GEOLOGY



Lumen Learning
Lumen Learning



Book: Geology (Lumen)

This text is disseminated via the Open Education Resource (OER) LibreTexts Project (https://LibreTexts.org) and like the thousands of other texts available within this powerful platform, it is freely available for reading, printing, and "consuming."

The LibreTexts mission is to bring together students, faculty, and scholars in a collaborative effort to provide an accessible, and comprehensive platform that empowers our community to develop, curate, adapt, and adopt openly licensed resources and technologies; through these efforts we can reduce the financial burden born from traditional educational resource costs, ensuring education is more accessible for students and communities worldwide.

Most, but not all, pages in the library have licenses that may allow individuals to make changes, save, and print this book. Carefully consult the applicable license(s) before pursuing such effects. Instructors can adopt existing LibreTexts texts or Remix them to quickly build course-specific resources to meet the needs of their students. Unlike traditional textbooks, LibreTexts' web based origins allow powerful integration of advanced features and new technologies to support learning.



LibreTexts is the adaptable, user-friendly non-profit open education resource platform that educators trust for creating, customizing, and sharing accessible, interactive textbooks, adaptive homework, and ancillary materials. We collaborate with individuals and organizations to champion open education initiatives, support institutional publishing programs, drive curriculum development projects, and more.

The LibreTexts libraries are Powered by NICE CXone Expert and was supported by the Department of Education Open Textbook Pilot Project, the California Education Learning Lab, the UC Davis Office of the Provost, the UC Davis Library, the California State University Affordable Learning Solutions Program, and Merlot. This material is based upon work supported by the National Science Foundation under Grant No. 1246120, 1525057, and 1413739.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation nor the US Department of Education.

Have questions or comments? For information about adoptions or adaptions contact info@LibreTexts.org or visit our main website at https://LibreTexts.org.

This text was compiled on 05/19/2026

TABLE OF CONTENTS

Licensing

1.1: Assignments

1: Science of Geology

- 1.1: Why It Matters- Science of Geology
- 1.2: Outcome- What is Geology?
- 1.3: Reading- The Science of Geology
- 1.4: Reading- The Branches of Geology
- 1.5: Self Check- What is Geology?
- 1.6: Outcome- Scientific Processes in Geology
- 1.7: Reading- The Nature of Science
- 1.8: Self Check- Scientific Processes in Geology
- 1.9: Outcome- Scientific Tools
- 1.10: Reading- Geologic Tools
- 1.11: Reading- Maps
- 1.12: Video- Exploring Topographic Maps
- 1.13: Reading- Location and Direction
- 1.14: Reading- Scientific Models
- 1.15: Reading- Geologic Modelling
- 1.16: Self Check- Scientific Tools
- 1.17: Putting It Together- Science of Geology
- 1.18: Assignment- Science of Geology

2: Rock Forming Minerals

- 2.1: Why It Matters- Rock Forming Minerals
- 2.2: Outcome- Chemistry of Minerals
- 2.3: Reading- The Building Blocks of Matter
- 2.4: Reading- Atomic Bonds
- 2.5: Self Check- Chemistry of Minerals
- 2.6: Outcome- Identifying Minerals
- 2.7: Reading- Physical Characteristics of Minerals
- 2.8: Reading- Classifying Minerals
- 2.9: Self Check- Identifying Minerals
- 2.10: Outcome- Most Common Elements
- 2.11: Reading- Abundance of Elements in Earth's Crust
- 2.12: Reading- Silicate Minerals and the Silicate Tetrahedron
- 2.13: Self Check- Most Common Elements
- 2.14: Putting It Together- Rock Forming Minerals
- 2.15: Assignment- Rock Forming Minerals

3: Rocks and the Rock Cycle

- 3.1: Why It Matters- Rocks and the Rock Cycle
- 3.2: Outcome- Igneous Rocks
- 3.3: Reading- Characteristics of Igneous Rocks

- 3.4: Reading- How Are Igneous Rocks Classified?
- 3.5: Reading- Identifying Igneous Rocks
- 3.6: Reading- Uses of Igneous Rocks
- 3.7: Self Check- Igneous Rocks
- 3.8: Outcome- Sedimentary Rocks
- 3.9: Reading- Characteristics of Sedimentary Rocks
- 3.10: Self Check- Sedimentary Rocks
- 3.11: Outcome- Metamorphic Rocks
- 3.12: Reading- Characteristics of Metamorphic Rocks
- 3.13: Video- Identifying Metamorphic Rocks
- 3.14: Self Check- Metamorphic Rocks
- 3.15: Putting It Together- Rocks and the Rock Cycle

4: Weathering and Soil Formation

- 4.1: Why It Matters- Weathering and Soil Formation
- 4.2: Outcome- Weathering and Erosion
- 4.3: Reading- What Is Weathering?
- 4.4: Reading- Mechanical Weathering
- 4.5: Reading- Chemical Weathering
- 4.6: Reading- Influences on Weathering
- 4.7: Self Check- Weathering and Erosion
- 4.8: Outcome- Soil Profiles and Types
- 4.9: Reading- Soil Texture and Composition
- 4.10: Reading- Soil Horizons and Profiles
- 4.11: Reading- Types of Soils
- 4.12: Self Check- Soil Profiles and Types
- 4.13: Outcome- Soil Conservation
- 4.14: Reading- Causes of Soil Erosion
- 4.15: Video- The Dust Bowl
- 4.16: Reading- Avoiding Soil Loss
- 4.17: Self Check- Soil Conservation
- 4.18: Putting It Together- Weathering and Soil Formation
- 4.19: Assignment- Weathering and Soil Formation

5: Plate Tectonics

- 5.1: Why It Matters- Plate Tectonics
- 5.2: Outcome- Continental Drift
- 5.3: Reading- Continental Drift
- 5.4: Reading- Wegener and the Continental Drift Hypothesis
- 5.5: Self Check- Continental Drift
- 5.6: Outcome- The Theory of Plate Tectonics
- 5.7: Reading- Theory of Plate Tectonics
- 5.8: Reading- Developing the Theory
- 5.9: Self Check- The Theory of Plate Tectonics
- 5.10: Outcome- Geological Processes
- 5.11: Reading- Supercontinents
- 5.12: Reading- Volcanic Arcs
- 5.13: Video- Ocean Basins
- 5.14: Reading- Hot Spots

- 5.15: Self Check- Geological Processes
- 5.16: Putting It Together- Plate Tectonics
- 5.17: Assignment- Plate Tectonics

6: Earth's Interior

- 6.1: Why It Matters- Earth's Interior
- 6.2: Outcome- Layers of the Geosphere
- 6.3: Reading- Characteristics of the Crust
- 6.4: Reading- Characteristics of the Mantle
- 6.5: Reading- Characteristics of the Inner and Outer Core
- 6.6: Reading- The Lithosphere and Asthenosphere
- 6.7: Self Check- Layers of the Geosphere
- 6.8: Outcome- Understanding the Earth's Interior
- 6.9: Reading- Studying the Earth's Interior
- 6.10: Self Check- Understanding the Earth's Interior
- 6.11: Putting It Together- Earth's Interior
- 6.12: Assignment- Earth's Interior

7: Crustal Deformation

- 7.1: Why It Matters- Crustal Deformation
- 7.2: Outcome- Stress and Strain
- 7.3: Reading- Stress In Earth's Crust
- 7.4: Reading- Strain
- 7.5: Self Check- Stress and Strain
- 7.6: Outcome- Geologic Structures
- 7.7: Reading- Folds
- 7.8: Reading- Faults
- 7.9: Reading- Mountains
- 7.10: Self Check- Geologic Structures
- 7.11: Putting It Together- Crustal Deformation

8: Earthquakes

- 8.1: Why It Matters- Earthquakes
- 8.2: Outcome- Causes and Location of Earthquakes
- 8.3: Reading- The Nature of Earthquakes
- 8.4: Reading- Causes of Earthquakes
- 8.5: Reading- Common Locations of Earthquakes
- 8.6: Reading- The Ring of Fire
- 8.7: Self Check- Causes and Location of Earthquakes
- 8.8: Outcome- Types of Waves
- 8.9: Reading- Body Waves
- 8.10: Reading- Surface Waves
- 8.11: Self Check- Types of Waves
- 8.12: Outcome- Magnitude and Intensity
- 8.13: Reading- Measuring Earthquakes
- 8.14: Reading- Magnitude versus Intensity
- 8.15: Self Check- Magnitude and Intensity
- 8.16: Outcome- Earthquake Hazards and Prediction

- 8.17: Reading- Earthquake Hazards
- 8.18: Reading- Earthquake Prediction
- 8.19: Reading- Seismicity and Earthquake Prediction
- 8.20: Self Check- Earthquake Hazards and Prediction
- 8.21: Putting It Together- Earthquakes
- 8.22: Assignment- Earthquakes

9: Volcanoes

- 9.1: Why It Matters- Volcanoes
- 9.2: Outcome- Volcano Types
- 9.3: Reading- Types of Volcanoes
- 9.4: Reading- Types of Eruptions
- 9.5: Reading- Supervolcanoes
- 9.6: Self Check- Volcano Types
- 9.7: Outcome- The Formation of Volcanoes
- 9.8: Reading- Volcanoes at Plate Boundaries
- 9.9: Reading- Volcanoes Hotspots
- 9.10: Self Check- The Formation of Volcanoes
- 9.11: Outcome- Igneous Features
- 9.12: Reading- Pyroclastic Deposits
- 9.13: Reading- Dikes and Sills
- 9.14: Reading- Volcanic Landforms
- 9.15: Self Check- Igneous Features
- 9.16: Outcome- Volcanic Hazards
- 9.17: Reading- Volcanic Gases, Pyroclastic Flow, and Tephra
- 9.18: Reading- Lahars, Landslides, and Lavaflow
- 9.19: Self Check- Volcanic Hazards
- 9.20: Outcome- Monitoring Volcanoes
- 9.21: Reading- Signs of an Eruption
- 9.22: Reading- Tools to Monitor Volcanoes
- 9.23: Self Check- Monitoring Volcanoes
- 9.24: Putting It Together- Volcanoes

10: Mass Movement

- 10.1: Why It Matters- Mass Movement
- 10.2: Outcome- Types of Mass Movement
- 10.3: Reading- Slides
- 10.4: Reading- Falls
- 10.5: Reading- Slump and Creep
- 10.6: Self Check- Types of Mass Movement
- 10.7: Outcome- Driving and Resisting Forces
- 10.8: Reading- Natural Mass Wasting
- 10.9: Reading- Human Impact on Mass Wasting
- 10.10: Self Check- Driving and Resisting Forces
- 10.11: Putting It Together- Mass Wasting
- 10.12: Assignment- Mass Movement

11: Hydrology

- 11.1: Why It Matters- Hydrology
- 11.2: Outcome- The Hydrologic Cycle
- 11.3: Reading- Phases of the Hydrologic Cycle
- 11.4: Self Check- The Hydrologic Cycle
- 11.5: Outcome- Rivers and Streams
- 11.6: Reading- Types of Streams and Rivers
- 11.7: Reading- Drainage Basins
- 11.8: Reading- Geologic Processes and Flowing Water
- 11.9: Self Check- Rivers and Streams
- 11.10: Outcome- Components of Groundwater
- 11.11: Reading- Groundwater
- 11.12: Reading- Porosity and Permeability
- 11.13: Reading- Aquifers and Well-Potential
- 11.14: Reading- Groundwater Withdrawal
- 11.15: Reading- Quality of Groundwater
- 11.16: Self Check- Components of Groundwater
- 11.17: Outcome- Geologic Features
- 11.18: Reading- Karst Topography
- 11.19: Reading- Geysers
- 11.20: Reading- Springs
- 11.21: Self Check- Geologic Features
- 11.22: Outcome- Oceans and Shorelines
- 11.23: Reading- Ocean Movement
- 11.24: Reading- Shorelines
- 11.25: Reading- Coastal Hazards
- 11.26: Reading- Human Modifications of Coastal Processes
- 11.27: Self Check- Oceans and Shorelines
- 11.28: Putting It Together- Hydrology
- 11.29: Assignment- Hydrology

12: Geological Resources

- 12.1: Why It Matters- Geological Resources
- 12.2: Outcome- Rock and Mineral Resources
- 12.3: Reading- Ore Genesis
- 12.4: Reading- Petroleum
- 12.5: Reading- Natural Gas
- 12.6: Reading- Coal
- 12.7: Self Check- Rock and Mineral Resources
- 12.8: Outcome- Extraction of Resources
- 12.9: Reading- Mining
- 12.10: Reading- Effects of Mining
- 12.11: Self Check- Extraction of Resources
- 12.12: Outcome- Getting Energy from Resources
- 12.13: Reading- Earth's Energy
- 12.14: Reading- Energy Consumption on Earth
- 12.15: Reading- Use and Conservation of Resources
- 12.16: Self Check- Getting Energy from Resources
- 12.17: Putting It Together- Geological Resources

- 12.18: Assignment- Geological Resources

Index

Detailed Licensing

Detailed Licensing

Licensing

*A detailed breakdown of this resource's licensing can be found in **Back Matter/Detailed Licensing**.*

1.1: Assignments

The assignments in this course are openly licensed, and are available as-is, or can be modified to suit your students' needs. If you import this course into your learning management system (Blackboard, Canvas, etc.), the assignments will automatically be loaded into the assignment tool. You can view them below or throughout the course.

Assignments and Alignment	
Assignment	Module
Assignment: Science of Geology	Module 1: Science of Geology
Assignment: Rock Forming Minerals	Module 2: Rock Forming Minerals
Assignment: Rocks and the Rock Cycle	Module 3: Rocks and the Rock Cycle
Assignment: Weathering and Soil Formation	Module 4: Weathering and Soil Formation
Assignment: Plate Tectonics	Module 5: Plate Tectonics
Assignment: Earth's Interior	Module 6: Earth's Interior
Assignment: Earthquakes	Module 8: Earthquakes
Assignment: Mass Movement	Module 10: Mass Movement
Assignment: Hydrology	Module 11: Hydrology
Assignment: Geological Resources	Module 12: Geological Resources

Contributors and Attributions

CC licensed content, Original

- Assignments. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Pencil Cup. **Authored by**: IconfactoryTeam. **Provided by**: Noun Project. **Located at**: https://thenounproject.com/term/pencil-cup/628840/. **License**: *CC BY: Attribution*

CHAPTER OVERVIEW

1: Science of Geology

Learning Objectives

Define geology as a science and identify methods used in its study.

- Define the science of geology.
- Identify and use scientific processes and the scientific methods as used by geologists and with other related scientific disciplines.
- List tools and concepts commonly used by geologists.

1.1: Why It Matters- Science of Geology
1.2: Outcome- What is Geology?
1.3: Reading- The Science of Geology
1.4: Reading- The Branches of Geology
1.5: Self Check- What is Geology?
1.6: Outcome- Scientific Processes in Geology
1.7: Reading- The Nature of Science
1.8: Self Check- Scientific Processes in Geology
1.9: Outcome- Scientific Tools
1.10: Reading- Geologic Tools
1.11: Reading- Maps
1.12: Video- Exploring Topographic Maps
1.13: Reading- Location and Direction
1.14: Reading- Scientific Models
1.15: Reading- Geologic Modelling
1.16: Self Check- Scientific Tools
1.17: Putting It Together- Science of Geology
1.18: Assignment- Science of Geology

This page titled 1: Science of Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.1: Why It Matters- Science of Geology

Define geology as a science and understand the basic methods of science used in geology and related scientific disciplines

Introduction

When you ask the question “What is geology?” most people will initially respond that it is the study of rocks. This is true, but geology is also so much more than that. What if I told you geology is an intricate part of your everyday life? You may have to stop and think for a minute about that statement, but let’s consider the following questions:

1. Where do your energy resources come from—not just the gas in car, but the components in your cell phones and tablets as well?
2. Why does Japan have so many active volcanoes and earthquakes?
3. Do you enjoy eating or cooking or gardening?
4. Do you enjoy bottled, spring, or tap water?

While some of those questions are obviously geology related, it may take so exploring to find the answers to all of them. Throughout the course, you will learn the information necessary to answer these questions and others like them. We will see that geology is not just rocks but is far more encompassing than that. However, I can’t let this introduction go by without saying GEOLOGY ROCKS!

Learning Outcomes

- Define the science of geology.
- Identify and use scientific processes and the scientific methods as used by geologists and with other related scientific disciplines.
- List tools and concepts commonly used by geologists.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte. **Provided by**: Columbia Basin College. **Located at**: https://www.columbiabasin.edu/. **License**: *CC BY: Attribution*

This page titled 1.1: Why It Matters- Science of Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.2: Outcome- What is Geology?

Define the science of geology.

This section will introduce you to the science of geology. You will not only learn what geology is but you will also learn the various fields and concentrations of geology.

What You'll Learn to Do

- Describe "geology" and identify some of its main principles.
- Identify the main branches of geology.

Learning Activities

The learning activities for this section include the following:

- Reading: The Science of Geology
- Reading: The Branches of Geology
- Self Check: What is Geology?

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Lumen Learning and SBCTC. **License**: *CC BY: Attribution*

This page titled 1.2: Outcome- What is Geology? is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.3: Reading- The Science of Geology

Why Do People Study Geology?

A lot of people are attracted to geology and other earth sciences because they love to be outdoors. These people wonder how the magnificent rock formations that they see, like those in Yosemite in California (see figure 1), were formed. They want to study the processes that create and modify landforms.



Figure 1. Half dome in Yosemite, National Park, California, USA

But earth science is not just about what we can see with the naked eye—the molten lava, icy mountain peaks, steep canyons, and towering waterfalls. Some people want to go deeper, to learn about what drives the surface processes and other features of the planet; for example, why does Earth have a magnetic field? These people are interested in learning about the layers of material that lie beneath the surface, the mantle and the core. Since more than 70 percent of Earth is covered with oceans, it's not surprising that many people wonder what lies within and at the bottom of the seas.



Figure 2. The "Blue Marble"

Some people look up and wonder what lies beyond our skies. These people are interested in applying what we know about Earth to our more distant surroundings. They want to understand our near neighbors, the planets and satellites of our Solar System, and objects that lie far beyond.

What is Geology?

In its broadest sense, geology is the study of Earth—its interior and its exterior surface, the rocks and other materials that are around us, the processes that have resulted in the formation of those materials, the water that flows over the surface and lies underground, the changes that have taken place over the vastness of geological time, and the changes that we can anticipate will take place in the near future. Geology is a science: we use deductive reasoning and scientific methods to understand geological problems.

Geology is arguably the most integrated of all of the sciences because it involves the understanding and application of all of the other sciences: physics, chemistry, biology, mathematics, astronomy, and others. But unlike most of the other sciences, geology has an extra dimension, that of time—billions of years of it. Geologists study the evidence that they see around them, but in most cases, they are observing the results of processes that happened thousands, millions, and even billions of years in the past. Those were processes that took place at incredibly slow rates—millimeters per year to centimeters per year—but because of the amount of time available, they produced massive results.



Figure 3. Rearguard Mountain and Robson Glacier in the Rocky Mountains of British Columbia

Geology is displayed on a grand scale in mountainous regions, perhaps nowhere better than the Rocky Mountains in Canada (Figure 3). The peak on the right is Rearguard Mountain, which is a few kilometers northeast of Mount Robson, the tallest peak in the Canadian Rockies (3,954 m). The large glacier in the middle of the photo is the Robson Glacier. The river flowing from Robson Glacier drains into Berg Lake in the bottom right.

The sedimentary rock that these mountains are made of formed in ocean water over 500 million years ago. A few hundred million years later, these beds were pushed east for tens to hundreds of kilometers by tectonic plate convergence and also pushed up to thousands of meters above sea level. Over the past two million years this area—like most of the rest of Canada—has been repeatedly glaciated, and the erosional effects of those glaciations are obvious. The Robson Glacier is now only a small remnant of its size during the Little Ice Age of the fifteenth to eighteenth centuries, as shown by the distinctive line on the slope on the left. Like almost all other glaciers in the world, it is now receding even more rapidly because of human-caused climate change.

Geology is also about understanding the evolution of life on Earth; about discovering resources such as metals and energy; about recognizing and minimizing the environmental implications of our use of those resources; and about learning how to mitigate the hazards related to earthquakes, volcanic eruptions, and slope failures. All of these aspects of geology, and many more, are covered in this course.

Contributors and Attributions

CC licensed content, Original

- Revision and adaptation. **Provided by**: Lumen Learning. **License**: *CC BY-NC: Attribution-NonCommercial*

CC licensed content, Shared previously

- 1.2: Earth Science and Its Branches. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-Middle-School/section/1.2/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Chaptert2: Studying Earth Science. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-Concepts-For-High-School/section/2.0/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Half Dome in Yosemite National Park, California, USA. **Authored by**: Heiko von Rauu00dfendorff. **Located at**: https://commons.wikimedia.org/wiki/File:03_yosemite_half_dome.jpg. **License**: *CC BY-SA: Attribution-ShareAlike*
- 1.1 What Is Geology?. **Authored by**: Steven Earle. **Located at**: https://opentextbc.ca/geology/chapter/1-1-what-is-geology/. **Project**: Physical Geology. **License**: *CC BY: Attribution*

Public domain content

- Blue Marble 2002. **Provided by**: NASA. **Located at**: http://www.nasa.gov/content/goddard/earth-from-space-15-amazing-things-in-15-years. **License**: *Public Domain: No Known Copyright*

This page titled 1.3: Reading- The Science of Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.4: Reading- The Branches of Geology

As we mentioned, there are many varieties of geology. There is so much to know about our home planet that most geologists become specialists in one area. These specialties are known as **branches of geology**, and have specific titles. For example, a mineralogist studies minerals while a seismologist monitors earthquakes to help protect people and property from harm (figure 1).

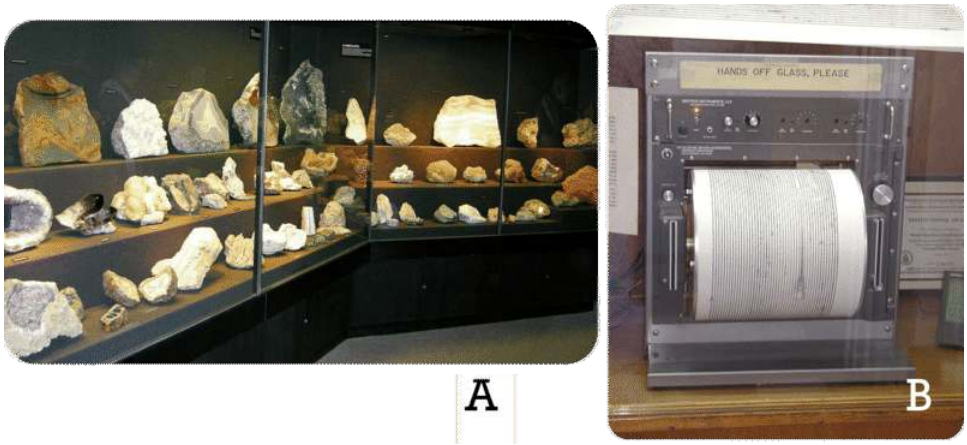


Figure 1. (A) Mineralogists focus on all kinds of minerals. (B) Seismographs are used to measure earthquakes and pinpoint their origins.

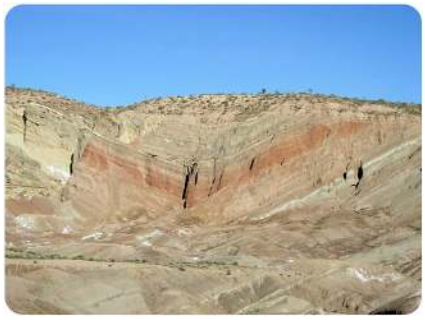


Figure 2. These folded rock layers have bent over time. Studying rock layers helps scientists to explain these layers and the geologic history of the area.

Volcanologists brave molten lava to study volcanoes. Scientists who compare the geology of other planets to Earth are planetary geologists. Some geologists study the Moon. Others look for petroleum. Still others specialize in studying soil. Some geologists can tell how old rocks are and determine how different rock layers formed (figure 2). There is probably an expert in almost anything you can think of related to Earth!

Geologists might study rivers and lakes, the underground water found between soil and rock particles, or even water that is frozen in glaciers. Earth scientists also need geographers who explore the features of Earth's surface and work with cartographers, who make maps. Studying the layers of rock beneath the surface helps us to understand the history of planet Earth.

Some Branches of Geology

As you've seen, different branches of geology study one particular part of earth. Since all of the branches are connected, specialists work together to answer complicated questions. Let's look at some other important branches of geology.

Geochemistry

Geochemistry is the study of the chemical processes which form and shape the Earth. It includes the study of the cycles of matter and energy which transport the Earth's chemical components and the interaction of these cycles with the hydrosphere and the atmosphere.

It is a subfield of inorganic chemistry, which is concerned with the properties of all the elements in the periodic table and their compounds. Inorganic chemistry investigates the characteristics of substances that are not organic, such as nonliving matter and minerals found in the Earth's crust.

Oceanography

Oceanography is the study of the composition and motion of the water column and the processes which are responsible for that motion. The principal oceanographic processes influencing continental shelf waters include waves and tides as well as wind-driven and other oceanic currents. Understanding the oceanography of shelf waters and the influence this has on seabed dynamics, contributes to a wide range of activities such as the following:

- assessment of offshore petroleum production infrastructure
- seabed mapping and characterisation for environmental management
- marine biodiversity surrogacy research
- assessment of renewable energy potential

Paleontology

Paleontologists are interested in fossils and how ancient organisms lived. Paleontology is the study of fossils and what they reveal about the history of our planet. In marine environments, microfossils collected within in layers of sediment cores provide a rich source of information about the environmental history of an area.

Sedimentology

Sedimentology is the study of sediment grains in marine and other deposits, with a focus on physical properties and the processes which form a deposit. Deposition is a geological process where geological material is added to a landform. Key physical properties of interest include:

- the size and shape of sediment grains
- the degree of sorting of a deposit
- the composition of grains within a deposit
- sedimentary structures.

These properties together provide a record of the mechanisms active during sediment transportation and deposition which allows the interpretation of the environmental conditions that produced a sediment deposit, either in modern settings or in the geological record.

Additional Branches

- **Benthic Ecology.** Benthic ecology is the study of living things on the seafloor and how they interact with their environment.
- **Biostratigraphy.** Biostratigraphy is the branch of stratigraphy that uses fossils to establish relative ages of rock and correlate successions of sedimentary rocks within and between depositional basins.
- **Geochronology.** Geochronology is a discipline of geoscience which measures the age of earth materials and provides the temporal framework in which other geoscience data can be interpreted in the context of Earth history.
- **Geophysics.** Information relating to various techniques including: airborne electromagnetics, gravity, magnetics, magnetotellurics, radiometrics, rock properties and seismic.
- **Marine Geochemistry.** Marine geochemistry is the science used to help develop an understanding of the composition of coastal and marine water and sediments.
- **Marine Geophysics.** Marine geophysics is a scientific discipline which uses the quantitative observation of physical properties to understand the seafloor and sub-seafloor geology.
- **Marine Surveying.** The survey environment varies from oceanographic studies in the water column to investigating sediment and geochemical processes on the seafloor and imaging the sub-seafloor rocks. Surveys are carried over Australia's entire marine jurisdiction, from coastal estuaries and bays, across the continental shelf and slope, to the deep abyssal plains.
- **Spectral Geology.** Spectral geology is the measurement and analysis of portions of the electromagnetic spectrum to identify spectrally distinct and physically significant features of different rock types and surface materials, their mineralogy and their alteration signatures.

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 1.2: Earth Science and Its Branches. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-Middle-School/section/1.2/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Disciplines and Techniques. **Provided by**: Geoscience Australia. **Located at**: http://www.ga.gov.au/scientific-topics/disciplines. **License**: *CC BY: Attribution*

This page titled 1.4: Reading- The Branches of Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.5: Self Check- What is Geology?

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1073

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 1.5: Self Check- What is Geology? is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.6: Outcome- Scientific Processes in Geology

Identify and use scientific processes and the scientific methods as used by geologists and with other related scientific disciplines.

This section discusses the importance of the scientific process as it relates to geology and other scientific disciplines.

What You'll Learn to Do

- Order the steps of the scientific process.
- Form a hypothesis and use it to design a scientific experiment.

Learning Activities

The learning activities for this section include the following:

- Reading: The Nature of Science
- Self Check: Scientific Processes in Geology

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Lumen Learning and SBCTC. **License**: *CC BY: Attribution*

This page titled 1.6: Outcome- Scientific Processes in Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.7: Reading- The Nature of Science

Sometime in your life you've asked a question about the world around you. Probably you've asked a lot of questions over the years. The best way to answer questions about the natural world is by using science. Scientists ask questions every day, and then use a set of steps to answer those questions. The steps are known as the scientific method. By following the scientific method, scientists come up with the best information about the natural world. As a scientist, you need to do experiments to find out about the world. You also need to wonder, observe, talk, and think. Everything we learn helps us to ask new and better questions.

Scientific Method

The scientific method is a set of steps that help us to answer questions. When we use logical steps and control the number of things that can be changed, we get better answers. As we test our ideas, we may come up with more questions. The basic sequence of steps followed in the scientific method is illustrated in figure 1.

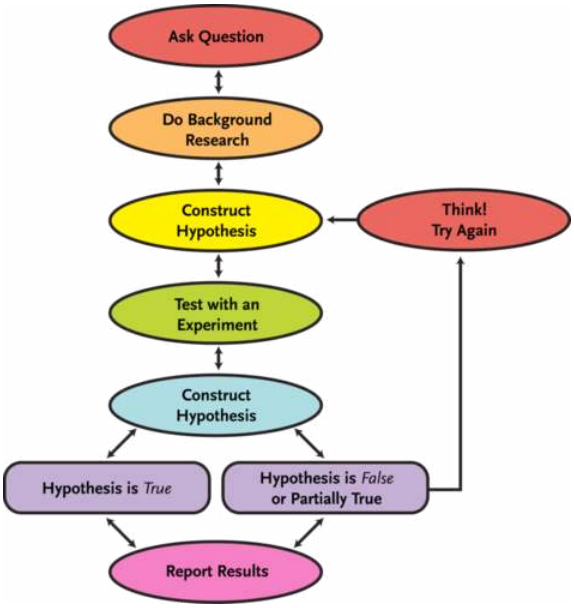


Figure 1. The Scientific Method

Questions



Figure 2. Soil is often lost from ground that has been plowed.

Asking a question is one really good way to begin to learn about the natural world. You might have seen something that makes you curious. You might want to know what to change to produce a better result.

Let's say a farmer is having an erosion problem. She wants to keep more soil on her farm. The farmer learns that a farming method called "no-till farming" allows farmers to plant seeds without plowing the land. She wonders if planting seeds without plowing will reduce the erosion problem and help keep more soil on her farmland. Her question is this: "Will using the no-till method of farming help me to lose less soil on my farm?" (figure 2).

Research



Figure 3. Rather than breaking up soil like in this picture, the farmer could try no-till farming methods.

Before she begins, the farmer needs to learn more about this farming method. She can look up information in books and magazines in the library. She may also search the Internet. A good way for her to learn is to talk to people who have tried this way of farming. She can use all of this information to figure out how she is going to test her question about no-till farming. Farming machines are shown in the figure 3.

Hypothesis

After doing the research, the farmer will try to answer the question. She might think, “If I don’t plow my fields, I will lose less soil than if I do plow the fields. Plowing disrupts the soil and breaks up roots that help hold soil in place.” This answer to her question is a **hypothesis**. A hypothesis is a reasonable explanation. A hypothesis can be tested. It may be the right answer, it may be a wrong answer, but it must be testable. Once she has a hypothesis, the next step is to do experiments to test the hypothesis. A hypothesis can be proved or disproved by testing. If a hypothesis is repeatedly tested and shown to be true, then scientists call it a **theory**.

Experiment

When we design experiments, we choose just one thing to change. The thing we change is called the **independent variable**. In the example, the farmer chooses two fields and then changes only one thing between them. She changes how she plows her fields. One field will be tilled and one will not. Everything else will be the same on both fields: the type of crop she grows, the amount of water and fertilizer that she uses, and the slope of the fields she plants on. The fields should be facing the same direction to get about the same amount of sunlight. These are the experimental **controls**. If the farmer only changes how she plows her fields, she can see the impact of the one change. After the experiment is complete, scientists then measure the result. The farmer measures how much soil is lost from each field. This is the **dependent variable**. How much soil is lost from each field “depends” on the plowing method.

Data and Experimental Error



Figure 4. A pair of farmers take careful measurements in the field.

During an experiment, a scientist collects data. The data might be measurements, like the farmer is taking in figure 4. The scientist should record the data in a notebook or onto a computer. The data is kept in charts that are clearly labeled. Labeling helps the scientist to know what each number represents. A scientist may also write descriptions of what happened during the experiment. At

the end of the experiment the scientist studies the data. The scientist may create a graph or drawing to show the data. If the scientist can picture the data the results may be easier to understand. Then it is easier to draw logical conclusions.

Even if the scientist is really careful it is possible to make a mistake. One kind of mistake is with the equipment. For example, an electronic balance may always measure one gram high. To fix this, the balance should be adjusted. If it can't be adjusted, each measurement should be corrected. A mistake can come if a measurement is hard to make. For example, the scientist may stop a stopwatch too soon or too late. To fix this, the scientist should run the experiment many times and make many measurements. The average of the measurements will be the accurate answer. Sometimes the result from one experiment is very different from the other results. If one data point is really different, it may be thrown out. It is likely a mistake was made in that experiment.

Conclusions

The scientist must next form a conclusion. The scientist must study all of the data. What statement best explains the data? Did the experiment prove the hypothesis? Sometimes an experiment shows that a hypothesis is correct. Other times the data disproves the hypothesis. Sometimes it's not possible to tell. If there is no conclusion, the scientist may test the hypothesis again. This time he will use some different experiments. No matter what the experiment shows the scientist has learned something. Even a disproved hypothesis can lead to new questions.

The farmer grows crops on the two fields for a season. She finds that 2.2 times as much soil was lost on the plowed field as compared to the unplowed field. She concludes that her hypothesis was correct. The farmer also notices some other differences in the two plots. The plants in the no-till plots are taller. The soil moisture seems higher. She decides to repeat the experiment. This time she will measure soil moisture, plant growth, and the total amount of water the plants consume. From now on she will use no-till methods of farming. She will also research other factors that may reduce soil erosion.

Theory

When scientists have the data and conclusions, they write a paper. They publish their paper in a scientific journal. A journal is a magazine for the scientists who are interested in a certain field. Before the paper is printed, other scientists look at it to try to find mistakes. They see if the conclusions follow from the data. This is called peer review. If the paper is sound it is printed in the journal.

Other papers are published on the same topic in the journal. The evidence for or against a hypothesis is discussed by many scientists. Sometimes a hypothesis is repeatedly shown to be true and never shown to be false. The hypothesis then becomes a theory. Sometimes people say they have a "theory" when what they have is a hypothesis.

In science, a theory has been repeatedly shown to be true. A theory is supported by many observations. However, a theory may be disproved if conflicting data is discovered. Many important theories have been shown to be true by many observations and experiments and are extremely unlikely to be disproved. These include the theory of plate tectonics and the theory of evolution.

Contributors and Attributions

CC licensed content, Shared previously

- 1.1: The Nature of Science. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-Middle-School/section/1.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 1.7: Reading- The Nature of Science is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.8: Self Check- Scientific Processes in Geology

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1074

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 1.8: Self Check- Scientific Processes in Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.9: Outcome- Scientific Tools

List tools and concepts commonly used by geologists.

This section discusses some of the common tools and concepts geologists employ.

What You'll Learn to Do

- Discuss several tools and their use in geology.
- Understand how to read various maps.
- Find a location using longitude and latitude.
- Identify commonly used geological models.

Learning Activities

The learning activities for this section include the following:

- Reading: Geologic Tools
- Reading: Maps
- Video: Exploring Topographic Maps
- Reading: Location and Direction
- Reading: Scientific Models
- Reading: Geologic Modelling
- Self Check: Scientific Tools

This page titled 1.9: Outcome- Scientific Tools is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.10: Reading- Geologic Tools

Geologists use a lot of tools to aid their studies. Some of the most common tools used are compasses, rock hammers, hand lenses, and field books.

Compasses

There are a number of different (specialised) magnetic compasses used by geologists to measure orientation of geological structures, as they map in the field, to analyse (and document) the geometry of bedding planes, joints, and/or metamorphic foliations and lineations.[1] In this aspect the most common device used to date is the analogue compass.

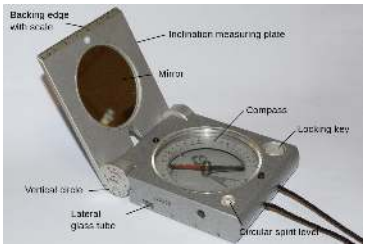
Classic geological compasses

Classic geological compasses that are of practical use combine two functions, direction finding and navigation (especially in remote areas), and the ability to measure strike and dip of bedding surfaces and/or metamorphic foliation planes. Structural geologists (i.e. those concerned with geometry and the pattern of relative movement) also have a need to measure the plunge and plunge direction of lineations.

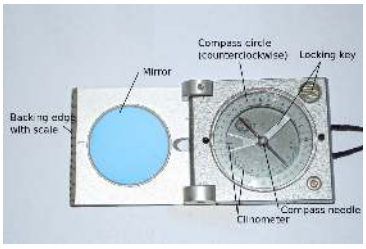
Compasses in common use include the Brunton compass and the Silva compass.

Modern Geological Compasses

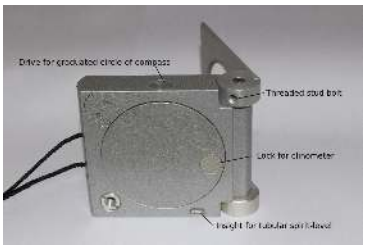
The concept of modern geological compass was developed by Eberhard Clar of the University of Vienna during his work as structural geologist. He published it in 1954.[2] An advantage of his concept is that strike and dip is measured in one step, using the vertical circle for dip angle and the compass for the strike direction. The first implementation was done by the VEB Freiberger Präzisionsmechanik in Freiberg, Germany. The details of the design were made in a close cooperation with the Freiberg University of Mining and Technology.[3]



Setup of a modern geological compass after Prof. Clar (Freiberger), total view

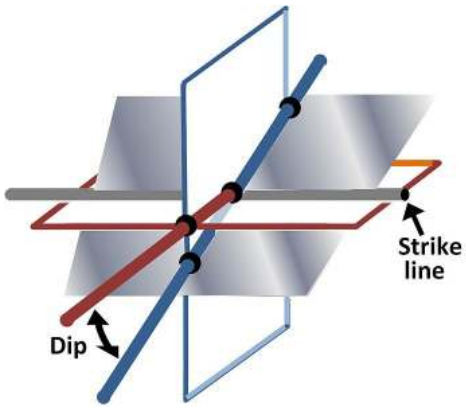


top view



bottom side

Usage



Strike line and dip of a plane describing attitude relative to a horizontal plane and a vertical plane perpendicular to the strike line

At first sight it appears confusing to the novice user, for the numbers on the compass dial ascend in an anticlockwise direction. This is because the compass is used to determine dip and dip-direction of surfaces (foliations), and plunge and plunge-direction of lines

(lineations). To use the compass one aligns the lid of the compass with the orientation of the surface to be measured (to obtain dip and dip direction), or the edge of the lid of the compass with the orientation of the line (to obtain plunge and plunge direction). The compass must be twisted so that the base of the compass becomes horizontal, as accomplished using the spirit level incorporated in it. The needle of the compass is then freed by using the side button, and allowed to spin until the damping action slows its movement, and then stabilises. The side button is released and the needle is then firmly held in place, allowing the user thereafter to conveniently read the orientation measured. One first reads the scale that shows the angle subtended by the lid of the compass, and then depending on the colour shown (red or black) the end of the compass needle with the corresponding colour. Data are then recorded as (for example) 25°->333° (dip and dip-direction) or (plunge and plunge-direction).

This compass has the most use by structural geologists, measuring foliation and lineation in metamorphic rocks, or faults and joints in mining areas.

Digital Compasses

With the advent of the smartphone, geological compass programs based on the 3-axis teslameter and the 3-axis accelerometer have also begun to appear. These compass programs use vector algebra to compute plane and lineation orientations from the accelerometer and magnetometer data, and permit rapid collection of many measurements. However, some problems are potentially present. Smartphones produce a strong magnetic field of their own which must be compensated by software; as well, because the Earth's magnetic field fluctuates rapidly, measurements made by smartphone geological compasses can potentially be susceptible to considerable noise. Users of a smartphone compass should carefully calibrate their devices and run several tests against traditional magnetic compasses in order to understand the limitations of their chosen program.

Rock Hammers



A geologist's hammer used to break up rocks, as well as a scale in the photograph

A **geologist's hammer**, **rock hammer**, **rock pick**, or **geological pick** is a hammer used for splitting and breaking rocks. In field geology, they are used to obtain a fresh surface of a rock to determine its composition, nature, mineralogy, history, and field estimate of rock strength. In fossil and mineral collecting, they are employed to break rocks with the aim of revealing fossils inside. Geologist's hammers are also sometimes used for scale in a photograph.

Shape

Geologist's hammers, as with most hammers, have two heads, one on either side. Most commonly, the tool consists of a flat head on one end, with either a chisel or a pick head at the other end.[4]

- A chisel head (pictured), which is shaped like a chisel, is useful for clearing covering vegetation from exposures and is sometimes (though inadvisedly) used to pry open fissures. Some rocks can be easily split, like slate or shale, to reveal any fossils.
- A pick head, which terminates in a sharp point to deliver maximum pressure, is often preferred for harder rocks. A geologist's hammer bearing a pick end is often referred to as a rock pick or geological pick instead of a geologist's hammer.
- A flat head is used to deliver a blow to a rock with the intention of splitting it. Specimens or samples can be trimmed to remove sharp corners or reduce them in size.

Construction



A geologist's hammer with tubular shaft and chisel head

The effective power of a geologist's hammer is mainly considered to be a reflection of its head weight and handle length. Head weight may range from 8 oz (225 g) or less on a small hammer—such as would generally be used for casual use or by children—to 24 oz (680 g) and greater. A hammer of 16 oz (450 g) is often quoted as sufficient for all rock types, although metamorphic or igneous rocks often require heavier hammers for a more powerful blow.

The best geologist's hammers are forged from one piece of hardened steel, which renders them sturdy and long-lasting. Alternatives such as tubular- and wooden-shafted hammers are more commonly used, in part due to their lower cost. Such alternative handles sacrifice strength and make the hammer unsuitable for high-strain activities such as prying.

The form and weighting of the shaft defines the balance, which itself defines the ease, efficiency, and comfort of use of the geologist's hammer.

Hand Lenses



Loupe used by a geologist

The hand lens is a vital geological field tool used to identify small mineral crystals and structures in rocks. It is a simple, small magnification device used to see small details more closely. Unlike a magnifying glass, a loupe does not have an attached handle, and its focusing lens(es) are contained in an opaque cylinder or cone or fold into an enclosing housing that protects the lenses when not in use.

Three basic types of hand lenses exist:

- Simple lenses, which result in the highest degree of optical aberration and are generally lower magnification.
- Multiple lenses, generally higher magnification because of the reduced optical aberration.
- Prismatic, Multiple lenses with prisms used to change the perspective.

Jewelers typically use a monocular, handheld loupe in order to magnify gemstones and other jewelry that they wish to inspect.[5] A 10x magnification is good to use for inspecting jewelry and hallmarks[6] and is the Gemological Institute of America's standard for grading diamond clarity. Stones will sometimes be inspected at higher magnifications than 10x, although the depth of field, which is the area in focus, becomes too small to be instructive.[7] The accepted standard for grading diamonds is therefore that inclusions and blemishes visible at 10x impact the clarity grade.[8]

Field Books

Field books are used to take fieldnotes; they can be anything from a composition type notebook to a spiral, but most use an actual "field book" like those available for purchase here. **Fieldnotes** refer to qualitative notes recorded by scientists during or after their observation of a specific phenomenon they are studying. They are intended to be read as evidence that gives meaning and aids in the understanding of the phenomenon. Fieldnotes allow the researcher to access the subject and record what they observe in an unobtrusive manner.

One major disadvantage of taking fieldnotes is that they are recorded by an observer and are thus subject to (a) memory[9] and (b) possibly, the conscious or unconscious bias of the observer. It is best to record fieldnotes immediately after leaving the site to avoid forgetting important details.

Fieldnotes are particularly valued in geology and other descriptive sciences such as ethnography, biology, and archaeology.

Structure

There are two components of fieldnotes: descriptive information and reflective information.[10]

- Descriptive information is factual data that is being recorded. Factual data includes time and date, the state of the physical setting, social environment, descriptions of the subjects being studied and their roles in the setting, and the impact that the observer may have had on the environment.[11]
- Reflective information is the observer's reflections about the observation being conducted. These reflections are ideas, questions, concerns, and other related thoughts.[12]

Fieldnotes can also include sketches, diagrams, and other drawings. Visually capturing a phenomenon requires the observer to pay more attention to every detail as to not overlook anything.[13]

---

1. *The Mapping of Geological Structures* (Geological Society of London Handbook Series) [Paperback] K. R. McClay; *Statistics of Earth Science Data: Their Distribution in Time, Space and Orientation* [Paperback] Graham J. Borradaile (Author) ↵
2. Clar, E.: *A dual-circle geologist's and miner's compass for the measurement of areal and linear geological elements.* Separate print from the negotiations of the Federal Institute of Geology Vienna, 1954, vol. 4 ↵
3. "Geologist's Compass: Operating Manual," *Freiberger Präzisionsmechanik*. http://www.fpm.de/downloads/GeologistCompass_eng.pdf. ↵
4. MartinS (2006). "'Geological Hammers' info page"↵
5. "Jewelry - How to Use a Loupe - Using Jewelry Magnifiers". Jewelry.About.com ↵
6. *Ibid*. ↵
7. http://www.gemsociety.org/article/10x-loupe-the-gemologists-best-friend/ ↵
8. "The 4C's Of Diamonds: Diamond Clarity". Leibish & Co. ↵
9. Canfield, Michael (2011). *Field Notes on Science & Nature*. Harvard University Pres. p. 21. ↵
10. Labaree, Robert V. "Research Guides: Organizing Your Social Sciences Research Paper: Writing Field Notes". *libguides.usc.edu*. Retrieved 2016-04-12. ↵
11. *Ibid*. ↵
12. *Ibid*. ↵
13. Canfield,Michael (2011). *Field Notes on Science & Nature*. p. 162. ↵

Contributors and Attributions

CC licensed content, Original

- Revision, Adaptation, and Original Content. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY-SA: Attribution-ShareAlike*

CC licensed content, Shared previously

- Geological compass. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Geological_compass. **License**: *CC BY-SA: Attribution-ShareAlike*
- Geologist's hammer. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Geologist%27s_hammer. **License**: *CC BY-SA: Attribution-ShareAlike*

- Loupe. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Loupe. **License**: *CC BY-SA: Attribution-ShareAlike*
- Fieldnotes. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Fieldnotes. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 1.10: Reading- Geologic Tools is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.11: Reading- Maps

Maps are essential tools in geology. Maps are as important in geology as written texts are in the study of literature. By studying maps, a geologist can see the shape and geology of the earth's surface and deduce the geological structures that lie hidden beneath the surface. Geologists are trained in map reading and map making. Many geologists have experience mapping some part of the earth's surface.

It takes some training to read maps skillfully. You are not expected to become a geological expert in reading maps. However, you will be expected to develop your map reading skills as you use maps to help you learn geology.

Topographic Maps

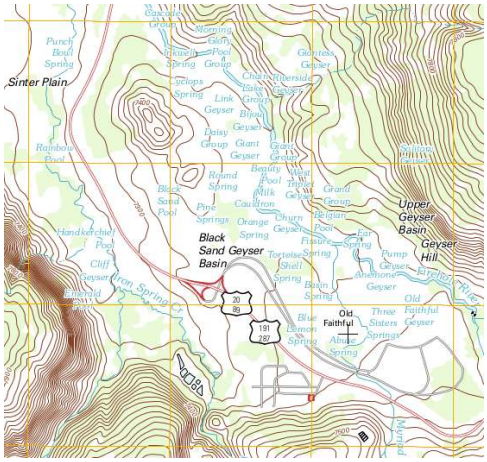


Figure 1. Map of Yellowstone.

A **topographic map** (like the one in figure 1) is one type of map used by geologists. Topographic maps show the three-dimensional shape of the land and features on the surface of the earth. Topographic maps are also used by hikers, planners who make decisions on zoning and construction permits, government agencies involved in land use planning and hazard assessments, and civil engineers. The topographic maps drawn and published by the U. S. Geological Survey portray the grids that are used on deeds to identify the location of real estate, so homeowners and property owners sometimes find it useful to refer to topographic maps of their area.

Most topographic maps make use of contour lines to depict elevations above sea level. The contour lines reveal the shape of the land in the vertical direction, allowing the 3-dimensional shape of the land to be portrayed on a 2-dimensional sheet of paper or computer screen. When you know how to read contour lines, you can look at them on a topographic map and visualize the mountains, plains, ridges, or valleys that they portrays.

Topographic maps are important in geology because they portray the surface of the earth in detail. This view of the surface shows patterns that provide information about the geology beneath the surface.

The landforms of the earth result from surface processes such as erosion or sedimentation combined with internal geological processes such as magma rising to create a volcano or a ridge of bedrock pushed up along a fault. By studying the shape of the earth's surface through topographic maps, geologists can understand the nature of surface processes in a given area, including zones subjected to landsliding, places undergoing erosion and places where sediment is accumulating. They can also find clues to the underlying geologic structure and geologic history of the area.

In addition to a topographic map, a complete understanding of the underlying geologic structure and history of an area requires completion of a geologic map and cross-sections. A topographic map provides the frame of reference upon which most geologic maps are constructed.

Reading a Topographic Map

Reading a topographic map requires familiarity with how it portrays the three-dimensional shape of the land, so that in looking at a topographic map you can visualize the shape of the land. To read a topographic map, you need to understand the rules of contour

lines.

Rules for Contour Lines

- *A contour line connects all the points on a map area that are at a specific elevation. For example, every point on a 600-foot contour line represents a point on earth that is 600 feet above sea level. You can visualize a contour line as the shoreline that would exist if the ocean were to cover the land to that elevation.*
- *The contour interval is the vertical distance, also known as the elevation difference, between adjacent contour lines. On a map with a 40-foot contour interval, the* ***vertical distance*** *between two contour lines that are next to each other, is 40 feet, regardless of the horizontal distance between the two lines on the map.*
- Contour lines do not intersect each other, because a point on the surface of the earth cannot be at two different elevations. *(However, in the rare case of a vertical cliff showing up on a topographic map, contour lines along the cliff may appear to join together into a single line.)*
- Circles that are closed contours generally signify hills.
- Depressions that have no outlet are signified by closed contours with short lines that stick out of them and point toward the center. (The short lines sticking out of the contour lines are called hachures, hatch marks, or tick marks.)
- Contour lines on standard US Geological Survey topographic maps are brown — e*xcept on the surfaces of glaciers, where the contour lines are blue.*
- The elevation of a point on the map that is not on a contour line must be estimated as greather than the elevation of the nearest contour line below it, and less than elevation of the nearest contour line above it. *For example, a point lying midway between the contours 5440 ft and 5480 ft would be at approximately 5460 ft elevation.*
- Contour lines curve upstream when they cross a valley. *This leads to the* ***"Rule of Vs"****: Where they cross streams, contour lines make Vs that point upstream.*
- Where contours are close together, the topography is steep; where contour lines are far apart, the slope is gentle or flat.
- The relief on a landscape is the elevation difference between two given points. *The maximum relief on a topographic map is the elevation difference between the highest and lowest points on the map.*

Map Quadrangles, Latitudes, and Longitudes

Standard United States Geological Survey topographic maps cover a quadrangle. A map quadrangle spans a fraction of a degree of longitude east-to-west and the same fraction of a degree of latitude north-to-south. Because lines of longitude degrees (also called meridians) in the Northern Hemisphere come closer and closer together the nearer they get to the North Pole, whereas lines of latitude degrees remain the same distance apart as they circle the earth, quadrangle maps span less distance east-to-west than they do north-to-south.

Latitude is how far north or south of the equator a point is on earth, measured in degrees, from 0° at the equator to 90° at the poles. When specifying a latitude, always state whether it is in the Northern Hemisphere (N) or Southern Hemisphere (S).

Longitude is how far east or west, up to a maximum of 180°, a point on earth is from the Prime Meridian. The Prime Meridian, 0° longitude, is a north-south line that runs through Greenwhich, England. When specifying a longitude, state whether it is in the Western Hemisphere (W) or Eastern Hemisphere (E).

Meridians, lines of longitude, run from the South Pole to the North Pole, converging (coming together) at the poles. Because the meridians converge at the poles, a degree of longitude gets smaller and smaller near each pole. In contrast, a degree of latitude remains approximately 69 miles across, no matter how near or far from the poles or equator it is.

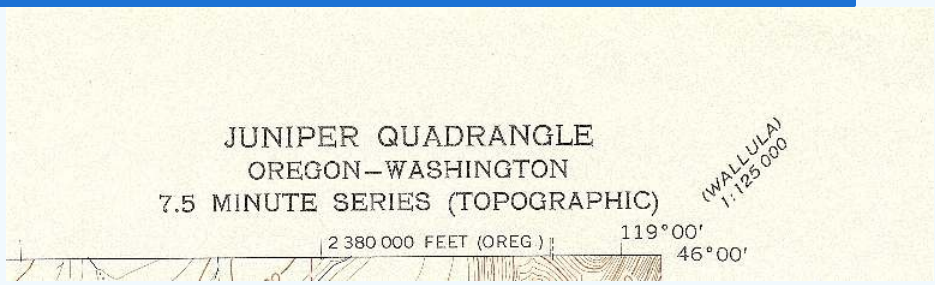
Degrees of latitude and longitude are divided into arc minutes and arc seconds. In this context, they are usually just called minutes and seconds, but it must be kept in mind that these minutes and seconds are units of angles, not units of time. These units, which divide angles into smaller parts, work as follows:

1. There are 60 arc minutes in 1 degree.
2. The symbol for minutes is a single apostrophe: ‘.
3. In symbols, 60′ = 1° means there are 60 minutes in 1 degree.
4. There are 60 arc seconds in 1 arc minute.

