow [23] covering 230 square miles of forest with ash and debris. The effects of the blast are shown on the before and after images. The pyroclastic flow (see below) moved at speeds of 50 – 80 miles per hour (80-130 km/hr), flattened trees, and ejected a giant ash cloud into the air. Watch the 7-minute USGS video for an account of May 18, 1980, which killed 57. Pyroclastic flows are common in explosive eruptions of stratovolcanoes.

In 79 AD, Mount Vesuvius, located near Naples, Italy, violently erupted, sending a pyroclastic flow over the Roman countryside, including the cities of Herculaneum and Pompeii. The buried towns were discovered in an archeological expedition in the 18th century. Pompeii famously contains the remains (casts) of people suffocated by ash and covered by 10 feet (3 m) of ash, pumice lapilli, and collapsed roofs. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

Pyroclastic Flows

The most dangerous volcanic hazard are **pyroclastic flows**. These flows are a mix of lava blocks, pumice, ash, and hot gases between 400 to 1,300 degrees Fahrenheit. The turbulent cloud of ash and gas races down the steep flanks at high speeds up to 120 mph (much faster than people can run) into the valleys around composite volcanoes. Most explosive, silica-rich, high viscosity magma volcanoes such as composite cones usually have pyroclastic flows. The rock tuff and welded tuff is often formed from these pyroclastic flows.

There are numerous examples of deadly pyroclastic flows. In 2014, the Mount Ontake pyroclastic flow in Japan killed 47 people. The flow was caused by magma heating groundwater into steam, which then rapidly ejected with ash and volcanic bombs. Some were killed by inhalation of toxic gases and hot ash, while volcanic bombs struck others. Two short videos below document the eyewitness video of pyroclastic flows. In the early 1990s, Mount Unzen erupted several times with pyroclastic flows. The pyroclastic flow shown in this short video killed 41 people. In 1902, on the Caribbean Island Martinique, Mount Pelee erupted with a violent pyroclastic flow that destroyed the entire town of St. Pierre and killing 28,000 people in moments. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

“Pyroclastic Flow at Mayon Volcano” by the United States Geologic Survey is licensed under Public Domain.

Lahars

A **lahar** is an Indonesian word for a mudflow that is a mixture of water, ash, rock fragments, and other debris moving down the flanks of a volcano (or other nearby mountains covered with freshly-erupted ash) and entering adjacent river valleys. They form from the rapid melting of snow or glaciers on volcanoes. They are like a slurry of concrete but can flow up to 50 mph while still on the steep flanks. Since lahars are slurry-like, they can travel long distances in river valleys like a flash flood.

During the 1980 Mount St. Helens eruption, lahars reached 17-miles (27 km) down the North Fork of the Toutle River.

Prehistoric lahar flows have been mapped at significant vol-canoes such as Mount Rainier near Tacoma, Washington (Rosi et al. 1999). Prehistoric lahars occupied river floodplains where large cities are found today, as shown on the map. Similarly, Mount Baker poses a hazard as shown by this hazard map for Mount Baker north of Seattle, Washington. A recent scenario played out when a lahar from the volcano Nevado del Ruiz Colombia, buried a town in 1985 and killed an estimated 25,000 people.

"Lahar off Mount St. Helens" by the United States Geologic Survey is licensed under Public Domain.

Landslides and Landslide-Generated Tsunamis

The flanks of a volcano are steep and unstable, which can lead to slope failure and generate dangerous landslides. For example, the landslide at Mount St. Helens 1980 released a considerable amount of materials as the entire north flank collapsed. The landslide moved at speeds of 100-180 mph. Movement of magma, explosive eruptions, massive earthquakes, and heavy rainfall can trigger these landslides. In unique situations, the landslide material can reach water and cause a tsunami. In 1792 in Japan, Mount Unzen erupted, causing a giant landslide that reached the Ariake Sea and made a tsunami that killed 15,000 people on the opposite shore.

Tephra and Ash

Volcanoes, mainly composite volcanoes, eject substantial amounts of **tephra** (ejected rock materials) and ash (fragments less than 2 mm or 0.08 inches. Tephra is heavier and falls closer to the vent. Larger blocks and bombs pose hazards to those close to the eruption, such as at the 2014 Mount Ontake disaster in Japan discussed earlier. **Ash** is fine and can be carried long distances away from the vent, and can cause building collapses and respiratory issues like silicosis. Hot ash can be dangerous to those close to the eruption and disrupt services such as airline transportation farther away. For example, in 2010, the Eyjafjallajökull volcano in Iceland created a giant ash cloud in the upper atmosphere that caused the most significant air travel disruption in northern Europe since a seven-day airline shut down during World War II. No one was hurt, but the cost to the world economy was estimated to be billions of dollars. (4 Igneous Processes and Volcanoes – An Introduction to Geology, n.d.)

"Ash Plume from Mount Cleveland" by NASA's Earth Observatory is licensed under Public Domain.

Volcanic Gases

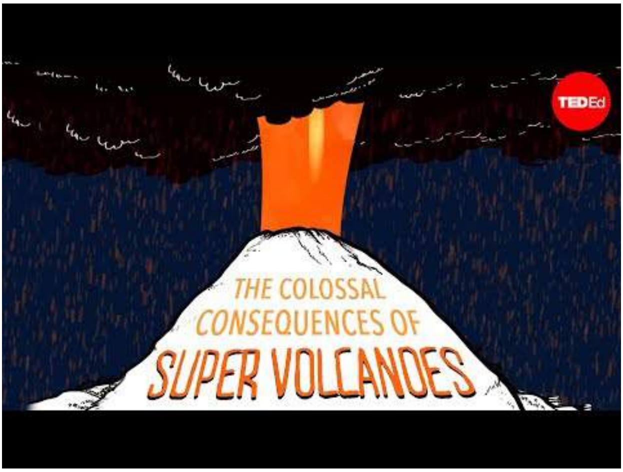
Magma contains dissolved gases. As rising magma reaches the surface, the confining pressure decreases, allowing gases to escape, like gases coming out of solution after opening a soda bottle. Therefore, volcanoes, when not erupting, release hazardous gases such as carbon dioxide (CO2), sulfur dioxide (SO2), hydrogen sulfide (H2S), and hydrogen halides (HF, HCl, or HBr). Carbon dioxide can sink and accumulate in low-lying depressions on the earth's surface. Mammoth Mountain Ski Resort in Mammoth Lakes, California, is located within the Long Valley Caldera. Therefore, the whole ski resort and town are within the caldera. In 2006, three ski patrol members were killed after skiing into snow depressions near fumaroles filled with carbon dioxide (info).

Therefore, in volcanic areas where carbon dioxide emissions occur, avoid low-lying areas that may trap carbon dioxide.

In rare cases, a volcano can suddenly release gases without warning. Called a **limnic eruption**, this commonly occurs in crater lakes as gases pour from the water. It infamously occurred in 1986 in Lake Nyos, Cameroon, killing almost 2,000 people due to carbon dioxide asphyxiation.

Volcanic Monitoring

Volcano monitoring requires geologists to use many instruments to detect changes that may indicate an eruption is imminent. Some of the main observations include regular monitoring for earthquakes (including unique vibrational earthquakes called harmonic tremors, caused by magma movement), changes in the orientation and elevation of the land surface, and an increase in gas emissions.



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Volcanic Landforms and Geothermal Activity

Volcanic Landforms and Vents

Volcanoes are associated with many types of landforms. The landforms vary with the composition of the magma that created them. Hot springs and geysers are also examples of surface features related to volcanic activity.

The most apparent landforms created by lava are volcanoes, most commonly as cinder cones, composite volcanoes, and shield volcanoes or eruptions that take place through fissures. The eruptions that created the entire ocean floor are fissure eruptions. Magma intrusions ALSO can create landforms. The image on the right is of Shiprock in New Mexico, which is the neck of an old volcano that has eroded.

Lava Domes

When lava is viscous, it flows slowly. If there is not enough magma or enough pressure to create an explosive eruption, the magma may form a **lava dome**. However, because the magma's viscosity is so thick, the lava does not flow far from the volcanic vent. Lava flows often make mounds right in the middle of craters at the top of volcanoes.

Lava Plateaus and Land

A **lava plateau** forms when enormous amounts of fluid lava flow over an extensive area. When the lava solidifies, it creates a large, flat surface of the igneous rock. Lava creates new land as it solidifies on the coast or emerges from beneath the water. Over time the eruptions can create whole islands. The Hawaiian Islands are formed from shield volcano eruptions that have grown over the last 5 million years.

Hot Springs and Geysers

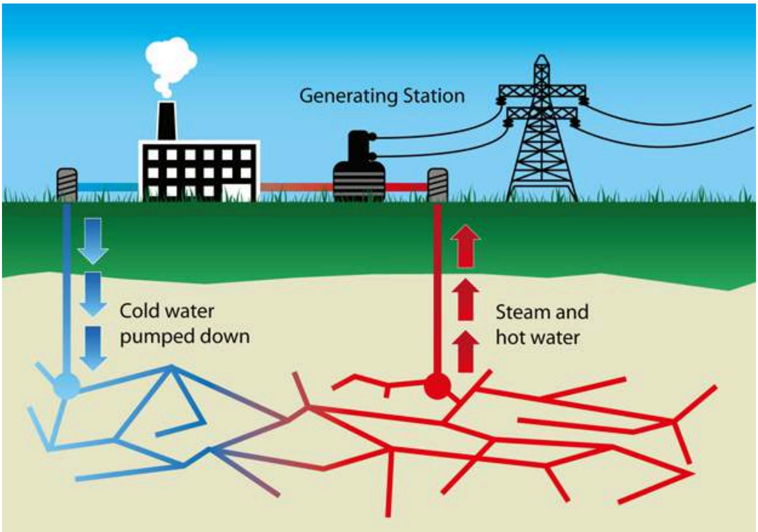
Water sometimes encounters the hot rock. The water may emerge at the surface as either a **hot spring** or a **geyser**. Water heated below ground that rises through a crack to the surface creates a hot spring. The water in hot springs may reach temperatures in the hundreds of degrees Celsius beneath the surface, although most hot springs are much cooler.

Benefits of Volcanic Activity

There are many benefits to volcanic activity. One of the significant benefits is the fact that volcanic activity can create very fertile soil for agriculture. The problem is that many civilizations developed near volcanoes for this reason – with sometimes deadly effects. Volcanic activity can also create many mineral resources such as gold, silver, nickel, copper, and lead. Volcanic rock is often used for landscaping, tile, and cement.

Some of the most amazing landscapes are near volcanoes because volcanic activity builds land creating, breathtaking scenery. Volcanoes are economically vital for many regions because of the recreational activity and tourism they bring.

Finally, a new but essential trend is **geothermal power**. The heat generated by volcanoes can create electricity to power civilization. Geothermal power is an entirely renewable resource free of pollution and energy dependence from fossil fuels. Iceland – the surface manifestation of the mid-Atlantic ridge – has a goal of powering the entire nation on geothermal energy. Geothermal energy is also being used in California, Kilauea, Hawaii, and now Utah.



“Geothermal Energy” is licensed under Creative Commons Attribution-ShareAlike 4.0 International.

“Nesjavellir Power Station in Southwest Iceland” is licensed under Public Domain.

4.7 TSUNAMIS

Most people never thought much about tsunamis until the cataclysmic event that occurred on December 26, 2004, in Indonesia. **Tsunami** is a Japanese term that means “harbor wave”. There are four significant ways tsunamis form: underwater earthquakes, volcanic eruptions, landslides, or extraterrestrial impacts such as asteroids. These four seismic events will be looked at in greater detail in a minute. The formation of a tsunami by these catastrophic events is called **tsunami initiation**.

“Aerial of Sukuiso, Japan” by the United States Navy is licensed under Public Domain.

Now once a tsunami is generated, it will travel outward in a circular radius from the tsunami epicenter at speeds of 500 mph. However, the height of each wave crest in the deep ocean is only 2-3 feet; thus, large ships never feel tsunamis in the deep ocean. It is essential to stop here and briefly discuss the physics of energy traveling through water. First, a wave of water is called a wave – that was easy! Next, the distance between two wave peaks or heights is called a **wavelength**. The frequency is when it takes one wavelength (distance between two wave peaks) to pass a given position. Thus, waves with long wavelengths have low frequencies because it takes a long time for the wave to cross a given point. Waves that have short wavelengths have high frequencies.

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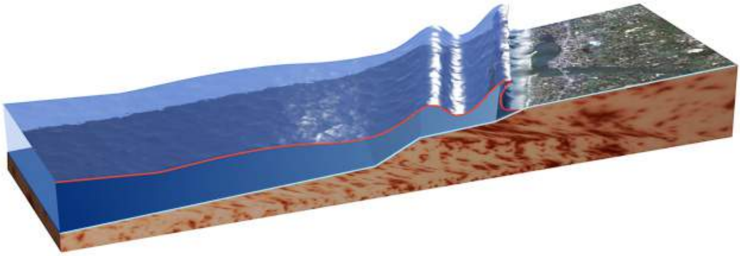
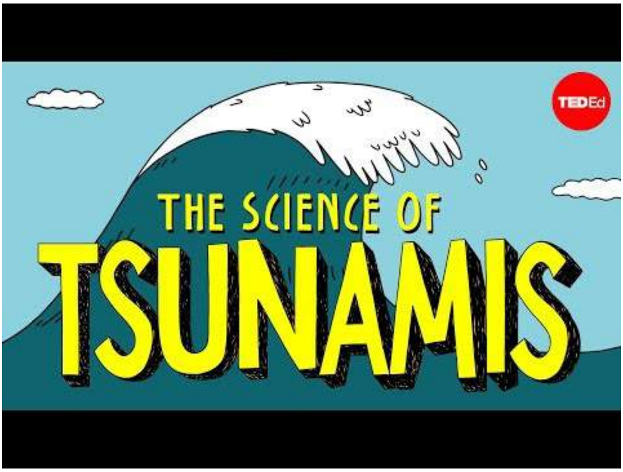
Have you ever watched an object floating in the water as a wave passes by it? Let's say it is a stick in the ocean. Now when that wave passes by, the stick does not travel with the wave; rather, the stick bops up and down but stays relatively in the same place. That is because the water does not travel with the wave's energy; instead, the energy passes through the water causing the water to travel in a circle (which appears as an up, slightly forward, down, and backward motion). The depth of the circular size of motion generated by waves is half the distance from each wave crest. Thus if the distance from one wave crest to the next wave crest is one mile, the depth of the water's circular motion is half a mile. This is important because tsunamis have very long wavelengths; thus, their depths reach the ocean floor.

It was noted above that the height of a tsunami is only a few feet high with very long wavelengths out in the deep ocean. This is because in the deep water, the amplitude of the waves is minimal, and the wavelengths quite large for anyone on a boat to notice. As the tsunami approaches the shoreline, it begins to slow down and grow taller because the friction between the oscillating tsunami waves comes into more contact with the rising elevation of the seafloor. This friction causes the wave's amplitude to grow, the wavelength shortens (distance between each successive tsunami wave), and the frequency becomes shorter, causing the energy of the tsunami to grow taller. The height of a tsunami is called the **run-up**. Thus when a tsunami reaches the shore, it may have slowed to 30-40 mph but dramatically higher. The size of the run-up is determined by the distance between the tsunami epicenter and the shoreline, the energy released by the tsunami initiation, and the steepness of the continental slope.



"Tsunami" is licensed under Creative Commons Attribution-ShareAlike 3.0 Unported.

Tsunamis are also not a massive, single wave coming ashore; rather, they are a series of powerful, rippling waves called a **tsunami train**. As the waves approach shore, the shoreline frequently disappears as the water is pulled back into the ocean to build up the waves. Many people find this strange event enticing and go onto the beach to see the fish flapping on the newly bare ground. However, this is a false sense of security, and within minutes the series of waves come crashing ashore. Often, there can be up to ten individual tsunami waves, and the most powerful waves tend to be the second or third wave. So if the water along the coastline disappears, people need to quickly gather their family and friends and head to higher ground.



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Formation of a Tsunami

Earthquakes

Most tsunamis occur because of powerful subduction zone such as the Ring of Fire. Thus, most tsunamis are generated by a reverse fault or thrust fault earthquakes along subduction zones because of the amount of water displaced by these events. However, not all reverse fault earthquakes can initiate tsunamis. The minimum magnitude of an earthquake needed to create a tsunami is a 7.5; the Asian tsunami of 2004 was generated by a 9.1 magnitude thrust fault along an oceanic-to-oceanic subduction zone. Strike-slip faults along transform boundaries do not generate tsunamis because their parallel movement does not displace enough water.

The potential for a tsunami striking the United States is very high for a variety of reasons. One is because of the oceanic-to-continental subduction zone in the northwestern states of Washington, Oregon, and northern California. Recall from previous modules that this subduction zone generates earthquakes, but has produced the major volcanoes of the region such as Mount St. Helens, Mt. Rainer, and Mt. Shasta. Research shows that ever few hundred years, the region experiences a 9.0 magnitude earthquake generating a significant tsunami that would reach coastal cities within 20 minutes. There would be no time to evacuate the people in time.

The Great East Japan Earthquake of 2011 was the most documented natural disaster in human history.

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Volcanoes

Less common, but still a force to consider, are large, violent, composite volcanoes. There are a couple of ways a volcano can generate a tsunami. Sometimes just the energy released by the volcano along with the pyroclastic flow can initiate a tsunami. Other times, a violent eruption can cause a portion of a volcano's slope to slide off into the ocean. The most dangerous way would be if a volcano explodes or collapses to generate a caldera in the ocean.

There are some real-world examples of this occurring. In 1883 on the volcanic island of Krakatau (image on the right), a violent eruption occurred, producing a tsunami that killed 35,000 people and destroyed two-thirds of the island. It is believed a massive pyroclastic flow slammed into the ocean, producing a massive tsunami. Ultimately the eruption was so violent that the island collapsed to produce a massive caldera of the former island.

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A concern today is the volcanic islands off western Africa called the Canary Islands. Scientists are concerned with an unstable slope on the western side of one of the volcanic islands. Their concern is that a significant eruption could cause a portion of the slope to slide off into the Atlantic Ocean, generating a massive tsunami. Within 9 hours – traveling at 500 mph – this tsunami would reach the eastern United States with a run-up of nearly 150 feet!

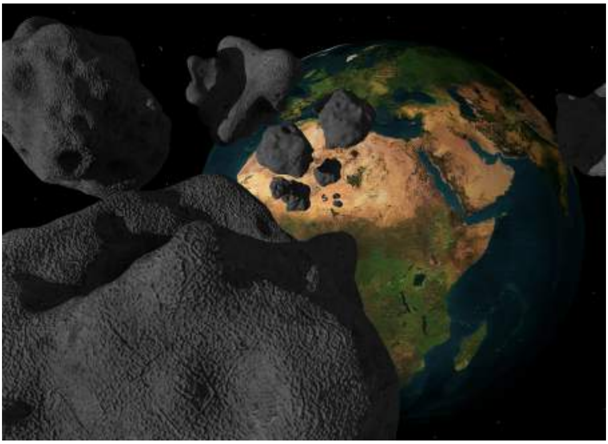
Last but not least is the major island of Mauna Loa, Hawaii. Scientific studies of the former volcanic islands that use to be over this hot spot show that shield volcanoes tend to grow fastest just before they move off the hot spot. Mauna Loa is the most active volcano in the world and is about to move off the hot spot. A new volcanic island is beginning to form underwater just east of the main island. Studies show that the increased activity and lava flows can destabilize portions of the slopes as more weight is added. Fieldworks has discovered that Mauna Loa has had over 60 giant debris avalanches that slide into the Pacific Ocean. These slides tend to be 10-20 miles long and could ultimately generate a tsunami 900 feet high.

Landslides

Large scale landslides can also displace large amounts of water to generate massive tsunamis. Often, it is a volcanic eruption or earthquake that generates the landslide, which creates a tsunami. One concern for the United States is an underwater landslide – a **submarine landslide** – off the eastern coast of the continental shelf can displace enough water to generate a 20-foot tsunami and reach the nation within 20 minutes. The most massive landslide ever recorded in human history happened in Lituya Bay, Alaska. A magnitude 7.0 earthquake along the Denali Fault generated a massive rockfall into the bay, which produced a 1,700-foot tsunami. However, the bay contained most of the energy, and thus a major catastrophe was averted. Nevertheless, the concern is another such event occurring in Glacier Bay, Alaska, which is a significant tourist attraction for cruise lines.

Asteroid Impacts

The rarest, but most lethal tsunami would be generated by an asteroid or comet impact. If an asteroid were to make it through the earth's atmosphere, there is a 70 percent chance it would land in the ocean. For example, an asteroid striking the Atlantic Ocean could produce a tsunami that would cover over half of the nation. All coastal cities around the world would also be destroyed. Furthermore, with 90 percent of all humans living near a large body of water, well, you see the impact! The last asteroid impact in the ocean occurred 65 million years ago and produced a tsunami half a mile high.



"Asteroid Impact" by Reimund Betrams from Pixabay.

Coastal Impacts

There are a variety of coastal vulnerabilities caused by tsunamis. As noted in previous modules, there are two types of effects of tsunamis (and all disasters). The **primary effects** are pretty straight forward. Areas at most risks of tsunamis are highly populated coastal regions such as major cities. Moreover, if the tsunami occurs during high tide, the fingers of destruction will reach farther inland. Most of the deaths from the Asian tsunami of 2004 were from flooding and the actual debris within the water. Other primary effects include coastal erosion and the destruction of ecosystems. The following are aerial photographs of tsunamis from National Geographic.

"Aerial View of Ache, Sumatra, Indonesia" by the United States Navy is licensed under Public Domain.

The **secondary effects** of tsunamis are less noticeable. These include contaminated water sources, disease outbreaks, chemical pollution, homelessness, and economic loss. Sometimes the secondary effects are worse than the primary effects because all the new attention occurs with the primary effects, but very little attention is on the region after a few months.

Mitigation Against Tsunamis

People and ecosystems are quite resilient to natural disasters, but a lot must be done to prevent massive death and destruction, to begin with. After a deadly tsunami in Hawaii in the 1950s, the United States developed the Pacific Tsunami Warning Center. If a 7.5 magnitude earthquake occurs somewhere in the Ring of Fire, a tsunami watch is released by NOAA, indicating that a seismic event just occurred that could have generated a tsunami. In the Pacific Ocean, a system of instruments on the ocean floor and buoys monitors the Pacific Ocean for tsunamis. If the system detects a tsunami, a signal is sent to satellites, which is then sent to coastal areas, and a **tsunami warning** is announced.

Warning	Dangerous coastal flooding & powerful currents possible	Move to high ground or inland
Advisory	Strong currents & waves dangerous to those in/very near water possible	Stay out of water, away from beaches & waterways
Watch	Distant tsunami possible	Stay tuned for information Be prepared to act
Information Statement	No threat or very distant event & threat not determined	Relax

"Understanding Tsunami Alerts" by the National Weather Service is licensed under Public Domain.

Another mitigation measure is **tsunami run-up maps**. A tsunami run-up map indicates how far a tsunami will travel inland based on the continental shelf and strength of the tsunami. By understanding where and how far a tsunami will travel inland, government agencies can determine proper zoning and building codes. Before the Asian tsunami of 2004, the United States had tsunami run-up maps of Indonesia but were considered classified. Indonesia, being a more impoverished nation, did not have run-up maps for their nation. After the catastrophic event, the U.S. military saw how destabilizing this was to the nation and decided to release this information from the run-up maps to the region.

Other ways the impacts of tsunamis can be minimized include:

- Strong building codes and zoning policies that are enforced by local officials
- Planting and protecting existing natural barriers such as vegetation and coastal areas
- Proper education of how to prepare and what to do during and after a tsunami

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PART V

WEATHERING, EROSION, AND DEPOSITION

5.1 WEATHERING

Weathering is what takes place when a body of rock is exposed to the "weather" — in other words, to the forces and conditions that exist at Earth's surface. Most rocks are formed at some depth within the crust except for volcanic rocks and some sedimentary rocks. They experience relatively constant temperature, high pressure, no contact with the atmosphere, and little or no moving water. Once a rock is exposed at the surface, which is what happens when the overlying rock is eroded, conditions change dramatically. Temperatures vary widely, there is much less pressure, oxygen and other gases are plentiful, and in most climates, water is abundant.

Weathering includes two main processes that are entirely different. One is the mechanical breakdown of rock into smaller fragments, and the other is the chemical change of the minerals within the rock to forms that are stable in the surface environment. Mechanical weathering provides fresh surfaces for attack by chemical processes, and chemical weathering weakens the rock so that it is more susceptible to mechanical weathering. Together, these processes create two significant products, one being the sedimentary clasts and ions in solution that can eventually become sedimentary rock, and the other is the soil necessary for our existence on Earth.

"Bryce Canyon" by Luca Galuzzi is licenced under Creative Commons Attribution-ShareAlike 2.5 Generic.

Mechanical Weathering

Intrusive igneous rocks form at depths of several hundreds of meters to several tens of kilometers. Sediments are turned into sedimentary rocks only when other sediments bury them to depths more than several hundreds of meters. Most metamorphic rocks are formed at depths of kilometers to tens of kilometers. Weathering cannot even begin until these rocks are uplifted through various mountain-building processes — most of which are related to plate tectonics — and the overlying material has been eroded, and the rock is exposed as an **outcrop**. The critical agents of mechanical weathering are:

- The decrease in pressure that results from the removal of

overlying rock
- Freezing and thawing of water in cracks in the rock
- Formation of salt crystals within the rock
- Cracking from plant roots and exposure by burrowing animals

When a mass of rock is exposed by weathering and removal of the overlying rock, there is a decrease in the confining pressure on the rock, and the rock expands. This unloading promotes cracking of the rock, known as **exfoliation**.

Granitic rock tends to exfoliate parallel to the exposed surface because it is typically homogenous, and it does not have predetermined planes along which it must fracture. Sedimentary and metamorphic rocks, on the other hand, tend to exfoliate along predetermined planes.

Frost wedging, also called **ice wedging**, is the process by which water seeps into cracks in a rock, expands on freezing, and thus enlarges the cracks. The effectiveness of frost wedging is related to the frequency of freezing and thawing. Frost wedging is most effective in mountainous climates. In warm areas where freezing is infrequent, in very cold areas where thawing is infrequent, or in arid areas, where there is little water to seep into cracks, the role of frost wedging is limited.

In many mountainous regions, the transition between freezing nighttime temperatures and thawing daytime temperatures is frequent — tens to hundreds of times a year. Even in warm coastal areas, freezing and thawing transitions are frequent at higher elevations. A common feature in areas of active frost wedging is a

talus slope — a fan-shaped deposit of fragments removed by frost wedging from the steep rocky slopes above.

"Talus Cones" by Mark Wilson is licensed under Public Domain.

A related process, **frost heaving**, takes place within unconsolidated materials on gentle slopes. In this case, water in the soil freezes and expands, pushing the overlying material up. Frost heaving is responsible for winter damage to roads all over North America.

When saltwater seeps into rocks and then evaporates on a hot sunny day, salt crystals grow within cracks and pores. The growth of these crystals exerts pressure on the rock and can push grains apart, causing the rock to weaken and break. Salt weathering can also occur away from the coast because most environments have some salt in them.

The effects of plants and animals are significant in mechanical weathering. Roots can force their way into even the tiniest cracks, and they exert tremendous pressure on the rocks as they grow, widening the cracks and breaking the rock. Although animals do generally not burrow through solid rock, they can excavate and remove vast volumes of soil, and thus expose the rock to weathering by other mechanisms.

Mechanical weathering is greatly facilitated by erosion, which is the removal of weathering products, allowing for the exposure of more rock for weathering. On the steep rock faces at the top of the cliff, rock fragments have been broken off by ice wedging, and then removed by gravity. This is a form of **mass wasting**, which will be looked at later in this chapter. Other essential agents of erosion that have the effect of removing the products of weathering include water in streams, ice in glaciers, and waves on the coasts.

Chemical Weathering

Chemical weathering results from chemical changes to minerals that become unstable when they are exposed to surface conditions. The kinds of changes that take place are highly specific to the mineral and the environmental conditions. Some minerals, like quartz, are virtually unaffected by chemical weathering, while others, like feldspar, are easily altered. In general, the degree of chemical weathering is most significant in warm and wet climates and least in cold and dry climates. The essential characteristics of surface conditions that lead to chemical weathering are the presence of water (in the air and on the ground surface), the abundance of oxygen, and the presence of carbon dioxide, which produces weak carbonic acid when combined with water.

The Products of Weathering and

Erosion

The products of weathering and erosion are the unconsolidated materials that we find around us on slopes, beneath glaciers, in stream valleys, on beaches, and in deserts. The nature of these materials — their composition, size, degree of sorting, and degree of rounding — is determined by the type of rock that is being weathered, the nature of the weathering, the erosion, and transportation processes, and the climate.

A summary of the weathering products of some of the common minerals present in rocks is provided below.

Common Mineral	Typical Weathering Products
Quartz	Quartz as sand grains
Feldspar	Clay minerals plus potassium, sodium, and calcium in solution
Biotite and Amphibole	Chlorite plus iron and magnesium in solution
Pyroxene and Olivine	Serpentine plus iron and magnesium in solution
Calcite	Calcium and carbonate in solution
Pyrite	Iron oxide minerals plus iron in solution and sulphuric acid

The produces created from weathering range widely in size and shape, depending on the processes involved. If and when deposits like these are turned into sedimentary rocks, the textures of those rocks will vary significantly. Importantly, when we describe sedimentary rocks that formed millions of years in the past, we can use those properties to make inferences about the conditions that existed during their formation.

5.2 WEATHERING AND SOIL FORMATION

Weathering is a vital part of the process of soil formation, and soil is critical to our existence on Earth. Many people refer to any loose material on Earth's surface as soil, but to geographers, soil is the material that includes organic matter, lies within the top few tens of centimeters of the surface, and is vital in sustaining plant growth.

Soil is a complex mixture of minerals (approximately 45 percent), organic matter (approximately 5 percent), and empty space (approximately 50 percent, filled to varying degrees with air and water). The mineral content of soils is variable but is dominated by clay minerals and quartz, along with minor amounts of feldspar and small fragments of rock. The types of weathering that take place within a region have a significant influence on soil composition and texture. For example, in a warm climate, where chemical weathering dominates, soils tend to be more abundant in clay. Soil scientists describe soil texture in terms of the relative proportions of sand, silt, and clay. The sand and silt components in this diagram are dominated by quartz, with lesser amounts of feldspar and rock fragments, while the clay minerals dominate the clay component.

Soil forms through accumulation and decay of organic matter and the mechanical and chemical weathering processes described above. The factors that affect the nature of soil and the rate of its formation include climate (especially average temperature and precipitation amounts, and the following types of vegetation), the type of parent material, the slope of the surface, and the amount of time available.

Formation of Soil

Climate

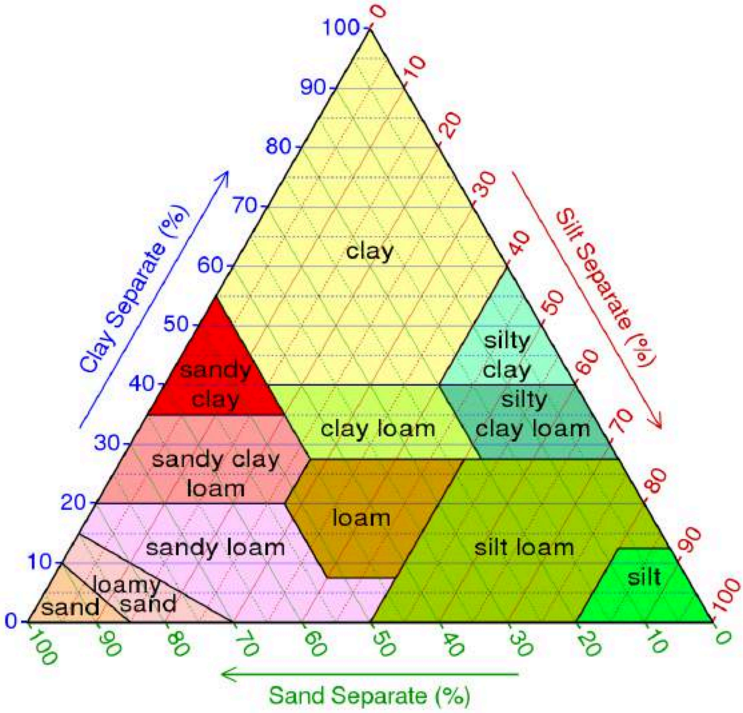
Soils develop because of the weathering of materials on Earth's surface, including the mechanical breakup of rocks, and the chemical weathering of minerals. The downward percolation of water facilitates soil development. Soil forms most readily under temperate to tropical conditions (not cold), and precipitation amounts are moderate (not dry, but not too wet). Chemical weathering reactions (especially the formation of clay minerals) and biochemical reactions proceed fastest under warm conditions, and plant growth is enhanced in warm climates. Too much water (e.g., in rainforests) can lead to the leaching of critical chemical nutrients and, hence, acidic soils. In humid and poorly drained regions, swampy conditions may prevail, producing soil that is dominated by organic matter. Too little water (e.g., in deserts and semi-deserts), results in minimal downward chemical transportation and the accumulation of salts and carbonate minerals (e.g., calcite) from upward-moving water. Soils in dry regions also suffer from a lack of organic material.

Parent Material

Soil **parent materials** can include all different bedrock types and any unconsolidated sediments, such as glacial deposits and stream deposits. Soils are described as residual soils if they develop on bedrock, and transported soils if they develop on transported material such as glacial sediments. However, the term “transported soil” is misleading because it implies that the soil itself has been transported, which is not the case. When referring to such soil, it is better to be specific and say “soil developed on unconsolidated material,” because that distinguishes it from soil developed on bedrock.

Parent materials provide essential nutrients to residual soils. For example, a minor constituent of granitic rocks is the calcium-phosphate mineral apatite, which is a source of the critical soil nutrient phosphorus. Basaltic parent material tends to generate very fertile soils because it also provides phosphorus, along with significant amounts of iron, magnesium, and calcium.

Some unconsolidated materials, such as river-flood deposits, make for especially good soils because they tend to be rich in clay minerals. Clay minerals have large surface areas with negative charges that are attractive to positively charged elements like calcium, magnesium, iron, and potassium, which are essential nutrients for plant growth.



“Soil Texture” by the United States Department of Agriculture is licensed under Creative Commons Attribution-Share Alike 4.0 International.

Slope

Soil can only develop where surface materials remain in place and are not frequently moved away by mass wasting. Soils cannot develop where the rate of soil formation is less than the rate of erosion, so steep slopes tend to have little or no soil.

Time

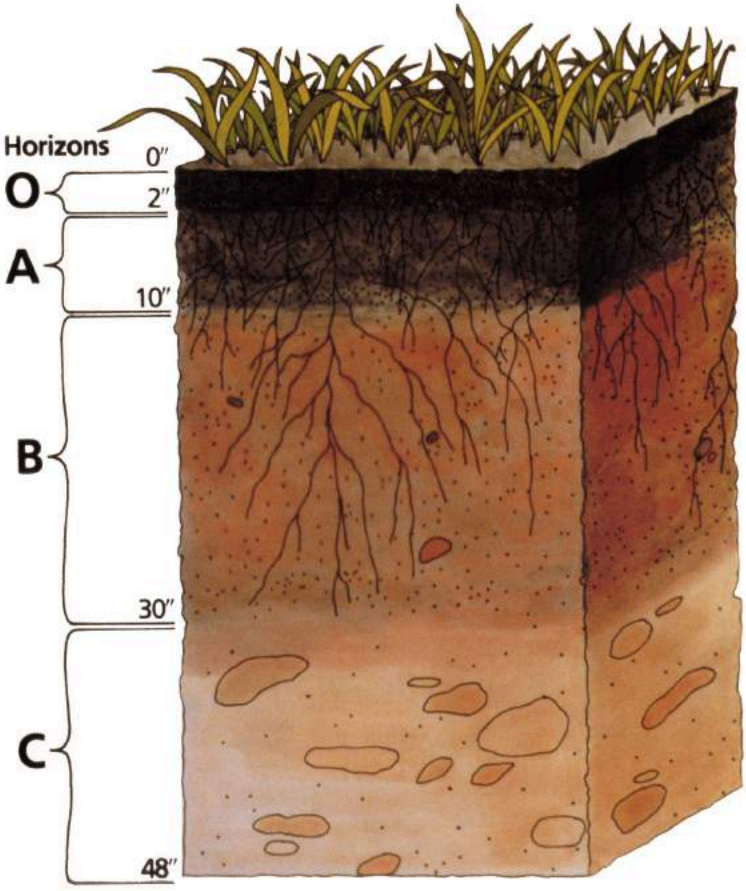
Even under ideal conditions, soil takes thousands of years to develop. Virtually all of northern North America was still glaciated up until 14 ka. Glaciers still dominated the central and northern parts of Canada until around 10 ka, and so, at that time, conditions were still not ideal for soil development even in the southern regions. Therefore, soils in Canada, and especially in central and northern Canada, are relatively young and not well developed.

The same applies to soils forming on newly created surfaces, such as recent deltas or sandbars, or in areas of mass wasting.

Soil Horizons

The process of soil formation generally involves the downward movement of clay, water, and dissolved ions, and a typical result of that is the development of chemically and texturally different layers known as **soil horizons**. The typically developed soil horizons are:

- O — the layer of organic matter
- A — the layer of partially decayed organic matter mixed with mineral material
- E— the eluviated (leached) layer from which some of the clay and iron have been removed to create a pale layer that may be sandier than the other layers
- B — the layer of accumulation of clay, iron, and other elements from the overlying soil
- C — the layer of incomplete weathering



"Soil Profile" by the United State Department of Agriculture is licensed under Public Domain.

Another type of layer develops in hot, arid regions known as **caliche** (pronounced ca-lee-chee). It forms from the downward (or in some cases upward) movement of calcium ions, and the precipitation of calcite within the soil. When well developed, caliche cements the surrounding material together to form a layer that has the consistency of concrete.

Like all geological materials, soil is subject to erosion, although, under natural conditions on gentle slopes, the rate of soil formation either balances or exceeds the rate of erosion. Human practices related to forestry and agriculture have significantly upset this balance.

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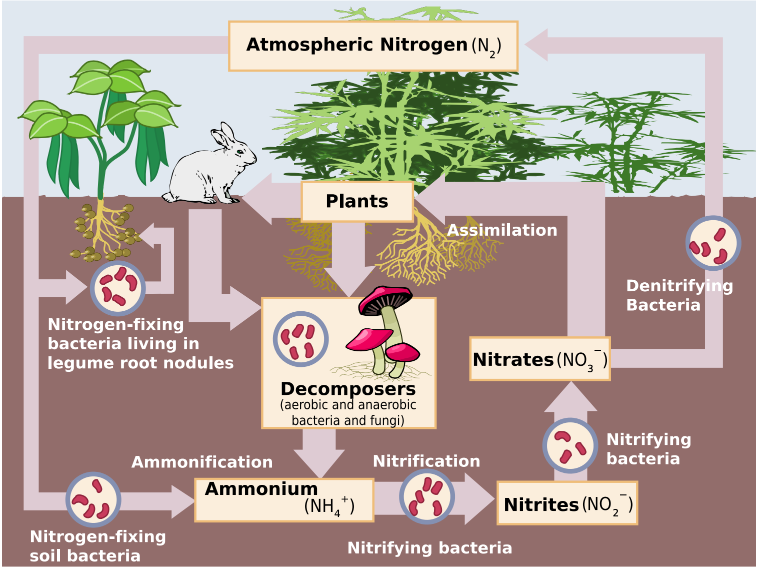
Soils are held in place by vegetation. When vegetation is removed, either through cutting trees or routinely harvesting crops and tilling the soil, that protection is either temporarily or permanently lost. The primary agents of the erosion of unprotected soil are water and wind.

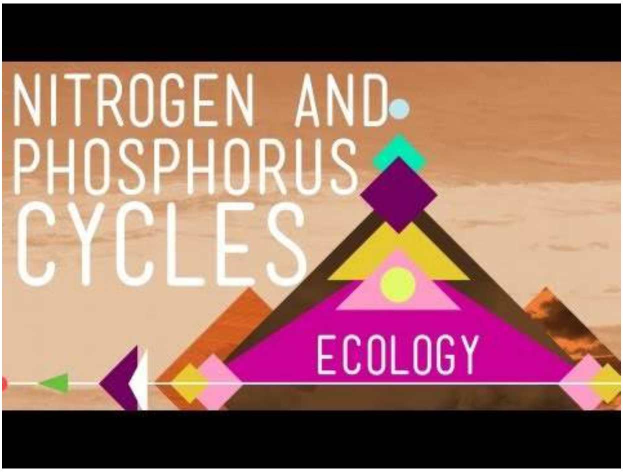
Soil is an important reservoir for organic components necessary for plants, animals, and microorganisms to live. The organic component of soil, called **humus**, is a rich source of bioavailable nitrogen. Nitrogen is the most common element in the atmosphere, but it exists in a form most life forms are unable to use. Special bacteria found only in soil provide most nitrogen compounds that are usable, bioavailable, by life forms.



"Nitrogen Cycle" by the Environmental Protection Agency is licensed under Public Domain.

These nitrogen-fixing bacteria absorb nitrogen from the atmosphere and convert it into nitrogen compounds. These compounds are absorbed by plants and used to make DNA, amino acids, and enzymes. Animals obtain bioavailable nitrogen by eating plants, and this is the source of most of the nitrogen used by life. That nitrogen is an essential component of proteins and DNA.

Soils range from poor to rich, depending on the amount of humus they contain. Soil productivity is determined by water and nutrient content. Freshly created volcanic soils, called **andisols**, and clay-rich soils that hold nutrients and water are examples of productive soils.



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Water erosion is accentuated on sloped surfaces because fast-flowing water has higher eroding power than still water. Raindrops can disaggregate exposed soil particles, putting the finer material (e.g., clays) into suspension in the water. **Sheetwash**, unchannelled flow across a surface carries suspended material away, and channels erode right through the soil layer, removing both fine and coarse material.

Wind erosion is exacerbated by the removal of trees that act as windbreaks and by agricultural practices that leave bare soil exposed.

Tillage is also a factor in soil erosion, especially on slopes, because each time a cultivator lifts the soil, it is moved a few centimeters down the slope.

Weathering and Climate Change

Earth has two important carbon cycles. One is the biological one, wherein living organisms, mostly plants, consume carbon dioxide from the atmosphere to make their tissues, and then, after they die, that carbon is released back into the atmosphere when they decay over years or decades. A small proportion of this biological-cycle carbon becomes buried in sedimentary rocks: during the slow formation of coal, as tiny fragments and molecules in organic-rich shale, and as the shells and other parts of marine organisms in limestone. This becomes part of the geological carbon cycle, a cycle that involves a majority of Earth's carbon but operates only very slowly.

The geological carbon cycle below shows the various steps in the process (not necessarily in this order):

- Organic matter from plants is stored in peat, coal, and permafrost for thousands to millions of years.
- Weathering of silicate minerals converts atmospheric carbon dioxide to dissolved bicarbonate, stored in the oceans for thousands to tens of thousands of years.
- Marine organisms convert dissolved carbon to calcite, which is

stored in carbonate rocks for tens to hundreds of millions of years.
- Carbon compounds are stored in sediments for tens to hundreds of millions of years; some end up in petroleum deposits.
- Carbon-bearing sediments are transferred to the mantle, where the carbon may be stored for tens of millions to billions of years.
- During volcanic eruptions, carbon dioxide is released back to the atmosphere, where it is stored for years to decades.

During much of Earth's history, the geological carbon cycle has been balanced, with carbon being released by volcanism at approximately the same rate that the other processes store it. Under these conditions, the climate remains relatively stable.

During some periods of Earth's history, that balance has been upset. This can happen during prolonged periods of higher than average volcanism. One example is the eruption of the Siberian Traps at around 250 Ma, which appears to have led to strong climate warming over a few million years.

A carbon imbalance is also associated with significant mountain-building events. For example, the Himalayan Range was formed between about 40 and 10 million years ago. Over that period, and still today, the rate of weathering on Earth has been enhanced because those mountains are so high, and the range is so extensive. The weathering of these rocks, most importantly the hydrolysis of feldspar, has resulted in the consumption of atmospheric carbon dioxide and transfer of the carbon to the oceans and ocean-floor carbonate minerals. The steady drop in carbon dioxide levels over the past 40 million years, which led to the Pleistocene glaciations, is partly attributable to the Himalayan Range formation.