5. To convert arc minutes into a decimal fraction of a degree, multiply the number of arc minutes by 1°/60′. For example, to convert 15′ into a decimal fraction of a degree, 15′ x 1°/60′ = 0.25°. In simpler terms, just divide the number of arc minutes by 60 to convert to decimal degrees.
6. The symbol for arc seconds is a double apostrophe or quotation mark: “.
7. In symbols, 60″ = 1′ means there are 60 seconds in 1 minute.

Two common quadrangle sizes are 7.5 minutes (1/8 of a degree), and 15 minutes (1/4 of a degree).

? Name, Size, and Latitude-Longitude of a Topographic Map Quadrangle



The image above shows the northeastern corner portion of the topographic map of the Juniper quadrangle, which spans the border of the states of Oregon and Washington. The name of the quadrangle comes from the name of a place on the map. Find the following information using this corner of the map:

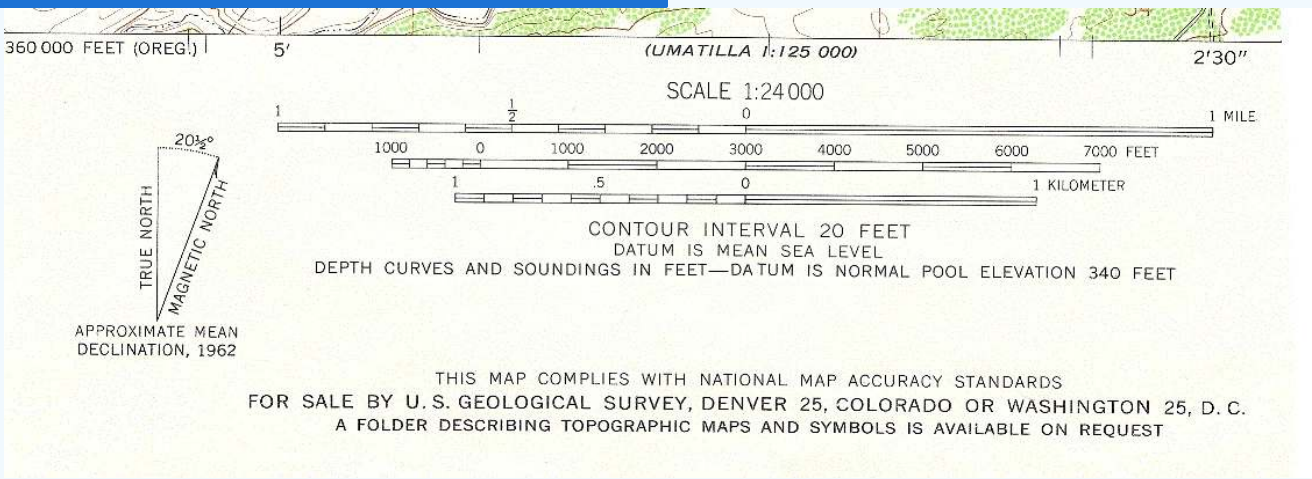
1. The name of the quadrangle
2. The state(s) in which the quadrangle is located
3. The size of the quadrangle
4. The name and fractional scale of the quadrangle map that is located adjacent to the northeast of the corner corner
5. The longitude of the eastern boundary of the map
6. The latitude of the northern boundary of the map

[reveal-answer q=”588761″]Show Answer[/reveal-answer]
[hidden-answer a=”588761″]

1. Juniper
2. Oregon and Washington
3. 7.5 minutes
4. Wallula, 1:125,000
5. 119° 00′
6. 46° 00′

[/hidden-answer]

? Map Scale, Contour Interval, and Magnetic Declination



Important information is shown at the bottom of a USGS quadrangle map, including the map scale, the contour interval, and the magnetic declination. The image above is from the bottom of the Juniper 7.5 minute quadrangle. It tells you, among other things:

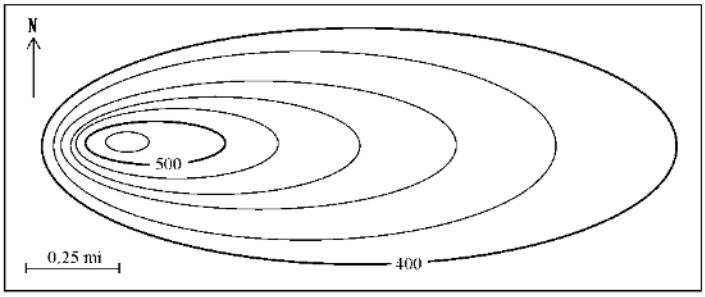
1. The map scale. The map scale is listed in terms of the fractional scale as 1:24,000. This means that 1 inch on the map corresponds to 24,000 inches in the real world represented by the map, or 1 cm equals 24,000 cm; in other words, distances on the map have been shrunk by a factor of 24,000 from their real-world size. Beneath the fractional scale, the map scale is also depicted a different way, in bar scales using three different units. One of the bar scales is in miles, one is in units of thousands of feet, and one is in kilometers.
2. The contour interval, the difference in elevation between adjacent contour lines on the map, is listed below the map scale as 20 feet.
3. There is also a reminder that elevations shown on the map are elevations above mean (average) sea level on earth.
4. (You might note that this map does something unusual for a topographic map. It shows depths in the Columbia River in feet below the surface of the river when the river is backed up in its reservoir behind a dam to a normal pool surface elevation of 340 feet above sea level.)
5. To the left of the bar scales, the magnetic declination is shown as an arrow diverging from a line oriented toward true north. True north is the direction toward the geographic North Pole. The geographic North Pole is where the northern end of earth's axis of rotation is located. The magnetic North Pole is in northeastern Canada. In 1962, the magnetic North Pole, as measured from the Juniper quadrangle, was located 20.5° east of true north. If you took a magnetic compass to the Juniper quadrangle in 1962, its north arrow would point 20.5° east of true north, so you would have had to set your magnetic compass to compensate for the declination. The magnetic North Pole wanders a few miles every year and the magnetic declination of 20.5° east of true north was determined in the year 1962; it may be slightly different now.

Constructing a Topographic Profile

One of the important tools you can use to extract the vertical information from a topographic map, and see more clearly the shape of the earth's surface that it represents is a topographic profile.

Construction of a topographic profile allows you to visualize the vertical component of a landscape. A topographic profile is similar to the view you have of a landscape while standing on earth, looking at hills and valleys from the side rather than from above.

Given a topographic map such as the one below, here's how to construct a topographic profile.



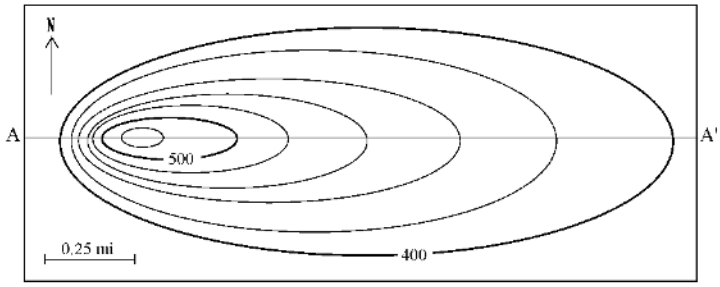
Step 1

Determine the line of profile, the line across that part of the map that you want to see in profile or cross-section view. Depending on which part of the map you want to see in profile, you can draw your line of profile in any direction you choose, across any part of the map you choose. For the map used in this example, we choose to draw the profile from A to A' as shown in the diagram below, to see the entire length of the hill in profile.

Step 2

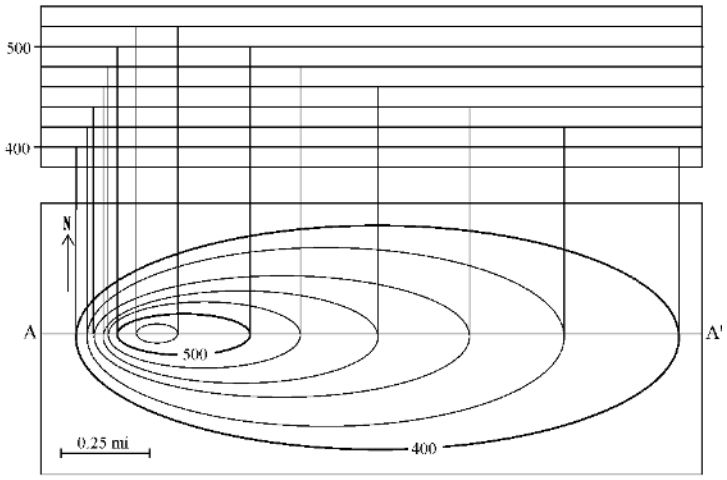
Draw a grid that will contain the profile. The width of the grid should be the same as the length of the line of profile. To draw the profile, the grid must be crossed by evenly-spaced horizontal lines that represent the contour elevations. The grid must extend high enough to span the elevation range of the contour lines spanned by the line of profile. You can see that the grid, shown below, includes the range of elevations that the line of profile crosses on the map. In addition, the grid must have an extra horizontal line at the bottom and top to accommodate the parts of the profile that go above the highest contour elevation and below the lowest contour elevation. That is why the grid in the example below goes below 400 feet and above 500 feet in elevation.





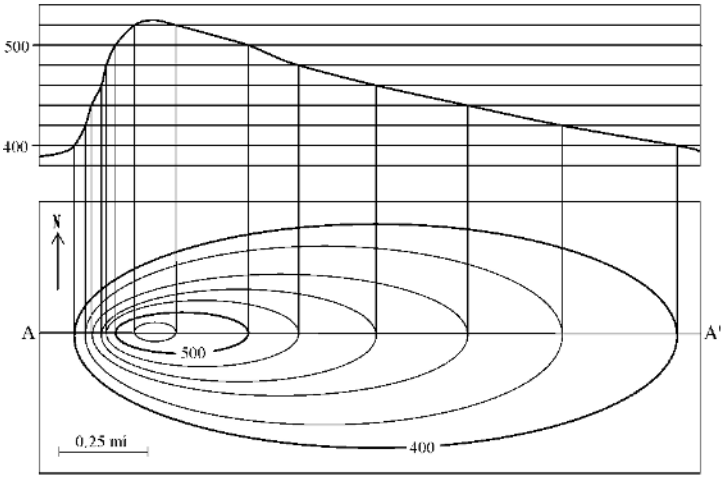
Step 3

Transfer the contour elevations from the topographic map to the profile grid. The point where each contour line crosses the line of profile on the topographic map determines the horizontal coordinate of each corresponding point on the grid of the topographic profile. The elevation of each contour line corresponds to the vertical coordinate of each corresponding point on the profile grid, as shown on the diagram below.



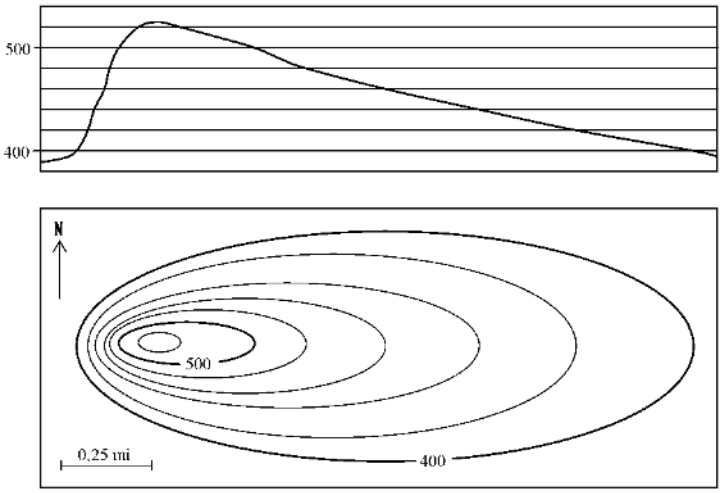
Step 4

Now that you have marked the elevation points on the profile grid, draw a smooth line connecting the data points as shown below. Note that the ends of this profile go below the 400 foot contour elevation but they do not extend to the 380 foot elevation because on the map the line of profile did not reach the 380 foot contour line. Also note that the top of the profile reaches a peak above 520 feet but less than 540 feet because the line of profile does not cross the 540 foot contour line.



Step 5

The completed topographic profile and the map it was drawn from are shown below. Topographic profiles are usually constructed without drawing any lines on the map. Instead, the edge of a piece of paper is laid along the line of profile and the contour line data is transferred to the edge of the piece of paper. From the edge of the piece of paper, the data are transfered to the profile grid, which is on a separate piece of paper.



Notice on the topographic profile constructed above that the peak of the hill is above 520 ft, but below 540 ft. Similarly, the ends of the profile are below 400 ft but above 380. This is consistent with the elevations of those parts of the line of profile on the map.

Note that the vertical scale on the profile is very different from the horizontal scale on the map. In this example, the map covers 0.25 miles horizontally in less distance than the profile covers 100 feet vertically. As a result, the topographic profile is greatly exaggerated vertically. In an actual view of the hill, looking at it from the side, it would not look nearly as steep as it does in the topographic profile that we have constructed.

If the vertical scale on a topographic profile is different from the map scale, as it is in this case, then the profile will exhibit a *vertical exaggeration*. The vertical exaggeration of a topographic profile can be calculated. It is the fractional scale of the topographic profile's vertical axis, divided by the fractional scale of the map. For example, if the vertical scale on the profile is 1:200 and the map scale is 1:24,000, the vertical exaggeration is $\displaystyle\frac{\left(\frac{1}{200}\right)}{\left(\frac{1}{24,000}\right)}$. To divide by a fraction, you can invert and multiply, so this becomes $\displaystyle\left(\frac{1}{200}\right)\times\left(\frac{24,000}{1}\right)=\frac{24,000}{200}=120$. A topographic profile with a VE of 120 would be a very exaggerated topographic profile. It would be as if a rubber model of the landscape has been pulled in the vertical direction, until it is 120 times taller than it really is.

If the vertical scale of a topographic profile is different from the map scale, the vertical exaggeration should be listed next to the profile, such as VE = 10 or VE 10x if the vertical exaggeration is 10.

Compare the profile to the topographic map. You will see that the hill is steeper on the west (left) side than on the east (right) side. This is consistent with the contour lines being spaced more closely on the west side of the hill and farther apart on the east side of the hill. This accords with the rules of contour lines, which state that slopes are steeper where contour lines are more closely spaced, and slopes are less steep where contour lines are more widely spaced.

If you drew a profile from north to south across the peak of the hill, do you think the profile would be symmetric or asymmetric?

Checklist for a Complete Topographic Profile

A properly drawn topographic profile will have the following attributes:

- The topographic profile is drawn on a rectilinear graph with evenly spaced grid lines. (Vertical grid lines are not required.)
- Elevation lines are labeled along the left-hand vertical axis.
- The profile is a smooth curve where its gradient changes, rather than straight-line segments connecting the dots and only bending at the dots.
- If the vertical scale on the profile is different from the map scale, the resulting amount of vertical exaggeration is listed.
- The ends and any high points or low points of the topographic profile should be above or below elevation lines, not on them, except in cases where an end, high point, or low point of a line of profile happens to fall right on a contour line.

? Explore More: Topographic Maps

Use this resource to answer the questions that follow. You may stop watching at the 4:04 mark.

A link to an interactive elements can be found at the bottom of this page.

1. What do topographic maps do and how do they do it?
2. What are the meanings of the terms topographic map, contour line, contour interval and index contour?
3. If you were to walk along a contour line, what would happen to your elevation?
4. If you walk perpendicular to contour lines what are you doing?
5. What do close contour lines indicate?

Bathymetric Maps

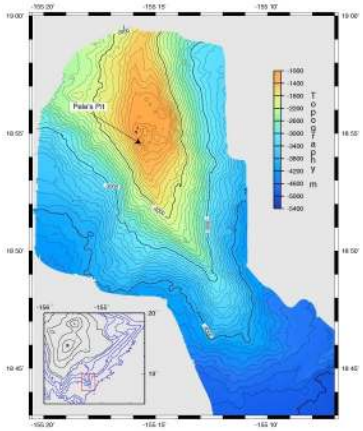


Figure 3. Loihi volcano growing on the flank of Kilauea volcano in Hawaii. Black lines in the inset show the land surface above sea level and blue lines show the topography below sea level. Click on the image to view a larger version.

A **bathymetric map** is like a topographic map with the contour lines representing depth below sea level, rather than height above. Numbers are low near sea level and become higher with depth.

Kilauea is the youngest volcano found above sea level in Hawaii. On the flank of Kilauea is an even younger volcano called Loihi. The bathymetric map pictured in figure 3 shows the form of Loihi.

Geologic Maps

A **geologic map** shows the geological features of a region (see figure 4 for an example). Rock units are color-coded and identified in a key. Faults and folds are also shown on geologic maps. The geology is superimposed on a topographic map to give a more complete view of the geology of the region.

A geologic map shows mappable rock units, mappable sediment units that cover up the rocks, and geologic structures such as faults and folds. A mappable unit of rock or sediment is one that a geologist can consistently recognize, trace across a landscape, and describe so that other people are able to recognize it and verify its presence and identity. Mappable units are shown as different colors or patterns on a base map of the geographic area.

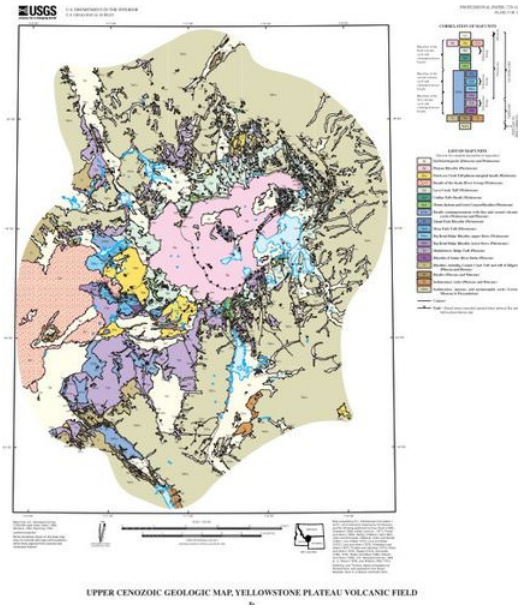


Figure 4. A geologic map of the region around Old Faithful, Yellowstone National Park.

Geologic maps are important for two reasons. First, as geologists make geologic maps and related explanations and cross-sections, they develop a theoretical understanding of the geology and geologic history of a given area.

Second, geologic maps are essential tools for practical applications such as zoning, civil engineering, and hazard assessment. Geologic maps are also vital in finding and developing geological resources, such as gravel to help build the road you drive on, oil to power the car you travel in, or aluminum to build the more fuel-efficient engine in your next vehicle. Another resource that is developed on the basis of geologic maps is groundwater, which many cities, farms, and factories rely on for the water they use.

Essential Components of Geologic Maps

A complete geologic map has at least two features:

- the map itself
- the map legend or key that explains all the symbols on the map.

Professional geologic maps usually have two other components as well:

- an accompanying explanation of the rock or sediment units
- geologic cross-sections of the map area.

The legend or key to a geologic map is usually printed on the same page as the map and follows a customary format. The symbol for each rock or sediment unit is shown in a box next to its name and brief description. These symbols are stacked in age sequence from oldest at the bottom to youngest at the top. The geologic era, or period, or epoch–the geologic age–is listed for each rock unit in the key. By stacking the units in age sequence from youngest at the top to oldest at the bottom, and identifying which interval of geologic time each unit belongs to, the map reader can quickly see the age of each rock or sediment unit. The map key also contains a listing and explanation of the symbols shown on the map, such as the symbols for different types of faults and folds. See the Table of Geologic Map Symbols for pictures and an overview of the map symbols, including strikes and dips, faults, folds, and an overview.

Table of Geologic Map Symbols

Strike and Dip Symbols		
Strike and dip are a way of representing the three-dimensional orientation of a planar surface on a two-dimensional map. The strike is the compass direction of a horizontal line on the plane. All the horizontal lines on a plane are parallel, so they all have the same characteristic compass direction. The dip is the angle at which the plane slopes downhill from the horizontal, at its maximum slope, which is at right angles (90°) from strike.		
Map Symbol	Definition	Explanation of symbol
	strike and dip of beds other than horizontal or vertical	• strike (longer line) is horizontal line on bedding plane • strike parallels nearby contacts between stratified rocks • dip shows which way beds run downhill • dip angle, number at end of dip symbol, is how much beds tilt down from horizontal
	horizontal beds	• because the bed is horizontal it strikes in all directions • because the bed is horizontal, the dip is 0%
	strike and dip of vertical beds	• strike (longer line) is horizontal line on bedding plane • because the bed dips vertically (has a 90% dip), it dips equally in either direction at right angles to strike, so the dip line is shown extending in both directions

Geologic Fault Symbols				
Type of Fault	Map Symbol	Definition	Type of Regional Stress	Geologic Associations
normal		hanging wall down, footwall up	tension	• zones of crustal extension • divergent plate boundaries • edges of horsts and grabens • Basin and Range region
detachment		low-angle normal fault, footwall—gneiss, hanging wall—shallow-crust rocks	tension	• boundaries of metamorphic core complexes
thrust		hanging wall up, footwall down	compression	• zones of crustal compression • convergent plate boundaries
reverse		high-angle (45° or more dip) thrust fault	compression	• zones of crustal compression • convergent plate boundaries
strike-slip		rocks on either side move horizontally in opposite directions	shear	• continental margins undergoing oblique (not straight on) plate convergence • transform plate boundaries
oblique-slip		combines horizontal and vertical motion	combination	• orogenic mountain belts • continental margins undergoing oblique (not straight on) plate convergence

Geologic Fold Symbols			
Type of Fold	Map Symbol	Definition	Appearance of Beds in Map View
anticline		up fold	• roughly parallel stripes • dip away from center (away from axis) • oldest at center (along axis) • youngest farthest from center
plunging anticline		up fold with tilted axis	• roughly a U-shaped pattern • plunges in direction U points • oldest at center (along axis) • youngest farthest from center
syncline		down fold	• roughly parallel stripes • dip toward center (toward axis) • oldest farthest from center • youngest at center (along axis)
plunging syncline		down fold with tilted axis	• roughly a U-shaped pattern • plunges in direction U opens • oldest farthest from center • youngest at center (along axis)
monocline		strata tilted in one direction	• all dip in same direction
structural dome		upward bulge in layered rocks	• roughly a bull’s eye pattern • dip away from center • oldest in center • youngest farthest from center
structural basin		downward bulge in layered rocks	• roughly a bull’s eye pattern • dip toward center • youngest in center • oldest farthest from center

The explanations of rock units are often given in a separate pamphlet that accompanies the map. The explanations include descriptions with enough detail for any geologist to be able to recognize the units and learn how their ages were determined.

If included, cross-sections are usually printed on the same page as the geologic map. They are important accompaniments to geologic maps, especially if the map focuses on the geology of the bedrock underneath the soil and loose sediments.

Geologic Cross-Sections

A geologic cross-section is a sideways view of a slice of the earth. It shows how the different types of rock are layered or otherwise configured, and it portrays geologic structures beneath the earth’s surface, such as faults and folds. Geologic cross-sections are

constructed on the basis of the geology mapped at the surface combined with an understanding of rocks in terms of physical behavior and three-dimensional structures.

Summary

- Earth scientists regularly use topographic, bathymetric, and geologic maps.
- Topographic maps reveal the shape of a landscape. Elevations indicate height above sea level.
- Bathymetric maps are like topographic maps of features found below the water. Elevations indicate depth below sea level.
- Geologic maps show rock units and geologic features like faults and folds.

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 2.5: Maps. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-Concepts-For-High-School/section/2.5/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Basics -- Topographic & Geologic Maps. **Authored by**: Ralph L. Dawes, Ph.D. and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: https://commons.wvc.edu/rdawes/G101OCL/Basics/mapkey.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

Public domain content

- Loihi Bathemetric. **Authored by**: NOAA. **Located at**: https://commons.wikimedia.org/wiki/File:LoihiBathemetric.jpg. **License**: *Public Domain: No Known Copyright*

This page titled 1.11: Reading- Maps is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.12: Video- Exploring Topographic Maps

Check out this augmented reality map originally developed by The University of California–Davis. It was created to help students understand topographic maps.

A link to an interactive elements can be found at the bottom of this page.

Check out UC Davis's website to learn more about the project.

Contributors and Attributions

All rights reserved content

- UCLA's Augmented Reality Sandbox. **Authored by**: UCLA. **Located at**: https://youtu.be/CE1B7tdGCw0. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 1.12: Video- Exploring Topographic Maps is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.13: Reading- Location and Direction

If you found this feature while out in the field, could you find it again?



Figure 1. Old Faithful

If you're going to make observations of geological features, you're going to need to know the location where you are so you can mark it on a map. If you find a rock formation filled with gold, you'll want to be able to find the location again!

You may need to tell someone when your truck gets stuck when you're in the field so you'll need a direction to give them.

The photo in figure 1 is of Old Faithful Geyser in Yellowstone National Park. Let's explore just a few of the ways we can pinpoint the location of this famous geological icon.

Location

How would you find Old Faithful? One way is by using latitude and longitude. Any **location** on Earth's surface — or on a map — can be described using these coordinates. Latitude and longitude are expressed as degrees that are divided into 60 minutes. Each minute is divided into 60 seconds.

Latitude

A look on a reliable website shows us that Old Faithful Geyser is located at N44º27' 43''. What does this mean?

Latitude tells the distance north or south of the Equator. Latitude lines start at the Equator and circle around the planet. The North Pole is 90°N, with 90 degree lines in the Northern Hemisphere. Old Faithful is at 44 degrees, 27 minutes and 43 seconds north of the Equator. That's just about exactly half way between the Equator and the North Pole!

Longitude

The latitude mentioned above does not locate Old Faithful exactly, since a circle could be drawn that latitude north of the Equator. To locate Old Faithful we need another point – longitude. At Old Faithful the longitude is W110^{o}49'57''.

Longitude lines are circles that go around the Earth from north to south, like the sections of an orange. Longitude is measured perpendicular to the Equator. The Prime Meridian is 0° longitude and passes through Greenwich, England. The International Date Line is the 180° meridian. Old Faithful is in the Western Hemisphere, between the Prime Meridian in the east and the International Date Line in the west.

Elevation

An accurate location must take into account the third dimension. **Elevation** is the height above or below sea level. **Sea level** is the average height of the ocean's surface or the midpoint between high and low tide. Sea level is the same all around Earth.

Old Faithful is higher above sea level than most locations at 7,349 ft (2240 m). Of course, the highest point on Earth, Mount Everest, is much higher at 29,029 ft (8848 m).

Global Positioning System

Satellites continually orbit Earth and can be used to indicate location. A **global positioning system** receiver detects radio signals from at least four nearby GPS satellites. The receiver measures the time it takes for radio signals to travel from a satellite and then calculates its distance from the satellite using the speed of radio signals. By calculating distances from each of the four satellites the receiver can triangulate to determine its location. You can use a GPS meter to tell you how to get to Old Faithful.

Direction

Direction is important if you want to go between two places. **Directions** are expressed as north (N), east (E), south (S), and west (W), with gradations in between. The most common way to describe direction in relation to the Earth's surface is with a **compass**, a device with a floating needle that is actually a small magnet. The compass needle aligns itself with the Earth's magnetic north pole. Since the magnetic north pole is 11.5 degrees offset from its geographic north pole on the axis of rotation, you must correct for this discrepancy.

Without using a compass, we can say that to get to Old Faithful, you enter Yellowstone National Park at the South Entrance, drive north-northeast to West Thumb, and then drive west-northwest to Old Faithful.

Summary

- Latitude is the distance north or south of the Equator and is expressed as a number between 0 and 90 degrees north or south.
- Longitude is the distance east or west of the Prime Meridian and is expressed as a number between 0 and 180 degrees east or west.
- Elevation is the height above sea level.
- Direction is expressed as north, south, east, or west, or some gradation between them.

? Explore More

Use this resource to answer the questions that follow.

A link to an interactive elements can be found at the bottom of this page.

1. What are lines of latitude?
2. How far apart are the lines of latitude, in degrees, in miles?
3. What are the latitudes of the Equator, the Tropic of Cancer, and the Tropic of Capricorn? What are the characteristics of the regions found between the Tropic of Cancer and Tropic of Capricorn?
4. Where are the Arctic and Antarctic circle? What are the characteristics of the regions that are found poleward of these circles?
5. What are lines of longitude?
6. Where do the meridians meet?
7. What is the Prime Meridian? Where is it located?
8. How are longitude and latitude measured?

Contributors and Attributions

CC licensed content, Original

- Revision and adaptation. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 2.4: Location and Direction. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-Concepts-For-High-School/section/2.4/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Old Faithful Rainbow. **Authored by**: Flicka. **Located at**: https://commons.wikimedia.org/wiki/File:Old_Faithful_Rainbow.jpg. **License**: *CC BY-SA: Attribution-ShareAlike*

All rights reserved content

- Latitude and Longitude. **Authored by**: Andy Jensen. **Located at**: https://youtu.be/swKBi6hHHMA. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 1.13: Reading- Location and Direction is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.14: Reading- Scientific Models

Scientists use models to help them understand and explain ideas. Models explain objects or systems in a more simple way. Models often only show only a part of a system. The real situation is more complicated. Models help scientists to make predictions about complex systems. Some models are something that you can see or touch. Other types of models use an idea or numbers. Each type is useful in certain ways.

Scientists create models with computers. Computers can handle enormous amounts of data. This can more accurately represent the real situation. For example, Earth's climate depends on an enormous number of factors. Climate models can predict how climate will change as certain gases are added to the atmosphere. To test how good a model is, scientists might start a test run at a time in the past. If the model can predict the present it is probably a good model. It is more likely to be accurate when predicting the future.

Physical Models

A **physical model** is a representation of something using objects. It can be three-dimensional, like a globe. It can also be a two-dimensional drawing or diagram. Models are usually smaller and simpler than the real object. They most likely leave out some parts, but contain the important parts. In a good model the parts are made or drawn to scale. Physical models allow us to see, feel and move their parts. This allows us to better understand the real system.

An example of a physical model is a drawing of the layers of Earth (figure 1). A drawing helps us to understand the structure of the planet. Yet there are many differences between a drawing and the real thing. The size of a model is much smaller, for example. A drawing also doesn't give good idea of how substances move. Arrows showing the direction the material moves can help. A physical model is very useful but it can't explain the real Earth perfectly.

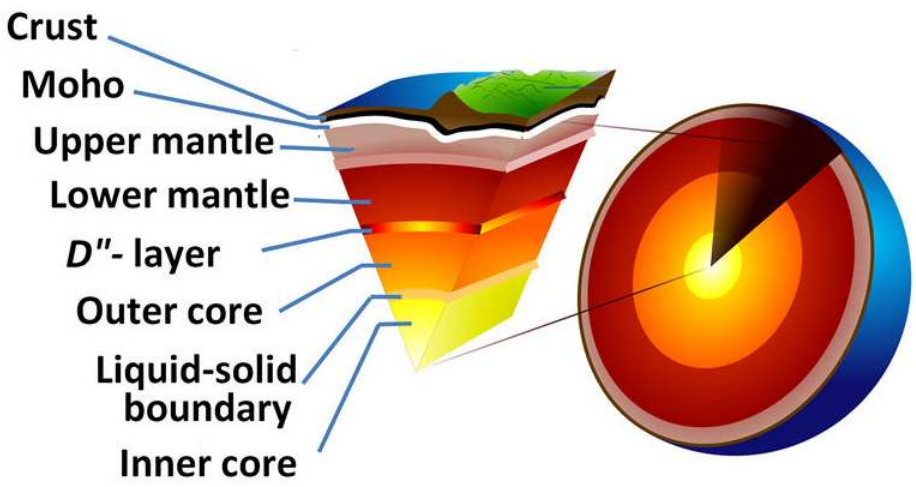


Figure 1. Earth's Center.

Ideas as Models



Figure 2. A collision showing a meteor striking Earth.

Some models are based on an idea that helps scientists explain something. A good idea explains all the known facts. An example is how Earth got its Moon. A Mars-sized planet hit Earth and rocky material broke off of both bodies (figure 2). This material orbited Earth and then came together to form the Moon. This is a model of something that happened billions of years ago. It brings together many facts known from our studies of the Moon's surface. It accounts for the chemical makeup of rocks from the Moon,

Earth, and meteorites. The physical properties of Earth and Moon figure in as well. Not all known data fits this model, but much does. There is also more information that we simply don't yet know.

Models that Use Numbers

Models may use formulas or equations to describe something. Sometimes math may be the only way to describe it. For example, equations help scientists to explain what happened in the early days of the universe. The universe formed so long ago that math is the only way to describe it. A climate model includes lots of numbers, including temperature readings, ice density, snowfall levels, and humidity. These numbers are put into equations to make a model. The results are used to predict future climate. For example, if there are more clouds, does global temperature go up or down? Models are not perfect because they are simple versions of the real situation. Even so, these models are very useful to scientists. These days, models of complex things are made on computers.

Contributors and Attributions

CC licensed content, Shared previously

- 1.1: The Nature of Science. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-Middle-School/section/1.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 1.14: Reading- Scientific Models is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.15: Reading- Geologic Modelling



Figure 1. Geological mapping software displaying a screenshot of a structure map generated for an 8500ft deep gas & Oil reservoir in the Erath field, Vermilion Parish, Erath, Louisiana. The left-to-right gap, near the top of the contour map indicates a Fault line. This fault line is between the blue/green contour lines and the purple/red/yellow contour lines. The thin red circular contour line in the middle of the map indicates the top of the oil reservoir. Because gas floats above oil, the thin red contour line marks the gas/oil contact zone.

Geologic modelling, or **Geomodelling**, is the applied science of creating computerized representations of portions of the Earth's crust based on geophysical and geological observations made on and below the Earth surface. A Geomodel is the numerical equivalent of a three-dimensional geological map complemented by a description of physical quantities in the domain of interest. Geomodelling is related to the concept of Shared Earth Model; which is a multidisciplinary, interoperable and updatable knowledge base about the subsurface.

Geomodelling is commonly used for managing natural resources, identifying natural hazards, and quantifying geological processes, with main applications to oil and gas fields, groundwater aquifers and ore deposits. For example, in the oil and gas industry, realistic geologic models are required as input to reservoir simulator programs, which predict the behavior of the rocks under various hydrocarbon recovery scenarios. A reservoir can only be developed and produced once; therefore, making a mistake by selecting a site with poor conditions for development is tragic and wasteful. Using geological models and reservoir simulation allows reservoir engineers to identify which recovery options offer the safest and most economic, efficient, and effective development plan for a particular reservoir.

Geologic modelling is a relatively recent subdiscipline of geology which integrates structural geology, sedimentology, stratigraphy, paleoclimatology, and diagenesis;

In 2-dimensions (2D), a geologic formation or unit is represented by a polygon, which can be bounded by faults, unconformities or by its lateral extent, or crop. In geological models a geological unit is bounded by 3-dimensional (3D) triangulated or gridded surfaces. The equivalent to the mapped polygon is the fully enclosed geological unit, using a triangulated mesh. For the purpose of property or fluid modelling these volumes can be separated further into an array of cells, often referred to as voxels (volumetric elements). These 3D grids are the equivalent to 2D grids used to express properties of single surfaces.

Geomodelling generally involves the following steps:

1. Preliminary analysis of geological context of the domain of study.
2. Interpretation of available data and observations as point sets or polygonal lines (e.g. "fault sticks" corresponding to faults on a vertical seismic section).
3. Construction of a structural model describing the main rock boundaries (horizons, unconformities, intrusions, faults)
4. Definition of a three-dimensional mesh honoring the structural model to support volumetric representation of heterogeneity (see Geostatistics) and solving the Partial Differential Equations which govern physical processes in the subsurface (e.g. seismic

wave propagation, fluid transport in porous media).

Geologic modelling components

Structural framework

Incorporating the spatial positions of the major formation boundaries, including the effects of faulting, folding, and erosion (unconformities). The major stratigraphic divisions are further subdivided into layers of cells with differing geometries with relation to the bounding surfaces (parallel to top, parallel to base, proportional). Maximum cell dimensions are dictated by the minimum sizes of the features to be resolved (everyday example: On a digital map of a city, the location of a city park might be adequately resolved by one big green pixel, but to define the locations of the basketball court, the baseball field, and the pool, much smaller pixels – higher resolution – need to be used).

Rock type

Each cell in the model is assigned a rock type. In a coastal clastic environment, these might be beach sand, high water energy marine upper shoreface sand, intermediate water energy marine lower shoreface sand, and deeper low energy marine silt and shale. The distribution of these rock types within the model is controlled by several methods, including map boundary polygons, rock type probability maps, or statistically emplaced based on sufficiently closely spaced well data.

Reservoir quality

Reservoir quality parameters almost always include porosity and permeability, but may include measures of clay content, cementation factors, and other factors that affect the storage and deliverability of fluids contained in the pores of those rocks. Geostatistical techniques are most often used to populate the cells with porosity and permeability values that are appropriate for the rock type of each cell.

Fluid saturation

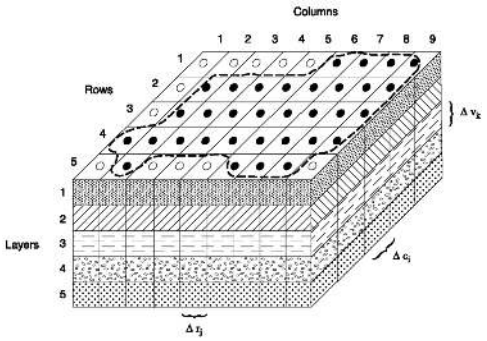


Figure 2. A 3D finite difference grid used in MODFLOW for simulating groundwater flow in an aquifer.

Most rock is completely saturated with groundwater. Sometimes, under the right conditions, some of the pore space in the rock is occupied by other liquids or gases. In the energy industry, oil and natural gas are the fluids most commonly being modelled. The preferred methods for calculating hydrocarbon saturations in a geologic model incorporate an estimate of pore throat size, the densities of the fluids, and the height of the cell above the water contact, since these factors exert the strongest influence on capillary action, which ultimately controls fluid saturations.

Geostatistics

An important part of geologic modelling is related to geostatistics. In order to represent the observed data, often not on regular grids, we have to use certain interpolation techniques. The most widely used technique is kriging which uses the spatial correlation among data and intends to construct the interpolation via semi-variograms. To reproduce more realistic spatial variability and help assess spatial uncertainty between data, geostatistical simulation based on variograms, training images, or parametric geological objects is often used.

Mineral Deposits

Geologists involved in mining and mineral exploration use geologic modelling to determine the geometry and placement of mineral deposits in the subsurface of the earth. Geologic models help define the volume and concentration of minerals, to which economic

constraints are applied to determine the economic value of the mineralization. Mineral deposits that are deemed to be economic may be developed into a mine.

Technology

Geomodelling and CAD share a lot of common technologies. Software is usually implemented using object-oriented programming technologies in C++, Java or C# on one or multiple computer platforms. The graphical user interface generally consists of one or several 3D and 2D graphics windows to visualize spatial data, interpretations and modelling output. Such visualization is generally achieved by exploiting graphics hardware. User interaction is mostly performed through mouse and keyboard, although 3D pointing devices and immersive environments may be used in some specific cases. GIS (Geographic Information System) is also a widely used tool to manipulate geological data.

Geometric objects are represented with parametric curves and surfaces or discrete models such as polygonal meshes.

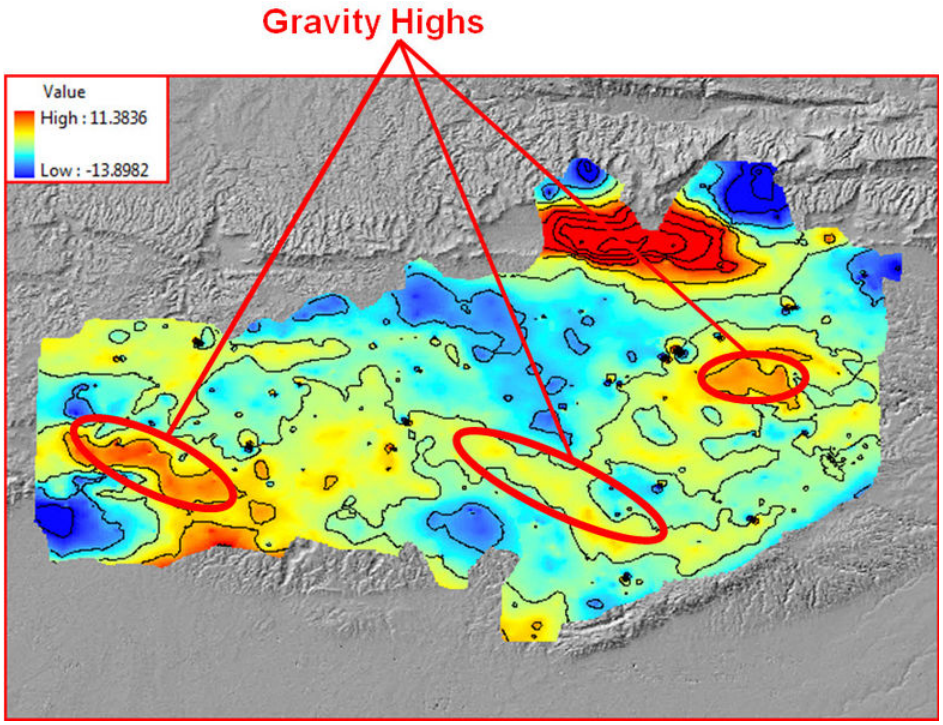


Figure 3. Gravity Highs

Research in Geomodelling

Problems pertainting to Geomodelling cover

- Defining an appropriate Ontology to describe geological objects at various scales of interest
- Integrating diverse types of observations into 3D geomodels: geological mapping data, borehole data and interpretations, seismic images and interpretations, potential field data, well test data, etc.
- Better accounting for geological processes during model building
- Characterizing uncertainty about the geomodels to help assess risk. Therefore, Geomodelling has a close connection to Geostatistics and Inverse problem theory
- Applying of the recent developed Multiple Point Geostatistical Simulations (MPS) for integrating different data sources
- Automated geometry optimization and topology conservation

History

In the 1970s, geomodelling mainly consisted of automatic 2D cartographic techniques such as contouring, implemented as FORTRAN routines communicating directly with plotting hardware. The advent of workstations with 3D graphics capabilities

during the 1980s gave birth to a new generation of geomodelling software with graphical user interface which became mature during the 1990s.

Since its inception, geomodelling has been mainly motivated and supported by oil and gas industry.

Geologic modelling software

Software developers have built several packages for geologic modelling purposes. Such software can display, edit, digitise and automatically calculate the parameters required by engineers, geologists and surveyors. Current software is mainly developed and commercialized by oil and gas or mining industry software vendors:

Geologic modelling and visualisation

- SGS Genesis
- IRAP RMS Suite
- Geomodeller3D
- Geosoft provides GM-SYS and VOXI 3D modelling software
- GSI3D
- Petrel
- Rockworks
- Move

Groundwater modelling

- FEFLOW
- FEHM
- MODFLOW
  - GMS
  - Visual MODFLOW
- ZOOMQ3D

Moreover, industry Consortia or companies are specifically working at improving standardization and interoperability of earth science databases and geomodelling software:

- Standardization: GeoSciML by the Commission for the Management and Application of Geoscience Information, of the International Union of Geological Sciences.
- Standardization: RESQML(tm) by Energistics
- Interoperability: OpenSpirit, by TIBCO(r)

Contributors and Attributions

CC licensed content, Original

- Revision and adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY-SA: Attribution-ShareAlike*

CC licensed content, Shared previously

- Geologic modelling. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Geologic_modelling. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 1.15: Reading- Geologic Modelling is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.16: Self Check- Scientific Tools

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1075

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 1.16: Self Check- Scientific Tools is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.17: Putting It Together- Science of Geology

Summary

In this section, you learned the following:

1. The extensive definition of geology
2. The various fields within geology and what they study
3. How scientists use the scientific method to answer questions

Synthesis

While we have not thoroughly answered our questions from the beginning of the outcome, we should be able to understand the connection these questions have to geology. We now know that geology is more than rocks—it deals with the resources we use in our everyday life, and it explains why some areas are more tectonically active than others. As we move through the course, keep these questions in mind.

So let's get started on this course and see why geology *rocks*.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte. **Provided by**: Columbia Basin College. **Located at**: https://www.columbiabasin.edu/. **License**: *CC BY: Attribution*

This page titled 1.17: Putting It Together- Science of Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

1.18: Assignment- Science of Geology

You have been tasked with creating a brochure on geology to hand out at a high school career day event. The goal is to inform students what geology is, what types of careers geologists use and why they need a good foundation in science if they want to be a geologist.

Basic Requirements (assignment criteria):

Prepare a brochure or flyer that clearly and accurately informs the students about the field of geology. The brochure of flyer should include:

- An introduction with a clear understanding and definition of geology
- A section describing what geologists can do or the various fields (at least 3) geologists can be a part of
- Conclude with a discussion as to why a solid understanding of science and the scientific method is needed

Be creative with your brochure. You can use the following formats: Word, PDF, PPT or Publisher files.

Make sure you cite and reference any sources that you use. Remember to not only list references but cite WITHIN the text itself.

Science of Geology Assessment

Criteria Ratings Pts

Section on geologists careers included

Complete description, all components present 5.0 pts	Incomplete description, missing one or two components. 4.0 pts	More than 2 components missing. 0.0 pts

5.0 pts

Careers include at 3 different areas geologists can specialize in

Includes 3 or more careers choices. 5.0 pts	Includes 2 career choices 4.0 pts	Includes less than 2 career choices 0.0 pts

5.0 pts

Section discussing the importance of science in geology

Discussion is thorough and clearly makes the connect between geology and a solid background in science. 5.0 pts	Discussion makes some connections but is not thorough in explanation. 4.0 pts	Discussion is lacks clearly connect between geology and a solid background in science. 0.0 pts

5.0 pts

Creativity of design

Design is original, clear, easy to read and colorful. 5.0 pts	Design is lacking in originality, not easy to read. 4.0 pts	Design is generic with little information and detail. 0.0 pts

5.0 pts

Any and all references cited within the text and listed

All references cited within the text and listed as references. 5.0 pts	References are not cited within the text but are listed as references. 4.0 pts	References are not cited within the text and are not listed as references. 0.0 pts

5.0 pts

Geology

Define geology as a science and understand the basic methods of science used in geology and related scientific disciplines

threshold: 0.0 pts

Does Not Meet Expectations	Exceeds Expectations	Meets Expectations
0.0 pts	0.0 pts	0.0 pts

0.0 pts
Total Points: 25.0

Contributors and Attributions

CC licensed content, Original

- Science of Geology Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 1.18: Assignment- Science of Geology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

2: Rock Forming Minerals

Learning Objectives

Identify and compare common rock forming minerals, mineral structures and mineral properties.

- Describe the basic chemistry involved in mineral formation and structures.
- Identify and classify common rock forming minerals.
- Identify the most common elements in the Earth's crust and their order of abundance.

2.1: Why It Matters- Rock Forming Minerals
2.2: Outcome- Chemistry of Minerals
2.3: Reading- The Building Blocks of Matter
2.4: Reading- Atomic Bonds
2.5: Self Check- Chemistry of Minerals
2.6: Outcome- Identifying Minerals
2.7: Reading- Physical Characteristics of Minerals
2.8: Reading- Classifying Minerals
2.9: Self Check- Identifying Minerals
2.10: Outcome- Most Common Elements
2.11: Reading- Abundance of Elements in Earth's Crust
2.12: Reading- Silicate Minerals and the Silicate Tetrahedron
2.13: Self Check- Most Common Elements
2.14: Putting It Together- Rock Forming Minerals
2.15: Assignment- Rock Forming Minerals

This page titled 2: Rock Forming Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.1: Why It Matters- Rock Forming Minerals

Identify and compare common rock forming minerals, mineral structures and mineral properties.

One of the related fields of geology is mineralogy: the study of minerals. Geologists rely on minerals for many reasons. Not only are some minerals considered resources we use, such as gypsum, but they are the basis for the formation of rocks. Minerals are classified in different ways based on the elements that they contain. Matter (elements) makes up the minerals and minerals make up rocks. We can't understand rocks and rock forming process or some of the other areas of geology until we have a basic knowledge of minerals.

? Occupation Focus: Mineralogist

Mineralogists specialize in minerals—their identification, their chemistry, and their formation. Mineralogists work can work in laboratories, in museums, for corporations, or for the government, but they mainly work "in the field." It is not uncommon to find them in very remote locations such as caves. They can focus on mineral identification for resource locations, the economic value of the mineral such as diamonds, they can examine the chemical content of minerals to help learn about the interior of the Earth and the various geologic processes. Regardless of what they area they are focusing on, mineralogists need a solid foundation in both chemistry and geology.

Learning Outcomes

- Describe the basic chemistry involved in mineral formation and structures.
- Identify and classify common rock forming minerals.
- Identify the most common elements in the Earth's crust and their order of abundance.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte. **Provided by**: Columbia Basin College. **License**: *CC BY: Attribution*

This page titled 2.1: Why It Matters- Rock Forming Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.2: Outcome- Chemistry of Minerals

Describe the basic chemistry involved in mineral formation and structures.

In this section, you will learn the basic chemistry associated with the different types and classes of minerals.

What You'll Learn to Do

- Identify the building blocks of matter.
- Differentiate between different kinds of atomic bonds.

Learning Activities

The learning activities for this section include the following:

- Reading: The Building Blocks of Matter
- Reading: Atomic Bonds
- Self Check: Chemistry of Minerals

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Lumen Learning and SBCTC. **License**: *CC BY: Attribution*

This page titled 2.2: Outcome- Chemistry of Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.3: Reading- The Building Blocks of Matter

Why study the chemistry of minerals? Minerals are made of **atoms**, which have an impact on the behavior and characteristics of the mineral. Thus, to understand, explain, and predict the behavior of minerals, and rocks—which are made of minerals—we must understand some basic facts about atoms and how they behave. This requires a basic understanding of some chemistry. We will begin by constructing atoms in our thinking in terms of the three sub-atomic particles of which atoms are made.

Atoms

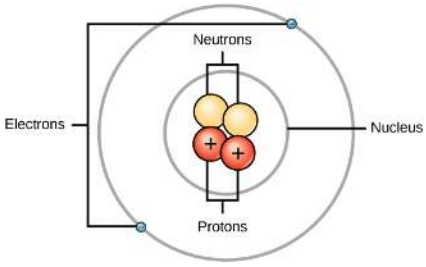


Figure 1. Elements, such as helium, depicted here, are made up of atoms. Atoms are made up of protons and neutrons located within the nucleus, with electrons in orbitals surrounding the nucleus.

Atoms consist of protons, neutrons, and electrons. **Protons** have a positive (+) electrical charge. **Electrons** have a negative (−) charge that is exactly equal and opposite to the electrical charge of a proton. **Neutrons** are electrically neutral.

Most of the mass of an atom is packed into its tiny nucleus. An atomic nucleus is made of protons and neutrons, which have approximately the same mass (about 1.67×10^{-24} grams). Electrons, on the other hand, are arranged in specific orbitals around the nucleus of an atom; they are also much smaller in mass than protons and neutrons, weighing only 9.11×10^{-28} grams, or about 1/1800 the weight of protons and neutrons.

Even though the mass of an electron is a tiny mass compared to the mass of a proton or a neutron, the electrons occupy most of the volume of an atom (see Figure 1).

Ions

A neutral atom has the same number of electrons as it does protons. An atom that has lost or gained any electrons is no longer an electrically neutral atom. That type of atom, which is not electrically neutral and has an electrical charge associated with it, is called an **ion**. Atoms that have gained electrons are negatively (−) charged ions, or **anions**. Atoms that have lost electrons are positively (+) charged ions, or **cations**.

It is also possible to have ions that are actually small groups of atoms bonded together. These are known as polyatomic ions. One example of a polyatomic ion is the carbonate ion, $(CO_3)^{2-}$, which has two extra electrons, giving it the net electrical charge of 2−.

? Chemical Formulas

We've just seen that a carbonate ion can also be called $(CO_3)^{2-}$. But what exactly does this mean?

First let's look at the letters: CO. Atoms have chemical symbols; each element has been assigned one or two letters to represent it. Thus, C stands in for carbon, and O stands in for oxygen (all of these chemical symbols can be seen in the periodic table in figure 2 below).

As we read above, the $^{2-}$ means that the ion has two extra electrons. But what about the $_3$? This means there are three oxygen atoms in the ion. The number of atoms in a particular formula is always notated in subscript. Charge is always written in superscript at the end of the formula (a superscript at the beginning of the formula means something else—we'll get to this when we discuss isotopes below). The parentheses around CO_3 indicate that the charge belongs to the whole polyatomic unit rather than just the O_3.

Thus the carbonate ion is one carbon atom (C), three oxygen atoms (O_3), and two extra electrons ($^{2-}$), which charge the whole polyatomic ion.

The Periodic Table

Naturally occurring atoms found in the earth range from hydrogen, with just one proton in its nucleus, to uranium, with 92 protons in its nucleus. These are the naturally occurring chemical elements, which includes such commonly known elements as carbon, oxygen, iron, and so on. The periodic table lists all the chemical elements in a way that tells us how many protons each of them has, how its electrons are arranged, and what the general chemical behavior of each element is.

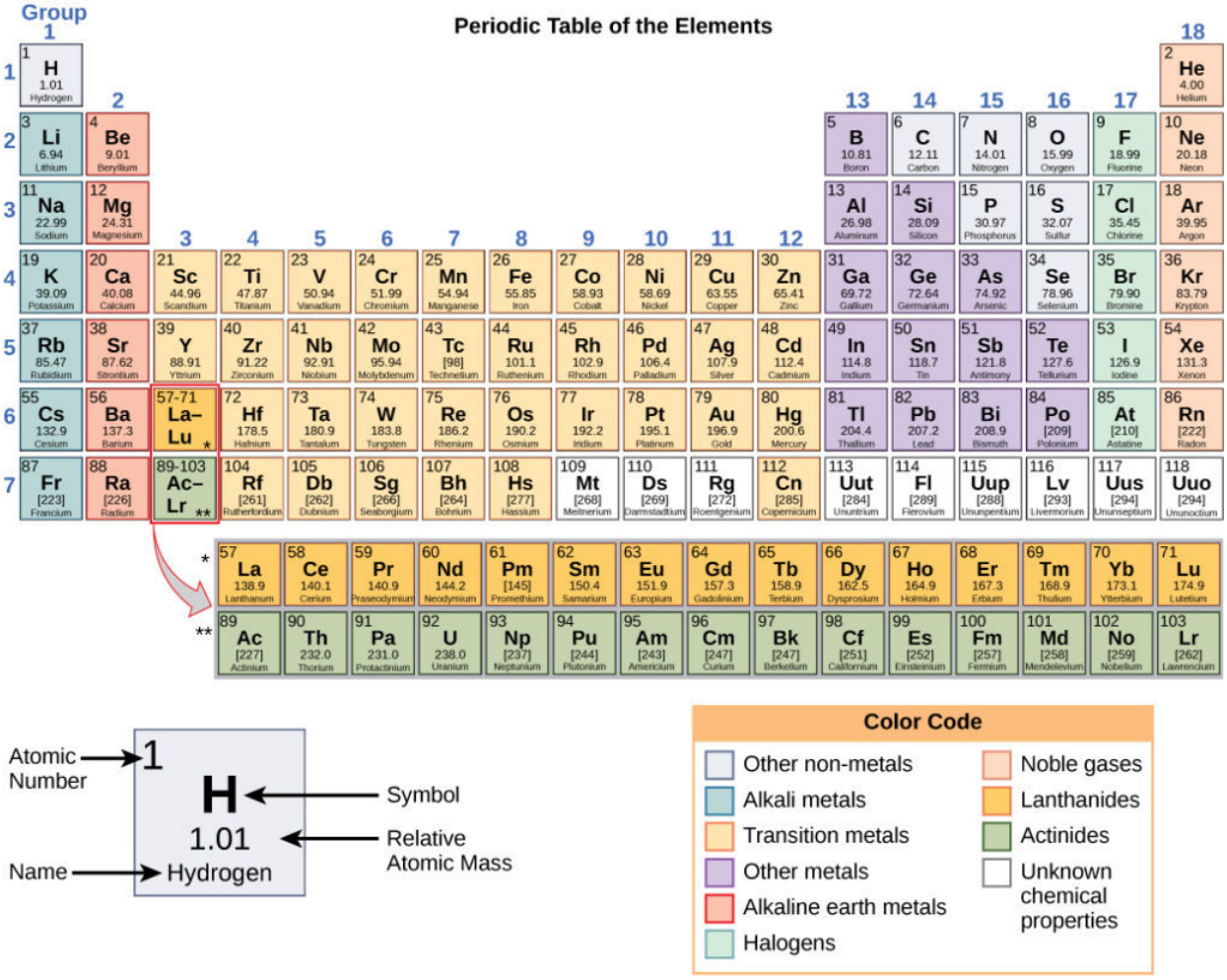


Figure 2. Follow this link to a large version of the Periodic Table. The link will open in a new window so you can easily refer to it as you read through this page.

As shown in Figure 2, the periodic table consists of eighteen groups and seven periods. Two additional rows of elements, known as the lanthanides and actinides, are placed beneath the main table. These elements are placed separately to make the table more compact. All the elements in a group have a similar chemical behavior. This is because all the elements in a group have a similar arrangement of electrons in their atoms, and it is the electron arrangement that determines the chemical behavior of an element.

For each element, the name, atomic symbol, atomic number, and atomic mass are provided. The atomic number is a whole number that represents the number of protons: each chemical element is distinguished by the number of protons in its nucleus. For example, every atom of the element oxygen has eight protons in its nucleus. That is why the atomic number of oxygen is 8. If an atom has greater or fewer than eight protons in its nucleus, it is not oxygen, it is some other chemical element. In the periodic table, the atomic number of each element is listed above the chemical symbol of the element.

The atomic mass, which is the average mass of different isotopes, is estimated to two decimal places. For example, hydrogen has the atomic symbol H, the atomic number 1, and an atomic mass of 1.01. The atomic mass is always larger that the atomic number. For most small elements, the atomic mass is approximately double the atomic number, as the number of protons and neutrons is about equal.

The elements are divided into three categories: metals, nonmetals and metalloids. These form a diagonal line from period two, group thirteen to period seven, group sixteen. All elements to the left of the metalloids are metals, and all elements to the right are nonmetals.

The periodic table was created to help chemists better understand elements and how they function. It is a map to elemental behavior.

Isotopes

Every atom of a specific element must have the same number of protons in its nucleus. This number is its atomic number. However, there is a range of possible numbers of neutrons it can have in its nucleus. The fact that atoms of a chemical element may have different numbers of neutrons results in each chemical element having several isotopes. Isotopes are atoms of a given chemical element that have different numbers of neutrons in their nuclei.

For example, while all atoms of the element oxygen have eight protons in their nuclei, those oxygen atoms may have eight, nine, or ten neutrons. The different numbers of neutrons in the nucleus distinguishes the three isotopes of oxygen. Oxygen-16 is the isotope of oxygen with 8 neutrons in its nucleus. The number 16 is called the atomic mass number. The atomic mass number is the total number of protons and neutrons in the nucleus of an isotope. From this definition, and knowing that all oxygen atoms have 8 protons in the nucleus, you can deduce that oxygen-17 is the oxygen isotope with 9 neutrons and oxygen-18 is the oxygen isotope with 10 neutrons. Abbreviated into symbols, the three isotopes of oxygen are written as ^{16}O, ^{17}O and ^{18}O.

Isotopes are not very important for understanding minerals, but are important in understanding how to apply chemistry and nuclear physics to geology, such as how to use measurements of radioactive isotopes to measure the ages of rocks and minerals and how to use oxygen isotopes from layers of glacial ice to determine what the temperature of the earth was during an ice age.

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Basics - Minerals. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/minerals.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*
- Periodic Table of Elements. **Provided by**: OpenStax. **Located at**: http://cnx.org/contents/185cbf87-c72e-48f5-b51e-f14f21b5eabd@9.74:6/Biology. **License**: *CC BY: Attribution*

All rights reserved content

- The Periodic Table: Crash Course Chemistry #4. **Authored by**: CrashCourse. **Located at**: https://youtu.be/0RRVV4Diomg. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 2.3: Reading- The Building Blocks of Matter is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.4: Reading- Atomic Bonds

Chemical Reactions

Minerals form as a result of chemical reactions. Chemical reactions are driven mainly by the arrangement and rearrangement of electrons in atoms. In a mineral, the atoms are held together by chemical bonds, which derive from the electrons.

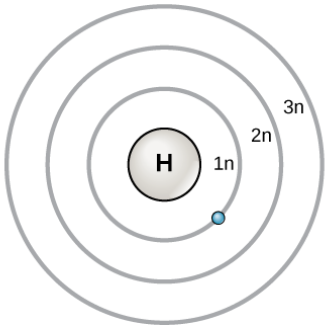


Figure 1. The Bohr model of the atom.

Electrons can be thought of as occupying energy levels, or shells, in an atom. The lowest-energy shell is closest to the nucleus. Each shell can accommodate only a limited number of electrons. The first shell can hold two electrons, the second and third shells can hold eight electrons, and the next two shells can hold eighteen electrons. Unless energy is added to an atom to excite it from its low-energy state, the electrons in the atom will occupy the lowest-energy shells available to them.

The Bohr model (see figure 1) was developed by Niels Bohrs in 1913. In this model, electrons exist within principal shells. An electron normally exists in the lowest energy shell available, which is the one closest to the nucleus. Energy from a photon of light can bump it up to a higher energy shell, but this situation is unstable, and the electron quickly decays back to the ground state.

Chemical Bonds

If atoms interact with other atoms, they can gain or lose electrons to the other atoms, or share electrons with other atoms. In an individual atom, the most stable arrangement is a full outer shell of electrons. Therefore, chemical reactions will occur, and chemical bonds will form that hold atoms together to each other, when atoms encounter other atoms and change their electron configurations toward more stable, lower-energy arrangements, which generally involves achieving full outer electron shells in the atoms.

This stable configuration—a full outer shell of electrons—is exemplified by the inert gases. In the periodic table the inert gases are the elements of group 18 or VIIIA, the last column on the right. Inert gases do not have to undergo any chemical reactions or form any chemical bonds with other atoms in order to have a full outer shell of electrons. The inert gases already have full outer shells of electrons. That is why they are chemically inert. Their electrons are as stable as can be arranged. For this reason, inert gases are extremely unlikely to undergo any chemical reactions and it is almost impossible for them to bond with any other atoms. Because they do not bond with any other atoms to form a liquid, a solid, a molecule, or a mineral, the inert gases consist of atoms that stay separate from each other, in the gas state.

Individual atoms of all the other chemical elements, when they are neutral atoms, do not have full outer shells of electrons like the inert gases do. Therefore, they do not have the most stable arrangement of electrons that they possibly can. That is why most chemical elements have a strong tendency to either gain or lose electrons, or to enter into other arrangements of their valence electrons, the electrons in their outer shell. Chemical reactions and chemical bonds are generally a result of electrons being rearranged within and among atoms to give the atoms full outer electron shells.

For an atom to lose or gain one electron takes less energy than to lose or gain two, which in turn takes less energy than to lose or gain a third electron. For an individual atom to gain or lose four electrons will only occur in extremely high-energy environments such as in a star. In common chemical reactions on earth, and in the formation of chemical bonds, no element will completely gain or lose four electrons. This limits the charges of atomic cations to +1, +2 or +3 and the charges of atomic anions to –1, –2, or –3.

Reading this far, you have learned about one group of elements in the periodic table, group 18, the inert gases. Another group of chemical elements in the periodic table is the alkali elements. The alkali elements compose group 1 or IA, the left hand column, including the elements sodium (Na) and potassium (K).

Hydrogen is not usually considered as an alkali element because, even though it is shown in group 1 in the periodic table. Hydrogen is so light and small, with just a single proton in its nucleus, that it has some unique behaviors and is considered in a class by itself.

The alkali elements have a single electron in their outer electron shell. If an alkali element loses a single electron, it becomes an ion with a +1 charge and a full outer shell. If an opportunity arises, alkali elements will easily turned into +1 cations.

Ionic bonds

Now look at group 17 or VIIA in the periodic table, which includes the chemical elements fluorine (F), chlorine (Cl) and so on. These are the halogen elements. If a halogen element gains a single electron, it becomes an ion with a–1 charge and a full outer electron shell. If an opportunity arises, halogen elements have a strong tendency to take in an extra electron and become -1 anions because by doing so they achieve a full outer shell of electrons, which is the most stable arrangement of electrons possible.

If sodium and chlorine atoms get together in the right conditions, such as in an evaporating solution of salt water, each sodium atoms will give up an electron to a chlorine atom. This turns the sodium atoms into sodium ions, Na^+, and the chlorine atoms into chloride ions, Cl^-. Opposite electrical charges attract, so the sodium ions and chloride ions will tend to stick together with each other, joined by what are called ionic bonds.

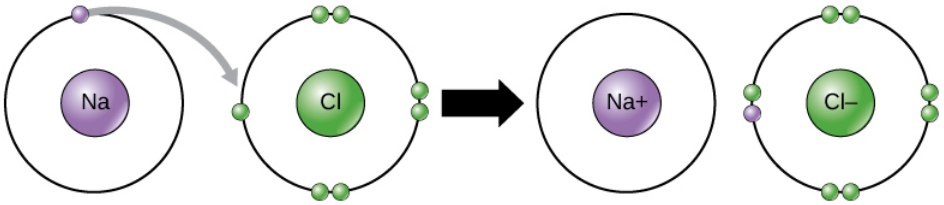


Figure 2. In the formation of an ionic compound, metals lose electrons and nonmetals gain electrons to achieve an octet. Ionic bonds are formed between ions with opposite charges. For instance, positively charged sodium ions and negatively charged chloride ions bond together to make crystals of sodium chloride, or table salt, creating a crystalline molecule with zero net charge.

Not only will the sodium and chloride ions have a very strong tendency to join together with each other via ionic bonds, in most situations they will naturally arrange into a configuration where there is no wasted space and no wasted energy. This leads them to form the crystal lattice of the mineral halite. Halite is a mineral with the chemical formula NaCl, sodium chloride, in which the bonds between the atoms are all ionic bonds.

Look at the diagram of halite showing the sodium and chloride ions arranged into the crystal lattice. All the ionic bonds are at the same angle and the same distance, so they are all of equal strength. This is the lowest-energy arrangement of the ions, the most stable arrangement. If any of the ions were spaced located at different angles or at different distances, there would be extra energy available. This extra energy would drive the ions toward equal angles and distances from each other, until the extra energy is used up and the ions are arranged into their lowest energy state. That is why minerals form, as a natural way for atoms to arrange themselves into the lowest energy state currently available to them.

Covalent bonds

Some elements, such as carbon (C) and silicon (Si) have a half-full valence shell. (The valence shell is another name for the outer shell, where the most reactive electrons are.) If an element such as carbon were to gain 4 electrons or lose 4 electrons, it would have a full valence shell. However, it is very difficult for an atom to gain or lose four electrons—the energy barrier becomes too strong. Therefore, carbon and silicon, along with a few other elements, tend to form a different type of bond in which they share their outer electrons with other atoms, which in turn share their outer electrons with the carbon (or silicon) atom. The atoms all end up with a full outer shell of electrons, even though some or all of those electrons are being shared with neighboring atoms. This electron sharing keeps the atoms bonded together. This type of chemical bond is called a covalent bond.

It is not uncommon for covalent bonds to be relatively strong. An extreme example can be in diamond. Diamond is a mineral consisting of nothing but carbon atoms, so its chemical formula is simply C. Each carbon atom in the diamond crystal lattice is

covalently bonded to—sharing its valence electrons with—four neighboring carbon atoms. A diamond crystal is held together by nothing but extremely strong covalent bonds in all directions, which makes diamond a very hard mineral, the hardest known.

Metallic bonds

Gold forms a naturally occurring mineral of more or less pure gold, Au, held together by another type of bond, the metallic bond. Metallic elements such as gold and copper, when they bond with other metallic elements, are sharing some of their electrons not just with adjacent atoms, but throughout the whole substance. That is why metallic substances such as copper, gold, and aluminum make such good electrical conductors, because it is so easy to get the “loose” electrons to respond through the whole extent of the metal.

Hydrogen bonds

Another type of chemical bond that occurs in some minerals is the hydrogen bond. Hydrogen bonds are caused by the positive and negative ends of polar molecules attracting each other strongly enough to hold each other in fixed positions. For example, water molecules can join together through hydrogen bonds to form the mineral known as ice. In a water molecule, H_2O, each of the hydrogen atoms forms a covalent bond with the oxygen atom.

Contributors and Attributions

CC licensed content, Shared previously

- Basics - Minerals. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/minerals.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*
- Atoms, Isotopes, Ions, and Molecules: The Building Blocks. **Provided by**: OpenStax. **Located at**: http://cnx.org/contents/185cbf87-c72e-48f5-b51e-f14f21b5eabd@10.8. **Project**: Biology. **License**: *CC BY: Attribution*

This page titled 2.4: Reading- Atomic Bonds is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.5: Self Check- Chemistry of Minerals

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1078

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 2.5: Self Check- Chemistry of Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.6: Outcome- Identifying Minerals

Identify and classify common rock forming minerals.

The solid earth is made of rocks, which are made of minerals. To understand rocks you need to become familiar with minerals and how they are identified. This outcome gives you the background needed to understand the terms used in identifying minerals.

This section will introduce you to minerals. You will learn the various techniques used by geologists to identify and classify minerals.

What You'll Learn to Do

- Identify minerals based on their physical characteristics.
- Sort minerals into the correct mineral class.

Learning Activities

The learning activities for this section include the following:

- Reading: Physical Characteristics of Minerals
- Reading: Classifying Minerals
- Self Check: Identifying Minerals

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Lumen Learning and SBCTC. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Basics - Minerals. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/minerals.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 2.6: Outcome- Identifying Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.7: Reading- Physical Characteristics of Minerals

What are Minerals?

All rocks except obsidian and coal are made of minerals. (Obsidian is a volcanic rock made of glass and coal is made of organic carbon.) Most rocks contain several minerals in a mixture characteristic of the particular rock type. When identifying a rock you must first identify the individual minerals that make up that rock.

Minerals are naturally occurring, inorganic solids with a definite chemical composition and a crystal lattice structure. Although thousands of minerals in the earth have been identified, just ten minerals make up most of the volume of the earth's crust—plagioclase, quartz, orthoclase, amphibole, pyroxene, olivine, calcite, biotite, garnet, and clay.

Together, the **chemical formula** (the types and proportions of the chemical elements) and the **crystal lattice** (the geometry of how the atoms are arranged and bonded together) determine the physical properties of minerals.

The chemical formula and crystal lattice of a mineral can only be determined in a laboratory, but by examining a mineral and determining several of its physical properties, you can identify the mineral. First, you need to become familiar with the physical properties of minerals and how to recognize them.

Minerals can be identified by their physical characteristics. 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 certainly obvious, but it is usually less reliable than other physical properties.

How are Minerals Identified?



Figure 1. This mineral has shiny, gold, cubic crystals with striations, so it is pyrite.

Mineralogists are scientists who study minerals. One of the things mineralogists must do is identify and categorize minerals. While a mineralogist might use a high-powered microscope to identify some minerals, most are recognizable using physical properties.

Check out the mineral in figure 1. What is the mineral's color? What is its shape? Are the individual crystals shiny or dull? Are there lines (striations) running across the minerals?

Color, Streak, and Luster

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



Figure 2. This mineral is shiny, very soft, heavy, and gold in color, and is actually gold.

Color is often useful, but should not be relied upon. Different minerals may be the same color. Real gold, as seen in figure 2, is very similar in color to the pyrite in figure 1.

Additionally, Some minerals come in many different colors. Quartz, for example, may be clear, white, gray, brown, yellow, pink, red, or orange. So color can help, but do not rely on color as the determining property. Figure 3 shows one sample of quartz that is

colorless and another quartz that is purple. A tiny amount of iron makes the quartz purple. Many minerals are colored by chemical impurities.



Figure 3. Purple quartz, known as amethyst, and clear quartz are the same mineral despite the different colors.

Luster

Luster describes the reflection of light off a mineral's surface. Mineralogists have special terms to describe luster. One simple 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.

Luster is how the surface of a mineral reflects light. It is not the same thing as color, so it crucial to distinguish luster from color. For example, a mineral described as "shiny yellow" is being described in terms of luster ("shiny") and color ("yellow"), which are two different physical properties. Standard names for luster include metallic, glassy, pearly, silky, greasy, and dull. It is often useful to first determine if a mineral has a metallic luster. A metallic luster means shiny like polished metal. For example cleaned polished pieces of chrome, steel, titanium, copper, and brass all exhibit metallic luster as do many other minerals. Of the nonmetallic lusters, glassy is the most common and means the surface of the mineral reflects light like glass. Pearly luster is important in identifying the feldspars, which are the most common type of mineral. Pearly luster refers to a subtle irridescence or color play in the reflected light, same way pearls reflect light. Silky means relecting light with a silk-like sheen. Greasy luster looks similar to the luster of solidified bacon grease. Minerals with dull luster reflect very little light. Identifying luster takes a little practice. Remember to distinguish luster from color.

Different types of non-metallic luster are described in table 1.

Table 1. Six types of non-metallic luster.

Luster	Appearance
Adamantine	Sparkly
Earthy	Dull, clay-like
Pearly	Pearl-like
Resinous	Like resins, such as tree sap
Silky	Soft-looking with long fibers
Vitreous	Glassy

Can you match the minerals in figure 4 with the correct luster from table 1?



Figure 4. (a) Diamond has an adamantine luster. (b) Quartz is not sparkly and has a vitreous, or glassy, luster. (c) Sulfur reflects less light than quartz, so it has a resinous luster.

Streak



Figure 5. The streak of hematite across an unglazed porcelain plate is red-brown.

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 in the figure 3, do not have streak.

To check streak, scrape the mineral across an unglazed porcelain plate (Figure 5). Yellow-gold pyrite has a blackish streak, another indicator that pyrite is not gold, which has a golden yellow streak.

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. The amount of space an object takes up is described by its volume. 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.

The specific gravity of a substance compares its density to that of water. Substances that are more dense have higher specific gravity.

Hardness

Hardness is the strength with which a mineral resists its surface being scraped or punctured. In working with hand samples without specialized tools, mineral hardness is specified by the Mohs hardness scale. The Mohs hardness scale is based 10 reference minerals, from talc the softest (Mohs hardness of 1), to diamond the hardest (Mohs hardness of 10). It is a relative, or nonlinear, scale. A hardness of 2.5 simply means that the mineral is harder than gypsum (Mohs hardness of 2) and softer than calcite (Mohs hardness of 3). To compare the hardness of two minerals see which mineral scratches the surface of the other.

Table 2. Mohs Hardness Scale

Hardness	Index Minerals	Common Objects
1	talc	
2	gypsum	2.5-fingernail
3	calcite	3.5-pure, untarnished copper
4	fluorite	
5	feldspar	5 to 5.5-stainless steel
		5.5 to 6-glass
6	apatite	6 to 6.5-hard steel file
7	quartz	
8	topaz	
9	corundum	
10	diamond	

With a Mohs scale, anyone can test an unknown mineral for its hardness. Imagine you have an unknown mineral. You find that it can scratch fluorite or even feldspar, but apatite scratches it. You know then that the mineral's hardness is between 5 and 6. Note that no other mineral can scratch diamond.

Cleavage and Fracture

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 weaker. For that reason, minerals break apart in characteristic ways.

Cleavage

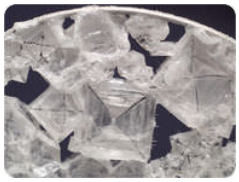


Figure 6. A close-up view of sodium chloride in a water bubble aboard the International Space Station.

Cleavage is the tendency of a mineral to break along certain planes to make smooth surfaces. Halite breaks between layers of sodium and chlorine to form cubes with smooth surfaces (figure 6).

A mineral that naturally breaks into perfectly flat surfaces is exhibiting cleavage. Not all minerals have cleavage. A cleavage represents a direction of weakness in the crystal lattice. Cleavage surfaces can be distinguished by how they consistently reflect light, as if polished, smooth, and even. The cleavage properties of a mineral are described in terms of the number of cleavages and, if more than one cleavage, the angles between the cleavages. The number of cleavages is the number or directions in which the mineral cleaves. A mineral may exhibit 100 cleavage surfaces parallel to each other. Those represent a single cleavage because the surfaces are all oriented in the same diretion. The possible number of cleavages a mineral may have are 1,2,3,4, or 6. If more than 1 cleavage is present, and a device for measuring angles is not available, simply state whether the cleavages intersect at 90° or not 90°.

To see mineral cleavage, hold the mineral up beneath a strong light and move it around, move it around some more, to see how the different sides reflect light. A cleavage direction will show up as a smooth, shiny, evenly bright sheen of light reflected by one set of parallel surfaces on the mineral.

Mica has cleavage in one direction and forms sheets (figure 7).



Figure 7. Sheets of mica.



Figure 8. This rough diamond shows its octahedral cleavage.

Minerals can cleave into polygons. Fluorite forms octahedrons (figure 8).

One reason gemstones are beautiful is that the cleavage planes make an attractive crystal shape with smooth faces.

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 fracture is not determined by the structure of the mineral.

Minerals may have characteristic fractures (figure 9). Metals usually fracture into jagged edges. If a mineral splinters like wood, it may be fibrous. Some minerals, such as quartz, form smooth curved surfaces when they fracture.

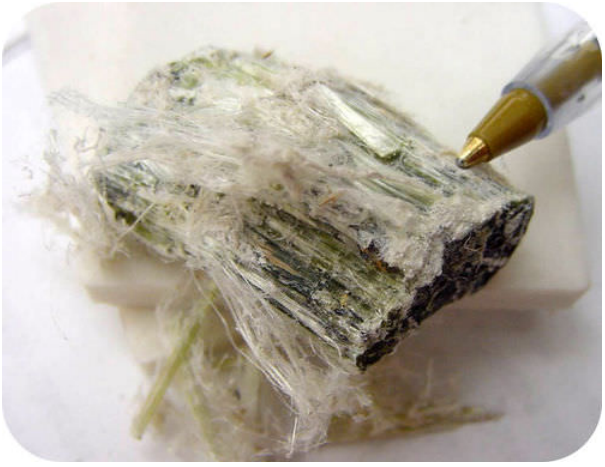


Figure 9. Chrysotile has splintery fracture.

All minerals have fracture. Fracture is breakage, which occurs in directions that are not cleavage directions. Some minerals, such as quartz, have no cleavage whatsoever. When a mineral with no cleavage is broken apart by a hammer, it fractures in all directions. Quartz is said to exhibit conchoidal fracture. Conchoidal fracture is the way a thick piece of glass breaks with concentric, curving ridges on the broken surfaces. However, some quartz crystals have so many flaws that instead of exhibiting conchoidal fracture they simply exhibit irregular fracture. Irregular fracture is a standard term for fractures that do not exhibit any of the qualities of the

other fracture types. In introductory geology, the key fracture types to remember are irregular, which most minerals exhibit, and conchoidal, seen in quartz.

Crystal Shape

All minerals are crystalline, but only some have the opportunity to exhibit the shapes of their crystals, their crystal forms. Many minerals in an introductory geology lab do not exhibit their crystal form. If a mineral has space while it grows, it may form natural crystals, with a crystal shape reflecting the geometry of the mineral's internal crystal lattice. The shape of a crystal follows the symmetry of its crystal lattice. Quartz, for instance, forms six-sided crystals, showing the hexagonal symmetry of its crystal lattice. There are two complicating factors to remember here: (1) minerals do not always form nice crystals when they grow, and (2) a crystal face is different from a cleavage surface. A crystal face forms during the growth of the mineral. A cleavage surface is formed when the mineral is broken.

Other Identifying Characteristics

There are some properties that only help to distinguish a small number of minerals, or even just a single mineral. An example of such a special property is the effervescent reaction of calcite to a weak solution of hydrochloric acid (5% HCl). Calcite fizzes or effervesces as the HCl solution dissolves it and creates CO_2 gas. Calcite is easy to identify even without testing the reaction to HCl, by its hardness, luster and cleavage.

Another special property is magnetism. This can be tested by seeing if a small magnet responds to the mineral. The most common mineral that is strongly magnetic is the mineral magnetite. A special property that shows up in some sample of plagioclase feldspar is its tendency to exhibit striations on cleavage surfaces. Striations are perfectly straight, fine, parallel lines. Magnification may be required to see striations on plagioclase cleavage surfaces. Other special properties may be encountered on a mineral to mineral basis.

Some minerals have other unique properties, some of which are listed in table 3. Can you name a unique property that would allow you to instantly identify a mineral that's been described quite a bit in this chapter? (Hint: It is most likely found on your dinner table.)

Table 3. Some minerals have unusual properties that can be used for identification.

Property	Description	Example of Mineral
Fluorescence	Mineral glows under ultraviolet light	Fluorite
Magnetism	Mineral is attracted to a magnet	Magnetite
Radioactivity	Mineral gives off radiation that can be measured with Geiger counter	Uraninite
Reactivity	Bubbles form when mineral is exposed to a weak acid	Calcite
Smell	Some minerals have a distinctive smell	Sulfur (smells like rotten eggs)
Taste	Some minerals taste salty	Halite

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 3.3: Mineral Identification. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/3.3/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Basics - Minerals. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/minerals.html. **Project**: Geology 101 - Introduction to Physical Geology.

License: *CC BY: Attribution*

This page titled 2.7: Reading- Physical Characteristics of Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.8: Reading- Classifying Minerals

Classes of Minerals

Minerals are classified according to their chemical properties. Except for the native element class, the chemical basis for classifying minerals is the anion, the negatively charged ion that usually shows up at the end of the chemical formula of the mineral. For example, the sulfides are based on the sufur ion, S^{2-}. Pyrite, for example, FeS_2, is a sulfide mineral. In some cases, the anion is of a mineral class is polyatomic, such as $(CO_3)^{2-}$, the carbonate ion. The major classes of minerals are:

- silicates
- sulfides
- carbonates
- oxides
- halides
- sulfates
- phosphates
- native elements

Silicates

Based on the polyatomic anion, $(SiO_4)^{4-}$, which has a tetrahedral shape. Most minerals in the earth's crust and mantle are silicate minerals. All silicate minerals are built of silicon-oxygen tetrahedra $(SiO_4)^{4-}$ in different bonding arrangements which create different crystal lattices. You can understand the properties of a silicate mineral such as crystal shape and cleavage by knowing which type of crystal lattice it has.

- In **nesosilicates**, also called island silicates, the silicate tetrahedra are separate from each other and bonded completely to non silicate atoms. Olivine is an island silicate.
- In **sorosilicates** or paired silicates, such as epidote, the silicate tetrahedra are bonded in pairs.
- In **cyclosilicates**, also called ring silicates, the silicate tetrahedra are joined in rings. Beryl or emerald is a ring silicate.
- In **phyllosilicates** or sheet silicates, the tetrahedra are bonded at three corners to form flat sheets. Biotite is a sheet silicate.
- In **single-chain inosilicates** the silicate tetrahedra are bonded in single chains. Pyroxenes are singele-chain inosilicates.
- In **double-chain inosilicates** the silicate tetrahedra are bonded in double chains. Amphiboles are double-chain inosilicates.
- In **tectosilicates**, also known as framework silicates, all corners of the silicate tetrahedra are bonded to corners of other silicate tetrahedra, forming a complete framework of silicate tetrahedra in all directions. Feldspar, the most common mineral in earth's crust, and quartz are both framework silicates.

Sulfides

These are based on the sulfide ion, S^{2-}. Examples include pyrite, FeS_2, galena, PbS, and sphalerite, ZnS in its pure zinc form. Some sulfides are mined as sources of such metals as zinc, lead, copper, and tin.

Carbonates

These are based on the carbonate ion, $(CO_3)^{2-}$. Calcite, $CaCO_3$, and dolomite, $CaMg(CO_3)2$, are carbonate minerals. Carbonate minerals tend to dissolve relatively easily in water, especially acid water, and natural rain water is slightly acid.

Oxides

These are based on the oxygen anion, O^{2-}. Examples include iron oxides such as hematite, Fe_2O_3 and magnetite, Fe_3O_4, and pyrolusite, MgO.

Halides

These have a halogen element as the anion, whether it be fluoride, F^-, chloride, Cl^-, bromide, Br^-, iodide, I^-, or astatide, At^-. Halite, NaCl, is a halide mineral.

Sulfates

These have the polyatomic sulfate ion, $(SO_4)^{2-}$, as the anion. Anhydrite, $CaSO_4$, is a sulfate.

Phosphates

These have the polyatomic phosphate ion, $(PO_4)^{3-}$, as the anion. Fluorapatite, $Ca_5(PO_4)_3F$, which makes your teeth hard, is a phosphate mineral.

Native Elements

These are made of nothing but a single element. Gold (Au), native copper (Cu), and diamond and graphite, which are made of carbon, are all native element minerals. Recall that a mineral is defined as naturally occurring. Therefore, elements purified and crystallized in a laboratory do not qualify as minerals, unless they have also been found in nature.

Mineral Classification Tables

In tables 1–3, hardness is measured on Mohs Hardness Scale. As you read through the tables, you can click on the images of minerals to see a larger version of the photo.

Table 1. Nonmetallic Luster—Light Color

Typical Color	Hardness	Cleavage/Fracture	Mineral Name	Photo of Mineral
colorless	7	conchodial fracture	quartz	
variable	7	conchodial fracture	chalcedony (chert, etc.)	
pink or white	5–6	2 planes at right angles	orthoclase (feldspar)	
white	5–6	2 planes at right angles	Na-plagioclase (feldspar)	
white to gray	5–6	2 planes at right angles	Ca-plagioclase (feldspar)	
variable	4	4 planes	fluorite	
colorless or white	3	3 planes at odd angles	calcite	
pink or white	3	3 planes at odd angles	dolomite	

Table 1. Nonmetallic Luster—Light Color

colorless or white	2.5–3	3 planes at odd angles	halite	
colorless or white	2.5	1 plane	muscovite	
colorless or white	2	2 planes at right angles	gypsum	
variable	1	1 plane	talc	
white	< 1	uneven (turns to powder)	kaolinite	

Table 2. Nonmetallic Luster—Dark Color				
Typical Color	Hardness	Cleavage/Fracture	Mineral Name	Photo of Mineral
green	5–6	irregular	olivine	
red	5–6	irregular	garnet	
red	3–6	irregular	hematite	
dark green	3–6	2 planes at right angles	pyroxene	
black	4.5–6	2 planes at odd angles	hornblende (amphibole)	
black	2.5	1 plane	biotite	
green	2	1 plane	chlorite	

Table 3. Metallic Luster

Typical Color	Hardness	Cleavage/Fracture	Mineral Name	Photo of Mineral
black or dark gray	6	irregular	magnetite	
brassy yellow	6	irregular	pyrite	
coppery yellow	4	irregular	chalcopyrite	
silver	3	3 planes at right angles	galena	

How to Identify Minerals

First, you need good light and a hand lens or magnifying glass. A hand lens is a small, double-lens magnifying glass that has a magnification power of at least 8× and can be purchased at some bookstores and nature stores.

Minerals are identified on the basis of their physical properties, which have been described in the the previous section. To identify a mineral, you look at it closely. At a glance, calcite and quartz look similar. Both are usually colorless, with a glassy luster. However, their other properties they are completely different. Quartz is much harder, hard enough to scratch glass. Calcite is soft, and will not scratch glass. Quartz has no mineral cleavage and fractures the same irregular way glass breaks. Calcite has three cleavage directions which meet at angles other than 90°, so it breaks into solid pieces with perfectly flat, smooth, shiny sides.

When identifying a mineral, you must:

1. Look at it closely on all visible sides to see how it reflects light
2. Test its hardness
3. Identify its cleavage or fracture
4. Name its luster
5. Evaluate any other physical properties necessary to determine the mineral's identity

In the minerals tables that accompanies this section, the minerals are grouped according to their luster and color. They are also classified on the basis of their hardness and their cleavage or fracture. If you can identify several of these physical properties, you can identify the mineral.

A simple lesson on how to identify minerals is seen in this video.

A link to an interactive elements can be found at the bottom of this page.

Contributors and Attributions

CC licensed content, Shared previously

- Basics - Minerals. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/minerals.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

All rights reserved content

- Rocks & Minerals : Identifying Minerals. **Authored by**: eHow. **Located at**: https://youtu.be/JeFVwqBuYl4. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

Public domain content

- Talc block. **Provided by**: USGS. **Located at**: https://en.Wikipedia.org/wiki/File:Talc_block.jpg. **License**: *Public Domain: No Known Copyright*
- Chlorite. **Provided by**: USGS. **Located at**: https://commons.wikimedia.org/wiki/File:ChloriteUSGOV.jpg. **License**: *Public Domain: No Known Copyright*

This page titled 2.8: Reading- Classifying Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.9: Self Check- Identifying Minerals

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1079

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 2.9: Self Check- Identifying Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.10: Outcome- Most Common Elements

Identify the most common elements in the Earth's crust and their order of abundance.

This section will introduce you to the most common elements present in the Earth's crust that directly influence types of minerals formed.

What You'll Learn to Do

- Identify the eight most common elements in Earth's crust.
- Organize the eight most common elements in Earth's crust by order of abundance.

Learning Activities

The learning activities for this section include the following:

- Reading: Abundance of Elements in Earth's Crust
- Reading: Silicate Minerals and the Silicate Tetrahedron
- Self Check: Most Common Elements

Contributors and Attributions

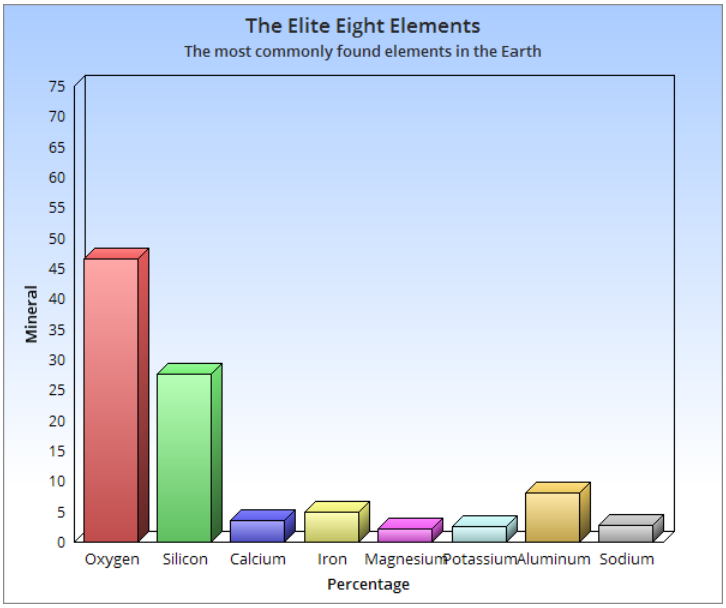
CC licensed content, Original

- **Authored by**: Lumen Learning and SBCTC. **License**: *CC BY: Attribution*

This page titled 2.10: Outcome- Most Common Elements is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.11: Reading- Abundance of Elements in Earth's Crust

The table shows the **abundance of elements in Earth's crust**.



The Elite Eight Elements

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 2.11: Reading- Abundance of Elements in Earth's Crust is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.12: Reading- Silicate Minerals and the Silicate Tetrahedron

Most of the minerals in the earth are silicate minerals. The building block of silicate minerals—the essential component that makes them silicate minerals—is the silicate tetrahedron. The silicate tetrahedron consists of four oxygen atoms arranged as close as they can get around a central silicon atom. The result is a pyramidal shape known as a tetrahedron, with an oxygen atom at each of its four apices. (The apices are the points on the tetrahedron where three corners come together.)

The silicon atom by itself has four electrons in its outer shell. In the silicate tetrahedron each of those four electrons is being shared with one of the four attached oxygen atoms. In turn, each oxygen atom is sharing one of the 6 electrons it has in its outer shell.

The result is that the silicon at the center of the tetrahedron has, in effect, a full outer shell with eight electrons in it. Those eight electrons are shared, in pairs, with the four oxygen atoms of the tetrahedron. Each oxygen atom in the tetrahedron, in turn, will have seven electrons in its outer shell—if there is nothing more to the system than the one silicon atom bonded to the four oxygen atoms. This would leave each oxygen atom one electron short of having a full outer shell of electrons.

However, oxygen is a strongly electronegative element, which means that it has the strength to attract electrons from other elements to its nucleus in most situations. In a mineral, each oxygen atom in the silicate tetrahedron will actually have eight electrons: the six electrons that each oxygen atom had in its outer electron shell to begin with, the electron it gained by sharing a pair of electrons in a covalent bond with the silicon atom in the tetrahedron, and one more electron from another atom (or another small group of atoms) in the mineral, outside the tetrahedron.

Silicate tetrahedra are able to bond with many common elements in many different crystal lattice arrangements. In addition, silicate tetrahedra are able to bond with other silicate tetrahedra in a variety of geometric arrangements, including rings, sheets, chains, and three-dimensional networks.

Contributors and Attributions

CC licensed content, Shared previously

- Basics - Minerals. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/minerals.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 2.12: Reading- Silicate Minerals and the Silicate Tetrahedron is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.13: Self Check- Most Common Elements

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1080

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 2.13: Self Check- Most Common Elements is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.14: Putting It Together- Rock Forming Minerals

Summary

In this section, you learned the following:

1. The basic chemistry involved with mineral formation
2. The most common mineral forming elements
3. Common techniques used to identify minerals
4. How to use these techniques to identify common minerals
5. What a mineralogist does and where they work

Synthesis

In this module we took a closer look at minerals. Minerals are very complex, and they form in a variety of ways and in a variety of settings. We examined some of the ways the mineralogist identifies minerals; some of the methods were very simple while others were a bit more complex (some of these include cleavage and reaction to acid). We can now understand why mineralogists need the firm foundation in chemistry and geology. In mineralogy, chemistry and geology are very tightly woven together. We saw just how those elements go into making up minerals. We stated earlier that elements make up minerals and minerals make up rocks, but we can also look at it in a different more familiar way: chocolate makes up chocolate chips and then the chocolate chips make up the cookie (along with the dough of course). Now that we have an insight into minerals, we can move on to the next concept—ROCKS!

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte. **Provided by**: Columbia Basin College. **License**: *CC BY: Attribution*

This page titled 2.14: Putting It Together- Rock Forming Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

2.15: Assignment- Rock Forming Minerals

For this assessment, you will be identifying various minerals. You will use the information you learned in this module to complete the chart below. Remember to access the tips and hints below.

Basic Requirements (assignment criteria):

1. You will need to use the mineral identification chart provided to help identify these minerals.
2. The mineral identification chart has different tabs for the different mineral classifications. These tabs are located at the bottom and are listed: Metallic Minerals, Nonmetallic Minerals Dark and Nonmetallic Minerals Light.
3. Complete the various columns for each mineral and answer the questions at the end of the document.
4. You will ONLY submit the completed chart and responses to the questions, not the entire document.
5. Make sure your name is on the document before saving.

Tips and hints can be found here (Links to an external site.).

Mineral #1



Mineral #2



Mineral #3



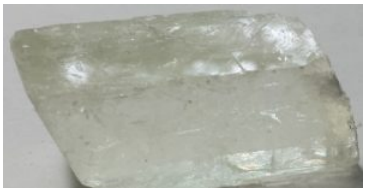
Mineral #4



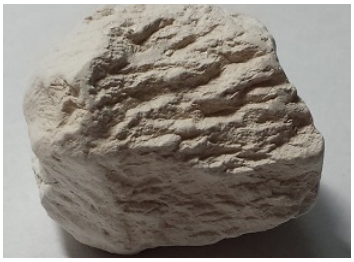
Mineral #5



Mineral #6



Mineral #7



Mineral #8



Mineral #9



Mineral #10





Contributors and Attributions

CC licensed content, Original

- Rock Forming Minerals Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 2.15: Assignment- Rock Forming Minerals is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

3: Rocks and the Rock Cycle

Learning Objectives

Identify processes of the rock cycle and the different rock types associated with each step.

- Identify igneous rocks and the steps of the rock cycle related to their formation.
- Identify sedimentary rocks and the steps of the rock cycle related to their formation.
- Identify metamorphic rocks and the steps of the rock cycle related to their formation.

3.1: Why It Matters- Rocks and the Rock Cycle
3.2: Outcome- Igneous Rocks
3.3: Reading- Characteristics of Igneous Rocks
3.4: Reading- How Are Igneous Rocks Classified?
3.5: Reading- Identifying Igneous Rocks
3.6: Reading- Uses of Igneous Rocks
3.7: Self Check- Igneous Rocks
3.8: Outcome- Sedimentary Rocks
3.9: Reading- Characteristics of Sedimentary Rocks
3.10: Self Check- Sedimentary Rocks
3.11: Outcome- Metamorphic Rocks
3.12: Reading- Characteristics of Metamorphic Rocks
3.13: Video- Identifying Metamorphic Rocks
3.14: Self Check- Metamorphic Rocks
3.15: Putting It Together- Rocks and the Rock Cycle

This page titled 3: Rocks and the Rock Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.1: Why It Matters- Rocks and the Rock Cycle

Identify processes of the rock cycle and the different rock types associated with each step.

Introduction

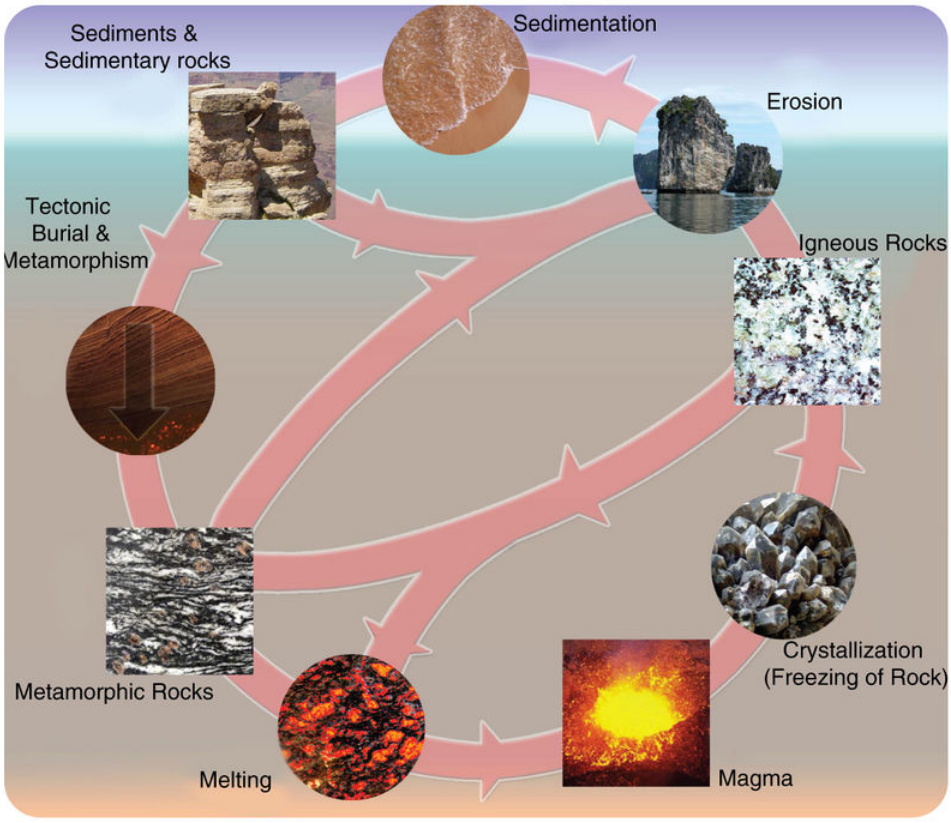
In this section we will learn about the rock cycle and the different types of rocks. Please watch this short video for an introduction:

A link to an interactive elements can be found at the bottom of this page.

As you can see, the rock cycle is never ending. The video explained how rocks change from one rock type to another, and—just as important—it showed the processes that cause those changes.

Learning the rock cycle and understanding the processes involved helps all of us. For example, you saw in the video how all rocks are eroded into fine particles. This is how soil forms, through the breakdown of rocks. We need soil to survive—imagine trying to grow vegetables without it. This is an immediate connection to the food chain. The rock cycle also gives scientists and engineers an idea on where energy sources (mainly fossil fuels, which are found only in sedimentary rock) and building materials such as marble or granite may be located. We will see throughout the course how this cycle plays into just about every aspect of geology.

Here's a visual representation of the rock cycle:



As you continue through the module, refer back to this image. Remember that all the processes of the rock cycle are interconnected.

Learning Outcomes

- Identify igneous rocks and the steps of the rock cycle related to their formation.
- Identify sedimentary rocks and the steps of the rock cycle related to their formation.
- Identify metamorphic rocks and the steps of the rock cycle related to their formation.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 4.1: Types of Rocks. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/4.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

All rights reserved content

- Rocks. **Authored by**: sciencemadefun. **Located at**: https://youtu.be/G7AWGhQynTY. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 3.1: Why It Matters- Rocks and the Rock Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.2: Outcome- Igneous Rocks

Identify igneous rocks and the steps of the rock cycle related to their formation.

We'll start by learning about igneous rocks and their formation.

What You'll Learn to Do

- Define the characteristics of an igneous rock.
- Discuss the role of melting and subsequent cooling in the rock cycle.

Learning Activities

The learning activities for this section include the following:

- Reading: Characteristics of Igneous Rocks
- Reading: How Are Igneous Rocks Classified?
- Reading: Identifying Igneous Rocks
- Uses of Igneous Rocks
- Self Check: Igneous Rocks

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 3.2: Outcome- Igneous Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.3: Reading- Characteristics of Igneous Rocks

Magma is molten rock inside the earth. It is the source of all igneous rock. Because the earth was largely molten at its origin, magma may be considered the beginning of the rock cycle. Igneous rocks contain information about how they originate. By carefully analyzing igneous rocks and interpreting the information they contain, we can deduce processes that take place within the earth and we can understand volcanic processes that take place on the earth's surface.

The study of igneous rocks enables us to understand the igneous part of geologic history. For example, at the end of the Triassic period, 245 million years ago, the greatest mass extinction ever known took place, wiping out more life forms on earth than the mass extinction that led to the demise of dinosaurs 65 million years ago at the end of the Cretaceous. At the end of the Triassic, a huge amount of basalt erupted onto the earth. Many geologists think that the gases and particles released into the atmosphere by those eruptions may have been a major factor in the end of Triassic mass extinction. Those scientists are studying the information contained in the basalts of that age to further test their hypotheses.

Igneous rocks contain three essential sources of information: their minerals, their overall chemical composition, and their igneous texture. Igneous rock names are based on specific combinations of these features. Igneous rocks also contain isotopic information that is used in determining absolute ages and in further characterizing the origin of the magma. Special equipment and expertise is required to conduct isotopic and precise chemical analyses. Fortunately, with some basic training and practice anyone can learn to identify the minerals, composition and texture of an igneous rock; name the rock; and interpret key information about its origins.

All igneous rocks, other than pure volcanic glass, contain minerals. The minerals provide details on the chemical composition of the rock, and on the conditions in which the magma originated, cooled, and solidified. Geologists conduct chemical analyses of minerals to determine the temperatures and pressures at which they formed and to identify the dissolved gases and chemical elements that were present in the magma.

Most magmas are predominantly silicate liquids, composed largely of silica tetrahedra that have not yet bonded together to become silicate minerals. The chemical composition of an igneous rock tells us about the origin of the magma, beginning with which type of rock melted within the earth to form the magma in the first place, and how deep in the earth the melting occurred. Once magma has formed inside the earth, its composition may be modified. Minerals can grow from the magma and separate from it, changing the chemistry of the remaining liquid. Or, one body of magma can mix with another that has a different composition.

Magmas come in a range of compositions, from rich in silica and poor and iron and magnesium (felsic) to moderate in silica and high in iron and magnesium (mafic). Felsic igneous rocks, as a whole rock, tend to have light colors or shades: white, pink, light brown, light gray. Mafic igneous rocks, on the whole, tend to be dark colored, commonly black or dark gray. Most mafic magma originates by melting of rocks in the mantle that are extremely rich in iron and magnesium. Felsic magma usually originates in the crust or by the shedding of mafic minerals as magma rises through the crust.

The igneous texture tells us how the magma cooled and solidified. Magma can solidify into igneous rock in several different ways, each way resulting in a different igneous texture. Magma may stay within the earth, far below ground level, and crystallize into plutonic igneous rock (also known as intrusive igneous rock). Or, magma may flow out onto surface of the earth as a lava flow. Another way that igneous rock forms is by magma erupting explosively into the air and falling to earth in pieces known as pyroclastic material, also called tephra. Lava flows and pyroclastic material are volcanic igneous rock (also known as extrusive igneous rock).

The igneous texture of a rock is not how it feels in your hand, not whether it is rough or smooth. The igneous texture describes whether the rock has mineral crystals or is glassy, the size of the mineral grains, and the rock's porosity (empty spaces).

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY-SA: Attribution-ShareAlike*

CC licensed content, Shared previously

- Basics - Igneous Rocks. **Authored by**: Ralph L. Dawes, Ph.D. and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: https://commons.wvc.edu/rdawes/G101OCL/Basics/igneous.html. **Project**: Geology 101 - Introduction to Physical

Geology. **License**: *CC BY: Attribution*

- Igneous textures. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Igneous_textures. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 3.3: Reading- Characteristics of Igneous Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.4: Reading- How Are Igneous Rocks Classified?

This page focuses on igneous rocks and gives you the background needed to understand the terms used in the igneous rock classification table (at the bottom of this page).

Intrusive and Extrusive Igneous Rocks



Figure 2. Granite is made of four minerals, all visible to the naked eye: feldspar (white), quartz (translucent), hornblende (black), and biotite (black, platy).

Igneous rocks are called **intrusive** when they cool and solidify beneath the surface. Intrusive 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. Slow cooling allows time for large crystals to form, so intrusive igneous rocks have visible crystals. Granite is the most common intrusive igneous rock (see figure 2 for an example).

Igneous rocks make up most of the rocks on Earth. Most igneous rocks are buried below the surface and covered with sedimentary rock, or are buried beneath the ocean water. In some places, geological processes have brought igneous rocks to the surface. Figure 3 below shows a landscape in California's Sierra Nevada made of granite that has been raised to create mountains.

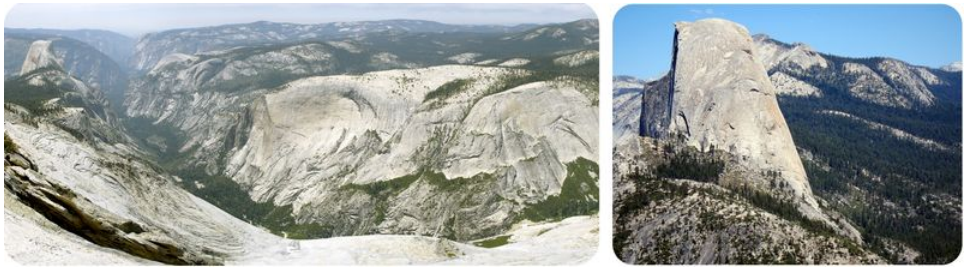


Figure 3. California's Sierra Nevada is intrusive igneous rock exposed at Earth's surface.

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** (figure 4).



Figure 4. Extrusive igneous rocks form after lava cools above the surface.



Figure 5. Cooled lava forms basalt with no visible crystals. Why are there no visible crystals?

Extrusive igneous rocks cool much more rapidly than intrusive rocks. There is little time for crystals to form, so extrusive igneous rocks have tiny crystals (figure 5).