Another, non-geological form of carbon-cycle imbalance is happening today on a very rapid time scale. We are in the process of extracting vast volumes of fossil fuels (coal, oil, and gas) that were stored in rocks over the past several hundred million years, and converting these fuels to energy and carbon dioxide. By doing so, we are changing the climate faster than has ever happened in the past.

5.3 MASS WASTING

Mass wasting, which is synonymous with *slope failure*" is the failure and downslope movement of rock or unconsolidated materials in response to gravity. The term *landslide* is almost synonymous with mass wasting, but not entirely because some people reserve "landslide" for relatively rapid slope failures, while others do not. Other than the video below, this textbook will avoid using the term "landslide."

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Factors That Control Slope Stability

Mass wasting happens because tectonic processes have created uplift. **Erosion**, driven by gravity, is the inevitable response to that uplift, and various types of erosion, including mass wasting, have created slopes in the uplifted regions. Slope stability is ultimately determined by two factors: the angle of the slope and the strength of the materials on it.

A block of rock is typically situated on a rock slope that is being pulled toward Earth's center (vertically down) by gravity. The vertical gravitational force can be split into two components relative to the slope: one pushing the block down the slope, called the **shear force**, and the other pushing into the slope, called the **normal force**. The shear force, which wants to push the block down the slope, has to overcome the strength of the connection between the block and the slope, which may be quite weak if the block has split away from the main body of rock, or may be very strong if the block is still a part of the rock. If the **shear strength** is greater than the shear force, the block should not move. However, if the shear force becomes stronger than the shear strength, the block of rock will slide down the slope.

As already noted, slopes are created by uplift, followed by erosion. In areas with relatively recent uplift, slopes tend to be quite steep. This is especially true where glaciation has taken place because glaciers in mountainous terrain create steep-sided valleys. In areas without recent uplift, slopes are less steep because hundreds of millions of years of erosion (including mass wasting) have made them that way. However, as we will see, some mass wasting can happen even on relatively gentle slopes.

The strength of the materials on slopes can vary widely. Solid rocks tend to be strong, but there is an extensive range of rock strength. If we consider just the strength of the rocks and ignore issues like fracturing and layering, then most crystalline rocks, like granite, basalt, or gneiss, are very strong, while some metamorphic rocks, like schist, are moderately strong. Sedimentary rocks have variable strength. Dolostone and some limestone are strong, most sandstone and conglomerate are moderately strong, and some sandstone and all mudstones are quite weak.

Fractures, metamorphic foliation, or bedding can significantly reduce the strength of a body of rock, and in the context of mass wasting, this is most critical if the planes of weakness are parallel to the slope and least critical if they are perpendicular to the slope.

Internal variations in the composition and structure of rocks can significantly affect their strength. Schist, for example, may have layers rich in sheet silicates (mica or chlorite), and these will tend to be weaker than other layers. Some minerals tend to be more susceptible to weathering than others, and the weathered products are commonly quite weak (e.g., the clay formed from feldspar).

Unconsolidated sediments are generally weaker than sedimentary rocks because they are not cemented and, in most cases, have not been significantly compressed by overlying materials. This binding property of sediment is sometimes referred to as cohesion. Sand and silt tend to be particularly weak, clay is generally a little stronger, and sand mixed with clay can be stronger still. Finer deposits are relatively strong (they maintain a steep slope), while the overlying sand is relatively weak, and has a shallower slope that has recently failed. Glacial till, typically a mixture of clay, silt, sand, gravel, and larger clasts, forms and is compressed beneath tens to thousands of meters of glacial ice so it can be as strong as some sedimentary rock.

Apart from the type of material on a slope, the amount of water that the material contains is the most critical factor controlling its strength. This is especially true for unconsolidated materials, but it also applies to bodies of rock. Granular sediments, like the sand at Point Grey, have lots of spaces between the grains. Those spaces may be arid (filled only with air); or moist (often meaning that some spaces are water-filled, some grains have a film of water around them, and small amounts of water are present where grains are touching each other); or completely saturated. Unconsolidated sediments tend to be strongest when they are moist because the small amounts of water at the grain boundaries hold the grains together with surface tension. Dry sediments are held together only by the friction between grains, and if they are well sorted or well rounded, or both, that cohesion is weak. Saturated sediments tend to be the weakest of all because the large amount of water pushes the grains apart, reducing the mount friction between grains. This is especially true if the water is under pressure.

Water will also reduce the strength of solid rock, especially if it has fractures, bedding planes, or clay-bearing zones. This effect is even more significant when the water is under pressure, which is why holes are drilled into rocks on road cuts to relieve this pressure.

Water also has a particular effect on clay-bearing materials. All clay minerals will absorb a little bit of water, and this reduces their strength. The **smectite clays**, such as the **bentonite** used in cat litter, can absorb much water, and that water pushes the sheets apart at a molecular level and makes the mineral swell. Smectite that has expanded in this way has almost no strength; it is incredibly slippery.

Moreover, finally, water can significantly increase the mass of the material on a slope, which increases the gravitational force pushing it down. A body of sediment that has 25% porosity and is saturated with water weighs approximately 13% more than it does when it is completely dry, so the gravitational shear force is also 13% higher.

Mass-Wasting Triggers

The shear force and the shear strength of materials on slopes, and about factors that can reduce the shear strength. Shear force is primarily related to the slope angle, and this does not change quickly. However, shear strength can change quickly for various reasons, and events leading to a rapid reduction in shear strength are considered to be *triggers* for mass waste.

An increase in water content is the most common mass-wasting trigger. This can result from the rapid melting of snow or ice, heavy rain, or some event that changes the pattern of water flow on the surface. Rapid melting can be caused by a dramatic increase in temperature (e.g., in spring or early summer) or by a volcanic eruption. Heavy rains are typically related to storms. Earthquakes can cause changes in water flow patterns, previous slope failures that dam up streams, or human structures that interfere with runoff (e.g., buildings, roads, or parking lots).

In some cases, a decrease in water content can lead to failure. This is most common with clean sand deposits, which lose strength when there is no more water around the grains. Freezing and thawing can also trigger some forms of mass wasting. More specifically, the thawing can release a block of rock attached to a slope by a film of ice. One other process that can weaken a body of rock or sediment is shaking. The most apparent source of shaking is an earthquake, but shaking from highway traffic, construction, or mining will also do the job. Several deadly mass-wasting events (including snow avalanches) were triggered by the M7.8 earthquake in Nepal in April 2015.

Classification of Mass Wasting

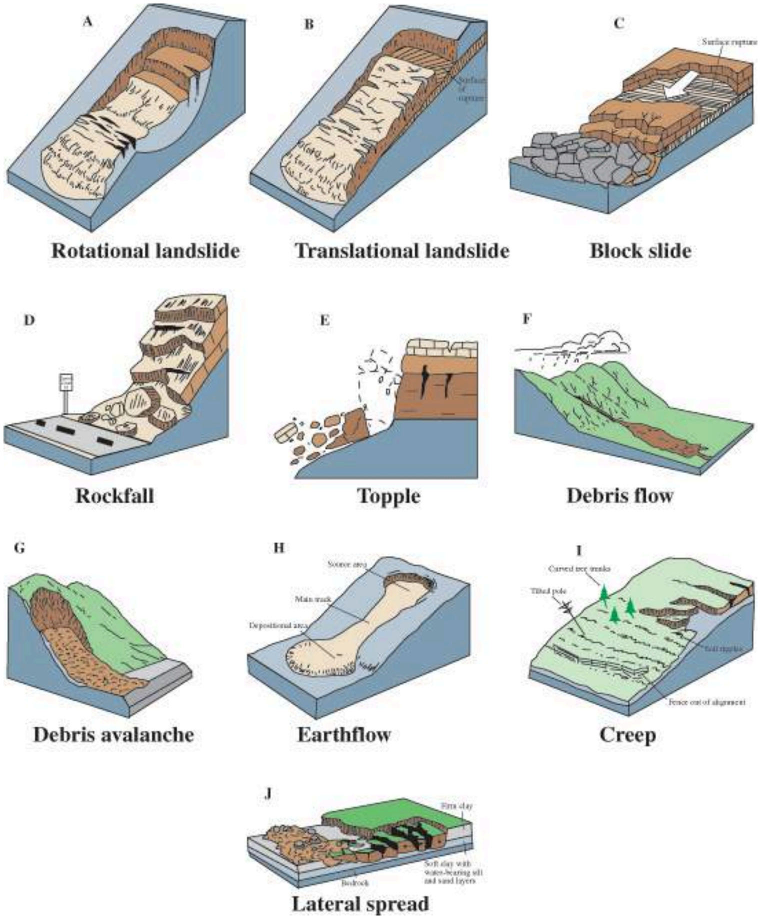
It is crucial to classify slope failures so that we can understand what causes them and how to mitigate them. The three criteria used to describe slope failures are:

- The type of material that failed (typically either bedrock or unconsolidated sediment).
- The mechanism of the failure (how the material moved).
- The rate at which it moved.

The type of motion is the essential characteristic of slope failure, and there are three different types of motion:

- If the material drops through the air, vertically or nearly vertically, it is known as a **fall**.
- If the material moves as a mass along a sloping surface

(without internal motion within the mass), it is a **slide**.
- If the material has internal motion, like a fluid, it is a **flow**.



"Mass Wasting Types" by the United States Geologic Survey is licensed under Public Domain.

Unfortunately, it is not typically that simple. Many slope failures involve two of these types of motion, some involve all three, and in many cases, it is not easy to tell how the material moved. The types of slope failure are summarized below.

Failure Type	**Type of Material**	**Type of Motion**	**Rate of Motion**
Rock fall	Rock fragments	Vertical or near-vertical fall (plus bouncing in many cases)	Very fast (>10s m/s)
Rock slide	A large rock body	Motion as a unit along a planar surface (translational sliding)	Typically very slow (mm/y to cm/y), some can be faster
Rock avalanche	A large rock body that slides and then breaks into smaller fragments	Flow (at high speeds, the mass of rock fragments is suspended on a cushion of air)	Very fast (>10s m/s)
Creep or solification	Soil or other overburden in some small cases, mixed with ice	Flow (although sliding motion may also occur)	Very slow (mm/y to cm/y)
Slump	Thick deposits of unconsolidated sediment	Motion as a unit along a curved surface (rotational sliding)	Slow (cm/y to m/y)
Mudflow	Loose sediment with a significant component of silt and clay	Flow (a mixture of sediment and water moves down a channel)	Moderate to fast (cm/s to m/s)

Debris flow	Sand, gravel, and larger fragments	Flow (similar to a mudflow, but typically faster)	Fast (m/s)

Rock Fall

A **rock fall** is when fragments or rock break off relatively easily from steep bedrock slopes, most commonly due to frost-wedging in areas where there are many freeze-thaw cycles per year. When hiking along a steep mountain trail on a cool morning, one might have heard the occasional fall of rock fragments onto a **talus slope**. This happens because the water between cracks freezes and expands overnight. When that same water thaws in the morning sun, the fragments that had been pushed beyond their limit by the ice fall to the slope below.

"Jalalabad Rock Fall" by Wien Sven Dirks is licensed under Creative Commons Attribution-ShareAlike 4.0 International.

Rock Slide

A **rock slide** is the sliding motion of rock along a sloping surface. In most cases, the movement is parallel to a fracture, bedding, or metamorphic foliation plane, and it can range from very slow to moderately fast. The word **sackung** describes a slope's very slow motion of a block of rock (mm/y to cm/y).

Rock Avalanche

If a rock slides and then starts moving quickly (m/s), the rock is likely to break into many small pieces, and at that point, it turns into a **rock avalanche**, in which the large and small fragments of rock move in a fluid manner supported by a cushion of air within and beneath the moving mass.

“Goodell Creek Debris Avalanche” is licensed under Public Domain.

Creep or Solifluction

The very slow, millimeters per year to centimeters per year, movement of soil or other unconsolidated material on a slope is known as creep. **Creep**, which generally only affects the upper several centimeters of loose material, is typically a very slow flow, but in some cases, sliding may occur. Creep can be facilitated by freezing and thawing because particles are lifted perpendicular to the surface by the growth of ice crystals within the soil, and then let down vertically by gravity when the ice melts. The same effect can be produced by frequent wetting and drying of the soil. In cold environments, **solifluction** is a more intense form of freeze-thaw-triggered creep.

Creep is most noticeable on moderate-to-steep slopes where trees, fence posts, or grave markers are consistently leaning in a downhill direction. In the case of trees, they try to correct their lean by growing upright, and this leads to a curved lower trunk known as a "pistol butt."

"Soil Creep" by Derek Harper is licensed under Creative Commons Share-Alike 2.0 Unported.

Slump is a type of slide (movement as a mass) that takes place within thick unconsolidated deposits (typically thicker than 10 m). Slumps involve movement along one or more curved failure surfaces, with downward motion near the top and outward motion toward the bottom. They are typically caused by an excess of water within these materials on a steep slope.

Mudflows and Debris Flows

When a mass of sediment becomes wholly saturated with water, the mass loses strength, to the extent that the grains are pushed apart, and it will flow, even on a gentle slope. This can happen during rapid spring snowmelt or heavy rains and is also relatively common during volcanic eruptions because of the rapid melting of snow and ice. (A mudflow or debris flow on a volcano or during a volcanic eruption is a lahar.) If the material involved is primarily sand-sized or smaller, it is known as a **mudflow**.

If the material involved is gravel-sized or larger, it is known as a **debris flow**. Because it takes more gravitational energy to move more massive particles, a debris flow typically forms in an area with steeper slopes and more water than a mudflow. In many cases, a debris flow takes place within a steep stream channel and is triggered by the collapse of bank material into the stream. This creates a temporary dam and a significant flow of water and debris when the dam breaks.

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Preventing, Delaying, Monitoring, and Mitigating Mass Wasting

As already noted, we cannot prevent mass wasting in the long term as it is a natural and ongoing process; however, in many situations, there are actions that we can take to reduce or mitigate its damaging effects on people and infrastructure. Where we can neither delay nor mitigate mass wasting, we should consider moving out of the way.

Preventing and Delaying Mass Wasting

Delaying mass wasting is a worthy endeavor, of course, because during the time that the measures are still effective, they can save lives and reduce damage to property and infrastructure. The other side of the coin is that we must be careful to avoid activities that could make mass wasting more likely. One of the most common anthropogenic causes of mass waste is road construction, and this applies to both remote gravel roads built for forestry and mining and large urban and regional highways. Road construction is a potential problem for two reasons. First, creating a flat road surface on a slope inevitably involves creating a cut bank that is steeper than the original slope. This might also involve creating a filled bank that is both steeper and weaker than the original slope. Second, roadways typically cut across natural drainage features, and unless great care is taken to reroute the runoff water and prevent it from forming concentrated flows, oversaturating fill of materials can result — a specific example of the contribution of construction-related impeded drainage to slope instability.

Apart from water issues, engineers building roads and other infrastructure on bedrock slopes must be acutely aware of the geology, especially of any weaknesses or discontinuities in the rock related to bedding, fracturing, or foliation.

It is widely believed that the construction of buildings on the tops of steep slopes can contribute to the instability of the slope. This is probably true, but not because of the weight of the building. A typical house is not usually heavier than the fill that was removed from the hole in the ground made to build it. A more likely contributor to the instability of the slope around a building is the effect that it and the changes made to the surrounding area have on drainage.

Monitoring Mass Wasting

In some areas, it is necessary to establish warning systems so that we know if conditions have changed at a known slide area, or if a rapid failure, such as a debris flow, is actually on its way downslope.

Mt. Rainier, a glacier-covered volcano in Washington State, has the potential to produce massive mudflows or debris flows (lahars) with or without a volcanic eruption. Over 100,000 people in the Tacoma, Puyallup, and Sumner areas are in harm's way because they currently reside on deposits from past lahars. In 1998, a network of acoustic monitors was established around Mt. Rainier. The monitors are embedded in the ground adjacent to expected lahar paths. They are intended to provide warnings to emergency officials, and when a lahar is detected, the residents of the area will have anywhere from 40 minutes to three hours to get to safe ground.

Mitigating the Impacts of Mass Wasting

In situations where we cannot predict, prevent, or delay mass-wasting hazards, some effective measures can be taken to minimize the associated risk. In some parts of the world, similar features have been built to protect infrastructure from other types of mass wasting. Debris flows are inevitable, unpreventable, and unpredictable. The results have been deadly and expensive many times in the past. It would be costly to develop a new route in this region, so provincial authorities have taken steps to protect residents and traffic on the highway and the railway. Debris-flow defensive structures have been constructed in several drainage basins. One strategy is to allow the debris to flow quickly through to the ocean along a smooth channel. Another is to capture the debris within a constructed basin that allows the excess water to continue through but catches the debris materials.

The United States Geologic Survey and the Utah Geologic Survey are excellent sources for more information regarding mass wasting.

5.4 EROSION

Erosion is a mechanical process, usually driven by water, gravity, wind, or ice that removes sediment from weathering. Liquid water is the principal agent of erosion. Erosion resistance is essential in the creation of distinctive geological features. This is well demonstrated in the cliffs of the Grand Canyon. The cliffs are made of rock left standing after less resistant materials have weathered and eroded. Rocks with different levels of erosion resistance also create unique-looking features called hoodoos in Bryce Canyon National Park and Goblin Valley State Park in Utah.

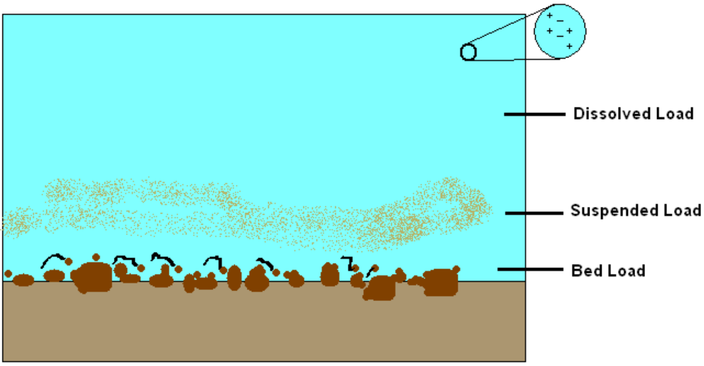
"Bryce Canyon" by R. Adam Dastrup, is licensed under Creative Commons Attribution-NoncCommercial-ShareAlike 4.0 International.

Erosion by Streams

Streams, any running water from a rivulet to a raging river, complete the hydrologic cycle by returning precipitation that falls on land to the oceans. Some of this water moves over the surface, and some moves through the ground as groundwater. Flowing water does the work of both erosion and deposition.

Flowing streams pick up and transport weathered materials by eroding sediments from their banks. Streams also carry ions and ionic compounds that dissolve easily in the water. Sediments are carried as the following loads: dissolved, suspended, and bed. A dissolved load is composed of ions in solution. These ions are usually carried in the water to the ocean.

Sediments carried as solids as the stream flows are called a **suspended load**. The stream's velocity determines the size of particles that can be carried within a load. Faster streams can carry larger particles. Streams that carry larger particles have greater competence. Streams with a steep gradient (slope) have a faster velocity and greater competence.



“Stream Load” is licensed under Public Domain.

Particles that are too large to be carried as suspended loads are bumped and pushed along the stream bed, called **bed load**. Bed load sediments do not move continuously, but rather in intermittent movements, called **saltation**. Streams with high velocities and steep gradients do a great deal of down-cutting into the stream bed, which is primarily accomplished by movement of particles that make up the bed load.

Stages of Streams

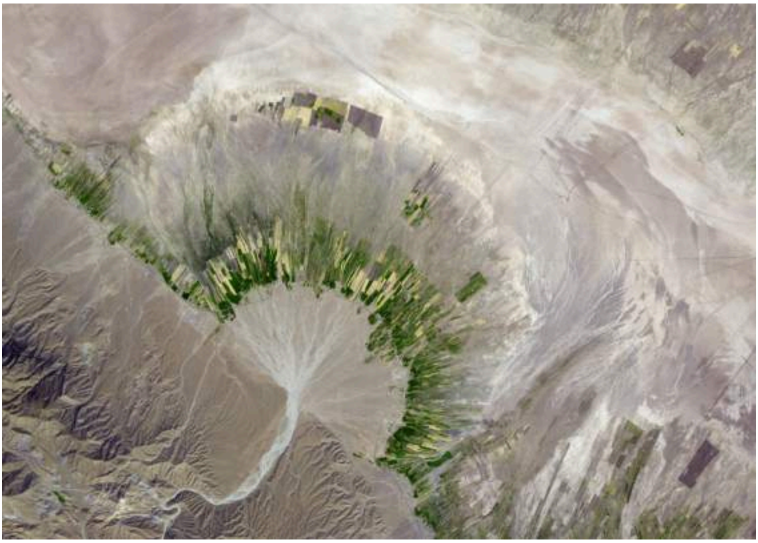
As a stream flows from higher elevations, like in the mountains, towards lower elevations, like the ocean, the work of the stream changes. At a stream’s headwaters, often high in the mountains, gradients are steep. The stream moves fast and does lots of work eroding the stream bed.

As a stream moves into lower areas, the gradient is not as steep. Now the stream does more work eroding the edges of its banks. Many streams develop curves in their channels called meanders. As streams move onto flatter ground, the stream erodes the banks' outer edges to carve a floodplain, which is a flat-level area surrounding the stream channel.

The **base level** is where a stream meets a large body of standing water, usually the ocean, but sometimes a lake or pond. Streams work to down cut in their stream beds until they reach base level. The higher the elevation, the further the stream from which it will reach the base level, and the more cutting it has to do.

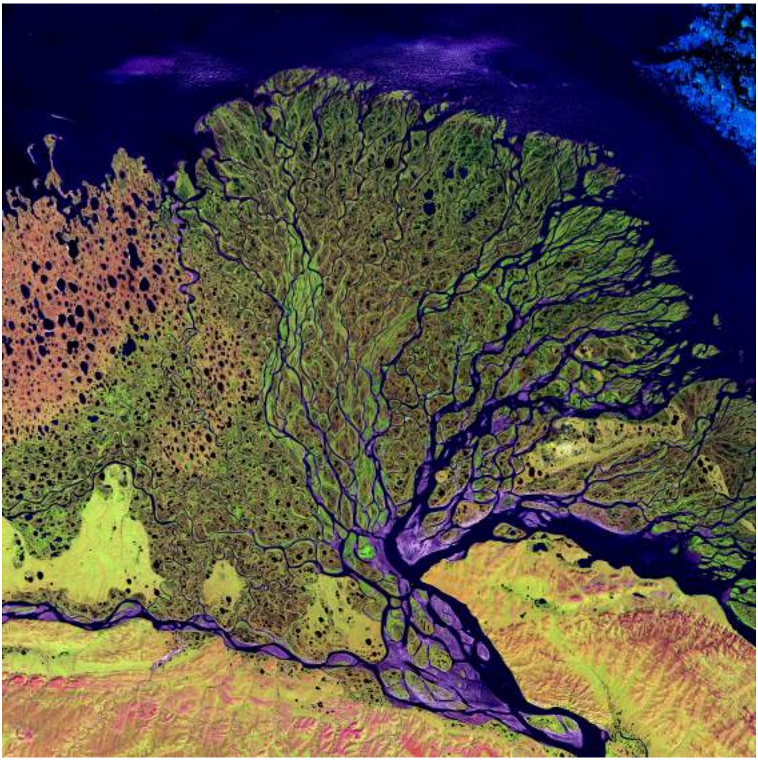
Stream Deposition

As a stream gets closer to the base level, its gradient lowers, and it deposits more material than it erodes. On flatter ground, streams deposit material on the inside of meanders. A stream's floodplain is much broader and shallower than the stream's channel. When a stream flows onto its floodplain, its velocity slows, and it deposits much of its load. These sediments are rich in nutrients and make excellent farmland.



"Alluvial Fan in Iran" by NASA's Earth Observatory is licensed under Public Domain.

A stream at flood stage carries lots of sediments. When its gradient decreases, the stream overflows its banks and broadens its channel. The decrease in gradient causes the stream to deposit its sediments, the largest first. These large sediments build a higher area around the edges of the stream channel, creating **natural levees**.



“Lena River Delta” by NASA Landsat Science is licensed under Public Domain.

When a river enters standing water, its velocity slows to a stop. The stream moves back and forth across the region and drops its sediments in an extensive triangular-shaped deposit called a delta. If a stream falls down a steep slope onto a broad flat valley, an alluvial fan develops. Alluvial fans generally form in arid regions.

"Nile River and Delta" by NASA is licensed as Public Domain.

Ground Water Erosion and Deposition

Groundwater is a strong erosional force, as it works to dissolve away solid rock. Carbonic acid is especially good at dissolving the rock limestone. Over many years, groundwater travels along small cracks. The water dissolves and carries away the solid rock, gradually enlarging the cracks, eventually forming a cave. The video below is drone footage of the world's largest cave, Hang Son Doong, in Vietnam.

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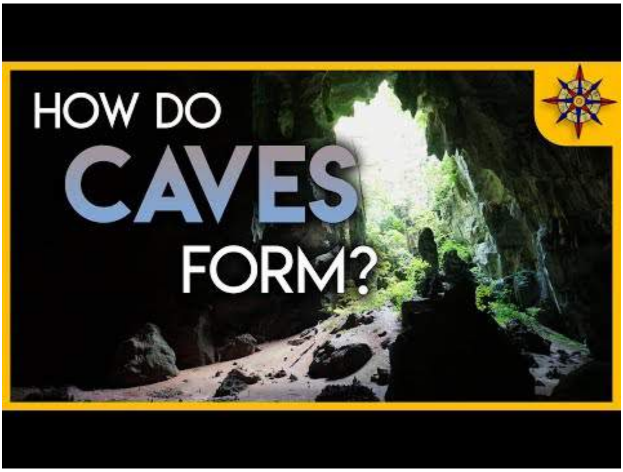

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Groundwater carries the dissolved minerals in solution. The minerals may then be deposited, for example, as **stalagmites** (grows from the top) or **stalactites** (grows from the bottom). If a stalactite and stalagmite join together, they form a column. One wonders of visiting a cave are witnessing the beauty of these fantastic and strangely captivating structures. Caves also produce a beautiful rock, formed from calcium carbonate, travertine. Groundwater saturated with calcium carbonate precipitates as the mineral calcite or aragonite. Mineral springs that produce travertine can be hot, warm, or even cold.

If the roof of a cave collapses, a **sinkhole** could form. Some sinkholes are large enough to swallow up a home or several homes in a neighborhood.

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Wave Action and Erosion

Waves are essential for building up and breaking down shorelines. Waves transport sand onto and off of beaches, transport sand along beaches, carves structures along the shore. The most massive waves form when the wind is powerful, blows steadily for a long time, and blows over a long distance.

"Wavecut Platform" by under Creative Commons Attribution-Share Alike 2.5 Generic.

The wind could be strong, but if it gusts for just a short time, large waves will not form. Wave energy does the work of erosion at the shore. Waves approach the shore at some angle, so the inshore part of the wave reaches shallow water sooner than the part that is further out. The shallow part of the wave 'feels' the bottom first. This slows down the inshore part of the wave and makes the wave 'bend.' This bending is called **refraction**.

Wave refraction either concentrates wave energy or disperses it. In quiet water areas, such as bays, wave energy is dispersed, so sand is deposited. Areas that stick out into the water are eroded by the intense wave energy that concentrates its power on the wave-cut cliff.

A wave-cut platform is the level area formed by wave erosion as the waves undercut a cliff. An **arch** is produced when waves erode through a cliff. When a sea arch collapses, the isolated towers of rocks that remain are known as sea stacks.

Wave Deposition

Rivers carry sediments from the land to the sea. If wave action is high, a delta will not form. Waves will spread the sediments along the coastline to create a beach. Waves also erode sediments from cliffs and shorelines and transport them onto beaches.

Beaches can be made of mineral grains, like quartz, rock fragments, and also pieces of shell or coral. Waves continually move sand along the shore and move sand from the beaches on shore to bars of sand offshore as the season's change. In the summer, waves have lower energy, so they bring sand up onto the beach. In the winter, higher energy waves bring the sand back offshore.

Some features form by wave-deposited sand, such as barrier islands and spits. A spit is sand connected to the land and extending into the water. A **spit** may hook to form a tombolo. Shores that are relatively flat and gently sloping may be lined with long narrow barrier islands. Most barrier islands are a few kilometers wide and tens of kilometers long.

In its natural state, a barrier island acts as the first line of defense against storms such as hurricanes. When barrier islands are urbanized, hurricanes damage houses and businesses rather than vegetated sandy areas in which sand can move. A large hurricane brings massive problems to the urbanized area.

Protecting Shorelines

Intact shore areas protect inland areas from storms that come off the ocean. Where the natural landscape is altered, or the amount of development does damage from a storm too costly to consider, people use several types of structures to attempt to slow down wave erosion. A **groin** is a long narrow pile of rocks built perpendicular to the shoreline to keep sand at that beach. A **breakwater** is a structure built in the water parallel to the shore to protect the shore from strong incoming waves. A **seawall** is also parallel to the shore, but it is built onshore.

"Aerial of Siloso Beach Singapore" is licensed under Creative Commons Attribution 2.0 Generic.

People do not always want to choose safe building practices, and instead choose to build a beach house right on the beach. Protecting development from wave erosion is difficult and expensive, and it does not always work. Anti-tsunami seawalls protected the northeastern coast of Japan, yet waves from the 2011 tsunami that resulted from the Tohoku earthquake washed over some seawalls and caused others to collapse. Japan is now planning to build even higher seawalls to prepare for any future (and inevitable) tsunami.

5.5 TRANSPORT BY WIND

The power of the wind to erode depends on particle size, wind strength, and whether the particles can be picked up. Wind is a crucial erosional force in arid than humid regions. Wind transports small particles, such as silt and clay, over great distances, even halfway across a continent or an entire ocean basin. Particles may be suspended for days. Wind more easily picks up particles on the ground that has been disturbed, such as a construction site or a dune. Just like flowing water, wind transports particles as both bed load and suspended load. For wind, **bed load** is made of sand-sized particles, many of which move by **saltation**. The suspended load is tiny particles of silt and clay.

Wind Erosion

Wind is a more potent erosional force in arid regions than it is in humid regions. In humid areas, water and vegetation bind the soil, so it is harder to pick up. In arid regions, small particles are selectively picked up and transported. As they are removed, the ground surface gets lower and rockier, causing deflation. What is left is desert pavement, a surface covered by gravel-sized particles that are not easily moved by wind.

"Delicate Arch" by John Buie is licensed under Creative Commons Attribution 2.0 Generic.

Particles moved by the wind do the work of **abrasion**. As a grain strikes another grain or surface, it erodes that surface. Abrasion by wind may polish natural or human-made surfaces, such as buildings. Stones that have become polished and faceted due to abrasion by sand particles are called **ventifacts**.

Exposed rocks in desert areas often develop a dark brown to black coating called **desert varnish**. Wind transports clay-sized particles that chemically react with other substances at high temperatures. The coating is formed of iron and manganese oxides. Often petroglyphs are carved into the desert varnish by earlier civilizations in arid regions.

“Wind Erosion in the Altiplano Region of Bolivia” is licensed under the Creative Commons Attribution 2.0 Generic license.

Wind Deposition

Deserts and seashores sometimes have **dunes**. **Beach dunes** have different compositions depending on their location, and are usually quartz because, in humid areas, other minerals weather into clays. In the tropics, dunes may be composed of calcium carbonate, which is typical. In deserts, **sand dunes** may be composed of a variety of minerals. There is little weathering, and so less stable minerals are left behind.

Sand dunes are usually very uniform in size and shape. Particles are sand-sized because more massive particles are too heavy for the wind to transport by suspension. They are rounded since rounded grains roll more easily than angular grains.

"Sand Dunes in Namibia, Africa" is Free for Commercial Use by Pikrepo.

For dunes to form, there must be an abundant supply of sand and steady winds. A strong wind slows down, often over some obstacles, such as a rock or some vegetation, and drops its sand. As the wind moves up and over the obstacle, it increases in speed. It carries the sand grains up the gently sloping, upwind side of the dune by saltation. As the wind passes over the dune, its speed decreases — sand cascades down the crest, forming the slip face of the dune. The slip face is steep because it is at the angle of repose for dry sand, about 34 degrees.

Wind deposits dunes layer by layer. If the wind changes directions, cross-beds form. Cross beds are named for the way each layer is formed at an angle to the ground. The types of a dune that forms depend on the amount of sand available, the character and direction of the wind, and the type of ground the sand is moving over.

Loess

Windblown silt and clay deposited layer on a layer over a large area are **loesses** that come from the German word loose. Loess deposits form downwind of glacial outwash or desert, where fine particles are available. Loess deposits make very fertile soils in many regions of the world.

Fine-grained mud in the deep ocean is formed from silts and clays brought from the land by the wind. The particles are deposited on the sea surface, then slowly settle to the deep ocean floor, forming brown, greenish, or reddish clays. Volcanic ash may also settle on the seafloor.

"Loess Plateau Geomorphology" is licensed under Creative Commons Attribution-Share Alike 3.0 Unported.

5.6 GLACIAL INFLUENCE ON EROSION AND DEPOSITION

Formation and Movement of Glaciers

Glaciers cover about 10 percent of the land surface near Earth's poles, and they are also found in high mountains. During the Ice Ages, glaciers covered as much as 30 percent of Earth. Around 600 to 800 million years ago, geologists think that almost all of the Earth was covered in snow and ice, called the **Snowball Theory**. Scientists use the evidence of erosion and deposition left by glaciers to do a kind of detective work to figure out where the ice once was and where it came from.

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Glaciers are solid ice that moves exceptionally slowly along the land surface. They erode and shape the underlying rocks. Glaciers also deposit sediments in characteristic landforms. The two types of glaciers are: continental and alpine. **Continental glaciers** are large ice sheets that cover relatively flat ground. These glaciers flow outward from where the most considerable amount of snow and ice accumulate. **Alpine** or **valley glaciers** flow downhill through mountains along existing valleys.

"Thwaites Glacier" is a continental glacier taken by NASA and is licensed under Public Domain.

"Perito Moreno Glacier" by Luca Galuzzi is an alpine glacier and is licensed under the Creative Commons Attribution-ShareAlike 2.5 Generic license.

Glacial Erosion

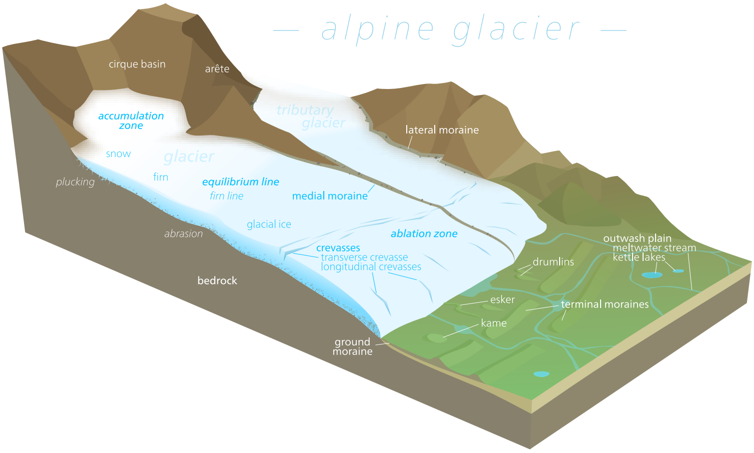
Glaciers erode the underlying rock by abrasion and plucking. Glacial meltwater seeps into cracks of the underlying rock, the water freezes and pushes pieces of rock outward. The rock is then plucked out and carried away by the flowing ice of the moving glacier. With the weight of the ice over them, these rocks can scratch deeply into the underlying bedrock making long, parallel grooves in the bedrock, called **glacial striations**.

Mountain glaciers leave behind unique erosional features. When a glacier cuts through a 'V' shaped river valley, the glacier pucks rocks from the sides and bottom. This widens the valley and steepens the walls, making a 'U' shaped valley.

Smaller **tributary glaciers**, like tributary streams, flow into the main glacier in their own shallower 'U' shaped valleys. A **hanging valley** forms where the main glacier cuts off a tributary glacier and creates a cliff. Streams plunge over the cliff to create waterfalls. Up high on a mountain, where a glacier originates, rocks are pulled away from valley walls.

"U-Shaped Valley" by Dan Hobley is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

Depositional Features of Glaciers



"Alpine Glacier Diagram" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

As glaciers flow, mechanical weathering loosens rock on the valley walls, which falls as debris on the glacier. Glaciers can carry rocks of any size, from giant boulders to silt. These rocks can be carried for many miles over many years and decades. These rocks that are different in type or origin from the surrounding bedrock are glacial erratics. Melting glaciers deposit all the big and small bits of solid material they are carrying in a pile. These unsorted deposits of rock are called **glacial till**.

Glacial till is found in different types of deposits. Linear rock deposits are called moraines and are named by their location relative to the glacier. Geologists study moraines to figure out how far glaciers extended and how long it took them to melt away. **Lateral moraines** form at the edges of the glacier as material drops onto the glacier from erosion of the valley walls. **Medial moraines** form where the lateral moraines of two tributary glaciers join together in the middle of a more massive glacier. Sediment from underneath the glacier becomes a ground moraine after the glacier melts. Ground moraine contributes to the fertile transported soils in many regions.

Terminal moraines are long ridges of till left at the furthest point the glacier reached. **End moraines** are deposited where the glacier stopped for a long enough period to create a rocky ridge as it retreated. Two end moraines form long Island in New York.

While glaciers dump unsorted sediments, glacial meltwater can sort and re-transport the sediments. As water moves through unsorted glacial till it leaves behind the larger particles and takes away the smaller bits of sand and silt.

Several types of stratified deposits form in glacial regions but are not formed directly by the ice. **Varves** form where lakes are covered by ice in the winter. Dark, fine-grained clay sinks to the bottom in winter, but melting ice in spring brings running water that deposits lighter colored sands. Each alternating dark/light layer represents one year of deposits. If during a year, a glacier accumulates more ice than melts away, the glacier advances downhill. If a glacier melts more than it accumulates over a year, it is retreating.

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There has been a lot of conversations and research in the scientific community about the dramatic amount of glacial melt that has been occurring around the planet as of late. Glaciers flow incredibly slowly downslope under the influence of gravity. However, satellite imagery and on the ground data have shown that these glaciers are melting back and receding at an incredible rate. Because glaciers take so long to form and flow, they are excellent indicators of the planet's temperature. As the planet has continued to warm over the last 100 years, glaciers from all around the world are retreating. This is important to humanity because glaciers make up a large portion of the usable freshwater on the planet. As these glaciers melt away, so do vast amounts of fresh drinking water, just when the human population continues to grow exponentially.

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5.7 SUBSIDENCE

Subsidence occurs when loose, water-saturated sediment begins to compact, causing the ground surface to collapse. Now there are two types of subsidence.

Slow Subsidence

Slow subsidence occurs when the water within the sediment is slowly squeezed out because of overlying weight. There are several examples of slow subsidence, but the best one is Venice, Italy. Venice was built at sea level on the now submerged delta of the Brenta River. The city is sinking because of the overlying weight of the city and the pumping of groundwater. The problem now is that sea levels are rising as glaciers melt and water expands due to global warming.

"Gondola on the Grand Canal, Venice, Italy" by Peter K Burian is licensed under the Creative Commons Attribution-ShareAlike 4.0 International license.

An example of slow subsidence in the U.S. includes New Orleans, Louisiana. As we all know from Hurricane Katrina, the Mississippi River has a vast network of levees that prevent the massive river from flooding – most of the time. But by preventing the spring-time flooding, we are preventing the river from depositing sediment onto the land. Instead, the sediment is being transported to the Gulf of Mexico creating the massive Mississippi delta.

Fast Subsidence

Fast subsidence occurs when naturally acidic water begins to dissolve limestone rock to form a network of water-filled underground caverns. But if droughts or pumping of groundwater reduces the water table below the level of the caves, they caverns collapse creating surface sinkholes. A dramatic example of fast subsidence occurred in Guatemala City in 2007 when a massive sinkhole formed 300 feet deep. As noted above, the underground region surrounding Guatemala is composed of limestone and a vast underground network of caverns. It is believed that the water table has been dropping in the region and thus draining the caves. Afterward, the caves can not support the overlying weight and collapse in.

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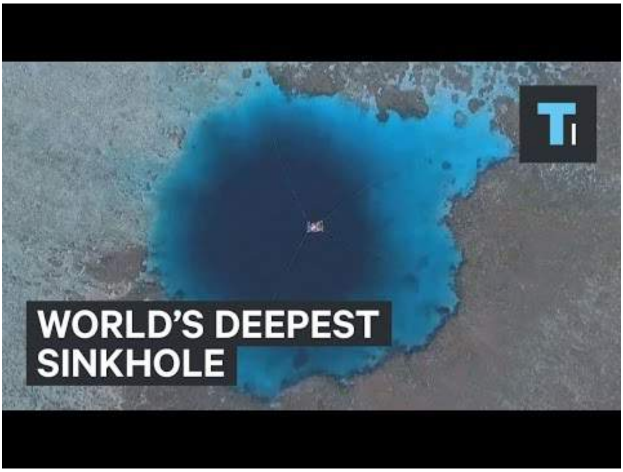

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5.7 AVALANCHES

Coming soon…

5.8 ATTRIBUTION AND REFERENCES

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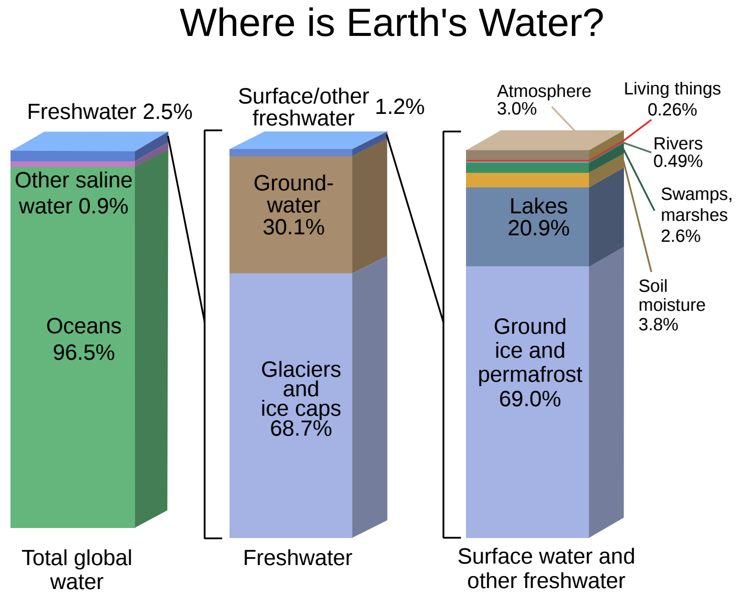
PART VI

FLUVIAL PROCESSES AND SYSTEMS

6.1 DISTRIBUTION OF EARTH'S WATER

Water is composed of two atoms of hydrogen and one atom of oxygen bonded together. Despite its simplicity, water has remarkable properties. Water expands when it freezes and has high surface tension because of the molecules' polar nature that they tend to stick together. Without water, life might not exist on Earth, and it certainly would not have the tremendous complexity and diversity that we see.



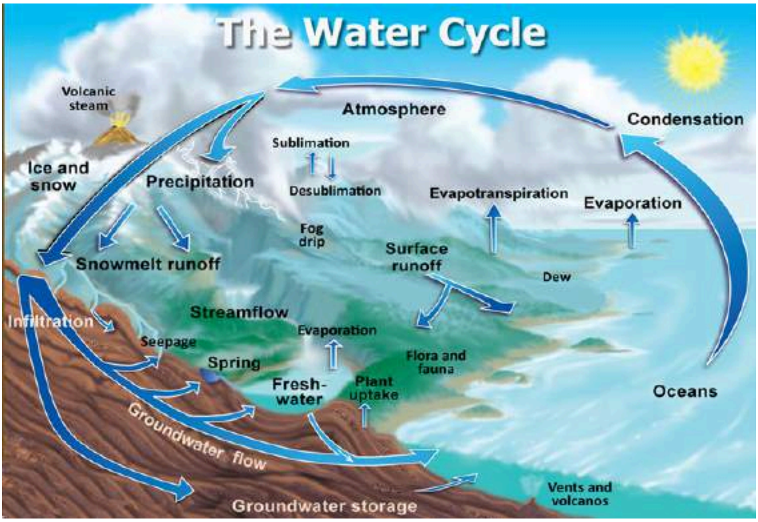
"Distribution of the Locations of Water on Earth" by the United States Geologic Survey is licensed under Public Domain.