Classifying Igneous Rocks

As we just learned, there are two main types of igneous rocks: intrusive rocks (also known as plutonic rocks) and extrusive rocks (also known as volcanic rocks). Volcanic rocks break down into two more categories: (a) lava flows and (b) tephra (pyroclastic material).

Igneous rocks are classified on the basis of their composition and their texture. Magma, and the igneous rock it becomes, has a range of chemical compositions. For example, basalt is a mafic lava flow rock which originates from melting of the upper mantle. The way that magma turns into a solid rock gives it a distinctive igneous texture. For example, magma that becomes a pluton by slowly crystallizing (growing minerals) within the crust will develop a very different texture from magma that becomes an ash flow tuff as a result of semi-molten volcanic ash spewing across a landscape and then settling down and welding itself together into solid rock.

Igneous Rock Textures

Igneous textures include the rock textures occurring in igneous rocks. Igneous textures are used by geologists in determining the mode of origin igneous rocks and are used in rock classification. There are six main types of textures; phaneritic, aphanitic, porphyritic, glassy, pyroclastic and pegmatitic.

Aphanitic (*a* = not, *phaner* = visible) rocks in contrast to phaneritic rocks, typically form from lava which crystallize rapidly on or near Earth' surface. Because extrusive rocks make contact with the atmosphere they cool quickly, so the minerals do not have time to form large crystals. The individual crystals in an aphanitic igneous rock are not distinguishable to the naked eye. Examples of aphanitic igneous rock include basalt, andesite andrhyolite.

Glassy or *vitreous* textures occur during some volcanic eruptions when the lava is quenched so rapidly that crystallization cannot occur. The result is a natural amorphous glass with few or no crystals. Examples includeobsidian and pumice.

Pegmatitic texture occurs during magma cooling when some minerals may grow so large that they become massive (the size ranges from a few centimetres to several metres). This is typical of pegmatites.

Phaneritic (*phaner* = visible) textures are typical of intrusive igneous rocks, these rocks crystallized slowly below Earth's surface. As magma cools slowly the minerals have time to grow and form large crystals. The minerals in a phaneritic igneous rock are sufficiently large to see each individual crystal with the naked eye. Examples of phaneritic igneous rocks are gabbro, diorite and granite.

Porphyritic textures develop when conditions during cooling of a magma change relatively quickly. The earlier formed minerals will have formed slowly and remain as large crystals, whereas, sudden cooling causes the rapid crystallization of the remainder of the melt into a fine grained (aphanitic) matrix. The result is an aphanitic rock with some larger crystals (phenocrysts) imbedded within its matrix. Porphyritic texture also occurs when magma crystallizes below a volcano but is erupted before completing crystallization thus forcing the remaining lava to crystallize more rapidly with much smaller crystals.

Pyroclastic (*pyro* = igneous, *clastic* = fragment) textures occur when explosive eruptions blast the lava into the air resulting in fragmental, typically glassy material which fall as volcanic ash, lapilli and volcanic bombs.

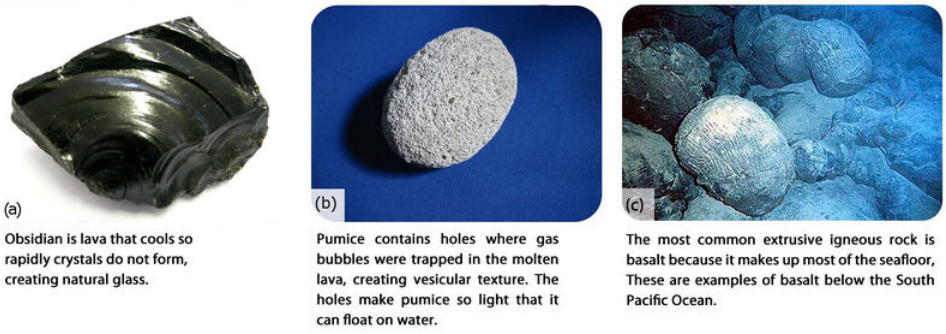


Figure 1. Different cooling rate and gas content resulted in these different textures.

Volcanic Rocks

Let us start with textures associated with rocks formed by lava flows. Magmas that erupt as lava onto the earth's surface cool and solidify rapidly. Rapid cooling results in an aphanitic igneous texture, in which few or none of the individual minerals are big enough to see with the naked eye. This is sometimes referred to as a fine-grained igneous texture.

Some lava flows, however, are not purely fine-grained. If some mineral crystals start growing while the magma is still underground and cooling slowly, those crystals grow to a large enough size to be easily seen, and the magma then erupts as a lava flow, the resulting texture will consist of coarse-grained crystals embedded in a fine-grained matrix. This texture is called porphyritic.

If lava has bubbles of gas escaping from it as it solidifies, it will end up with "frozen bubble holes" in it. These "frozen bubble holes" are called vesicles, and the texture of a rock containing them is said to be vesicular.

If so many bubbles are escaping from lava that it ends up containing more bubble holes than solid rock, the resulting texture is said to be frothy. Pumice is the name of a type of volcanic rock with a frothy texture.

If lava cools extremely quickly, and has very little water dissolved in it, it may freeze into glass, with no minerals (glass by definition is not a mineral, because it does not have a crystal lattice). Such a rock is said to have a glassy texture. Obsidian is the common rock that has a glassy texture, and is essentially volcanic glass. Obsidian is usually black.

Now let us briefly consider textures of tephra or pyroclastic rocks. Like lava flow rocks, these are also extrusive igneous rocks. However, instead of originating from lava that flowed on the earth's surface, tephra is volcanic material that was hurled through the air during a volcanic eruption.

A pyroclastic rock made of fine-grained volcanic ash may be said to have a fine-grained, fragmental texture. Volcanic ash consists mainly of fine shards of volcanic glass. It may be white, gray, pink, brown, beige, or black in color, and it may have some other fine crystals and rock debris mixed in. The term "fine-grained, fragmental" is easy to confuse with the term fine-grained (aphanitic). An equivalent term that is less ambiguous is tuffaceous. Rocks made of volcanic ash are called tuff.

A pyroclastic rock with many big chunks of material in it that were caught up in the explosive eruption is said to have a coarse-grained, fragmental texture. However, a better word that will avoid confusion is to say it has a brecciated texture, and the rock is usually called a volcanic breccia. The bigger chunks of material in a volcanic breccia are more than 1 cm (5/8 inch) across, and sometimes are much bigger.

Plutonic Rocks

When magma cools slowly underground and solidifies there, it usually grows crystals big enough to be seen easily with the naked eye. These visible crystals comprise the whole rock, not just part of it as in a porphyritic, fine-grained igneous rock. The texture of an igneous rock made up entirely of crystals big enough to be easily seen with the naked eye is phaneritic. Phaneritic texture is sometimes referred to as coarse-grained igneous texture. Granite, the most well known example of an intrusive igneous rock, has a phaneritic texture.

Sometimes an intrusion of magma that is crystallizing slowly underground releases large amounts of hot water. The water is released from the magma as extremely hot fluid with lots of chemical elements dissolved in it. This hydrothermal fluid gets into cracks and voids in the earth's crust, and as it cools it may grow very large minerals from the dissolved chemical elements. A rock consisting of such large minerals is said to have a pegmatitic texture, which means the average mineral size is greater than 1 cm in

diameter (and sometimes is much larger). The name of an igneous rock with a pegmatitic texture is pegmatite. Pegmatites are commonly found in or near the margins of bodies of granite.

Igneous Rock Compositions

The most common igneous compositions can be summarized in three words: mafic (basaltic), intermediate (andesitic), and felsic (granitic).

Felsic composition is higher in silica (SiO_2) and low in iron (Fe) and magnesium (Mg). Mafic composition is higher in iron and magnesium and lower in silica. Intermediate compositions contain silica, iron, and magnesium in amounts that are intermediate to felsic and mafic compositions.

Composition and Color

Composition influences the color of igneous rocks. Felsic rocks tend to be light in color (white, pink, tan, light brown, light gray). Mafic rocks tend to be dark in color (black, very dark brown, very dark gray, dark green mixed with black). The color distinction comes from the differences in iron and magnesium content. Iron and, to a lessor extent, magnesium give minerals a darker color. Intermediate igneous rocks tend to have intermediate shades or colors (green, gray, brown).

The association between color and composition is useful because before you can name and interpret an igneous rock you need to determine both its texture AND its composition. If you have an aphanitic igneous rock, which has no crystals big enough to see without a microscope, you can estimate its composition based on its color: pink or nearly white, felsic; medium gray, intermediate; very dark or black, mafic.

This color rule works most of the time but there are two problems that you need to keep in mind. First, the rule does not work for glassy igneous rocks. Obsidian, which is volcanic glass, is usually black, even though it has a felsic composition. That is because a tiny amount of iron, too little to color minerals very darkly, can color glass darkly.

The second problem is that when igneous rocks have been exposed to air and water for a long time, they start to weather, which changes their color. Geologists working in the field carry a rock hammer, so they can break off the weathered, outer parts of rocks to see the “fresh,” unweathered rock inside.

If you can see and identify the minerals in an igneous rock, you can gain further information about the igneous composition. Igneous rocks with quartz in them are usually felsic. Igneous rocks with olivine in them are usually mafic. Igneous rocks with neither quartz nor olivine in them are most commonly intermediate.

Origins of Igneous Rocks

Once you have determined the texture and composition of an igneous rock, you can name it and you can also say something important about how it formed. For example, a coarse-grained, felsic igneous rock is not only a granite, it is an intrusive igneous rock that formed from slow cooling and crystallization of a body of magma within the earth’s crust. The intrusion of large bodies of granite—batholiths—is usually part of the origin of a mountain range. Similarly, a fine-grained, mafic igneous rock is not only a basalt, it is an extrusive igneous rock that formed from rapid cooling and crystallization of a lava flow at earth’s surface.

Igneous Rock Classification

Pegmatitic Texture (Extremely Coarse-Grained) *Originates from water-rich intrusions, which cool and crystallize underground*		
Composition	Most Common Minerals	Rock Name
felsic	Na-plagioclase, orthoclase, quartz, biotite, amphibole, muscovite	pegmatite
Phanertitic Texture (Coarse-Grained) *Originates in deep intrusions, which cool and crystallize slowly underground*		

Composition	Most Common Minerals	Rock Name
felsic	Na-plagioclase, orthoclase, quartz, biotite, amphibole, muscovite	granite
intermediate	Na-plagioclase, quartz, orthoclase, amphibole, biotite	granodiorite
	Na-plagioclase, amphibole, pyroxene, biotite	diorite
mafic	Ca-plagioclase, pyroxene, olivine, amphibole	gabbro

Aphanitic Texture (Fine-Grained)
Originates in lava flows (or very shallow intrusions), which cool rapidly

Composition	Most Common Minerals	Rock Name
felsic	Na-plagioclase, orthoclase, quartz, biotite, amphibole, muscovite	rhyolite
intermediate	Na-plagioclase, quartz, orthoclase, amphibole, biotite	dacite
	Na-plagioclase, amphibole, pyroxene, biotite	andesite
mafic	Ca-plagioclase, pyroxene, olivine, amphibole	basalt

Frothy Texture (Porous, Pumiceous)
Originates in gas-charged volcanic eruptions, commonly pyroclastic

Composition	Most Common Minerals	Rock Name
felsic	glass (may contain a few minerals typical of felsic rocks)	pumice
mafic	glass (may contain a few mineral typical of mafic rocks)	scoria

Note: Basalt with fewer holes, known as vesicles, is called vesicular basalt. *Scoria has more holes and may be black or red in color.*

Glassy Texture
Originates from cooling too rapid to allow crystal lattices to form

Composition	Most Common Minerals	Rock Name
felsic to mafic	glass (no minerals)	obsidian

Note: Obsidian that is transparent at thin edges and has good conchoidal fracture is probably felsic.

Fragmental Texture—Coarse (Contains Large Rock Fragments)
Originates from pyroclastic (explosive) eruptions

Composition	Most Common Minerals	Rock Name
felsic to mafic	variable (depending on rock fragments and ash content)	volcanic breccia

Fragmental Texture—Fine (Mainly Volcanic Ash)
Originates from pyroclastic (explosive) eruptions

Composition	Most Common Minerals	Rock Name
felsic	may contain a few minerals typical of felsic rocks	rhyolitic tuff
medium	may contain a few minerals typical of intermediate rocks	andesitic tuff
mafic	may contain a few minerals typical of mafic rocks	

Contributors and Attributions

CC licensed content, Shared previously

- Basics - Igneous Rocks. **Authored by**: Ralph L. Dawes, Ph.D. and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: https://commons.wvc.edu/rdawes/G101OCL/Basics/igneous.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*
- HS Rocks. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/4.0/. **License**: *Public Domain: No Known Copyright*

This page titled 3.4: Reading- How Are Igneous Rocks Classified? is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.5: Reading- Identifying Igneous Rocks

Igneous rocks can be distinguished from sedimentary rocks by the lack of beds, lack of fossils, and lack of rounded grains in igneous rocks, and the presence of igneous textures. A granite, for example, can be distinguished from a sandstone because rather than being a mixture of weathered, rounded grains compressed and cemented together, granite consists of a small number of minerals in shiny black, white, or pink colors, with excellent crystal forms, grown together into a completely interlocking pattern. Sandstones, by contrast, have sedimentary bedding (layers) and consist of rounded grains with some spaces between the grains, which you can see with a hand lens or magnifying glass.

Igneous rocks can be distinguished from most regional metamorphic rocks by the lack of foliation (layering) in igneous rocks. Unfoliated metamorphic rocks lack igneous textures and usually contain minerals not found in igneous rocks.

Granite may look like gneiss at first glance, but granite has no layering, no preferred orientation of the minerals. The minerals in a granite grow randomly in all directions, rather than tending to grow parallel to each other.

Igneous rocks are classified on the basis of their texture and their composition. See the previous sections for descriptions of the different igneous textures and compositions.

The igneous rock classification tables that accompany this section are arranged on the basis of igneous textures first, and further broken down on the basis of igneous composition. Remember that igneous composition is estimated on the basis of color: light = felsic composition, medium = intermediate composition, and dark = mafic composition.

Watch this video for an example of identifying igneous rocks:

A link to an interactive elements can be found at the bottom of this page.

Contributors and Attributions

CC licensed content, Shared previously

- Basics - Igneous Rocks. **Authored by**: Ralph L. Dawes, Ph.D. and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: https://commons.wvc.edu/rdawes/G101OCL/Basics/igneous.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

All rights reserved content

- Identifying Rocks : Identifying Igneous Rocks. **Authored by**: eHow. **Located at**: https://youtu.be/Q0XtLjE3siE. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 3.5: Reading- Identifying Igneous Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.6: Reading- Uses of Igneous Rocks



Figure 1. This diorite statue was made in approximately 2090 BC.

Igneous rocks have a wide variety of uses. One important use is as stone for buildings and statues. Diorite was used extensively by ancient civilizations for vases and other decorative artwork and is still used for art today (Figure 1).

Granite (figure 2) is used both in building construction and for statues. It is also a popular choice for kitchen countertops. Peridotite is sometimes mined for peridot, a type of olivine that is used in jewelry.

Pumice is commonly used as an abrasive. Pumice is used to smooth skin or scrape up grime around the house. When pumice is placed into giant washing machines with newly manufactured jeans and tumbled, the result is “stone-washed” jeans. Ground up pumice stone is sometimes added to toothpaste to act as an abrasive material to scrub teeth.



Figure 2. Granite is an igneous rock used commonly in statues and building materials.

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- HS Rocks. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/4.0/. **License**: *CC BY-NC: Attribution-NonCommercial*

Public domain content

- Statue of Gudea. **Authored by**: Unknown. **Provided by**: Metropolitan Museum of Art. **Located at**: https://commons.wikimedia.org/wiki/File:Statue_of_Gudea_-_MET_-_59.2.jpg. **License**: *Public Domain: No Known Copyright*

This page titled 3.6: Reading- Uses of Igneous Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.7: Self Check- Igneous Rocks

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1083

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 3.7: Self Check- Igneous Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.8: Outcome- Sedimentary Rocks

Identify sedimentary rocks and the steps of the rock cycle related to their formation.

Let’s move onto sedimentary rocks and their formation.

What You’ll Learn to Do

- Define the characteristics of an sedimentary rock.
- Discuss the role of weathering, deposition, and erosion in the rock cycle.

Learning Activities

The learning activities for this section include the following:

- Reading: Characteristics of Sedimentary Rocks
- Self Check: Sedimentary Rocks

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 3.8: Outcome- Sedimentary Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.9: Reading- Characteristics of Sedimentary Rocks



Figure 1. The White House of the USA is made of a sedimentary rock called sandstone.

The White House (shown in figure 1) is the official home and workplace of the President of the United States of America. Why do you think the White House is white? If you answered, “Because it is made of white rock,” you would be only partially correct. Construction for the White House began in 1792. Its outside walls are made of the sedimentary rock sandstone. This sandstone is very porous and is easily penetrated by rainwater. Water damage was common in the early days of construction for the building. To stop the water damage, workers covered the sandstone in a mixture of salt, rice, and glue, which help to give the White House its distinctive white color.

Lithification—Sediments to Sedimentary rocks

Sedimentary rocks are rocks made of lithified sediment. Sediments are grains of rocks, minerals, or mineraloids deposited on the surface of the earth. Reflect on the rock cycle for an indication of the relationships between the rocks that erode to become sediments and sedimentary rocks. For sediment to become sedimentary rock, it usually undergoes burial, compaction, and cementation.

Clastic sedimentary rocks are the result of weathering and erosion of source rocks, which turns them into pieces—clasts—of rocks and minerals. Once they become pieces, these clasts are free to move away from their source rock and they usually do. They are most often transported by water and deposited as layers of sediment.

The burial stage of lithification involves the deposition of more sediment layers top of those that had been deposited earlier. In a sedimentary basin where sediment is being deposited, it is common for subsidence (lowering) of the basin to be taking place, either because the crust and lithosphere beneath it are subsiding into the mantle to some extent, or because the surrounding uplands are undergoing uplift relative to the basin, or both. This allows thousands of feet of burial, in some cases tens of thousands of feet of burial, to occur.

As sediments are buried, the weight of overlying material exerts pressure, causing compaction of the sediments. The pressure, known as lithostatic pressure, “squeezes” the sediments from all sides into a smaller volume. Lithostatic pressure packs the sediment grains closer together and reduces the porosity – space between the sediment grains.

Some chemical sedimentary rocks are rock as soon as the sediments have been deposited by crystallization of minerals from substances dissolved in water, at the earth’s surface. Examples include rock salt and other evaporite deposits. These sediments of salt crystals and other minerals form sedimentary rock without having to undergo burial and compaction.

During burial and compaction, sediments will undergo some amount of cementation. Cementation refers to the growth of new minerals between the sediment grains. These new minerals bind the sediment grains together. One form of cementation is growth of quartz rims on the surfaces of pre-existing quartz grains in the sediment. This new mineral growth is a result of water in the pore spaces that dissolves and precipiates quartz. A second common cementing mineral is hematite, a red or rust-colored iron oxide mineral, which precipitates onto the sediment grains from a combination of dissolved iron and oxygen from water in the pore spaces. A third common cementing mineral is calcite, which also precipitates from ions dissolved in the water in the pore spaces during lithification. Although there are other cementing minerals, quartz, hematite, and calcite are common cementing minerals that grow between or on the surfaces of the original sedimentary grains.

Generalized steps from source to sedimentary rock:
weathering >> erosion >> transport >> deposition >> burial >> compaction >> cementation >> sedimentary rock

Minerals and Sedimentary Rocks

Any type of rock containing any type of mineral will undergo weathering and erosion at the earth's surface. However, some minerals are more stable than others in earth's surface environments and are more likely to be found in sedimentary rocks.

Grains of clastic sediment, which are called clasts are winnowed and modified during the weathering-to-deposition process. Weathering of minerals will gradually eliminate the physically weaker and chemically more reactive minerals, increasing the relative abundance of more resistant minerals. Quartz tends to become increasingly abundant during the process, due to its common occurrence in the source rocks combined with its hardness and lack of cleavage, which makes it resistant to breaking down physically. Quartz is not easily dissolved or chemically altered, so it is resistant to breakdown by chemical reactions as well. That is why beach sand is often more rich in quartz than any other mineral. Sediments rich in quartz are considered mineralogically "mature" because they have been subjected to a longer interval of physical and chemical modification during the erosion-to-deposition process. Mature sediments are deposited farther from their source rocks in space and/or time than immature sediments.

Feldspars are the most common type of mineral in earth's crust and are also abundant in many clastic sediments and sedimentary rocks. Although feldspar is a fairly hard mineral, it does cleave (split apart) and is chemically reactive, especially in the presence of water. The most abundant product of chemical reaction of feldspar and water is clay minerals. During the erosion-to-deposition process, clastic sediments lose feldspar and gain a larger proportion of clay. Other minerals such as amphiboles, micas, and carbonates are relatively soft and chemically reactive and tend to be scarce or absent as sediment grains in mature clastic sediments, although calcite may be present in clastic sedimentary rocks as a secondary, cementing mineral that grew during lithification.

Minerals in chemical sedimentary rocks precipitate from water and usually remain in place or are not transported far before lithification. Such mineral sediments are subjected to little, if any, erosion and transportation. Therefore, the minerals in chemical sedimentary rocks are not winnowed during the weathering-to-deposition process as are the minerals in clastic sedimentary rocks. In some cases, during the formation of chemical sediments, the minerals may change as a result of chemical reactions. For example, dolostone is a chemical sedimentary rock that forms in certain coastal environments by alteration of precipitated calcite to dolomite.

Besides minerals, mineraloid solids occur in some chemical sedimentary rocks. For example, the carbonaceous material in coal is an organic mineraloid rather than a mineral. Another example, opal, is a chemical sedimentary rock that does not have a fully developed crystal lattice and therefore is a mineraloid.

Sediments



Figure 2. Water erodes the land surface in Alaska's Valley of Ten Thousand Smokes.

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 rock into smaller pieces. Physical weathering simply breaks the rocks apart. 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 (figure 2).



Figure 3. A river dumps sediments along its bed and on its banks.

Streams carry huge amounts of sediment (figure 3). 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. Avalanches drop large piles of sediment. Glaciers leave large piles of sediments, too. 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. Different colors of sedimentary rock are determined by the environment where they are deposited. Red rocks form where oxygen is present. Darker sediments form when the environment is oxygen poor.

Sedimentary Rock Formation



Figure 4. This cliff is made of sandstone. Sands were deposited and then lithified.

Accumulated sediments harden into rock by **lithification**, as illustrated in figure 4. Two important steps are needed for sediments to lithify.

1. Sediments are squeezed together by the weight of overlying sediments on top of them. This is called **compaction**. Cemented, non-organic sediments become **clastic** rocks. If organic material is included, they are **bioclastic** rocks.
2. Fluids fill in the spaces between the loose particles of sediment and crystallize to create a rock by **cementation.**

The sediment size in clastic sedimentary rocks varies greatly (see table 1).

Table 1. Sedimentary rock sizes and features

Rock	Sediment Size	Other Features
Conglomerate	Large	Rounded
Breccia	Large	Angular
Sandstone	Sand-sized	
Siltstone	Silt-sized, smaller than sand	
Shale	Clay-sized, smallest	



Figure 5. The evaporite, halite, on a cobble from the Dead Sea, Israel.

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**. As discussed in the "Earth's Minerals" chapter, dissolved ions in fluids precipitate out of the fluid and settle out, just like the halite in figure 5.

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 a biochemical sediment, which may then become compacted and cemented into solid rock (figure 6).



Figure 6. Fossils in a biochemical rock, limestone, in the Carmel Formation in Utah.

Sedimentary Rock Textures

In clastic sediments the sedimentary texture includes the grain size, rounding, and sorting of the grains, all of which are related to what happened to the sediment during the weathering-to-deposition process.Because the processes that lead to the formation of chemical sedimentary rocks do not involve the weather-to-deposition process, there is no widely agreed-upon texture scheme that applies to chemical sedimentary rocks.

Clastic Textures

Clastic sedimentary textures are described in terms of the size of the sediment grains, how round they are, and how well they are sorted.

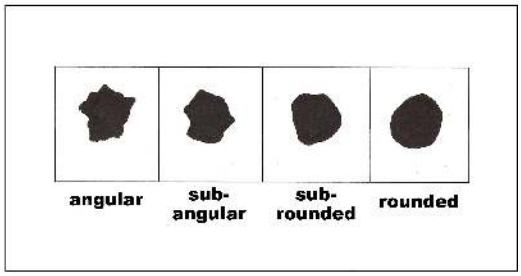
Grain Characteristics

The diameter or width of a clastic sediment grain determines its grain size. Specific ranges of grain size have specific names.

- Gravel is an overall name for large sediment grain size, which includes boulder, cobble, and pebble.
- Sand includes sediment grains ranging in size from 2mm to 0.625 mm.
- Silt is the name of a sediment grain that range in size from 0.625 mm to 0.0039 mm.
- Mud is the smallest grain size and is also known as clay. It is important to distinguish the grain size called clay from the mineral called clay. Clay sized grains are too small to see individually without the aid of a microscope.

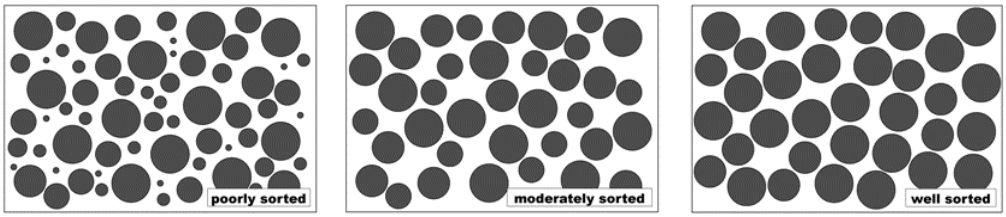
Rounding

Clastic sediment grains can be round, angular, or in-between (subangular or subrounded). Breccia is a clastic sedimentary rock that by definition consists largely of angular grains of pebble size or larger. Conglomerate, another sedimentary rock, consists largely of rounded grains of pebble size or larger. The schematic diagram below shows classes of rounding, from the left: angular, subangular, subrounded, rounded. Not shown are very angular and well-rounded, which are less common.



Sorting

The extent to which all the grains are the same size is known as sorting. If all the grains are the same size, they are well sorted. Some sandstones are well sorted, and some are not. Most conglomerates are poorly sorted, and consist of a mixture of grain sizes ranging from sand to pebble. The schematic diagrams below represent poorly-sorted, moderately-sorted, and well-sorted sediments.



Other Aspects of Texture

Other aspects of clastic sedimentary texture include the packing of the grains, the porosity of the rock, and the hardness of the rock as a whole.

The packing of the grains applies only to poorly sorted sediments in which the finer clasts form a matrix around the coarser clasts. If the large grains are touching each other, the packing is said to be clast-supported. If the coarse grains are separate and not touching each other, with the finer-grained sediment between them, the packing is said to be matrix-supported.

The porosity of a rock or sediment is the amount of empty space between the grains of sediment.

The hardness of the rock refers to how easily it breaks apart. Shale is harder than claystone, for example.

How to Identify Sedimentary Rocks

Clastic Textures

The common names of clastic sedimentary rocks—conglomerate, sandstone, siltstone, and shale—are based solely on grain size. However, there are more precise names within these broader categories that are based on clastic sediment features other than grain size. Breccia is a clastic sedimentary rock distinguished from conglomerate by the angularity of its clasts.

A clastic sedimentary rock simply made of sand-sized grains qualifies as sandstone, regardless of what minerals the grains are made of. More complete names for various sandstones are based on their mineral composition. Some sandstones are made almost entirely of quartz. Sandstone made virtually entirely of quartz is called arenite. Other sandstones have lots of feldspar mixed with quartz. Such sandstones are called arkose. Other sandstones are a mixture of feldspar, quartz, clay, and small fragments of “lithics,” dark-appearing minerals and rock fragments, which represent mineralogically immature sediments. Such sandstones are technically known as lithic wackes, although geologists often call them by their old name, graywackes, and the rocks are sometimes informally described as “dirty sandstones.”

In using the sedimentary rock classification table that accompanies this section, you will see that the clastic sedimentary rocks are classified on the basis of grain size. Sandstones are rocks made of sand-size grains. Shale is layered sedimentary rock made of fine mud-size grains too small to see with the naked eye.

Chemical Textures

The key to naming chemical sedimentary rocks is the minerals from which they are made. For example, all limestones consist mostly of the mineral calcite. Rock salt is made of salt minerals such as halite. Gypsum rock is made of the mineral gypsum. Chalcedony is made of microcrystalline quartz, quartz grains so tiny that they cannot be distinguished even with a standard optical microscope.

Table 2 shows some common types of sedimentary rocks.

Biochemical Textures

Biochemical sedimentary rocks form with the help of past life. This can be in the form of fossils, shells or plant remains. For example, coal is made up of plant remains.

Table 2. Common Sedimentary Rocks

Picture	Rock Name	Type of Sedimentary Rock
	Conglomerate	Clastic (fragments of non-organic sediments)
	Breccia	Clastic
	Sandstone	Clastic
	Siltstone	Clastic

	Shale	Clastic
	Rock Salt	Chemical precipitate
	Gypsum	Chemical precipitate
	Dolostone	Chemical precipitate
	Limestone	Biochemical

	Coal	Biochemical

Sedimentary Rock Classification

Clastic Sedimentary Rocks

Grain Size	Rounding	Sorting	Rock Name
gravel coarse (> 2 mm)	angular	poorly	breccia
	rounded	poorly	conglomerate
sand medium (0.0625–2 mm)	variable	variable	sandstone
	rounded to subangular	well to moderately	quartz arenite— >90% quartz
	subrounded to angular	well to moderately	arkose— >25% feldspar
	subangular to angular	moderately to poorly	graywacke—high % lithics, clay matrix
silt fine (0.004–0.0625 mm)	variable	well	siltstone
clay extra fine (< 0.004 mm)	not visible	well	shale—breaks along bedding planes
			mudstone—lacks bedding planes
			claystone—pure mineral clay, very soft

Mineral	Distinguishing Characteristics	Rock Name	Common Depositional Environment
calcite	softer than glass, reacts to HCl	limestone	warm shallow ocean
calcite	visible fossils, softer than glass, reacts to HCl	fossiliferous limestone (biochemical)	warm shallow ocean
dolomite	white to pink, softer than glass, reacts to HCl only when powdered	dolostone	saline lagoon
calcite	gray or brown, porous, reacts to HCl	travertine	evaporated spring or cave water
calcite	white, powdery, reacts to HCl	chalk	warm shallow ocean
microscopic quartz	conchoidal fracture	chert	deep ocean floor
microscopic quartz	red, conchoidal fracture	jasper	deep ocean floor
microscopic quartz	black, conchoidal fracture	flint	nodules in limestone
microscopic quartz	translucent, layered, conchoidal fracture	agate	nodules in volcanic rocks
microscopic quartz	white, powdery	diatomite	lakes in volcanic environments
carbon	black, soft, low density	coal (biochemical)	heavily vegetated swamp
halite	tastes like salt, cubic crystals and cleavage	rock salt	evaporating water body
gypsum	softer than fingernail	gypsum rock	evaporating water body

Uses of Sedimentary Rocks

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.

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: LumenLearning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- HS Rocks. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/4.0/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Basics -- Sedimentary Rocks. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/sedimentary.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 3.9: Reading- Characteristics of Sedimentary Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.10: Self Check- Sedimentary Rocks

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1084

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 3.10: Self Check- Sedimentary Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.11: Outcome- Metamorphic Rocks

Identify metamorphic rocks and the steps of the rock cycle related to their formation.

The last type of rock is metamorphic rocks. Let’s see what these rocks are like and how they’re formed.

What You’ll Learn to Do

- Define the characteristics of a metamorphic rock.
- Discuss the effect of heat, pressure and deformation on rocks.

Learning Activities

The learning activities for this section include the following:

- Reading: Characteristics of Metamorphic Rocks
- Video: Identifying Metamorphic Rocks
- Self Check: Metamorphic Rocks

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 3.11: Outcome- Metamorphic Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.12: Reading- Characteristics of Metamorphic Rocks

A metamorphic rock used to be some other type of rock, but it was changed inside the Earth to become a new type of rock. The word metamorphism comes from ancient Greek words for “change” (meta) and “form” (morph). The type of rock that a metamorphic rock used to be, prior to metamorphism, is called the protolith. During metamorphism the mineral content and texture of the protolith are changed due to changes in the physical and chemical environment of the rock. Metamorphism can be caused by burial, tectonic stress, heating by magma, or alteration by fluids. At advanced stages of metamorphism, it is common for a metamorphic rock to develop such a different set of minerals and such a thoroughly changed texture that it is difficult to recognize what the protolith was.

A rock undergoing metamorphism remains a solid rock during the process. Rocks do not melt during most conditions of metamorphism. At the highest grade of metamorphism, rocks begin to partially melt, at which point the boundary of metamorphic conditions is surpassed and the igneous part of the rock cycle is entered.

Even though rocks remain solid during metamorphism, fluid is generally present in the microscopic spaces between the minerals. This fluid phase may play a major role in the chemical reactions that are an important part of how metamorphism occurs. The fluid usually consists largely of water.

Metamorphic rocks provide a record of the processes that occurred inside Earth as the rock was subjected to changing physical and chemical conditions. This gives the geologist literally “inside information” on what occurs within the Earth during such processes as the formation of new mountain ranges, the collision of continents, the subduction of oceanic plates, and the circulation of sea water into hot oceanic crust. Metamorphic rocks are like probes that have gone down into the Earth and come back, bringing an record of the conditions they encountered on their journey in the depths of the Earth.



Figure 1. The platy layers in this large outcrop of metamorphic rock show the effects of pressure on rocks during metamorphism.

In the large outcrop of metamorphic rocks in figure 1, the rocks’ platy appearance is a result of the process metamorphism. 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.

Metamorphism

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.



Figure 2. A foliated metamorphic rock.

Rocks change during metamorphism because 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 different chemical composition. Hornfels, with its alternating bands of dark and light crystals, is a good example of how minerals rearrange themselves during metamorphism. Hornfels is shown in table 1.

Extreme pressure may also lead to **foliation**, the flat layers that form in rocks as the rocks are squeezed by pressure (figure 2). Foliation normally forms when pressure is exerted in only one direction. Metamorphic rocks may also be non-foliated. Quartzite and limestone, shown in table 6, are nonfoliated.

The two main types of metamorphism are both related to heat within Earth:

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

Factors that Control Metamorphism

The reason rocks undergo metamorphism is that the minerals in a rock are only stable under a limited range of pressure, temperature, and chemical conditions. When rocks are subjected to large enough changes in these factors, the minerals will undergo chemical reactions that result in their replacement by new minerals, minerals that are stable in the new conditions.

Chemical Composition of the Protolith

The type of rock undergoes metamorphism is a major factor in determing what type of metamorphic rock it becomes. In short the identify of the protolith plays a big role the identity of the metamorphic rock. A fluid phase may introduce or remove chemical substances into or out of the rock during metamorphism, but in most metamorphic rock, most of the atoms in the protolith are be present in the metamorphic rock after metamorphism; the atoms will likely be rearranged into new mineral forms within the rock. Therefore, not only does the protolith determine the initial chemistry of the metamorphic rock, most metamorphic rocks do not change their bulk (overall) chemical compositions very much during metamorphism. The fact that most metamorphic rocks retain most of their original atoms means that even if the rock was so thoroughly metamorphosed that it no longer looks at all like the protolith, the rock can be analyzed in terms of its bulk chemical composition to determine what type of rock the protolith was.

Temperature

Temperature is another major factor of metamorphism. There are two ways to think about how the temperature of a rock can be increased as a result of geologic processes.

If rocks are buried within the Earth, the deeper they go, the higher the temperatures they experience. This is because temperature inside the Earth increases along what is called the geothermal gradient, or geotherm for short. Therefore, if rocks are simply buried deep enough enough sediment, they will experience temperatures high enough to cause metamorphism. This temperature is about 200ºC (approximately 400ºF).

Tectonic processes are another way rocks can be moved deeper along the geotherm. Faulting and folding the rocks of the crust, can move rocks to much greater depth than simple burial can.

Yet another way a rock in the Earth's crust can have its temperature greatly increased is by the intrusion of magma nearby. Magma intrusion subjects nearby rock to higher temperature with no increase in depth or pressure.

Pressure

Pressure is a measure of the stress, the physical force, being applied to the surface of a material. It is defined as the force per unit area acting on the surface, in a direction perpendicular to the surface.

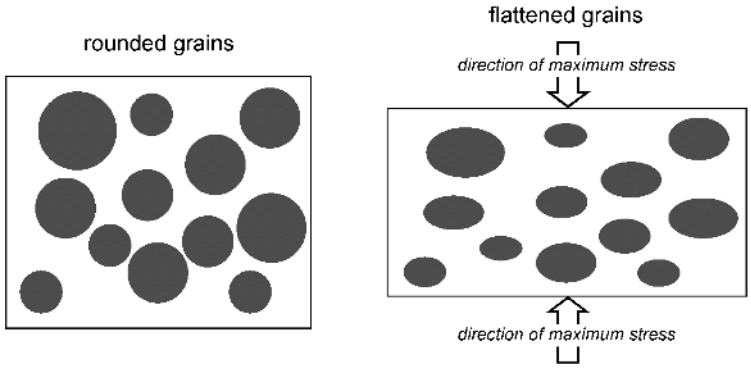
Lithostatic pressure is the pressure exerted on a rock by all the surrounding rock. The source of the pressure is the weight of all the rocks above. Lithostatic pressure increases as depth within the Earth increases and is a *uniform stress*—the pressure applies equally in all directions on the rock.

If pressure does not apply equally in all directions, differential stress occurs. There are two types of *differential stress*.

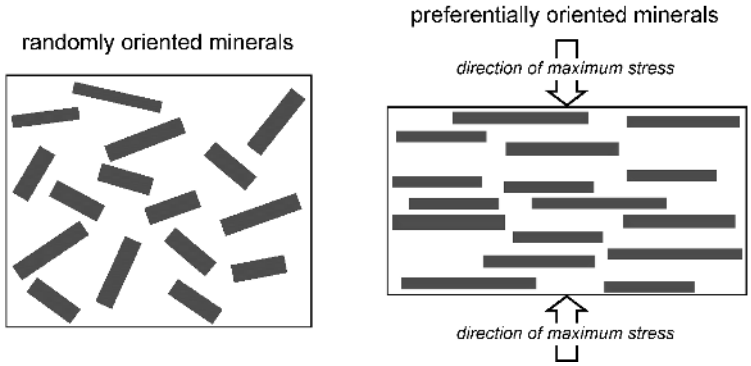
Normal stress compresses (pushes together) rock in one direction, the direction of maximum stress. At the same time, in a perpendicular direction, the rock undergoes tension (stretching), in the direction of minimum stress.

Shear stress pushes one side of the rock in a direction parallel to the side, while at the same time, the other side of the rock is being pushed in the opposite direction.

Differential stress has a major influence on the the appearance of a metamorphic rock. Differential stress can flatten pre-existing grains in the rock, as shown in the diagram below.



Metamorphic minerals that grow under differential stress will have a preferred orientation if the minerals have atomic structures that tend to make them form either flat or elongate crystals. This will be especially apparent for micas or other sheet silicates that grow during metamorphism, such as biotite, muscovite, chlorite, talc, or serpentine. If any of these flat minerals are growing under normal stress, they will grow with their sheets oriented perpendicular to the direction of maximum compression. This results in a rock that can be easily broken along the parallel mineral sheets. Such a rock is said to be foliated, or to have foliation.



Fluids

Any open space between the mineral grains in a rock, however microscopic, may contain a fluid phase. Most commonly, if there is a fluid phase in a rock during metamorphism, it will be a hydrous fluid, consisting of water and things dissolved in the water. Less commonly, it may be a carbon dioxide fluid or some other fluid. The presence of a fluid phase is a major factor during metamorphism because it helps determine which metamorphic reactions will occur and how fast they will occur. The fluid phase can also influence the rate at which mineral crystals deform or change shape. Most of this influence is due to the dissolved ions that pass in and out of the fluid phase. If during metamorphism enough ions are introduced to or removed from the rock via the fluid to change the bulk chemical composition of the rock, the rock is said to have undergone metasomatism. However, most metamorphic rocks do not undergo sufficient change in their bulk chemistry to be considered metasomatic rocks.

Time

Most metamorphism of rocks takes place slowly inside the Earth. Regional metamorphism takes place on a timescale of millions of years. Metamorphism usually involves slow changes to rocks in the solid state, as atoms or ions diffuse out of unstable minerals that are breaking down in the given pressure and temperature conditions and migrate into new minerals that are stable in those conditions. This type of chemical reaction takes a long time.

Grades of Metamorphism

Metamorphic grade refers to the general temperature and pressure conditions that prevailed during metamorphism. As the pressure and temperature increase, rocks undergo metamorphism at higher metamorphic grade. Rocks changing from one type of metamorphic rock to another as they encounter higher grades of metamorphism are said to be undergoing prograde metamorphism.

Low-grade metamorphism takes place at approximately 200–320 ºC and relatively low pressure. This is not far beyond the conditions in which sediments get lithified into sedimentary rocks, and it is common for a low-grade metamorphic rock to look somewhat like its protolith. Low grade metamorphic rocks tend to characterized by an abundance of hydrous minerals, minerals that contain water within their crystal structure. Examples of low grade hydrous minerals include clay, serpentine, and chlorite. Under low grade metamorphism many of the metamorphic minerals will not grow large enough to be seen without a microscope.

Medium-grade metamorphism takes place at approximately at 320–450 ºC and at moderate pressures. Low grade hydrous minerals are replaced by micas such as biotite and muscovite, and non-hydrous minerals such as garnet may grow. Garnet is an example of a mineral which may form porphyroblasts, metamorphic mineral grains that are larger in size and more equant in shape (about the same diameter in all directions), thus standing out among the smaller, flatter, or more elongate minerals.

High-grade metamorphism takes place at temperatures above about 450 ºC. Micas tend to break down. New minerals such as hornblende will form, which is stable at higher temperatures. However, as metamorphic grade increases to even higher grade, all hydrous minerals, which includes hornblende, may break down and be replaced by other, higher-temperature, non-hydrous minerals such as pyroxene.

Index Minerals

Index minerals, which are indicators of metamorphic grade. In a given rock type, which starts with a particular chemical composition, lower-grade index minerals are replaced by higher-grade index minerals in a sequence of chemical reactions that proceeds as the rock undergoes prograde metamorphism. For example, in rocks made of metamorphosed shale, metamorphism may prograde through the following index minerals:

- chlorite characterizes the lowest regional metamorphic grade
- biotite replaces chlorite at the next metamorphic grade, which could be considered medium-low grade
- garnet appears at the next metamorphic grade, medium grade
- staurolite marks the next metamorphic grade, which is medium-high grade
- sillimanite is a characteristic mineral of high grade metamorphic rocks

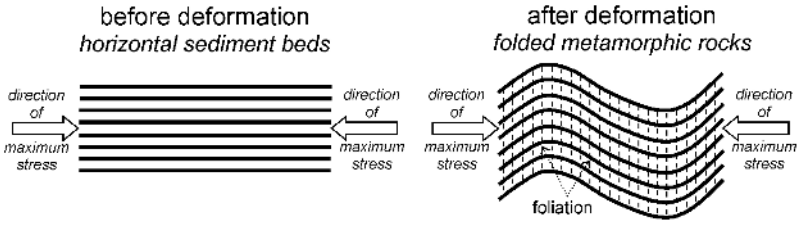
Index minerals are used by geologists to map metamorphic grade in regions of metamorphic rock. A geologist maps and collects rock samples across the region and marks the geologic map with the location of each rock sample and the type of index mineral it contains. By drawing lines around the areas where each type of index mineral occurs, the geologist delineates the zones of different metamorphic grades in the region. The lines are known as isograds.

Types of Metamorphism

Regional Metamorphism

Regional metamorphism occurs where large areas of rock are subjected to large amounts of differential stress for long intervals of time, conditions typically associated with mountain building. Mountain building occurs at subduction zones and at continental collision zones where two plates each bearing continental crust, converge upon each other.

Most foliated metamorphic rocks—slate, phyllite, schist, and gneiss—are formed during regional metamorphism. As the rocks become heated at depth in the Earth during regional metamorphism they become ductile, which means they are relatively soft even though they are still solid. The folding and deformation of the rock while it is ductile may greatly distort the original shapes and orientations of the rock, producing folded layers and mineral veins that have highly deformed or even convoluted shapes. The diagram below shows folds forming during an early stage of regional metamorphism, along with development of foliation, in response to normal stress.



The photograph below shows high-grade metamorphic rock that has undergone several stages of foliation development and folding during regional metamorphism, and may even have reached such a high temperature that it began to melt.



Contact Metamorphism

Contact metamorphism occurs to solid rock next to an igneous intrusion and is caused by the heat from the nearby body of magma. Because contact metamorphism is not caused by changes in pressure or by differential stress, contact metamorphic rocks do not become foliated. Where intrusions of magma occur at shallow levels of the crust, the zone of contact metamorphism around the intrusion is relatively narrow, sometimes only a few m (a few feet) thick, ranging up to contact metamorphic zones over 1000 m (over 3000 feet) across around larger intrusions that released more heat into the adjacent crust. The zone of contact metamorphism surrounding an igneous intrusion is called the metamorphic aureole. The rocks closest to the contact with the intrusion are heated to the highest temperatures, so the metamorphic grade is highest there and diminishes with increasing distance away from the contact. Because contact metamorphism occurs at shallow to moderate depths in the crust and subjects the rocks to temperatures up to the verge of igneous conditions, it is sometimes referred to as high-temperature, low-pressure metamorphism. Hornfels, which is a hard metamorphic rock formed from fine-grained clastic sedimentary rocks, is a common product of contact metamorphism.

Hydrothermal Metamorphism

Hydrothermal metamorphism is the result of extensive interaction of rock with high-temperature fluids. The difference in composition between the existing rock and the invading fluid drives the chemical reactions. The hydrothermal fluid may originate from a magma that intruded nearby and caused fluid to circulate in the nearby crust, from circulating hot groundwater, or from

ocean water. If the fluid introduces substantal amounts of ions into the rock and removes substantial amounts of ions from it, the fluid has metasomatized the rock—changed its chemical composition.

Ocean water that penetrates hot, cracked oceanic crust and circulates as hydrothermal fluid in ocean floor basalts produces extensive hydrothermal metamorphism adjacent to mid-ocean spreading ridges and other ocean-floor volcanic zones. Much of the basalt subjected to this type of metamorphism turns into a type of metamorphic rock known as greenschist. Greenschist contains a set of minerals, some of them green, which may include chlorite, epidote, talc, Na-plagioclase, or actinolite. The fluids eventually escape through vents in the ocean floor known as black smokers, producing thick deposits of minerals on the ocean floor around the vents.

Burial Metamorphism

Burial metamorphism occurs to rocks buried beneath sediments to depths that exceed the conditions in which sedimentary rocks form. Because rocks undergoing burial metamorphism encounter the uniform stress of lithostatic pressure, not differential pressure, they do not develop foliation. Burial metamorphism is the lowest grade of metamorphism. The main type of mineral that usually grows during burial metamorphism is zeolite, a group of low-density silicate minerals. It usually requires a strong microscope see the small grains of zeolite minerals that form during burial metamorphism.

Subduction Zone Metamorphism

During subduction, a tectonic plate, consisting of oceanic crust and lithospheric mantle, is recycled back into the deeper mantle. In most subduction zones the subducting plate is relatively cold compared with the high temperature it had when first formed at a mid-ocean spreading ridge. Subduction takes the rocks to great depth in the Earth relatively quickly. This produces a characteristic type of metamorphism, sometimes called high-pressure, low-temperature (high-P, low-T) metamorphism, which only occurs deep in a subduction zone. In oceanic basalts that are part of a subducting plate, the high-P, low-T conditions create a distinctive set of metamorphic minerals including a type of amphibole, called glaucophane, that has a blue color. Blueschist is the name given to this type of metamorphic rock. Blueschist is generally interpreted as having been produced within a subduction zone, even if the plate boundaries have subsequently shifted and that location is no longer at a subduction zone.

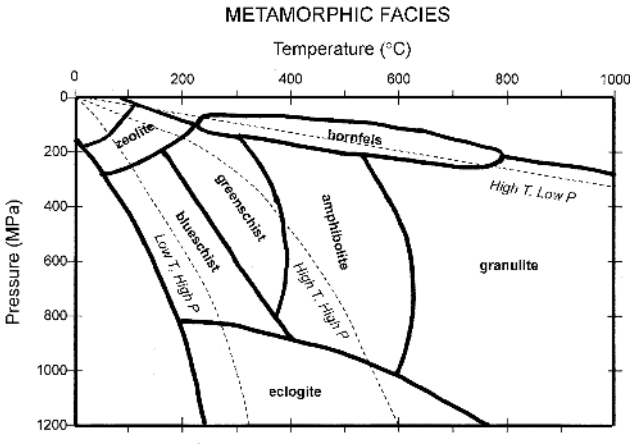
Metamorphic Facies

Much as the minerals and textures of sedimentary rocks can be used as windows to see into the environment in which the sediments were deposited on the Earth's surface, the minerals and textures of metamorphic rocks provide windows through which we view the conditions of pressure, temperature, fluids, and stress that occurred inside the Earth during metamorphism. The pressure and temperature conditions under which specific types of metamorphic rocks form has been determined by a combination labratory experiments, physics-based theoretical calculations, along with evidence in the textures of the rocks and their field relations as recorded on geologic maps. The knowledge of temperatures and pressures at which particular types of metamorphic rocks form led to the concept of metamorphic facies. Each metamorphic facies is represented by a specific type of metamorphic rock that forms under a specific pressure and temperature conditions.

Even though the name of the each metamorphic facies is taken from a type of rock that forms under those conditions, that is not the only type of rock that will form in those conditions. For example, if the protolith is basalt, it will turn into greenschist under greenschist facies conditions, and that is what facies is named for. However, if the protolith is shale, a muscovite-biotite schist, which is not green, will form instead. If it can be determined that a muscovite-biotite schist formed at around 350ºC temperature and 400 MPa pressure, it can be stated that the rock formed in the greenschist facies, even though the rock is not itself a greenschist.

The diagram below shows metamorphic facies in terms of pressure and temperature condiditons inside the Earth. Earth's surface conditions are near the top left corner of the graph at about 15ºC which is the average temperature at Earth's surface and 0.1 MPa (megapascals), which is about the average atmospheric pressure on the Earth's surface. Just as atmospheric pressure comes from the weight of all the air above a point on the Earth's surface, pressure inside the Earth comes from the weight of all the rock above a given depth. Rocks are much denser than air and MPa is the unit most commonly uses to express pressures inside the Earth. One MPa equals nearly 10 atmospheres. A pressure of 1000 MPa corresponds to a depth of about 35 km inside the Earth. Although pressure inside the Earth is determined by the depth, temperature depends on more than depth. Temperature depends on the heat flow, which varies from location to location. The way temperature changes with depth inside the Earth is called the geothermal

gradient, geotherm for short. In the diagram below, three different geotherms are marked with dashed lines. The three geotherms represent different geological settings in the Earth.



High-pressure, low-temperature geotherms occurs in subduction zones. As the diagram shows, rocks undergoing prograde metamorphism in subduction zones will be subjected to zeolite, blueschist, and ultimately eclogite facies conditions.

High-temperature, low-pressure geotherms occur in the vicinity of igneous intrusions in the shallow crust, underlying a volcanically active area. Rocks that have their pressure and temperature conditions increased along such a geotherm will metamorphose in the hornfels facies and, if it gets hot enough, in the granulite facies.

Blueschist facies and hornfels facies are associated with unusual geothermal gradients. The most common conditions in the Earth are found along geotherms between those two extremes. Most regional metamorphic rocks are formed in conditions within this range of geothermal gradients, passing through the greenschist facies to the amphibolites facies. At the maximum pressures and temperatures the rocks may encounter within the Earth in this range of geotherms, they will enter either the granulite or eclogite facies. Regionally metamorphosed rocks that contain hydrous fluids will begin to melt before they pass beyond the amphibolite facies.

Types of Metamorphic Rocks

Metamorphic rock fall into two categories, foliated and unfoliated. Most foliated metamorphic rocks originate from regional metamorphism. Some unfoliated metamorphic rocks, such as hornfels, originate only by contact metamorphism, but others can originate either by contact metamorphism or by regional metamorphism. Quartz and marble are prime examples of unfoliated that can be produced by either regional or contact metamorphism. Both rock types consist of metamorphic minerals that do not have flat or elongate shapes and thus cannot become layered even if they are produced under differential stress.

A geologist working with metamorphic rocks collects the rocks in the field and looks for the patterns the rocks form in outcrops as well as how those outcrops are related to other types of rock with which they are in contact. Field evidence is often required to know for sure whether rocks are products of regional metamorphism, contact metamorphism, or some other type of metamorphism. If only looking at rock samples in a laboratory, one can be sure of the type of metamorphism that produced a foliated metamorphic rock such as schist or gneiss, or a hornfels, which is unfoliated, but one cannot be sure of the type of metamorphism that produced an unfoliated marble or quartzite.

Foliated Metamorphic Rocks

Foliated metamorphic rocks are named for their style of foliation. However, a more complete name of each particular type of foliated metamorphic rock includes the main minerals that the rock comprises, such as biotite-garnet schist rather than just schist.

- slate—slates form at low metamorphic grade by the growth of fine-grained chlorite and clay minerals. The preferred orientation of these sheet silicates causes the rock to easily break along parallel planes, giving the rock a slaty cleavage. Some slate breaks into such extensively flat sheets of rock that it is used as the base of pool tables, beneath a layer of rubber and felt. Roof tiles are also sometimes made of slate.

- phyllite—phyllite is a low-medium grade regional metamorphic rock in which the clay minerals and chlorite have been at least partly replaced by mica mica minerals, muscovite and biotite. This gives the surfaces of phyllite a satiny luster, much brighter than the surface of a piece of slate. It is also common for the differential stresses under which phyllite forms to have produced a set of folds in the rock, making the foliation surfaces wavy or irregular, in contrast to the often perfectly flat surfaces of slaty cleavage.
- schist—the size of mineral crystals tends to grow larger with increasing metamorphic grade. Schist is a product of medium grades of metamorphism and is characterized by visibly prominent, parallel sheets of mica or similar sheet silicates, usually either muscovite or biotite, or both. In schist, the sheets of mica are usually arranged in irregular planes rather than perfectly flat planes, giving the rock a schistose foliation (or simply schistosity). Schist often contains more than just micas among its minerals, such as quartz, feldspars, and garnet.
- amphibolite—a poorly foliated to unfoliated mafic metamorphic rock, usually consisting largely of the common black amphibole known as hornblende, plus plagioclase, plus or minus biotite and possibly other minerals; it usually does not contain any quartz. Amphibolite forms at medium-high metamorphic grades. Amphibolite is also listed below in the section on unfoliated metamorphic rocks.
- gneiss—like the word schist, the word gneiss is originated from the German language; it is pronounced “nice.” As metamorphic grade continue to increase, sheet silicates become unstable and dark minerals such as hornblende or pyroxene start to grow. The dark-colored minerals tend to form separate bands or stripes in the rock, giving it a gneissic foliation of dark and light streaks. Gneiss is a high-grade metamorphic rock. Many types of gneiss look somewhat like granite, except that the gneiss has dark and light stripes whereas in granite randomly oriented and distributed minerals with no stripes or layers.
- migmatite—a combination of high-grade regional metamorphic rock – usually gneiss or schist – and granitic igneous rock. The granitic rock in migmatite probably originated from partial melting of some of the metamorphic rock, though in some migmatites the granite may have intruded the rock from deeper in the crust. In migmatite you can see metamorphic rock that has reached the limits of metamorphism and begun transitioning into the igneous stage of the rock cycle by melting to form magma.

Names of different styles of foliation come from the common rocks that exhibit such foliation:

- slate has ***slaty*** foliation
- phyllite has ***phyllitic*** foliation
- schist has ***schistose*** foliation
- gneiss has ***gneissic*** foliation (also called gneissose foliation)

Nonfoliated Metamorphic Rocks

Nonfoliated metamorphic rocks lack a planar (oriented) fabric, either because the minerals did not grow under differential stress, or because the minerals that grew during metamorphism are not minerals that have elongate or flat shapes. Because they lack foliation, these rocks are named entirely on the basis of their mineralogy.

- hornfels—hornfels are very hard rocks formed by contact metamorphism of shale, siltstone, or sandstone. The heat from the nearby magma “bakes” the sedimentary rocks and recrystallizes the minerals in them into a new texture that no longer breaks easily along the original sedimentary bedding planes. Depending on the composition of the rock and the temperature reached, minerals indicative of high metamorphic grade such as pyroxene may occur in some hornfels, though many hornfels have minerals indicating medium grade metamorphism.
- amphibolite—amphibolites are dark-colored rocks with amphibole, usually the common black amphibole known as hornblende, as their most abundant mineral, along with plagioclase and possibly other minerals, though usually no quartz. Amphibolites are poorly foliated to unfoliated and form at medium to medium-high grades of metamorphism from basalt or gabbro.
- quartzite—quartzite is a metamorphic rock made almost entirely of quartz, for which the protolith was quartz arenite. Because quartz is stable over a wide range of pressure and temperature, little or no new minerals form in quartzite during metamorphism. Instead, the quartz grains recrystallize into a denser, harder rock than the original sandstone. If struck by a rock hammer, quartzite will commonly break right through the quartz grains, rather than around them as when quartz arenite is broken.
- marble—marble is a metamorphic rock made up almost entirely of either calcite or dolomite, for which the protolith was either limestone or dolostone, respectively. Marbles may have bands of different colors which were deformed into convoluted folds

while the rock was ductile. Such marble is often used as decorative stone in buildings. Some marble, which is considered better quality stone for carving into statues, lacks color bands.

Table 1. Common Metamorphic Rocks and Their Parent Rock

Picture	Rock Name	Type of Metamorphic Rock	Comments
	Slate	Foliated	Metamorphism of shale
	Phyllite	Foliated	Metamorphism of slate, but under greater heat and pressure than slate
	Schist	Foliated	Often derived from metamorphism of claystone or shale; metamorphosed under more heat and pressure than phyllite
	Gneiss	Foliated	Metamorphism of various different rocks, under extreme conditions of heat and pressure
	Hornfels	Non-foliated	Contact metamorphism of various different rock types

Table 1. Common Metamorphic Rocks and Their Parent Rock

	Quartzite	Non-foliated	Metamorphism of sandstone
	Marble	Non-foliated	Metamorphism of limestone
	Metaconglomerate	Non-foliated	Metamorphism of conglomerate

Metamorphic Rock Classification

Foliated Metamorphic Rocks				
Crystal Size	Mineralogy	Protolith	Metamorphism	Rock Name
very fine	clay minerals	shale	low grade regional	slate
fine	clay minerals, biotite, muscovite	shale	low grade regional	phyllite
medium to coarse	biotite, muscovite, quartz, garnet, plagioclase	shale, basalt	medium grade regional	schist
medium to coarse	amphibole, plagioclase, biotite	basalt	medium grade regional	amphibolite *(Note: may be unfoliated)*
medium to coarse	plagioclase, orthoclase, quartz, biotite, amphibole, pyroxene	basalt, granite, shale	high grade regional	gneiss
Unfoliated Metamorphic Rocks				

Crystal Size	Mineralogy	Protolith	Metamorphism	Rock Name
fine to coarse	quartz	sandstone	regional or contact	quartzite
fine to coarse	calcite	limestone	regional or contact	marble
fine	pyroxene, amphibole, plagioclase	shale	contact	hornfels

Note that not all minerals listed in the mineralogy column will be present in every rock of that type and that some rocks may have minerals not listed here.

Uses of Metamorphic Rocks



Figure 3. Marble is used for decorative items and in art.

Quartzite and marble are commonly used for building materials and artwork. Marble is beautiful for statues and decorative items such as vases (see an example in figure 3). Ground up marble is also a component of toothpaste, plastics, and paper.

Quartzite is very hard and is often crushed and used in building railroad tracks (see figure 4). Schist and slate are sometimes used as building and landscape materials. Graphite, the “lead” in pencils, is a mineral commonly found in metamorphic rocks.



Figure 4. Crushed quartzite is sometimes placed under railroad tracks because it is very hard and durable.

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Basics -- Metamorphic Rocks. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/metamorphic.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*
- HS Rocks. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/4.0/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 3.12: Reading- Characteristics of Metamorphic Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.13: Video- Identifying Metamorphic Rocks

This video discusses how to identify a metamorphic rocks:

A link to an interactive elements can be found at the bottom of this page.

Contributors and Attributions

All rights reserved content

- Identifying Rocks : Identifying Metamorphic Rocks. **Authored by**: eHow. **Located at**: https://youtu.be/qs9x_bTCiew. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 3.13: Video- Identifying Metamorphic Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.14: Self Check- Metamorphic Rocks

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1085

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 3.14: Self Check- Metamorphic Rocks is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

3.15: Putting It Together- Rocks and the Rock Cycle

Summary

In this section, you learned the following:

1. The three rock types and how they are classified
2. How each of the different rock types form
3. The techniques geologist use to identify different rocks
4. How to use these techniques to identify common rocks
5. How the rock cycle works

Synthesis

In the rock cycle, illustrated in figure 1, the three main rock types—igneous, sedimentary, and metamorphic—are shown. Arrows connecting the three rock types show the processes that change one rock type into another. The cycle has no beginning and no end. Rocks deep within the Earth are right now becoming other types of rocks. Rocks at the surface are lying in place before they are next exposed to a process that will change them.

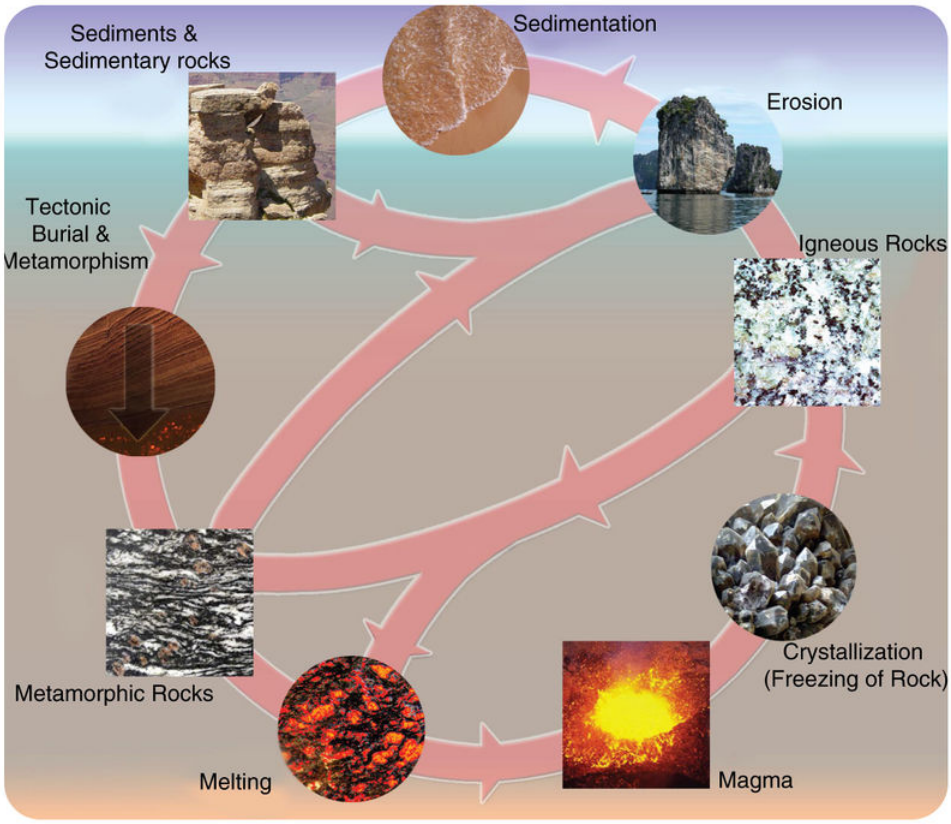


Figure 1. The Rock Cycle.

The rock cycle is a continuous and dynamic cycle that has no starting or stopping point and no set progression. Rocks can move through different paths within the cycle. The rock cycle explains how each rock type forms and the processes involved. We saw how the processes within the cycle influence everything from soil formation to recording the history of the Earth to the role deformation plays in rocks. It is easy to see how the rock cycle influences our dynamic and ever changing earth.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 4.1: Types of Rocks. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/4.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 3.15: Putting It Together- Rocks and the Rock Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

4: Weathering and Soil Formation

Learning Objectives

Explain the formation of soils, different weathering processes and erosion.

- Describe types and processes of weathering and erosion.
- Describe and compare typical soil profiles and basic soil types
- Discuss the importance of soil conservation.

4.1: Why It Matters- Weathering and Soil Formation
4.2: Outcome- Weathering and Erosion
4.3: Reading- What Is Weathering?
4.4: Reading- Mechanical Weathering
4.5: Reading- Chemical Weathering
4.6: Reading- Influences on Weathering
4.7: Self Check- Weathering and Erosion
4.8: Outcome- Soil Profiles and Types
4.9: Reading- Soil Texture and Composition
4.10: Reading- Soil Horizons and Profiles
4.11: Reading- Types of Soils
4.12: Self Check- Soil Profiles and Types
4.13: Outcome- Soil Conservation
4.14: Reading- Causes of Soil Erosion
4.15: Video- The Dust Bowl
4.16: Reading- Avoiding Soil Loss
4.17: Self Check- Soil Conservation
4.18: Putting It Together- Weathering and Soil Formation
4.19: Assignment- Weathering and Soil Formation

This page titled 4: Weathering and Soil Formation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.1: Why It Matters- Weathering and Soil Formation

Explain the formation of soils, different weathering processes and erosion.

Introduction

When most people think about the resources we use, most of them will immediately think about water and air and fossil fuels. However, one resource that is absolutely vital to our existence (and other species as well) is soil. In this section, we will see how soil is formed, we will see why all soils are not the same, and we will see what the soil looks like in different biomes.

You may recall from the rock cycle that soil is formed from the weathering of rocks, but this is just one piece of what goes into soil formation. If we stop and think about soil for just a minute, we can come up with an impressive resume of what soil does:

1. The most obvious area where soil is important is in agriculture and growing food to feed our population. But on a more personal level, do you like to garden? Do you grow your own vegetables? Imagine what would happen without this vital resource.
2. Soils are also an important part of the water cycle. They help regulate the flow and quality of water. What would happen without soil in areas that get a lot of rainfall?
3. Did you know there are more organisms in just 1 tablespoon of soil than there are people on the planet? The soil is home to billions of different species. Where would these species be without soil?

These are just a few examples of why soil is essential as a resource. So, let's see how soil forms and why there are so many different types of soil.

Learning Outcomes

- Describe types and processes of weathering and erosion.
- Describe and compare typical soil profiles and basic soil types.
- Discuss the importance of soil conservation.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 4.1: Why It Matters- Weathering and Soil Formation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.2: Outcome- Weathering and Erosion

Describe types and processes of weathering and erosion.

This section introduces you to weathering and erosion, both important parts of the rock cycle. You will learn how different rocks are weathered and eroded and the implications of this weathering.

What You'll Learn to Do

- Identify the ways mechanical weathering alters materials on Earth.
- Identify the ways chemical weathering alters materials on Earth.
- Identify several influences on weathering.

Learning Activities

The learning activities for this section include the following:

- Reading: What Is Weathering?
- Reading: Mechanical Weathering
- Reading: Chemical Weathering
- Reading: Influences on Weathering
- Self Check: Weathering and Erosion

Contributors and Attributions

CC licensed content, Shared previously

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 4.2: Outcome- Weathering and Erosion is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.3: Reading- What Is Weathering?

The footprints that astronauts left on the Moon will be there forever. Why? This is because the Moon has no atmosphere and, as a result, has no weathering. Weathering is one of the forces on Earth that destroy rocks and landforms. Without weathering, geologic features would build up but would be less likely to break down.

What is Weathering?

Weathering is the process that changes solid rock into sediments. Sediments were described in the Rocks chapter. With weathering, rock is disintegrated. It breaks into pieces.

Once these sediments are separated from the rocks, erosion is the process that moves the sediments. Erosion is the next chapter's topic. The four forces of erosion are water, wind, glaciers, and gravity.

- Water is responsible for most erosion. Water can move most sizes of sediments, depending on the strength of the force.
- Wind moves sand-sized and smaller pieces of rock through the air.
- Glaciers move all sizes of sediments, from extremely large boulders to the tiniest fragments.
- Gravity moves broken pieces of rock, large or small, downslope.



Figure 1. A once smooth road surface has cracks and fractures, plus a large pothole.

While plate tectonics forces work to build huge mountains and other landscapes, the forces of weathering gradually wear those rocks and landscapes away. Together with erosion, tall mountains turn into hills and even plains. The Appalachian Mountains along the east coast of North America were once as tall as the Himalayas.

No human being can watch for millions of years as mountains are built, nor can anyone watch as those same mountains gradually are worn away. But imagine a new sidewalk or road. The new road is smooth and even. Over hundreds of years, it will completely disappear, but what happens over one year? What changes would you see (figure 1)? What forces of weathering wear down that road, or rocks or mountains over time?

Follow this link to view some animations of different types of weathering processes.

Contributors and Attributions

CC licensed content, Shared previously

- 9.1: Weathering. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/9.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.3: Reading- What Is Weathering? is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.4: Reading- Mechanical Weathering

Mechanical weathering (also called physical weathering) breaks rock into smaller pieces. These smaller pieces are just like the bigger rock, just smaller. That means the rock has changed physically without changing its composition. The smaller pieces have the same minerals, in just the same proportions as the original rock.

There are many ways that rocks can be broken apart into smaller pieces. **Ice wedging** is the main form of mechanical weathering in any climate that regularly cycles above and below the freezing point (figure 2). Ice wedging works quickly, breaking apart rocks in areas with temperatures that cycle above and below freezing in the day and night, and also that cycle above and below freezing with the seasons.



Figure 2. Ice wedging.

Ice wedging breaks apart so much rock that large piles of broken rock are seen at the base of a hillside, as rock fragments separate and tumble down. Ice wedging is common in Earth's polar regions and mid latitudes, and also at higher elevations, such as in the mountains. **Abrasion** is another form of mechanical weathering. In abrasion, one rock bumps against another rock.



Figure 3. Rocks on a beach are worn down by abrasion as passing waves cause them to strike each other.

- Gravity causes abrasion as a rock tumbles down a mountainside or cliff.
- Moving water causes abrasion as particles in the water collide and bump against one another.
- Strong winds carrying pieces of sand can sandblast surfaces.
- Ice in glaciers carries many bits and pieces of rock. Rocks embedded at the bottom of the glacier scrape against the rocks below.

Abrasion makes rocks with sharp or jagged edges smooth and round. If you have ever collected beach glass or cobbles from a stream, you have witnessed the work of abrasion (figure 3).

Now that you know what mechanical weathering is, can you think of other ways it could happen? Plants and animals can do the work of mechanical weathering (figure 4). This could happen slowly as a plant's roots grow into a crack or fracture in rock and gradually grow larger, wedging open the crack. Burrowing animals can also break apart rock as they dig for food or to make living spaces for themselves.

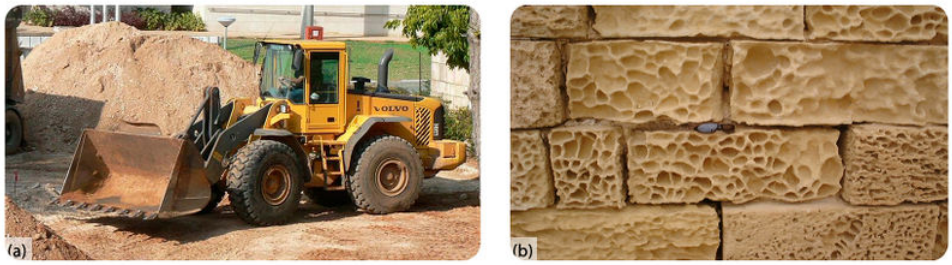


Figure 4. (a) Human activities are responsible for enormous amounts of mechanical weathering, by digging or blasting into rock to build homes, roads, subways, or to quarry stone. (b) Salt weathering of building stone on the island of Gozo, Malta.

Mechanical weathering increases the rate of chemical weathering. As rock breaks into smaller pieces, the surface area of the pieces increases figure 5. With more surfaces exposed, there are more surfaces on which chemical weathering can occur.

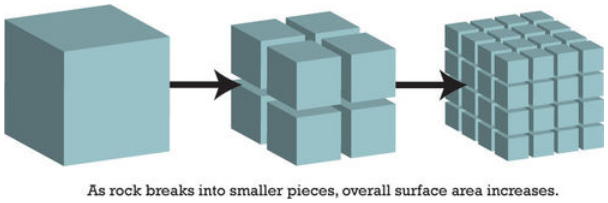


Figure 5. Mechanical weathering may increase the rate of chemical weathering.

Contributors and Attributions

CC licensed content, Shared previously

- 9.1: Weathering. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/9.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.4: Reading- Mechanical Weathering is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.5: Reading- Chemical Weathering

Chemical weathering is the other important type of weathering. Chemical weathering is different from mechanical weathering because the rock changes, not just in size of pieces, but in composition. That is, one type of mineral changes into a different mineral. Chemical weathering works through chemical reactions that cause changes in the minerals.



Figure 1. Deforestation in Brazil reveals the underlying clay-rich soil.

Most minerals form at high pressure or high temperatures deep in the crust, or sometimes in the mantle. When these rocks reach the Earth's surface, they are now at very low temperatures and pressures. This is a very different environment from the one in which they formed and the minerals are no longer stable. In chemical weathering, minerals that were stable inside the crust must change to minerals that are stable at Earth's surface.

Remember that the most common minerals in Earth's crust are the silicate minerals. Many silicate minerals form in igneous or metamorphic rocks. The minerals that form at the highest temperatures and pressures are the least stable at the surface. Clay is stable at the surface and chemical weathering converts many minerals to clay (figure 1).

There are many types of chemical weathering because there are many agents of chemical weathering. Water is the most important agent of chemical weathering. Two other important agents of chemical weathering are carbon dioxide and oxygen.

Chemical Weathering by Water

A water molecule has a very simple chemical formula, H_2O, two hydrogen atoms bonded to one oxygen atom. But water is pretty remarkable in terms of all the things it can do. Remember from the Earth's Minerals chapter that water is a polar molecule. The positive side of the molecule attracts negative ions and the negative side attracts positive ions. So water molecules separate the ions from their compounds and surround them. Water can completely dissolve some minerals, such as salt. Follow this link to check out this animation of how water dissolves salt.

Hydrolysis is the name of the chemical reaction between a chemical compound and water. When this reaction takes place, water dissolves ions from the mineral and carries them away. These elements have undergone **leaching**. Through hydrolysis, a mineral such as potassium feldspar is leached of potassium and changed into a clay mineral. Clay minerals are more stable at the Earth's surface.



Figure 7. This statue has been damaged by acid rain.

Chemical Weathering by Acid Rain

Carbon dioxide (CO_2) combines with water as raindrops fall through the atmosphere. This makes a weak acid, called carbonic acid. Carbonic acid is a very common in nature where it works to dissolve rock.

Pollutants, such as sulfur and nitrogen, from fossil fuel burning, create sulfuric and nitric acid. Sulfuric and nitric acids are the two main components of acid rain, which accelerate chemical weathering (figure 7). Acid rain is discussed in the Human Actions and the Atmosphere chapter.

Chemical Weathering by Oxygen



Figure 8. When iron rich minerals oxidize, they produce the familiar red color found in rust.

Oxidation is a chemical reaction that takes place when oxygen reacts with another element. Oxygen is very strongly chemically reactive. The most familiar type of oxidation is when iron reacts with oxygen to create rust (figure 8). Minerals that are rich in iron break down as the iron oxidizes and forms new compounds. Iron oxide produces the red color in soils.

Now that you know what chemical weathering is, can you think of some other ways chemical weathering might occur? Chemical weathering can also be contributed to by plants and animals. As plant roots take in soluble ions as nutrients, certain elements are exchanged. Plant roots and bacterial decay use carbon dioxide in the process of respiration.

Contributors and Attributions

CC licensed content, Shared previously

- 9.1: Weathering. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/9.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.5: Reading- Chemical Weathering is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.6: Reading- Influences on Weathering

Weathering rates depend on several factors. These include the composition of the rock and the minerals it contains as well as the climate of a region.

Rock and Mineral Type



Figure 1. Devil's Tower is the central plug of resistant lava from which the surrounding rock weathered and eroded away.

Different rock types weather at different rates. Certain types of rock are very resistant to weathering. Igneous rocks, especially intrusive igneous rocks such as granite, weather slowly because it is hard for water to penetrate them. Other types of rock, such as limestone, are easily weathered because they dissolve in weak acids.

Rocks that resist weathering remain at the surface and form ridges or hills. Devil's Tower in Wyoming is an igneous rock from beneath a volcano (figure 1). As the surrounding less resistant rocks were worn away, the resistant center of the volcano remained behind.

Different minerals also weather at different rates. Some minerals in a rock might completely dissolve in water but the more resistant minerals remain. In this case, the rock's surface becomes pitted and rough. When a less resistant mineral dissolves, more resistant mineral grains are released from the rock.

Climate

A region's **climate** strongly influences weathering. Climate is determined by the temperature of a region plus the amount of precipitation it receives. Climate is weather averaged over a long period of time. Chemical weathering increases as:

- Temperature increases: Chemical reactions proceed more rapidly at higher temperatures. For each 10°C increase in average temperature, the rate of chemical reactions doubles.
- Precipitation increases: More water allows more chemical reactions. Since water participates in both mechanical and chemical weathering, more water strongly increases weathering.



Figure 2. Wet, warm tropical areas have the most weathering.

So how do different climates influence weathering? A cold, dry climate will produce the lowest rate of weathering. A warm, wet climate will produce the highest rate of weathering. The warmer a climate is, the more types of vegetation it will have and the greater the rate of biological weathering (figure 2). This happens because plants and bacteria grow and multiply faster in warmer temperatures.

Some resources are concentrated by weathering processes. In tropical climates, intense chemical weathering carries away all soluble minerals, leaving behind just the least soluble components. The aluminum oxide, bauxite, forms this way and is our main source of aluminum ore.

Contributors and Attributions

CC licensed content, Shared previously

- 9.1: Weathering. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/9.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.6: Reading- Influences on Weathering is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.7: Self Check- Weathering and Erosion

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1088

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 4.7: Self Check- Weathering and Erosion is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.8: Outcome- Soil Profiles and Types

Describe and compare typical soil profiles and basic soil types.

This section provides information on the different types of soil and soil profiles. You will become familiar with different soil types, their components and common locations.

What You'll Learn to Do

- Identify the measurable components of soil: sand, silt, and clay.
- Identify the primary soil horizons: organic, topsoil, subsoils, and C horizon.
- Identify three common (and important!) types of soil: pedalfer, pedocal, and laterite.

Learning Activities

The learning activities for this section include the following:

- Reading: Soil Texture and Composition
- Reading: Soil Horizons and Profiles
- Reading: Types of Soils
- Self Check: Soil Profiles and Types

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 4.8: Outcome- Soil Profiles and Types is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.9: Reading- Soil Texture and Composition



Figure 1. A loam field.

The inorganic portion of soil is made of many different size particles, and these different size particles are present in different proportions. The combination of these two factors determines some of the properties of the soil.

- A **permeable** soil allows water to flow through it easily because the spaces between the inorganic particles are large and well connected. Sandy or silty soils are considered 'light' soils because they are permeable, water-draining types of soils.
- Soils that have lots of very small spaces are water-holding soils. For example, when clay is present in a soil, the soil is heavier, holds together more tightly, and holds water.
- When a soil contains a mixture of grain sizes, the soil is called a **loam** (figure 1).

When soil scientists want to precisely determine soil type, they measure the percentage of sand, silt, and clay. They plot this information on a triangular diagram, with each size particle at one corner (figure 2). The soil type can then be determined from the location on the diagram. At the top, a soil would be clay; at the left corner, it would be sand, and at the right corner it would be silt. Soils in the lower middle with less than 50% clay are loams.

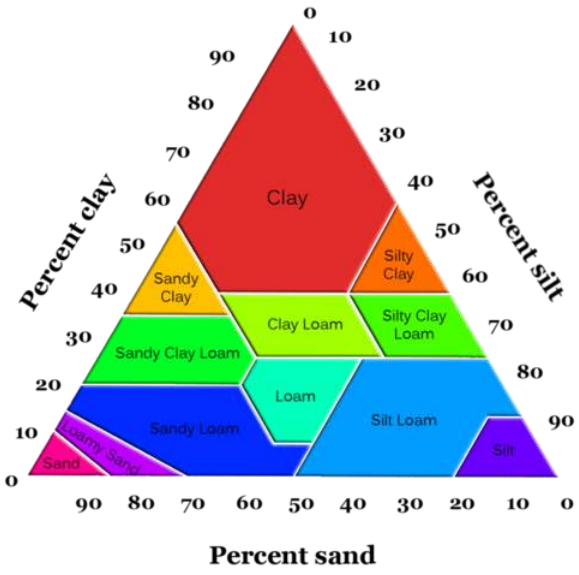


Figure 2. Soil types by particle size.

Using the chart as a guide, what is the composition of a sandy clay loam? If you would like to determine soil type by feel, here's a chart from the USDA to help you.

Contributors and Attributions

CC licensed content, Shared previously

- 9.2: Soils. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/9.2/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.9: Reading- Soil Texture and Composition is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.10: Reading- Soil Horizons and Profiles

A residual soil forms over many years, as mechanical and chemical weathering slowly change solid rock into soil. The development of a residual soil may go something like this.



Figure 1. Soil is an important resource. Each soil horizon is distinctly visible in this photograph.

1. The bedrock fractures because of weathering from ice wedging or another physical process.
2. Water, oxygen, and carbon dioxide seep into the cracks to cause chemical weathering.
3. Plants, such as lichens or grasses, become established and produce biological weathering.
4. Weathered material collects until there is soil.
5. The soil develops **soil horizons**, as each layer becomes progressively altered. The greatest degree of weathering is in the top layer. Each successive, lower layer is altered just a little bit less. This is because the first place where water and air come in contact with the soil is at the top.

A cut in the side of a hillside shows each of the different layers of soil. All together, these are called a **soil profile** (figure 1).

The simplest soils have three horizons: topsoil (A horizon), subsoil (B horizon), and C horizon.

Topsoil

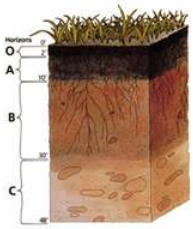


Figure 2. A soil profile is the complete set of soil layers. Each layer is called a horizon.

Called the A horizon, the **topsoil** is usually the darkest layer of the soil because it has the highest proportion of organic material. The topsoil is the region of most intense biological activity: insects, worms, and other animals burrow through it and plants stretch their roots down into it. Plant roots help to hold this layer of soil in place. In the topsoil, minerals may dissolve in the fresh water that moves through it to be carried to lower layers of the soil. Very small particles, such as clay, may also get carried to lower layers as water seeps down into the ground.

Subsoil

The **B horizon** or **subsoil** is where soluble minerals and clays accumulate. This layer is lighter brown and holds more water than the topsoil because of the presence of iron and clay minerals. There is less organic material. Look at figure 2.

C horizon

The **C horizon** is a layer of partially altered bedrock. There is some evidence of weathering in this layer, but pieces of the original rock are seen and can be identified.

Not all climate regions develop soils, and not all regions develop the same horizons. Some areas develop as many as five or six distinct layers, while others develop only very thin soils or perhaps no soils at all.

Contributors and Attributions

CC licensed content, Shared previously

- 9.2: Soils. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/9.2/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.10: Reading- Soil Horizons and Profiles is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.11: Reading- Types of Soils

Although soil scientists recognize thousands of types of soil—each with its own specific characteristics and name—let's consider just three soil types. This will help you to understand some of the basic ideas about how climate produces a certain type of soil, but there are many exceptions to what we will learn right now (figure 1).



Figure 1. Just some of the thousands of soil types.

Pedalfer



Figure 2. A pedalfer is the dark, fertile type of soil that will form in a forested region.

Deciduous trees, the trees that lose their leaves each winter, need at least 65 cm of rain per year. These forests produce soils called **pedalfers**, which are common in many areas of the temperate, eastern part of the United States (figure 2).

The word pedalfer comes from some of the elements that are commonly found in the soil. The *Al* in ped**al**fer is the chemical symbol of the element aluminum, and the *Fe* in pedal**fe**r is the chemical symbol for iron.

Pedalfers are usually a very fertile, dark brown or black soil. Not surprising, they are rich in aluminum clays and iron oxides. Because a great deal of rainfall is common in this climate, most of the soluble minerals dissolve and are carried away, leaving the less soluble clays and iron oxides behind.

Pedocal



Figure 3. A pedocal is the alkaline type of soil that forms in grassland regions.

Pedocal soils form in drier, temperate areas where grasslands and brush are the usual types of vegetation (figure 3). The climates that form pedocals have less than 65 cm rainfall per year, so compared to pedalfers, there is less chemical weathering and less water to dissolve away soluble minerals so more soluble minerals are present and fewer clay minerals are produced. It is a drier region with less vegetation, so the soils have lower amounts of organic material and are less fertile.

A pedocal is named for the calcite enriched layer that forms. Water begins to move down through the soil layers, but before it gets very far, it begins to evaporate. Soluble minerals, like calcium carbonate, concentrate in a layer that marks the lowest place that water was able to reach. This layer is called caliche.

Laterite



Figure 4. A laterite is the type of thick, nutrient poor soil that forms in the rainforest.

In tropical rainforests where it rains literally every day, **laterite** soils form (figure 4). In these hot, wet, tropical regions, intense chemical weathering strips the soils of their nutrients. There is practically no humus. All soluble minerals are removed from the soil and all plant nutrients are carried away. All that is left behind are the least soluble materials, like aluminum and iron oxides. These soils are often red in color from the iron oxides. Laterite soils bake as hard as a brick if they are exposed to the sun.

Many climates types have not been mentioned here. Each produces a distinctive soil type that forms in the particular circumstances found there. Where there is less weathering, soils are thinner but soluble minerals may be present. Where there is intense weathering, soils may be thick but nutrient poor. Soil development takes a very long time, it may take hundreds or even thousands of years for a good fertile topsoil to form. Soil scientists estimate that in the very best soil-forming conditions, soil forms at a rate of about 1mm/year. In poor conditions, soil formation may take thousands of years!

Contributors and Attributions

CC licensed content, Shared previously

- 9.2: Soils. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/9.2/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.11: Reading- Types of Soils is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.12: Self Check- Soil Profiles and Types

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1089

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 4.12: Self Check- Soil Profiles and Types is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.13: Outcome- Soil Conservation

Describe types and processes of weathering and erosion.

This section introduces you to weathering and erosion, both important parts of the rock cycle. You will learn how different rocks are weathered and eroded and the implications of this weathering.

What You'll Learn to Do

- Identify causes of soil erosion and soil loss.
- Identify strategies to conserve and replenish soil.

Learning Activities

The learning activities for this section include the following:

- Reading: Causes of Soil Erosion
- Video: The Dust Bowl
- Reading: Avoiding Soil Loss
- Self Check: Soil Conservation

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 4.13: Outcome- Soil Conservation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.14: Reading- Causes of Soil Erosion

The agents of soil erosion are the same as the agents of all types of erosion: water, wind, ice, or gravity. Running water is the leading cause of soil erosion, because water is abundant and has a lot of power. Wind is also a leading cause of soil erosion because wind can pick up soil and blow it far away.

Activities that remove vegetation, disturb the ground, or allow the ground to dry are activities that increase erosion. What are some human activities that increase the likelihood that soil will be eroded?

Farming

Agriculture is probably the most significant activity that accelerates soil erosion because of the amount of land that is farmed and how much farming practices disturb the ground (Figure 1). Farmers remove native vegetation and then plow the land to plant new seeds. Because most crops grow only in spring and summer, the land lies fallow during the winter. Of course, winter is also the stormy season in many locations, so wind and rain are available to wash soil away. Tractor tires make deep grooves, which are natural pathways for water. Fine soil is blown away by wind.

The soil that is most likely to erode is the nutrient-rich topsoil, which degrades the farmland.



Figure 1. (a) The bare areas of farmland are especially vulnerable to erosion. (b) Slash-and-burn agriculture leaves land open for soil erosion and is one of the leading causes of soil erosion in the world.

Grazing

Grazing animals (Figure 2) wander over large areas of pasture or natural grasslands eating grasses and shrubs. Grazers expose soil by removing the plant cover for an area. They also churn up the ground with their hooves. If too many animals graze the same land area, the animals' hooves pull plants out by their roots. A land is overgrazed if too many animals are living there.



Grazing animals can cause erosion if they are allowed to overgraze and remove too much or all of the vegetation in a pasture.

Logging and Mining



Figure 3. Logging exposes large areas of land to erosion.

Logging removes trees that protect the ground from soil erosion. The tree roots hold the soil together and the tree canopy protects the soil from hard falling rain. Logging results in the loss of **leaf litter**, or dead leaves, bark, and branches on the forest floor. Leaf litter plays an important role in protecting forest soils from erosion (Figure 3).

Much of the world's original forests have been logged. Many of the tropical forests that remain are currently the site of logging because North America and Europe have already harvested many of their trees (Figure 4). Soils eroded from logged forests clog rivers and lakes, fill estuaries, and bury coral reefs.



Figure 4. Deforested swatches in Brazil show up as gray amid the bright red tropical rainforest.

Surface mining disturbs the land (Figure 5) and leaves the soil vulnerable to erosion.

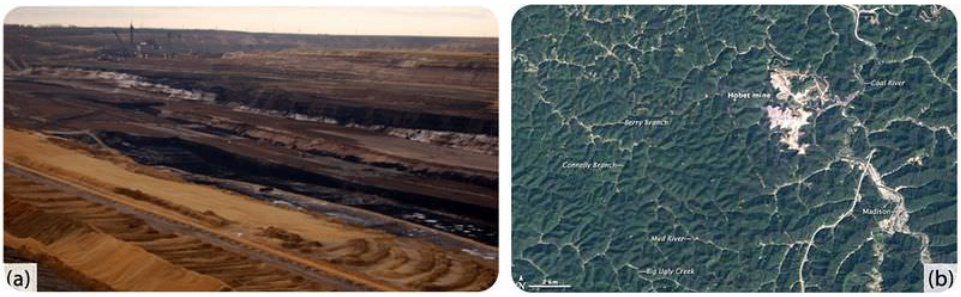


Figure 5. (a) Disturbed land at a coal mine pit in Germany. (b) This coal mine in West Virginia covers more than 10,000 acres (15.6 square miles). Some of the exposed ground is being reclaimed by planting trees.

Construction

Constructing buildings and roads churns up the ground and exposes soil to erosion. In some locations, native landscapes, such as forest and grassland, are cleared, exposing the surface to erosion (in some locations the land that will be built on is farmland). Near construction sites, dirt, picked up by the wind, is often in the air. Completed construction can also contribute to erosion (Figure 6).



Figure 6. Urban areas and parking lots result in less water entering the ground. Water runs off the parking lot onto nearby lands and speeds up erosion in those areas.

Recreational Activities

Recreational activities may accelerate soil erosion. Off-road vehicles disturb the landscape and the area eventually develops bare spots where no plants can grow. In some delicate habitats, even hikers' boots can disturb the ground, so it's important to stay on the trail (Figure 7).



Figure 7. (a) ATVs churn up the soil, accelerating erosion. (b) Hiking trails may become eroded.

Soil erosion is as natural as any other type of erosion, but human activities have greatly accelerated soil erosion. In some locations soil erosion may occur about 10 times faster than its natural rate. Since Europeans settled in North America, about one-third of the topsoil in the area that is now the United States has eroded away.

Summary

- Although soil erosion is a natural process, human activities have greatly accelerated it.
- The agents of soil erosion are the same as of other types of erosion: water, ice, wind, and gravity.
- Soil erosion is more likely where the ground has been disturbed by agriculture, grazing animals, logging, mining, construction, and recreational activities.

Contributors and Attributions

CC licensed content, Shared previously

- Soil Erosion. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Soil-Erosion/lesson/Soil-Erosion-HS-ES/?referrer=featured_content. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.14: Reading- Causes of Soil Erosion is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.15: Video- The Dust Bowl

Page created for new attachment

This page titled 4.15: Video- The Dust Bowl is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.16: Reading- Avoiding Soil Loss



Figure 1. Terraced fields in Sa Pa, Vietnam

How does the terracing shown in Figure 1 photo prevent soil erosion?

Terracing keeps the soil from moving very far downhill since it will only get as far as the next terrace downhill. Water will also be slowed by the terraces and so will be less able to carry tremendous amounts of soil downhill. Terracing is a great way to preserve soil when farming is being done on hillsides.

Soil Erosion

Bad farming practices and a return to normal rainfall levels after an unusually wet period led to the Dust Bowl. In some regions more than 75% of the topsoil blew away. This is the most extreme example of soil erosion the United States has ever seen.



Figure 1. A farmer and his sons walk through a dust storm in Cimarron County, Oklahoma in 1936.

Still, in many areas of the world, the rate of soil erosion is many times greater than the rate at which it is forming. Drought, insect plagues, or outbreaks of disease are natural cycles of events that can negatively impact ecosystems and the soil, but there are also many ways in which humans neglect or abuse this important resource. Soils can also be contaminated if too much salt accumulates in the soil or where pollutants sink into the ground.

One harmful practice is removing the vegetation that helps to hold soil in place. Sometimes just walking or riding your bike over the same place will kill the grass that normally grows there. Land is also deliberately cleared or deforested for wood. The loose soils then may be carried away by wind or running water.

Soil Conservation

Soil is only a renewable resource if it is carefully managed. There are many practices that can protect and preserve soil resources.



Figure 3. Organic material can be added to soil to help increase its fertility.

Adding organic material to the soil in the form of plant or animal waste, such as compost or manure, increases the fertility of the soil and improves its ability to hold on to water and nutrients (Figure 3). Inorganic fertilizer can also temporarily increase the fertility of a soil and may be less expensive or time consuming, but it does not provide the same long-term improvements as organic materials.

Preventing Soil Erosion

Soil is a natural resource that is vitally important for sustaining natural habitats and for growing food. Although soil is a renewable resource, it is renewed slowly, taking hundreds or thousands of years for a good fertile soil to develop.



Figure 4. Steep slopes can be terraced to make level planting areas and decrease surface water runoff and erosion.

Most of the best land for farming is already being cultivated. With human populations continuing to grow, it is extremely important to protect our soil resources. Agricultural practices such as rotating crops, alternating the types of crops planted in each row, and planting nutrient-rich cover crops all help to keep soil more fertile as it is used season after season. Planting trees as windbreaks, plowing along contours of the field, or building terraces into steeper slopes will all help to hold soil in place (Figure 4). No-till or low-tillage farming helps to keep soil in place by disturbing the ground as little as possible when planting.

The rate of topsoil loss in the United States and other developed countries has decreased recently as better farming practices have been adopted. Unfortunately, in developing nations, soil is often not protected.

The table below shows some steps that we can take to prevent erosion. Some are things that can be done by farmers or developers. Others are things that individual homeowners or community members can implement locally.

Source of Erosion	Strategies for Prevention
Agriculture	• Leave leaf litter on the ground in the winter. • Grow cover crops, special crops grown in the winter to cover the soil. • Plant tall trees around fields to buffer the effects of wind. • Drive tractors as little as possible. • Use drip irrigation that puts small amounts of water in the ground frequently. • Avoid watering crops with sprinklers that make big water drops on the ground. • Keep fields as flat as possible to avoid soil eroding down hill.
Grazing Animals	• Move animals throughout the year, so they don't consume all the vegetation in one spot. • Keep animals away from stream banks, where hills are especially prone to erosion.
Logging and Mining	• Reduce the amount of land that is logged and mined. • Reduce the number of roads that are built to access logging areas. • Avoid logging and mining on steep lands. • Cut only small areas at one time and quickly replant logged areas with new seedlings.
Development	• Reduce the amount of land area that is developed into urban areas, parking lots, etc. • Keep as much "green space" in cities as possible, such as parks or strips where plants can grow. • Invest in and use new technologies for parking lots that make them permeable to water in order to reduce runoff of water.
Recreational Activities	• Avoid using off-road vehicles on hilly lands. • Stay on designated trails.
Building Construction	• Avoid building on steep hills. • Grade surrounding land to distribute water rather than collecting it in one place. • Where water collects, drain to creeks and rivers. • Landscape with plants that minimize erosion.

Contributors and Attributions

CC licensed content, Shared previously

- Avoiding Soil Loss. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Avoiding-Soil-Loss/lesson/Avoiding-Soil-Loss-HS-ES/?referrer=featured_content. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 4.16: Reading- Avoiding Soil Loss is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.17: Self Check- Soil Conservation

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1090

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 4.17: Self Check- Soil Conservation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.18: Putting It Together- Weathering and Soil Formation

Summary

In this section, you learned the following:

1. How weathering and erosion contribute to soil formation
2. How different processes alter rocks
3. The different types of soil
4. The different types of soil profiles

Synthesis

Wow, who knew soil was so complex and involved? It is easy to see how soil is an important resource and why soils are different from one place to another. The processes involved in soil formation are very slow. It takes anywhere from 200–1,000 years (depending on your location) for just one inch of soil to form. With the importance of soil and the time it takes to form, soil is a resource that is just as important as clean water and air. Watch this six minute video as a review of the topics we learned in this section. (Just ignore the bad jokes.)

A link to an interactive elements can be found at the bottom of this page.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

All rights reserved content

- Science - Soil Formation and soil layers - English. **Authored by**: Bodhaguru. **Located at**: https://youtu.be/amt-sPIbgK0. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 4.18: Putting It Together- Weathering and Soil Formation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

4.19: Assignment- Weathering and Soil Formation

In this assessment, you will visit a cemetery to observe weathering and erosion. You will also identify the types of rocks present, speculate on the weathering process and explain what happens during erosion. Remember to access the tips and hints at the bottom of the page.

Basic Requirements (assignment criteria):

For this assessment, you will investigate your local soil and you will need to visit a local cemetery. This will require you to make sure you know the hours for visitation. Make sure you have these instructions and a camera with you.

If you can't identify a rock, describe it as thoroughly as possible so you can recognize each time you see it. Listing any minerals you see present can also help with recognition. At the least, you should be able to identify the stones as igneous, sedimentary or metamorphic.

You will need to look at the lettering on the stones, both for a date and to see how deep and clear the lettering remains. It can also be beneficial to make "rubbings" of the writing on the tombstones. This can make it easier to see the degree of weathering.

You will also want to look at how well the decorations on the stones have been preserved.

Part I:

Look over the questions below for other ideas on making observations.

IMPORTANT: Remember that the cemetery is a reserve. You should not scratch the stones or deface them or the grave plots in any way.

Make a chart to log and record your data. You can also insert your pictures into the chart.

Questions:

1. What is the oldest tombstone you found? What material is this stone made of?
2. What is the youngest tombstone? What material is it composed of?
3. Visit and record the data for at least 10 tombstones. Make sure you do not visit ones side by side, visit other areas of the cemetery. It may be possible to tell which area is the oldest. If so, gather information there and then move to the newer parts of the cemetery.

Take a picture of each tombstone for use later. Make sure you make a note of which picture goes with which number in your chart. It would be best to number them as you take the picture and save it.

4. Look over the chart and your pictures. What material(s) seem to you to be the most resistant to weathering? Why is this?
5. What material(s) seem to you to be the least resistant to weathering? Why is this?
6. Describe the processes that seem to be the most important in weathering the gravestones. Which rock type(s) are affected by each of these processes?
7. How has weathering affected other materials in the cemetery besides the tombstones?
8. Speculate what happened to the rock that has been weathered away.
9. Explain the role weathering and erosion play in the process of soil formation?

Make sure you include pictures of the oldest and the youngest tombstone.

Make sure you include your name and the name of the cemetery on your document.

Part II:

Go the this USDA Soil Taxonomy Wiki Site (Links to an external site.) and read about the different soil types. Click on the map on the right hand side in the box to enlarge it. As best as you can, identify the soil type found in your area (state is probably easier on that map). Once you have identified your soil type, you can read about it on this site or any others of your choosing. In your own words, describe the soil in your area. Then choose one other soil type listed to compare it to. How are the two soils similar? How are the two soils different? Include a drawing or picture of both soil profiles. If you use a picture or information from a different site, please make sure you list the source beneath the picture (just the website will do).

This assessment is adapted from “Cemetery Geology” by Mary Savina, originally found here (Links to an external site.)

Contributors and Attributions

CC licensed content, Original

- Weathering and Soil Formation Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 4.19: Assignment- Weathering and Soil Formation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

5: Plate Tectonics

Learning Objectives

Recognize the ongoing development of, evidence for, and large scale planetary effects of the Theory of Plate Tectonics.

- Describe Continental Drift including supporting evidence.
- Critique and interpret major types of evidence supporting the Theory of Plate Tectonics.
- Describe different geological processes in relation to plate tectonics.

5.1: Why It Matters- Plate Tectonics
5.2: Outcome- Continental Drift
5.3: Reading- Continental Drift
5.4: Reading- Wegener and the Continental Drift Hypothesis
5.5: Self Check- Continental Drift
5.6: Outcome- The Theory of Plate Tectonics
5.7: Reading- Theory of Plate Tectonics
5.8: Reading- Developing the Theory
5.9: Self Check- The Theory of Plate Tectonics
5.10: Outcome- Geological Processes
5.11: Reading- Supercontinents
5.12: Reading- Volcanic Arcs
5.13: Video- Ocean Basins
5.14: Reading- Hot Spots
5.15: Self Check- Geological Processes
5.16: Putting It Together- Plate Tectonics
5.17: Assignment- Plate Tectonics

This page titled 5: Plate Tectonics is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.1: Why It Matters- Plate Tectonics

Recognize the ongoing development of, evidence for, and large scale planetary effects of the Theory of Plate Tectonics.

Introduction

Plate tectonics is often seen as the missing piece of the puzzle for geologists. Plate tectonics explains, either directly or indirectly, just about every topic discussed in geology. It is the glue that binds everything together. Before plate tectonics, geologists had no explanation for these (and other) questions:

1. What causes the tectonic plates to move the way they do?
2. Why is the oceanic crust younger than continental crust?
3. Why do the continents look the way they do, like puzzle pieces or are positioned as they are?
4. Why are Japan and California so prone to earthquakes and volcanoes?
5. How did the Himalayas form?
6. Why do we find evidence of aquatic species at the very top of the Himalayas and other mountainous areas?
7. How do mountains form?
8. Why do the oceans look the way they do?
9. What factors contributed to the occurrence of the ice ages?
10. Why the same species can be found on continents on opposite sides of the oceans?

As you move through this section, keep in mind all of these questions and make note of any other impacts the Theory of Plate Tectonics has had on the field of geology.

Learning Outcomes

- Describe Continental Drift including supporting evidence.
- Critique and interpret major types of evidence supporting the Theory of Plate Tectonics.
- Describe different geological processes in relation to plate tectonics.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 5.1: Why It Matters- Plate Tectonics is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.2: Outcome- Continental Drift

Describe Continental Drift including supporting evidence.

The continental drift hypothesis was developed in the early part of the twentieth century, mostly by Alfred Wegener. Wegener said that continents move around on Earth's surface and that they were once joined together as a single supercontinent. While Wegener was alive, scientists did not believe that the continents could move.

In this outcome, we will discuss the basics of the hypothesis, as well as the contributions of Alfred Wegener.

What You'll Learn to Do

- Identify key components and evidence of Continental Drift.
- Know the shortcomings of Continental Drift.

Learning Activities

The learning activities for this section include the following:

- Reading: Continental Drift
- Reading: Wegener and the Continental Drift Hypothesis
- Self Check: Continental Drift

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 6.2: Continental Drift. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/6.2/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 5.2: Outcome- Continental Drift is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.3: Reading- Continental Drift

The Continental Drift Idea



Figure 1. The continents fit together like pieces of a puzzle. This is how they looked 250 million years ago.

Find a map of the continents and cut each one out. Better yet, use a map where the edges of the continents show the continental shelf. That's the true size and shape of a continent. Can you fit the pieces together? The easiest link is between the eastern Americas and western Africa and Europe, but the rest can fit together too (Figure 1).

Alfred Wegener proposed that the continents were once united into a single supercontinent named Pangaea, meaning *all earth* in ancient Greek. He suggested that Pangaea broke up long ago and that the continents then moved to their current positions. He called his hypothesis **continental drift.**

Evidence for Continental Drift

Besides the way the continents fit together, Wegener and his supporters collected a great deal of evidence for the continental drift hypothesis.

- Identical rocks, of the same type and age, are found on both sides of the Atlantic Ocean. Wegener said the rocks had formed side-by-side and that the land had since moved apart.
- 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 (figure 2). Wegener concluded that they formed as a single mountain range that was separated as the continents drifted.



Figure 2. The similarities between the Appalachian and the eastern Greenland mountain ranges are evidences for the continental drift hypothesis.

- Ancient fossils of the same species of extinct plants and animals are found in rocks of the same age but are on continents that are now widely separated (figure 3). Wegener proposed that the organisms had lived side by side, but that the lands had moved apart after they were dead and fossilized. He suggested that the organisms would not have been able to travel across the oceans.
  - Fossils of the seed fern *Glossopteris* were too heavy to be carried so far by wind.
  - *Mesosaurus* was a swimming reptile but could only swim in fresh water.
  - *Cynognathus* and *Lystrosaurus* were land reptiles and were unable to swim.

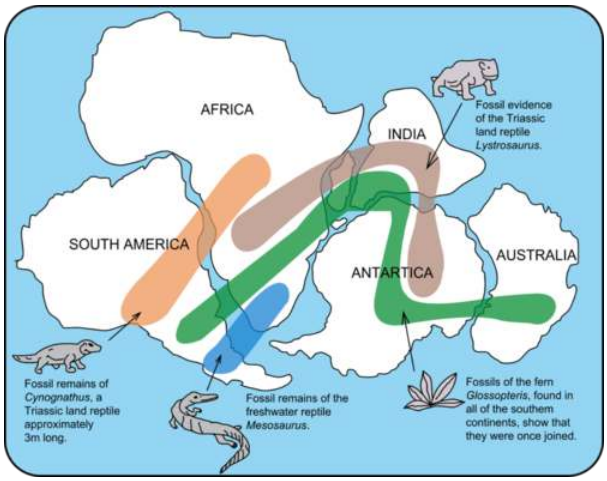


Figure 3. Wegener used fossil evidence to support his continental drift hypothesis. The fossils of these organisms are found on lands that are now far apart.

- Grooves and rock deposits left by ancient glaciers are found today on different continents very close to the equator. This would indicate that the glaciers either formed in the middle of the ocean and/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 land mass close to the South Pole and the continents moved to their present positions later on.
- Coral reefs and coal-forming swamps are found in tropical and subtropical environments, but ancient coal seams and coral reefs are found in locations where it is much too cold today. Wegener suggested that these creatures were alive in warm climate zones and that the fossils and coal later had drifted to new locations on the continents.

Take a look at this animation showing that Earth's climate belts remain in roughly the same position while the continents move and this animation showing how the continents split up.

Although Wegener's evidence was sound, most geologists at the time rejected his hypothesis of continental drift. Why do you think they did not accept continental drift?

Scientists argued that there was no way to explain how solid continents could plow through solid oceanic crust. Wegener's idea was nearly forgotten until technological advances presented even more evidence that the continents moved and gave scientists the tools to develop a mechanism for Wegener's drifting continents.

Magnetic Polarity Evidence

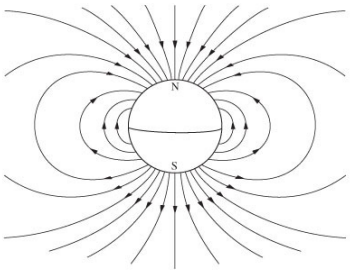


Figure 4. Earth's magnetic field is like a magnet with its north pole near the geographic North Pole and the south pole near the geographic South Pole.