Earth's oceans contain 97 percent of the planet's water, and just 3 percent is freshwater with relatively low concentrations of salts. Most freshwater is trapped as ice in the vast glaciers and ice sheets of Greenland and Antarctica. A storage location for water such as an ocean, glacier, pond, or even the atmosphere is known as a **reservoir**. A water molecule may pass through a reservoir very quickly or may remain for much longer. The amount of time a molecule stays in a reservoir is known as its **residence time**.

Hydrologic Cycle

Because of the unique properties of water, water molecules can cycle through almost any-where on Earth. The water molecule found in a glass of water today could have erupted from a volcano early in Earth history. In the intervening billions of years, the molecule probably spent time in a glacier or far below the ground. The molecule surely was high up in the atmosphere and maybe deep in the belly of a dinosaur.

Water is the only substance on Earth that is present in all three states of matter – as a solid, liquid, or gas. Along with that, Earth is the only planet where water is present in all three states. Because of the ranges in temperature in specific locations around the planet, all three phases may be present in a specific location or region. The three phases are solid (ice or snow), liquid (water), and gas (water vapor).



"The Water Cycle" by the United States Geologic Survey is licensed under Public Domain.

Water is continuously on the move. It is **evaporated** from the oceans, lakes, streams, the surface of the land, and plants (**transpiration**) by solar energy. It is moved through the atmosphere by winds and condenses to form clouds of water droplets or ice crystals. It comes back down as rain or snow and flows through streams, into lakes, and eventually back to the ocean. Water on the surface and in streams and lakes infiltrates the ground to become groundwater. Groundwater slowly moves through the rock and surficial materials. Some groundwater returns to other streams and lakes, and some go directly back to the oceans. (Earle, 2019)

Because Earth's water is present in all three states, it can get into various environments around the planet. The movement of water around the Earth's surface is the hydrologic (water) cycle. Water changes from a liquid to a gas by evaporation to become water vapor. The Sun's energy can evaporate water from the ocean surface or lakes, streams, or puddles on land. Only the water molecules evaporate; the salts remain in the ocean or a freshwater reservoir. The water vapor stays in the atmosphere until it undergoes condensation to become tiny droplets of liquid. The droplets gather in clouds, which are blown about the globe by the wind. As the water droplets in the clouds collide and grow, they fall from the sky as precipitation. **Precipitation** can be rain, sleet, hail, or snow. Sometimes precipitation falls back into the ocean, and sometimes it falls onto the land surface.

When water falls from the sky as rain, it may enter streams and rivers that flow down to oceans and lakes. Water that falls as snow may sit on a mountain for several months. Snow may become part of the ice in a glacier, where it may remain for hundreds or thousands of years. Snow and ice may go directly back into the air by **sublimation**, the process in which a solid changes directly into a gas without first becoming a liquid. Although it is hard to see water vapor sublimate from a glacier, it is possible to see dry ice sublimate in the air.

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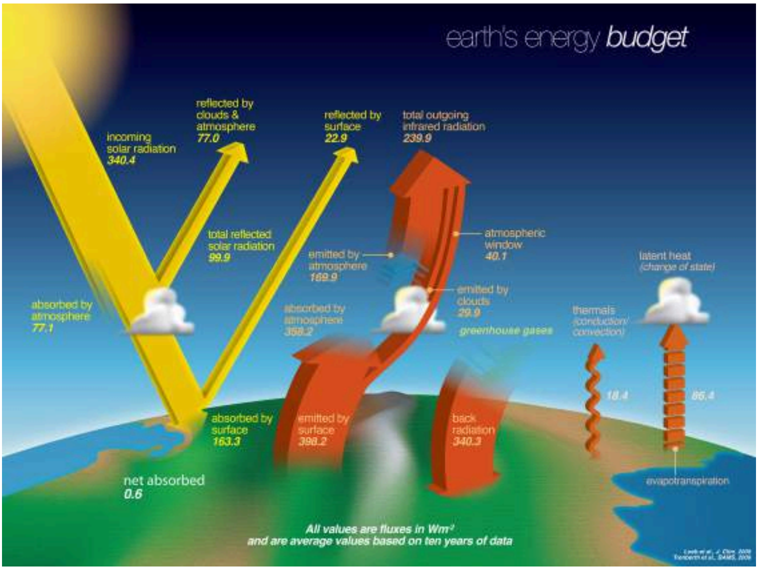
Snow and ice slowly melt over time to become liquid water, which provides a steady flow of freshwater to streams, rivers, and lakes below. A water droplet falling as rain could also become part of a stream or a lake. At the surface, the water may eventually evaporate and reenter the atmosphere.



"Earth's Energy Budget" from NASA is licensed under Public Domain.

A significant amount of water infiltrates into the ground, and soil moisture is an important reservoir for that water. Water trapped in the soil is essential for plants to grow. Water may seep through dirt and rock below the soil through pores infiltrating the ground to go into Earth's groundwater system. Groundwater may enter aquifers that may store freshwater for centuries. Alternatively, the water may come to the surface through springs or find its way back to the oceans. Plants and animals depend on water to live, and they also play a role in the water cycle. Plants take water from the soil and release substantial amounts of water vapor into the air through their leaves, a process known as transpiration. NASA has an excellent online animation of the hydrologic cycle.

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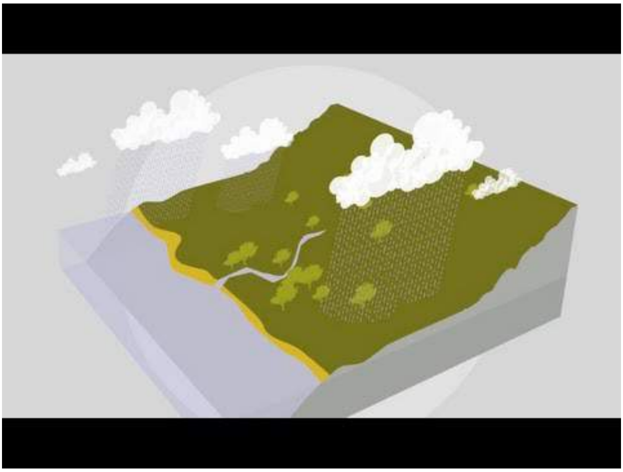
People also depend on water as a natural resource. Not content to get water directly from streams or ponds, humans create canals, aqueducts, dams, and wells to collect water and direct it to where they want it.

Use	United States	Global
Agriculture	34 percent	70 percent
Domestic (drinking, cooking, bath, etc.)	12 percent	10 percent
Industry	5 percent	20 percent
Power Plant Cooling	49 percent	small

The table above displays water use in the United States and globally (Estimated Use of Water in the United States in 2005, USGS). It is important to note that water molecules cycle around. If climate cools and glaciers and ice caps grow, there is less water for the oceans, and sea level will fall. The reverse can also happen.



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6.2 STREAMS AND RIVER SYTEMS

Freshwater in streams, ponds, and lakes is an essential part of the hydrologic cycle if only because of its importance to living creatures. Along with wetlands, these freshwater regions contain a tremendous variety of organisms. **Streams** are bodies of water that consist of constant motion, called a **current**. Geologists recognize many categories of streams depending on their size, depth, speed, and location. Creeks, brooks, tributaries, bayous, and rivers might all be lumped together as streams. In streams, water always flows downhill, but the form that downhill movement takes varies with rock type, topography, and many other factors.

"Stream Landscape in British Columbia" is licensed under Public Domain.

Streams are the most important agents of erosion and transportation of sediments on Earth's surface. They are responsible for the creation of much of the topography that we see around us. They are also places of great beauty and tranquility, and of course, they supply much of the water that is essential to our existence. However, streams are not always peaceful and soothing. During large storms and rapid snowmelts, they can become raging torrents capable of moving cars and houses and destroying roads and bridges. When they spill over their banks, they can flood vast areas, devastating populations, and infrastructure. (11 Water – An Introduction to Geology, n.d.)

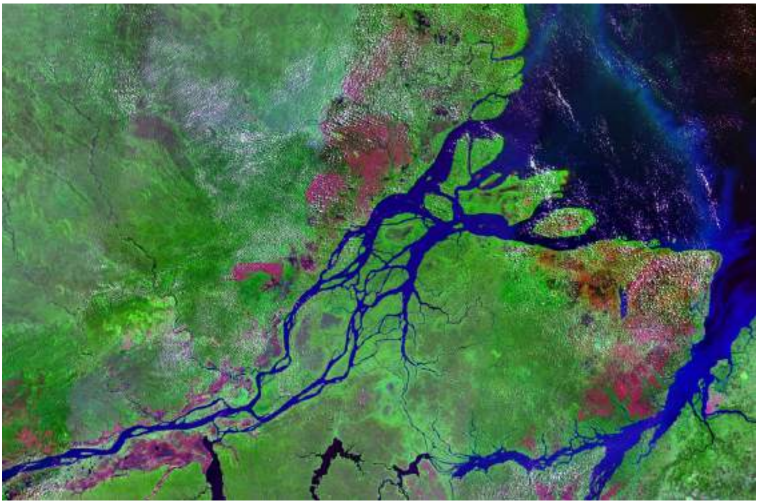
Parts of a Stream

There are a variety of distinct types of streams. A stream originates at its **source**s, such as high mountains where snows collect in winter and melt in summer, or a source might be a **spring**. A stream may have more than one source, and when two streams come together, it is called a **confluence**. The smaller of the two streams is a **tributary** of the larger stream. A stream may create a pool where the water slows and becomes more profound.

"River Source" by Tony Ferrie is licensed under the Creative Commons Attribution-ShareAlike 2.0 Generic.

“Flooding at the junction of the Mississippi and Ohio River” by NASA Landsat Science is licensed under Public Domain.

The point at which a stream comes into a large body of water, like an ocean or a lake, is called the **mouth**. Where the stream meets the ocean or lake, it is called an **estuary**. The mix of fresh and saltwater, where a river runs into the ocean, creates a diversity of environments where many different organisms create unique ecosystems.



"Mouths of the Amazon River" by NASA is licensed under Public Domain.

Stream Erosion and Deposition

Flowing water is a fundamental mechanism for both erosion and deposition. Water flow in a stream is primarily related to the stream's gradient, but the stream channel's geometry also controls it. The water flow velocity is decreased by friction along the stream bed, so it is slowest at the bottom and edges and fastest near the surface and in the middle. The velocity below the surface is typically slightly higher than right at the surface because of friction between the water and the air. On a curved section of a stream, flow is fastest on the outside and slowest on the inside.

Other factors that affect stream-water velocity are the size of sediments on the stream bed – because large particles tend to slow the flow more than small ones – and the discharge, or volume of water passing a point in a unit of time. During a flood, the water level always rises, so there is a more cross-sectional area for the water to flow in. However, as long as a river remains confined to its channel, the velocity of the water flow also increases.

image

"Relative Velocity of Stream Flow" by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

Large particles rest on the bottom, bedload, and may only be moved during rapid flows under flood conditions. They can be moved by **saltation** (bouncing) and by **traction** (being pushed along by the force of the flow). Smaller particles may rest on the bottom some of the time, where they can be moved by saltation and traction, but they can also be held in suspension in the flowing water, especially at higher velocities. Streams that flow fast tend to be turbulent (flow paths are chaotic, and the water surface appears rough), and the water may be muddy, while those that flow more slowly tend to have laminar flow (straight-line flow and a smooth water surface) and clear water. Turbulent flow is more effective than laminar flow at keeping sediments in suspension. Stream water also has a **dissolved load**, representing roughly 15 percent of the mass of material transported, and includes ions such as calcium and chloride in solution. The solubility of these ions is not affected by flow velocity.

The faster the water is flowing, the larger the particles that can be kept in suspension and transported within the flowing water. However, as Swedish geographer Filip Hjulström dis-covered in the 1940s, the relationship between grain size and the likelihood of a grain being eroded, transported, or deposited is not as simple as one might imagine. Consider, for example, a 1 mm grain of sand. If it is resting on the bottom, it will remain there until the velocity is high enough to erode it. However, once it is in suspension, that same 1 mm particle will remain in suspension as long as the velocity does not drop below 10 centimeters per second (cm/s.) For a 10 mm gravel grain, the velocity is 105 cm/s to be eroded from the bed but only 80 cm/s to remain in suspension.

On the other hand, a 0.01 mm silt particle only needs a velocity of 0.1 cm/s to remain in suspension but requires 60 cm/s to be eroded. A tiny silt grain requires a higher velocity to be eroded than a grain of sand that is 100 times larger. For clay-sized particles, the discrepancy is even more significant. In a stream, the most easily eroded particles are small sand grains between 0.2 mm and 0.5 mm. Anything smaller or larger requires a higher water velocity to be eroded and entrained in the flow. The main reason for this is that those small particles, especially the tiny grains of clay, have a strong tendency to stick together, so they are challenging to erode from the stream bed.

image

"Particles in Suspension and Ions in Solution" by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

It is essential to be aware that a stream can erode and deposit sediments simultaneously. At 100 cm/s, for example, silt, sand, and medium gravel will be eroded from the stream bed and transported in suspension, coarse gravel will be held in suspension, pebbles will be both transported and deposited, and cobbles and boulders will remain stationary on the stream bed.

A stream typically reaches its highest velocity when it is close to flooding over its banks, known as the **bank-full stage**. As soon as the flooding stream overtops its banks and occupies the broad area of its flood plain, the water has a much larger area to flow through, and the velocity drops significantly. At this point, sediment that was being carried by the high-velocity water is deposited near the edge of the channel, forming a natural bank or levée. (11 Water – An Introduction to Geology, n.d.)

Stream Types

Stream channels can be straight or curved, deep and slow, or rapid and choked with coarse sediments. The cycle of erosion has some influence on the nature of a stream, but several other factors are essential. Youthful streams that are actively downcutting their channels tend to be relatively straight and are typically ungraded (meaning that rapids and falls are frequent). Youthful streams commonly have a step-pool morphology, meaning that the stream consists of a series of pools connected by rapids and waterfalls. They also have steep gradients and steep and narrow **V-shaped valleys**, in some cases steep enough to be called **canyons**.

"Black Canyon and Gunnison River" is a V-shaped river taken by Terry Foote and is licensed under the Creative Commons Attribution 4.0 International license.

In mountainous terrains, steep youthful streams typically flow into broad and low-gradient **U-shaped glaciated valleys**. The youthful streams have high sediment loads, and when they flow into the lower-gradient glacial valleys where the velocity is not high enough to carry all of the sediment, braided patterns develop, characterized by a series of narrow channels separated by gravel bars.

“U-Shaped Valley in Norway” by Petr Smerkl is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

Braided streams can develop anywhere there is more sediment than a stream can transport. One such environment is in volcanic regions, where explosive eruptions produce enormous amounts of unconsolidated material that gets washed into streams. The Coldwater River next to Mt. St. Helens in Washington State is an excellent example.

A stream that occupies a vast, flat flood plain with a low gradient typically carries only sand-sized and finer sediments and develops a sinuous flow pattern. When a stream flows around a corner, the water on the outside has farther to go and tends to flow faster. This leads to erosion of the banks on the outside of the curve, deposition on the inside, and formation of a point bar. Over time, the sinuosity of the stream becomes increasingly exaggerated, and the channel migrates around within its flood plain, forming a meandering pattern.

"Braided Stream" by the National Oceanic and Atmospheric Administration is licensed under Public Domain.

The meander in the photo below has reached the point where the thin neck of land between two parts of the channel is about to be eroded. When this happens, **an oxbow lake** will form. Finally, at the point where a stream enters a still body of water, a lake, or the ocean, sediment is deposited and a delta forms.

Rivers

Rivers are the largest types of stream, moving substantial amounts of water from higher to lower elevations. The Amazon River, the planet's most enormous river, has a flow rate of nearly 220,000 cubic meters per second! People have used rivers since the beginning of civilization as a source of water, food, transportation, defense, power, recreation, and waste disposal.

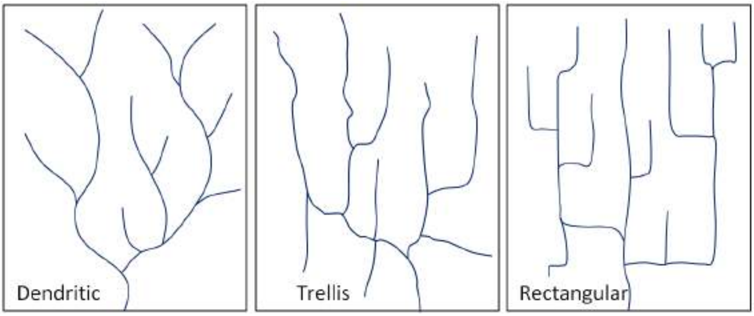
"Red River Meanders" by the US Department of Agriculture is licensed under Public Domain.

Divides

A **divide** is a topographically high area that separates a landscape into different water basins. The rain that falls on the north side of a ridge flows into the northern drainage basin, and rain that falls on the south side flows into the southern drainage basin. On a much grander scale, entire continents have divides, known as **continental divides**.

"North America Water Divides" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

The pattern of tributaries within a drainage basin depends mainly on the type of rock beneath, and on structures within that rock (folds, fractures, faults, etc.). **Dendritic patterns**, which are by far the most common, develop in areas where the rock (or unconsolidated material) beneath the stream has no particular fabric or structure and can be eroded equally easily in all directions. Examples would be granite, gneiss, volcanic rock, and sedimentary rock that has not been folded. **Trellis drainage** patterns typically develop where sedimentary rocks have been folded or tilted and then eroded to varying degrees depending on their strength. The Rocky Mountains of B.C. and Alberta are an excellent example of this, and many of the drainage systems within the Rockies have trellis patterns. **Rectangular patterns** develop in areas with little topography and a system of bedding planes, fractures, or faults that form a rectangular network. The fourth type of drainage pattern, which is not specific to a drainage basin, is known as **radial**. Radial patterns form around isolated mountains (such as volcanoes) or hills, and the individual streams typically have dendritic drainage patterns. (11 Water – An Introduction to Geology, n.d.)



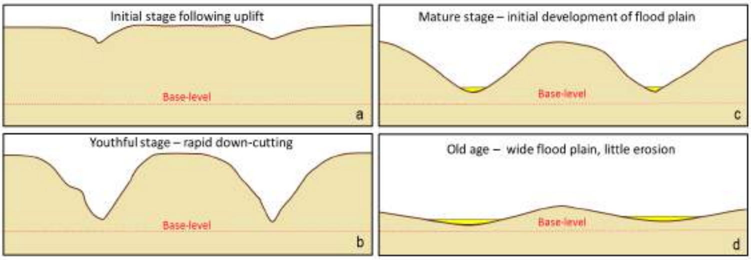
“Stream Patterns” by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

Over geological time, a stream will erode its drainage basin into a smooth profile. If we compare this with an ungraded stream like Cawston Creek, we can see that graded streams are steepest in their headwaters, and their gradient gradually decreases toward their mouths. Ungraded streams have steep sections at various points, and typically have rapids and waterfalls at numerous locations along their lengths.

The ocean is the ultimate base level, but lakes and other rivers act as base levels for many smaller streams. Engineers can create an artificial base level on a stream by constructing a dam. Sediments accumulate within the flood plain of a stream, and then, if the base level changes, or if there is less sediment to deposit, the stream may cut down through those existing sediments to form terraces.

In the late 19th century, American geologist William Davis proposed that streams and the surrounding terrain develop in a cycle of erosion. Following tectonic uplift, streams erode quickly, developing deep V-shaped valleys that follow relatively straight paths. Gradients are high, and profiles are ungraded. Rapids and waterfalls are common. During the mature stage, streams erode more broad valleys and start to deposit thick sediment layers. Gradients are slowly reduced, and grading increases. In old age, streams are surrounded by rolling hills, and they occupy broad sediment-filled valleys. Meandering patterns are common.

Davis's work was done long before the idea of plate tectonics, and he was not familiar with the impacts of glacial erosion on streams and their environments. While some parts of his theory are out of date, it is still a useful way to understand streams and their evolution.


Initial stage following uplift
Base-level
a
Youthful stage – rapid down-cutting
Base-level
b
Mature stage – initial development of flood plain
Base-level
c
Old age – wide flood plain, little erosion
Base-level
d

6.3 WETLANDS

Wetlands are lands that are wet for significant periods. They are common where water and land meet. Wetlands can be large flat areas or small and steep areas. Wetlands are vibrant and unique ecosystems with many species that rely on both the land and the water for survival. Only specialized plants can grow in these conditions. Wetlands tend to have a great deal of biological diversity. Wetland ecosystems can also be fragile systems sensitive to the amounts and quality of water present within them. Learn more about wetlands further from the U.S. Environmental Protection Agency.

"Sunrise at Viru Bog, Estonia" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

Types of Wetlands

There are a variety of distinct types of wetlands. **Marshes** are shallow wetlands around lakes, streams, or the ocean where grasses and reeds are common, but trees are not. Frogs, turtles, muskrats, and many varieties of birds are at home in marshes.

"Bride Book Salt Marsh" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

A **swamp** is a wetland with lush trees and vines found in a low-lying area beside slow-moving rivers. Like marshes, they are often or always inundated with water. Since the water in a swamp moves slowly, oxygen in the water is often scarce. Swamp plants and animals must be adapted for these low-oxygen conditions. Like marshes, swamps can be freshwater, saltwater, or a mixture of both.

"National Wildlife Refuge, Georgia" by the United States Fish and Wildlife Service is licensed as Public Domain.

In an **estuary**, salt water from the sea mixes with fresh water from a stream or river. These semi-enclosed areas are home to plants and animals that can tolerate the sharp changes in salt content that the constant motion and mixing of waters create. Estuaries contain brackish water, water that has more salt than freshwater but less than seawater. Because of the rapid changes in salt content, estuaries have many different habitats for plants, animals, and extremely high biodiversity.

“Sierra Leone River Estuary” by the European Space Agency is licensed under the Creative Commons Attribution-ShareAlike 3.0 IGO license.

Ecological Role of Wetlands

As mentioned above, wetlands are home to many varied species of organisms. Although they make up only 5 percent of the United States area, wetlands contain more than 30 percent of the plant types. Many endangered species live in wetlands, so wetlands are protected from human use. Wetlands also offer protection from storm surges from tropical storm systems like hurricanes and supply safe, hidden protection for hatchlings.

Wetlands also play a critical biological role by removing pollutants from water. For example, they can trap and use fertilizer that has washed off a farmer’s field, and therefore they prevent that fertilizer from contaminating another body of water. Since wetlands naturally purify water, preserving wetlands also help to maintain clean supplies of water.

Ponds and Lakes

Ponds and lakes are bordered by hills or low rises so that the water is blocked from flowing directly downhill. **Ponds** are small bodies of freshwater that usually have no outlet; ponds are often are fed by underground springs. **Lakes** are more substantial bodies of water. Lakes are usually freshwater, although the Great Salt Lake in Utah is just one exception. Water usually drains out of a lake through a river or a stream, and all lakes lose water to evaporation.

Large lakes have tidal systems and currents, and can even affect weather patterns. The Great Lakes in the United States contain 22 percent of the world's fresh surface water. The largest them, Lake Superior, has a tide that rises and falls several centimeters each day. The Great Lakes are large enough to alter the Northeastern United States' weather system by the "lake effect," which is an increase in snow downwind of the relatively warm lakes. The Great Lakes are home to countless species of fish and wildlife.

Lakes form in various ways: in depressions carved by glaciers, in calderas, and along tectonic faults, to name a few. Subglacial lakes are even found below an ice cap. As a result of geologic history and landmasses' arrangement, most lakes are in the Northern Hemisphere.

Limnology is the study of bodies of freshwater and the organisms that live there. The ecosystem of a lake is divided into three distinct sections:

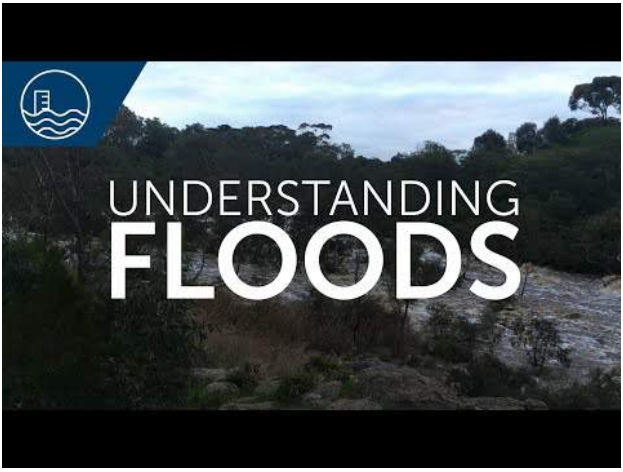
- **Surface (littoral) zone** is the sloped area closest to the edge of the water.
- **Open-water zone** (also the photic or limnetic zone) has abundant sunlight.
- **Deep-water zone** (also the aphotic or profundal zone) has little or no sunlight.

There are several life zones found within a lake. In the littoral zone, sunlight promotes plant growth, which provides food and shelter to animals such as snails, insects, and fish. In the open-water zone, other plants and fish, such as bass and trout, live. The deep-water zone does not have photosynthesis since there is no sunlight. Most deep-water organisms are scavengers, such as crabs and catfish that feed on dead organisms that fall to the bottom of the lake. Fungi and bacteria aid in the decomposition in the deep zone. Though different creatures live in the oceans, ocean waters also have these same divisions based on sunlight with similar types of creatures that live in each of the zones.

Lakes are not permanent features of a landscape. Some come and go with the seasons, as water levels rise and fall. Over a longer time, lakes disappear when they fill with sediments, if the springs or streams that fill them diminish, or if their outlets grow because of erosion. When the climate of an area changes, lakes can either expand or shrink. Lakes may disappear if precipitation significantly diminishes.

6.4 FLOODS

Floods, an overflow of water in one place, are a natural part of the water cycle, but they can be terrifying forces of destruction. Floods can occur for a variety of reasons, and their effects can be minimized in several ways. Perhaps unsurprisingly, floods tend to affect low-lying areas most severely. Floods usually occur when precipitation falls more quickly than that water can be absorbed into the ground or carried away by rivers or streams. Waters may build up gradually throughout weeks when an extended period of rainfall or snowmelt fills the ground with water and raises stream levels.



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Flash floods are sudden and unexpected, taking place when very heavy rains fall over a very brief period. A flash flood may do its damage miles from where the rain falls if the water travels far down a dry streambed so that the flash flood occurs far from the location of the original storm.

Densely vegetated lands are less likely to experience flooding. Plants slow down water as it runs over the land, giving it time to enter the ground. Even if the ground is too wet to absorb more water, plants still slow the water's passage and increase the time between rainfall and the water's arrival in a stream; this could keep all the water falling over a region to hit the stream at once. Wetlands function as a buffer between land and high-water levels and play a key role in minimizing the impacts of floods. Flooding is often more severe in areas that have been recently logged.

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When a dam breaks along a reservoir, flooding can be catastrophic. High water levels have also caused small dams to break, wreaking havoc downstream. People try to protect areas that might flood with dams, and dams are remarkably effective. People may also line a riverbank with **levees**, high walls that keep the stream within its banks during floods. A levee in one location may force the high water up or downstream and cause flooding there. The New Madrid Overflow in the image above was created with the recognition that the Mississippi River sometimes cannot be contained by levees and must be allowed to flood.

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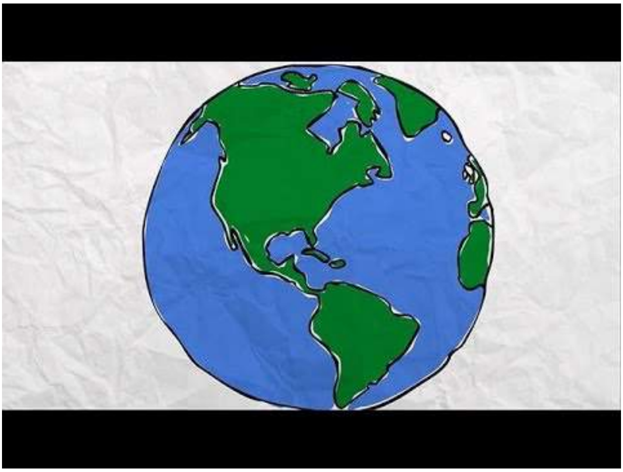
Not all the consequences of flooding are negative. Rivers deposit new nutrient-rich sediments when they flood, and so floodplains have traditionally been suitable for farming. Flooding as a source of nutrients was essential to Egyptians along the Nile River until the Aswan Dam was built in the 1960s. Although the dam protects crops and settlements from the annual floods, farmers must now use fertilizers to feed their crops.

Floods are also responsible for moving substantial amounts of sediments about within streams. These sediments provide habitats for animals, and the periodic movement of sediment is crucial to the lives of several types of organisms. Plants and fish along the

Colorado River, for example, depend on seasonal flooding to rearrange sand bars.

6.5 GROUNDWATER

Groundwater is stored in the open spaces within rocks and within unconsolidated sediments. Rocks and sediments near the surface are under less pressure than those at significant depth and therefore tend to have more open space. For this reason, and because it is expensive to drill deep wells, most of the groundwater that is accessed by individual users is within the first 100 m of the surface. Some municipal, agricultural, and industrial groundwater users get their water from greater depth, but deeper groundwater tends to be of lower quality than shallow groundwater, so there is a limit to how deep we can go.



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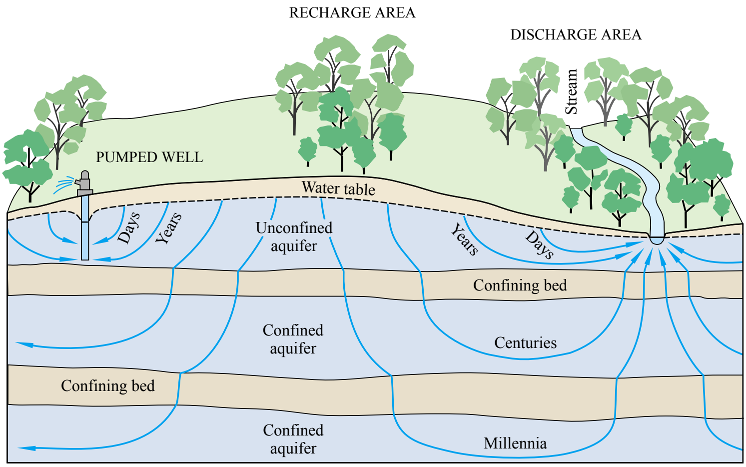
Porosity is the percentage of open space within unconsolidated sediment or rock. **Primary porosity** is represented by the spaces between grains in a sediment or sedimentary rock. **Secondary porosity** is porosity that has developed after the rock has formed. It can include **fracture porosity**, space within fractures in any rock. Some volcanic rock has a particular type of porosity related to vesicles, and some limestone has increased porosity related to cavities within fossils.



“Groundwater Flow” by the United States Geologic Survey is licensed under Public Domain.

Porosity is expressed as a percentage calculated from the volume of open space in a rock compared with the total volume of rock. Unconsolidated sediments tend to have higher porosity than consolidated ones because they have no cement, and most have not been strongly compressed. Finer-grained materials (e.g., silt and clay) tend to have greater porosity, some as high as 70 percent, than coarser materials (e.g., gravel). Primary porosity tends to be higher in well-sorted sediments compared to poorly sorted sediments, where there is a range of smaller particles to fill the spaces made by the larger particles. **Glacial till**, which has a wide range of grain sizes and is typically formed under compression beneath glacial ice, has relatively low porosity.

"Terminus of the Fox Glacier, New Zealand" by Paul Morris is licensed under the Creative Commons Attribution-ShareAlike 2.0 Generic license.

Consolidation and cementation during the process of lithification of unconsolidated sediments into sedimentary rocks reduce primary porosity. Sedimentary rocks generally have porosities in the range of 10 percent to 30 percent, some of which may be secondary (fracture) porosity. The grain size, sorting, compaction, and degree of cementation of the rocks all primary influence porosity. For example, poorly sorted and well-cemented sandstone and well-compressed mudstone can have incredibly low porosity. Igneous or metamorphic rocks have the lowest primary porosity because they commonly form at depth and have interlocking crystals. Most of their porosity comes in the form of secondary porosity in fractures. Of the consolidated rocks, well-fractured volcanic rocks and limestone with cavernous openings produced by dissolution have the highest potential porosity, while intrusive igneous and metamorphic rocks, which formed under enormous pressure, have the lowest. Porosity is a measure of how much water can be stored in geological materials. Most rocks have some porosity and therefore contain groundwater. Groundwater is found under the ground and everywhere on the planet. Considering that sedimentary rocks and unconsolidated sediments cover about 75 percent of the continental crust with an average thickness of a few hundred meters and that they are likely to have around 20 percent porosity on average, it is easy to see that a considerable volume of water can be stored in the ground.

Porosity is a description of how much space there could be to hold water under the ground, and permeability describes how those pores are shaped and interconnected. This determines how easy it is for water to flow from one pore to the next. Larger pores mean there is less friction between flowing water and the sides of the pores. Smaller pores mean more friction along pore walls, but also more twists and turns for the water to have to flow-through. A permeable material has a sizable number of well-connected pores spaces, while an impermeable material has fewer, smaller pores that are poorly connected. Permeability is the most crucial variable in groundwater. Permeability describes how easily water can flow through the rock or unconsolidated sediment and how easy it will be to extract it for our purposes. The characteristic of permeability of a geological material is quantified by geoscientists and engineers using some different units, but the most common is the hydraulic conductivity. The symbol used for hydraulic conductivity is K. Although hydraulic conductivity can be expressed in a range of different units, in this book, we will always use m/s. (Earle, 2015)

Unconsolidated materials are generally more permeable than the corresponding rocks (compare sand with sandstone, for example), and the coarser materials are much more permeable than the finer ones. The least permeable rocks are unfractured intrusive igneous and metamorphic rocks, followed by unfractured mudstone, sandstone, and limestone. The permeability of sandstone can vary widely depending on the degree of sorting and the amount of cement present. Fractured igneous and metamorphic rocks, especially fractured volcanic rocks, can be highly permeable, as can limestone dissolve along fractures and bedding planes to create solutional openings. Both sand and clay deposits (and sandstone and mudstone) are quite porous (30 percent to 50 percent for sand and 40 percent to 70 percent for silt and clay), but while sand can be quite permeable, clay and mudstone are not.

We have now seen a wide range of porosity in geological materials and an even more extensive range of permeability. Groundwater exists everywhere there is porosity. However, whether groundwater can flow in significant quantities depends on the permeability. An **aquifer** is a body of rock or unconsolidated sediment with sufficient permeability to allow water to flow through it. Unconsolidated materials like gravel, sand, and even silt make relatively good aquifers, as do rocks like sandstone. Other rocks can be suitable aquifers if they are well fractured. An **aquitard** is a body that does not transmit a significant amount of water, such as clay, a till, or a poorly fractured igneous or metamorphic rock. These are relative terms, not absolute, and are usually defined based on someone's desire to pump groundwater; an aquifer to someone who does not need much water may be an aquitard to someone else who does. An aquifer that is exposed at the ground surface is called an **unconfined aquifer**. An aquifer where there is a lower permeability material between the aquifer and the ground surface is known as a **confined aquifer**, and the aquitard separating the ground surface, and the aquifer is known as the **confining layer**.

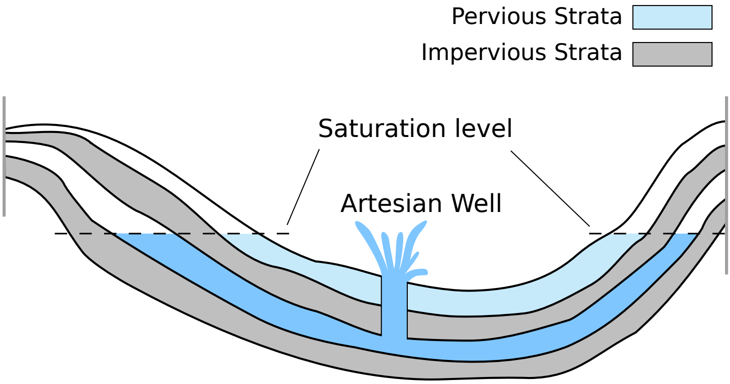
If a person were to go out into their garden or a forest or a park and start digging, they would find that the soil is moist (unless you are in a desert), but it is not saturated with water. This means that some of the pore space in the soil is occupied by water, and some of the pore space is occupied by air (unless you are in a swamp). This is known as the **unsaturated zone**. If a person were to dig down far enough, they would get to the point where all of the pore spaces are 100 percent filled with water (saturated), and the bottom of your hole would fill up with water. The level of water in the hole represents the water table, which is the surface of the **saturated zone**.

Water falling on the ground surface as precipitation (rain, snow, hail, fog, etc.) may flow off a hill slope directly to a stream in the form of runoff, or it may infiltrate the ground, where it is stored in the unsaturated zone. The water in the unsaturated zone may be used by plants (transpiration), evaporate from the soil (evaporation), or continue past the root zone and flow down to the water table, where it recharges the groundwater.

In areas with topographic relief, the water table generally follows the land surface, but tends to come closer to surface in valleys, and intersects the surface where there are streams or lakes. The water table can be determined from the depth of water in a well that is not being pumped. Although, that only applies if the well is within an unconfined aquifer. In this case, most of the hillside forms the recharge area, where water from precipitation flows downward through the unsaturated zone to reach the water table. The area at the stream or lake to which the groundwater is flowing is a discharge area.

What makes water flow from the recharge areas to the discharge areas? Recall that water is flowing in pores where there is friction, which means it takes work to move the water. There is also some friction between water molecules themselves, which is determined by the viscosity-ty. Water has a low viscosity, but friction is still a factor. All flowing fluids are always losing energy to friction with their surroundings. Water will flow from areas with high energy to those with low energy. Recharge areas are at higher elevations, where the water has high gravitational energy. It was energy from the sun that evaporated the water into the atmosphere and lifted it to the recharge area. The water loses this gravitational energy as it flows from the recharge area to the discharge area.

The situation gets a lot more complicated in the case of confined aquifers, but they are es-essential sources of water, so we need to understand how they work. There is always a water table, which applies even if the geological materials at the surface have incredibly low permeability. Where there is a confined aquifer, meaning one that is separated from the surface by a confining layer, this aquifer will have its own "water table," which is called a **potentiometric surface**, as it is a measure of the total potential energy of the water. However, if we drill a well through both the unconfined aquifer and the confining layer and into the confined aquifer, the water will rise above the top of the confined aquifer to its potentiometric surface. This is known as an **artesian well** because the water rises above the top of the aquifer. In some situations, the potentiometric surface may be above the ground level. The water in a well drilled into the confined aquifer in this situation would rise above ground level, and flow out if it is not capped. This is known as a **flowing artesian well**.



“Artesian Well” by Andrew Dunn is licensed under the Creative Commons Attribution-ShareAlike 2.0 Generic license.

It is critical to understand that groundwater does not flow in underground streams nor form underground lakes. Except karst areas, with caves in limestone, groundwater flows very slowly through granular sediments or solid rock with fractures in it. Flow velocities of several centimeters per day are possible in significantly permeable sediments with significant hydraulic gradients. However, in many cases, permeabilities are lower than the ones we have used as examples here, and in many areas, gradients are much lower. It is common for groundwater to flow at velocities of a few millimeters to a few centimeters per year.

As already noted, groundwater does not flow in straight lines. It flows from areas of higher hydraulic head to areas of lower hydraulic head, and this means that it can flow “uphill” in many situations. Groundwater flows at right angles to the equipotential lines in the same way that water flowing down a slope would flow at right angles to the contour lines. The stream in this scenario is the location with the lowest hydraulic potential, so the groundwater that flows to the lower parts of the aquifer has to flow upward to reach this location. It is forced upward by the pressure differences, for example, the difference between the 112 and 110 equipotential lines.

Groundwater that flows through caves, including those in karst areas, where caves have been formed in limestone because of dissolution, behaves differently from groundwater in other situations. Caves above the water table are air-filled conduits, and the water that flows within these conduits is not under pressure; it responds only to gravity. In other words, it flows downhill along the gradient of the cave floor. Many limestone caves also extend below the water table and into the saturated zone. Here water behaves in a similar way to any other groundwater, and it flows according to the hydraulic gradient.

The Water Table

For a groundwater aquifer to hold the same amount of water, the amount of recharge must equal the amount of discharge. In wet regions, streams are fed by groundwater; the stream's surface is the top of the water table. In dry regions, water seeps down from the stream into the aquifer, often dry much of the year. Water leaves a groundwater reservoir in streams or springs, where people take water from aquifers.

Although groundwater levels do not rise and fall as rapidly as at the surface, over time, the water table will rise during wet periods and fall during droughts. One of the most interesting but extremely atypical types of aquifers are found in Florida. Although aquifers are very rarely underground rivers, in Florida, water has dissolved the limestone so that streams travel underground and aboveground. (Components of Groundwater | Geology, n.d.)

Groundwater Use

Groundwater is a significant water source for people. Groundwater can be a renewable resource, as long as when the water pumped from the aquifer is replenished. It is essential for anyone who intends to dig a well to know how deep the water table is beneath the surface. Because groundwater involves interaction between the Earth and the water, the study of groundwater is called **hydrogeology**. Some aquifers are overused; people pump out more water than is replaced. As the water is pumped out, the water table slowly falls, requiring wells to be dug deeper, which takes more money and energy. Wells may go completely dry if they are not deep enough to reach into the lowered water table.

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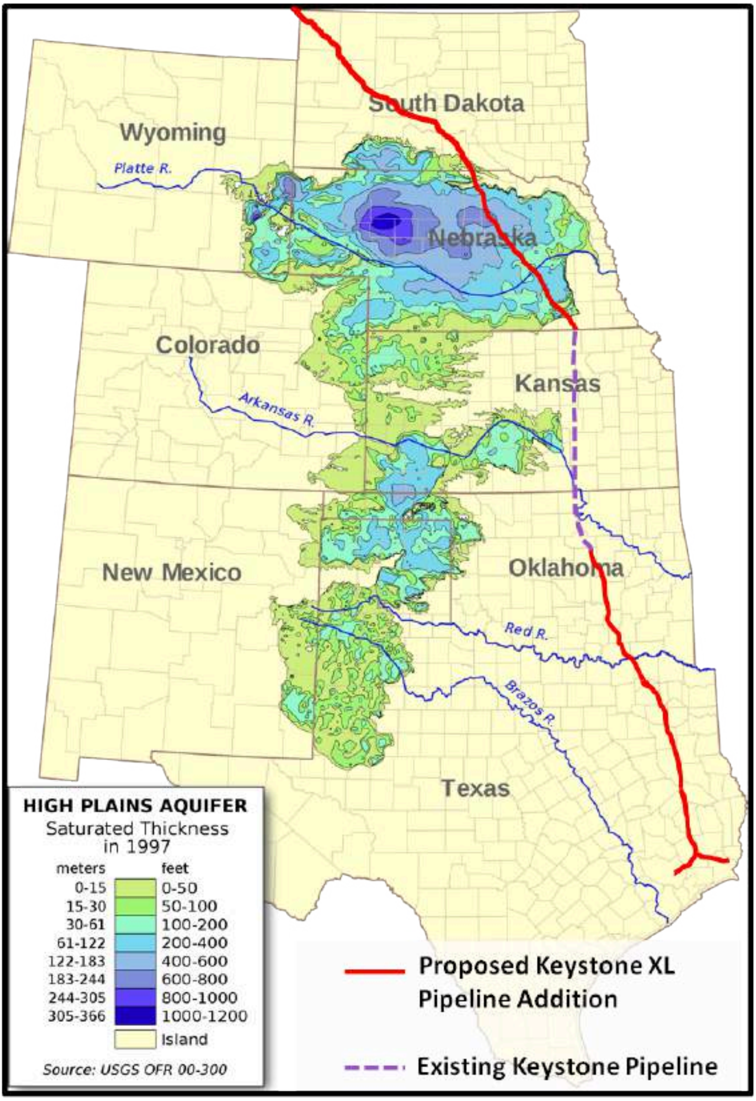
The Ogallala Aquifer supplies about one-third of the irrigation water in the United States. The aquifer is found from 30 to 100 meters deep over about 440,000 square kilometers! The water in the aquifer is mostly from the last ice age. People widely use the Ogallala Aquifer for municipal and agricultural needs. About eight times more water is taken from the Ogallala Aquifer each year than is replenished. Much of the water is used for irrigation of crops in the Breadbasket of the central plains. Currently, there is great concern about the long-term health of this vast aquifer because it is being tapped into and used at a higher rate than being replenished by natural processes. This could have huge implications regarding food production in the country if this critical water source is depleted. At current rates of use, 70 percent of the aquifer could be gone by 2050.



"Ogallala Aquifer and Keystone Pipeline" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

Overuse and lowering of the water tables of aquifers could have other impacts as well. Lowering the water table may cause the ground surface to sink. **Subsidence** may occur beneath houses and other structures. When coastal aquifers are overused, salt water from the ocean may enter the aquifer, contaminating the aquifer and making it less useful for drinking and irrigation. Saltwater incursion is a problem in developed coastal regions, such as in Hawaii.

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Springs and Wells

Groundwater meets the surface in a stream or a spring. A spring may be constant, or may only flow at certain times of the year. Towns in many locations depend on water from springs. Springs can also be a vital source of water in locations where surface water is scarce.

A well is created by digging or drilling to reach groundwater. When the water table is close to the surface, wells are a convenient method for extracting water. When the water table is far below the surface, specialized equipment must be used to dig a well. Most wells use motorized pumps to bring water to the surface, but some still require people to use a bucket to draw water up.

Finally, it is also essential to understand how water is cleaned, filtered, and delivered to our homes and work. Many of us do not know where our water comes from, and we take it for granted. This often leads to the wasteful water use of our lawns, showers, and other appliances.

Groundwater Quality

One good thing about groundwater as a source of water is that it is not as easily contaminated as surface water. However, there are two caveats to that: one is that groundwater can become naturally contaminated because of its very close connection to the materials of its aquifer, and the second is that once contaminated by human activities, groundwater is very difficult to clean up. (Earle, 2019)

Natural Contamination of Groundwater

Groundwater moves slowly through an aquifer, and unlike the surface water of a stream, it has many contacts with the surrounding rock or sediment. In most aquifers, the geological materials that make up the aquifer are relatively inert or are made up of minerals that dissolve very slowly into the groundwater. Over time, however, all groundwater gradually has increased material dissolved within it as it remains in contact with the aquifer. In some areas, that rock or sediment includes some minerals that could contaminate the water with elements that might make the water less than ideal for human consumption or agricultural use. Examples include copper, arsenic, mercury, fluorine, sodium, and boron. In some cases, contamination may occur because the aquifer material has unusually high levels of the element in question. In other cases, the aquifer material is just natural rock or sediment, but some particular feature of the water or the aquifer allows contaminants to build up to significant levels.

Rural residents in the densely populated country of Bangladesh (over 1,000 residents/km2, compared with 3.4/km2 in Canada) used to rely mostly on surface supplies for their drinking water, and many of these were subject to bacterial contamination. Infant mortality rates were among the highest in the world, and other illnesses such as diarrhea, dysentery, typhoid, cholera, and hepatitis were common. In the 1970s, international agencies, including UNICEF, started a program of drilling wells to access abundant groundwater supplies at depths of 20 m to 100 m. Eventually, over 8 million such wells were drilled. Infant mortality and illness rates dropped dramatically, but it was later discovered that the water from a high proportion of these wells has arsenic above safe levels.

Most of the wells in the affected areas are drilled into recent sediments of the vast delta of the Ganges and Brahmaputra Rivers. While these sediments are not particularly enriched in arsenic, they have enough organic matter to use up any oxygen present. This leads to water with a naturally low oxidation potential (anoxic conditions); arsenic is highly soluble under these conditions, and so any arsenic present in the sediments easily gets dissolved into the groundwater. Arsenic poisoning leads to headaches, confusion, and diarrhea, and eventually to vomiting, stomach pain, and convulsions. If not treated, the outcomes are heart disease, stroke, cancer, diabetes, coma, and death. There are ways to treat arsenic-rich groundwater, but it is a challenge in Bangladesh to implement the simple and effective technology that is available. (Earle, 2019)

Anthropogenic Contamination of Groundwater

Groundwater can become contaminated by pollution at the surface (or at depth), and there are many different anthropogenic (human-caused) sources of contamination. The vulnerability of aquifers to pollution depends on several factors, including the depth to the water table, the permeability of the material between the surface and the aquifer, the aquifer's permeability, the slope of the surface, and the amount of precipitation. Confined aquifers tend to be much less vulnerable than unconfined ones, and deeper aquifers are less vulnerable than shallow ones. Steeper slopes mean that surface water tends to run off rather than infiltrate (and this can reduce the possibility of contamination). Contamination risk is also less in dry areas than in areas with heavy rainfall. (Earle, 2019)

"Crop Circles, Kansas " by NASA is licensed under Public Domain.

The principal sources of anthropogenic groundwater contamination include the following:

- Chemicals and animal waste related to agriculture, and chemicals applied to golf courses and domestic gardens
- Agriculture
- Landfills
- Industrial operations

- Mines, quarries, and other rock excavations
- Leaking fuel storage tanks (especially those at gas stations)
- Septic systems
- Runoff from roads (e.g., winter salting) or chemical spills of materials being transported

Landfills

In the past, domestic and commercial refuse was commonly trucked to a “dump” (typically a hole in the ground), and when the hole was filled, it was covered with soil and forgotten. In situations like this, rain and melting snow can easily pass through the soil used to cover the refuse. This water passes into the waste itself, and the resulting landfill leachate that flows from the bottom of the landfill can seriously contaminate the surrounding groundwater and surface water. In the past few decades, regulations around refuse disposal have been significantly strengthened, and significant steps have been taken to reduce the amount of landfill waste by diverting recyclable and compostable materials to other locations.

A modern engineered landfill has an impermeable liner (typically heavy plastic, although engineered clay liners or natural clay may be adequate in some cases), a plumbing system for draining leachate (the rainwater that flows through the refuse and becomes contaminated), and a network of monitoring wells both within and around the landfill. Once a part or all of a landfill site is full, it is sealed over with a plastic cover, and a system is put in place to extract landfill gas (typically a mixture of carbon dioxide and methane). That gas can be sent to a nearby location where it is burned to create heat or used to generate electricity. The leachate must be treated, and that can be done in a typical sewage treatment plant.

The monitoring wells are used to assess the water table level around the landfill and collect groundwater samples so that any leakage can be detected. Because some leakage is almost inevitable, the ideal placement for landfills is in areas where the depth to the water table is significant (tens of meters if possible) and where the aquifer material is relatively impermeable. Landfills should also be situated far from streams, lakes, or wetlands to avoid contamination of aquatic habitats.

Today, hundreds of abandoned dumps are scattered across the country; most have been left to contaminate groundwater that we might wish to use sometime in the future. In many cases, it is unlikely that we will be able to do so. (Earle, 2019)

Mines, Quarries, and Rock Excavations

Mines and other operations that involve the excavation of substantial amounts of rock (e.g., highway construction) have the potential to create severe environmental damage. The exposure of rock that has previously not been exposed to air and water can lead to the oxidation of sulfide-bearing minerals, such as pyrite, within the rock. The combination of pyrite, water, oxygen, and a particular type of bacteria (Acidithiobacillus ferrooxidans) that thrives in acidic conditions leads to the generation of acidity, in some cases, to pH less than 2. Water that acidic is hazardous by itself, but the low pH also increases the solubility of certain heavy metals. The water that is generated by this process is known as acid rock drainage (ARD). ARD can occur naturally where sulfide-bearing rocks are near the surface. The issue of ARD is a primary environmental concern at both operating mines and abandoned mines. Groundwater adjacent to the contaminated streams in the area is very likely contaminated as well.

Leaking Fuel Tanks

Underground storage tanks (USTs) are used to store fuel at gas stations, industrial sites, airports, and anywhere that large volumes of fuel are used. They do not last forever, and eventually, they start to leak their contents into the ground. This is a problem at older gas stations, although it may also become a future problem at newer gas stations. Sometimes a gas station can be seen that is closed and surrounded by a chain-link fence. In virtually all such cases, the discovery of leaking USTs and the requirement has triggered the closure to cease operations and remediate the site.

Petroleum fuels are complex mixtures of hydrocarbon compounds and the properties of their components – such as density, viscosity, solubility in water, and volatility – tend to vary widely. As a result, a petroleum spill is like several spills for the price of one. The petroleum liquid slowly settles through the unsaturated zone and then tends to float on the surface of the groundwater. The more readily soluble components of the spill dissolve in the groundwater and are dispersed along with the normal groundwater flow, and the more volatile components of the spill rise toward the surface, potentially contaminating buildings. (Earle, 2019)

6.6 ATTRIBUTIONS AND REFERENCES

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6.7 ATTRIBUTIONS AND REFERENCES

PART VII

OCEANS AND COASTAL ENVIRONMENTS

7.1 SIGNIFICANCE OF OCEAN

The oceans makeup 70 percent of the planet and contain 97 percent of all the water on Earth. It also makes up most of the water stores the majority of the planet's moisture, terrestrial energy, and heat from the Sun. This energy is transferred between the equator and the two poles by larger surface currents by winds and deep ocean currents driven by ocean density differences. It also supplies the moisture and energy for storm systems and, ultimately, global climates.

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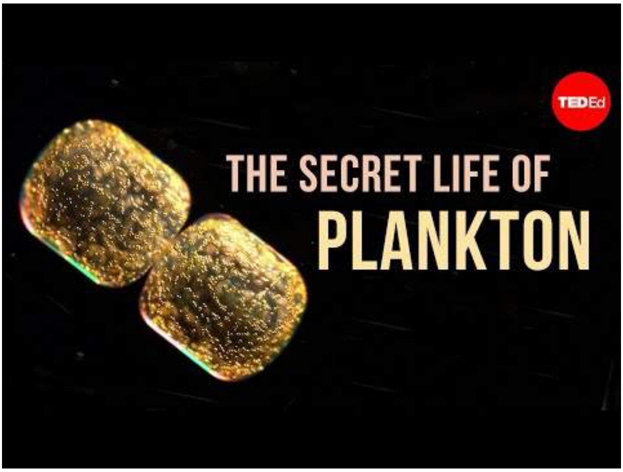
Phytoplankton, microscopic plants, and animals in the oceans provide the foundation of the **global food web** of species. The earth's oceans are so vital for life that over 40 percent of the world's population lives near coastal areas. (Ch 4 Earth's Hydrosphere, n.d.)



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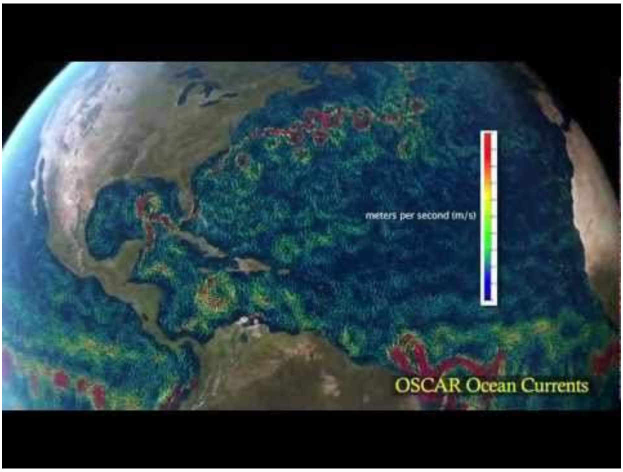
Moderate Climates

As terrestrial creatures, humans think of the importance of the planet's land surfaces, yet Earth is a planet consisting of 70 percent water. From space, the dominance of water is clear because most of it is stored in Earth's oceans. (Oceans and Coastal Environments | Earth Science, n.d.)

Earth would not be the same planet without its oceans. The oceans, along with the atmosphere, keep Earth's surface temperatures relatively constant worldwide. Some places on Earth reach as cold as -7 degrees Celsius, while other places reach as hot as 55 degrees

Celsius. On other planets like Mercury, temperatures range from -180 degrees Celsius to 430 degrees Celsius. (Significance of the Oceans | Physical Geography, n.d.)



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The oceans, along with the atmosphere, distribute heat around the planet. The oceans absorb heat near the equator and then transport that solar energy to polar regions. The oceans also moderate the climate within a region. At the same latitude, the temperature range is smaller and coastal areas compared to areas farther inland. Along coastal areas, summer temperatures are not as hot, and winter temperatures are not as cold, because water takes a long time to heat up or cool down.

Biologically Rich

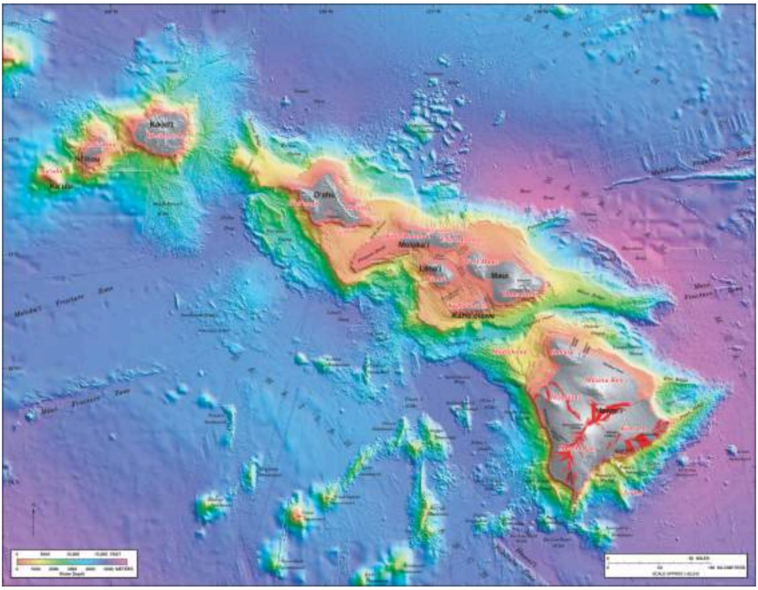
The oceans are an essential part of Earth's water cycle. Since they cover so much of the planet, most evaporation comes from the ocean, and most precipitation falls on the oceans.

"Coral Reef at the Andaman Islands" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

The oceans are also home to an enormous amount of life. That is, they have tremendous biodiversity. Tiny ocean plants create the base of a food web that supports all sorts of life forms. Marine life makes up most of all biomass on Earth. **Biomass** is the total mass of living organisms in a given area. These organisms supply us with food and even the oxygen created by marine plants.

Continental Margins

Recall from the chapter on Plate Tectonics that the ocean floor is not flat. Mid-ocean ridges, deep-sea trenches, and other features all rise sharply above or plunge deeply below the abyssal plains. Earth's tallest mountain is Mauna Kea volcano, which rises 10,203 m (33,476 ft.) from the Pacific Ocean floor to become one of the volcanic mountains of Hawaii. The deepest canyon is also on the ocean floor, the Challenger Deep in the Marianas Trench, 10,916 m (35,814 ft). The mapping of the ocean floor and coastal margins is called **bathymetry**. (Introduction to the Oceans | Earth Science, n.d.)

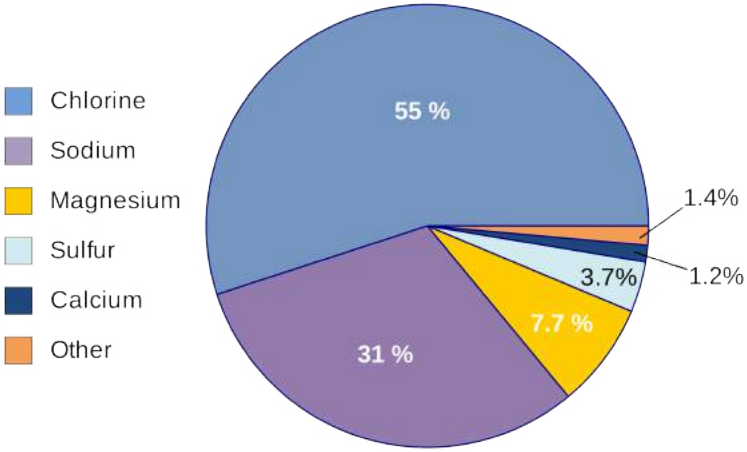


"Bathymetry of the Hawaiian Archipelago" by the USGS is licensed as Public Domain.

The **continental margin** is the transition from the land to the deep sea or, geologically speaking, from continental crust to oceanic crust. More than one-quarter of the ocean basin is the continental margin.

Composition of Ocean Water

The ocean's water is a complex system of organic and inorganic substances. Water is a polar molecule that can dissolve many substances such as salts, sugars, acids, bases, and organic molecules. Saltwater comes come water that moves through rock and soil on the land and picks up ions. This is the flip side of weathering. Salts comprise about 3.5 percent of the mass of ocean water, but the salt content or **salinity** is different in various locations.



"Composition of Ocean Water" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

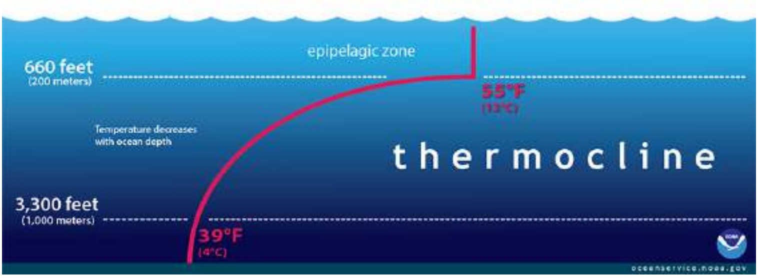
In places like estuaries, seawater mixes with freshwater, causing salinity to be much lower than average. Where there is lots of evaporation, but minimal circulation of water, salinity can be much higher. The Dead Sea has 30 percent salinity, nearly nine times the average salinity of ocean water. It is called the Dead Sea because nothing can survive within it because of its salinity. (Significance of the Oceans | Physical Geography, n.d.)

Layers of the Ocean

In 1960, two scientists in a specially designed submarine called the **Trieste** descended into a submarine trench called the Challenger Deep (10,910 meters). The average depth of the ocean is 3,790 m, a lot shallower than the deep trenches but still an incredible depth for sea creatures to live in. Three significant factors make the deep ocean hard to inhabit: the absence of light, low temperature, and extremely high pressure. The National Weather Service as information on the layers of the ocean. (Layers of the Ocean | Physical Geography, n.d.)

Vertical Divisions

To better understand regions of the ocean, scientists define the **water column** by depth. They divide the entire ocean into two zones vertically, based on the light level. Large lakes are divided into similar regions. Sunlight only penetrates the sea surface to a depth of about 200 m, creating the **photic zone** (consisting of the Sunlight Zone and Twilight Zone). Organisms that photosynthesize depend on sunlight for food and so are restricted to the photic zone. Since tiny photosynthetic organisms, known as **phytoplankton**, supply nearly all of the energy and nutrients to the rest of the marine food web, most other marine organisms live in or at least visit the photic zone. In the aphotic zone (consisting of the Midnight Zone and the Abyss), there is not enough light for photosynthesis. The **aphotic zone** makes up most of the ocean, but has a small amount of its life, both in the diversity of type and numbers. (Introduction to the Oceans | Earth Science, n.d.)



"Thermocline" by NOAA is licensed as Public Domain.

Horizontal Divisions

The seabed is also divided into the zones described above, but the ocean itself is separated horizontally by distance from the shore. Nearest to the shore lies the **intertidal zone**, the region between the high and low tidal marks. This hallmark of the intertidal is changed, where water is in constant motions from ocean waves, tides, and currents. The land is sometimes underwater and sometimes is exposed. The **neritic zone** is from low tide mark and slopes gradually down to the edge of the seaward side of the continental shelf. Some sunlight penetrates the seabed here. The

oceanic zone is the entire rest of the ocean from the bottom edge of the neritic zone, where sunlight does not reach the bottom.

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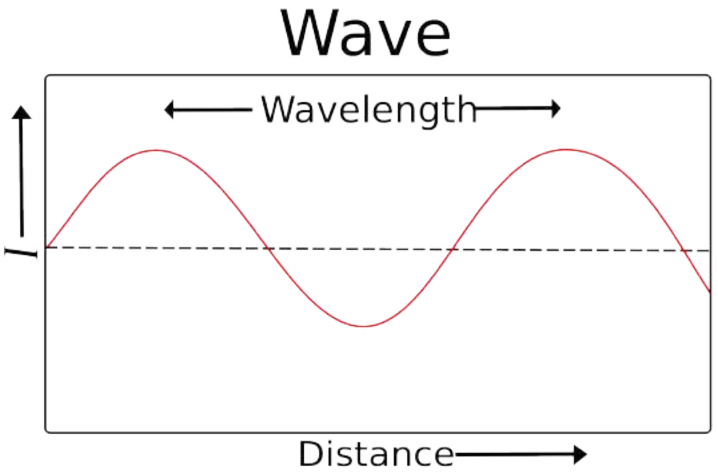
7.2 WAVES

Waves form on the ocean and lakes because energy from the wind is transferred to the water. The stronger the wind, the longer it blows, and the larger the area of water over which it blows (the fetch), the larger the waves are likely to be.

The essential parameters of a wave are its **wavelength** (the horizontal distance between two crests or two troughs), its **amplitude** (the vertical distance between a **trough** and a **crest**), and its velocity (the speed at which wave crests move across the water). Relatively small waves move up to about 10 km/h and arrive on a shore about once every 3 seconds. Huge waves move about five times faster (over 50 km/h), but because their wavelengths are so much longer, they arrive less often – about once every 14 seconds. (17.1 Waves – Physical Geology, n.d.)



“Wavelength” is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

As a wave moves across the water’s surface, the water itself mostly moves up and down and only moves a small amount in the direction of wave motion. As this happens, a point on the water surface describes a circle with a diameter equal to the wave amplitude. This motion is also transmitted to the water underneath, and the water is disturbed by a wave to a depth of approximately one-half of the wavelength.

The one-half wavelength depth of disturbance of the water beneath a wave is known as the **wave base**. Since ocean waves rarely have wavelengths higher than 200 m, and the open ocean is several thousand meters deep, the wave base does not frequently interact with the ocean’s bottom. However, as waves approach the much shallower water near the shore, they start to “feel” the bottom, and they are affected by that interaction. The wave “orbits” are both flattened and slowed by dragging, and the implications are that the wave amplitude (height) increases, and the wavelength decreases (the waves become much steeper). The ultimate result of this is that the waves lean forward, and eventually break. (17.1 Waves – Physical Geology, n.d.)

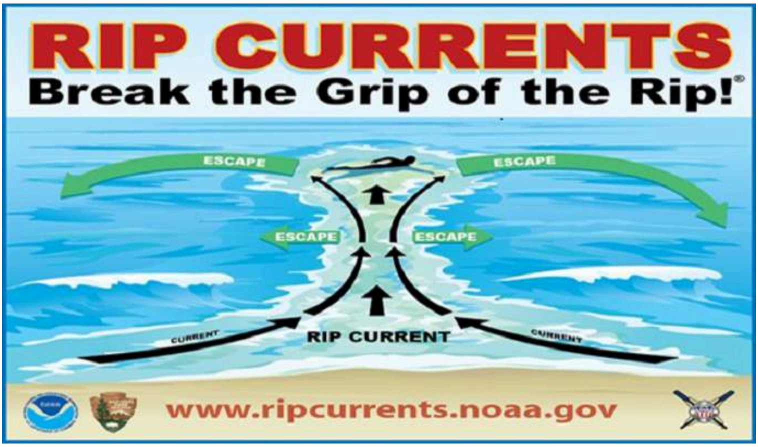
Waves usually approach the shore at an angle, and this means that one part of the wave feels the bottom sooner than the rest of it, so the part that feels the bottom first slows down first. In open water, these waves had wavelengths close to 100 m. In the shallow water closer to shore, the wavelengths decreased to around 50 m, and in some cases, even less.

Even though they bend and become nearly parallel to the shore, most waves still reach the shore at a small angle, and as each one arrives, it pushes water along the shore, creating what is known as a **longshore current** within the **surf zone** where waves are breaking. (Ocean Movements | Earth Science, n.d.)

Another significant effect of waves reaching the shore at an angle is that when they wash up onto the beach, they do so at an angle, but when that same wave water washes back down the beach, it moves straight down the slope of the beach. The upward-moving water, known as the **swash**, pushes sediment particles along the beach, while the downward-moving water, the **backwash**, brings them straight back. With every wave that washes up and down the beach, particles of sediment are moved along the beach in a zigzag pattern.

The combined effects of sediment transport within the surf zone by the longshore current and sediment movement along the beach by swash and backwash is known as **longshore drift**. Longshore drift moves a tremendous amount of sediment along coasts (both oceans and large lakes) around the world, and it is responsible for creating a variety of depositional features.

A **rip current** is another type of current that develops in the nearshore area and has the effect of returning water that has been pushed up to the shore by incoming waves. Rip currents flow straight out from the shore and are fed by the longshore currents. They die out quickly outside the surf zone but can be dangerous to swimmers who get caught in them. If part of a beach does not have a strong unidirectional longshore current, the rip currents may be fed by longshore currents going in both directions.



"Rip Currents" by the National Weather Service is licensed as Public Domain.

Behavior of Waves Approaching Shore

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In the open sea, waves generally appear choppy because wave trains from many directions interact with each other. Where crests converge with other crests, called **constructive interference**, they add together producing peaks, a process referred to as **wave amplification**. Constructive interference of troughs produces **hollows**. Where crests converge with troughs, they cancel each other out, called **destructive interference**. As waves approach the shore and begin to make frictional contact with the seafloor (i.e., water depth is a half wavelength or less), they begin to slow down, but the energy carried by the wave remains the same, so they build up higher. The water moves in a circular motion as the wave passes, with the water that feeds each circle being drawn from the trough in front of the advancing wave. As the wave encounters shallower water at the shore, there is eventually insufficient water in front of the wave to supply a complete circle, and the crest pours over, creating a breaker. (12 Coastlines – An Introduction to Geology, n.d.)

Some of the damage done by storms is from **storm surges**. The water piles up at a shoreline as storm winds push waves into the coast. Storm surge may raise sea level as much as 7.5 m (25 ft), which can be devastating in a shallow land area when winds, waves, and rain are heavy.

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Tsunamis

A particular type of wave is generated by an energetic event affecting the seafloor, such as earthquakes, submarine landslides, and volcanic eruptions. Called **tsunamis**, these waves are created when a portion of the seafloor is suddenly elevated by movement in the crustal rocks below that are involved in an earthquake. The water is suddenly lifted, and a wave train spreads out in all directions from the mound carrying enormous energy and traveling very fast (hundreds of miles per hour).

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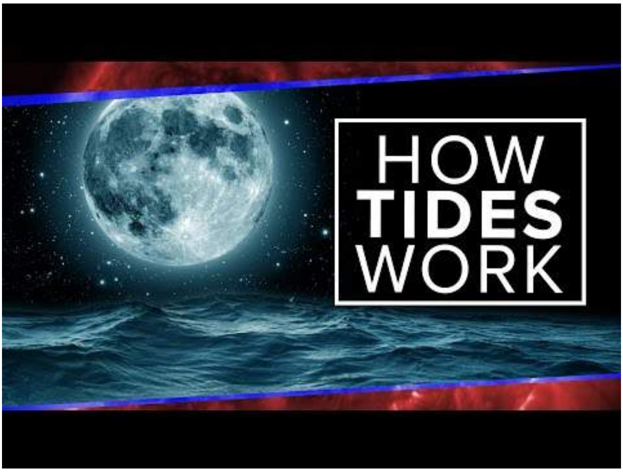
Tsunamis may pass unnoticed in the open ocean because the wavelength is very long, and the wave height is shallow. However, as the wave train approaches the shore, each wave makes contact with the shallow seafloor, friction increases, and the wave slows down. Wave height builds up, and the wave strikes the shore as a wall of water a hundred or more feet high. The massive wave may sweep inland well beyond the beach. This is called the tsunami **run-up**, which destroys structures far inland. Tsunamis deliver a catastrophic blow to observers at the beach as the water in the trough in front of it is drawn back toward the tsunami wave, exposing the seafloor. Curious and unsuspecting people on the beach may run out to see exposed offshore sea life only to be overwhelmed when the breaking crest hits. (12 Coastlines – An Introduction to Geology, n.d.)

Tidal Waves

Tides are the daily rise and fall of sea level at any given place. The pull of the Moon's gravity on Earth is the primary cause of tides, and the pull of the Sun's gravity on Earth is the secondary cause. The Moon has a more significant effect because, although it is much smaller than the Sun, it is much closer. The Moon's pull is about twice that of the Sun's.



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Daily Tide Patterns

To understand the tides, it is easiest to start with the effect of the Moon on Earth. As the Moon revolves around our planet, its gravity pulls Earth toward it. The lithosphere is unable to move much, but the gravity pulls the water above it, and a bulge is created. This bulge is the high tide beneath the Moon. The Moon's gravity then pulls the Earth toward it, leaving the water on the opposite side of the planet behind. This creates a second-high tide bulge on the opposite side of Earth from the Moon. These two water bulges on opposite sides of the Earth aligned with the Moon are the high tides. (Tides | Earth Science, n.d.)

Since so much water is pulled into the two high tides, **low tides** form between the two high tides. As the Earth rotates beneath the Moon, a single spot will experience two high tides and two low tides every day.

The **tidal range** is the difference between the ocean level at high tide and the ocean at low tide. The tidal range in a location depends on some factors, including the slope of the seafloor. Water appears to move a greater distance on a gentle slope than on a steep slope. (Ocean Movements | Earth Science, n.d.)

Monthly Tidal Patterns

Waves are additive, so when the gravitational pull of the Sun and Moon are in the same direction, the high tides add, and the low tides add. High tides are higher and low tides are lower than at other times throughout the month. These more extreme tides, with a greater tidal range, are called **spring tides**. Spring tides do not just occur in the spring; they occur whenever the Moon is in a new-moon or full-moon phase, about every 14 days. (Tidal Waves | Physical Geography, n.d.)

Neap tides are tides that have the smallest tidal range, and they occur when the Earth, the Moon, and the Sun form a 90-degree angle. They occur precisely halfway between the spring tides when the Moon is at first or last quarter. How do the tides add up to create neap tides? The Moon's high tide occurs in the same place as the Sun's low tide and the Moon's low tide in the same place as the Sun's high tide. At neap tides, the tidal range relatively small.

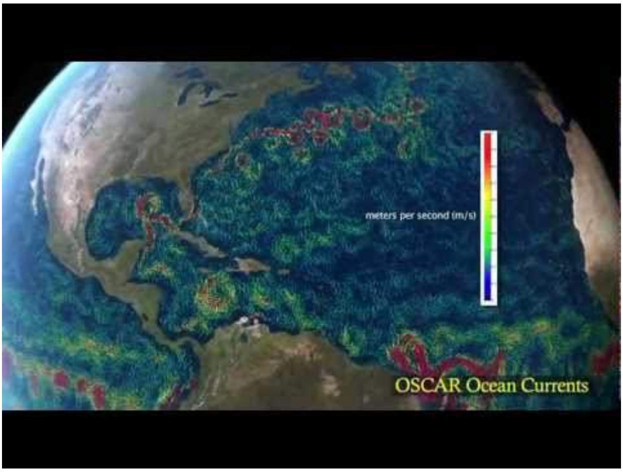
High tides occur about twice a day, about every 12 hours and 25 minutes. The reason is that the Moon takes 24 hours and 50 minutes to rotate once around the Earth, so the Moon is over the same location 24 hours and 50 minutes later. Since high tides occur twice a day, one arrives every 12 hours and 25 minutes. (Tides | Earth Science, n.d.)

Some coastal areas do not follow this pattern at all. These coastal areas may have one high and one low tide per day or a different amount of time between two high tides. These differences are often because of local conditions, such as the shape of the coastline that the tide is entering. The National Ocean Service has a wealth of information on tides and water levels.

7.3 OCEAN CURRENTS

Surface Currents

Ocean water moves in predictable ways along the ocean surface. **Surface currents** can flow for thousands of kilometers and can reach depths of hundreds of meters. These surface currents do not depend on the weather; they remain unchanged even in large storms because they depend on factors that do not change. (Surface Currents | Physical Geography, n.d.)



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Surface currents are created by three things: global wind patterns, the rotation of the earth, and ocean basins' shape. Surface currents are significant because they distribute heat around the planet and are a significant factor influencing climate around the globe.

"What Causes Ocean Currents." story map by Esri.

Global Wind Currents

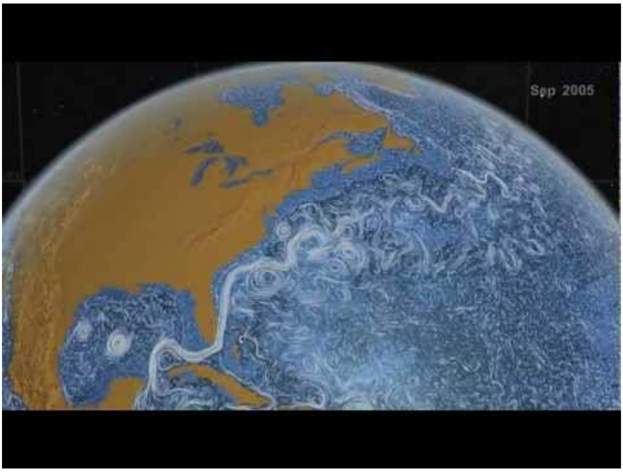
Winds on Earth are either global or local. **Global winds** blow in the same directions all the time and are related to the unequal heating of Earth by the Sun, that is that more solar radiation strikes the equator than the polar regions, and the rotation of the Earth called the Coriolis effect. The causes of the global wind patterns will be described later when we look at the atmosphere. (Surface Currents | Physical Geography, n.d.) Water in the surface currents is pushed in the direction of the significant wind belts:

- **Trade winds** are consistent winds that flow east to west between the equator and 30 degrees North and 30 degrees South.

- **Westerlies** are winds that flow west to east in the middle latitudes.
- **Polar easterlies** are winds that flow east to west between 50 degrees and 60 degrees north and south of the equator and the north and south pole.

Rotation of the Earth

The wind is not the only factor that affects ocean currents. The **Coriolis effect** describes how Earth's rotation steers winds and surface ocean currents. The Coriolis effect causes freely moving objects to appear to move to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The objects themselves are moving straight, but the Earth is rotating beneath them, so they seem to bend.



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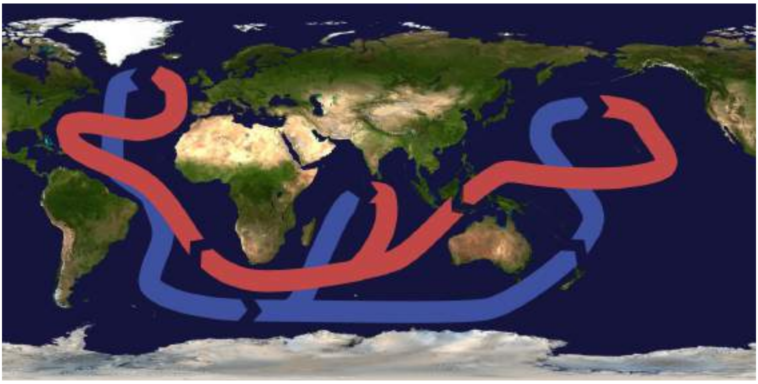
An example might make the Coriolis effect easier to visualize. If an airplane flies five hundred miles due north, it will not arrive at the city that was due north of it when it began its journey. Over the time it takes for the airplane to fly five hundred miles, that city moved, along with the Earth it sits on. Therefore, the airplane will arrive at a city to the west of the original city (in the Northern Hemisphere) unless the pilot has compensated for the change. So, to reach his intended destination, the pilot must also veer right while flying north.

As wind or ocean currents move, the Earth spins underneath it. As a result, an object moving north or south along the Earth will appear to move in a curve, instead of in a straight line. Wind or water that travels toward the poles from the equator is deflected to the east, while wind or water that travels toward the equator from the poles gets bent to the west. The Coriolis effect bends the direction of surface currents to the right in the Northern Hemisphere and left in the Southern Hemisphere. (Surface Currents | Physical Geography, n.d.)

Deep Currents

Thermohaline circulation drives deep ocean circulation. Thermo means heat, and haline refers to salinity. Differences in temperature and salinity change the density of seawater. Thermohaline circulation is the result of density differences in water masses because of their different temperature and salinity. (Ch 4 Earth's Hydrosphere, n.d.)



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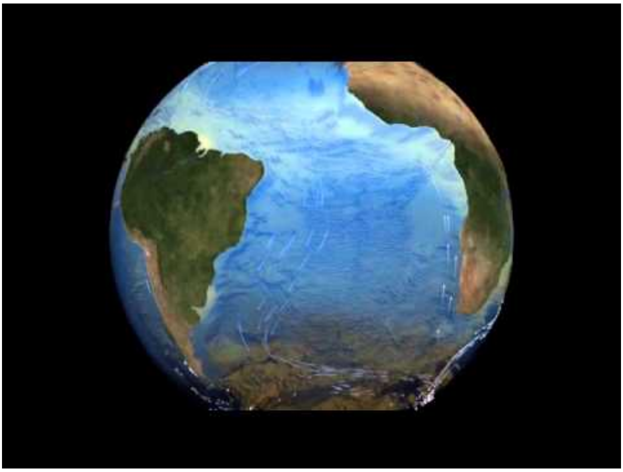
Lower temperature and higher salinity yield the densest water. When a volume of water is cooled, the molecules move less vigorously, so the same number of molecules takes up less space, and the water is denser. If salt is added to a volume of water, there are more molecules in the same volume, so it is denser. Changes in temperature and salinity of seawater take place at the surface. Water becomes dense near the poles. Cold polar air cools the water and lowers its temperature, increasing its salinity. Freshwater freezes out of seawater to become sea ice, which also increases the salinity of the remaining water. This frigid, very saline water is very dense and sinks, a process called **downwelling**.

Two things then happen. The dense water pushes deeper water out of its way, and that water moves along the bottom of the ocean. This deep-water mixes with less dense water as it flows. Surface currents move water into the space vacated at the surface where the dense water sank. Water also sinks into the deep ocean off Antarctica. Since unlimited amounts of water cannot sink to the ocean's bottom, water must rise from the deep ocean to the surface somewhere. This process is called **upwelling**.



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Upwelling occurs along the coast when the wind blows water strongly away from the shore. This leaves a void that is filled with deep water that rises to the surface. Upwelling is significant where it occurs. During its time on the bottom, the cold deep water has collected nutrients that have fallen through the water column.

Upwelling brings those nutrients to the surface. That nutrient supports the growth of plankton and forms the base of a vibrant ecosystem. California, South America, South Africa, and the Arabian Sea all benefit from offshore upwelling. Upwelling also takes place along the equator between the North and South Equatorial Currents. Winds blow the surface water north and south of the equator, so deep water undergoes upwelling. The nutrients rise to the surface and support a great deal of life in the equatorial oceans. (Deep Currents | Physical Geography, n.d.)

"How Ocean Currents Impact the World" story map by Esri.

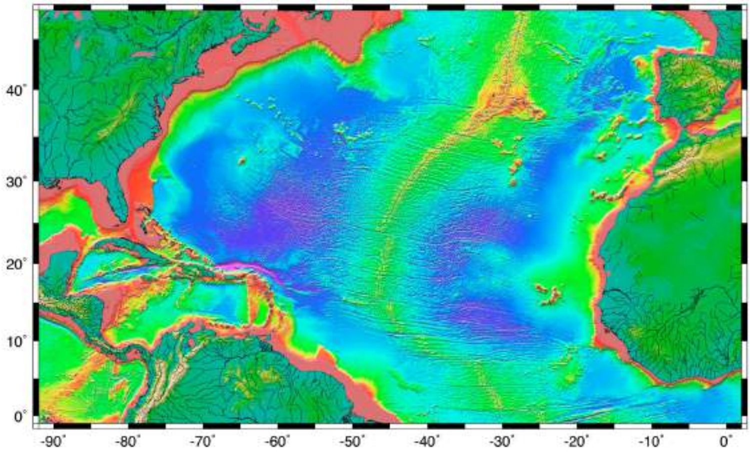
7.4 TOPOGRAPHY AND LANDFORMS

Topology of the Sea Floor

Oceans cover 71 percent of Earth's surface and hold 97 percent of Earth's water. The water the oceans hold is critical to plate tectonics, volcanism, and, of course, life on Earth. We know more about the surface of the Moon than the floor of the oceans. Whether this is true or not, the critical point is that the ocean floor is covered with an average of nearly 4,000 m of water, and it is pitch black below a few hundred meters, so it is not easy to discover what is down there. We know a lot more about the oceans than we used to, but there is still a great deal more to discover. (Earle, 2015)

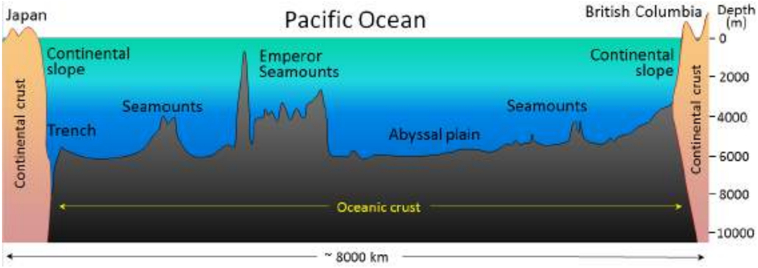
Earth has had oceans for a very long time, dating back to the point where the surface had cooled enough to allow liquid water, only a few hundred million years after Earth's formation. At that time, there were no continental rocks, so the water that was here was likely spread out over the surface in one giant (but relatively shallow) ocean. (Earle, 2019)

We examined the seafloor's topography from the perspective of plate tectonics, but here we are going to take another look at the essential features from an oceanographic perspective. The essential features are the extensive **continental shelves** less than 250 m deep (pink); the vast deep **ocean plains** between 4,000 and 6,000 m deep (light and dark blue); the mid-Atlantic ridge, in many areas shallower than 3,000 m; and the deep ocean trench north of Puerto Rico. (18.1 The Topography of the Sea Floor – Physical Geology, n.d.)



"Topography of the Atlantic Ocean Sea Floor" by NASA is licensed as Public Domain.

The main features of the Pacific Ocean floor are the continental slopes, which drop from about 200 m to several thousand meters over a distance of a few hundred kilometers; the abyssal plains – exceedingly flat and from 4,000 m to 6,000 m deep; volcanic seamounts and islands; and trenches at subduction zones that are up to 11,000 m deep.



"Generalized Topography of the Pacific Ocean Sea Floor" by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

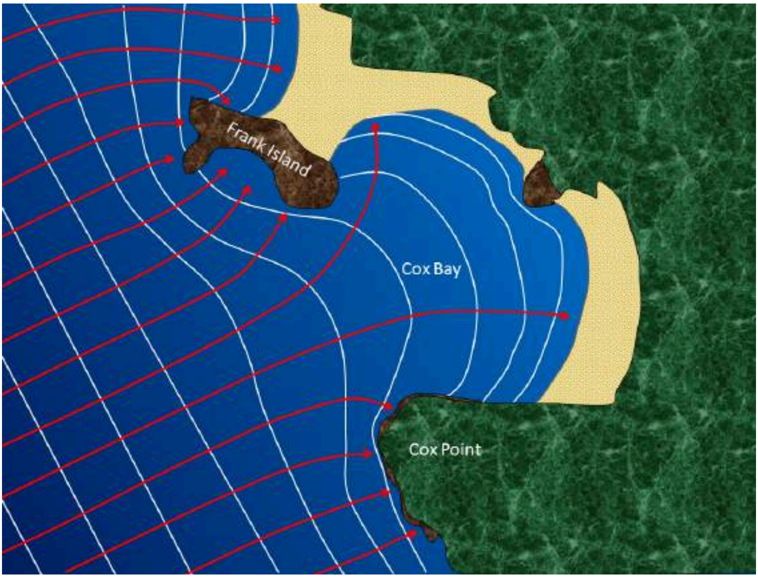
The ocean floor is entirely underlain by mafic oceanic crust, while the continental slopes are underlain by felsic continental crust (mostly granitic and sedimentary rocks). Moreover, the denser oceanic crust floats lower on the mantle than continental crust does, and that is why oceans are oceans. Although the temperature of the ocean surface varies widely, from a few degrees either side of freezing in polar regions to over 25°C in the tropics, in most parts of the ocean, the water temperature is around 10°C at 1,000 m depth and about 4°C from 2,000 m depth to the bottom. (18.1 The Topography of the Sea Floor – Physical Geology, n.d.)

The deepest parts of the ocean are within the subduction trenches, and the deepest of these is the Marianas Trench in the southwestern Pacific (near Guam) at 11,000 m. Other trenches in the southwestern Pacific are over 10,000 m deep; the Japan Trench is over 9,000 m deep, and the Puerto Rico and Chile-Peru Trenches are over 8,000 m deep. Shallow trenches tend to be that way because they have significant sediment infill. There is no recognizable trench along the subduction zone of the Juan de Fuca

Plate because it has been filled with sediments from the Fraser and Columbia Rivers. (Earle, 2015)

Landforms of Coastal Erosion

Large waves crashing onto a shore bring a tremendous amount of energy that has a significant eroding effect, and several unique erosion features commonly form on rocky shores with strong waves. When waves approach an irregular shore, they are slowed down to varying degrees, depending on differences in the water depth, and as they slow, they are bent or refracted. That energy is evenly spaced out in the deep water, but because of refraction, the waves' energy, which moves perpendicular to the wave crests, is being focused on the **headlands**. On irregular coasts, the headlands receive much more wave energy than the intervening bays, and thus they are more strongly eroded. The result of this is **coastal straightening**. An irregular coast, like the west coast of Vancouver Island, will eventually become straightened, although that process will take millions of years.