Puzzling new evidence came in the 1950s from studies on the Earth's magnetic history (figure 4). Scientists used **magnetometers**, devices capable of measuring the magnetic field intensity, to look at the magnetic properties of rocks in many locations.

Magnetite crystals are like tiny magnets that point to the north magnetic pole as they crystallize from magma. The crystals record both the direction and strength of the **magnetic field** at the time. The direction is known as the field's **magnetic polarity.**

Magnetic Polarity on the Same Continent with Rocks of Different Ages

Geologists noted important things about the magnetic polarity of different aged rocks on the same continent:

- Magnetite crystals in fresh volcanic rocks point to the current magnetic north pole (figure 5) no matter what continent or where on the continent the rocks are located.

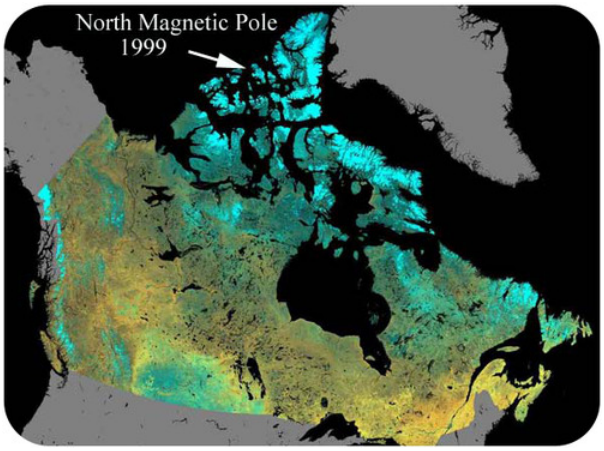


Figure 5. Earth's current north magnetic pole is in northern Canada.

- Older rocks that are the same age and are located on the same continent point to the same location, but that location is not the current north magnetic pole.
- Older rock that are of different ages do not point to the same locations or to the current magnetic north pole.

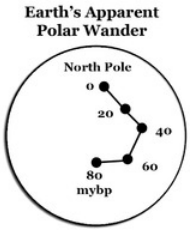


Figure 6. The location of the north magnetic north pole 80 million years before present (mybp), then 60, 40, 20, and now.

In other words, although the magnetite crystals were pointing to the magnetic north pole, the location of the pole seemed to wander. Scientists were amazed to find that the north magnetic pole changed location through time (figure 6).

There are three possible explanations for this:

1. The continents remained fixed and the north magnetic pole moved.
2. The north magnetic pole stood still and the continents moved.
3. Both the continents and the north pole moved.

Magnetic Polarity on Different Continents with Rocks of the Same Age

Geologists noted that for rocks of the same age but on different continents, the little magnets pointed to different magnetic north poles.

- 400-million-year-old magnetite in Europe pointed to a different north magnetic pole than the same-aged magnetite in North America.
- 250 million years ago, the north poles were also different for the two continents.

The scientists looked again at the three possible explanations. Only one can be correct. If the continents had remained fixed while the north magnetic pole moved, there must have been two separate north poles. Since there is only one north pole today, the only reasonable explanation is that the north magnetic pole has remained fixed but that the continents have moved.

To test this, geologists fitted the continents together as Wegener had done. It worked! There has only been one magnetic north pole and the continents have drifted (figure 7). They named the phenomenon of the magnetic pole that seemed to move but actually did not **apparent polar wander.**

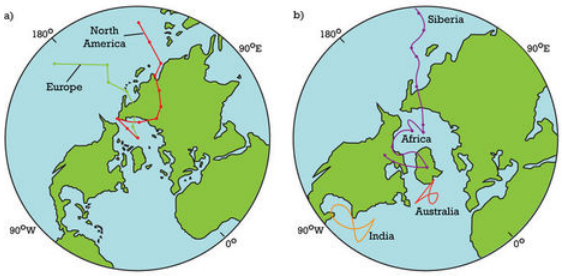


Figure 7. On the left: The apparent north pole for Europe and North America if the continents were always in their current locations. The two paths merge into one if the continents are allowed to drift.

This evidence for continental drift gave geologists renewed interest in understanding how continents could move about on the planet's surface.

Lesson Summary

- In the early part of the 20th century, scientists began to put together evidence that the continents could move around on Earth's surface.
- The evidence for continental drift included the fit of the continents; the distribution of ancient fossils, rocks, and mountain ranges; and the locations of ancient climatic zones.
- Although the evidence for continental drift was extremely strong, scientists rejected the idea because no mechanism for how solid continents could move around on the solid earth was developed.
- The discovery of apparent polar wander renewed scientists interest in continental drift.

Contributors and Attributions

CC licensed content, Shared previously

- 6.2: Continental Drift. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/6.2/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 5.3: Reading- Continental Drift is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.4: Reading- Wegener and the Continental Drift Hypothesis

Scientists still do not appear to understand sufficiently that all earth sciences must contribute evidence toward unveiling the state of our planet in earlier times, and that the truth of the matter can only be reached by combing all this evidence. . . . It is only by combing the information furnished by all the earth sciences that we can hope to determine 'truth' here, that is to say, to find the picture that sets out all the known facts in the best arrangement and that therefore has the highest degree of probability. Further, we have to be prepared always for the possibility that each new discovery, no matter what science furnishes it, may modify the conclusions we draw.

— Alfred L. Wegener, *The Origins of Continents and Oceans*, first published in 1915.

Wegener put together a tremendous amount of evidence that the continents had been joined. He advocated using scientific evidence to find the "truth." As his colleague, are you convinced? Let's explore.

Wegener's Continental Drift Hypothesis



Figure 1. Alfred Wegener suggested that continental drift occurred as continents cut through the ocean floor, in the same way as this icebreaker plows through sea ice.

Wegener put his idea and his evidence together in his book *The Origin of Continents and Oceans*, first published in 1915. New editions with additional evidence were published later in the decade. In his book he said that around 300 million years ago the continents had all been joined into a single landmass he called Pangaea, meaning "all earth" in ancient Greek. The supercontinent later broke apart and the continents having been moving into their current positions ever since. He called his hypothesis **continental drift**.

The Problem with the Hypothesis

Wegener's idea seemed so outlandish at the time that he was ridiculed by other scientists. What do you think the problem was? To his colleagues, his greatest problem was that he had no plausible mechanism for how the continents could move through the oceans. Based on his polar experiences, Wegener suggested that the continents were like icebreaking ships plowing through ice sheets. The continents moved by centrifugal and tidal forces. As Wegener's colleague, how would you go about showing whether these forces could move continents? What observations would you expect to see on these continents?



Figure 2. Early hypotheses proposed that centrifugal forces moved continents. This is the same force that moves the swings outward on a spinning carnival ride.

Scientists at the time calculated that centrifugal and tidal forces were too weak to move continents. When one scientist did calculations that assumed that these forces were strong enough to move continents, his result was that if Earth had such strong

forces the planet would stop rotating in less than one year. In addition, scientists also thought that the continents that had been plowing through the ocean basins should be much more deformed than they are.

Wegener answered his question of whether Africa and South America had once been joined. But a hypothesis is rarely accepted without a mechanism to drive it. Are you going to support Wegener? A very few scientists did, since his hypothesis elegantly explained the similar fossils and rocks on opposite sides of the ocean, but most did not.

Mantle Convection

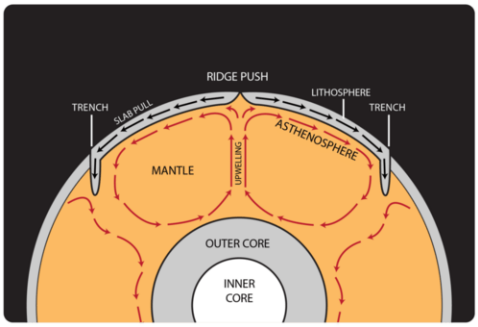


Figure 3. Thermal convection occurs as hot rock in the deep mantle rises towards the Earth's surface. This rock then spreads out and cools, sinking back towards the core, where it can be heated again. This circulation of rock through the mantle creates convection cells.

Wegener had many thoughts regarding what could be the driving force behind continental drift. Another of Wegener's colleagues, Arthur Holmes, elaborated on Wegener's idea that there is thermal convection in the mantle.

In a **convection cell**, material deep beneath the surface is heated so that its density is lowered and it rises. Near the surface it becomes cooler and denser, so it sinks. Holmes thought this could be like a conveyor belt. Where two adjacent convection cells rise to the surface, a continent could break apart with pieces moving in opposite directions. Although this sounds like a great idea, there was no real evidence for it, either.

Alfred Wegener died in 1930 on an expedition on the Greenland icecap. For the most part the continental drift idea was put to rest for a few decades, until technological advances presented even more evidence that the continents moved and gave scientists the tools to develop a mechanism for Wegener's drifting continents. Since you're on a virtual field trip, you get to go along with them as well.

Summary

- Alfred Wegener published his idea that the continents had been joined as a single landmass, which he called Pangaea, about 300 million years ago.
- Wegener's idea was mostly ridiculed, in part because Wegener could not develop a plausible mechanism for continents moving through oceanic crust.
- Calculations showed that his idea about centrifugal and tidal forces powering the continents could not be right.
- Wegener also thought about mantle convection an idea expanded on by Arthur Holmes as the driving force for continental drift. There was no evidence available to support the idea at the time.

Contributors and Attributions

CC licensed content, Shared previously

- Wegener and the Continental Drift Hypothesis. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Wegener-and-the-Continental-Drift-Hypothesis/lesson/Wegener-and-the-Continental-Drift-Hypothesis-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 5.4: Reading- Wegener and the Continental Drift Hypothesis is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.5: Self Check- Continental Drift

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1093

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 5.5: Self Check- Continental Drift is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.6: Outcome- The Theory of Plate Tectonics

Critique and interpret major types of evidence supporting the Theory of Plate Tectonics.

Plate tectonics is the most important concept in modern geology. This section will introduce you to the concept of plate tectonics, how it works, why it is important and how it is shaping the world today.

What You'll Learn to Do

- Describe and compare different types of plate motions, rates of motion and the driving mechanisms and forces involved with each.
- Know the role of technology in Plate Tectonics.

Learning Activities

The learning activities for this section include the following:

- Reading: Theory of Plate Tectonics
- Reading: Developing the Theory
- Self Check: Theory of Plate Tectonics

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 5.6: Outcome- The Theory of Plate Tectonics is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.7: Reading- Theory of Plate Tectonics

When the concept of seafloor spreading came along, scientists recognized that it was the mechanism to explain how continents could move around Earth's surface. Like the scientists before us, we will now merge the ideas of continental drift and seafloor spreading into the theory of plate tectonics.

Watch this video about continental drift and the mechanism of seafloor spreading create plate tectonics.

Earth's Tectonic Plates

Seafloor and continents move around on Earth's surface, but what is actually moving? What portion of the Earth makes up the "plates" in plate tectonics? This question was also answered because of technology developed during war times – in this case, the Cold War. The **plates** are made up of the lithosphere.

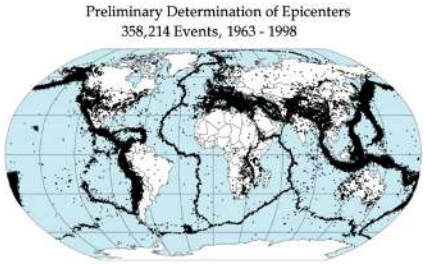


Figure 1. Earthquakes outline the plates.

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 of 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 place where the earthquake occurs.

Earthquake epicenters outline the plates. Mid-ocean ridges, trenches, and large faults mark the edges of the plates, and this is where earthquakes occur (figure 1).

The lithosphere is divided into a dozen major and several minor plates (figure 2). The plates' edges can be drawn by connecting the dots that mark earthquakes' epicenters. A single plate can be made of all oceanic lithosphere or all continental lithosphere, but nearly all plates are made of a combination of both.

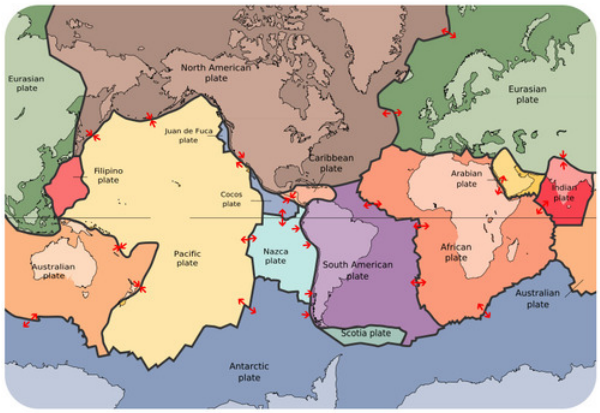


Figure 2. The lithospheric plates and their names. The arrows show whether the plates are moving apart, moving together, or sliding past each other.

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.

How Plates Move

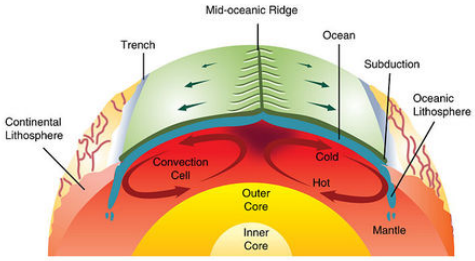


Figure 3. Mantle convection drives plate tectonics. Hot material rises at mid-ocean ridges and sinks at deep sea trenches, which keeps the plates moving along the Earth's surface.

If seafloor spreading drives the plates, what drives seafloor spreading? Picture two convection cells side-by-side in the mantle, similar to the illustration in figure 3.

1. Hot mantle from the two adjacent cells rises at the ridge axis, creating new ocean crust.
2. The top limb of the convection cell moves horizontally away from the ridge crest, as does the new seafloor.
3. The outer limbs of the convection cells plunge down into the deeper mantle, dragging oceanic crust as well. This takes place at the deep sea trenches.
4. The material sinks to the core and moves horizontally.
5. The material heats up and reaches the zone where it rises again.

Check out this animation of mantle convection and watch this video:

A link to an interactive elements can be found at the bottom of this page.

Plate Boundaries

Plate boundaries are the edges where two plates meet. Most geologic activities, including volcanoes, earthquakes, and mountain building, take place at plate boundaries. How can two plates move relative to each other?

- **Divergent plate boundaries**: the two plates move away from each other.
- **Convergent plate boundaries**: the two plates move towards each other.
- **Transform plate boundaries**: the two plates slip past each other.

The type of plate boundary and the type of crust found on each side of the boundary determines what sort of geologic activity will be found there.

Divergent Plate Boundaries

Plates move apart at mid-ocean ridges where new seafloor forms. Between the two plates is a rift valley. Lava flows at the surface cool rapidly to become basalt, but deeper in the crust, magma cools more slowly to form gabbro. So the entire ridge system is made up of igneous rock that is either extrusive or intrusive. Earthquakes are common at mid-ocean ridges since the movement of magma and oceanic crust results in crustal shaking. The vast majority of mid-ocean ridges are located deep below the sea (figure 4).

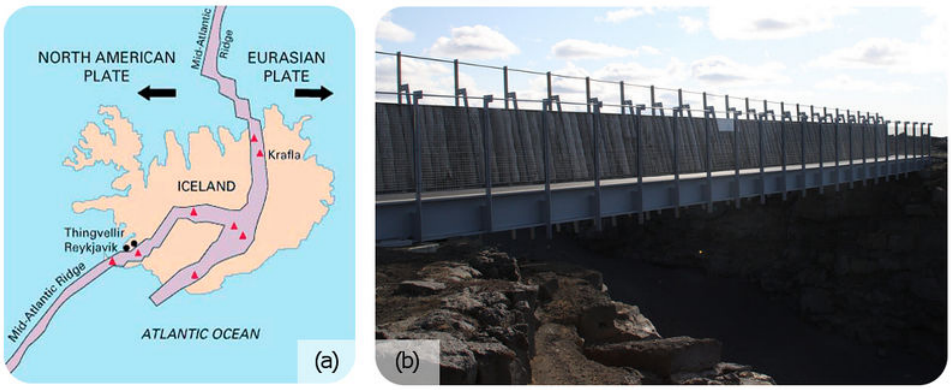


Figure 4. (a) Iceland is the one location where the ridge is located on land: the Mid-Atlantic Ridge separates the North American and Eurasian plates; (b) The rift valley in the Mid-Atlantic Ridge on Iceland.



Figure 5. The Arabian, Indian, and African plates are rifting apart, forming the Great Rift Valley in Africa. The Dead Sea fills the rift with seawater.

Check out these animations:

- Divergent plate boundary at mid-ocean ridge
- Divergent plate boundary

Can divergent plate boundaries occur within a continent? What is the result? **Incontinental rifting** (figure 5), magma rises beneath the continent, causing it to become thinner, break, and ultimately split apart. New ocean crust erupts in the void, creating an ocean between continents.

Convergent Plate Boundaries

When two plates converge, the result depends on the type of lithosphere the plates are made of. No matter what, smashing two enormous slabs of lithosphere together results in magma generation and earthquakes.

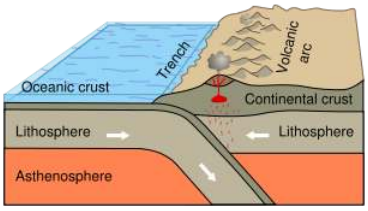


Figure 6. Subduction of an oceanic plate beneath a continental plate causes earthquakes and forms a line of volcanoes known as a continental arc.

Ocean-Continent

When oceanic crust converges with continental crust, the denser oceanic plate plunges beneath the continental plate. This process, called **subduction**, occurs at the oceanic trenches (figure 6). The entire region is known as a **subduction zone**. Subduction zones have a lot of intense earthquakes and volcanic eruptions. The subducting plate causes melting in the mantle. The magma rises and erupts, creating volcanoes. These coastal volcanic mountains are found in a line above the subducting plate (figure 7). The volcanoes are known as a **continental arc**.

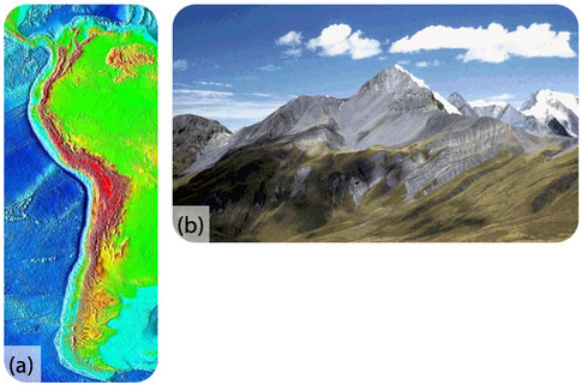


Figure 7. (a) At the trench lining the western margin of South America, the Nazca plate is subducting beneath the South American plate, resulting in the Andes Mountains (brown and red uplands); (b) Convergence has pushed up limestone in the Andes Mountains where volcanoes are common.

The movement of crust and magma causes earthquakes. Look at this map of earthquake epicenters at subduction zones. This animation shows the relationship between subduction of the lithosphere and creation of a volcanic arc.

The volcanoes of northeastern California—Lassen Peak, Mount Shasta, and Medicine Lake volcano—along with the rest of the Cascade Mountains of the Pacific Northwest are the result of subduction of the Juan de Fuca plate beneath the North American plate (figure 8). The Juan de Fuca plate is created by seafloor spreading just offshore at the Juan de Fuca ridge.

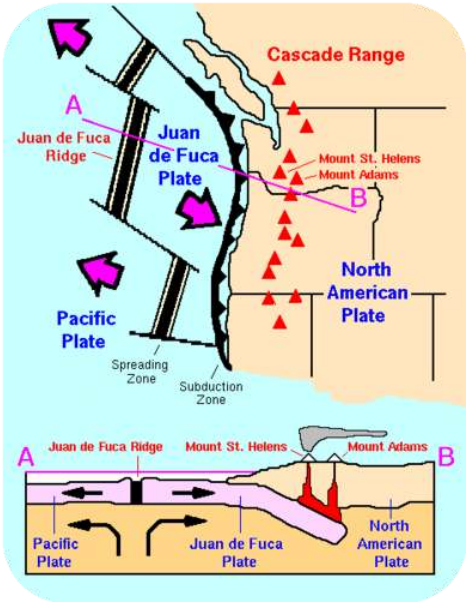


Figure 8. The Cascade Mountains of the Pacific Northwest are a continental arc.

If the magma at a continental arc is felsic, it may be too viscous (thick) to rise through the crust. The magma will cool slowly to form granite or granodiorite. These large bodies of intrusive igneous rocks are called **batholiths**, which may someday be uplifted to form a mountain range (figure 9).



Figure 9. The Sierra Nevada batholith cooled beneath a volcanic arc roughly 200 million years ago. The rock is well exposed here at Mount Whitney. Similar batholiths are likely forming beneath the Andes and Cascades today.

Ocean-Ocean

When two oceanic plates converge, the older, denser plate will subduct into the mantle. An ocean trench marks the location where the plate is pushed down into the mantle. The line of volcanoes that grows on the upper oceanic plate is an **island arc**. Do you think earthquakes are common in these regions (figure 10)?

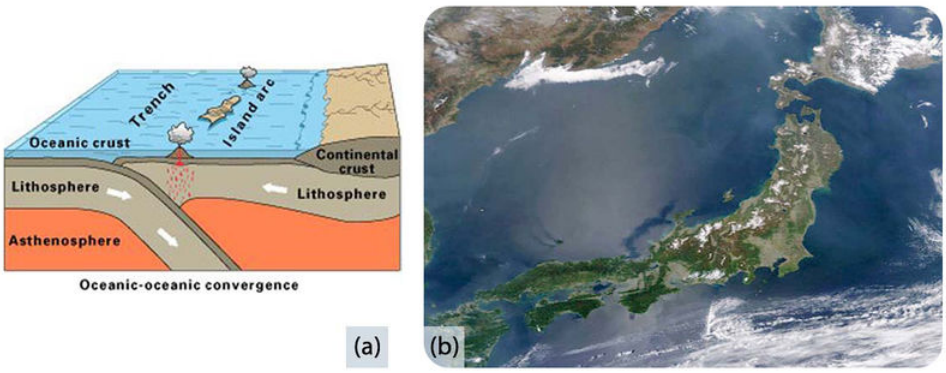


Figure 10. (a) Subduction of an ocean plate beneath an ocean plate results in a volcanic island arc, an ocean trench and many earthquakes. (b) Japan is an arc-shaped island arc composed of volcanoes off the Asian mainland, as seen in this satellite image.

Check out this animation of an ocean continent plate boundary.

Continent-Continent

Continental plates are too buoyant to subduct. What happens to continental material when it collides? Since it has nowhere to go but up, this creates some of the world's largest mountains ranges (figure 11). Magma cannot penetrate this thick crust so there are no volcanoes, although the magma stays in the crust. Metamorphic rocks are common because of the stress the continental crust experiences. With enormous slabs of crust smashing together, continent-continent collisions bring on numerous and large earthquakes.

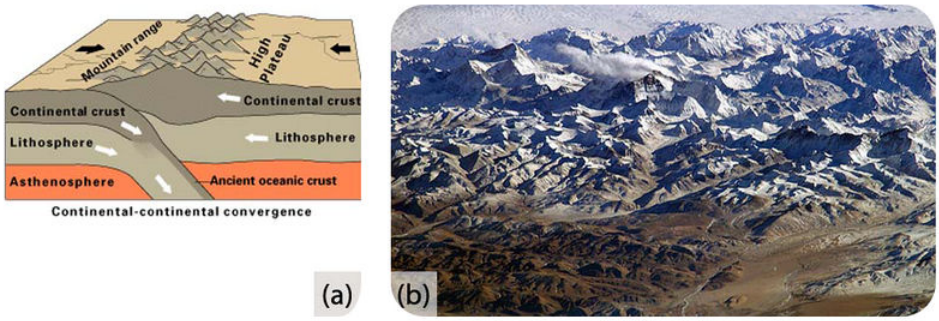
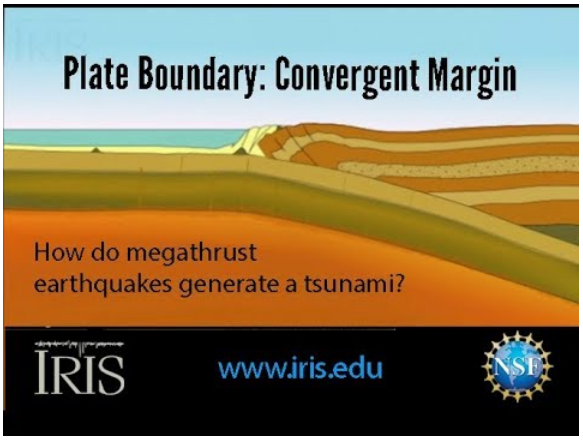


Figure 11. (a) In continent-continent convergence, the plates push upward to create a high mountain range. (b) The world's highest mountains, the Himalayas, are the result of the collision of the Indian Plate with the Eurasian Plate, seen in this photo from the International Space Station.

Check out this short animation of the Indian Plate colliding with the Eurasian Plate.

Watch this animation of the Himalaya rising.



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=196

The Appalachian Mountains are the remnants of a large mountain range that was created when North America rammed into Eurasia about 250 million years ago.

Transform Plate Boundaries

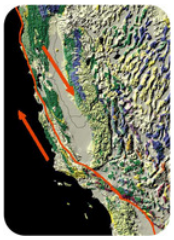


Figure 12. At the San Andreas Fault in California, the Pacific Plate is sliding northwest relative to the North American plate, which is moving southeast. At the northern end of the picture, the transform boundary turns into a subduction zone.

Transform plate boundaries are seen as **transform faults**, where two plates move past each other in opposite directions. Transform faults on continents bring massive earthquakes (figure 12).

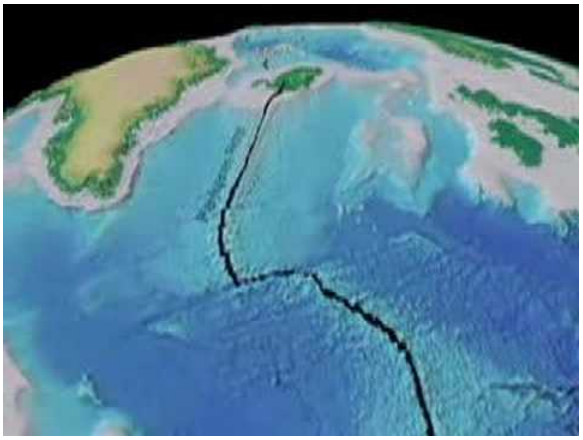
California is very geologically active. What are the three major plate boundaries in or near California (figure 13)?

1. A transform plate boundary between the Pacific and North American plates creates the San Andreas Fault, the world's most notorious transform fault.
2. Just offshore, a divergent plate boundary, Juan de Fuca ridge, creates the Juan de Fuca plate.
3. A convergent plate boundary between the Juan de Fuca oceanic plate and the North American continental plate creates the Cascades volcanoes.



Figure 13. This map shows the three major plate boundaries in or near California.

A brief review of the three types of plate boundaries and the structures that are found there is the subject of this wordless video.



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=196

Earth's Changing Surface

Geologists know that Wegener was right because the movements of continents explain so much about the geology we see. Most of the geologic activity that we see on the planet today is because of the interactions of the moving plates.

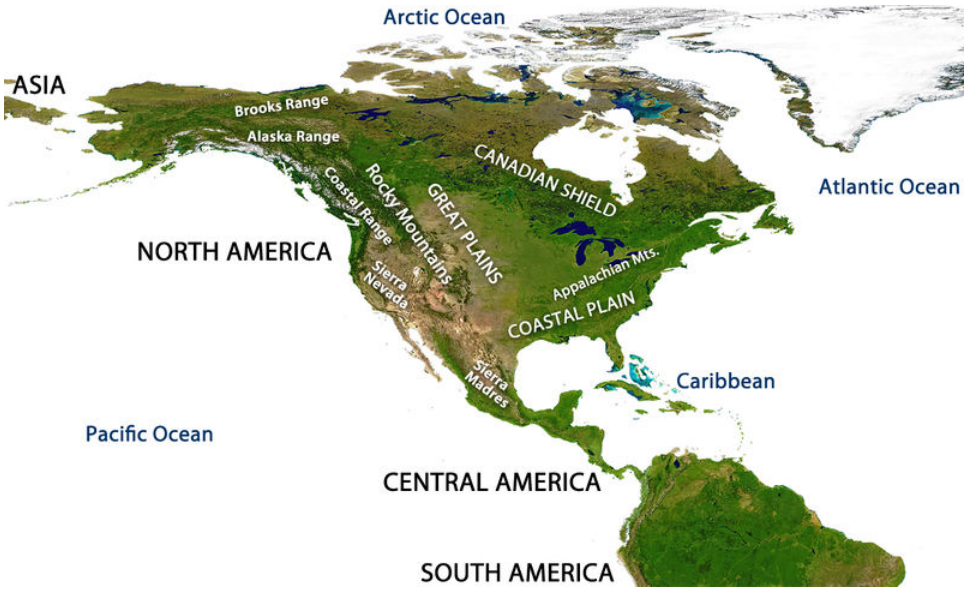


Figure 14. Mountain ranges of North America.

In the map of North America (figure 14), where are the mountain ranges located? Using what you have learned about plate tectonics, try to answer the following questions:

1. What is the geologic origin of the Cascades Range? The Cascades are a chain of volcanoes in the Pacific Northwest. They are not labelled on the diagram but they lie between the Sierra Nevada and the Coastal Range.
2. What is the geologic origin of the Sierra Nevada? (Hint: These mountains are made of granitic intrusions.)
3. What is the geologic origin of the Appalachian Mountains along the Eastern US?



Figure 15. About 200 million years ago, the Appalachian Mountains of eastern North America were probably once as high as the Himalaya, but they have been weathered and eroded significantly since the breakup of Pangaea.

Remember that Wegener used the similarity of the mountains on the west and east sides of the Atlantic as evidence for his continental drift hypothesis. The Appalachian mountains formed at a convergent plate boundary as Pangaea came together (figure 15).

Before Pangaea came together, the continents were separated by an ocean where the Atlantic is now. The proto-Atlantic ocean shrank as the Pacific ocean grew. Currently, the Pacific is shrinking as the Atlantic is growing. This **supercontinent cycle** is responsible for most of the geologic features that we see and many more that are long gone (figure 16).

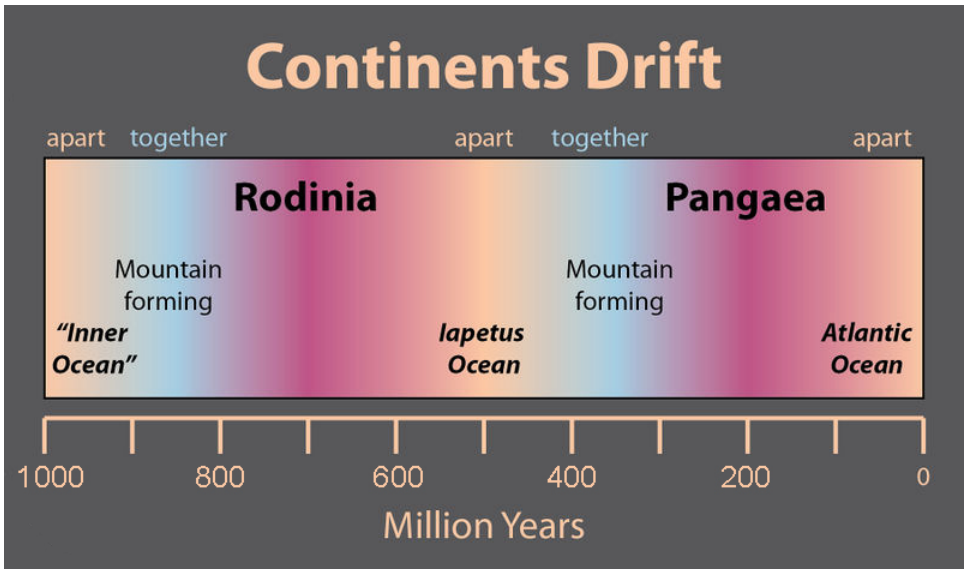


Figure 16. Scientists think that the creation and breakup of a supercontinent takes place about every 500 million years. The supercontinent before Pangaea was Rodinia. A new continent will form as the Pacific ocean disappears.

This animation shows the movement of continents over the past 600 million years beginning with the breakup of Rodinia.

Lesson Summary

- Plates of lithosphere move because of convection currents in the mantle. One type of motion is produced by seafloor spreading.
- Plate boundaries can be located by outlining earthquake epicenters.
- Plates interact at three types of plate boundaries: divergent, convergent and transform.
- Most of the Earth's geologic activity takes place at plate boundaries.
- At a divergent boundary, volcanic activity produces a mid ocean ridge and small earthquakes.
- At a convergent boundary with at least one oceanic plate, an ocean trench, a chain of volcanoes develops and many earthquakes occur.
- At a convergent boundary where both plates are continental, mountain ranges grow and earthquakes are common.
- At a transform boundary, there is a transform fault and massive earthquakes occur but there are no volcanoes.
- Processes acting over long periods of time create Earth's geographic features.

Contributors and Attributions

CC licensed content, Shared previously

- 6.4: Theory of Plate Tectonics. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/6.4/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 5.7: Reading- Theory of Plate Tectonics is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.8: Reading- Developing the Theory

In line with other previous and contemporaneous proposals, in 1912 the meteorologist Alfred Wegener amply described what he called continental drift, expanded in his 1915 book *The Origin of Continents and Oceans*[1], and the scientific debate started that would end up fifty years later in the theory of plate tectonics.[2] Starting from the idea (also expressed by his forerunners) that the present continents once formed a single land mass (which was called Pangea later on) that drifted apart, thus releasing the continents from the Earth's mantle and likening them to "icebergs" of low density granite floating on a sea of denser basalt.[3]

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

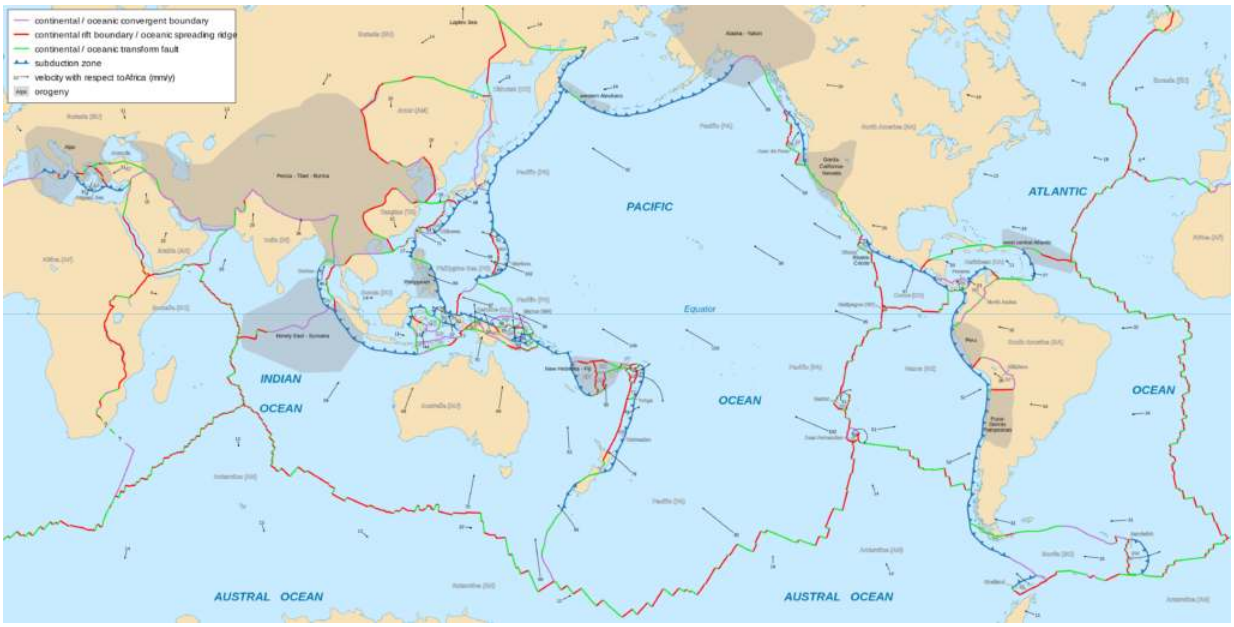


Figure 1. Detailed map showing the tectonic plates with their movement vectors. (Click on the image to open a larger version of the map.)

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

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

One of the first pieces of geophysical evidence that was used to support the movement of lithospheric plates came from paleomagnetism. This is based on the fact that rocks of different ages show a variable magnetic field direction, evidenced by studies since the mid–nineteenth century. The magnetic north and south poles reverse through time, and, especially important in paleotectonic studies, the relative position of the magnetic north pole varies through time. Initially, during the first half of the twentieth century, the latter phenomenon was explained by introducing what was called "polar wander" (see apparent polar wander), i.e., it was assumed that the north pole location had been shifting through time. An alternative explanation, though, was that the continents had moved (shifted and rotated) relative to the north pole, and each continent, in fact, shows its own "polar

wander path". During the late 1950s it was successfully shown on two occasions that these data could show the validity of continental drift: by Keith Runcorn in a paper in 1956,[4] and by Warren Carey in a symposium held in March 1956.[5]

The second piece of evidence in support of continental drift came during the late 1950s and early 60s from data on the bathymetry of the deep ocean floors and the nature of the oceanic crust such as magnetic properties and, more generally, with the development of marine geology which gave evidence for the association of seafloor spreading along the mid-oceanic ridges and magnetic field reversals, published between 1959 and 1963 by Heezen, Dietz, Hess, Mason, Vine & Matthews, and Morley.[6]

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

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

Continental Drift



Figure 2. Alfred Wegener in Greenland in the winter of 1912-13.

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

It was observed as early as 1596 that the opposite coasts of the Atlantic Ocean—or, more precisely, the edges of the continental shelves—have similar shapes and seem to have once fitted together.[7]

Since that time many theories were proposed to explain this apparent complementarity, but the assumption of a solid Earth made these various proposals difficult to accept.[8]

The discovery of radioactivity and its associated heating properties in 1895 prompted a re-examination of the apparent age of the Earth.[9] This had previously been estimated by its cooling rate and assumption the Earth's surface radiated like a black body.[10] Those calculations had implied that, even if it started at red heat, the Earth would have dropped to its present temperature in a few tens of millions of years. Armed with the knowledge of a new heat source, scientists realized that the Earth would be much older, and that its core was still sufficiently hot to be liquid.

By 1915, after having published a first article in 1912,[11] Alfred Wegener was making serious arguments for the idea of continental drift in the first edition of *The Origin of Continents and Oceans*.[12] In that book (re-issued in four successive editions up to the final one in 1936), he noted how the east coast of South America and the west coast of Africa looked as if they were once attached. Wegener was not the first to note this (Abraham Ortelius, Antonio Snider-Pellegrini, Eduard Suess, Roberto Mantovani and Frank Bursley Taylor preceded him just to mention a few), but he was the first to marshal significant fossil and paleo-topographical and climatological evidence to support this simple observation (and was supported in this by researchers such as Alex du Toit). Furthermore, when the rock strata of the margins of separate continents are very similar it suggests that these rocks were formed in

the same way, implying that they were joined initially. For instance, parts of Scotland and Ireland contain rocks very similar to those found in Newfoundland and New Brunswick. Furthermore, the Caledonian Mountains of Europe and parts of the Appalachian Mountainsof North America are very similar in structure and lithology.

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

Floating Continents, Paleomagnetism, and Seismicity Zones

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

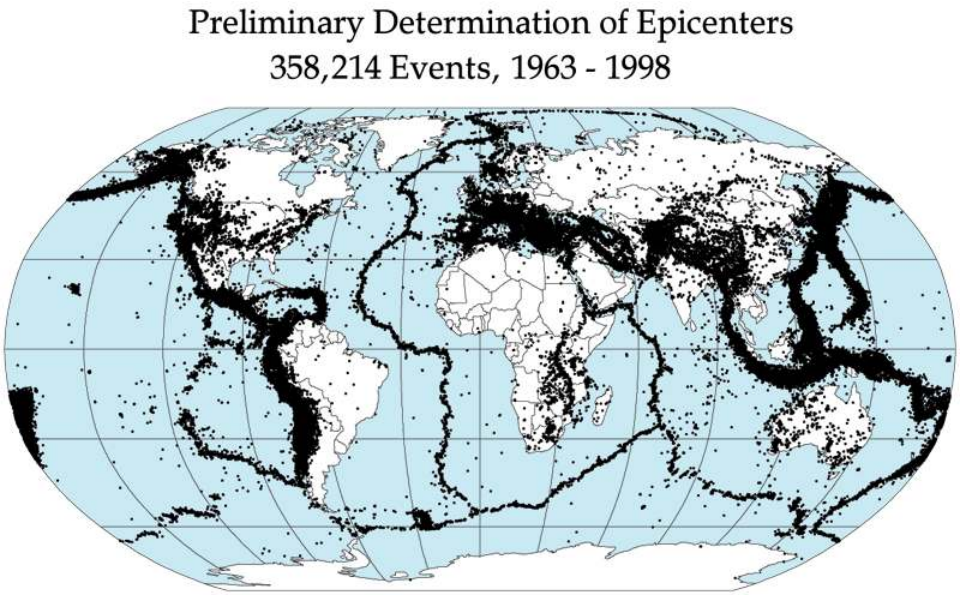


Figure 3. Global earthquake epicenters, 1963–1998

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

During the 20th century, improvements in and greater use of seismic instruments such as seismographs enabled scientists to learn that earthquakes tend to be concentrated in specific areas, most notably along the oceanic trenches and spreading ridges. By the late 1920s, seismologists were beginning to identify several prominent earthquake zones parallel to the trenches that typically were inclined 40–60° from the horizontal and extended several hundred kilometers into the Earth. These zones later became known as Wadati-Benioff zones, or simply Benioff zones, in honor of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of the United States. The study of global seismicity greatly advanced in the 1960s with the establishment of the Worldwide Standardized Seismograph Network (WWSSN)[13] to monitor the compliance of the 1963 treaty banning above-ground testing of nuclear weapons. The much improved data from the WWSSN instruments allowed seismologists to map precisely the zones of earthquake concentration worldwide.

Meanwhile, debates developed around the phenomena of polar wander. Since the early debates of continental drift, scientists had discussed and used evidence that polar drift had occurred because continents seemed to have moved through different climatic zones during the past. Furthermore, paleomagnetic data had shown that the magnetic pole had also shifted during time. Reasoning

in an opposite way, the continents might have shifted and rotated, while the pole remained relatively fixed. The first time the evidence of magnetic polar wander was used to support the movements of continents was in a paper by Keith Runcorn in 1956,[14] and successive papers by him and his students Ted Irving (who was actually the first to be convinced of the fact that paleomagnetism supported continental drift) and Ken Creer.

This was immediately followed by a symposium in Tasmania in March 1956.[15] In this symposium, the evidence was used in the theory of an expansion of the global crust. In this hypothesis the shifting of the continents can be simply explained by a large increase in size of the Earth since its formation. However, this was unsatisfactory because its supporters could offer no convincing mechanism to produce a significant expansion of the Earth. Certainly there is no evidence that the moon has expanded in the past 3 billion years; other work would soon show that the evidence was equally in support of continental drift on a globe with a stable radius.

During the thirties up to the late fifties, works by Vening-Meinesz, Holmes, Umbgrove, and numerous others outlined concepts that were close or nearly identical to modern plate tectonics theory. In particular, the English geologist Arthur Holmes proposed in 1920 that plate junctions might lie beneath the sea, and in 1928 that convection currents within the mantle might be the driving force.[16] Often, these contributions are forgotten because:

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

Mid-Oceanic Ridge Spreading and Convection

In 1947, a team of scientists led by Maurice Ewing utilizing the Woods Hole Oceanographic Institution's research vessel *Atlantis* and an array of instruments, confirmed the existence of a rise in the central Atlantic Ocean, and found that the floor of the seabed beneath the layer of sediments consisted of basalt, not the granite which is the main constituent of continents. They also found that the oceanic crust was much thinner than continental crust. All these new findings raised important and intriguing questions.[17]

The new data that had been collected on the ocean basins also showed particular characteristics regarding the bathymetry. One of the major outcomes of these datasets was that all along the globe, a system of mid-oceanic ridges was detected. An important conclusion was that along this system, new ocean floor was being created, which led to the concept of the "Great Global Rift." This was described in the crucial paper of Bruce Heezen (1960),[18] which would trigger a real revolution in thinking. A profound consequence of seafloor spreading is that new crust was, and still is, being continually created along the oceanic ridges. Therefore, Heezen advocated the so-called "expanding Earth" hypothesis of S. Warren Carey (see above). So, still the question remained: how can new crust be continuously added along the oceanic ridges without increasing the size of the Earth? In reality, this question had been solved already by numerous scientists during the forties and the fifties, like Arthur Holmes, Vening-Meinesz, Coates and many others: The crust in excess disappeared along what were called the oceanic trenches, where so-called "subduction" occurred. Therefore, when various scientists during the early sixties started to reason on the data at their disposal regarding the ocean floor, the pieces of the theory quickly fell into place.

The question particularly intrigued Harry Hammond Hess, a Princeton University geologist and a Naval Reserve Rear Admiral, and Robert S. Dietz, a scientist with the U.S. Coast and Geodetic Survey who first coined the term *seafloor spreading*. Dietz and Hess (the former published the same idea one year earlier in *Nature*,[19] but priority belongs to Hess who had already distributed an unpublished manuscript of his 1962 article by 1960)[20] were among the small handful who really understood the broad implications of sea floor spreading and how it would eventually agree with the, at that time, unconventional and unaccepted ideas of continental drift and the elegant and mobilistic models proposed by previous workers like Holmes.

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

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

Magnetic Striping

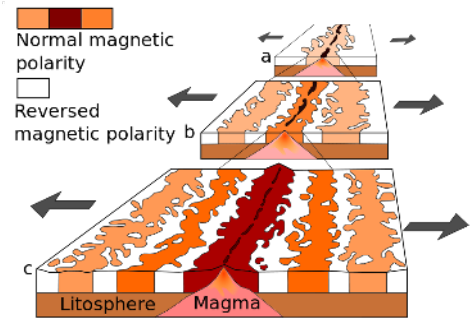


Figure 4. Seafloor magnetic striping.

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

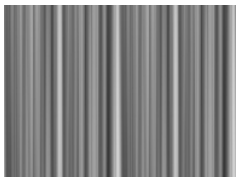


Figure 5. A demonstration of magnetic striping. (The darker the color is, the closer it is to normal polarity)

As more and more of the seafloor was mapped during the 1950s, the magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns. When these magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern: one stripe with normal polarity and the adjoining stripe with reversed polarity. The overall pattern, defined by these alternating bands of normally and reversely polarized rock, became known as magnetic striping, and was published by Ron G. Mason and co-workers in 1961, who did not find, though, an explanation for these data in terms of sea floor spreading, like Vine, Matthews and Morley a few years later.[21]

The discovery of magnetic striping called for an explanation. In the early 1960s scientists such as Heezen, Hess and Dietz had begun to theorise that mid-ocean ridges mark structurally weak zones where the ocean floor was being ripped in two lengthwise along the ridge crest (see the previous paragraph). New magma from deep within the Earth rises easily through these weak zones

and eventually erupts along the crest of the ridges to create new oceanic crust. This process, at first denominated the “conveyer belt hypothesis” and later called seafloor spreading, operating over many millions of years continues to form new ocean floor all across the 50,000 km-long system of mid-ocean ridges.

Only four years after the maps with the “zebra pattern” of magnetic stripes were published, the link between sea floor spreading and these patterns was correctly placed, independently byLawrence Morley, and by Fred Vine and Drummond Matthews, in 1963, [22] now called the Vine-Matthews-Morley hypothesis. This hypothesis linked these patterns to geomagnetic reversals and was supported by several lines of evidence:[23]

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

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

Definition and Refining of the Theory

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

- In 1965, Tuzo Wilson who had been a promotor of the sea floor spreading hypothesis and continental drift from the very beginning[24] added the concept of transform faults to the model, completing the classes of fault types necessary to make the mobility of the plates on the globe work out.[25]
- A symposium on continental drift was held at the Royal Society of London in 1965 which must be regarded as the official start of the acceptance of plate tectonics by the scientific community, and which abstracts are issued as Blacket, Bullard & Runcorn (1965). In this symposium, Edward Bullard and co-workers showed with a computer calculation how the continents along both sides of the Atlantic would best fit to close the ocean, which became known as the famous “Bullard’s Fit”.
- In 1966 Wilson published the paper that referred to previous plate tectonic reconstructions, introducing the concept of what is now known as the “Wilson Cycle.”[26]
- In 1967, at the American Geophysical Union’s meeting, W. Jason Morgan proposed that the Earth’s surface consists of 12 rigid plates that move relative to each other.[27]
- Two months later, Xavier Le Pichon published a complete model based on 6 major plates with their relative motions, which marked the final acceptance by the scientific community of plate tectonics.[28]
- In the same year, McKenzie and Parker independently presented a model similar to Morgan’s using translations and rotations on a sphere to define the plate motions.[29]

---

1. Wegener, Alfred (1929). *Die Entstehung der Kontinente und Ozeane* (4 ed.). Braunschweig: Friedrich Vieweg & Sohn Akt. Ges. ↵
2. Hughes, Patrick (8 February 2001). "Alfred Wegener (1880–1930): A Geographic Jigsaw Puzzle." *On the shoulders of giants*. Earth Observatory, NASA. Retrieved 2007-12-26. ... on January 6, 1912, Wegener... proposed instead a grand vision of drifting continents and widening seas to explain the evolution of Earth's geography. ↵
3. Wegener, Alfred (1966). *The origin of continents and oceans*. Biram John (translator). Courier Dover. p. 246; Hughes, Patrick (8 February 2001). "Alfred Wegener (1880-1930): The origin of continents and oceans." On the Shoulders of Giants. Earth Observatory, NASA. Retrieved 2007-12-26. "By his third edition (1922), Wegener was citing geological evidence that some

300 million years ago all the continents had been joined in a supercontinent stretching from pole to pole. He called it Pangaea (all lands),..." ↵
4. Runcorn, S.K. (1956). "Paleomagnetic comparisons between Europe and North America". *Proceedings, Geological Association of Canada***8** (1088): 7785. ↵
5. Carey, S. W. (1958). "The tectonic approach to continental drift." In Carey, S.W. *Continental Drift—A symposium, held in March 1956*. Hobart: Univ. of Tasmania. pp. 177–363. Expanding Earth from p. 311 to p. 349. ↵
6. Korgen, Ben J. (1995). "A voice from the past: John Lyman and the plate tectonics story" (PDF). Oceanography (The Oceanography Society) **8** (1): 19–20; Spiess, Fred; Kuperman, William (2003). "The Marine Physical Laboratory at Scripps" (PDF). *Oceanography* (The Oceanography Society) **16** (3): 45–54. ↵
7. Kious, W. Jacquelyne; Tilling, Robert I. (February 2001) [1996]. "Historical perspective." *This Dynamic Earth: the Story of Plate Tectonics* (Online ed.). U.S. Geological Survey. Retrieved 2008-01-29. "Abraham Ortelius in his work Thesaurus Geographicus... suggested that the Americas were 'torn away from Europe and Africa . . . by earthquakes and floods. . . . The vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three [continents].'" ↵
8. Frankel, H. (1987). "The Continental Drift Debate." In H.T. Engelhardt Jr and A.L. Caplan. *Scientific Controversies: Case Solutions in the resolution and closure of disputes in science and technology*. Cambridge University Press. ↵
9. Joly, John (1909). *Radioactivity and Geology: An Account of the Influence of Radioactive Energy on Terrestrial History*. London: Archibald Constable. p. 36. ↵
10. Thomson, W (1863). "On the secular cooling of the earth." Philosophical Magazine 4 (25): 1–14 (inactive 2015-01-09). ↵
11. Wegener, Alfred (6 January 1912). "Die Herausbildung der Grossformen der Erdrinde (Kontinente und Ozeane), auf geophysikalischer Grundlage" (PDF). *Petermanns Geographische Mitteilungen***63**: 185–195, 253–256, 305–309. ↵
12. Wegener 1929. ↵
13. Stein, Seth; Wysession, Michael (2009). *An Introduction to Seismology, Earthquakes, and Earth Structure*. Chichester: John Wiley & Sons. ↵
14. Runcorn, 1956 ↵
15. Carey, S. W. (1958). "The tectonic approach to continental drift". In Carey, S.W. *Continental Drift—A symposium, held in March 1956*. Hobart: Univ. of Tasmania. pp. 177–363. Expanding Earth from p. 311 to p. 349; see also Quilty, Patrick G.; Banks, Maxwell R. (2003). "Samuel Warren Carey, 1911–2002." *Biographical memoirs*. Australian Academy of Science. Retrieved 2010-06-19. This memoir was originally published in *Historical Records of Australian Science* (2003) **14** (3). ↵
16. Holmes, Arthur (1928). "Radioactivity and Earth movements." *Transactions of the Geological Society of Glasgow***18**: 559–606; see also Holmes, Arthur (1978). *Principles of Physical Geology* (3 ed.). Wiley. pp. 640–641; Frankel, Henry (July 1978). "Arthur Holmes and continental drift." *The British Journal for the History of Science***11** (2): 130–150. doi: 10.1017/S0007087400016551. ↵
17. Lippsett, Laurence (2001). "Maurice Ewing and the Lamont-Doherty Earth Observatory." *Living Legacies*. Retrieved 2008-03-04; Lippsett, Laurence (2006). "Maurice Ewing and the Lamont-Doherty Earth Observatory". In William Theodore De Bary, Jerry Kisslinger and Tom Mathewson. *Living Legacies at Columbia*. Columbia University Press. pp. 277–297. ↵
18. Heezen, B. (1960). "The rift in the ocean floor." Scientific American 203 (4): 98–110. doi: 10.1038/scientificamerican1060-98. ↵
19. Dietz, Robert S. (June 1961). "Continent and Ocean Basin Evolution by Spreading of the Sea Floor". *Nature***190** (4779): 854–857. ↵
20. Hess, H. H. (November 1962). "History of Ocean Basins" (PDF). In A. E. J. Engel, Harold L. James, and B. F. Leonard. *Petrologic studies: a volume to honor of A. F. Buddington*. Boulder, CO: Geological Society of America. pp. 599–620. ↵
21. Mason, Ronald G.; Raff, Arthur D. (1961). "Magnetic survey off the west coast of the United States between 32°N latitude and 42°N latitude." *Bulletin of the Geological Society of America***72** (8): 1259–1266. ↵
22. Vine, F.J.; Matthews, D.H. (1963). "Magnetic anomalies over oceanic ridges." *Nature***199** (4897): 947–949. ↵
23. See summary in Heirtzler, James R.; Le Pichon, Xavier; Baron, J. Gregory (1966). "Magnetic anomalies over the Reykjanes Ridge." *Deep-Sea Research***13** (3): 427–432. ↵
24. Wilson, J.T. (8 June 1963). "Hypothesis on the Earth's behaviour." *Nature***198** (4884): 849–865. ↵
25. Wilson, J. Tuzo (July 1965). "A new class of faults and their bearing on continental drift." *Nature***207** (4995): 343–347. ↵
26. Wilson, J. Tuzo (13 August 1966). "Did the Atlantic close and then re-open?" *Nature***211** (5050): 676–681. ↵

27. Morgan, W. Jason (1968). "Rises, Trenches, Great Faults, and Crustal Blocks." *Journal of Geophysical Research* **73** (6): 1959–1982. ↵
28. Le Pichon, Xavier (15 June 1968). "Sea-floor spreading and continental drift." *Journal of Geophysical Research* **73** (12): 3661–3697. ↵
29. Mc Kenzie, D.; Parker, R.L. (1967). "The North Pacific: an example of tectonics on a sphere." *Nature* **216** (5122): 1276–1280. ↵

Contributors and Attributions

CC licensed content, Shared previously

- Plate tectonics. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Plate_tectonics#Development_of_the_theory. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 5.8: Reading- Developing the Theory is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.9: Self Check- The Theory of Plate Tectonics

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1094

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 5.9: Self Check- The Theory of Plate Tectonics is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.10: Outcome- Geological Processes

Describe different geological processes in relation to plate tectonics.