"Coastal Straightening" by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

Wave erosion is highest in the surf zone, where the wave base is impinging strongly on the seafloor and where the waves are breaking. The result is that the substrate in the surf zone is typically eroded to a flat surface known as a **wave-cut platform**, or **wave-cut terrace**. A wave-cut platform extends across the **intertidal zone**. (3.3 Crystallization of Magma – Physical Geology – 2nd Edition, n.d.)

Resistant rock that does not get eroded entirely during the formation of a wave-cut platform will remain behind to form a **stack**. Here the different layers of the sedimentary rock have different resistance to erosion. The upper part of this stack is made up of rock that resisted erosion, and that rock has protected a small pedestal of underlying softer rock. The softer rock will eventually be eroded, and the big rock will become just another boulder on the beach.

“Basalt Sea Stack” is licensed under the Creative Commons Attribution-ShareAlike 4.0 International license.

Arches and **sea caves** are related to stacks because they all form because of the erosion of non-resistant rock. (17.2 Landforms of Coastal Erosion | Physical Geology, n.d.)

“Akun Island Basalt Sea Cave” by the U.S. Fish and Wildlife Service is licensed as Public Domain.

Submarine Canyons

Submarine canyons are narrow and deep canyons located in the marine environment on continental shelves. They typically form at the mouths of sizeable landward river systems, both by cutting down into the continental shelf during low sea levels and by continual material slumping or flowing down from the mouth of the river or a delta. Underwater currents rich in sediment pass through the canyons, erode them and drain onto the ocean floor. Steep delta faces and underwater flows of sediments are released down the continental slope as underwater landslides, called turbidity flows. The erosive action of this type of flow continues to cut the canyon, and eventually, fan-shaped deposits develop on the ocean floor beyond the continental slope.

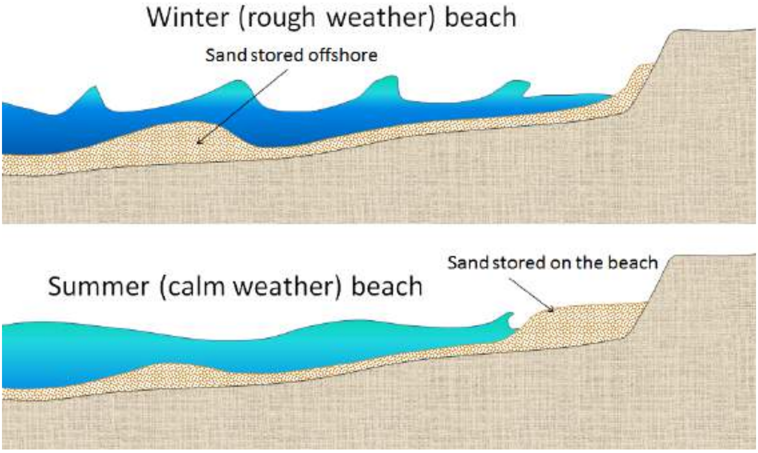
Landforms of Coastal Deposition

Some coastal areas are dominated by erosion, an example being the Pacific coast of Canada and the United States, while others are dominated by deposition, examples being the Atlantic and Caribbean coasts of the United States. However, on almost all coasts, deposition and erosion are happening to vary degrees most of the time, although in various places. On deposition-dominant coasts, the coastal sediments are still being eroded from some areas and deposited in others.

The main factor in determining if the coast is dominated by erosion or deposition is its history of tectonic activity. A coast like that of British Columbia is tectonically active, and compression and uplift have been going on for tens of millions of years. This coast has also been uplifted during the past 15,000 years by isostatic rebound due to deglaciation. The coasts of the United States along the Atlantic and the Gulf of Mexico have not seen significant tectonic activity in a few hundred million years, and except in the northeast, have not experienced post-glacial uplift. These areas have relatively little topographic relief, and there is now minimal erosion of coastal bedrock. (17.3 Landforms of Coastal Deposition – Physical Geology, n.d.)

On coasts dominated by depositional processes, most of the sediment being deposited typically comes from large rivers. An obvious example is where the Mississippi River flows into the Gulf of Mexico at New Orleans; another is the Fraser River in Vancouver. No large rivers bring sandy sediments to the west coast of Vancouver Island, but there are still long and wide sandy beaches there. In this area, most of the sand comes from glaciofluvial sand deposits situated along the shore behind the beach, and some come from the erosion of the rocks on the headlands.

On a sandy marine beach, the beach face is the area between the low and high tide levels. A berm is a flatter region beyond the reach of high tides; this area stays dry except during large storms.

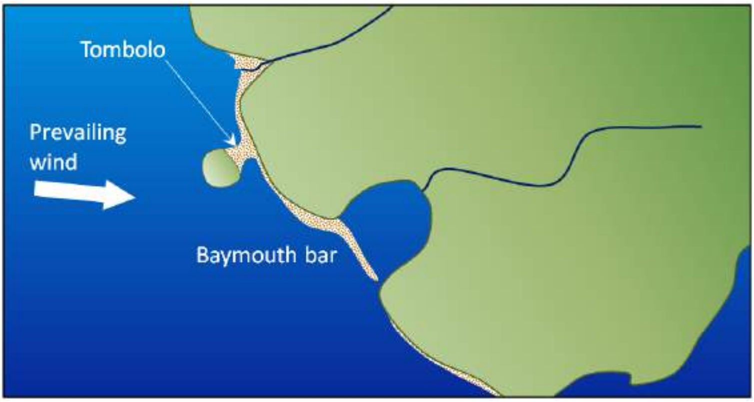


“Winter and Summer Beach Deposition” by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

Most beaches go through a seasonal cycle because conditions change from summer to winter. In summer, sea conditions are calm with long-wavelength, low-amplitude waves generated by distant winds. Winter conditions are rougher, with shorter-wavelength, higher-amplitude waves caused by strong local winds. The heavy seas of winter gradually erode sand from beaches, moving it to an underwater sandbar offshore. The gentler waves of summer gradually push this sand back toward the shore, creating a broader and flatter beach.

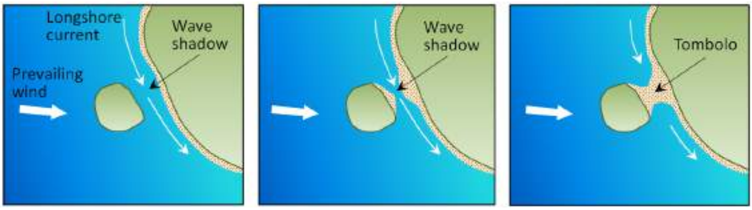
"Goose Spit at Comox on Vancouver Island" by the U.S. Fish and Wildlife Service is licensed as Public Domain.

The evolution of sandy depositional features on seacoasts is primarily influenced by waves and currents, especially longshore currents. As sediment is transported along a shore, either it is deposited on beaches, or it creates other depositional features. For example, a spit is an elongated sandy deposit that extends out into open water in the direction of a longshore current. (3.4 Classification of Igneous Rock – Physical Geology – 2nd Edition, n.d.)



"Baymouth Bar and Tombolo" by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

A spit that extends across a bay to the extent of closing, or almost closing it off, is known as a **baymouth bar**. Most bays have streams flowing into them, and since this water must get out, rarely, a baymouth bar will completely close the entrance to a bay. In areas where there is sufficient sediment being transported, and there are nearshore islands, a **tombolo** may form.



"Formation of a Tombolo" by Steven Earle is licensed under the Creative Commons Attribution 4.0 International license.

Tombolos are common where islands are abundant, and they typically form where there is a wave shadow behind a nearshore island. This becomes an area with reduced energy, and so the longshore current slows, and sediments accumulate. Eventually, enough sediments accumulate to connect the island to the mainland with a tombolo. (17.3 Landforms of Coastal Deposition – Physical Geology, n.d.)

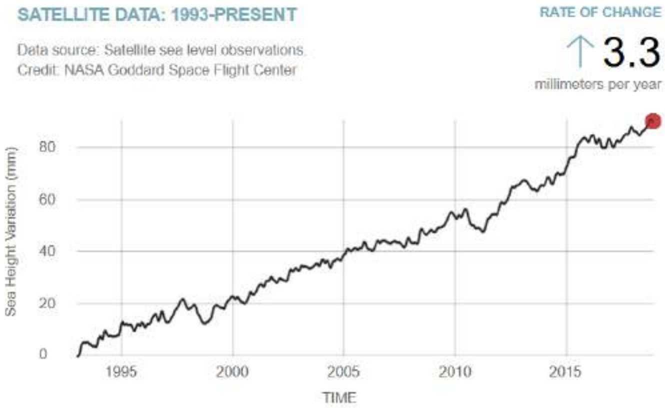
In areas where coastal sediments are abundant and coastal relief is low (because there has been little or no recent coastal uplift), it is common for barrier islands to form. **Barrier islands** are elongated islands composed of sand that form a few kilometers away from the mainland. They are common along the US Gulf Coast from Texas to Florida, and along the US Atlantic Coast from Florida to Massachusetts. North of Boston, the coast becomes rocky, partly because that area has been affected by a post-glacial crustal rebound.

Coasts in tropical regions, between 30 degrees North and South, are characterized by carbonate reefs. **Reefs** form in relatively shallow marine water within a few hundred to a few thousand meters of shore in areas where there is little or no input of clastic sediments from streams, and marine organisms such as corals, algae, and shelled organisms can thrive. The associated biological processes are enhanced where upwelling currents bring chemical nutrients from deeper water, but not so deep that the water is cooler than about 25 degrees Celsius. Sediments that form in the **back reef** (shore side) and **fore reef** (ocean side) are typically dominated by carbonate fragments eroded from the reef and from organisms that thrive in the back-reef area protected from wave energy by the reef. (17.3 Landforms of Coastal Deposition – Physical Geology, n.d.)

7.5 HUMAN IMPACTS ON THE OCEANS

Sea-Level Change

Sea-level change has been a feature on Earth for billions of years, and it has important implications for coastal processes and both erosional and depositional features. There are three primary mechanisms of sea-level change, as described below.



"NASA Satellite Sea-Level Rise Observations" by NASA is licensed as Public Domain.

Eustatic sea-level changes are global sea-level changes related to changes in the volume of glacial ice on land or changes in the shape of the seafloor caused by plate tectonic processes. For example, changes in the rate of mid-ocean spreading will change the seafloor's shape near the ridges, which affects sea level. (17.4 Sea-Level Change – Physical Geology, n.d.)

Over the past 20,000 years, there have been approximately 125 meters (410 feet) of eustatic sea-level rise due to glacial melting. Most of that took place between 15,000 and 7,500 years ago during the significant melting phase of the North American and Eurasian Ice Sheets. At around 7,500 years ago, the rate of glacial melting and sea-level rise decreased dramatically, and since that time, the average rate has been in the order of 0.7 mm/year. Anthropogenic climate change led to an accelerating sea-level rise starting around 1870. Since that time, the average rate has been 1.1 mm/year, but it has been gradually increasing. Since 1992, the average rate has been 3.2 mm/year. (17.4 Sea-Level Change – Physical Geology, n.d.) **Isostatic sea-level changes** are local changes caused by subsidence or uplift of the crust related either to changes in the amount of ice on the land or to growth or erosion of mountains.

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Almost all of Canada and parts of the northern United States were covered in thick ice sheets at the peak of the last glaciation. Following the melting of this ice, there has been an isostatic rebound of continental crust in many areas. This ranges from several hundred meters of rebound in the central part of the Laurentide Ice Sheet (around Hudson Bay) to 100 m to 200 m in the peripheral parts of the Laurentide and Cordilleran Ice Sheets – in places such as Vancouver Island and the mainland coast of BC. Although the global sea level was about 130 m lower during the last glaciation, the glaciated regions were depressed at least that much in most places, and more than that in places where the ice was thickest. (Webb, n.d.)

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Tectonic sea-level changes are local changes caused by tectonic processes. The subduction of the Juan de Fuca Plate beneath British Columbia creates tectonic uplift (about 1 mm/year) along the western edge of Vancouver Island, although much of this uplift is likely to be reversed when the next sizeable subduction-zone earthquake strikes.

Estuaries and **fiords** commonly characterize coastlines in areas where there has been a net sea-level rise in the geologically recent past. This valley was filled with ice during the last glaciation, and there has been a net rise in sea level here since that time. Uplifted wave-cut platforms or stream valleys characterize coastlines in areas where there has been a net sea-level drop in the geologically recent past. Uplifted beach lines are another product of relative sea-level drop, although these are difficult to recognize in areas with vigorous vegetation.

Emergent and Submergent Coasts

Coastlines that have a relative fall in sea level, either caused by tectonics or sea-level change, are called **emergent**. Where the shoreline is rocky, with a sea cliff, waves refracting around headlands attack the rocks behind the point of the headland.

They may cut out the rock at the base forming a sea arch that may collapse to isolate the point as a **stack**. Rocks behind the stack may be eroded, and sand eroded from the point collects behind it, forming a tombolo, a sand strip that connects the stack to the shoreline. Where sand supply is low, wave energy may erode a wave-cut platform across the surf zone, exposed as bare rock with tidal pools at low tide. Wave energy expended at the base of a sea cliff may cut a wave notch.

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Sea cliffs tend to be persistent features as the waves cut away at their base, and higher rocks calve off by mass wasting. If the coast is emergent, these erosional features may be elevated compared to the wave zone. Wave-cut platforms become marine terraces, with remnant sea cliffs inland from them.

Tectonic subsidence or sea-level rise produces a submergent coast. Features associated with submergence coasts include **estuaries**, **bays**, and **river mouths** flooded by the higher water. **Fjords** are ancient glacial valleys now flooded by post-Ice Age sea level rise. Elongated bodies of sand called **barrier islands** form parallel to the shoreline from the old beach sands, often isolated from the mainland by lagoons behind them. Some scientists hypothesize that barrier islands formed by rising sea levels as the ice sheets melted after the last ice age. Accumulation of spits and far offshore bar formations are also mentioned as formation hypotheses for barrier islands.

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Tidal flats or **mudflats** form where tides alternately flood and expose low areas along the coast. Combinations of symmetrical ripple marks, asymmetrical ripple marks from tidal currents, and mud cracks from drying form on these tidal flats. An example of ancient tidal flat deposits is exposed in the Precambrian strata found in the central part of the Wasatch Mountains of Utah. These ancient deposits provide an example of applying Hutton's Uniformity Principle. The presence of features common on modern tidal flats prompts the interpretation that these ancient deposits were formed in a similar environment. There were shorelines, tides, and shoreline processes acting at that time, yet the ancient rocks' age indicates that there were no land plants to hold products of mechanical weathering in place, so rates of erosion would have been different. The **Uniformity Principle** must be applied with some knowledge of the context of the application.

Typically, tidal flats are broken into three different sections, which may be abundant or absent in each tidal flat. **Barren zones** are areas with strong, flowing water and coarser sediment, with ripples and cross-bedding typical. **Marshes** are vegetated with natural sand and mud. **Salt pans** are the finest-grained parts of the tidal flats, with silty sediment, mud cracks, and are less often submerged.

Lagoons are locations where spits, barrier islands, or other features have partially cut off a body of water from the ocean. **Estuaries** are a (typically vegetated) type of lagoon where freshwater flows into the area and makes the water brackish (between salt and freshwater). However, terms like a lagoon, estuary, and even bay are often loosely used in place of one another. Lagoons and estuaries are transitional between terrestrial and marine geologic environments, where littoral, lacustrine, and fluvial processes can overlap.

Coral Reefs and Bleaching

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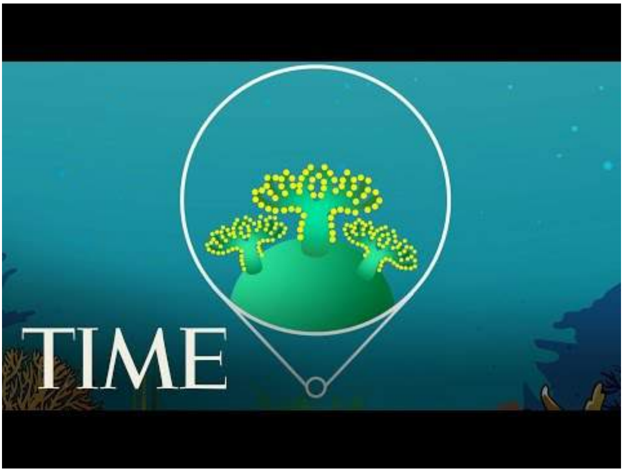

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Plastics in the Ocean

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7.6 HUMAN INTERFERENCE WITH SHORELINES

There are various modifications that we make to influence beach processes for our purposes. Sometimes these changes are effective and may appear to be beneficial, although in most cases, there are unintended negative consequences that we do not recognize until much later. (17.5 Human Interference with Shorelines | Physical Geology, n.d.)

Seawalls help limit erosion and are enjoyable amenities for the public, but they have geological and ecological costs. When a shoreline is "hardened" in this way, crucial marine habitats are lost, and sediment production is reduced, which can affect beaches elsewhere. Seawalls also affect the behavior of waves and longshore currents, sometimes with negative results.

“Seawall” by Oikos-team is licensed as Public Domain.

Groins have an effect similar to that of breakwaters, although groins are constructed perpendicular to the beach, and they trap sediment by slowing the longshore current. Most of the sediment that forms beaches along our coasts comes from rivers, so if we want to take care of the beaches, we have to take care of rivers. When a river is dammed, its sediment load is deposited in the resulting reservoir, and for the century or two, while the reservoir is filling up, that sediment cannot get to the sea. During that time, beaches (including spits, baymouth bars, and tombolos) within tens of kilometers of the river’s mouth (or more in some cases) are at risk of erosion.

"Groins and Jetties" by the National Park Service is licensed as Public Domain.

Coasts are prime real estate land that attracts the development of beach houses, condominiums, and hotels. This kind of interest and investment leads to ongoing efforts to manage the natural processes in coastal areas. Humans who find longshore drift is removing sand from their beaches often use groins in an attempt to retain it.

Similar but smaller than jetties, groins are bits of wood or concrete built across the beach perpendicular to the shoreline at the downstream end of one's property. Unlike jetties, they are used to preserve sand on a beach, rather than to divert it from an area. Sand erodes on the downstream side of the groin and collects against the upstream side. Every groin thus creates a need for another one downstream. The series of groins along a beach develops a scalloped appearance for the shoreline. (12 Coastlines – An Introduction to Geology, n.d.)

Sand for longshore drift and beaches comes from rivers flowing to the oceans from inland areas. Beaches may become starved of sand if sediment carried by streams and rivers is trapped behind dams. To mitigate, beach replenishment may be employed where sand is hauled from other areas by trucks or barges and dumped on the depleted beach. Unfortunately, this can disrupt the ecosystem that exists along the shoreline by exposing native creatures to foreign sandy material and foreign microorganisms and can even bring in foreign objects that impact humans on replenished beaches. Visitors to one replenished east coast beach found munitions and metal shards in the sand which had been brought from abandoned test ranges from which the sand had been dredged.

Another approach to reduce erosion or provide protected areas for boat anchoring is the construction of a breakwater, an offshore structure against which the waves break, leaving calmer waters behind it. Unfortunately, this means that waves can no longer reach the beach to keep the longshore drift of sand moving. The drift is interrupted, the sand is deposited in the quieter water, and the shoreline builds out, forming a tombolo behind the breakwater, eventually covering the structure with sand. The image shows this result at the breakwater constructed by the city of Venice, California, to create a quiet water harbor. The tombolo behind the breakwater is now acting as a large groin in the beach drift.

7.7 ATTRIBUTIONS AND REFERENCES

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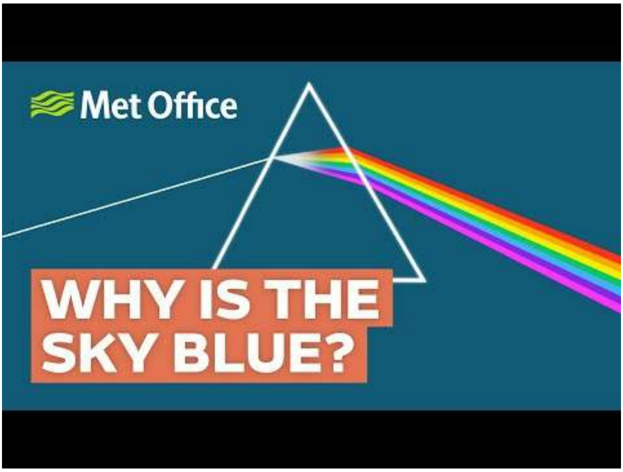
PART VIII

ATMOSPHERIC STRUCTURE

8.1 COMPOSITION AND STRUCTURE OF THE ATMOSPHERE

Composition of the Atmosphere

Vertical Structure of the Atmosphere



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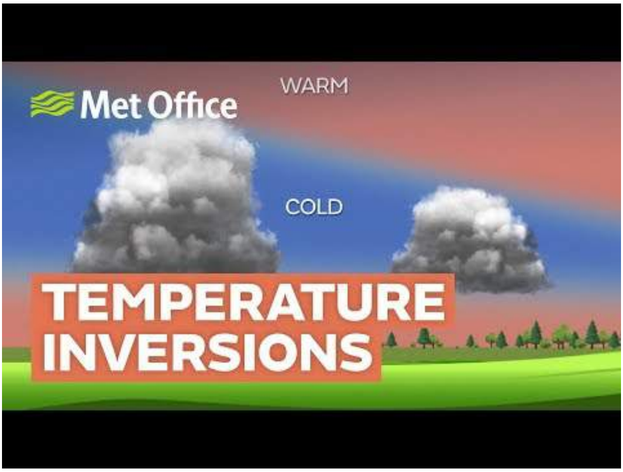

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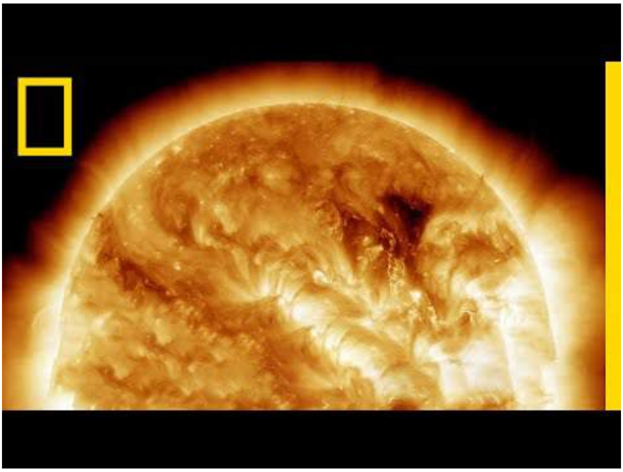
8.2 WARMING THE ATMOSPHERE

Incoming Solar Radiation

The sun is the driving force of our weather and climate. Its diameter is about 865,000 miles or 109 Earths lined up side-by-side and is so large that it makes up 99.99 percent of the mass of our Solar System. According to astronomers, our sun is the most common type of star in the known universe and has existed for nearly 4.6 billion years.

The sun's composition is about 92 percent hydrogen (the lightest element in the universe) and almost 8 percent helium (the second lightest element). Using these elements, the sun generates energy through a process called **thermonuclear reaction**. This energy is created when the sun fuses hydrogen atoms to make a heavier element called helium. This process not only creates new elements but also releases an enormous amount of energy.



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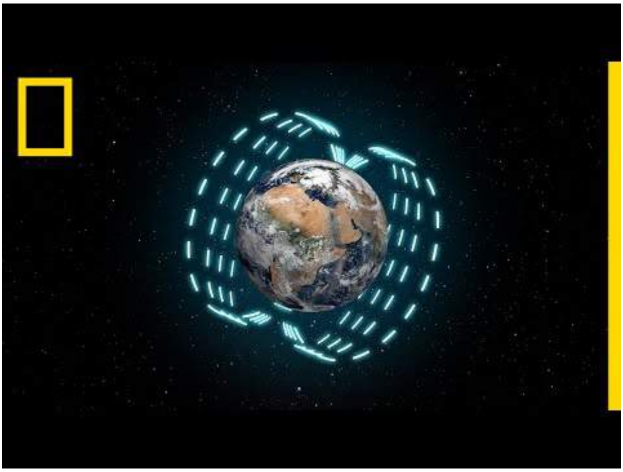
The energy emitted by the sun is called **electromagnetic energy**, a range of wavelengths from the shortwave to the longwave spectrum of light, which travels at the speed of light. Recall from the module on tsunamis that a wavelength is the distance between two wave crests, and frequency is the number of wavelengths that pass a given point in a given amount of time.



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The sun's life expectancy is already half over. In another 4 billion years, it will consume all the hydrogen within it, leaving behind helium and a few other newly created elements. When the hydrogen runs out, in about 5 billion years, the sun will grow into a red giant, expanding its diameter well past Mercury and possibly Venus and Earth. The sun will continue to fuse helium into carbon until the star begins to release its outer layers to form a **planetary nebula**. Left behind will be the white-hot core of our star, called a **white dwarf** that will slowly fade out over billions of years.

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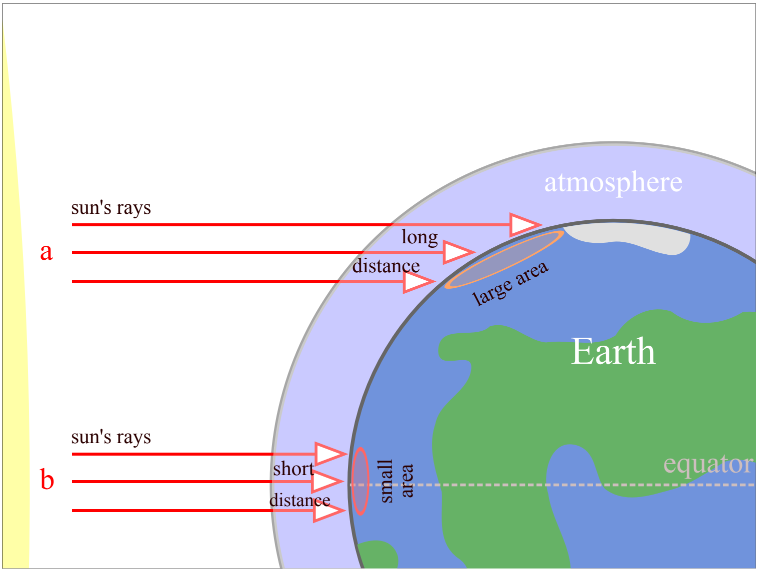
Why would you want to wear a black shirt in the winter and a white shirt in the summer? Would you rather walk barefoot on black pavement or grass? The answers to these questions relate to the idea that different objects absorb and reflect energy differently on the planet. Darker objects tend to absorb more energy, while lighter objects reflect less energy. The percent of energy an object reflects is an object's **albedo**. Because the planet has different albedos from cities, forests, deserts, oceans, rocks, glaciers, and more, the planet has uneven heating. The result is that of all the energy the Earth receives from the sun, only 51 percent is absorbed by the planet, while 49 percent is reflected into space.



"Obique Rays" by Peter Halasz has licensed under Creative Commons Attribution-Share Alike 3.0 Unported license.

Uneven heating of the planet also occurs because of the curvature of the Earth. The planet receives most of its energy near the equator, where the sun's rays are directly hitting the planet. Towards the poles, the sun's energy becomes more diffused and spread out over a greater area. The equator receives more energy from the sun than it can radiate back into space, producing a surplus of energy at 0 degrees latitude. At the poles, the planet radiates more energy out into space than it receives from the sun. There is a deficit of energy in these regions. The ultimate purpose of weather is to transfer the surplus of energy and heat from the equator to the poles, bring colder air toward the equator and find equilibrium.

Global Transfer of Heat

The source of energy for the weather on Earth is the sun. The earth-atmosphere energy balance is the balance of energy the earth absorbs, and the energy reflected into space. Roughly 51 percent of the energy the earth receives from the sun is absorbed, while approximately 49 percent of the sun's energy is reflected into space. To balance the energy deficit at the earth's poles and the energy surplus at the equator, the planet will transfer energy by conduction, convection, latent heat, and radiation.

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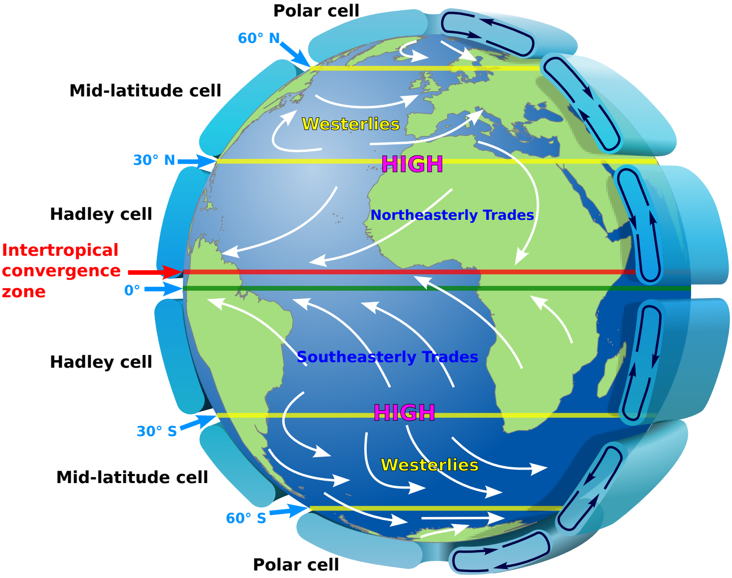
Conduction

Conduction is the transfer of heat from a warmer object to a colder object through molecule interaction. As the sun heats the ground, energy is transferred to the atmosphere by conduction. However, the atmosphere is an inferior conductor of heat. In calm weather, the heated ground only warms the first few centimeters of air. The atmosphere's temperature can be up to 50 percent colder five feet above the ground than at the surface. Since the atmosphere is such a poor conductor of heat, there must be other ways to transfer the energy.

Convection

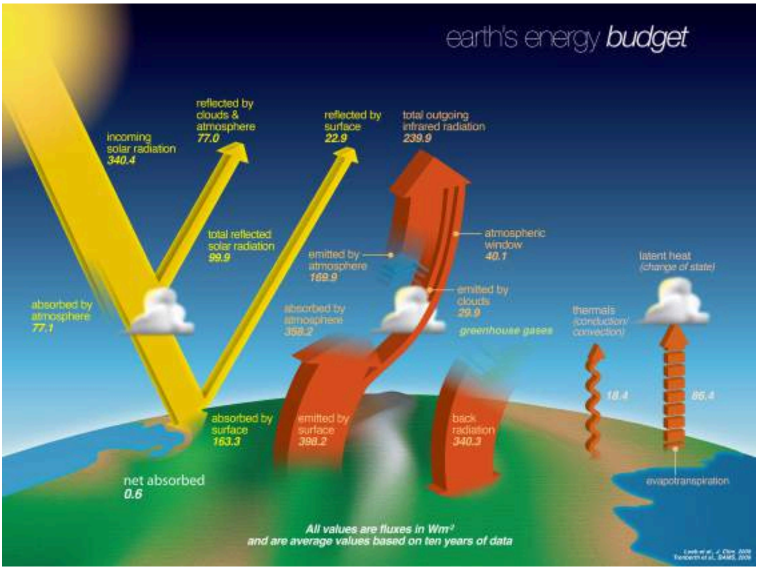
Convection is the transfer of heat by the mass movement of a fluid (such as water and air). It occurs mostly in liquids and gases because they are free to move around. Heat is transferred upward and outward away from its heat source, and cooler air is brought in to replace the rising air. On a local scale, convection in the summer can produce afternoon thunderstorms. On a global scale, convection transfers energy between the equator and poles.



"Earth Global Circulation" by NASA is licensed as Public Domain.

Radiation

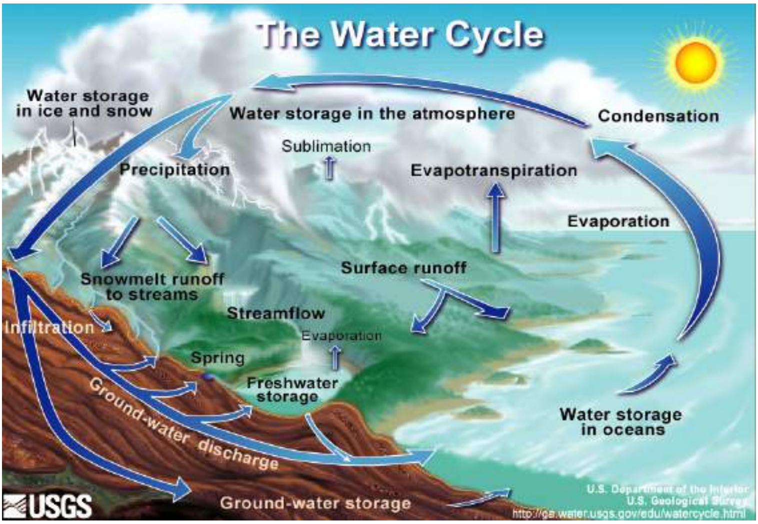
The final process of transferring heat around the planet is called **radiation**. The energy coming from the sun comes in various wavelengths. A **wavelength** is the distance measured along a wave of energy from one crest to another. The shorter the wavelength, the higher the energy. The energy received from the sun passes through the atmosphere without warming it. All objects that absorb radiation from the sun radiate some of that energy back into space, but in a weaker form of energy. This weaker energy becomes longwave radiation and is typically observed as heat. All living objects (including humans) radiate longwave radiation. The Earth itself radiates the energy absorbed from the sun in the form of longwave radiation, which is sometimes called **Earthlight**.



"Earth's Energy Budget" by NASA is licensed as Public Domain.

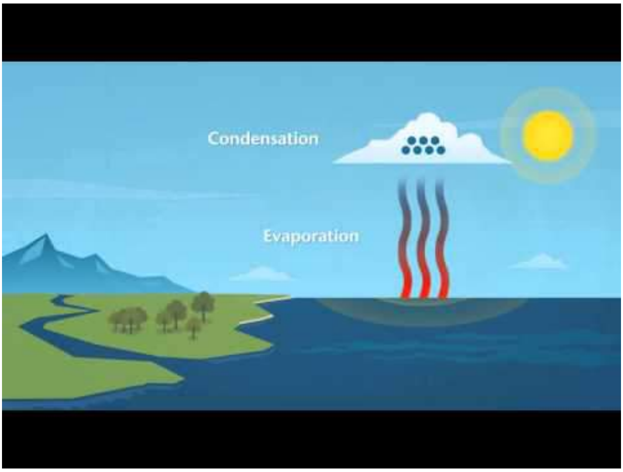
Latent Heat

Latent heat is a powerful force in the weather. When water transforms from gas to liquid or solid, or vice versa, it is called a **phase change**. The heat required to change phases is called latent heat. For water to change from a liquid to a gas, energy/heat must be taken from external sources such as the surrounding atmosphere. Therefore, evaporation is a cooling process because the water is taking heat from the surrounding air to evaporate.



"The Water Cycle" by the United States Geologic Survey is licensed as Public Domain.

The process of evaporation and condensation transfers substantial amounts of heat around the planet. The heat released in a typical thunderstorm is equal to one of the original atomic bombs. The heat and energy within a hurricane are equal to thousands of nuclear weapons or could power the United States for over a year.



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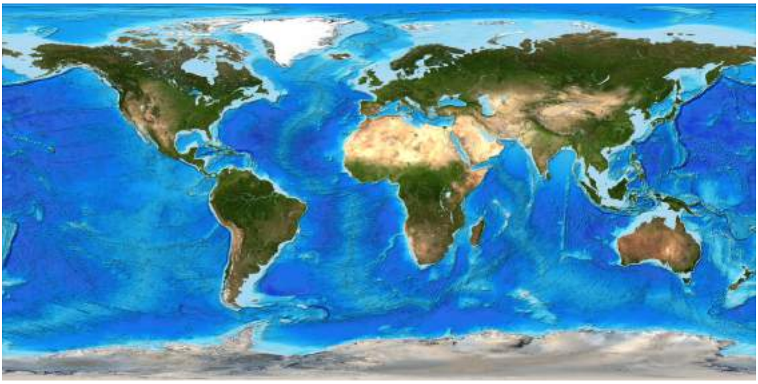
8.3 CONTROLS OF WEATHER AND CLIMATE

Latitude

Several controlling factors determine global temperatures. The first and most significant is **latitude**. Because of the Earth's shape and the sun's angle hitting the planet, temperatures are highest near the equator and decrease toward the poles. In fact, at the equator, more energy is absorbed from the sun than is radiated back into space. At the poles, more energy is radiated back into space than is absorbed by the sun. The purpose of weather and ocean currents is to balance out these two extremes.



"Large World Physical Map" is licensed as Creative Commons Attribution-ShareAlike 4.0 International.

Land-Water Distribution

The next impact on temperature is the **land-water distribution** on the planet. Places near the ocean tend to have milder climates year-round versus regions surrounded by land. This is because the earth can heat up and cool down faster and with more significant fluctuation than the ocean. The reason is that sunlight must heat a larger volume of area in the ocean because light can pass through water. Water requires five times more energy to heat one degree Celsius than for landmasses, called **specific heat**. Thus, the region's temperatures found near large bodies of water temperatures change slowly compared to land. Ocean currents are also vital controls in transferring heat around the planet. In the Northern Hemisphere, ocean currents rotate clockwise, bringing cold water from the North Pole toward the equator and warm water from the equator toward the North Pole. The opposite occurs in the Southern Hemisphere, where ocean currents rotate counterclockwise.

“Tennessee Valley Beach” by R. Adam Dastrup is licensed as Creative Commons Attribution-ShareAlike 4.0 International.

Elevation

The last control of temperature is **elevation.** On average, atmospheric temperature decreases 3.6 degrees Fahrenheit per 1,000 feet rise in elevation. This is called the **normal lapse rate** or also called the **temperature lapse rate**.

"Lake Blanch" is licensed under the Creative Commons Attribution-ShareAlike 4.0 International license.

Moisture and Humidity

For liquid water to evaporate, water molecules must absorb enough energy to break bonds between each other. To do this, the liquid water must absorb energy and heat from the surrounding environment. This release of energy is called **latent heat**. If the water vapor absorbs enough energy, they will begin to vibrate fast enough to break their molecular bonds and become individual water molecules or gas. **Evaporation** is a cooling process because it takes heat from the surrounding environment. The concept of latent heat is essential to understand and will be revisited later when cloud formation and severe weather are discussed.

"Evaporation" is licensed under the Creative Commons Attribution 2.0 Generic license.

The opposite must occur for water vapor to condense into liquid water. For fast vibrating water molecules to condense into liquid, it must release latent heat to the surrounding environment. Releasing energy allows the water molecules to slow down their vibration and attach to other water molecules to become liquid. However, one step is missing. For water vapor to become liquid, it needs something to condense onto condensation nuclei. **Condensation nuclei** consist of microscopic dust, smoke, salt particles, or even bacteria that float in the air. It is believed that bacteria make up nearly half of all condensation nuclei. To summarize, for water vapor to condense into small liquid or ice cloud droplets, condensation nuclei must be present.

"Dew" is by Piklist.

Humidity is defined as the amount of water vapor in the atmosphere. There are several ways to classify humidity, but we will focus on **relative humidity** for this course. Relative humidity is the ratio of the atmosphere's actual water vapor content divided by the amount of water vapor required for atmospheric saturation at that temperature; it is usually expressed as a percentage. If the relative humidity is 25 percent, the atmosphere is only holding a quarter of what it could hold. If the relative humidity is at 100 percent, the atmosphere is saturated.

There are two ways to change relative humidity: **moisture content** and **temperature**. If the air temperature stays the same, but the amount of water vapor increases or decreases, relative humidity will change. Next, it should first be noted that warm air can "hold" more moisture than cooler air. If the water content stays the same, but temperature increases, relative humidity will decrease. If the water content stays the same, but the temperature decreases, relative humidity will increase.

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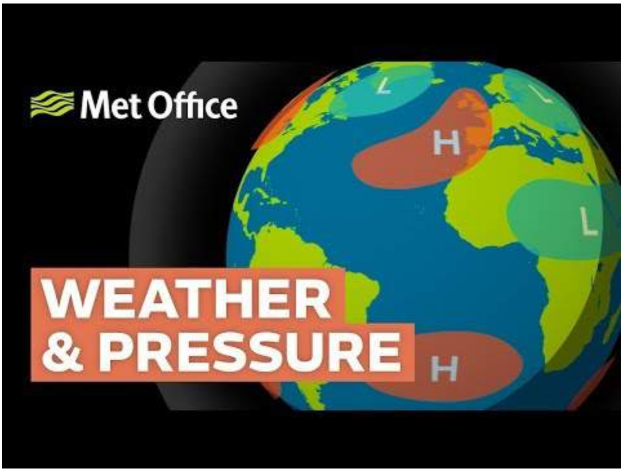
Relative humidity is just as the name implies; it is a relative measurement. A more direct measurement and analysis of humidity is **dew point**; the atmospheric temperature air must cool down to in order for it to condense into liquid water or solid ice crystals. So if the dew point is 42 degrees Fahrenheit for a particular geographic location at a particular time, then the current temperature must fall to 42 degrees for the air to become saturated. The higher the dew point reading, the less air must cool to become saturated and condense. The lower the dew point reading, the more air must cool to become saturated; thus, the air is quite dry. Dew point analysis is vital for weather forecasting in the summer to determine the likelihood of afternoon thunderstorms. If the humidity is high, providing a high dew point measurement, then afternoon convection does not require the unstable moisture to rise as high in order for condensation and thunderstorms genesis to occur. Recall that condensation from water vapor to liquid water or ice crystals releases latent heat is a crucial ingredient for the formation of thunderstorms.

Atmospheric Pressure and Wind

Atmospheric pressure is a force created by the weight of the atmosphere. Because of gravity, air pressure is highest at sea level and decreases with height. There is also high pressure and low pressure. **High pressure**, also called an **anticyclone**, occurs when descending air molecules "pile-up" at the surface and spread outward in a clockwise rotation in the Northern Hemisphere. In the Southern Hemisphere, the air within high pressure flows counterclockwise. In either case, the descending air will warm, which prevents water vapor from cooling and condensing into clouds to produce storms. Instead, regions under high pressure tend to experience clear skies. **Low pressure**, also called a **cyclone**, occurs when converging air is forced upward (in a counterclockwise manner in the Northern Hemisphere) where it cools and condenses into clouds and possible storms. Ultimately, air flows from high pressure to low pressure, and this is called **wind**.



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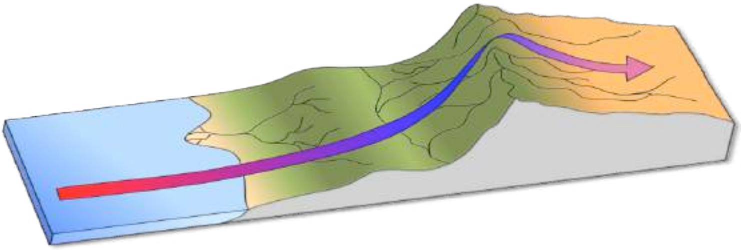
When atmospheric high pressure is near atmospheric pressure, there is an imbalance between the atmospheric pressure. The force to balance these two pressure imbalances is called the **pressure gradient force**, which creates wind. Wind is the horizontal movement of air from high pressure to low pressure to balance atmospheric pressure.

Atmospheric Stability

To have cloud formation, the air must be unstable. **Stable air** means air does not want to rise, cool, and condense. Thus, weather conditions tend to be clear skies with stable air. **Unstable air** means the air wants to rise, cool, and condense into clouds and potential storms. The forces that cause air to rise are convection, orographic uplift, convergence, and weather fronts.

Convection occurs when air rises, much like a hot air balloon. Because of albedo, some areas on the ground can get heated more than other areas. Where the land heats up more, the air above also warms, becomes less dense, and rises. If the air rises high enough, it may cool and condense to create clouds and possibly thunderstorms.

Orographic uplift is when mountains help destabilize air and occur when air must rise over a mountain range. As the air rises over the mountain, the moisture within it may begin to cool and condense to form thunderstorms. Often with orographic uplift, one side of the mountain will be very moist from the storms, while the other side is arid. The dry side of the mountain is called the **rainshadow effect**. Later we will discuss how this process can generate what is called dry thunderstorms and wildfires.



"Rainshadow Effect Caused by Orographic Uplift" is licensed as Public Domain.

"Mountains and Clouds" is licensed under the Creative Commons Attribution-ShareAlike 2.0 Generic license.

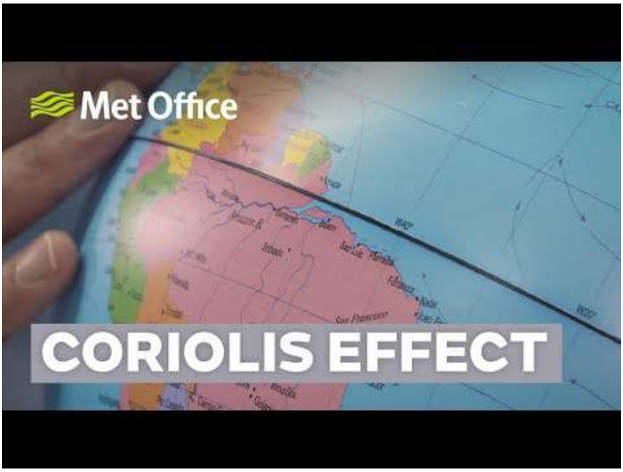
Convergence occurs when air is forced to rise because of low pressure above, causing the rising air to cool and condense into clouds. One of the best examples of this is over Florida. Because Florida is a peninsula, surrounded by water on three sides, the land heats up more than the surrounding water. This causes the air above the land to rise. To replace this rising air, humid and cooler air from the Gulf of Mexico and the Atlantic Ocean converges inward over Florida. This moist air is heated by the land and is forced upward to create powerful thunderstorms. Florida has more thunderstorms and lightning than any other state in the nation. Another excellent example of convergence is the eye of a hurricane because winds and moisture are rotating around the eye until they converge within the eye.

"Hurricane Lester on Approach to Hawaii" by NASA's Earth Observatory is licensed as Public Domain.

Finally, **weather fronts**, such as cold fronts, warm fronts, stationary fronts, and occluded fronts, can force air to rise. For example, a cold front occurs when a cold, dense air mass replaces a warm, lighter air mass. The cold air mass plows through, forcing the warmer air mass upward to cool and condense into clouds.

Coriolis Effect

All free moving objects appear to be deflected to the right in the Northern Hemisphere, and to the left in the Southern Hemisphere, because of the rotation of the Earth. This apparent deflection is called the **Coriolis effect**.



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Aside from a football, what else is considered a "free moving" object? Free moving objects include airplanes, ocean currents, clouds, wind, hurricanes, or anything else that is not attached to the earth's surface. So how does this influence the atmosphere? As winds flow from high to low pressure, it deflects to the right (in the Northern Hemisphere) because of the earth's rotation. This deflection is nonexistent at the equator and progressively gets stronger towards the poles. Because of this, hurricanes can only form 5-20 degrees north or south of the equator. Near the equator, the water is warm enough, but the Coriolis effect is too weak to make the hurricane rotate. Beyond 20 degrees latitude, the Coriolis effect is strong enough, but the waters are too cold.

8.4 MOISTURE AND HUMIDITY

Coming soon…

Types of Precipitation

For **precipitation** to occur, a variety of atmospheric conditions must occur. This includes a moisture source along with high and low pressure. Next, atmospheric instability needs to occur so that cloud formation may develop. Finally, moisture in the air needs to condense onto condensation nuclei so that the condensed moisture can become large enough to fall from the clouds in the form of precipitation. The atmosphere can produce a variety of **precipitation types**.

Rain is liquid water falling from nimbostratus or cumulonimbus clouds. Many times, in the midlatitudes, precipitation will fall from clouds in the form of ice or snow, which then melts on its way down toward the ground.

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Snow is precipitation in the form of ice crystals. The temperature the snow forms will determine the size, shape, and concentration of snowflakes. When temperatures are freezing, snowflakes tend to be small, dry, to produce "powder" and powdery. When the temperatures are warmer, the snowflakes are larger.

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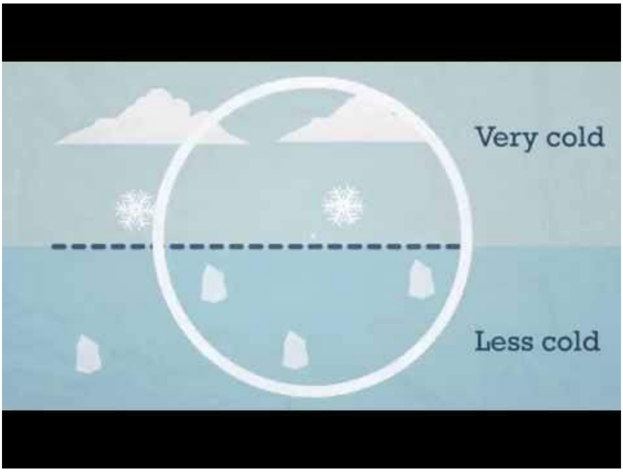
Sleet is precipitation that falls as ice pellets. It occurs when precipitation falls from the base of a cloud in the form of snow. As the snow falls, it enters a region of warm air and melts into rain. However, as the rain continues to fall, it enters a layer of cold air and refreezes in the form of ice pellets.



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Freezing rain (also called **glaze**) is similar to sleet except for the last step. As the rain falls, it enters a layer of cold air. However, the rain is not in this cold region long enough to freeze. Instead is stays as supercooled raindrops. However, once the supercooled raindrops reach the ground, they freeze instantly on any object it touches.

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Hail is precipitation in the form of hard pellets of ice and only forms in cumulonimbus clouds where the lower region of the cloud contains liquid water and is above freezing, while the upper region is below freezing. When an ice pellet falls within the cumulonimbus cloud, it enters the warm, liquid region and picks up moisture. Then the updrafts through the ice pellet back up above the freezing point hardening the newly gathered water. The ice pellet will fall again to collect liquid water and thrown back up to refreeze. This process will continue until the hailstone's weight becomes too heavy for the updrafts to hold it up. Once the hail becomes too heavy, the hail will precipitate from the cloud. (Dastrup, 2014)

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8.5 CLOUD TYPES AND FORMATION

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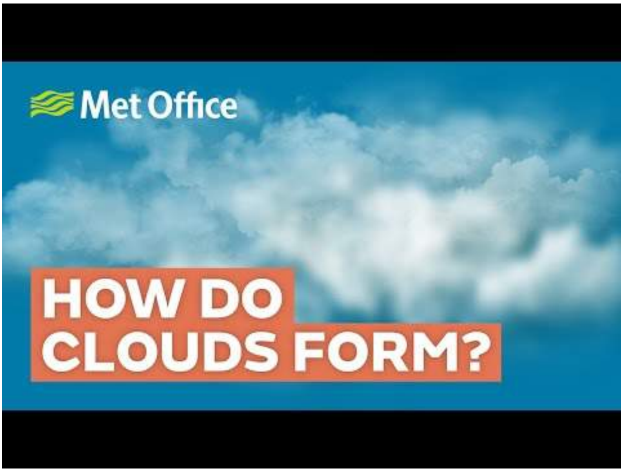

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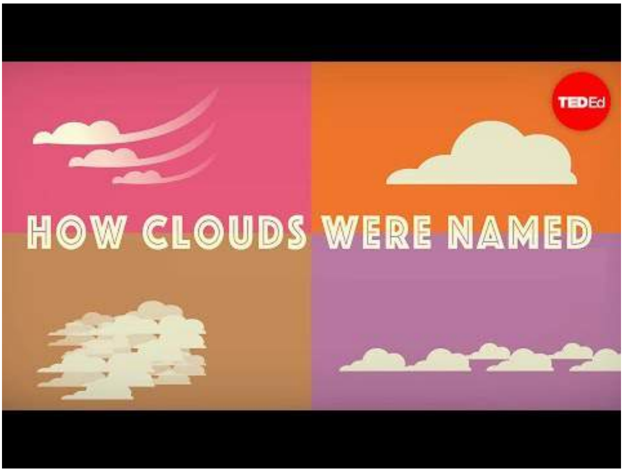

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8.6 ATMOSPHERIC PRESSURE AND WIND

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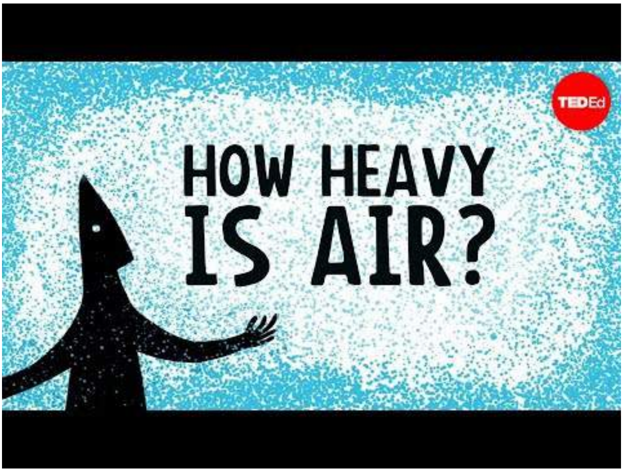

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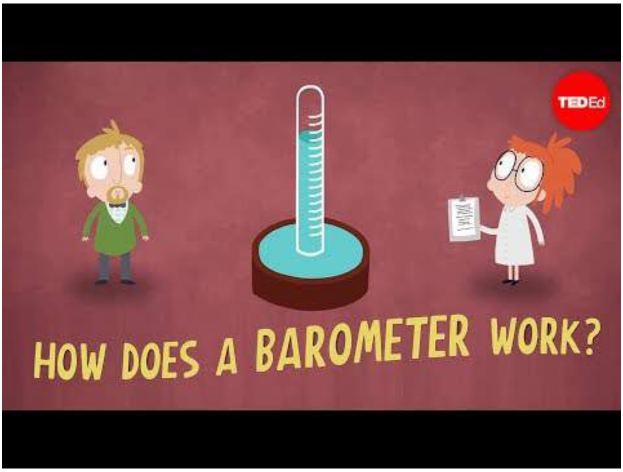

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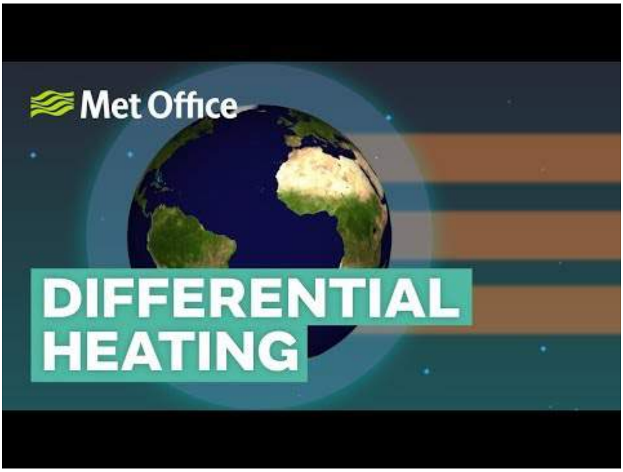

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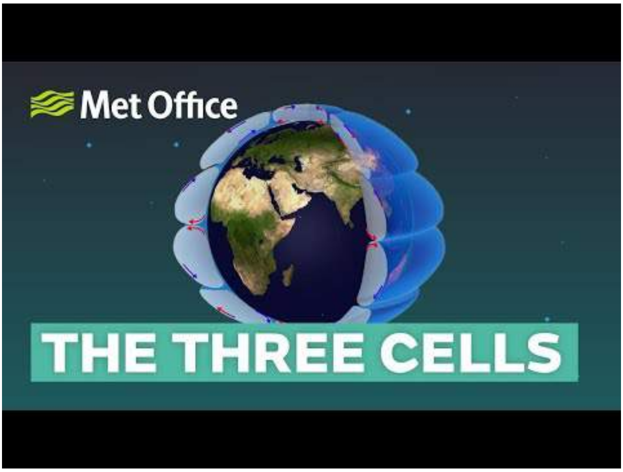

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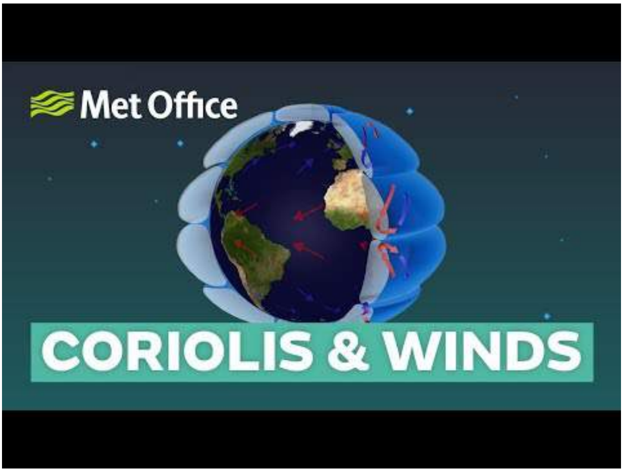

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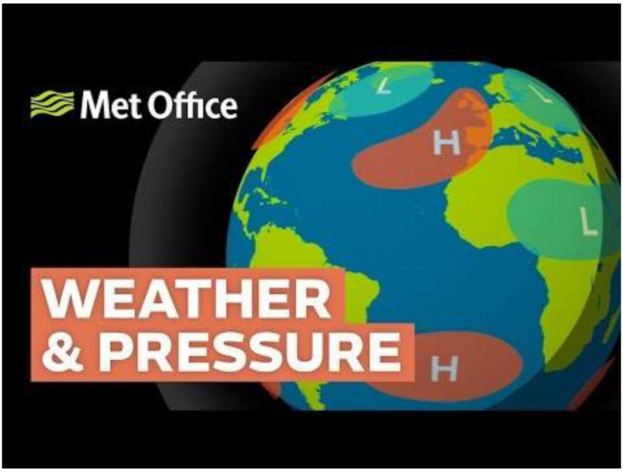

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8.7 ATTRIBUTIONS AND REFERENCES

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References

8.8 ATTRIBUTIONS AND REFERENCES

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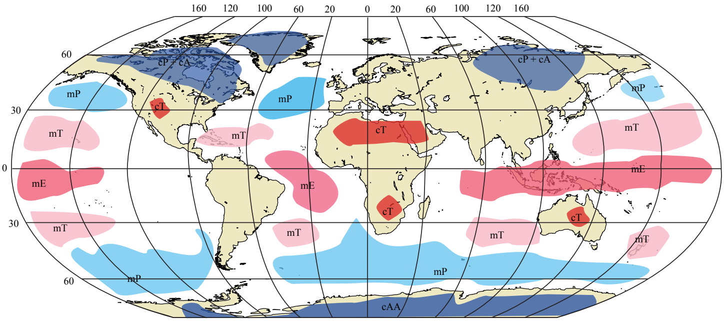
PART IX

WEATHER PROCESSES AND SYSTEMS

9.1 AIR MASSES AND WEATHER FRONTS

Air Masses

An **air mass** is a large body of air covering a relatively wide area and exhibiting "horizontally uniform properties of moisture and temperature. An air mass originates from the source region and determines the moisture and temperature characteristics of an air mass. For an air mass to develop, the surface of the source region must be relatively flat and uniform in composition (i.e., oceans, deserts, glaciers.), but not a combination. If the air mass stays long enough within the source region, it will begin to develop the characteristics of that source region. An air mass is classified by its temperature and moisture and is identified by using a "letter code" system. (Dastrup, 2014)



"Source Regions of Global Air Masses" by NASA is licensed as Public Domain.

The first letter is always lower case and determines the moisture content within the air mass:

- m (maritime) and is moist
- c (continental) and is dry

The second letter is always capital and determines latitude.

- E (equatorial) and is hot
- T (tropical) and is warm
- P (polar) and is cold
- A (arctic) and is very cold

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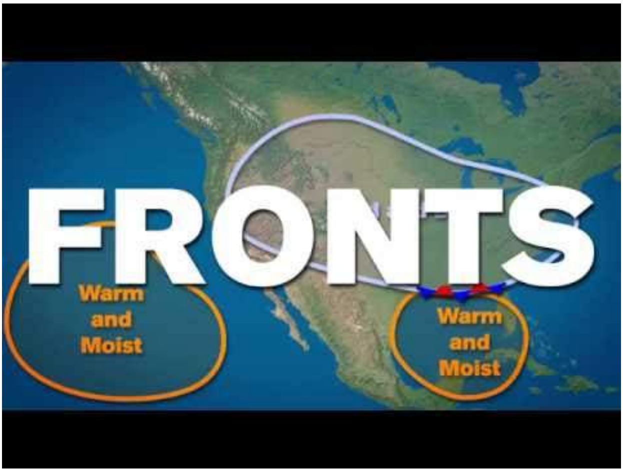
Weather Fronts

A **weather front** is a transition zone between two air masses of relatively different densities, temperatures, and moisture. When two air masses come into contact with each other, they do not like to mix well because of their different densities (much like water and oil.) Along a weather front, the warmer, less dense air rises over the colder, denser air to form clouds. There are several types of weather fronts: stationary fronts, cold fronts, warm fronts, and occluded fronts. (Dastrup, 2014)



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A **stationary front** occurs when two contrasting air masses of moisture and temperature connect, but neither of them will ground the other. In many ways, the two air masses are stuck or at a stalemate until one of them begins to give ground to the other. Typically, but not always, stationary fronts produce mild but prolonged precipitation.

Cold fronts are zones separating two distinct air masses, of which the colder, denser mass is advancing and replacing the warmer. The colder, denser air pushes under the warm air, forcing the warm, lighter air upward. If the warm air rising is unstable enough, massive thunderstorms are likely to occur. Cumulous and cumulonimbus clouds are common.

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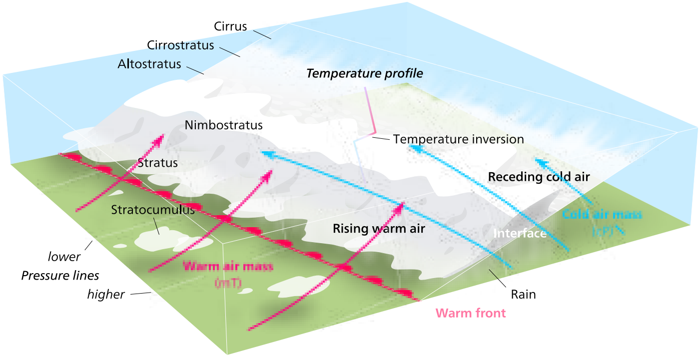
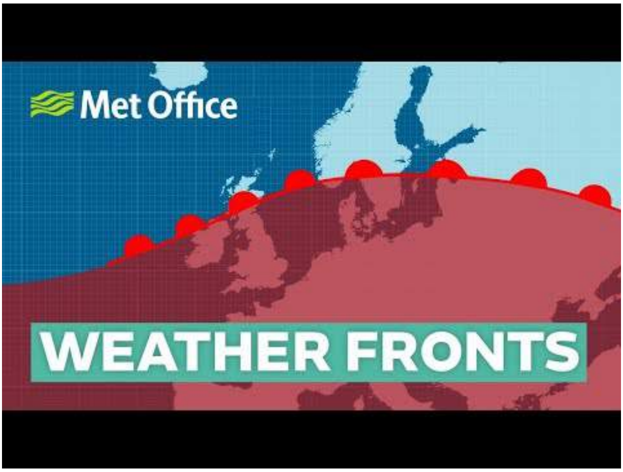
Warm fronts mark the boundary between a warm air mass that is replacing a colder air mass. When a warm air mass advances over a cold air mass, the warm air rises over, but at a gentler rate than a cold front. Since the warm air does not rise as fast as a cold front, more stratus clouds form, and precipitation is not as heavy.



"Warm Front" by Kelvin Ma is licensed under the Creative Commons Attribution-ShareAlike 4.0 International license.

Finally, **occluded fronts** occur when a cold front overtakes a warm front, causing the warmer air to rise above, and meets up with another cold air mass.



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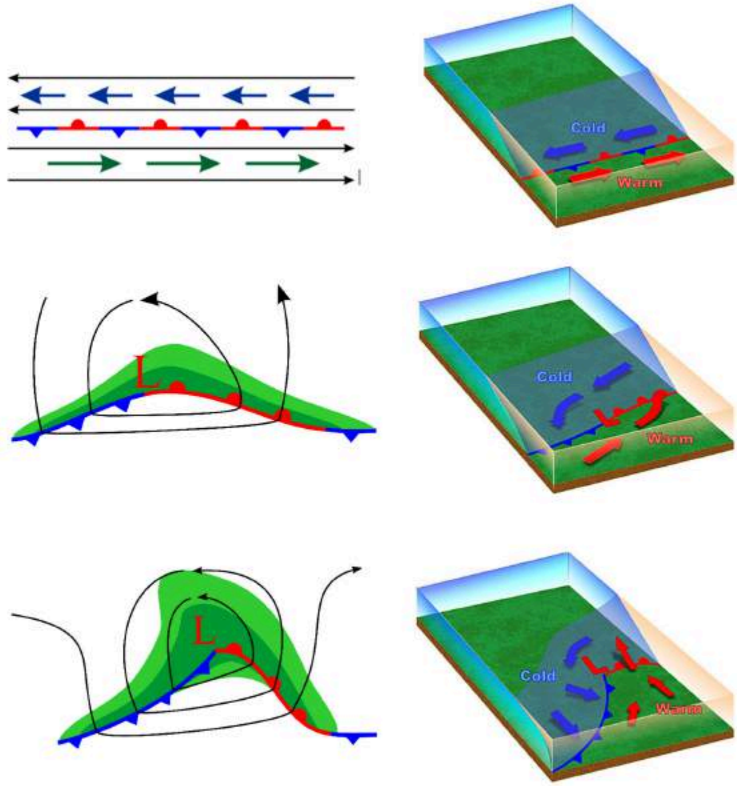
9.2 MIDLATITUDE CYCLONES

The **polar front theory**, also known as the **Norwegian model**, states that cyclones have a reasonably predictable, six-stage life cycle. We will focus on the northern hemisphere for this section. It all begins along the polar front at 60-65 degrees north, where two very different air masses with different densities meet. Clockwise rotation along with the polar high air mass (cold, dense air) and the subtropical high air mass (warm, less dense air) causes air to flow parallel to each other along the polar front but in opposite directions. Where these two different air masses meet is called a stationary front, and cyclogenesis (formating a mid-latitude cyclone) has begun.

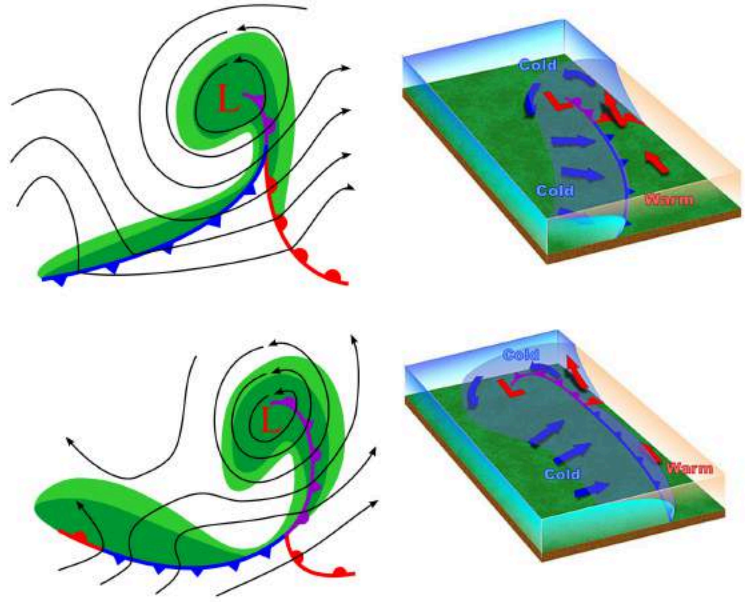
"Low-Pressure Area Over the United States" by NOAA is licensed as Public Domain.

The wind shear, caused by air that flows parallel but in the opposite direction, creates a wave rotating counter-clockwise along the polar front where warm subtropical air begins to migrate northward, and cold polar air migrates southward. In the center of this rotating wave, a low-pressure system develops, rotating counter-clockwise. The advancing boundary of the cold polar air is a cold front, and the boundary of the advancing warm sub-tropical air is a warm front.



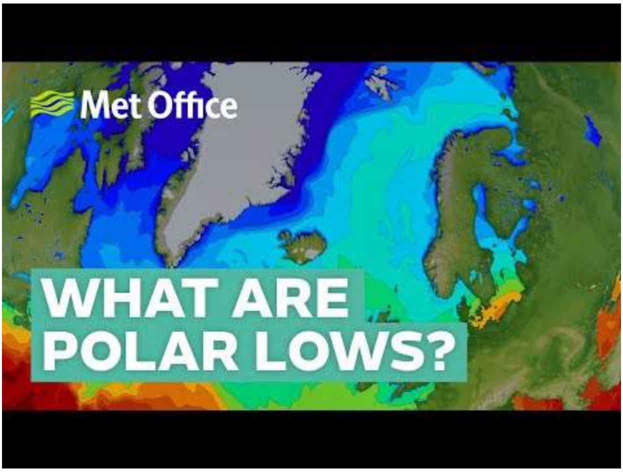
“Norwegian Model Stages 1-3” by NOAA Jetstream is licensed as Public Domain.

By stage three, the midlatitude cyclone has a defined warm front and cold front. The up-lifting of air begins to occur at this stage as the warmer, lighter, and moister air mass is forced to rise over the colder, denser, and drier air mass. A massive amount of latent heat is being released as water vapor condenses to form clouds. This release of heat strengthens the low pressure (pressure drops more), and the atmosphere becomes more unstable. In front of an advancing warm front, the air would be cool, and stratus-type clouds would begin to develop. As the weather front approaches, the stratus clouds would lower until nimbostratus clouds were overhead.



"Norwegian Model Stages 1-3" by NOAA Jetstream is licensed as Public Domain.

Typically with warm fronts, the precipitation is light but may last a few days. Once the front passed, it would feel warmer. In front of an advancing cold front, it would be warm at first with warm, southern winds blowing. Cumulus-type clouds would also begin to develop and lower as the cold front approached. Once the cold front is overhead, expect powerful cumulonimbus thunderstorms with the possibility of lightning and thunder, hail, strong winds, and intense precipitation in the form of rain or snow. Once the cold front has passed by, expect colder temperatures and winds from the north or northwest.



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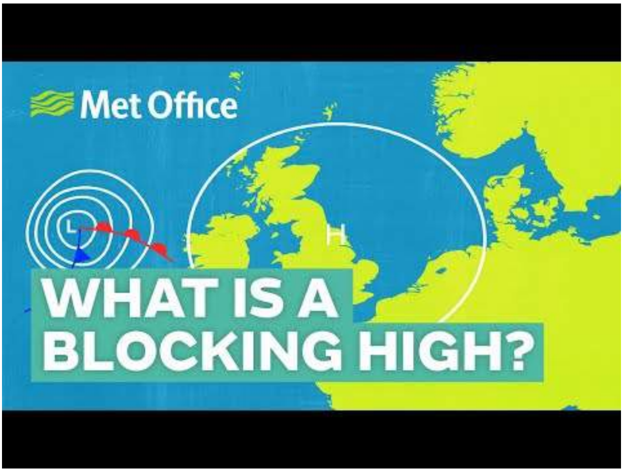
As the days move on, the cold front might begin to "catch up" to the warm front and an occluded front forms. During this stage, the cold front forces the rest of the warm air from the warm front into the upper atmosphere. Now, before the front passes, the air is cool, and afterward, the air is cold. This is when the storm is most intense powerful, as the pressure drops further, and the winds are most intense (indicated by the isobars). However, this also marks the end of the midlatitude cyclone's life cycle. Once the warm air is forced upward, there is less latent heat and less energy released into the storm. Remember that weather fronts mark the boundary between two high-pressure air masses. So once the midlatitude cyclone moves off, high pressure tends to follow. The results are clear skies, little wind, and pressure rising. (Dastrup, 2014)



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9.3 THUNDERSTORMS

Thunderstorm Basics

A **thunderstorm** is defined as a storm that has lightning and thunder. Worldwide there are over 40,000 thunderstorms every day with the United States alone having 100,000 thunder-storms yearly. The essential ingredients for a thunderstorm are warm, moist, unstable air that is forced to rise either through convection, convergence, orographic uplift, or weather fronts. The rising parcel of air condenses into various types of cumulus clouds. (Dastrup, 2014)

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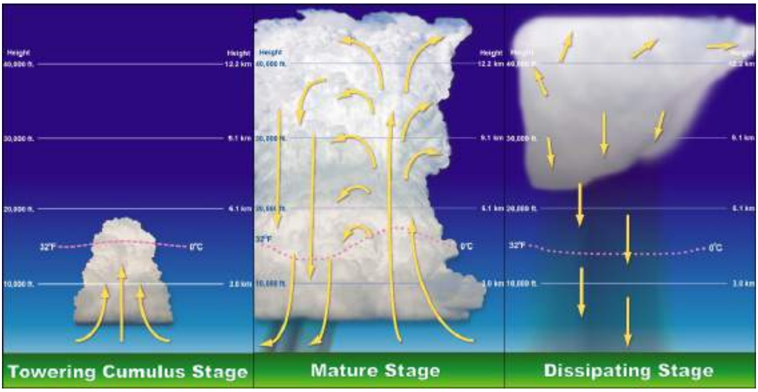
Thunderstorm Genesis

All thunderstorms go through a three-stage lifecycle. The first stage is called the **cumulus stage**, where an air parcel is forced to rise, cool, and condense, called the **lower condensation level**, to develop into a cumulus cloud. The process of water vapor condensing into liquid water releases large quantities of latent heat, which makes the air within the cloud warmer, and unstable causing the cloud continues to grow upward like a hot air balloon. These rising air parcels, called updrafts, prevent precipitation from falling from the cloud. However, once the precipitation becomes too heavy for the updrafts to hold up, the moisture begins to fall, creating downdrafts within the cloud. The downdrafts also begin to pull cold, dry air from outside the cloud toward the ground in a process called **entrainment**.



"Thunderstorm Formation" by NOAA Jetstream is licensed as Public Domain.

Once the precipitation begins to fall from the cloud, the storm has reached the mature stage. During this stage, updrafts and downdrafts exist side-by-side, and the cumulonimbus is called a **cell**. If the updrafts reach the top of the troposphere, the cumulus cloud will begin to spread outward, creating a defined **anvil**. At the same time, the downdrafts spread within the cloud and at first make the cloud more extensive, eventually overtaking the updrafts. Cold downdrafts form when precipitation and the cold air from entrainment are dragged down to the lower regions of a thunderstorm. It is also during the mature stage when the storm is most intense, producing strong, gusting winds, heavy precipitation, lightning, and possibly small hail.

Once the downdrafts overtake the updrafts, which prevents the release of latent heat energy, the thunderstorm will begin to weaken into the third and final stage, called the dissipating stage. During this stage, light precipitation and downdrafts become the dominate feature within the cloud as it weakens. Only twenty percent of the moisture within the cloud fell as precipitation, whereas the other eighty percent evaporates back into the atmosphere. (Dastrup, 2014)

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Types of Thunderstorms

Air Mass Thunderstorms

There is a variety of thunderstorms, all with defined characteristics. **Air mass thunderstorms**, sometimes called **ordinary thunderstorms**, go through the defined lifecycle sequence mentioned earlier. As the word implies, air mass thunderstorms occur when a warm, moist (mT) mass of air from a source region such as the Gulf of Mexico migrates over the land like the Great Plains. However, rather than a large-scale storm system forcing the mT air mass upward, localized uplift such as convection, sea-breezes, or orographic uplift forces the moist air within the air mass upward.

Most thunderstorms can also create other thunderstorms when downdrafts within a thunderstorm slam the ground and spread outward in an arc-shape. These rippling waves are called, **outflow boundaries** or **gust fronts**, because the cold air from the downdrafts acts like a mini-cold front. These mini-cold fronts can force warm air upward to generate new thunderstorms with cumulus development. On average, ordinary thunderstorms last about an hour. Ultimately, because of these outflow boundaries, an area may have several thunderstorms in various stages of development. These complex systems of thunderstorms can last several hours and are usually called **multi-cell thunderstorms**.

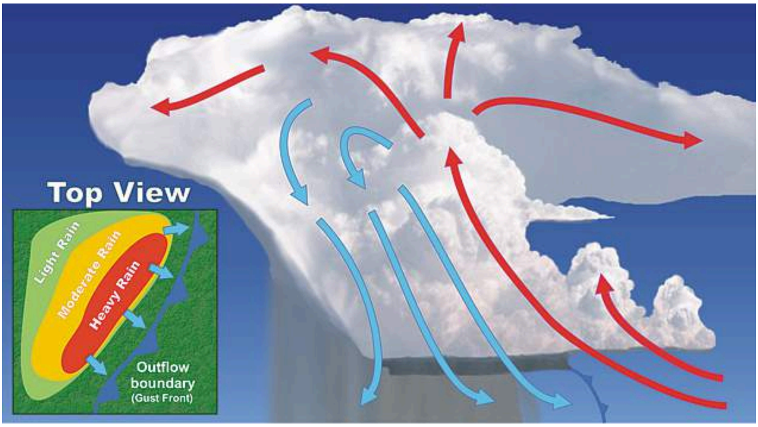
Severe Thunderstorms

The **Storm Prediction Center** classifies a severe thunderstorm as having winds that exceed 58 miles per hour or produces hail with a diameter of 1.9 centimeters. Of the 100,000 thunderstorms that develop within the United States' experiences every year, about ten percent (10,000 storms) become severe thunderstorms. These can include air mass thunderstorms, squall lines, dryline thunderstorms, and supercells.

"Squall Line" by Piklist is licensed as Public Domain.

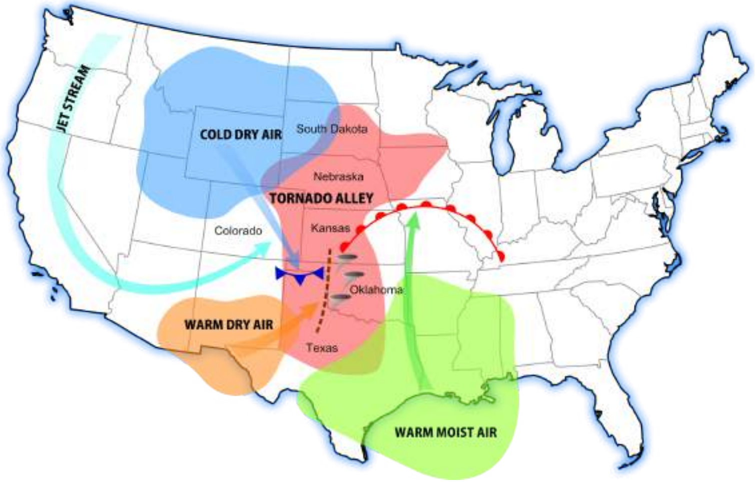
Severe thunderstorms go through the same stages as air-mass thunderstorms, but with one significant difference; severe thunderstorms last much longer in the mature stage. Ordinary thunderstorms do not last much longer than an hour because the downdrafts begin to cut off the updrafts. However, severe thunderstorms have vertical wind shear at different levels that keep the storm in the mature stage longer. This occurs when fast upper-level winds, such as the jet stream, causes the updrafts to pull away from the downdrafts. This prevents the downdrafts from cutting off the updrafts. Severe thunderstorms are capable of producing beautiful mammatus clouds, torrential downpours, flash flooding, large hail, lightning, and straight-line winds.

Squall lines are thunderstorms that develop linearly over hundreds of miles along the leading edge of outflow boundaries and are called gust fronts. Though these large storm systems are quite powerful, they do not tend to produce tornadoes. Rather, straight-line winds and precipitation form because of the powerful, horizontal movement of the gust front.



"Squall Line" by NOAA Jetstream is licensed as Public Domain.

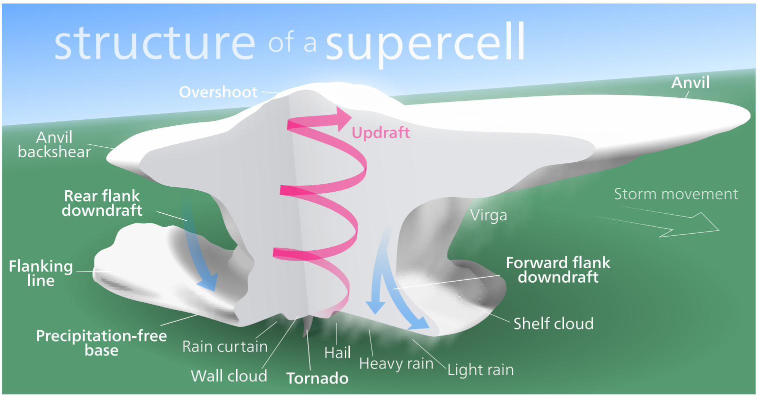
A squall line can also form along a boundary called a **dryline**. Recall from the section on mid-latitude cyclones, that the warm air in front of the cold front is usually an mT air mass. Sometimes a dry, warm cT air mass can penetrate the mT air mass and cP air mass. Drier air is denser than moist air, so when it infiltrates a storm system, it can cause the mT air mass to rise much like a cold front without the cold. The hallmark of a dryline is that the moisture within the air dramatically drops following the boundary. Drylines can produce severe thunderstorms that are often more powerful than the cold front behind it.



"Tornado Alley Diagram" by Dan Craggs is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

Supercells

The most powerful thunderstorm is a **supercell**, which is oddly enough for a single-cell thunderstorm on steroids. The United States alone has anywhere from 2,000 to 3,000 super-cells a year. Supercells consist of a single powerful thunderstorm that can last several hours and grow to a height of 65,000 feet and last several hours in the mature stage with winds reaching over 100 mph and form the majority of all tornadoes.



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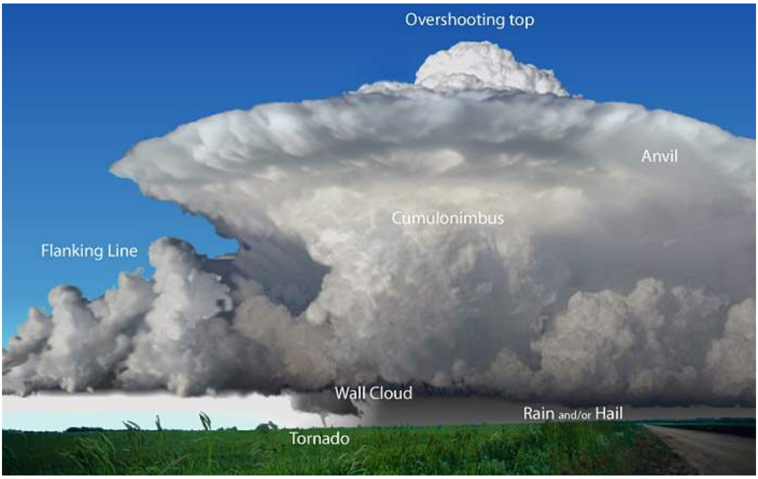
Like severe thunderstorms, supercells may have upper-level winds that can pull the up-drafts away from the downdrafts. Wind shear between the upper-level, mid-level, and surface winds can also cause the air beneath a forming supercell to rotate. For example, if there are upper-level and mid-level winds flowing from the northwest and low-level, warm southern surface winds converging together, a corkscrew flow of air could develop. This rotating column of air is then picked up by the thunderstorm's updrafts, causing the entire storm to rotate vertically, called a **mesocyclone**. Sometimes, the rotating portion of the supercell, the mesocyclone, can extend below the thunderstorm base, creating a cloud feature called a **wall cloud**.



"Idealized Supercell" by NOAA Jetstream is licensed as Public Domain.

9.4 WEATHER HAZARDS

Tornadoes

One of the most violent and destructive forces of weather are **tornadoes**. The National Weather Service states that "a tornado is a violently rotating (usually counter-clockwise in the northern hemisphere) column of air descending from a thunderstorm and in contact with the ground."

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It is pretty much an extension of a supercell's mesocyclone. They range in size from 300 feet to over two miles wide, last minutes to hours, travel a few miles to over 250 miles, at speeds of 30-65 mph. About 75 percent of all the tornadoes in the world occur in the United States; the United States has more tornadoes than the rest of the world combined.

What makes tornadoes so destructive are the wind speeds within them. Atmospheric pressure within a tornado can be 10 percent lower than the tornado's air, causing air to flow into the tornado from all directions. As the air flows into a tornado, the moisture begins to cool and condense into a cloud, allowing it to be seen. Debris picked up by the tornado will also cause it to darken.

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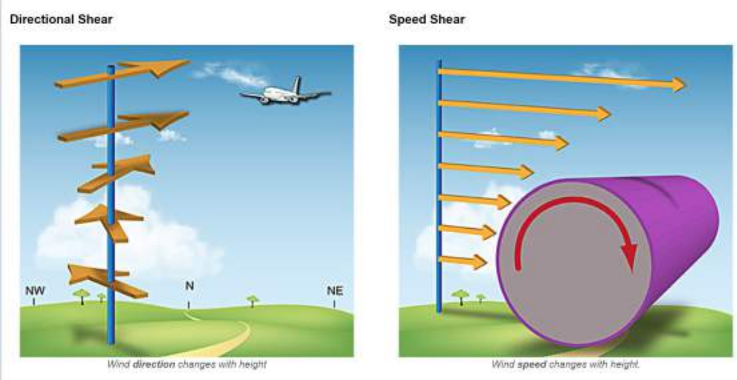
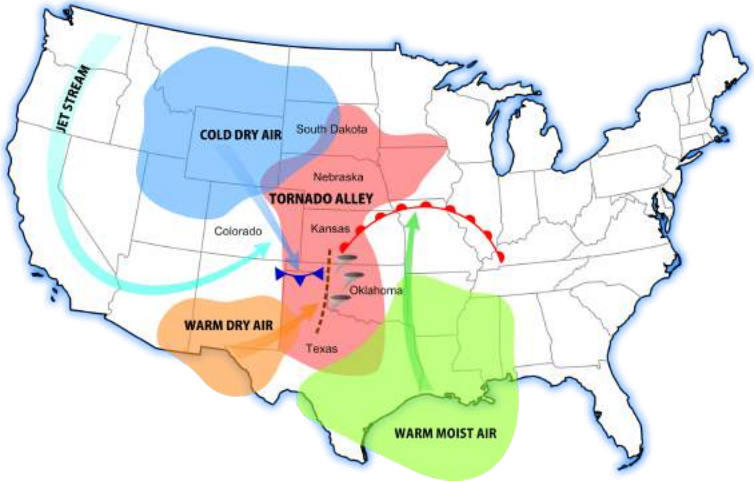
Tornado Formation

The anatomy and development of tornadoes are not fully understood, but they form from cold fronts, severe thunderstorms, squall lines, supercells, and hurricanes. Geography also plays a crucial role in determining where tornadoes can and can not form. The majority of thunderstorms in the United States form in the Midwest, called **Tornado Alley**. This region is where cP air masses from Canada collide with mT air from the Gulf of Mexico. This **wind shear** creates unstable atmospheric conditions and a rotating corkscrew column of air.

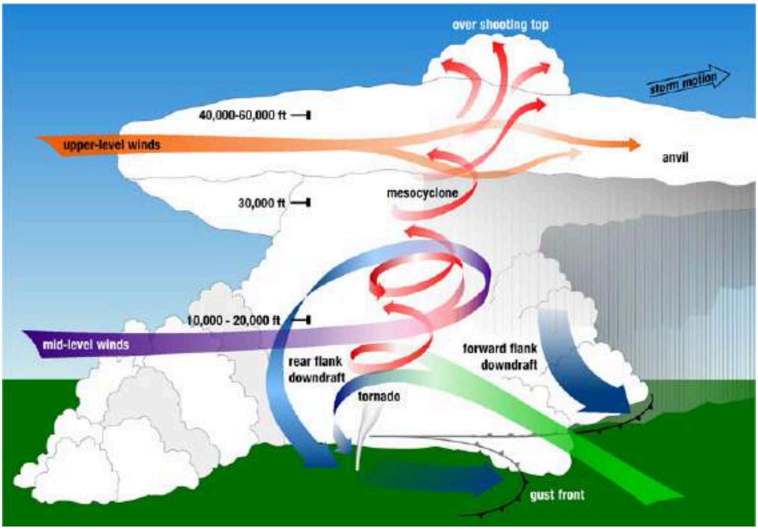


"Types of Atmospheric Wind Shear" by NOAA Jetstream is licensed as Public Domain.