This section demonstrations the implications of plate tectonics. You will be introduced to various formations and features that are attributed to plate tectonics.

What You'll Learn to Do

- Describe the development of continents, continental rifting, and supercontinents.
- Describe the development volcanic arcs.
- Describe the formation of ocean basins.
- Interpret and explain hot spots and how they relate to plate motion.

Learning Activities

The learning activities for this section include the following:

- Reading: Supercontinents
- Reading: Volcanic Arcs
- Video: Ocean Basins
- Reading: Hot Spots
- Self Check: Geological Processes

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 5.10: Outcome- Geological Processes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.11: Reading- Supercontinents

Early Continents

The first crust was made of basaltic rock, like the current ocean crust. Partial melting of the lower portion of the basaltic crust began more than 4 billion years ago. This created the silica-rich crust that became the felsic continents.

Craton

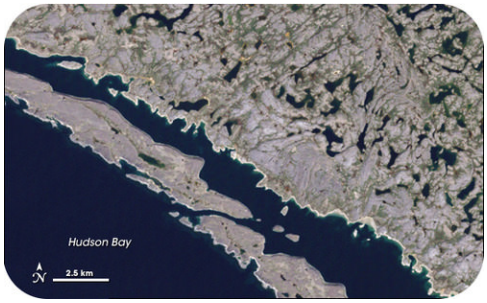


Figure 1. Ice age glaciers scraped the Canadian Shield down to the 4.28 billion year old greenstone in Northwestern Quebec.

The earliest felsic continental crust is now found in the ancient cores of continents, called the **cratons**. Rapid plate motions meant that cratons experienced many continental collisions. Little is known about the **paleogeography**, or the ancient geography, of the early planet, although smaller continents could have come together and broken up.

Geologists can learn many things about the Pre-Archean by studying the rocks of the cratons.

- Cratons also contain felsic igneous rocks, which are remnants of the first continents.
- Cratonic rocks contain rounded sedimentary grains. Of what importance is this fact? Rounded grains indicate that the minerals eroded from an earlier rock type and that rivers or seas also existed.
- One common rock type in the cratons is **greenstone**, a metamorphosed volcanic rock (Figure 1). Since greenstones are found today in oceanic trenches, what does the presence of greenstones mean? These ancient greenstones indicate the presence of subduction zones.

Shield

Places the craton crops out at the surface is known as a **shield**. Cratons date from the Precambrian and are called Precambrian shields. Many Precambrian shields are about 570 million years old (Figure 2).



Figure 2. The Canadian Shield is the ancient flat part of Canada that lies around Hudson Bay, the northern parts of Minnesota, Wisconsin and Michigan and much of Greenland.

Platform

In most places the cratons were covered by younger rocks, which together are called a **platform**. Sometimes the younger rocks eroded away to expose the Precambrian craton (Figure 3).



Figure 3. The Precambrian craton is exposed in the Grand Canyon where the Colorado River has cut through the younger sedimentary rocks.

Early Convection

During the Pre-Archean and Archean, Earth's interior was warmer than today. Mantle convection was faster and plate tectonics processes were more vigorous. Since subduction zones were more common, the early crustal plates were relatively small.

Since the time that it was completely molten, Earth has been cooling. Still, about half the internal heat that was generated when Earth formed remains in the planet and is the source of the heat in the core and mantle today.

The presence of water on ancient Earth is revealed in a zircon crystal:

A link to an interactive elements can be found at the bottom of this page.

Supercontinent Cycle

Look at Figure 4; is this Earth?

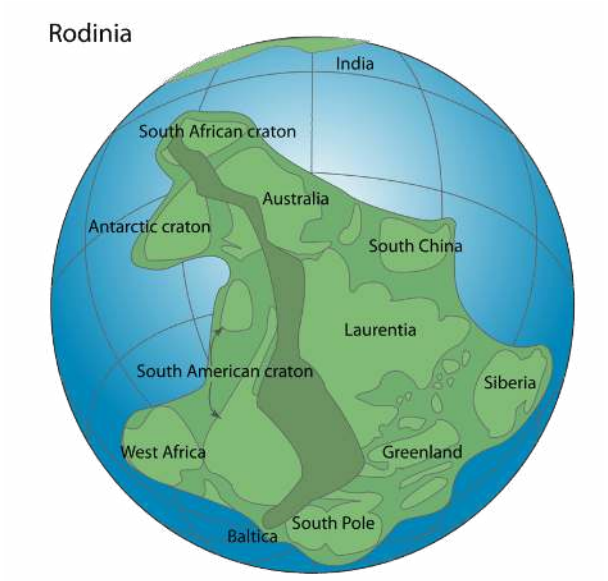


Figure 4. Rodinia

The existence of Wegener's supercontinent Pangaea is completely accepted by geologists today. The movements of continents explain so much about the geological activity we see. But did it all begin with Pangaea? Or were there other supercontinents that came before? What does the future of the continents hold?

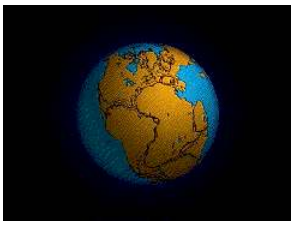


Figure 5. Pangea broke up to become our modern continents.

Wegener had lots of evidence for his continental drift hypothesis. One line of evidence was the similarity of the mountains on the west and east sides of the Atlantic. Those mountains rose at convergent plate boundaries. The continents on both sides of the ocean (where the Atlantic is now) smashed together to create Pangaea. The proto-Atlantic ocean shrank as the Pacific Ocean grew.

The Appalachian mountains of eastern North America formed at this convergent plate boundary (Figure 6a). About 200 million years ago, they were probably as high as the Himalayas.

Pangaea has been breaking apart since about 250 million years ago. Divergent plate boundaries formed within the continents to cause them to rift apart. The continents are still moving apart. The Pacific is shrinking as the Atlantic is growing. The Appalachians (Figure 6b) are now on a passive margin. The mighty mountains have weathered and eroded to what they are today.



Figure 6. (a) The Appalachian Mountains in New Hampshire. (b) The Appalachians along the eastern U.S. These mountains began when North America and Eurasia collided as Pangaea came together.

The Supercontinent Cycle

Back before Pangaea, there were earlier supercontinents. Rodinia existed 750 million to 1.1 billion years ago. Columbia existed 1.5 to 1.8 billion years ago. If the continents continue in their current directions, they will come together to create a supercontinent on the other side of the planet in around 200 million years.

This is known as the **supercontinent cycle**. The continents smash together on opposite side of the planet around every 500 million years. The creation of supercontinents is responsible for most of the geologic features that we see. It is responsible for many features that are long gone.

This animation shows the movement of continents over the past 600 million years, beginning with the breakup of Rodinia.

Summary

- The ancient core of a continent, at and beneath the surface, is its craton.
- The cratonic rock that is seen at the surface is called the shield. Where the shield is covered by younger sediments is the platform.
- Convection on early Earth was faster and so plate tectonics was faster. Since then, Earth has been cooling.
- Pangaea came together as a set of continent-continent convergent plate boundaries.
- Pangaea is still breaking up as the continents move apart. The Atlantic Ocean is getting bigger, and the Pacific Ocean is getting smaller.

- The continents come together and break apart about every 500 million years. This is called the supercontinent cycle.

Contributors and Attributions

CC licensed content, Shared previously

- Precambrian Continents. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Precambrian-Continents/lesson/Precambrian-Continents-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Supercontinent Cycle. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Supercontinent-Cycle/lesson/Supercontinent-Cycle-MS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

All rights reserved content

- Earth's First Rocks. **Authored by**: National Geographic. **Located at**: https://youtu.be/V21hFmZP5zM. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

Public domain content

- Pangea Breaks Up. **Provided by**: USGS. **Located at**: http://geomaps.wr.usgs.gov/parks/pltec/pangea.html. **License**: *Public Domain: No Known Copyright*

This page titled 5.11: Reading- Supercontinents is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.12: Reading- Volcanic Arcs

All subduction zones have, at some distance in from the edge of the upper plate, arcs or chains of composite cone volcanoes. The subducting plate, as it goes down deep into the mantle, releases water. This changes the chemistry of the already hot rocks in the mantle and causes them to melt, forming magma. The magma is less dense than the solid rocks around it, so it rises upward, culminating in volcanic eruptions at the earth's surface.

The volcanic arc at an ocean-continent subduction zone is not only a chain of volcanoes. The stress of plate convergence compresses the crust there, causing it to thicken through a combination of folds and thrust faults. Igneous intrusions and volcanic eruptions also thicken the crust there. Deep within the crust, the igneous intrusions solidify into batholiths of rocks such as granite, and the pre-existing rocks that are intruded by the batholiths are regionally metamorphosed into new rocks. The result is a high mountain range with granitic and metamorphic rock at its core, folded and faulted sedimentary and volcanic around its margins, and a chain of composite cone volcanoes distributed along the crest of the range.

Contributors and Attributions

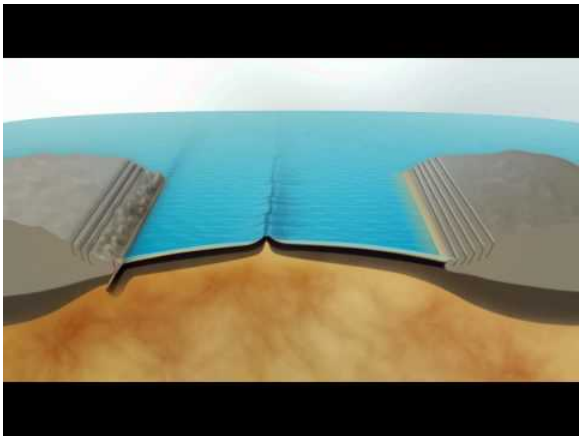
CC licensed content, Shared previously

- Basic -- Plate Tectonics. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/platetectonics.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 5.12: Reading- Volcanic Arcs is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.13: Video- Ocean Basins

This video provides an introduction to the Wilson cycle, a theory that describes the lifecycle of the ocean basin:



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=208

As you can see, it is very common for oceans to form and then disappear. Continental rifting plays a key role in the formation of an ocean. But how did the oceans form in the first place? Watch the following video for some current theories:

A link to an interactive elements can be found at the bottom of this page.

The low lying areas mentioned in the video are the ocean floors. Oceanic crust is basalt and continental crust is composed granite. Basalt is heavier so when they both rest on the top of the mantle, oceanic crust sinks lower forming a basin for the water to drain into.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

All rights reserved content

- Geology: Wilson Cycle. **Authored by**: mitartemis. **Located at**: https://youtu.be/I_q3sAcuzIY. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License
- Earth the Biography: Oceans. **Authored by**: National Geographic. **Located at**: https://youtu.be/hwVU0-2Qnso. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 5.13: Video- Ocean Basins is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.14: Reading- Hot Spots

In geology, the places known as **hotspots** or **hot spots** are volcanic regions thought to be fed by underlying mantle that is anomalously hot compared with the surrounding mantle. They may be on, near to, or far from tectonic plate boundaries. Currently, there are two hypotheses that attempt to explain their origins. One suggests that they are due to hot mantle plumes that rise as thermal diapirs from the core-mantle boundary. An alternative hypothesis postulates that it is not high temperature that causes the volcanism, but lithospheric extension that permits the passive rising of melt from shallow depths. This hypothesis considers the term “hotspot” to be a misnomer, asserting that the mantle source beneath them is, in fact, not anomalously hot at all. Well known examples include Hawaii and Yellowstone.

Background

The origins of the concept of hotspots lie in the work of J. Tuzo Wilson, who postulated in 1963 that the Hawaiian Islands result from the slow movement of a tectonic plate across a hot region beneath the surface. It was later postulated that hotspots are fed by narrow streams of hot mantle rising from the Earth’score-mantle boundary in a structure called amantle plume. Whether or not such mantle plumes exist is currently the subject of a major controversy in Earth science. Estimates for the number of hotspots postulated to be fed by mantle plumes has ranged from about 20 to several thousands, over the years, with most geologists considering a few tens to exist. Hawaii, Réunion, Yellowstone, Galápagos, and Iceland are some of the currently most active volcanic regions to which the hypothesis is applied.

Most hotspot volcanoes are basaltic (e.g., Hawaii, Tahiti). As a result, they are less explosive than subduction zone volcanoes, in which water is trapped under the overriding plate. Where hotspots occur in continental regions, basaltic magma rises through the continental crust, which melts to form rhyolites. These rhyolites can form violent eruptions. For example, the Yellowstone Caldera was formed by some of the most powerful volcanic explosions in geologic history. However, when the rhyolite is completely erupted, it may be followed by eruptions of basaltic magma rising through the same lithospheric fissures (cracks in the lithosphere). An example of this activity is the Ilgachuz Range in British Columbia, which was created by an early complex series of trachyte and rhyolite eruptions, and late extrusion of a sequence of basaltic lava flows.

The hotspot hypothesis is now closely linked to the mantle plume hypothesis.

Comparison with island arc volcanoes

Hotspot volcanoes are considered to have a fundamentally different origin from island arc volcanoes. The latter form over subduction zones, at converging plate boundaries. When one oceanic plate meets another, the denser plate is forced downward into a deep ocean trench. This plate, as it is subducted, releases water into the base of the over-riding plate, and this water mixes with the rock, thus changing its composition causing some rock to melt and rise. It is this that fuels a chain of volcanoes, such as the Aleutian Islands, near Alaska.

Hotspot volcanic chains

The joint mantle plume/hotspot hypothesis envisages the feeder structures to be fixed relative to one another, with the continents and seafloor drifting overhead. The hypothesis thus predicts that time-progressive chains of volcanoes are developed on the surface. Examples are Yellowstone, which lies at the end of a chain of extinct calderas, which become progressively older to the west. Another example is the Hawaiian archipelago, where islands become progressively older and more deeply eroded to the northwest.

Geologists have tried to use hotspot volcanic chains to track the movement of the Earth’s tectonic plates. This effort has been vexed by the lack of very long chains, by the fact that many are not time-progressive (e.g. the Galápagos) and by the fact that hotspots do not appear to be fixed relative to one another (e.g., Hawaii and Iceland.)



Figure 2. Kilauea is the most active shield volcano in the world. The volcano has erupted nonstop since 1983 and it is part of the Hawaiian-Emperor seamount chain.

- Hawaiian-Emperor seamount chain (Hawaii hotspot)
- Louisville seamount chain (Louisville hotspot)
- Walvis Ridge (Gough and Tristan hotspot)
- Kodiak–Bowie Seamount chain (Bowie hotspot)
- Cobb-Eickelberg Seamount chain (Cobb hotspot)
- New England Seamount chain (New England hotspot)
- Anahim Volcanic Belt (Anahim hotspot)
- Mackenzie dike swarm (Mackenzie hotspot)
- Great Meteor hotspot track (New England hotspot)
- St. Helena Seamount Chain – Cameroon Volcanic Line (Saint Helena hotspot)
- Southern Mascarene Plateau–Chagos-Maldives-Laccadive Ridge (Réunion hotspot)
- Ninety East Ridge (Kerguelen hotspot)
- Tuamotu–Line Island chain (Easter hotspot)
- Austral–Gilbert–Marshall chain (Macdonald hotspot)
- Juan Fernández Ridge (Juan Fernández hotspot)

Intraplate Activity

A small amount of geologic activity, known as **intraplate activity**, does not take place at plate boundaries but within a plate instead. Mantle plumes are pipes of hot rock that rise through the mantle. The release of pressure causes melting near the surface to form a **hotspot**. Eruptions at the hotspot create a volcano. Hotspot volcanoes are found in a line (figure 3). Can you figure out why? Hint: The youngest volcano sits above the hotspot and volcanoes become older with distance from the hotspot.

Here is an animation of the creation of a hotspot chain.

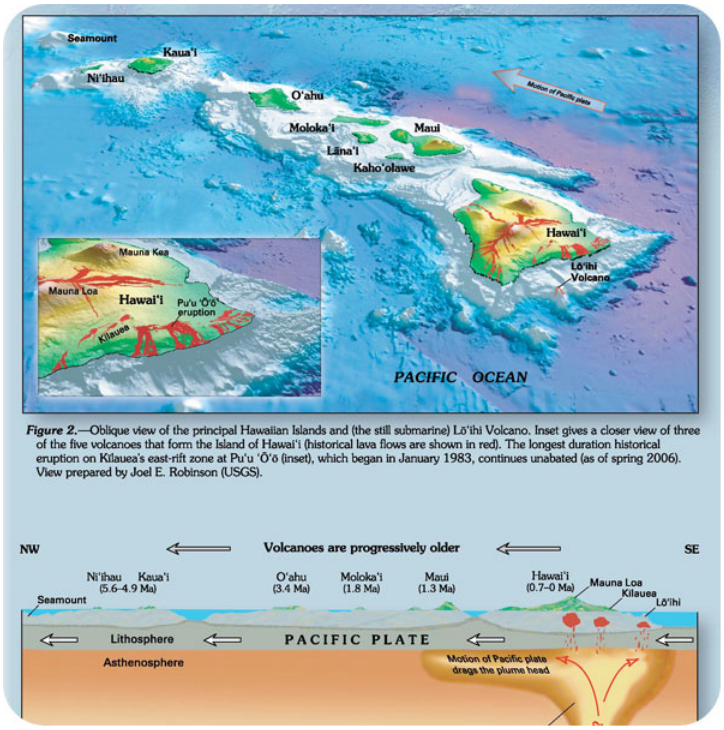


Figure 3. The Hawaiian Islands are a beautiful example of a hotspot chain. Kilauea volcano lies above the Hawaiian hotspot. Mauna Loa volcano is older than Kilauea and is still erupting, but at a lower rate. The islands get progressively older to the northwest because they are further from the hotspot. Loihi, the youngest volcano, is still below the sea surface.

Geologists use some hotspot chains to tell the direction and the speed a plate is moving (figure 4).

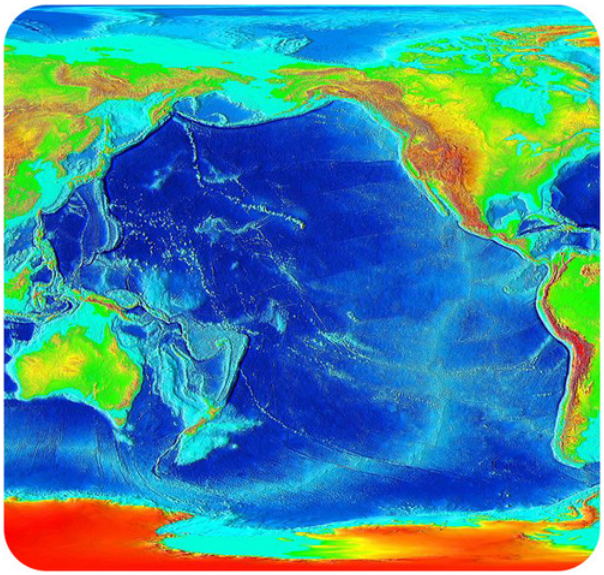


Figure 4. The Hawaiian chain continues into the Emperor Seamounts. The bend in the chain was caused by a change in the direction of the Pacific plate 43 million years ago. Using the age and distance of the bend, geologists can figure out the speed of the Pacific plate over the hotspot.

Hotspot magmas rarely penetrate through thick continental crust. One exception is the Yellowstone hotspot (figure 5).



Figure 5. Volcanic activity above the Yellowstone hotspot on the North American Plate can be traced from 15 million years ago to its present location.

Contributors and Attributions

CC licensed content, Original

- Revision and adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Hotspot (geology). **Provided by**: Wikipeida. **Located at**: http://en.Wikipedia.org/wiki/Hotspot_%28geology%29. **License**: *CC BY-SA: Attribution-ShareAlike*
- Theory of Plate Tectonics. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/6.4/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 5.14: Reading- Hot Spots is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.15: Self Check- Geological Processes

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1095

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 5.15: Self Check- Geological Processes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.16: Putting It Together- Plate Tectonics

As you have seen, this section is absolutely essential to understanding how the Earth works, why it looks the way it does, what processes have shaped and continue to shape the Earth, and the impact it has on us today. Everything from various geologic hazards such as volcanoes, landslides, and earthquakes can be explained—at least in part—by plate tectonics. You should now be able to look back at the questions asked at the beginning of this section and understand how plate tectonics has contributed to our understanding. In fact, it is very difficult to think of an area or topic in geology that has not been influenced by plate tectonics.

Plate Tectonics will be the base that the rest of the course is built on. This theory has impacts on each of the following:

- rock formations, geologic environments, mineral resources
- landforms, mountain building processes
- folds, faults, and earthquakes
- volcanoes and their eruptions

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 5.16: Putting It Together- Plate Tectonics is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

5.17: Assignment- Plate Tectonics

Plate tectonics is a unifying framework for understanding the dynamic geology of the Earth. The theory posits that the outermost layers of the Earth (the crust and uppermost mantle) make up the brittle lithosphere of the Earth. The lithosphere is broken up into a number of thin plates, which move on top of the asthenosphere (middle mantle). The asthenosphere is solid, but flows plastically over geologic time scales.

This assessment guides you through an examination of patterns on Earth—the topography of the earth's surface above sea level and the distribution of earthquakes and volcanic rock ages. You'll then use geologic data to determine long-term average plate motions.

To do this, you'll use the program Google Earth, and Google Earth layers compiled from various sources. Please answer EACH questions, they are divided by subsections. Remember to access the tips and hints at the bottom of the page.

Getting started with Google Earth

On your computer, install the latest version of Google Earth

1. Once installed, open Google Earth, under the Tools/Options/3D View/ menu choose the "**Decimal Degrees**" and **Meters Kilometers**" options and makes sure the "**Show Terrain**" box is checked.
2. Open the View menu. Go ahead and experiment with the options, but in general you should just have the **Tool Bar**, **Side Bar** and **Status Bar** checked. Also on the View menu, hover over Navigation and you will see several options for the compass arrow and slide bars in the upper right corner of the Google Earth screen. "**Automatically**" is a good choice as it leaves a ghost of the image visible until you hover over it.
3. Load the **DynamicEarth.kmz** file into GE. You should be able to double-click on the filename and it will open within GE. Or, you can download the file onto your computer, and open it in GE by using File/Open and navigating to the file. The original file info comes from https://serc.carleton.edu/sp/library/google_earth/examples/49004.html
4. Once the DynamicEarth.kmz is loaded, click and drag to move it from "Temporary Places" to "My Places." Then save "My Places" by clicking File/Save/Save My Places. DynamicEarth.kmz will now be available every time you open GE on this particular computer. When you exit, GE should save "My Places" for the next time.
5. ***But you should manually save "My Places" whenever you make significant changes to it, as GE does not auto save during a session.***
6. With an active Internet connection, you now have an interactive view of the earth! Take some time to explore the Earth with Google Earth and figure out how the navigation works using the keyboard, your touch pad and your mouse. For example: Zoom in and out, move N, S, E, W, grab and spin the globe, etc. The resolution will change as you zoom. Clicking on the "N" of the navigation compass reorients the view so north is "up."
7. At top left, "search" (and fly to) any place of interest. Zoom in and click on the "street view" icon (orange stick figure under the compass at top right) to explore an area as if you were on foot
8. Zoom in to see individual buildings, roads, cars, etc. (Find the crew team and motorboat on Lake Carnegie)
9. Go 3D – zoom into a significant topographic feature (e.g. Mount Everest, the Grand Canyon, Niagara Falls). Hold the Shift key down and tilt the terrain using the Up/Down arrows to tilt the terrain, and spin the terrain using the Right/Left buttons. Do the same thing for topographic features on the ocean floor. Note that under Tools/Options/3D View you can increase the vertical exaggeration by up to 3x. This is useful to emphasize subtle features, but is pretty scary when you look at the Grand Canyon that way!
10. On the Google Earth tool bar, click the clock-with-an-arrow icon to explore historical imagery in an area of interest (views through time of the Princeton campus, for example)
11. By clicking and dragging, you can move things that you have found and want to save, from the "Search" menu into "My Places." You can also re-organize "My Places" by adding and deleting items, changing the order of things, making subfolders, etc.
12. Explore the built-in items under the Layers menu at bottom left, and Dynamic Earth layers in your Places menu.
13. Expand and contract the folders and subfolders, turn various items on and off, etc. For example, with the Dynamic Earth/**Volcanoes of the World** layer displayed, left-clicking on a volcano brings up an information box about it.

Basic Requirements (assignment criteria):

Seismic Patterns

1. Expand the “Seismicity” layer item and click “on” the “Twenty years of large earthquakes” layer to show the epicenters of large earthquakes (those with magnitudes ≥ 6.0) during a 20-year period.
2. Describe any patterns you see in the distribution of earthquake epicenters over the Earth’s surface. You will need to move around the Earth to explore the different locations—do they form lines, arcs, circles or clusters? Are patterns connected or disconnected?
3. The different colors refer to the depths of the earthquakes. What color are the shallowest earthquakes? The deepest?
4. Look closely at and around the Earth’s ridges (Mid-Ocean Ridge in middle Atlantic) and trenches (southeast Pacific). The earthquake depth patterns associated with these features are different.
5. Complete the chart below. Using the earthquake depths as evidence, is the Earth’s lithosphere thicker in the vicinity of ridges or in the vicinity of trenches? Justify your answer.

	In the vicinity of ridges. (Scan 1500km or so on either side)	In the vicinity of trenches. (Scan ~1500 or so km on either side)
Describe the depth or range of depths of earthquakes, and the distribution (symmetric or asymmetric?) Is there any pattern to the depth distribution?		

Volcanoes & Volcanic Patterns

Leaving the earthquake layer on, click on the “Volcanoes of the World” layer. Describe the relationship between the locations of most active volcanoes and locations of earthquakes. What types of volcanoes are typically found along plate boundaries as opposed to interplate volcanoes? What are some common hazards associated with volcanic eruptions?

Plate Boundaries

1. Unclick all the layers, and then click on the “plate boundary model” layer (click the box to show it and then click the + or arrow to expand the legend). This shows plate boundaries and the names of major plates.
2. Find the boundary between the African and South American plates
3. Where is this plate boundary, relative to the coastlines of Africa and South America?
4. Now click the other layers on and off so that you can see relationships between plate boundaries and these features. If you did not have the “plate boundary layer” available to you, how could you determine where this plate boundary was? Be sure to consider topography as well as the earthquake and volcano layers. List several ways and be specific.
5. What type of deformation is occurring as a result of this boundary, if any? What type of structures or features would you expect to see, be specific?
6. Travel westward across the South American plate to its boundary with the Nazca plate
7. Where is this plate boundary, relative to South America?
8. If you did not have the “plate boundary layer” available to you, how could you determine where this plate boundary was? List several ways and be specific.
9. What type of deformation is occurring as a result of this boundary, if any?
10. What type of structures or features would you expect to see, be specific?

Plate motion

1. Motion across the mid-Atlantic ridge: the South American plate vs. the African plate
2. How many years does each colored band represent? _____
3. On average, continental crust is 2 billion years old; the oldest rocks are 3.8 billion years old, and some of the grains in those rocks are even older.
4. What is the age of the oldest seafloor? _____

5. On average, which is oldest – the continents or the ocean basins? _____
6. Find the South American plate, the African plate, and the Mid-Atlantic Ridge that marks the boundary between them. What happens to the age of the seafloor as distance increases away from the Mid-Atlantic Ridge?
7. Is crust being created or destroyed at this plate boundary (and other spreading ridges)? _____
8. Is this plate boundary divergent, convergent, or transform? _____
9. Focus on the northern Atlantic Ocean, near the east coast of the US and the northwest coast of Africa. How long ago did the northern Atlantic Ocean begin to open up or start spreading? Describe your reasoning.
10. Did the northern Atlantic Ocean basin start opening at the same time as the southern Atlantic Ocean basin (the area between to the south end of South America and Southern Africa)? How much older or younger is the northern Atlantic basin than the southern Atlantic basin? Describe your reasoning.
11. Clear all layers except the "Seafloor Age" layer. From the Mid-Atlantic ridge, choose either the South American plate side or the African plate side. Click on "Tools" and then "Ruler" to click and measure the distance from the MOR of the various ages of the oceanic crust. Use Excel (or other resource) to make a graph of *cumulative* distance away from the plate boundary (y-axis) vs. age (x-axis). Format the graph appropriate with title, axes, etc. Have Excel fit a trend line/best fit line from your data. NOTE: each color corresponds to a different age. Use the legend or key provided by Google Earth to determine the age. Copy, save and add your graph to your responses under #26.
12. Describe the motion of your chosen plate relative to the Mid-Atlantic ridge, based on this seafloor age data—the direction of motion, the average speed (slope of the best fit line) and whether or not speed and direction has been constant over time.
13. Compare these results to independent data from the Tristan da Cunha Volcanic Island/Seamount chain on the African plate off the southwest coast of Africa as follows:
14. To access this data, expand the "Volcanic Chains" layer on GE, then expand the "Atlantic Ocean Chains" layer, and then click to display "Tristan da Cunha". You may need to click off Sea Floor age layer. They are green dots off the southwest coast of Africa.
15. These islands and seamounts are volcanic edifices built up on older seafloor, formed by eruption of magma from relatively stationary sources ("hot spots") underneath the moving plates. The numbers are the radiometric ages in millions of years of volcanic rocks collected from each island/seamount.
16. Does data from the Tristan da Cunha Volcanic Island/Seamount chain support the plate motion you deduced from the sea floor age data? Explain.
17. If you prefer you can choose to compare your results to data from the New England Seamount chain off the northeast coast of North America—these are on the North American plate on west side of the mid-Atlantic ridge. Does this data support the African plate motion deduced above? Explain. NOTE: You do NOT have to do both but you are free to do so for verification.
18. Apply what you have learned—the Pacific Plate
19. Turn your attention to the Pacific plate. Note that the Pacific Ocean is comprised of several plates; we want to focus on the very large Pacific plate (not the Nazca plate, or Cocos plate, or Philippine plate or other plates.) The Pacific plate is "born" underwater at the East Pacific rise, the spreading ridge west of South America. It is being destroyed at convergent boundaries around its northern, western, and southern boundaries. NOTE: No instructions are provided for using the different layers. You should be familiar with them by now. If needed you can go back and review.
20. Is the East Pacific Rise spreading faster or slower than the mid-Atlantic Ridge and how can you tell – without doing any calculations? Has the rate been constant over time?
21. Make and print out a graph (similar to what you did in question 24) for movement of the Pacific plate away from the East Pacific Rise. Remember to save it under #31.
22. Describe the motion of the Pacific plate relative to the East Pacific Rise, based on this seafloor age data – direction of motion, average speed and whether or not speed and direction has been constant over time.
23. Consider the Volcanic Chains in the Pacific Ocean (Hawaiian/Emperor, Louisville, and Easter Island). Do these data support the movement you deduce for the Pacific Plate? Explain.
24. What does the bend in the Hawaiian/Emperor chain indicate happened about 50 million years ago to the direction of Pacific plate movement?
25. Based on the evidence of plate motion, explain how supercontinents form and how they rift apart.

Crustal Deformation

This section requires some critical thinking as you will NOT be using Google Earth for this short section. Thinking back over this activity and what you have learned about plate tectonics and plate motion, consider other effects it has on the Earth. Include a brief discussion on the effects plate tectonics has on crustal deformation. Make sure you include stress, strain, folds, faults and any other features you can think of. Discuss the types of forces needed to create the features, the time it would take and so on.

Continental Drift versus Plate Tectonics

1. Describe the relationship between continental drift and plate tectonics.
2. What evidence was used to support continental drift?
3. What evidence was used to support plate tectonics?
4. Do you agree or disagree with the evidence cited above?

Boundaries

1. What are the three types of plate boundaries?
2. What are the key features associated with each boundary?

The Role of Plate Tectonics

1. Review the overall activity, what role does plate tectonics play in modern geology? (This includes everything from rock types to earthquakes and volcanoes to mountain building, climate change to evolution of life.)
2. Save your completed assessment, make sure you name is on the document and you have included the necessary charts and graphs.

Tips and Hints can be found here.

This assessment is adapted from “Using Google Earth to Explore Plate Tectonics” by Laurel Goodell, originally found here.

Contributors and Attributions

CC licensed content, Original

- Plate Tectonics Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 5.17: Assignment- Plate Tectonics is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

6: Earth’s Interior

Learning Objectives

Describe the Earth including the characteristics of the various layers; learn the implications of the different layers.

- Analyze and compare the properties, material, and layers within the Earth’s geosphere.
- Understand how we know about the Earth’s interior and its magnetism.

6.1: Why It Matters- Earth’s Interior
6.2: Outcome- Layers of the Geosphere
6.3: Reading- Characteristics of the Crust
6.4: Reading- Characteristics of the Mantle
6.5: Reading- Characteristics of the Inner and Outer Core
6.6: Reading- The Lithosphere and Asthenosphere
6.7: Self Check- Layers of the Geosphere
6.8: Outcome- Understanding the Earth’s Interior
6.9: Reading- Studying the Earth’s Interior
6.10: Self Check- Understanding the Earth’s Interior
6.11: Putting It Together- Earth’s Interior
6.12: Assignment- Earth’s Interior

This page titled 6: Earth’s Interior is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.1: Why It Matters- Earth's Interior

Describe the Earth including the characteristics of the various layers; learn the implications of the different layers.

Introduction

Geologists cannot see directly into the interior of the Earth. They have to rely on various techniques and methods to infer the appearance and physical characteristics of earth's interior. In this section, we will see how the Earth is structured, what the physical characteristics are, and just how this impacts us living on the Earth.

The Earth's interior is the basis for geology. If you recall from the Plate Tectonics section, earth exists as we see it today because of plate tectonics. We also learned how plate tectonics is important in the formation of rock, mountains, volcanoes and earthquakes. Studying the interior of the Earth helps learn about all of these and the processes that helped create the Earth and currently drive plate tectonics.

Please watch this short video and take a trip through the various layers of the Earth down to its core:



Learning Outcomes

- Analyze and compare the properties, material, and layers within the Earth's geosphere.
- Understand how we know about the Earth's interior and its magnetism.

Contributors and Attributions

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 6.1: Why It Matters- Earth's Interior is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.2: Outcome- Layers of the Geosphere

Analyze and compare the properties, material, and layers within the Earth's geosphere.

This section will focus on the Earth's interior: what it is made of, why and how there are different layers of the Earth and where is each layer located.

What You'll Learn to Do

- Understand the physical and chemical characteristics of the two types of crust
- Understand the physical and chemical characteristics of the mantle
- Understand the physical and chemical characteristics of both the inner and outer core
- Differentiate between the Lithosphere and the Asthenosphere

Learning Activities

The learning activities for this section include the following:

- Reading: Characteristics of the Crust
- Reading: Characteristics of the Mantle
- Reading: Characteristics of the Inner and Outer Core
- Reading: The Lithosphere and Asthenosphere
- Self Check: Layers of the Geosphere

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 6.2: Outcome- Layers of the Geosphere is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.3: Reading- Characteristics of the Crust

How does a loaf of bread resemble Earth?



A loaf of homemade bread could almost resemble Earth. The raised parts of the crust are the continents and the depressed parts are the oceans. The inside is gooier than the brittle exterior, but it's still solid. How is a loaf of bread not like Earth?

Earth's outer surface is its crust, a cold, thin, brittle outer shell made of rock. The crust is very thin relative to the radius of the planet. There are two very different types of crust, each with its own distinctive physical and chemical properties, which are summarized in Table 1.

Crust	Thickness	Density	Composition	Rock Types
Oceanic	5–12 km (3–8 mi)	3.0 g/cm^3	Mafic	Basalt and gabbro
Continental	Avg. 35 km (22 mi)	2.7 g/cm^3	Felsic	All types

Oceanic Crust



Figure 1. Gabbro from ocean crust

Oceanic crust is composed of mafic magma that erupts on the seafloor to create basalt lava flows or cools deeper down to create the intrusive igneous rock gabbro (Figure 1).

Sediments, primarily mud and the shells of tiny sea creatures, coat the seafloor. Sediment is thickest near the shore, where it comes off the continents in rivers and on wind currents.

The oceanic crust is relatively thin and lies above the mantle. The cross section of oceanic crust in Figure 2 shows the layers that grade from sediments at the top to extrusive basalt lava, to the sheeted dikes that feed lava to the surface, to deeper intrusive gabbro, and finally to the mantle.

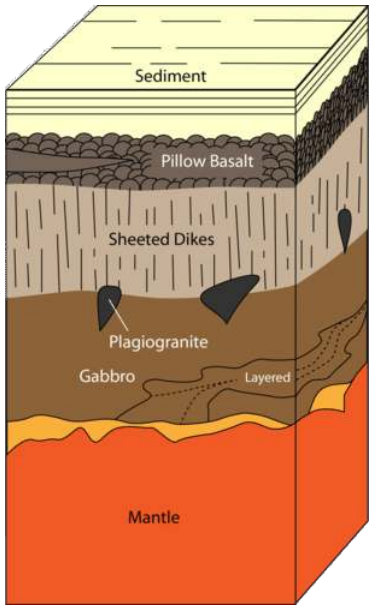


Figure 2. A cross-section of oceanic crust.

Continental Crust


Figure 3. This granite from Missouri is more than 1 billion years old.

Continental crust is made up of many different types of igneous, metamorphic, and sedimentary rocks. The average composition is granite, which is much less dense than the mafic rocks of the oceanic crust (Figure 3). Because it is thick and has relatively low density, continental crust rises higher on the mantle than oceanic crust, which sinks into the mantle to form basins. When filled with water, these basins form the planet's oceans.

Summary

- Oceanic crust is thinner and denser than continental crust.
- Oceanic crust is more mafic, continental crust is more felsic.
- Crust is very thin relative to Earth's radius.

Interactive Practice

Visit Annenberg Learner's *Dynamic Earth* and click on the crust to answer the questions below:

1. Describe the crust.
2. Where is the crust the thickest?

Contributors and Attributions

CC licensed content, Shared previously

- Earth's Crust. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Earths-Crust/lesson/Earths-Crust-HS-ES/?referrer=featured_content. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 6.3: Reading- Characteristics of the Crust is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.4: Reading- Characteristics of the Mantle

What is a diamond delivery system?



Some events happened when Earth was younger and hotter that do not happen any more. Kimberlite pipes shot up from deep in the mantle. These pipes are the most important source of diamonds, which form at very high pressure. Most kimberlites surfaced long ago.

The two most important things about the mantle are as follows:

1. It is made of semi-solid rock.
2. It is hot.

Solid Rock



Figure 1. Peridotite is formed of crystals of olivine (green) and pyroxene (black).

Scientists know that the mantle is made of rock based on evidence from seismic waves, heat flow, and meteorites. The properties fit the ultramafic rock peridotite, which is made of the iron- and magnesium-rich silicate minerals (Figure 1). Peridotite is rarely found at Earth's surface.

Heat Flow

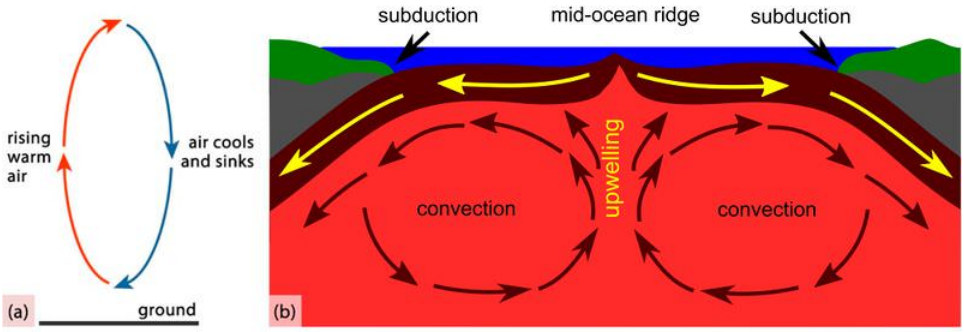
Scientists know that the mantle is extremely hot because of the heat flowing outward from it and because of its physical properties.

Heat flows in two different ways within the Earth:

1. **Conduction**: Heat is transferred through rapid collisions of atoms, which can only happen if the material is solid. Heat flows from warmer to cooler places until all are the same temperature. The mantle is hot mostly because of heat conducted from the core.
2. **Convection**: If a material is able to move, even if it moves very slowly, convection currents can form.

Convection in the mantle is the same as convection in a pot of water on a stove. Convection currents within Earth's mantle form as material near the core heats up. As the core heats the bottom layer of mantle material, particles move more rapidly, decreasing its density and causing it to rise. The rising material begins the convection current. When the warm material reaches the surface, it spreads horizontally. The material cools because it is no longer near the core. It eventually becomes cool and dense enough to sink

back down into the mantle. At the bottom of the mantle, the material travels horizontally and is heated by the core. It reaches the location where warm mantle material rises, and the mantle convection cell is complete (Figure 2).



In a convection cell, warm material rises and cool material sinks. In mantle convection, the heat source is the core.

Diagram of convection within Earth's mantle.

Figure 2. Convection

Contributors and Attributions

CC licensed content, Shared previously

- Earth's Mantle. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Earths-Mantle/lesson/Earths-Mantle-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 6.4: Reading- Characteristics of the Mantle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.5: Reading- Characteristics of the Inner and Outer Core

Do you want to take a journey to the center of the earth?



Jules Verne's imagined core was fiery. But we know that the outer core is molten metal, as seen above. As hot as a journey to Verne's center of the earth might have been, a visit to the real location would be worse.



Figure 1. An iron meteorite is the closest thing to the Earth's core that we can hold in our hands.

At the planet's center lies a dense metallic core. Scientists know that the core is metal because:

1. The density of Earth's surface layers is much less than the overall density of the planet, as calculated from the planet's rotation. If the surface layers are less dense than average, then the interior must be denser than average. Calculations indicate that the core is about 85% iron metal with nickel metal making up much of the remaining 15%.
2. Metallic meteorites are thought to be representative of the core. The 85% iron/15% nickel calculation above is also seen in metallic meteorites (Figure 1).

If Earth's core were not metal, the planet would not have a magnetic field. Metals such as iron are magnetic, but rock, which makes up the mantle and crust, is not.

Scientists know that the outer core is liquid and the inner core is solid because:

1. S-waves do not go through the outer core.
2. The strong magnetic field is caused by convection in the liquid outer core. Convection currents in the outer core are due to heat from the even hotter inner core.

The heat that keeps the outer core from solidifying is produced by the breakdown of radioactive elements in the inner core.

Explore More

Use this resource to answer the questions that follow.

A link to an interactive elements can be found at the bottom of this page.

1. What materials can P-waves travel through?

2. What materials can S-waves travel through?
3. How do we know the outer core is liquid?
4. What happens to P-waves when they go through a liquid?
5. What do P-waves tell about the inner core?

Contributors and Attributions

CC licensed content, Shared previously

- Earth's Core. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Earths-Core/lesson/Earths-Core-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

All rights reserved content

- INGE LEHMANN : How Inge Lehmann used Earthquakes to discover the Earthu2019s inner core. **Authored by**: Chandresh S. **Located at**: https://youtu.be/ELZ3B4flqNk. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 6.5: Reading- Characteristics of the Inner and Outer Core is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.6: Reading- The Lithosphere and Asthenosphere

Can you think of a solid that can flow?



You use one twice a day! Toothpaste is a solid that can flow. Is the asthenosphere made of toothpaste? Only if the toothpaste is ultramafic in composition, and then it would only be able to flow if it were really, really hot. Still the toothpaste analogy gives you a good image of how the asthenosphere might behave if you squeezed it!

Lithosphere

The lithosphere is composed of both the crust and the portion of the upper mantle that behaves as a brittle, rigid solid. The lithosphere is the outermost mechanical layer, which behaves as a brittle, rigid solid. The lithosphere is about 100 kilometers thick. How are crust and lithosphere different from each other?

The definition of the lithosphere is based on how Earth materials behave, so it includes the crust and the uppermost mantle, which are both brittle. Since it is rigid and brittle, when stresses act on the lithosphere, it breaks. This is what we experience as an earthquake.

Although we sometimes refer to Earth's plates as being plates of crust, the plates are actually made of lithosphere.

Asthenosphere

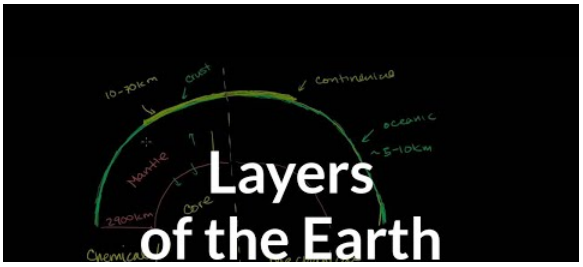
The asthenosphere is solid upper mantle material that is so hot that it behaves plastically and can flow. The lithosphere rides on the asthenosphere.

Summary

- The lithosphere is the brittle crust and uppermost mantle.
- The asthenosphere is a solid but it can flow, like toothpaste.
- The lithosphere rests on the asthenosphere.

Explore More

Watch this video to answer the questions that follow:





ion of the text. You can view it online here: http://pb.libretexts.org/geo/?p=230

a layer?

ayer? What are the two types of this layer and what are their main features?

ures?

4. What is the deepest layer? Why is this the densest layer?
5. What is the composition of this layer?
6. What is the lithosphere?
7. What are the mechanical properties of the material below the lithosphere and what is the layer called?
8. What is the composition and mechanical property of the mesosphere relative to the asthenosphere?

Contributors and Attributions

CC licensed content, Shared previously

- Lithosphere and Asthenosphere. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Lithosphere-and-Asthenosphere/lesson/Lithosphere-and-Asthenosphere-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Compositional and mechanical layers of the earth. **Authored by**: Sal Khan. **Provided by**: Khan Academy. **Located at**: https://www.khanacademy.org/science/cosmology-and-astronomy/earth-history-topic/plate-techtonics/v/compositional-and-mechanical-layers-of-the-earth. **License**: *CC BY-NC-SA: Attribution-NonCommercial-ShareAlike*

This page titled 6.6: Reading- The Lithosphere and Asthenosphere is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.7: Self Check- Layers of the Geosphere

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1098

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 6.7: Self Check- Layers of the Geosphere is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.8: Outcome- Understanding the Earth's Interior

Understand how we know about the Earth's interior and its magnetism.

This section extends the previous section by using models to understand the Earth's interior and its features.

What You'll Learn to Do

- Compare the different seismic waves and understand how seismic waves help interpret the Earth's interior.
- Understand what the Earth's magnetic field is and where it originates.

Learning Activities

The learning activities for this section include the following:

- Reading: Studying the Earth's Interior
- Self Check: Understanding the Earth's Interior

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 6.8: Outcome- Understanding the Earth's Interior is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.9: Reading- Studying the Earth's Interior

The following table summarizes the physical layers of the earth.

Physical Layers of Earth		
Layer	Physical Behavior	Thickness
Lithosphere	rigid, brittle at shallow depths	5–200 km
Asthenosphere	ductile	100–300 km
Upper Mesosphere	rigid, not brittle, rapid increase in density with depth	300–400 km
Lower Mesosphere	denser and more rigid than upper mesosphere	2,300 km
Outer Core	liquid	2,300 km
Inner Core	rigid, not brittle	1,200 km

Earth's Magnetic Field Originates in the Core

The liquid outer core is the source of the earth's magnetic field, as a result of its metallic nature, which means it contains electrons not attached to particular nuclei. Heat is transferred upward to the mantle from the inner core via convective cells, in which the liquid in the outer core flows in looping patterns. The combination of the loose electrons and looping convective flow with the rotation of the earth results in a geodynamo that produces a magnetic field. Because the magnetic field is generated by a dynamically convecting and rotating sphere of liquid, it is unstable. Every now and then, after several hundred thousand to several million years, the earth's magnetic field becomes unstable to the point that it temporarily shuts down. When it restarts, its north and south magnetic poles must inevitably be reversed, according to the physics of magnetic fields produced spontaneously from geodyamos. (For comparison, the magnetic field of the Sun, which is also produces by convecting electrical charges in a rotating sphere, becomes magnetically unstable and reverses its magnetic field on a more regular basis, every 11 years.)

Given that the inner core is a solid metallic sphere, made mostly of iron and nickel, surrounded entirely by liquid, it can be pictured as a giant ball bearing spinning in a pressurized fluid. Detailed studies of earthquake waves passing though the inner core have found evidence that it is spinning – rotating – just slightly faster than the rest of the earth.

Beyond Simple Layers

The interior of the earth is not simply layered. Some of the layers, particularly the crust and lithosphere, are highly variable in thickness. The boundaries between layers are rough and irregular. Some layers penetrate other layers at certain places. Variations in the thickness of the earth's layers, irregularities in layer boundaries, and interpenetrations of layers, reflect the dynamic nature of the earth.

For example, the lithosphere penetrates deep into the mesosphere at subduction zones. Although it is still a matter of research and debate, there is some evidence that subducted plates may penetrate all the way into the lower mesosphere. If so, plate tectonics is causing extensive mixing and exchange of matter in the earth, from the bottom of the mantle to the top of the crust.

As another example, hot spots may be places where gases and fluids rise from the core-mantle boundary, along with heat. Studies of helium isotopes in hot spot volcanic rocks find evidence that much of the helium comes from deep in the earth, probably from the lower mesosphere.

How Do We Know?

We humans have no hands-on access to samples of the earth's interior from deeper than the upper mantle. The earth's core is so dense and so deep, it is completely inaccessible. Contrary to a popular misconception, lava does not come from the earth's core. Magma and lava come from only the lithosphere and asthenosphere, the upper 200 km of earth's 6,400 km thickness. Attempts

have been made to drill through the crust to reach the mantle, without success. Given the lack of actual pieces of the earth from deeper than the asthenosphere, how do we know about the internal layers of the earth, what they are made of, and what their properties and processes are?

Igneous Rocks and Fault Blocks

There are two sources of rock samples from the lower lithosphere and asthenosphere, igneous rocks and fault blocks. Some igneous rocks contain xenoliths, pieces of solid rock that were adjacent to the body of magma, became incorporated into the magma, and were carried upward in the magma. From xenoliths in plutonic and volcanic igneous rocks, many samples of the lower crust and upper mantle have been identified and studied.

Another source of pieces of the lower crust and upper mantle is fault zones and exposed orogenic zones (root zones of mountains that have been exposed after much uplift and erosion). Some slabs of thrust-faulted rock contain lithospheric mantle rock. In ophiolites, ultramafic rock from the mantle part of the lithosphere is a defining attribute. Most ophiolites and thrust-faulted slices of rock that contain pieces of the upper mantle are related to either subduction zones or transform plate boundaries.

Seismic Waves

The energy from earthquakes travels in waves. The study of seismic waves is known as seismology. Seismologists use seismic waves to learn about earthquakes and also to learn about the Earth's interior.

One ingenious way scientists learn about Earth's interior is by looking at earthquake waves. Seismic waves travel outward in all directions from where the ground breaks and are picked up by seismographs around the world. Two types of seismic waves are most useful for learning about Earth's interior.

Body Waves

P-waves and S-waves are known as body waves because they move through the solid body of the Earth. P-waves travel through solids, liquids, and gases. S-waves only move through solids (Figure 1). Surface waves only travel along Earth's surface. In an earthquake, body waves produce sharp jolts. They do not do as much damage as surface waves.