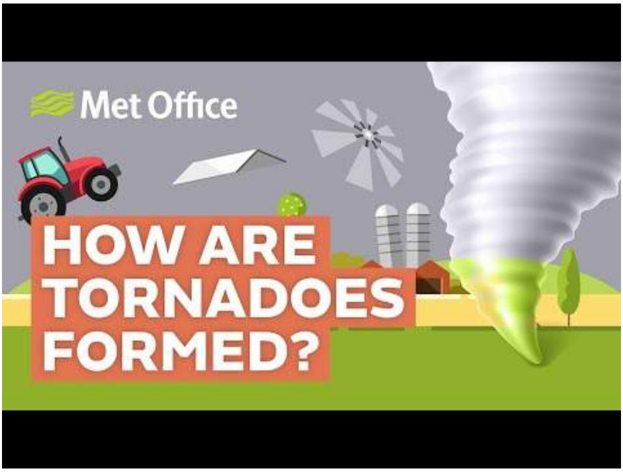


"Tornado Alley Diagram" by Dan Craggs is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

As the ground heats up through the day, updrafts pick up the rotating air into a portion of the thunderstorm to developing what is called a rotating **mesocyclone**. The updrafts stretch and tighten the now vertical column of air, causing it to rotate faster, much like an ice skater tightens to spin faster. As the rotating updrafts rise, a rotating wall cloud begins to form from the base of a mesocyclone. Sometimes a funnel cloud may begin to descend from the mesocyclone and may even be called a tornado if it reaches the ground.



"Tornadic Supercell" by the NOAA National Severe Storm Laboratory is licensed as Public Domain.



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Since 1990, the United States has averaged 1,200 tornadoes reported every year. However, the exact number per year can vary. Because the contrast between cold polar air and warm subtropical air is most significant in the spring and fall, most tornadoes in the United States develop during those seasons with April through June being the greatest.

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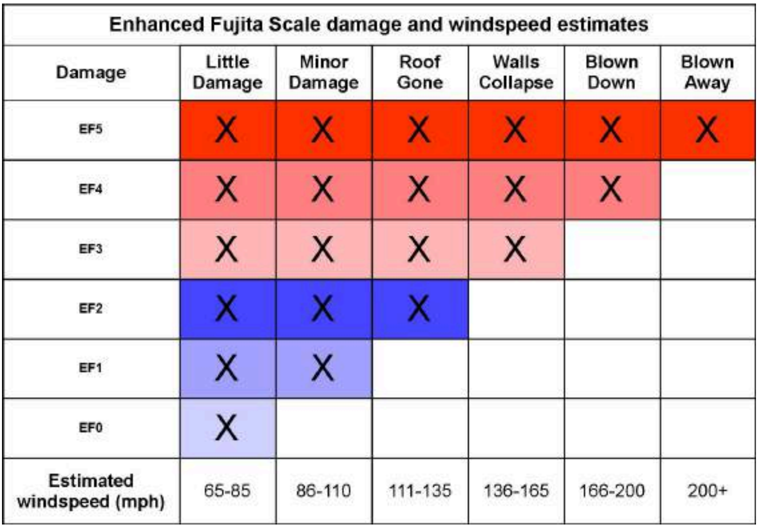
Tornado Destruction

The original way tornadoes were classified was based on a scale system developed by Dr. Fujita, which became called the **Fujita Intensity Scale** or simply the F-scale. The Storm Prediction Center states that the Fujita Intensity Scale's goal was to "categorize each tornado by its intensity and its area and estimate a wind speed associated with the damage caused by the tornado." The scale ranged from weak F0s to rare and obliterating F5s.



Enhanced Fujita Scale damage and windspeed estimates

Damage	Little Damage	Minor Damage	Roof Gone	Walls Collapse	Blown Down	Blown Away
EF5	X	X	X	X	X	X
EF4	X	X	X	X	X	
EF3	X	X	X	X		
EF2	X	X	X			
EF1	X	X				
EF0	X					
Estimated windspeed (mph)	65-85	86-110	111-135	136-165	166-200	200+

"Enhanced Fujita Scale Damage and Windspeed Estimates" by the Air Force Medical Service is licensed as Public Domain.

In February 2007, a new classification system began called the **Enhanced Fujita Scale**, or the EF-scale. The scale still ranges from 0-5 and is still an estimate of the tornado's wind speeds. However, the new scale is based on the amount of damage to different structures instead of actual wind speed. The stronger focus on the actual damage caused is because some structures and objects are built stronger than others. Examples of various strengths could include wood-framed homes, brick homes, malls, churches, and steel buildings.

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The majority of deaths caused by a tornado are not caused by wind, but by the flying debris. Sometimes a tornado will pass through a neighborhood and destroy some houses while leaving others with little damage. Scientists have discovered that some massive, intense tornadoes might contain several smaller tornadoes within them called suction vortices that makeup what is called multiple vortex tornadoes. (Dastrup, 2014)

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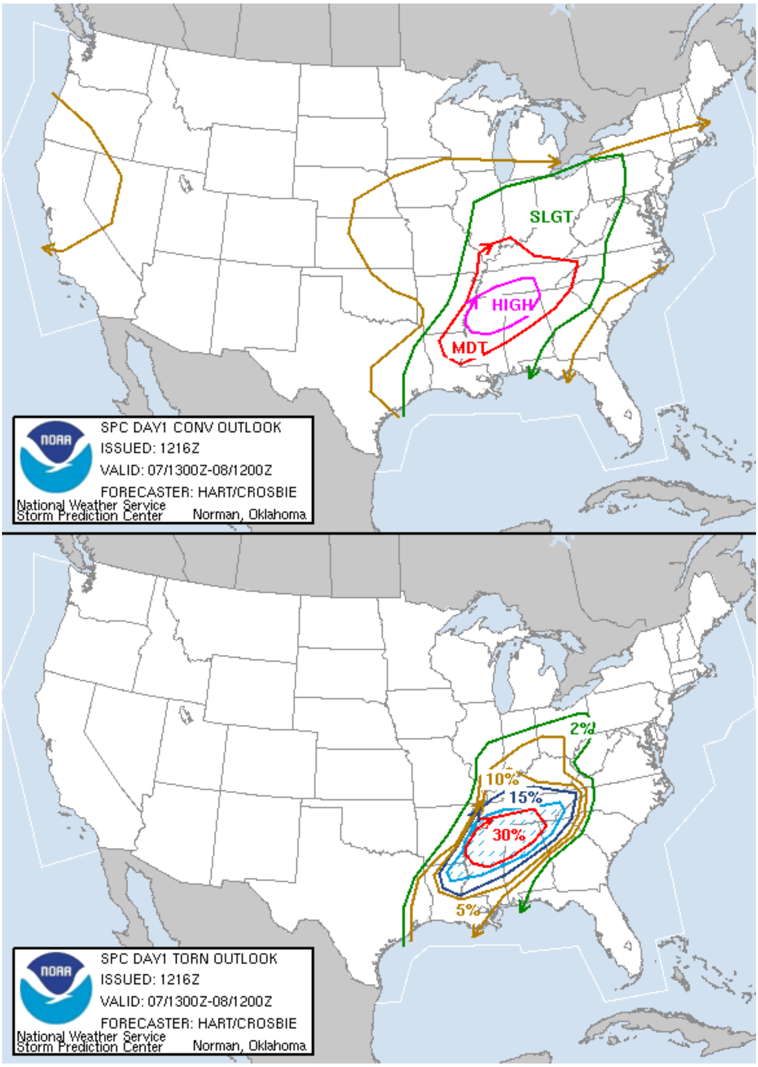
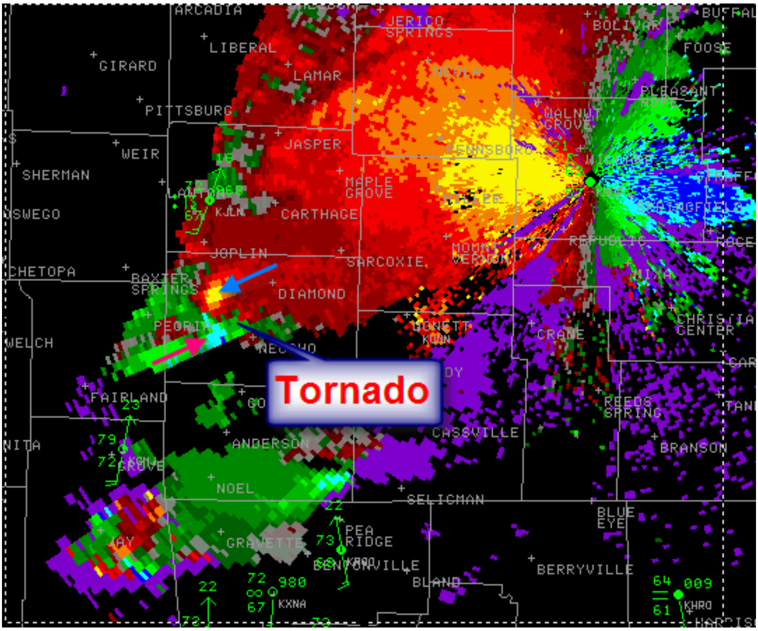
Tornado Forecasting

A lot of time, money, and research has gone into understanding tornadoes to provide better warnings to the public. When the atmospheric conditions are right, the Storm Prediction Center (SPC), which is part of the National Weather Service, analyzes severe weather and posts their forecasts to alert the public. If the conditions are right for a tornado to form, the SPC will send out a tornado watch alerting the public of the possibility of a tornado in a given area within a specific time. When a tornado has been cited, the National Weather Ser-vice will send a tornado warning out. A tornado warning warns of a “high probability of imminent danger” to a specific location.



“SPC Severe Outlook” by the NOAA Storm Prediction Center is licensed as Public Domain.

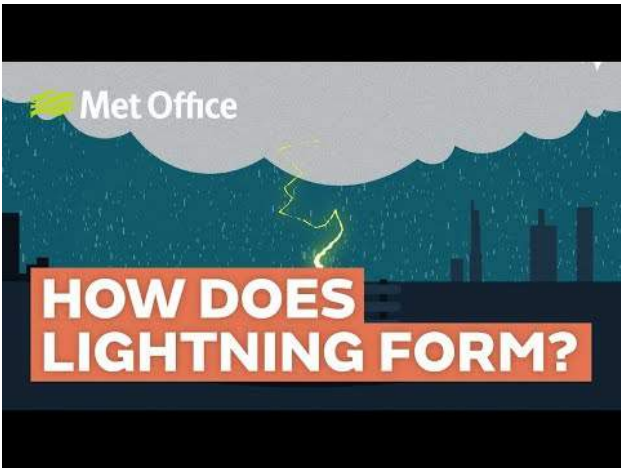
Doppler radar has become vital in determining the location and intensity of precipitation and locating where mesocyclones and tornadoes may be forming. Doppler radar can do this by monitoring the wind's flow toward or away from the tower, called the **Doppler effect**. Click here to view an image of an EF5 tornado approaches the Doppler. Notice a hook echo form in the red and begin rotating counter-clockwise, as most low-pressure systems do in the Northern Hemisphere. Weather satellites have also become instrumental in weather forecasting and monitoring. (Dastrup, 2014)



“Velocity Missouri Tornado” by the National Weather Service is licensed as Public Domain.

Lightning

Lighting is how the atmosphere balances out the buildup of opposite electrical charges within a cumulonimbus. The buildup occurs when charged atmospheric particles become segregated between a cloud and the ground, between clouds, or from a cloud and surrounding atmosphere. Scientists do not fully understand the reason for charged particle separation. However, some believe that ice crystals called **graupel** and supercooled raindrops interact with each other through collision, creating positive and negative charges that get separated within the cloud by updrafts and downdrafts. Others believe that ice pellet formation within the cloud charges the particles. As an ice pellet forms, the outer shell freezes first and becomes positively charged, and the liquid inner core is negatively charged. As the interior begins to freeze and expand, it breaks apart the positively charged outer layers. These positively charged fragments are taken into the cloud's upper regions, giving the top of the cloud a positive charge. The denser liquid water has a negative charge and is at the base of the cloud.



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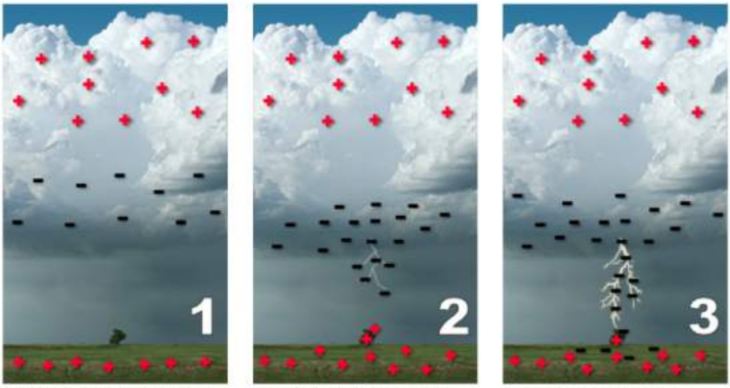
Once charged particles are separated, an electrical attraction exists between the negative and positive charges. The air between the oppositely charged particles tries to keep them separated. However, when the air can not keep the two opposite charges separated any longer, the negative charges move towards the positive charge in a zigzag manner called a **stepped leader**. As the stepped leader approaches the ground, the surface's positive charges will rise toward the steeped leader. It may rise through trees, buildings, or humans. When the steeped leader and the rising positively charged particles connect, the negatively charged particles flow from the cloud to the ground. At the same time, an electrical discharge called a return stroke, flows from the ground toward the cloud along the same path as the stepped leader. The return stroke is the part we see as lightning. When lightning flickers, it is because this process is repeating itself along the same path. Eighty percent of all lightning strikes occur cloud-to-cloud, but this process mentioned above can occur with cloud-to-ground, cloud-to-cloud, and cloud-to-air.



Thunderstorm gathers another pool of positively charged particles.

Negatively charged area in the storm will send out a charge.

Lightning channel develops

"Lightning Stages" by NOAA Jetstream is licensed as Public Domain.

Lightning is only a few centimeters thick but travels at 60,000 mph with a temperature of 54,000 degrees F (five times hotter than the surface of the sun). Lightning causes the surrounding air to become superheated, causing the air to expand violently, creating a shockwave called **thunder**. To estimate how far you are from lightning, count the number of seconds between the flash of lightning and when you hear the thunder reach you, then divide by five. However, if the lightning strike is more than 12 miles away, thunder will not be heard.

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In the summertime, convection or orographic uplift can create dry thunderstorms. **Dry thunderstorms** typically mean storms that have lightning, but little to no precipitation falling. Often this occurs when thunderstorms develop in dry atmospheric conditions. Because the air is so dry, rising eddies of moisture must reach great heights before being able to condense. This creates thunderstorms with very high cloud-bases. Any precipitation that does fall in these dry atmospheric conditions is likely to evaporate before reaching the ground. Thus these thunderstorms can create lighting, which can cause ignite wildfires, and the evaporating precipitation can produce strong, dry winds that can “push” the fires around.

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Hail

Hail is precipitation in the form of ice pellets that only forms in cumulonimbus clouds where the lower region of the cloud contains liquid water and the upper region containing ice freezing. When an ice pellet falls within the cumulonimbus cloud, it enters the warm, liquid region and picks up moisture. Then the updrafts through the ice pellet back up above the freezing point hardening the newly gathered water. The ice pellet will fall again to collect liquid water and thrown back up to refreeze. This process will continue until the hailstone's weight becomes too heavy for the updrafts to hold it up.

Once the hail becomes too heavy, the hail will precipitate on the downdraft side of the cumulonimbus. (Weather Processes and Systems | Earth Science, n.d.)

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Flash Floods

The number one weather-related cause of death in the United States are **flash floods**. The **National Weather Service** states that "flash floods are short-term events, occurring within 6 hours of the causative event (heavy rain, dam break, levee failure, rapid, snowmelt and ice jams) and often within 2 hours of the start of high-intensity rainfall. A flash flood is characterized by a rapid stream rise with depths of water that can reach well above the creek banks. Flash flood damage and most fatalities tend to occur in areas immediately adjacent to a stream or arroyo. Additionally, heavy rain falling on steep terrain can weaken the soil and cause mudslides, damaging homes, roads, and property." Urbanized areas are susceptible to flash floods because soil and vegetation are removed and replaced by concrete, roads, and buildings. When intense precipitation occurs, the water has nowhere to go. Learn more about flash floods from the National Weather Service. (Ch 9 Living with Disasters, n.d.)

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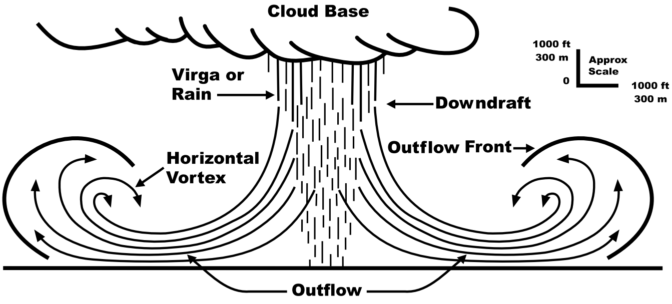
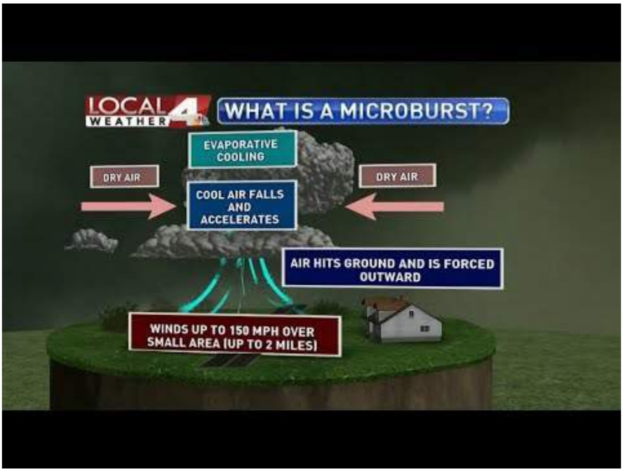
Microbursts

One weather-related hazard is **microbursts**, which are frequently caused by outflow boundaries. Sometimes the moisture within downdrafts falling from the thunderstorm evaporates as it enters dryer air below the cloud. As the moisture evaporates, the air cools because of latent heat, causing the air to become denser. This, in turn, causes the air to fall faster. As this denser air hits the ground, it spreads out laterally, producing cold winds reaching 100 miles per hour. Microbursts can uproot trees, damage property, and are very dangerous for airplanes taking off or landing.



"Microburst Cross-Section" by the Federal Aviation Administration is licensed under Public Domain.

Winds, crosswinds, and microbursts are all significant concerns for aviation pilots, especially when are traveling over 200 mph and are only 100-500 feet from the ground below. However, many of these near-crashes have been captured on video from all around the world because of technology. Below is a video on some of the best landings ever done by pilots fighting crosswinds and microbursts.



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Ice Storms

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9.5 HURRICANES

Tropical cyclones are considered some of the most powerful weather systems on the planet because of their size, strength, and potential loss to life and property. Tropical cyclones go by different names depending on their geographic location. In North and Central America, they are called **hurricanes**. In the northwestern portion of the Pacific Ocean near China and Japan, they are called **typhoons**. Furthermore, in the Indian Ocean and Australia, they are named **cyclones**. They all have winds exceeding 74 mph, can be hundreds of miles wide, and tower over 40,000 feet above sea level. (Dastrup, 2014)

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Anatomy of a Hurricane

The anatomy of a hurricane is relatively simple, though the processes involved are quite complex. As a low-pressure disturbance forms, the warm, moist air rushes towards the low pressure to rise upward to form towering thunderstorms. Around the low pressure, disturbance in a wall of clouds called an **eyewall**. Within the eyewall, the wind speeds are highest, the clouds are the tallest, atmospheric pressure is at its lowest, and precipitation is most intense.

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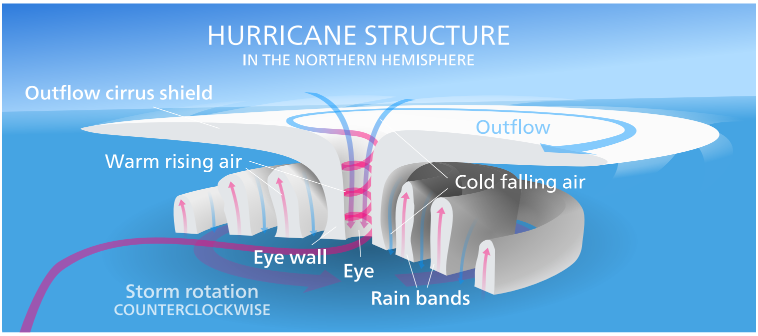
At the center or heart of the hurricane is called the **eye**. Within the eye of a hurricane, winds are light, precipitation is minimal, and the skies above are occasionally clear. It is the calm region of the tropical storm, but that is what makes it so dangerous. Many people tend to go outside as the eye moves overhead because they believe the storm is over. However, what some do not realize is that "round two" is coming from behind. Moving away from the eyewall are organized, intense thunderstorms, called **spiral rain bands**, that rotate around and toward the storm's eyewall. (Dastrup, 2014)



"Diagram of a Northern Hemisphere Hurricane" is licensed under the Creative Commons Attribution 3.0 Unported license.

Development of a Hurricane

There are several requirements needed for a hurricane to form. First, hurricanes must form over warm, moist oceans with surface temperatures that are at least 80 degrees Fahrenheit for at least 150 feet deep. This allows for water to evaporate, causing the air to become warm and humid. The atmosphere must also be warm and humid so that latent heat energy could be released as the moisture condenses within a hurricane. The third ingredient is a low-pressure disturbance, called an **easterly wave** or **tropical wave**, which is needed for air to converge toward and ascend to produce powerful thunderstorms.

Once these storms form, most need to be 5-20 degrees north or south of the equator to develop into a hurricane. If the tropical storm forms between 0-5 degrees north or south, the Coriolis effect is not strong enough to cause the storm to organize into a system and rotate. If the storm forms too far north or south, the water is too cold to develop into a hurricane. Finally, in order for a hurricane to form in the Atlantic Ocean, there must be little to no wind shear. If the jet stream is too low and blowing eastward while the trade winds are blowing west-ward, the wind shear will tear apart the forming cyclone before it can strengthen into a hurricane. Most hurricanes form under large regions of high pressure within the Atlantic Ocean. Recall that high pressure tends to have clear skies and mild winds.

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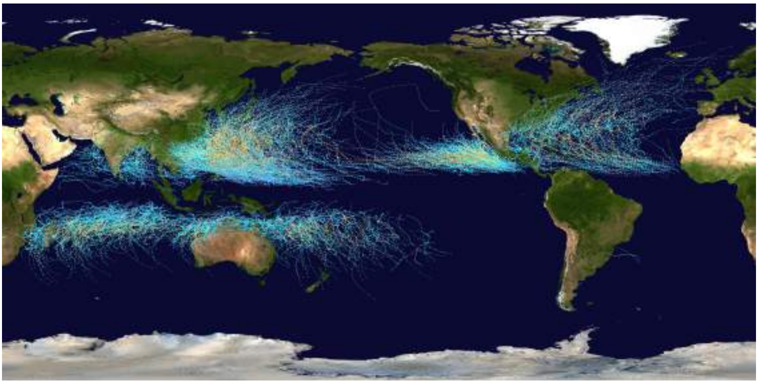
Now there are five primary stages a hurricane goes through. The first stage goes back to the low-pressure disturbance or easterly wave. Where easterly waves develop is currently being debated. However, it is believed that they form either off the west coast of

Africa near the Canary Islands or eastern Africa near Ethiopia. At this stage, warm, moist air begins to rise within the low-pressure disturbance releasing vast amounts of latent heat because of condensation, causing the storm to intensify. If the easterly waveforms under the right conditions, the Coriolis effect may allow the thunderstorms to organize and rotate, and it becomes a tropical depression. If the tropical storm continues to organize and strengthen with sustained winds between 39-73 mph, the storm is upgraded to a tropical storm and given a name by the National Hurricane Center. If intense rotation continues, the storm grows with winds reaching 74 mph or higher, it becomes a hurricane.

There are a variety of reasons why a hurricane will begin to die off. First, it could move in-to colder water, which does not supply the storm with as much latent heat energy. The idea is that colder water can not evaporate as easily, so no latent heat is released. Another way is if the storm moves over the land, causing it to lose its moisture source below. Finally, a third way a tropical storm could die-off is to move into an area where winds aloft begin to tear the storm apart.



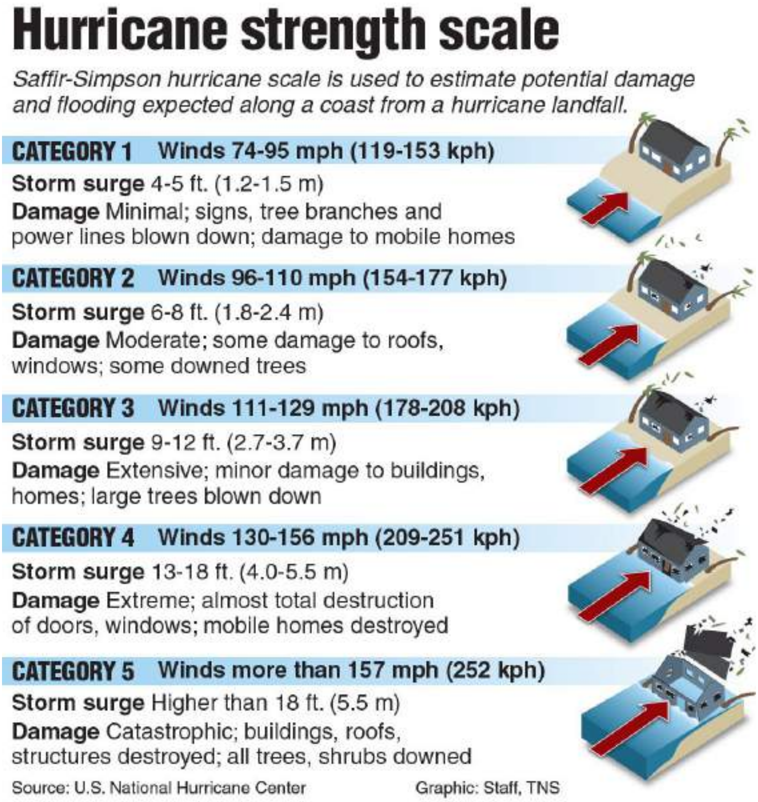
“Global Tropical Cyclone Tracks” by NASA is licensed as Public Domain.

An atmospheric event that can limit hurricane development occurs in the Pacific Ocean called **El Nino**. During an El Nino, the jet stream over the eastern United States migrates into lower latitudes. This upper wind shear caused by the jet stream moving eastward and the trade winds moving westward tends to tear apart hurricanes before they can form.

Another phenomenon that can deduce or eliminate hurricane development is dust storms coming off the coast of the Sahara Desert and into the Atlantic Ocean. In the summer of 2006, following the record activity of 2005 with Hurricane Katrina, the Sahara Desert in Africa had several sandstorms coming off into the Atlantic Ocean. Now recall two things: hurricanes originate near Africa, and the Atlantic Ocean must be over 80 degrees Fahrenheit for them to form. It is believed that the sandstorms blocked the sun over the eastern Atlan-tic, which ultimately cooled the ocean enough to hinder hurricane genesis. (Dastrup, 2014)

Hurricane Classification and Naming

The **Saffir-Simpson Scale** was created to determine the strength and intensity of hurricanes. Just like the Fujita scale, it ranges from 1-5, with category five being the strongest. The intensity of a hurricane increases as the atmospheric pressure near the eye decreases and the pressure-gradient force becomes steeper (atmospheric pressure decreases rapidly towards the eye), causing the winds to intensify, resulting in the potential for more damage. (Dastrup, 2014)



Hurricane strength scale

Saffir-Simpson hurricane scale is used to estimate potential damage and flooding expected along a coast from a hurricane landfall.

CATEGORY 1 **Winds 74-95 mph (119-153 kph)**
Storm surge 4-5 ft. (1.2-1.5 m)
Damage Minimal; signs, tree branches and power lines blown down; damage to mobile homes

CATEGORY 2 **Winds 96-110 mph (154-177 kph)**
Storm surge 6-8 ft. (1.8-2.4 m)
Damage Moderate; some damage to roofs, windows; some downed trees

CATEGORY 3 **Winds 111-129 mph (178-208 kph)**
Storm surge 9-12 ft. (2.7-3.7 m)
Damage Extensive; minor damage to buildings, homes; large trees blown down

CATEGORY 4 **Winds 130-156 mph (209-251 kph)**
Storm surge 13-18 ft. (4.0-5.5 m)
Damage Extreme; almost total destruction of doors, windows; mobile homes destroyed

CATEGORY 5 **Winds more than 157 mph (252 kph)**
Storm surge Higher than 18 ft. (5.5 m)
Damage Catastrophic; buildings, roofs, structures destroyed; all trees, shrubs downed

Source: U.S. National Hurricane Center Graphic: Staff, TNS

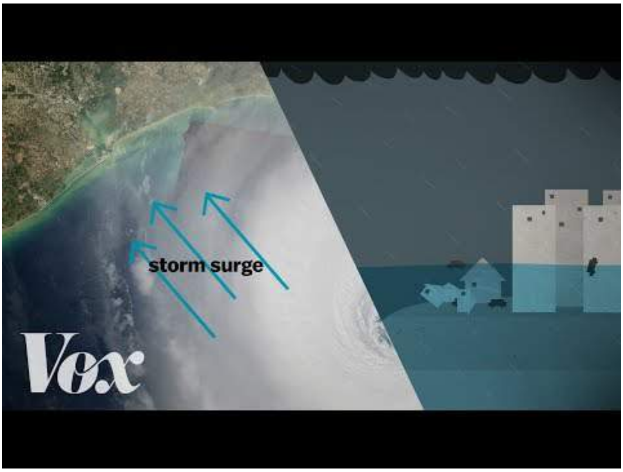
"Hurricane Strength Scale" by Thomas Cizauskas is licensed as Public Domain.

For many years, hurricanes were named based on where they struck land. For example, the Galveston Hurricane hit Galveston, Texas in 1900. In the early 1900s, scientists started naming hurricanes using female names; clearly a sexist action by mostly white, male scientists at the time. But by the 1950s, the National Hurricane Center started naming hurricanes alphabetically, starting with the letter A, and based on male and female names. If the first year started the letter A with a female name, the following year, the first name would be male. The names are also determined six years in advance so that politics do not get involved with the naming of these deadly storms.

Hazards

Storm Surge

Storm surges, defined as rising ocean levels along a coastal area because of low atmospheric pressure within a tropical cyclone, are the most dangerous hazard created by a tropical cyclone. They are blamed for 90 percent of all deaths and property damage. The height of a storm surge is dependent on the strength of winds, which is dependent on the low pressure near the eye. The low pressure does not "pull up" ocean water to create a storm surge; instead, the wind blowing towards the low pressure causes the water underneath to pile up near the hurricane's eye.



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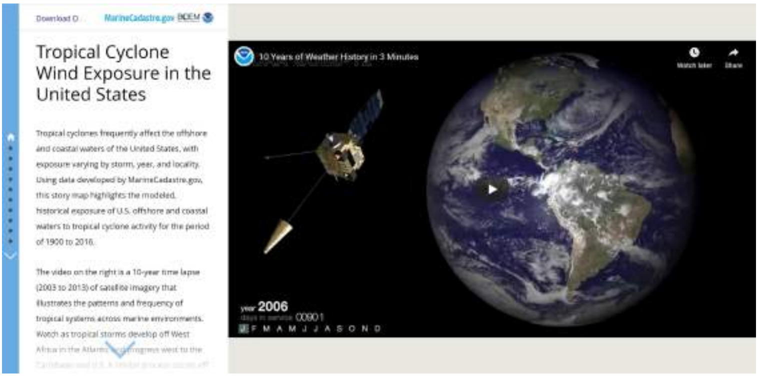
As it approaches the shore, the piling causes the sea level to rise and flood the area near the eye and eyewall. Storm surges are most damaging when the atmospheric pressure decrease, if the continental shelf rises slowly as it approaches the shore, or if the storm surge arrives during high tide. The storm surge is also highest on the right side of the eye as winds blow to-ward shore in a counter-clockwise rotation. New Orleans was struck on the left side of the storm surge, so they did not receive the highest portion of the surge. (Dastrup, 2014)

Wind Damage and Inland Flooding

Another hazard created by hurricanes is property damage caused by hurricane-force winds. Though property, such as mobile homes, is obvious, tall buildings are also susceptible to wind damage. People in tall buildings should get below the tenth floor because of powerful winds but should stay above the main floor in case of flooding. Hurricanes also produce tornadoes. It is believed that hurricanes Charley, Frances, Gaston, and Ivan that struck Florida in 2004 produced nearly 300 tornadoes!

Flooding, besides storm surges, is also a dangerous component of hurricanes. The 2004 hurricane season killed over 3,000. The majority of the deaths occurred in Haiti from flash floods and mudslides caused by heavy precipitation. Category 5 Hurricane Mitch in 1998 killed over 18,000 people, most in Central America, dropping nearly three feet of rain, causing massive flooding and mudslides.

Click on the story map below to learn more about tropical cyclones in the United States.



Tropical Cyclone Wind Exposure in the United States

Tropical cyclones frequently affect the offshore and coastal waters of the United States, with exposure varying by storm, year, and locality. Using data developed by MarineCadastre.gov, this story map highlights the modeled, historical exposure of U.S. offshore and coastal waters to tropical cyclone activity for the period of 1900 to 2016.

The video on the right is a 10-year time lapse (2003 to 2013) of satellite imagery that illustrates the patterns and frequency of tropical systems across marine environments. Watch as tropical storms develop off West Africa in the Atlantic [illegible] progress west to the

"Tropical Cyclone Wind Exposure in the United States" by NOAA is licensed as Public Domain.

Hurricane Forecasting

The governmental agency that analyzes and monitors hurricanes is NOAA's National Hurricane Center. Most hurricanes move westward as they approach North and Central America, then veer northeast. The reason is relatively simple. At around 30 degrees north, there is a sub-tropical high called the Bermuda High. As tropical storm systems move across the Atlantic Ocean, they are pushed westward from the underside of the subtropical high's clockwise rotation (a.k.a. the trade winds). As tropical storms move northward, the subtropical high's clockwise rotation (a.k.a. the westerly winds) pushes the storms northwestward into colder water. (Dastrup, 2014)

Click here to read about how the National Oceanic and Atmospheric Administration (NOAA) prepares for hurricanes season.

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PART X

GLOBAL CLIMATES AND CHANGE

Coming soon...

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10.1 CLIMATE SYSTEMS

Weather and Climate

Weather is the current state of the atmosphere for a particular place at a particular time. **Climate** is a statistical average of weather for a specific location, over 30 years or more. Weather can change at any minute, but climate takes years, if not decades, to change. Like the weather, the climate is a complex system involving the oceans, atmosphere, lithosphere, hydrosphere, and biosphere. (What is the Difference Between Climate and Weather? | NOAA Climate.Gov, n.d.)

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Millions of years ago, during the early part of the Cretaceous period, dinosaurs roamed the Earth when temperatures were much warmer than today. Geological evidence suggests that there were no ice caps at the North or South poles. Earth's historic climates were closely tied to changes in greenhouse gases, which make up the greenhouse effect. Scientists have determined that changes in greenhouse gas concentrations currently are due to human activity, rather than other national processes.

Humans are causing climate change through their everyday actions, and the socioeconomic forces underlying those actions. At the same time, people are feeling the consequences of climate change through various impacts on things they value and the responses they make to address climate change. (Dastrup et al., 2019)

All around the world, tens of thousands of weather stations are continuously monitoring weather conditions for their location on the planet. (How Do Weather Observations Become Climate Data? | NOAA Climate.Gov, n.d.) The raw weather data is collected by the National Oceanic and Atmospheric Administration (NOAA) at their National Center for Environmental Information (NCEI).

Over time, this data can be overaged over the years and decades to determine what the climate is typically there. Climate norms are determined by the National Oceanic and Atmospheric Administration (NOAA) at the beginning of every new decade. (Climate Normals | National Centers for Environmental Information (NCEI) formerly known as the National Climatic Data Center (NCDC), n.d.) Climate data is critically important for decision making for a variety of sectors of the economy and across governmental and non-governmental organizations.

The Climate System

The **climate system** is comprised of five natural components: atmosphere, hydrosphere, cryosphere, land surface, and biosphere. The **atmosphere** is the envelope of gases that surrounds Earth, including the naturally occurring greenhouse gases that warm the planet's surface. The **hydrosphere** includes all of Earth's liquid water and gaseous water (water vapor), whereas the cryosphere includes all frozen water (ice). Note that the **cryosphere** is technically part of the hydrosphere, but climate scientists usually treat it as a separate component of the climate system because its physical properties differ from those of water and water vapor. The **land surface** does not include water- or ice-covered surfaces but consists of all other vegetated and non-vegetated surfaces. The **biosphere** is the realm of life and is found in all other natural components, especially the hydrosphere and land surface. The biota is made up of and requires the presence of air, water, and mineral matter – that is, material from the atmosphere, hydrosphere, and land – to exist. Several **external forces** influence the five climate system components, with radiation from the Sun being most important. Climate scientists consider the impact of human activities on the climate system another example of external forcing.

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Why Understanding Climate is Important

Everything in the lighter shading would be flooded in the transition from the ice age to the modern pre-industrial climate. However, what sort of effort would that have taken? It turns out that the natural increase in atmospheric carbon dioxide that led to the thaw after the last Ice Age was an increase from 180 parts per million (ppm) to about 280 ppm. This was a smaller increase than the present-time increase due to human activities, such as fossil fuel burning, which thus far have raised carbon dioxide levels from the pre-industrial value of 280 ppm to a current level of over 400 ppm–a level which is increasing by 2 ppm every year. So, arguably, if the dawn of industrialization had occurred 18,000 years ago, we may very likely have sent the climate from an ice age into the modern pre-industrial state.

How long it would have taken to melt all of the ice is not precisely known, but it is conceivable it could have happened over a period as short as two centuries. The area ultimately flooded would be considerably more significant than that currently projected to flood due to the human-caused elevation of carbon dioxide that has taken place so far. The hypothetical city of "Old Orleans" would have to be relocated from its position in the Gulf of Mexico 100+ miles off the coast of New Orleans to the current "New Orleans" location.

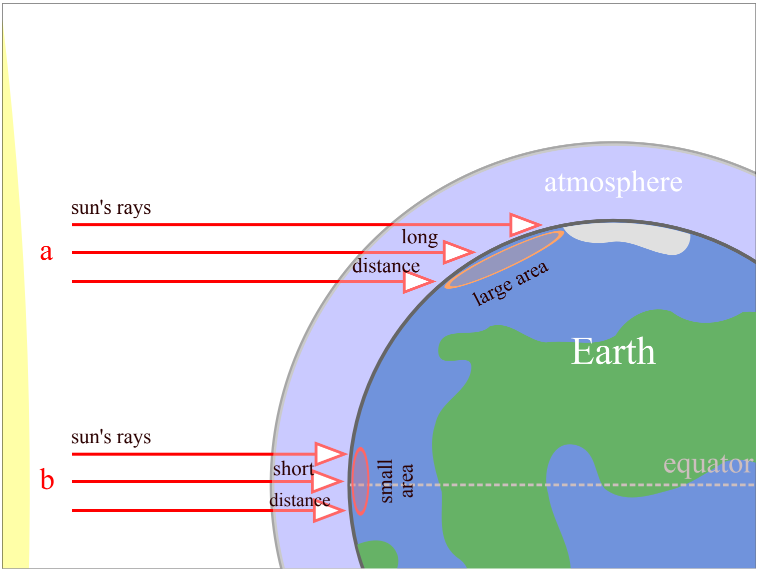
By some measures, human interference with the climate back then, had it been possible, would have been even more disruptive than the current interference with our climate. Nevertheless, that interference would merely be raising global mean temperatures from those of the last Ice Age to those that prevailed in modern times before industrialization. This thought experiment tells us that the issue is not whether some particular climate is objectively "optimal." The issue is that human civilization, natural ecosystems, and our environment are heavily adapted to a particular climate – in our case, the current climate. Rapid departures from that climate would likely exceed the adaptive capacity that we and other living things possess, and cause significant consequent disruption in our world.

10.2 CONTROLS OF CLIMATE

Earth's climate is composed of a complex system and interaction of other natural processes. To understand the current climate crisis, it is essential to understand the variables, controls, and systems that directly or indirectly affect it. (How Do Scientists Classify Different Types of Climate? | NOAA Climate.Gov, n.d.)

Latitude

The dominant control influencing the climate of a region is latitude because different latitudes receive different amounts of solar radiation. Depending on where the planet is on its revolution around the sun, the region between 23.5 degrees north and south receives the most solar radiation. The image below is during the equinox when the Sun's direct rays are striking at the equator.



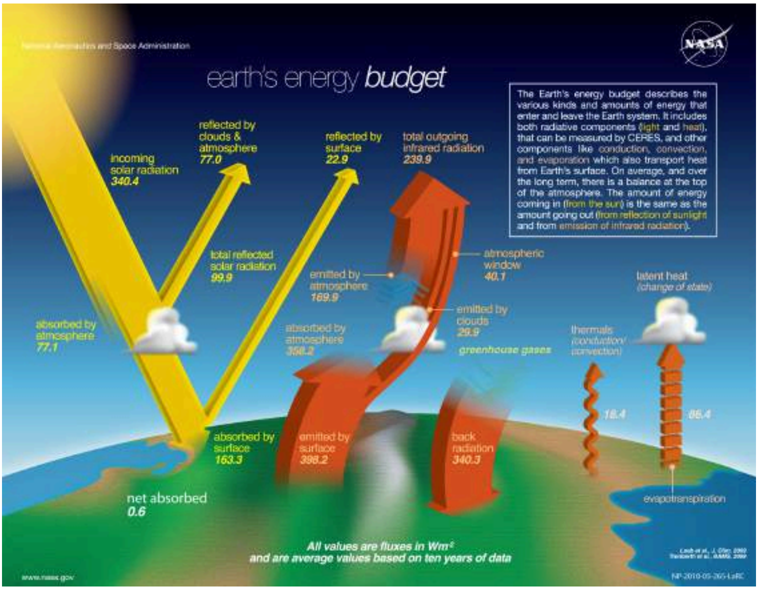
“Oblique Rays” by Peter Halasz is licensed under the Creative Commons Attribution-ShareAlike 2.5 Generic license.

The polar regions receive the least solar radiation because of the curvature of the Earth. The night lasts six months during the winter. Even in summer, the sun never rises high in the sky. Sunlight filters through a thick wedge of atmosphere, making the sunlight much less intense. The high albedo, because of ice and snow, reflects a good portion of the sun’s light. (Climate Systems and Change | Earth Science, n.d.)

Solar Energy Budget

The Earth’s climate is a solar-powered system. So to truly understand Earth’s climate, an understanding of the planet's **energy balance** is essential. Consider the image below from NASA on how incoming (yellow) and outcoming (red) energy sources of shortwave and longwave radiation achieve a net balance:

- At the surface
- Within the atmosphere
- At the top of the atmosphere



"Earth's Energy Budget" by NASA is licensed as Public Domain.

Next, let us note that the above image represents average climate conditions that averaged over the entire Earth's surface, and averaged over time. However, in reality, the incoming distribution of radiation varies in both space and time.

The dominant spatial variation occurs with latitude. There is more incoming solar radiation arriving at the surface near the equator than near the poles. On average, roughly 30 percent of this incident radiation is reflected out to space by clouds and reflective surfaces of the Earth, such as ice and desert sand, leaving roughly 70 percent of the incoming solar radiation to be absorbed by the Earth's surface. The portion reflected by clouds and by the surface also varies substantially with latitude, owing to the latitudinal variations in cloud and ice cover.

The intensity of the incoming solar radiation that the Earth receives is not constant over time. Over the lifetime of the sun, 4.6 billion years, energy output has varied considerably by roughly 30 percent. The amount of energy the planet receives from the sun is called the **solar constant**.

Even more dramatic changes in solar insolation take place on shorter timescales – the diurnal and annual timescale. These changes, however, do not have to do with the net output of the Sun, but rather the distribution of solar insolation over the Earth's surface. This distribution is influenced by the Earth's daily rotation about its axis, which of course leads to night and day, and the annual orbit of the Earth about the Sun, which leads to our seasons. While there is a small component of the seasonality associated with changes in the Earth-Sun distance during the course of the Earth's annual orbit about the Sun (because of the slightly elliptical nature of the orbit), the primary reason for the seasons is the tilt of Earth's rotation axis relative to the plane defined by the Earth and the Sun, which causes the Northern Hemisphere and Southern Hemisphere to be preferentially oriented either towards or away from the Sun, depending on the time of year.

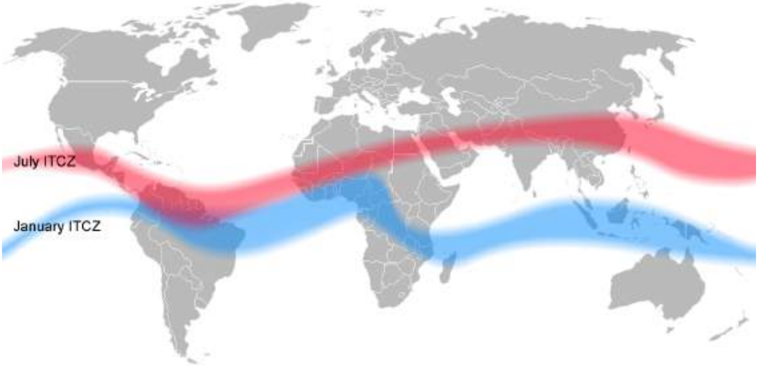
The consequence of all of this is that the amount of shortwave radiation received from the Sun at the top of the Earth's atmosphere varies as a function of both times of day and season. Subtle changes in the Earth's orbital geometry (i.e., changes in the tilt of the axis, the degree of ellipticity of the orbit, and the slow precession of the orbit) are responsible for the coming and going of the ice ages over tens of thousands of years. (Overview of the Climate System (Part 2) | METEO 469: From Meteorology to Mitigation: Understanding Global Warming, n.d.)

Global Atmospheric Circulation

Compared to the global circulation cells and wind belts, the position of a region has a significant effect on its climate. In an area where the air is mostly rising or sinking, there is not much wind.

Intertropical Convergence Zone

The I**ntertropical Convergence Zone (ITCZ)** is the low-pressure area near the equator in the boundary between the two Hadley Cells. The air rises so that it cools and condenses to create clouds and rain. The climate along the ITCZ is therefore warm and wet. Early mariners called this region the doldrums because their ships were often unable to sail because there were no steady winds.

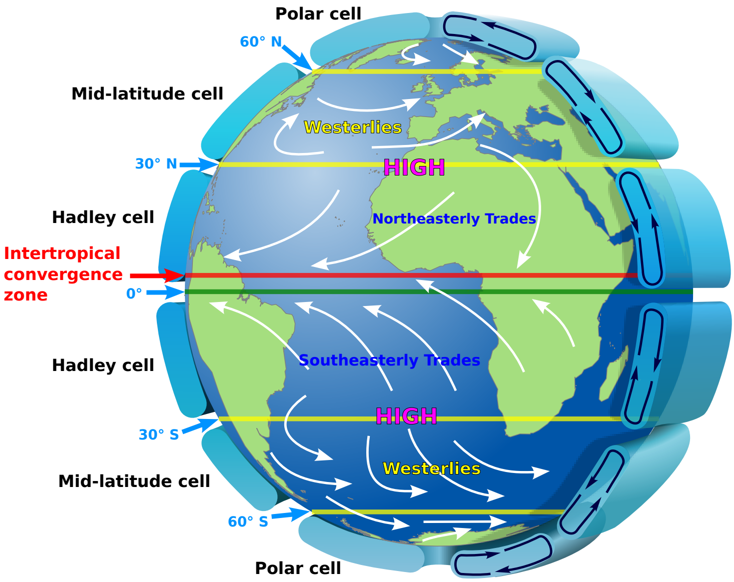


"Intertropical Convergence Zone January-July" by NASA is licensed as Public Domain.

The ITCZ migrates slightly with the season, following the relative motion of sunlight between the Tropic of Cancer and Tropic of Capricorn. Land areas heat more quickly than the oceans. Because there are more land areas in the Northern Hemisphere, the ITCZ is influenced by the heating effect of the land. During the Northern Hemisphere's summer, the ITCZ is approximately 5 degrees north of the equator, while in the winter, it shifts back and is approximately at the equator. As the ITCZ shifts, the dominant wind belts also shift slightly north in summer and south in winter, which causes the wet and dry seasons in this area.

Hadley Cell and Ferrell Cell Boundaries

At about 30 degrees north and south, the air is relatively warm and dry because much of it came from the equator where it lost most of its moisture at the ITCZ. At this location, the air is descending, and sinking air warms and causes evaporation. Sunny conditions, with little precipitation, tends to occur. (Climate and Its Causes | Earth Science, n.d.)



Mariners named this region the horse latitudes. Sailing ships were sometimes delayed for so long by the lack of wind that they would run out of water and food for their livestock. Sailors tossed horses and other animals over the side after they died. Sailors sometimes did not make it either. (Earth Science | Simple Book Production, n.d.)

Prevailing Winds

The prevailing winds are the bases of the Hadley, Ferrell, and Polar

Cells. These winds influence a region's climate because they bring the weather from the locations they come from. For example, in California, the predominant winds are the westerlies blowing in from the Pacific Ocean, which brings in relatively cool air in summer and relatively warm air in winter. Local winds also influence the local climate. For example, land breezes and sea breezes moderate coastal temperatures. (Earth Science | Simple Book Production, n.d.)

Landmasses

Location of Continents

When a location is near a large body of water, the local climate will be directly affected, creating a milder, maritime climate. Temperatures typically vary only slightly across the day and year. For a location to have an actual maritime climate, the winds must most often come off the sea. (Climate Systems and Change | Earth Science, n.d.)

When a location is not located near any large body of water, the region will typically experience a continental climate. A continental climate has more significant temperature differences between day and night and between summer and winter.

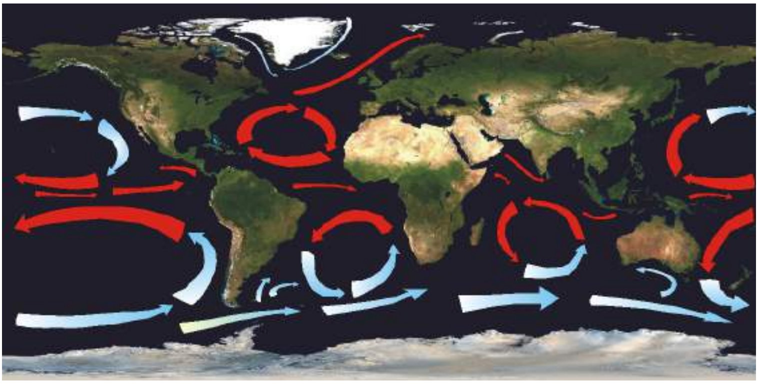
Altitude and Mountain Ranges

Atmospheric pressure and temperature decrease with altitude within the troposphere. The closer molecules are packed together, the more likely they are to collide. Collisions between molecules give off heat, which warms the air. At higher altitudes, the air is less dense, and air molecules are more spread out and less likely to collide. A location in the mountains has lower average temperatures than one at the base of the mountains. In Colorado, for example, Lakewood (5,640 feet) average annual temperature is 62 degrees F (17 degrees C), while Climax Lake (11,300 feet) is 42 degrees F (5.4 degrees C).

Mountain ranges have two effects on the climate of the surrounding region. The first is something called the rain shadow effect, which brings warm, dry climate to the leeward side of a mountain range, as described in the Earth's Atmosphere chapter. The second effect mountains have on climate systems is the ability to separate coastal regions from the rest of the continent. Since a maritime air mass may have trouble rising over a mountain range, the coastal area will have a maritime climate, but the inland area on the leeward side will have a continental climate.

Ocean Circulation Patterns

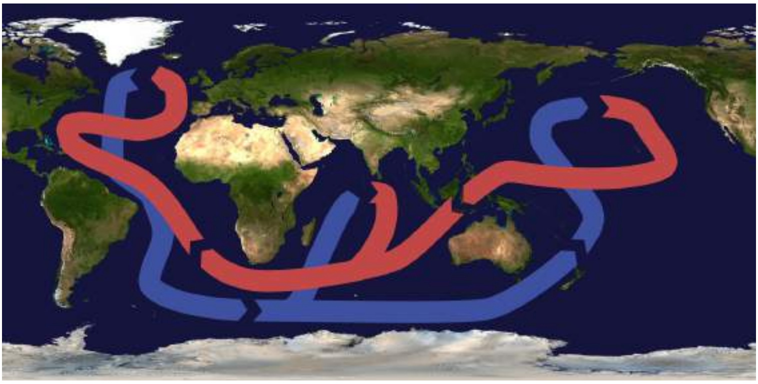
While we have focused primarily on the atmosphere thus far, the oceans, too, play a crucial role in relieving the radiation imbalance by transporting heat from lower to higher latitudes. The oceans also play a crucial role in both climate variability and climate change, as we will see. There are two primary components of ocean circulation. The first component is the horizontal circulation, characterized by wind-driven **ocean gyres**.



"Ocean Gyres Ocean Currents" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

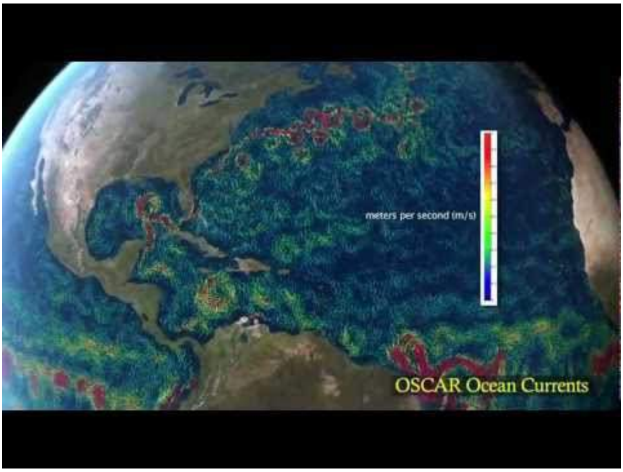
The major surface currents are associated with ocean gyres. These include the warm poleward western boundary currents such as the Gulf Stream, which is associated with the North Atlantic Gyre, and the Kuroshio Current associated with the North Pacific Gyre. These gyres also contain cold equatorward eastern boundary currents such as the Canary Current in the eastern North Atlantic and the California Current in the western North Atlantic. Similar current systems are found in the Southern Hemisphere. The horizontal patterns of ocean circulation are driven by the alternating patterns of wind as a function of latitude, and, in particular, by the tendency for westerly winds in mid-latitudes and easterly winds in the tropics, discussed above.

An essential additional mode of ocean circulation is the **thermohaline circulation**, which is sometimes referred to as the meridional overturning circulation or MOC. The circulation pattern is shown below. By contrast with the horizontal gyre circulations, the MOC can be viewed as a vertical circulation pattern associated with a tendency for sinking motion in the high-latitudes of the North Atlantic, and rising motion more broadly in the tropics and subtropics of the Indian and Pacific ocean. This circulation pattern is driven by contrasts in density, which are, in turn, primarily due to variations in both temperature and salinity (hence the term thermohaline). The sinking motion is associated with relatively cold, salty surface waters of the subpolar North Atlantic, and the rising motion with the relatively warm waters in the tropical and subtropical Pacific and Indian ocean.



"Thermohaline Circulation" is licensed under the Creative Commons Attribution-ShareAlike 3.0 Unported license.

The image above is a highly schematized and simple description of the actual vertical patterns of circulation in the ocean. Nonetheless, the conveyor belt is a useful mnemonic. The northward surface branch of this circulation pattern in the North Atlantic is sometimes erroneously called the Gulf Stream. The Gulf Stream, as discussed above, is part of the circulating waters of the wind-driven ocean gyre circulation. By contrast, the northward extension of the thermohaline circulation in the North Atlantic is rightfully referred to as the North Atlantic Drift. This current system represents a net transport of warm surface waters to higher latitudes in the North Atlantic and is also an essential means by which the climate system transports heat poleward from lower latitudes. Changes in this current system are speculated as having played a key role in past and potential future climate changes.



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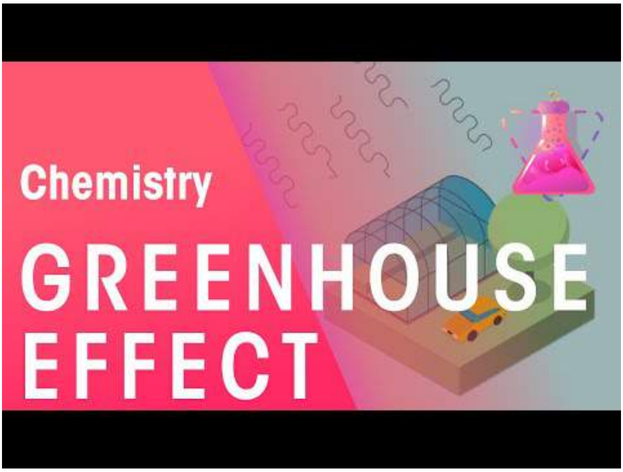
Air pressure and air temperature decrease with altitude. The closer molecules are packed together, the more likely they are to collide. Collisions between molecules give off heat, which warms the air. The air is less dense at higher altitudes, and air molecules are more spread out and less likely to collide. A location in the mountains has lower average temperatures than one at the base of the mountains.

In Colorado, for example, Lakewood (5,640 feet) average annual temperature is 17 degrees Celsius (62 degrees Fahrenheit), while Climax Lake (11,300 feet) is 5.4 degrees Celsius (42 degrees Fahrenheit). (Climate and Its Causes | Earth Science, n.d.)

Composition of the Atmosphere

The troposphere is composed of nitrogen (78 percent), oxygen (21 percent), argon (less than 1 percent), and a variety of other gases. There are a few outliers, which include ozone and methane. Ozone is primarily found in the stratosphere that creates the ozone layer. **Ozone** is also found near the Earth's surface from photochemical smog, from the emission of vehicles. Significant methane sources include the digestion of food from cattle, fracking of natural gas, coal mines, and deforestation. Because these sources have geographic locations where they occur, consistent sources on Earth's surface can be found.

Greenhouse gases are composed of carbon dioxide, water vapor, methane, and some other gasses in smaller quantities. These gasses are essential for scientists to monitor, analyze, and understand because of their ability to trap radiation in the lower atmosphere. The greenhouse effect's strength and intensity will depend on the atmosphere's temperature and the number of greenhouse gases that the atmosphere holds.



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The term “greenhouse effect” is an incorrect description of how energy is retained within the troposphere. Greenhouses warm the atmosphere within them by reducing airflow and circulation, not by “trapping heat.” Nevertheless, the Earth’s natural greenhouse effect is critical to supporting life. Human activities, such as burning fossil fuels and deforestation, have strengthened the natural greenhouse effect and causing the Earth’s atmosphere to warm over a noticeably short period.

Elevation

Atmospheric pressure and temperature decrease with altitude within the troposphere. The closer molecules are, the more likely they will collide into each other. Collisions between molecules give off energy and heat, which warms the surrounding atmosphere. At higher altitudes, the atmosphere is less dense, the air molecules are more spread out, and less likely to collide. On average, a location in the mountains has lower average temperatures than at the base of the mountains. Mountain ranges have two effects on the climate of the surrounding region. The first is called the rain shadow effect, which brings a warm, dry climate to the leeward side of a mountain range. The second effect mountains have on climate systems is the ability to separate coastal regions from the rest of the continent. Since a maritime air mass may have trouble rising over a mountain range, the coastal area will have a maritime climate, but the in-land area on the leeward side will have a continental climate. (Climate Systems and Change | Earth Science, n.d.)

10.3 KÖPPEN CLASSIFICATION SYSTEM

A **climate zone** results from an area's climate conditions: temperature, humidity, amount and type of precipitation, and seasonality. The significant factors that influence climate determine the different climate zones around the world. In general, the same climate zone will be found at similar latitudes and in similar positions on nearly all continents, both in the Northern and Southern Hemispheres. The one exception to this pattern is the continental climates, which are not found at higher latitudes in the Southern Hemisphere. This is because the Southern Hemisphere landmasses are not broad enough to produce a continental climate.

The most common system used to classify climatic zones is the Köppen classification system. This system is based on the temperature, amount of precipitation, and the year when precipitation occurs. Since climate determines the type of vegetation that grows in an area, vegetation is often used as an indicator of climate type.

A climate type and its plants and animals make up a biome. The organisms of a biome share specific characteristics worldwide because their environment has similar advantages and challenges. The organisms have adapted to that environment in similar ways over time. For example, distinct cactus species live on different continents, but they have adapted to the harsh desert in similar ways.

Köppen Classification System

The **Köppen classification system** was developed by the German climatologist, Wladimir Köppen in 1918. The classification system focuses on the average monthly and annual temperature and precipitation totals for a location. The Köppen classification system recognizes four major climate groups based on temperature values (identified by the capital letters A, C, D, and E), and the fifth based on moisture (identified by the capital letter B), to create global climate patterns. The major climate groups can then be subdivided into more specific categories based on a combination of temperature and moisture patterns for any region in the world. A newer system called the **modified Köppen classification system** is used today after several modifications by geographers and climatologists over time. The modified version still has the five major climate categories, which are broken down into fourteen subcategories. The modified version also has a new category for "highland," represented with the capital letter H, and focuses on mountainous regions.

The modified Köppen classification system is straightforward and quick to identify global and regional climates. The first letter (always a capital letter), represents the primary climate type. The second, lower-case letter identifies the precipitation patterns for a location. Finally, the third letter, again in the lower-case, is used to identify the precipitation patterns for that location.

Climatologists create **climographs** to identify and understand the precise climate for a location visually. Each climograph visualized average temperature and precipitation patterns for a location, over a single year. Temperature is represented as a continuous line, while precipitation is represented as monthly bars.

There are a variety of resources available from NOAA to analyze climate data. (Visualizing Climate Data | NOAA Climate.Gov, n.d.)

- Data Snapshots
- NOAA View Data Exploration Tool
- The Climate Explore
- Panopoly
- NOAA Weather and Climate Toolkit

Tropical Climates (Group A)

Tropical climates are found between 15 to 25 degrees north and south of the equator. These climates tend to have warm temperatures with every month averaging 18 degrees Celsius (64 degrees Fahrenheit), with abundant precipitation, approximately 150 cm (59 inches) per year. This climate group is broken down into three categories, based on precipitation.

Tropical Wet (Af)

Tropical wet climates are found between 10 degrees north and south of the equator. These regions have almost no annual temperature variation and tremendous amounts of rainfall year-round, between 175 and 250 cm (65 and 100 inches). These conditions support the tropical rainforest biome, which is densely packed, broadleaf evergreen trees. These regions tend to have the highest number of species or biodiversity of any ecosystem.

Tropical Monsoon (Am)

Tropical monsoon climates are defined by seasonal monsoonal wind patterns in southern Asia, northeastern South America, and western Africa. The monsoon tends to be strongest in regions where strong monsoonal winds blow from sea to land, such as India. These climates tend to have incredible amounts of precipitation (over 75 centimeters or 30 inches) for two or three months, followed by drier conditions for the rest of the year. Rainforests can still grow in these regions because most of the year supplies abundant moisture.

Tropical Savanna (Aw)

Tropical savanna climates lie between about 5 to 20 degrees north and south latitude and are defined by dry winters and very wet summers. During the summer months, the Intertropical Convergent Zone (ITCZ) migrates into the region, bringing vast quantities of moisture (90 to 180 centimeters or 35 to 70 inches annually). During the winter months, the ITCZ migrates away from the region, bringing arid conditions. The average annual temperature ranges are roughly 3 to 8 degrees Celsius (5 to 15 degrees Fahrenheit).

Dry Climates (Group B)

Dry climates have higher evapotranspiration than precipitation, creating a moisture deficit. **Transpiration** is the movement of water through a plant and evaporation from the plant. **Evapotranspiration** is the total between evaporation and plant transpiration. Dry climates are found in more regions of the world than any other climate group, covering roughly 30 percent of Earth's landmass. These regions tend to have abundant sunshine, hot summers, and cold winters. Precipitation tends to be irregular, but less than total evaporation. Short-term droughts are frequent, which can last several years or even decades. Dry climates are divided based mostly on the relationship between evapotranspiration and precipitation.

Arid Desert (Bw)

Arid deserts tend to be found between 15 and 30 degrees north and south, where warm, dry air sinks because of subtropical high zones. Vast deserts, such as the Sahara or Gobi deserts, make up roughly 12 percent of the Earth's landmass. The typical weather is sweltering summer days and chilly winter nights. Although annual rainfall is less than 25 cm (10 inches), precipitation tends to fall during two seasons.

Semi-Arid or Steppe (Bs)

Semi-arid deserts, also called **steppe**, are found in continental interiors or rainshadow regions. Semi-arid deserts receive between

20 and 40 cm (8 to 16 inches) of rain annually. In the United States, the Great Plains, portions of the southern California coast, and the Great Basin are semi-arid deserts.

Temperate Climates (Group C)

Temperate climates have been described as a transition zone between tropical climates and polar climates. Winter months tend to be -3 to 18 degrees Celsius (27 to 64 degrees Fahrenheit), summer months warmer than 10 degrees Celsius (50 degrees Fahrenheit), and plentiful annual precipitation. Temperature climates have four seasons, with summer and winter being dominant.

Mediterranean (Cs)

Mediterranean climates are found on the western sides of continents between 30 to 45 degrees north and south. There are several characteristics of Mediterranean climates. Most of their annual precipitation occurs during the winter months with totals of 30 to 90 cm (14 to 35 inches) and hot and dry summer months. Because of their relative location near the subtropical high-pressure zones, these climates tend to have plenty of sunshine during the summer.

Humid Subtropical (Cfa, Cwa, Cwb)

Humid subtropical climates are found mostly on the eastern sides of continents. Precipitation occurs throughout the year with annual averages between 80 and 165 cm (31 and 65 inches). Summer days are humid and hot, from the lower 30s up to 40 degrees Celsius (mid-80 is up to 104 degrees Fahrenheit). Afternoon and evening thunderstorms are frequent as warm tropical air passing over the hot continent. Winters are mild, but midlatitude storms, called **cyclones**, may bring substantial amounts of precipitation. The southeastern United States, with its hot humid summers and mild, but frosty winters, is typical of this climate zone.

Marine West Coast (Cfb, Cfc)

Marine west coast climates follow the coasts of continents, between 40 degrees and 65 degrees north. Common regions with this climate include the Pacific Northwest in the United States, western and central Europe, New Zealand, and southeast Australia. Ocean winds bring mild winters and cool summers, with daily and annual temperature ranges being relatively small. Precipitation tends to occur year-round, although summers are drier as the jet stream moves northward. Low clouds, fog, and drizzle are typical.

Continental Climates (Group D)

Continental climates are only found in the Northern Hemisphere, between 40 and 70 degrees north. What defines continental climates is the lack of large bodies of water. These climates are only found at midlatitudes, within large, continental landmasses. All four seasons, rather than wet and dry seasons, are found in continental climates. This climate group tends to have warm summer temperatures, with monthly averages over 10 degrees Celsius (50 degrees Fahrenheit). However, the coldest months can drop below -3 degrees Celsius (-27 degrees Fahrenheit). Their winters tend to be cold and stormy, and snowfall stays on the ground for extended periods is common. Trees grow in continental climates, even though winters are frigid because the average annual temperature is mild.

Humid Continental (Dfa, Dfb, Dwa, Dwb)

Humid continental climates are found around the polar front (roughly 60 degrees north) in North America and Europe. In the winter, midlatitude cyclones bring chilly temperatures, snow, and prolonged winters. In the summer, westerly winds bring continental weather and warm temperatures. The average summer temperatures are often above 20 degrees Celsius (70 degrees Fahrenheit). The region typically has deciduous trees, which protect themselves in winter by losing their leaves.

The two variations of this climate are based on summer temperatures. Dfa climates tend to have long, hot summers with temperatures over 38 degrees Celsius (over 100 degrees Fahrenheit). Nighttime temperatures are warm, with temperatures roughly 31 degrees Celsius (56 degrees Fahrenheit). The long summers and high humidity foster plant growth. Dfb climates tend to have cool summers and lower humidity levels. Winter temperatures can drop below -18 degrees Celsius for extended periods.

Subpolar (Dfc, Dfd, Dwc, Dwd)

Subpolar climates are dominated by continental polar air, over frigid continents. Snowfall is light, but cold temperatures keep snow on the ground for months. Most of the approximately 50 cm (20 inches) of annual precipitation falls during summer cyclonic storms. The sun's rays' angle is low, but the sun is visible for most or all of the day during the summer. These continental regions have extreme annual temperature ranges. The boreal, coniferous forests in the subpolar climate are called taiga and have small, hardy, and widely spaced trees. Taiga vast forests stretch across Eurasia and North America.

Polar Climates (Group E)

Polar climates are found across the continents that border the Arctic Ocean, Greenland, upper Canada, and Antarctica. These climates tend to have bitterly cold winters and cool summers because of the sun's low angle. The average temperature of the warmest months tends to be less than 10 degrees Celsius (50 degrees Fahrenheit). Regions with this climate tend to be quite dry, with annual precipitation less than 25 cm (10 inches). Most of the precipitation from this climate occurs during the summer months but stay on the ground year-round. Data shows that the polar regions are warming faster than any other climate group because of anthropogenic climate change. This causes places like Greenland to melt rapidly while creating a prolonged, ice-free North Pole during the summer months.

Tundra (ET)

Tundra climates were first described by the type of vegetation that grew in the region. Today, the climate is defined by the 10 degrees Celsius (50 degrees Fahrenheit) isotherm, where the warmest month of the year exists for the region. This isotherm's importance is because it corresponds to the **treeline**, which is the farthest limit of where trees can grow because of limited moisture and temperatures.

Temperatures in tundra climates are so cold that a layer of permanently frozen ground, called **permafrost** forms below the surface and can extend hundreds of meters below the surface. The average temperature of the warmest months is above freezing, so summer temperatures defrost the uppermost part of the permafrost, sometimes causing soggy conditions. In winter, the permafrost prevents water from draining downward. Although the precipitation is low enough in many places to qualify as a desert, evaporation rates are also low, so the landscape receives more usable water than a desert. Because of the lack of ice-free land near the South Pole, there is little tundra in the Southern Hemisphere.

Ice Cap (EF)

Ice cap climates are found mostly on Greenland and Antarctica and may be thousands of meters thick.   Because of their latitude and the sun's continuous low angle, these climates have extremely low average annual temperatures, around -29 degrees Celsius (-20 degrees Fahrenheit). Precipitation is low because the air is too cold to hold significant amounts of moisture. Because of the permanent ice cover, no vegetation exits in ice cap climates

Highland Climates (Group H)

When climate conditions in a small area are different from those of the surroundings, the climate of the small area is called **highland climates**. Altitude mimics latitude for climate groups and was not considered in the original Köppen classification system. Climates and biomes typically found at higher latitudes may also be found in other areas of the world at high altitudes. Other factors that will influence highland climates, specifically temperature and moisture patterns, include orographic uplifting, rainshadow effects, slope and aspect of mountains, and local wind patterns.

10.4 CLIMATE CHANGE IN EARTH'S HISTORY

For the past two centuries, the climate has been relatively stable. People placed their farms and cities in locations that were in a favorable climate without thinking that the climate could change. However, the climate has changed throughout Earth's history, and a stable climate is not the norm. In recent years, Earth's climate has begun to change again due to human activities that release greenhouse gases into the atmosphere. The effects of warming are already being seen and will become more extreme as temperature rise.

Climate has changed throughout Earth's history. Much of the time, Earth's climate was hotter and more humid than it is today, but the climate has also been colder, as when glaciers covered much more of the planet. The most recent ice ages were in the Pleistocene Epoch, between 1.8 million and approximately 10,000 years ago. During the Pleistocene, glaciers advanced and retreated in cycles, known as glacial and interglacial periods. With so much of the world's water-bound into the ice, sea level was about 125 meters (395 feet) lower than it is today. Climatologists think that we are now in a warm, interglacial period that has lasted about 10,000 years.

For the past few thousand years, the climate has been mild and stable compared with most of Earth's history. That climate stability has allowed the expansion of agriculture and the development of towns and cities.

Small temperature changes can have had significant effects on the global climate. The average global temperature during glacial periods was only about 5.5 degrees Celsius (10 degrees Fahrenheit) less than Earth's current average temperature. Global temperatures during the interglacial periods were about 1.1 degrees Celsius (roughly 2 degrees Fahrenheit) higher than today.

Since the end of the Pleistocene, the global average temperature has risen about 4 degrees Celsius (7 degrees Fahrenheit). Glaciers are retreating, and sea level is rising. While climate is getting steadily warmer, there have also been hot and cool times in the last 10,000 years, and those changes have had severe impacts on civilization. For example, the Medieval Warm Period from 900 to 1300 A.D. allowed Vikings to colonize Greenland and Great Britain to grow wine grapes. The Little Ice Age, from the 14th to 19th centuries, the Vikings were forced out of Greenland, and humans had to plant crops further south.

10.5 EL NINO AND LA NINA

Short-term changes in regional and global climate are frequent, with the largest and most important of these is the **El Niño Southern Oscillation (ENSO)**. The ENSO drives changes in climate that are experienced around the world about every two to seven years.

In a typical year, the trade winds blow across the Pacific Ocean near the equator from east to west (toward Asia). A low-pressure cell rises above the western equatorial Pacific, warming the ocean surface water in the western Pacific Ocean, raising sea levels by one-half meter because of thermal expansion. Along the western coast of South America, Peru Current carries cold water northward and then westward along the equator with the trade winds. Consequentially, **upwelling** brings cold, nutrient-rich waters from the deep sea to the surface near Peru.

In an El Niño year, when the water temperature reaches around 28 degrees Celsius (82 degrees Fahrenheit), the trade winds weaken or reverse direction and blow east (toward South America). Warm water is dragged back across the Pacific Ocean and piles up off the west coast of South America. With warm, low-density water at the surface, upwelling ceases to occur, causing nutrients in the water to become scarce, causing plankton populations to decline. Since plankton forms the base of the food web, fish cannot find food, and fish numbers decrease. All the animals that eat fish, including birds and humans, are affected by the decline in fish.

By altering atmospheric and oceanic circulation, El Niño events change global climate patterns. Some regions receive more than average rainfall, including the west coast of North and South America, the southern United States, and Western Europe. Drought occurs in other parts of South America, the western Pacific, southern and northern Africa, and southern Europe.

An El Niño cycle lasts only a few years, with normal circulation patterns resuming. Sometimes circulation patterns bounce back quickly and remarkably, called **La Niña**. During a La Niña year, as in a typical year, trade winds move from east to west, and warm water piles up in the western Pacific Ocean. Ocean temperatures along coastal South America are colder than average (instead of warmer, as in El Niño). Coldwater reaches farther into the western Pacific than usual.

Other significant oscillations are smaller and have a local, rather than global, effect. The North Atlantic Oscillation mostly alters the climate in Europe. The Mediterranean also goes through cycles, varying between being dry at sometimes, and warm and wet at others. (Dastrup, 2014)

10.6 LONG-TERM CLIMATE CHANGE

To have an intelligent and fact-driven conversation about the planet's current warming, one must have a strong understanding of the natural causes, processes, and cycles of naturally occurring climate change. Sophisticated climate models analyze these natural processes and cycles to analyze past, present, and future climate trends and patterns.

Plate Tectonics

As noted in the textbook regarding the theory of plate tectonics, tectonic plates are moving around the Earth's surface because of convection within the mantle. This is the driving force of mountain building, earthquakes, and volcanoes around the planet. However, the movement of tectonic plates can also alter regional and global climates. Over millions of years, as seas open and close, ocean currents may distribute heat differently across the planet. For example, when all the continents are together as one supercontinent (such as Pangaea), nearly all location experiences a continental climate. When the continents separate, heat is more evenly distributed.

Plate tectonic movements can also contribute or even start an ice age. When continents are near the poles, ice can accumulate, which may increase albedo and lower global temperature to start a global ice age.

Tectonic plate motions can trigger volcanic eruptions, which may release dust and carbon dioxide into the atmosphere. Frequent eruptions, even large ones, have only a short-term effect on weather. However, massive volcanic eruptions can create lava plateaus, releasing vast quantities of carbon dioxide that can change the climate for years or decades. This type of eruption is exceedingly rare and has not occurred in human history.

Milankovitch Cycles

The most extreme climate of recent Earth history was the Pleistocene. Scientists attribute a series of ice ages to variations in Earth's position relative to the sun, known as **Milankovitch cycles**. The Earth goes through regular variations in its position compared to the sun.

The shape of the Earth's orbit changes slightly as it goes around the sun, called **eccentricity**. The orbit varies from more circular to more elliptical in a cycle lasting between 90,000 and 100,000 years. When the orbit is more elliptical, there is a more significant difference in solar radiation between winter and summer.

The Earth also wobbles on its axis of rotation, called **precession**. At one extreme of this 27,000-year cycle, the Northern Hemisphere points toward the sun when the Earth is closest to the sun. Summers are much warmer, and winters are much colder than now. At the opposite extreme, the Northern Hemisphere points toward the sun when it is farthest from the sun, resulting in cool summers and warmer winters.

The planet's tilt on its axis varies between 22.1 degrees and 24.5 degrees, called **obliquity**, which has a 41,000-year cycle. Seasons are caused by the tilt of Earth's axis of rotation, which is currently 23.5 degrees. When the tilt angle is smaller, summers and winters differ less in temperature. (Causes of Long-Term Climate Change | Physical Geography, n.d.)

Sun Variation

The amount of energy the sun radiates is relatively constant over geologic time but slightly fluctuates over the decades. Part of this fluctuation occurs because of **sunspots**, magnetic storms on the sun's surface that increase and decrease over an 11-year cycle.

When the number of sunspots is high, solar radiation is also relatively high. However, the entire variation in solar radiation is tiny relative to the total amount of solar radiation, and there is no known 11-year cycle in climate variability. The Little Ice Age corresponded to a time when there were no sunspots on the sun. (Causes of Long-Term Climate Change | Physical Geography, n.d.)

Changes in Atmospheric Greenhouse Gas Levels

Climatic data from ice core drillings rings within coral reefs and trees, ocean and lake sediments, and other sources indicate that when greenhouse gasses increase in the atmosphere, global temperatures rise. When greenhouse gasses decrease in the atmosphere, global temperatures fall. In 1958, the National Oceanic and Atmospheric Administration (NOAA) began measuring carbon dioxide levels in real-time. What direct measurements of carbon dioxide in the atmosphere indicate is that every year, the concentration of the gas increases globally every six months and decreases six months later. This has mostly to do with the continents in the northern hemisphere, where the landmass and trees are located. During the warmer months, the trees in the northern hemisphere begin photosynthesizing by taking carbon dioxide out of the atmosphere and uses sunlight to create chlorophyll. This causes global greenhouse gases to decrease for six months. When the northern hemisphere experiences fall and winter, the trees stop photosynthesizing and become dormant, causing global greenhouse gases to increase. However, even though carbon dioxide levels increase and decrease every year, the global trend is that carbon dioxide levels are growing every year. Current measurements from NASA show that carbon dioxide levels are at 413 ppm, the highest the Earth has seen in nearly a million years. (NASA, n.d.)

Recently, NASA has created ultra-high-resolution computer models, giving scientists a data-driven visualization of carbon dioxide as it flows around the world.

Greenhouse gas levels have varied throughout Earth history. For example, carbon dioxide has been present at concentrations of less than 200 parts per million (ppm) and higher levels than today.

However, for at least 650,000 years, carbon dioxide has never risen above 300 ppm, during either glacial or interglacial periods. Natural processes add (volcanic eruptions and the decay or burning of organic matter) and remove absorption by plants, animal tissue, and the ocean) carbon dioxide from the atmosphere. When plants become a form of fossil fuel, the carbon dioxide in their tissue is stored with them, removing carbon dioxide from the atmosphere. (NASA, n.d.)

Fossil fuel use has skyrocketed in the past few decades more people want more cars and industrial products, releasing vast quantities of carbon dioxide into the atmosphere. Burning tropical rainforests, to clear land for agriculture, a practice called slash-and-burn agriculture, also increases atmospheric carbon dioxide. By cutting down trees, they can no longer remove carbon dioxide from the atmosphere. Burning the trees releases all the carbon dioxide stored in the trees into the atmosphere.

The atmosphere currently holds over 40 percent more carbon dioxide than it did during the Industrial Revolution. Approximately 65 percent of that increase has occurred since the first carbon dioxide measurements were made on Mauna Loa Volcano, Hawaii, in 1958. Carbon dioxide is a critical greenhouse that must monitor because of human activity. However, other greenhouse gases are increasing as well. (The Causes of Climate Change, n.d.) The primary greenhouse gases include:

- **Water vapor** (36 to 70 percent of total): is the most abundant and potent greenhouse gas on the planet and is part of the hydrologic cycle.

- **Carbon dioxide** (9 to 26 percent of total): released from the burning of fossil fuels.
- **Methane** (4 to 9 percent of total): released from raising livestock, rice production, and the incomplete burning of rainforest plants.
- **Tropospheric ozone** (3 to 7 percent of total): from vehicle exhaust, it has more than doubled since 1976.

10.7 ANTHROPOGENIC CLIMATE CHANGE

The scientific consensus is clear, in that most scientists who directly study climates and climate change state that the current warming of the planet is anthropogenic. Moreover, all the scientific evidence and vital planetary signs indicate that more greenhouse gases are trapping Earth's heat, causing average annual global temperatures to rise. While temperatures have risen since the end of the Pleistocene, roughly 10,000 years ago, most of the warming has occurred since 1900. The nine warmest years on record have all occurred since 1998, and NASA and NOAA reported in 2019 that the year 2018 was the fourth warmest ever recorded on the planet. (2019 Was 2nd Hottest Year on Record for Earth Say NOAA, NASA | National Oceanic and Atmospheric Administration, n.d.) It has now been determined that 2010-2020 was the warmest decade on record, followed by 2000-2010.

The United States has long been the largest emitter of greenhouse gases, with about 20 percent of total emissions. As a result of China's rapid economic growth, its emissions surpassed those of the United States in 2008. However, it is also essential to keep in mind that the United States has only about one-fifth of China's population. What is the significance of this? The average United States citizen produces far more greenhouse gases than the average Chinese person. (Dastrup et al., 2019)

Predicting Future Warming

Climate change can be a naturally occurring process and has created environments much warmer than today, such as the early Cretaceous period. During this time, life thrived even in regions, such as the interior of Antarctica, which is uninhabitable today.

One misconception is that the threat of climate change has to do with the absolute warmth of the Earth. The concern more for scientists has to do with the **rate of change** of that temperature increase. Living organisms, including humans, can quickly adapt to substantial changes in climate if the changes take place slowly, over thousands of years. However, adapting to changes that are taking place on timescales of decades is far more challenging. The Earth is warming at such a rate that most species will struggle to adapt and evolve quickly enough to the coming warmer climates.

The natural increase in atmospheric carbon dioxide that led to the thaw after the last Ice Age was an increase from 180 parts per million (ppm) to about 280 ppm. This was a smaller increase than the present-time increase due to human activities, such as fossil fuel burning, which thus far has raised carbon dioxide levels from the pre-industrial value of 280 ppm to a current level of over 410 ppm, a level which is increasing by 2 ppm every year. If the dawn of industrialization had occurred 18,000 years ago, we might have sent the climate from an ice age into the modern pre-industrial state.

How long it would have taken to melt all of the ice is not precisely known, but it is conceivable it could have happened over a period as short as two centuries. The area ultimately flooded would be considerably more significant than that currently projected to flood due to the human-caused elevation of carbon dioxide that has taken place so far. (Dastrup et al., 2019)

The amount of carbon dioxide levels will continue to rise in the decades to come. However, the impacts will not be evenly distributed across the planet. Those impacts will depend on environmental and climate factors; other impacts will depend on whether the countries are developed or emerging. Climatologists and other scientists use sophisticated computer models to predict the causes, effects, and impacts of greenhouse gas increase on climate systems globally, and for specific regions of the world. (Dastrup et al., 2019)

If nothing is done to control greenhouse gas emissions, and they continue to increase at current rates, the surface temperature of the Earth can be expected to increase between 0.5 to 2.0 degrees Celsius (0.9 to 3.6 degrees Fahrenheit) by 2050, and between 2 to 4.5 degrees Celsius (3.5 to 8 degrees Fahrenheit) by 2100, with carbon dioxide levels over 800 ppm.

Whatever the temperature increase, it will not be uniform around the globe. A rise of 2.8 degrees Celsius (5 degrees Fahrenheit) would result in 0.6-1.2 degrees Celsius (1 to 2 degrees Fahrenheit) at the equator, but up to 6.7 degrees Celsius (12 degrees Fahrenheit) at the poles. Climate change has affected the North Pole more than the South Pole, but temperatures are still increasing in Antarctica.

Effects of Anthropogenic Climate Change

There are a variety of possibilities and the effects of climate change on human and natural environments. NASA has tried to list some of those potential effects and can be found here. NASA also has a website called the Climate Time Machine, to help visualize Earth's key climate indicators and how they are changing over time.

HUMAN IMPACTS AND MIGRATION

Species Mating and Migration

The timing of events for species is changing. Mating and migrations are starting to occur earlier in the spring months, and species that are more mobile are migrating to cooler temperatures and more abundant water. Some regions that were already marginal for agriculture are no longer farmable because they have become too warm or dry.

Melting Snowpack and Glaciers

Decreased snowpacks, shrinking glaciers, and the earlier arrival of spring will lessen the amount of water available in some regions of the world, including the western United States and much of Asia. Ice will continue to melt, and sea level is predicted to rise 18 to 97 cm (7 to 38 inches) by 2100. An increase this large will gradually flood coastal regions where about one-third of the world's population lives, forcing millions of people to move inland.

Glaciers are melting, and vegetation zones are moving uphill. If fossil fuel use exploded in the 1950s, why do these changes begin early in the animation? Does this mean that the climate change we see is caused by natural processes and not by fossil fuel use?

Oceans and Rising Sea Levels

As greenhouse gases increase, changes will be more extreme. Oceans will become slightly more acidic, making it more difficult for creatures with carbonate shells to grow, and that includes coral reefs. A study monitoring ocean acidity in the Pacific Northwest found ocean acidity increasing ten times faster than expected, and 10 to 20 percent of shellfish (mussels) being replaced by acid-tolerant algae.

Plant and animal species seeking cooler temperatures will need to move poleward 100 to 150 km (60 to 90 miles) or upward 150 m (500 feet) for each 1.0 degrees Celsius (8 degrees Fahrenheit) rise in global temperature. There will be a tremendous loss of biodiversity because forest species cannot migrate that rapidly. Biologists have already documented the extinction of high-altitude species that have nowhere higher to go.

One may notice that the numerical predictions above contain wide ranges. Sea level, for example, is expected to rise somewhere between 18 and 97 centimeters by 2100. The reason for this uncertainty is that scientists cannot precisely predict how the Earth will respond to increased levels of greenhouse gases. How quickly greenhouse gases continue to build up in the atmosphere depends in part on the choices we make. (Dastrup et al., 2019)

Extreme Weather

Weather will become more extreme with heatwaves and droughts. Sophisticated computer models predict that the Midwestern United States will become too dry to support agriculture and that Canada will become the new breadbasket. In all, about 10 to 50 percent of current cropland worldwide may become unusable if carbon dioxide doubles. Global monitoring systems help monitor potential droughts that could turn into famines if they occur in politically and socially unstable regions of the world and if appropriate action is not taken in time. One example is the Famine Early Warning System Network (FEWS NET), a network of social and environmental scientists using geospatial technology to monitor these situations. However, even with proper monitoring, if nations do not act, catastrophes can occur like in Somalia from 2010-2012.

Although scientists do not all agree, hurricanes are likely to become more severe and more frequent. Tropical and subtropical insects will expand their ranges, resulting in the spread of tropical diseases such as malaria, encephalitis, yellow fever, and dengue fever.

An important question people ask is this: Are the increases in global temperature natural? In other words, can natural variations in temperature account for the increase in temperature that we see? The scientific data shows no, natural variations cannot explain the dramatic increase in global temperatures. Changes in the sun's irradiance, El Niño and La Niña cycles, natural changes in greenhouse gas, plate tectonics, and the Milankovitch Cycles cannot account for the increase in temperature that has already happened in the past decades. (Dastrup et al., 2019)

Changing the Climate Change Narrative

However, it is essential to get a sound, data-driven understanding of climate change. Along with the IPCC, other organizations like the United Nations Environmental Programme (UNEP), World Health Organizations, World Meteorological Organization (WMO), National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Environmental Protection Agency (EPA).

10.8 ATTRIBUTIONS AND REFERENCES

Creative Commons Attributions

References

PART XI

BIOMES AND ECOSYSTEMS

Coming soon...

PART XII

ENVIRONMENTAL DISASTERS

Coming soon...

PART XIII

WILDFIRES

Coming soon...

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This is where you can add appendices or other back matter.