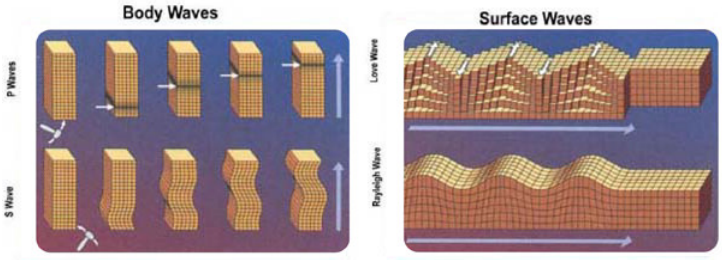


Figure 1. Body and Surface Waves

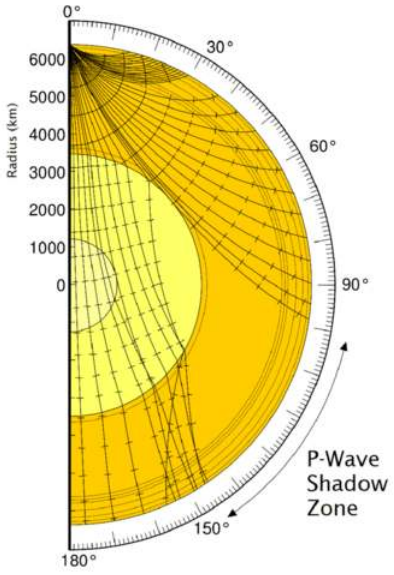


Figure 2. How P-waves travel through Earth's interior.

- **P-waves** (primary waves) are fastest, traveling at about 6 to 7 kilometers (about 4 miles) per second, so they arrive first at the seismometer. P-waves move in a compression/expansion type motion, squeezing and unsqueezing Earth materials as they travel. This produces a change in volume for the material. P-waves bend slightly when they travel from one layer into another. Seismic waves move faster through denser or more rigid material. As P-waves encounter the liquid outer core, which is less rigid than the mantle, they slow down. This makes the P-waves arrive later and further away than would be expected. The result is a P-wave shadow zone. No P-waves are picked up at seismographs 104° to 140° from the earthquakes focus.
- **S-waves** (secondary waves) are about half as fast as P-waves, traveling at about 3.5 km (2 miles) per second, and arrive second at seismographs. S-waves move in an up and down motion perpendicular to the direction of wave travel. This produces a change in shape for the Earth materials they move through. Only solids resist a change in shape, so S-waves are only able to propagate through solids. S-waves cannot travel through liquid.

Where seismic waves speed up or slow down, they refract, changing the direction in which they are traveling. Where seismic waves encounter an abrupt boundary between two very different layers, some of the seismic wave energy is reflected, bouncing back at the same angle it struck. The reflections and refractions of seismic waves allow the layers and boundaries within the earth to be located and studied.

By tracking seismic waves, scientists have learned what makes up the planet's interior (figure 2).

- P-waves slow down at the mantle core boundary, so we know the outer core is less rigid than the mantle.
- S-waves disappear at the mantle core boundary, so the outer core is liquid.

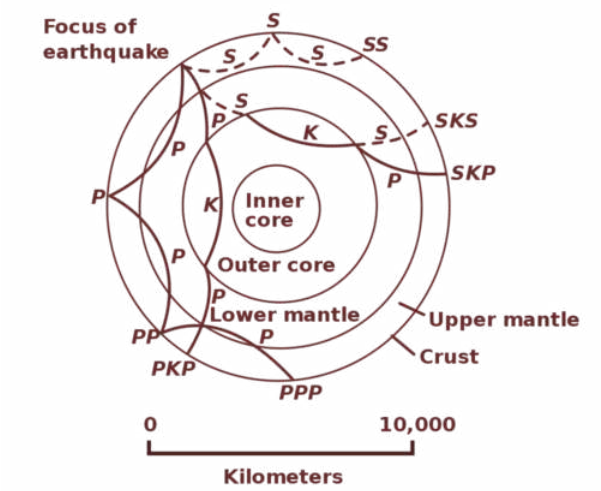


Figure 3. Letters describe the path of an individual P-wave or S-wave. Waves traveling through the core take on the letter K.

This animation shows a seismic wave shadow zone.

Here are some examples of what we have been able to distinguish in the earth's interior from the study of seismic waves and how they travel through the layers of the earth:

1. The thickness of the crust. This is a measure of the thickness of the crust based on the abrupt increase in speed of seismic waves that occurs when they enter the mantle. The boundary between the crust and mantle, as inferred from the change in the speed of P- and S-waves, is called the Mohorovicic discontinuity, named after the Croatian seismologist who first discerned it; usually it is referred to simply as the Moho. It is mainly from seismic waves that we know how thin oceanic crust is and how thick continental crust is.
2. The thickness of the lithosphere. Where seismic waves pass down from the lithosphere into the asthenosphere, they slow down. This is because of the lower rigidity and compressibility of the rocks in the layer below the lithosphere. The zone below the lithosphere where seismic waves travel more slowly is called the low velocity zone. The low velocity zone is probably coincident with the asthenosphere.
3. The boundary between the upper and lower mesosphere (upper and lower mantle). This shows up as an increase in seismic wave speed at a depth of 660 km.
4. The boundary between the mantle and the core. This is marked by S-waves coming to an abrupt stop, presumably because the outer core is liquid, and a sudden large reduction in the speed of P-waves, as they enter the liquid core where there is no rigidity to contribute to P-wave speed.
5. The inner core. This was first recognized by refraction of P-waves passing through this part of the core, due to an abrupt increase in their speed, which was not shown by P-waves traveling through only the outer part of the core.
6. Seismic tomography: imaging slabs and masses at various orientations in the earth, not just in layers. By combining data from many seismometers, three-dimensional images of zones in the earth that have higher or lower seismic wave speeds can be constructed. Seismic tomography shows that in some places there are masses of what may be subducted plates that have penetrated below the asthenosphere into the mesosphere and, in some cases, penetrated into the lower mesosphere, the deepest part of the mantle. In other places, subducted plates appear to have piled up at the base of the upper mesosphere without penetrating into the lower mesosphere.

Gravity

Isaac Newton was the first to calculate the total mass of the earth. This gives us an important constraint on what the earth is made of, because, by dividing the mass of the earth by the volume of the earth, we know the average density of the earth. Whatever the earth is made of, it must add up to the correct amount of mass. Gravity measurements, and the earth's mass, tell us that the interior of the earth must be denser than the crust, because the average density of earth is much higher than the density of the crust.

Because different parts of the crust, mantle, and core have different thicknesses and densities, the strength of gravity over particular points on earth varies slightly. These variations from the average strength of earth's gravity are called gravity anomalies. Mapping and analyzing gravity anomalies, in some cases by using satellites, and also be measuring the effect of gravity anomalies on the

surface shape of the ocean, has given us much insight into subduction zones, mid-ocean spreading ridges, and mountain ranges, including constraints on the depths of their roots.

Moment of Inertia

The earth's gravity tells us how much total mass the earth has, but does not tell us how the mass is distributed within the earth. A property known as moment of inertia, which is the resistance (inertia) of an object to changes in its spin (rotation), is determined by exactly how matter is distributed in a spinning object, from its core to its surface. The earth's moment of inertia is measured by its effect on other objects with which it interacts gravitationally, including the Moon, and satellites. Knowing the earth's moment of inertia provides a way of checking and refining our understanding of the mass and density of each of the earth's internal layers.

Meteorites

Studies of meteorites, which are pieces of asteroids that have landed on earth, along with astronomical studies of what the Sun, the other planets, and orbiting asteroids are made of, give us a model for the general chemical composition of objects in the inner solar system, which are made mainly of elements that form rocks and metals, as opposed to the outer planets such as Jupiter, which are made mostly of light, gas-forming elements. The general compositional model of the rocky and metallic part of the solar system has much higher percentages of iron, nickel, and magnesium than is found in the earth's crust.

If the earth's mantle is made of ultramafic rock, as is found in actual samples of the upper mantle in xenoliths and ophiolites, that would account for part of the missing iron, nickel, and magnesium. But much more iron and nickel would still be missing. If the core is made mostly of iron, and abundant nickel as well, it would give the earth an overall composition similar to the composition of other objects in the inner solar system, and similar to the proportions of rock and metal-forming elements measured in the Sun.

A mantle with an ultramafic composition, and a core made mostly of iron plus nickel, would make earth's composition match the composition of the rest of the solar system, and give those layers the right densities to account for the earth's moment of inertia and total mass.

Experiments

Geology, like other sciences, is based on experiment along with observation and theory. earth scientists and physicists have developed experimental methods to study how materials behave at the pressures and temperatures of the earth's interior, including core temperatures and pressures. They can measure such properties as the density, the state of matter (liquid or solid), the rigidity, the compressibility, and the speed at which seismic waves pass through these materials at high pressures and temperatures. These studies allow further refinement of our knowledge of what the interior of the earth is made of and how it behaves. These experiments support the theory that the mantle is ultramafic and the core is mostly iron and nickel, because they show that materials with those compositions have the same density and seismic wave speeds as have been observed in the earth.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Earth's Interior. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthinterior.html#magnetic. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*
- Seismic Waves. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Seismic-Waves/lesson/Seismic-Waves-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 6.9: Reading- Studying the Earth's Interior is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.10: Self Check- Understanding the Earth's Interior

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1099

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 6.10: Self Check- Understanding the Earth's Interior is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.11: Putting It Together- Earth's Interior

Summary

You should now have a better understanding of just important the study of the Earth's interior is and the impact it has on various aspects of our lives. In particular, we have looked at these items:

1. The various layers of the Earth including where they are, what they are made of and how they behave physically
2. How geologists use indirect methods to study earth's interior
3. Earth's magnetic field including how it is generated and why it's important
4. The influence the interior has on plate tectonics

Examples

Did you enjoy the video through the layers of the Earth we watched at the beginning of this outcome? It was a very short trip but very informative. Now you know why geologists sometimes have issues with Hollywood and the movies that we see sometimes. Journey to the Center of the Earth may be a fun movie (acting aside), but it is totally unrealistic. As you saw, the temperatures and pressures inside the Earth make it impossible for us to actually visit there, although I know a lot of geologists would love to make the trip!

Now that we have good understand of the interior of the Earth and how plate tectonics work, let's take an up-close look at earthquakes!

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 6.11: Putting It Together- Earth's Interior is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

6.12: Assignment- Earth's Interior

For this assessment, you will create an accurate representation of the Earth's interior. Not only will you demonstrate the different layers of the Earth but their physical and chemical characteristics as well. Remember to access the tips and hints at the bottom of the page.

Basic Requirements (assignment criteria):

This assessment requires you to use your imagination. It is up to you to decide what materials you will use for the model. Some ideas include—Play-Doh, variety of candies, pudding, Jello or other items. You will need to create an accurate representation of the thickness of the different layers as well as their physical characteristics. The model does NOT need to be round like the Earth.

I would recommend using a 9×13 pan, pie pan or a tall clear glass. You can use a normal pan or purchase a foil pan from the $1 store. In fact, a trip to a local dollar store could yield all sorts of ideas.

1. Make sure the thickness of EACH layer is accurate. Remember this is a model.
2. Make sure the physical properties of EACH layer are accurate. For the outer core, it may not be possible given that it is a liquid. However, you can vary the properties of the other layers. As you create the various layers, remember what you have learned about each layer.
3. For each layer, write a brief description. Make sure you include the physical property description as well as the material you chose for that layer. Include a brief description of the chemical makeup and chemical properties of the layer. Also, include anything unique or special about that layer (HINT: each layer – the inner core, the outer core, the mantle and the crust – have at least one unique or special feature worth mentioning.
4. Take a picture of the model AND a picture of YOU with the model together, save it with your layer summaries for submission. A clear picture of the model is required so the different levels can be easily seen.
5. Be creative and have fun!
6. Your final project should be unique!

Tips and hints can be found here (Links to an external site.)

.

Contributors and Attributions

CC licensed content, Original

- Earth's Interior Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 6.12: Assignment- Earth's Interior is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

7: Crustal Deformation

Learning Objectives

Correlate structural geology as it pertains to crustal deformation.

- Compare and contrast stress versus strain in the Earth's crust.
- Identify geologic structures created by deformation.

7.1: Why It Matters- Crustal Deformation
7.2: Outcome- Stress and Strain
7.3: Reading- Stress In Earth's Crust
7.4: Reading- Strain
7.5: Self Check- Stress and Strain
7.6: Outcome- Geologic Structures
7.7: Reading- Folds
7.8: Reading- Faults
7.9: Reading- Mountains
7.10: Self Check- Geologic Structures
7.11: Putting It Together- Crustal Deformation

This page titled 7: Crustal Deformation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.1: Why It Matters- Crustal Deformation

Correlate structural geology as it pertains to crustal deformation

Introduction



Figure 1. Chevron folds with flat-lying axial planes, Millook Haven, North Cornwall, UK

Understanding crustal deformation helps explain the forces necessary to bend and fold rocks like those shown above which help create mountains. This section will discuss the types of forces needed to accomplish such a powerful feat. Have you ever wondered how strong those forces would have to be? The answer to that is beyond our comprehension.

Along with these forces, we will investigate various types of folds as well as different types of faults. If you recall from the plate tectonics sections, earthquakes occur along active fault lines. This section helps us better understand how faults work.

Learning Outcomes

- Compare and contrast stress versus strain in the Earth's crust.
- Identify geologic structures created by deformation.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 7.1: Why It Matters- Crustal Deformation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.2: Outcome- Stress and Strain

Compare and contrast stress versus strain in the Earth's crust

This section introduces you to the concepts of stress and strain. You will learn their definitions and how they impact the Earth's crust.

What You'll Learn to Do

- Differentiate between the types of stress: tension, compression, shear.
- Differentiate between the types of strain: elastic, ductile, and fracture.

Learning Activities

The learning activities for this section include the following:

- Reading: Stress In Earth's Crust
- Reading: Strain
- Self Check: Stress and Strain

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 7.2: Outcome- Stress and Strain is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.3: Reading- Stress In Earth's Crust

Introduction

Enormous slabs of lithosphere move unevenly over the planet's spherical surface, resulting in earthquakes. This chapter deals with two types of geological activity that occur because of plate tectonics: mountain building and earthquakes. First, we will consider what can happen to rocks when they are exposed to stress.

Causes and Types of Stress

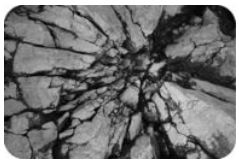


Figure 1. Stress caused these rocks to fracture.

Stress is the force applied to an object. In geology, stress is the force per unit area that is placed on a rock. Four types of stresses act on materials.

- A deeply buried rock is pushed down by the weight of all the material above it. Since the rock cannot move, it cannot deform. This is called **confining stress.**
- **Compression** squeezes rocks together, causing rocks to fold or fracture (break) (figure 1). Compression is the most common stress at convergent plate boundaries.
- Rocks that are pulled apart are under **tension**. Rocks under tension lengthen or break apart. Tension is the major type of stress at divergent plate boundaries.
- When forces are parallel but moving in opposite directions, the stress is called **shear** (figure 2). Shear stress is the most common stress at transform plate boundaries.



Figure 2. Shearing in rocks. The white quartz vein has been elongated by shear.

When stress causes a material to change shape, it has undergone **strain** or**deformation.** Deformed rocks are common in geologically active areas.

A rock's response to stress depends on the rock type, the surrounding temperature, and pressure conditions the rock is under, the length of time the rock is under stress, and the type of stress.

Rocks have three possible responses to increasing stress (illustrated in figure 3):

- **elastic deformation**: the rock returns to its original shape when the stress is removed.
- **plastic deformation**: the rock does not return to its original shape when the stress is removed.
- **fracture**: the rock breaks.

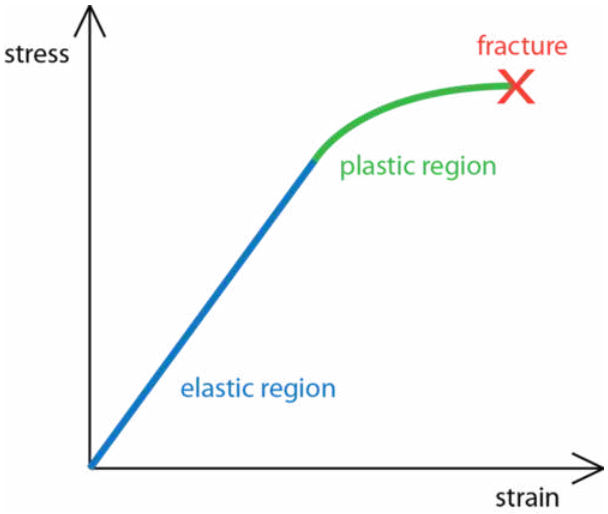


Figure 3. With increasing stress, the rock undergoes: (1) elastic deformation, (2) plastic deformation, and (3) fracture.

Under what conditions do you think a rock is more likely to fracture? Is it more likely to break deep within Earth's crust or at the surface? What if the stress applied is sharp rather than gradual?

- At the Earth's surface, rocks usually break quite quickly, but deeper in the crust, where temperatures and pressures are higher, rocks are more likely to deform plastically.
- Sudden stress, such as a hit with a hammer, is more likely to make a rock break. Stress applied over time often leads to plastic deformation.

Geologic Structures

Sedimentary rocks are important for deciphering the geologic history of a region because they follow certain rules.

1. Sedimentary rocks are formed with the oldest layers on the bottom and the youngest on top.
2. Sediments are deposited horizontally, so sedimentary rock layers are originally horizontal, as are some volcanic rocks, such as ash falls.
3. Sedimentary rock layers that are not horizontal are deformed.

You can trace the deformation a rock has experienced by seeing how it differs from its original horizontal, oldest-on-bottom position (figure 4a). This deformation produces geologic structures such as folds, joints, and faults that are caused by stresses (figure 4b). Using the rules listed above, try to figure out the geologic history of the geologic column below.

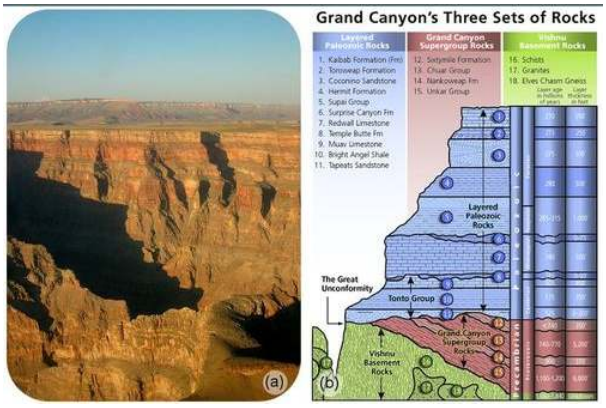


Figure 4. (a) In the Grand Canyon, the rock layers are exposed like a layer cake. Each layer is made of sediments that were deposited in a particular environment – perhaps a lake bed, shallow offshore region, or a sand dune. (b) In this geologic column of the Grand Canyon, the sedimentary rocks of the "Layered Paleozoic Rocks" column (layers 1 through 11) are still horizontal. Grand Canyon Supergroup rocks (layers 12 through 15) have been tilted. Vishnu Basement Rocks are not sedimentary (rocks 16 through 18). The oldest layers are on the bottom and youngest are on the top.

Folds

Rocks deforming plastically under compressive stresses crumple into **folds** (figure 5). They do not return to their original shape. If the rocks experience more stress, they may undergo more folding or even fracture.



Figure 5. Snow accentuates the fold exposed in these rocks in Provo Canyon, Utah.

Three types of folds are seen.

- Mononcline: A **monocline** is a simple bend in the rock layers so that they are no longer horizontal (see figure 6 for an example).



Figure 6. At Colorado National Monument, the rocks in a monocline plunge toward the ground.

- Anticline: An **anticline** is a fold that arches upward. The rocks dip away from the center of the fold (figure 7). The oldest rocks are at the center of an anticline and the youngest are draped over them.

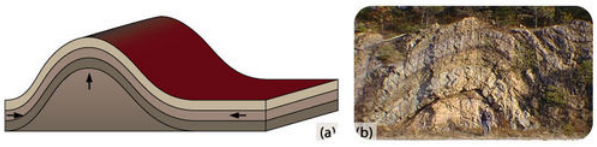


Figure 7. (a) Schematic of an anticline. (b) An anticline exposed in a road cut in New Jersey.

When rocks arch upward to form a circular structure, that structure is called a **dome.** If the top of the dome is sliced off, where are the oldest rocks located?

- Syncline: A **syncline** is a fold that bends downward. The youngest rocks are at the center and the oldest are at the outside (figure 8).

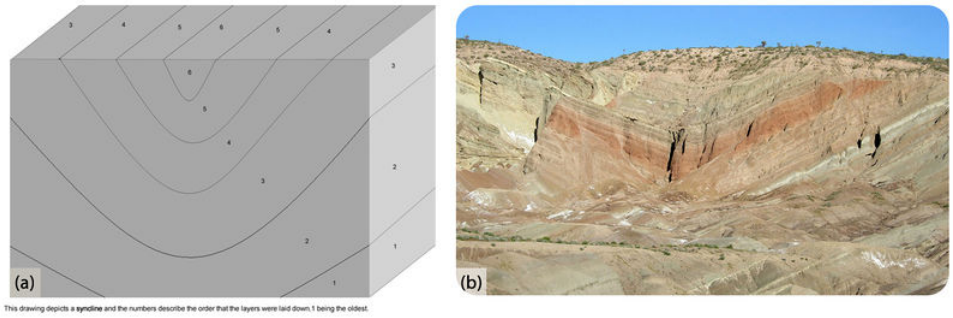


Figure 8. (a) Schematic of a syncline. (b) This syncline is in Rainbow Basin, California.

When rocks bend downward in a circular structure, that structure is called a **basin** (figure 9). If the rocks are exposed at the surface, where are the oldest rocks located?

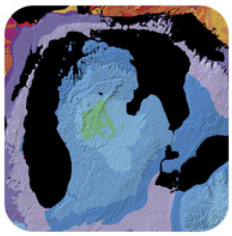


Figure 9. Basins can be enormous. This is a geologic map of the Michigan Basin, which is centered in the state of Michigan but extends into four other states and a Canadian province.

Faults

A rock under enough stress will fracture. If there is no movement on either side of a fracture, the fracture is called a **joint**, as shown in (figure 10).



Figure 10. Granite rocks in Joshua Tree National Park showing horizontal and vertical jointing. These joints formed when the confining stress was removed from the granite.

If the blocks of rock on one or both sides of a fracture move, the fracture is called a **fault** (figure 11). Sudden motions along faults cause rocks to break and move suddenly. The energy released is an earthquake.



Figure 11. Faults are easy to recognize as they cut across bedded rocks.

Slip is the distance rocks move along a fault. Slip can be up or down the fault plane. Slip is relative, because there is usually no way to know whether both sides moved or only one. Faults lie at an angle to the horizontal surface of the Earth. That angle is called the fault's **dip.** The dip defines which of two basic types a fault is. If the fault's dip is inclined relative to the horizontal, the fault is a **dip-slip fault** (figure 12). There are two types of dip-slip faults. In **normal faults**, the hanging wall drops down relative to the footwall. In **reverse faults**, the footwall drops down relative to the hanging wall.

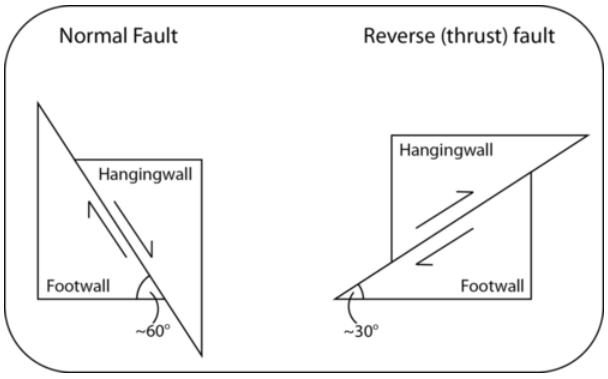


Figure 12. This diagram illustrates the two types of dip-slip faults: normal faults and reverse faults. Imagine miners extracting a resource along a fault. The hanging wall is where miners would have hung their lanterns. The footwall is where they would have walked.

Here is an animation of a normal fault.

A **thrust fault** is a type of reverse fault in which the fault plane angle is nearly horizontal. Rocks can slip many miles along thrust faults (**Figure** 13).



Figure 13. At Chief Mountain in Montana, the upper rocks at the Lewis Overthrust are more than 1 billion years older than the lower rocks. How could this happen?

Here is an animation of a thrust fault.

Normal faults can be huge. They are responsible for uplifting mountain ranges in regions experiencing tensional stress (figure 14).



Figure 14. The Teton Range in Wyoming rose up along a normal fault.

A **strike-slip fault** is a dip-slip fault in which the dip of the fault plane is vertical. Strike-slip faults result from shear stresses (figure 15).

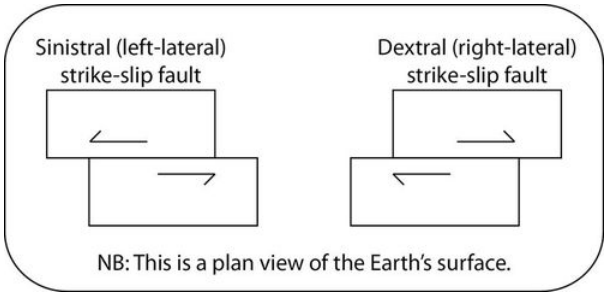


Figure 15. Imagine placing one foot on either side of a strike-slip fault. One block moves toward you. If that block moves toward your right foot, the fault is a right-lateral strike-slip fault; if that block moves toward your left foot, the fault is a left-lateral strike-slip fault.



Figure 16. The San Andreas is a massive transform fault.

California's San Andreas Fault is the world's most famous strike-slip fault. It is a right-lateral strike slip fault (figure 16).

Here is a strike-slip fault animation.

People sometimes say that California will fall into the ocean someday, which is not true. This animation shows movement on the San Andreas into the future.

Stress and Mountain Building

Two converging continental plates smash upwards to create mountain ranges (figure 17). Stresses from this **uplift** cause folds, reverse faults, and thrust faults, which allow the crust to rise upwards.

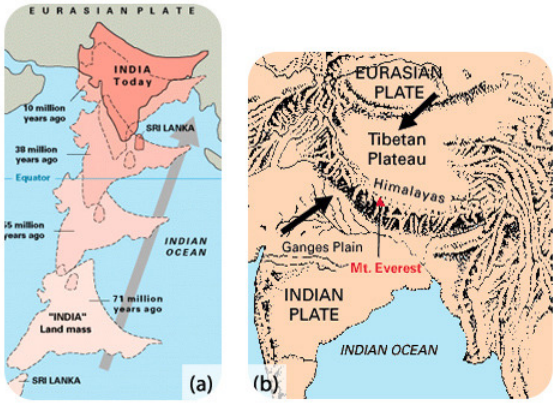


Figure 17. (a) The world's highest mountain range, the Himalayas, is growing from the collision between the Indian and the Eurasian plates. (b) The crumpling of the Indian and Eurasian plates of continental crust creates the Himalayas.

Subduction of oceanic lithosphere at convergent plate boundaries also builds mountain ranges (figure 18).



Figure 18. The Andes Mountains are a chain of continental arc volcanoes that build up as the Nazca Plate subducts beneath the South American Plate.

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 (figure 19).

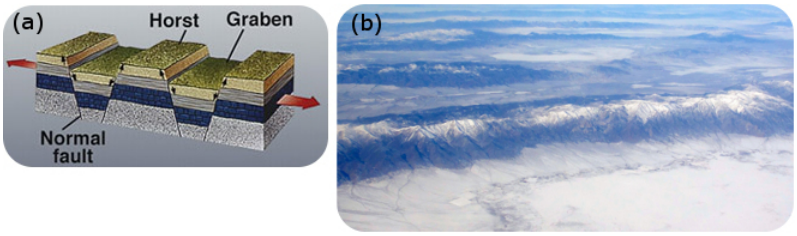


Figure 19. (a) In basin-and-range, some blocks are uplifted to form ranges, known as horsts, and some are down-dropped to form basins, known as grabens. (b) Mountains in Nevada are of classic basin-and-range form.

This is a very quick animation of movement of blocks in a basin-and-range setting.

Lesson Summary

- Stress is the force applied to a rock and may cause deformation. The three main types of stress are typical of the three types of plate boundaries: compression at convergent boundaries, tension at divergent boundaries, and shear at transform boundaries.
- Where rocks deform plastically, they tend to fold. Brittle deformation brings about fractures and faults.
- The two main types of faults are dip-slip (the fault plane is inclined to the horizontal) and strike-slip (the fault plane is perpendicular to the horizontal).
- The world's largest mountains grow at convergent plate boundaries, primarily by thrust faulting and folding.

Contributors and Attributions

CC licensed content, Shared previously

- 7.1: Stress in Earthu2019s Crust. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/7.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 7.3: Reading- Stress In Earth's Crust is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.4: Reading- Strain

As we've just learned, the earth's crust is constantly subjected to forces that push, pull, or twist it. These forces are called stress. In response to stress, the rocks of the earth undergo **strain**, also known as deformation.

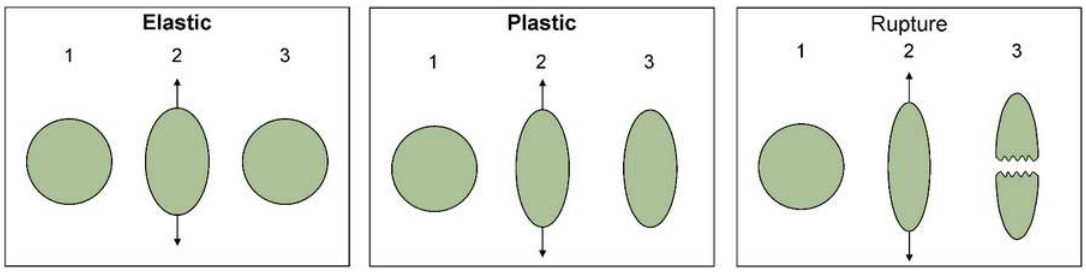
Strain is any change in volume or shape.There are four general types of stress. One type of stress is uniform, which means the force applies equally on all sides of a body of rock. The other three types of stress, tension, compression and shear, are non-uniform, or directed, stresses.All rocks in the earth experience a uniform stress at all times. This uniform stress is called lithostatic pressure and it comes from the weight of rock above a given point in the earth. Lithostatic pressure is also called hydrostatic pressure. (Included in lithostatic pressure are the weight of the atmosphere and, if beneath an ocean or lake, the weight of the column of water above that point in the earth. However, compared to the pressure caused by the weight of rocks above, the amount of pressure due to the weight of water and air above a rock is negligible, except at the earth's surface.) The only way for lithostatic pressure on a rock to change is for the rock's depth within the earth to change.Because lithostatic pressure is a uniform stress, a change in lithostatic pressure does not cause fracturing and slippage along faults. Nevertheless, it may be the cause of certain types of earthquakes. In subducting tectonic plates, the increased pressure of greater depth within the earth may cause the minerals in the plate to metamorphose spontaneously into a new set of denser minerals that are stable at the higher pressure. This is thought to be the likely cause of certain types of deep earthquakes in subduction zones, including the deepest earthquakes ever recorded.

Rocks are also subjected to the three types of directed (non-uniform) stress – tension, compression, and shear.

- **Tension** is a directed (non-uniform) stress that pulls rock apart in opposite directions. The tensional (also called extensional) forces pull away from each other.
- **Compression** is a directed (non-uniform) stress that pushes rocks together. The compressional forces push towards each other.
- **Shear** is a directed (non-uniform) stress that pushes one side of a body of rock in one direction, and the opposite side of the body of rock in the opposite direction. The shear forces are pushing in opposite ways.

In response to stress, rock may undergo three different types of strain – elastic strain, ductile strain, or fracture.

- **Elastic strain** is reversible. Rock that has undergone only elastic strain will go back to its original shape if the stress is released.
- **Ductile strain** is irreversible. A rock that has undergone ductile strain will remain deformed even if the stress stops. Another term for ductile strain is plastic deformation.
- **Fracture** is also called rupture. A rock that has ruptured has abruptly broken into distinct pieces. If the pieces are offset—shifted in opposite directions from each other—the fracture is a fault.



Ductile and Brittle Strain

Earth's rocks are composed of a variety of minerals and exist in a variety of conditions. In different situations, rocks may act either as ductile materials that are able to undergo an extensive amount of ductile strain in response to stress, or as brittle materials, which will only undergo a little or no ductile strain before they fracture. The factors that determine whether a rock is ductile or brittle include:

- Composition—Some minerals, such as quartz, tend to be brittle and are thus more likely to break under stress. Other minerals, such as calcite, clay, and mica, tend to be ductile and can undergo much plastic deformation. In addition, the presence of water in rock tends to make it more ductile and less brittle.
- Temperature—Rocks become softer (more ductile) at higher temperature. Rocks at mantle and core temperatures are ductile and will not fracture under the stresses that occur deep within the earth. The crust, and to some extent the lithosphere, are cold

enough to fracture if the stress is high enough.

- Lithostatic pressure—The deeper in the earth a rock is, the higher the lithostatic pressure it is subjected to. High lithostatic pressure reduces the possibility of fracture because the high pressure closes fractures before they can form or spread. The high lithostatic pressures of the earth's sub-lithospheric mantle and solid inner core, along with the high temperatures, are why there are no earthquakes deep in the earth.
- Strain rate—The faster a rock is being strained, the greater its chance of fracturing. Even brittle rocks and minerals, such as quartz, or a layer of cold basalt at the earth's surface, can undergo ductile deformation if the strain rate is slow enough.

Most earthquakes occur in the earth's crust. A smaller number of earthquakes occur in the uppermost mantle (to about 700 km deep) where subduction is taking place. Rocks in the deeper parts of the earth do not undergo fracturing and do not produce earthquakes because the temperatures and pressures there are high enough to make all strain ductile. No earthquakes originate from below the the earth's upper mantle.

Stress and Fault Types

The following correlations can be made between types of stress in the earth, and the type of fault that is likely to result:

- **Tension leads to normal faults.**
- **Compression leads to reverse or thrust faults.**
- **Horizontal shear leads to strike-slip faults.**

Correlations between type of stress and type of fault can have exceptions. For example, zones of horizontal stress will likely have strike-slip faults as the predominant fault type. However there may be active normal and thrust faults in such zones as well, particularly where there are bends or gaps in the major strike-slip faults.

To give another example, in a region of compression stress in the crust, where sheets of rock are stacked on active thrust faults, strike-slip faults commonly connect some of the thrust faults together.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Earthquakes. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 7.4: Reading- Strain is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.5: Self Check- Stress and Strain

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1102

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 7.5: Self Check- Stress and Strain is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.6: Outcome- Geologic Structures

Identify geologic structures created by deformation.

Geologic structures such as faults and folds are the architecture of the earth's crust. Geologic structures influence the shape of the landscape, determine the degree of landslide hazard, bring old rocks to the surface, bury young rocks, trap petroleum and natural gas, shift during earthquakes, and channel fluids that create economic deposits of metals such as gold and silver.

Folds, faults, and other geologic structures accommodate large forces such as the stress of tectonic plates jostling against each other, and smaller forces such as the stress of gravity pulling on a steep mountainside. An understanding of the structures that shape the earth's crust can help you see when and where the crust was subjected to pushing or pulling, terrane accretion or crustal rifting.

What You'll Learn to Do

- Interpret and model common fold types: anticlines, synclines, basins, and domes.
- Interpret and model common fault types.
- Understand the process of deformation and the origin of mountains

Learning Activities

The learning activities for this section include the following:

- Reading: Folds
- Reading: Faults
- Reading: Mountains
- Self Check: Geologic Structures

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Basics -- Geologic Structures. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/structures.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 7.6: Outcome- Geologic Structures is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

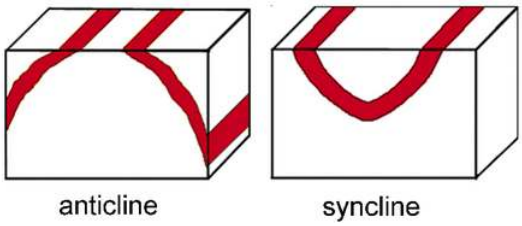
7.7: Reading- Folds

Ductile rocks behave plastically and become folded in response to stress. Even in the shallow crust where rocks are cool and relatively brittle, folding can occur if the stress is slow and steady and gives the rock enough time to gradually bend. If the stress is applied too quickly, rocks in the shallow crust will behave as brittle solids and break. Deeper in the crust, where the rocks are more ductile, folding happens more readily, even when the stress and strain occurs rapidly.

Anticlines and Synclines

The most basic types of folds are anticlines and synclines. Imagine a rug, the sides of which have been pushed toward each other forming ridges and valleys – the ridges are “up” folds and the valleys are “down” folds. In terms of geologic structures, the up folds are called anticlines and the down folds are called synclines.

In block diagrams like those shown below, the top of the block is the horizontal surface of the earth, the map view. The other two visible sides of the box are cross-sections, vertical slices through the crust. The colored layers represent stratified geologic formations that were originally horizontal, such as sedimentary beds or lava flows. Use the block diagrams to visualize the three-dimensional shapes of the geologic structures. Keep in mind that erosion has stripped away the upper parts of these structures so that map view reveals the interior of these structures.



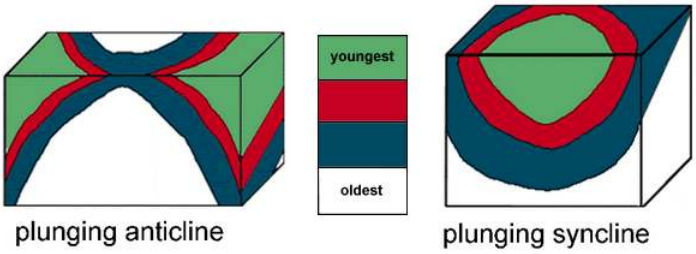
In map view, an anticline appears as parallel beds of the same rock type that dip away from the center of the fold. In an anticline, the oldest beds, the ones that were originally underneath the other beds, are at the center, along the axis of the fold. The axis is an imaginary line that marks the center of the fold on the map.

In map view, a syncline appears as a set of parallel beds that dip toward the center. In a syncline the youngest beds, the ones that were originally on top of the rest of the beds, are at the center, along the axis of the fold.

Anticlines and synclines form in sections of the crust that are undergoing compression, places where the crust is being pushed together.

Plunging Anticlines and Synclines

A plunging anticline or a plunging syncline is one that has its axis tilted from the horizontal so that the fold is plunging into the earth along its length. Plunge direction is the direction in which the axis of the fold tilts down into the earth.



In map view, a plunging anticline makes a U-shaped or V-shaped pattern that points, or closes, in the direction of plunge. A cross-section at a right angle to the axis of a plunging anticline looks the same as an anticline.

In map view, a plunging syncline makes a U-shaped or V-shaped pattern that opens in the direction of plunge.

Anticlines

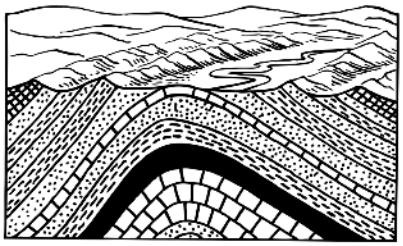


Figure 1. Diagram of an anticline.

In structural geology, an **anticline** is a fold that is convex up and has its oldest beds at its core. The term is not to be confused with *antiform*, which is a purely descriptive term for any fold that is convex up. Therefore if age relationships between various strata are unknown, the term antiform should be used.

On a geologic map, anticlines are usually recognized by a sequence of rock layers that are progressively older toward the center of the fold because the uplifted core of the fold is preferentially eroded to a deeper stratigraphic level relative to the topographically lower flanks. The strata dip away from the center, or *crest*, of the fold.



Figure 2. Anticline with syncline visible at far right. Note the man standing before the formation, for scale.

If an anticline plunges (i.e., is inclined to the Earth's surface), the surface strata will form *V*s that point in the direction of plunge. Anticlines are often flanked by synclines although faulting can complicate and obscure the relationship between the two. Folds often form during crustal deformation as the result of shortening that accompanies orogenic mountain building. In many cases anticlines are formed by movement on non-planar faults during both shortening and extension, such as *ramp anticlines* and rollover anticlines.

Terminology

Any fold whose form is **convex** upward is an antiform. Antiforms containing progressively younger rocks from their core outwards are anticlines.

An anticline or antiform has a *crest*, which is the highest point on a given stratum along the top of the fold. A *hinge* in an anticline is the locus of maximum curvature or bending in a given stratum in the fold. An *axis* is an imaginary line connecting the hinges in the different strata in a two-dimensional cross-section through the anticline. Connecting the hinges or points of maximum curvature in the different layers in three dimensions produces an *axial plane* or *axial surface*. In a symmetrical anticline, a surface trace of the axial plane coincides with the crest. With an asymmetrical anticline, the surface trace of the axial plane or axis will be offset from the crest toward the steeper flank of the fold. An*overturned anticline* is an asymmetrical anticline with a flank or limb that has been tilted beyond perpendicular so that the beds in that limb are upside-down.

A structure that plunges in all directions to form a circular or elongate structure is a dome. Domes are generally formed from one main deformation event, or via diapirism from underlying magmatic intrusions or movement of upwardly mobile, mechanically ductile material such as rock salt (salt dome) and shale (shale diapir). The Richat Structure of the Sahara is considered a dome that has been laid bare by erosion.

An anticline which plunges at both ends is termed a *doubly plunging anticline*, and may be formed from multiple deformations, or superposition of two sets of folds, or be related to the geometry of the underlying detachment fault and the varying amount of displacement along the surface of that detachment fault. The highest point on a doubly plunging anticline (or any geologic structure for that matter) is called the "culmination."

An elongate dome which developed as the sediments were being deposited is referred to as a *pericline*.

An *anticlinorium* is a series of anticlinal folds on a regional-scale anticline. Examples include the Late Jurassic to Early Cretaceous Purcell Anticlinorium in British Columbia and the Blue Ridge anticlinorium of northern Virginia and Maryland in the Appalachians, or the Nittany Valley in central Pennsylvania.

Economic significance



Figure 3. Structural trap: anticlinal fold

Doubly plunging or faulted anticlines, culminations, and structural domes are favored locations for oil and natural gas drilling; the low density of petroleum causes it to buoyantly migrate upward to the highest parts of the fold, until stopped by a low-permeability barrier such as an impermeable stratum or fault zone. Examples of low-permeability seals that contain the hydrocarbons, oil and gas, in the ground include shale, limestone, sandstone, and even salt domes. The actual type of stratum does not matter as long as it has low permeability.

Periclines are important focal points for pooling of hot, metal-laden formational brines, which can form manto ore deposits, Irish-type lead-zinc deposits and uranium deposits, amongst others.

Culminations in folded strata which are cut by shears and faults are favoured loci for deposition of saddle-reef style lode gold deposits.

Synclines



The Sideling Hill syncline as exposed in the Interstate 68 roadcut to the west of Hancock, Maryland, USA

In structural geology, a **syncline** is a fold with younger layers closer to the center of the structure. A **synclinorium** (plural **synclinoriums** or **synclinoria**) is a large syncline with superimposed smaller folds. Synclines are typically a downward fold, termed a synformal syncline (i.e. a trough); but synclines that point upwards, or perched, can be found when strata have been overturned and folded (an antiformal syncline).

Characteristics

On a geologic map, synclines are recognized by a sequence of rock layers that grow progressively younger, followed by the youngest layer at the fold's center or *hinge*, and by a reverse sequence of the same rock layers on the opposite side of the hinge. If the fold pattern is circular or elongate circular the structure is a basin. Folds typically form during crustal deformation as the result of compression that accompanies orogenic mountain building.

Notable Examples

- Powder River Basin, Wyoming, USA.

- Sideling Hill roadcut along Interstate 68 in western Maryland, USA, where the Rockwell Formation and overlying Purslane Sandstone are exposed.
- Western Lake Superior, which occupies a basin created by the Midcontinent Rift System
- Saou, a commune in the Drôme department in southeastern France
- The Catlins, an area in the southeastern corner of the South Island of New Zealand

Basins and Domes

A basin is a bowl-like depression in the strata (layers of rock). A basin is similar to a syncline, but instead of an axis it has a single point at the center. The strata all dip toward the center point and the youngest rock is at the center. In map view, the strata form concentric circles – a bull's eye pattern – around the center point.

A dome is an bulge in strata. A dome is similar to an anticline, but instead of an axis it has a single point at the center. The strata all dip away from the center point and the oldest rock is at the center. In map view, the strata form concentric circles – a bull's eye pattern – around the center point.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Geologic Structures. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/structures.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*
- Anticline. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Anticline. **License**: *CC BY-SA: Attribution-ShareAlike*
- Syncline. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Syncline. **License**: *CC BY-SA: Attribution-ShareAlike*
- Sideling Hill cut. **Authored by**: Acroterion. **Located at**: https://commons.wikimedia.org/wiki/File:Sideling_Hill_cut_MD1.jpg. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 7.7: Reading- Folds is shared under a CC BY-SA 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

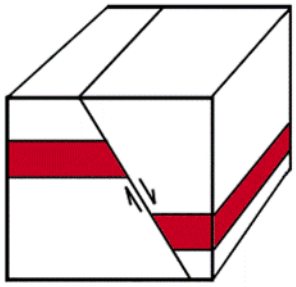
7.8: Reading- Faults

A fault is a planar surface within the earth, along which rocks have broken and slid. Faults are caused by elastic strain that culminates in brittle failure. The rocks on either side of a fault have shifted in opposite directions, called the offset directions. If a fault is not vertical, there are rocks above the fault and rocks beneath the fault.

- The rocks above a fault are called the hanging wall.
- The rocks beneath a fault are called the footwall.

Normal and Detachment Faults

In a normal fault, the hanging wall has moved down relative to the footwall.

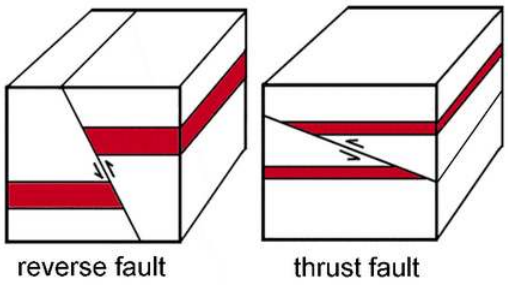


A detachment fault is a particular kind of normal fault that generally dips at a low angle. It separates rocks that were deep in the crust and ductile (granite and gneiss) from rocks of the upper crust (sedimentary or volcanic) that were brittle. Detachment faults occur along the boundaries of metamorphic core complexes (see below).

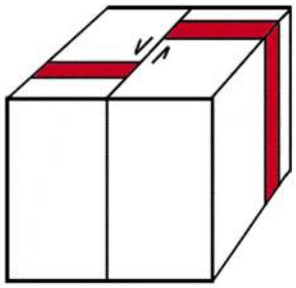
Normal and detachment faults form in sections of the crust that are undergoing tension, places where the crust is being stretched apart. A divergent plate boundary is a zone of large normal faults. Normal faults also occur in other zones of crustal tension, such as in the Basin and Range landscape region of the western United States.

Reverse and Thrust Faults

In a reverse or thrust fault, the hanging wall has moved up relative to the footwall. The difference between a reverse fault and a thrust fault is that a reverse fault has a steeper dip, more than 30°.



Reverse and thrust faults form in sections of the crust that are undergoing compression. A convergent plate boundary is a zone of major reverse and thrust faults. In fact, subduction zones are sometimes referred to as mega-thrust faults. Reverse and thrust faults also occur in other settings where the crust is being compressed, such as the Transverse Mountain Ranges, just north of Los Angeles.



strike-slip fault

Strike-Slip Faults

Strike-slip faults are steep or vertical faults along which the rocks on either side have moved horizontally in opposite directions. A transform plate boundary is a zone of large strike-slip faults. The San Andreas fault is an example of a major strike-slip fault at a transform boundary. Strike-slip faults also occur in other settings.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Geologic Structures. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/structures.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 7.8: Reading- Faults is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.9: Reading- Mountains

How do plate motions create mountains?



Plate tectonic processes create some of the world's most beautiful places. The North Cascades Mountains in Washington State are a continental volcanic arc. The mountains currently host some glaciers and there are many features left by the more abundant ice age glaciers. Changes in altitude make the range a habitable place for many living organisms.

Converging Plates

Converging plates create the world's largest mountain ranges. Each combination of plate types—continent-continent, continent-ocean, and ocean-ocean—creates mountains.

Converging Continental Plates

Two converging continental plates smash upwards to create gigantic mountain ranges (Figure 1). Stresses from this uplift cause folds, reverse faults, and thrust faults, which allow the crust to rise upwards. As was stated previously there is currently no mountain range of this type in the western U.S., but we can find one where India is pushing into Eurasia.

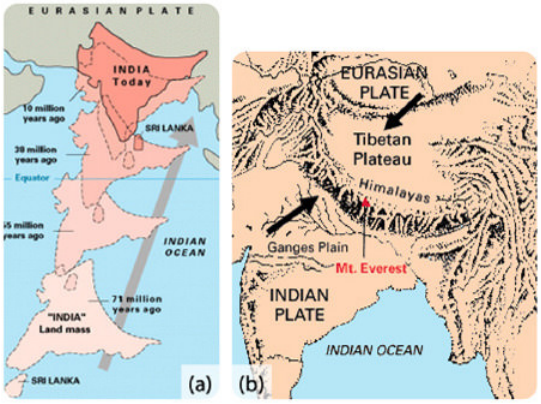


Figure 1. (a) The world's highest mountain range, the Himalayas, is growing from the collision between the Indian and the Eurasian plates. (b) The crumpling of the Indian and Eurasian plates of continental crust creates the Himalayas.

Subducting Oceanic Plates



Figure 2. The Andes Mountains are a chain of continental arc volcanoes that build up as the Nazca Plate subducts beneath the South American Plate.

Subduction of oceanic lithosphere at convergent plate boundaries also builds mountain ranges. This happens on continental crust, as in the Andes Mountains (Figure 2), or on oceanic crust, as with the Aleutian Islands, which we visited earlier. The Cascades Mountains of the western U.S. are also created this way.

Diverging Plates

Amazingly, even divergence can create 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 (Figure 3). In basin-and-range, some blocks are uplifted to form ranges, known as horsts, and some are down-dropped to form basins, known as grabens.

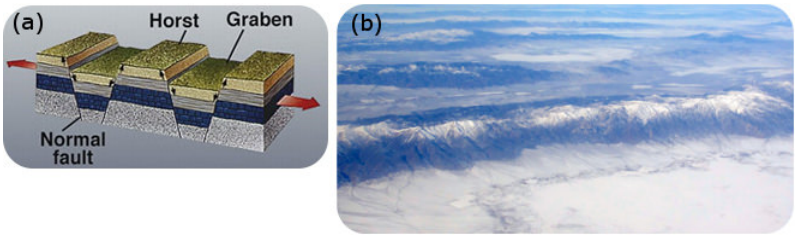


Figure 3. (a) Horsts and grabens. (b) Mountains in Nevada are of classic basin-and-range form.

Watch this quick animation of movement of blocks in a basin-and-range setting.

Summary

- Converging or diverging plates cause mountains to grow.
- Subduction of oceanic crust beneath a continental or oceanic plate creates a volcanic arc.
- Tensional forces bring about block faulting, which creates a basin-and-range topography.

Contributors and Attributions

CC licensed content, Shared previously

- Mountain Building. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Mountain-Building/lesson/Mountain-Building-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 7.9: Reading- Mountains is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.10: Self Check- Geologic Structures

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1103

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 7.10: Self Check- Geologic Structures is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

7.11: Putting It Together- Crustal Deformation

Summary

In this section, you learned the following:

1. The magnitude of forces needed to fold and deform the Earth's crust
2. The difference between stress and strain and what they can produce
3. The different types of forces acting on the Earth: tension, compression, and shearing
4. The different types of folds and forces associated with them
5. The different types of faults and forces associated with them
6. What the outcomes are of crustal deformation

Synthesis

In this section, we learned that besides providing more spectacular scenery, faults and folds help us interpret the history of the Earth, help trap vital resources (such as oil and water), help us determine the location and cause of earthquakes, and help us in our understanding of the processes that shaped the Earth. Since we live on a dynamic and ever changing planet, these forces will continue to help shape our planet for a very long time.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 7.11: Putting It Together- Crustal Deformation is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

8: Earthquakes

Learning Objectives

Interpret types, causes, effects, and scientific measurements of earthquakes and seismic waves.

- Investigate the causes and common locations of earthquakes.
- Compare and contrast properties and mechanics of different types of waves.
- Define and compare magnitude versus intensity.
- Understand the hazards of earthquakes and recognize our limited ability to predict seismic activity.

8.1: Why It Matters- Earthquakes
8.2: Outcome- Causes and Location of Earthquakes
8.3: Reading- The Nature of Earthquakes
8.4: Reading- Causes of Earthquakes
8.5: Reading- Common Locations of Earthquakes
8.6: Reading- The Ring of Fire
8.7: Self Check- Causes and Location of Earthquakes
8.8: Outcome- Types of Waves
8.9: Reading- Body Waves
8.10: Reading- Surface Waves
8.11: Self Check- Types of Waves
8.12: Outcome- Magnitude and Intensity
8.13: Reading- Measuring Earthquakes
8.14: Reading- Magnitude versus Intensity
8.15: Self Check- Magnitude and Intensity
8.16: Outcome- Earthquake Hazards and Prediction
8.17: Reading- Earthquake Hazards
8.18: Reading- Earthquake Prediction
8.19: Reading- Seismicity and Earthquake Prediction
8.20: Self Check- Earthquake Hazards and Prediction
8.21: Putting It Together- Earthquakes
8.22: Assignment- Earthquakes

This page titled 8: Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.1: Why It Matters- Earthquakes

Interpret types, causes, effects, and scientific measurements of earthquakes and seismic waves

Introduction

Have you ever wondered why California or Japan has so many earthquakes? Have you ever been in an earthquake and felt the solid ground shake beneath your feet?

Imagine you are going about your normal routine for the day and it is time for you to wrap up your day to head home. As you start gathering your things to take home and work your way out to your car, the following happens (note that this video and the next contain no significant audio):

A link to an interactive elements can be found at the bottom of this page.

This earthquake measured a 9.0 on the Richter scale and was the most powerful earthquake to hit Japan and the fourth most powerful recorded by humans. Aftershocks numbered over 1,000, with some over a 6.0 on the Richter scale. Almost 16,000 people died, over 6,000 were injured, and 2,500 were missing. The earthquake also damaged a nuclear facility causing major radioactive leaks. The World Bank estimated the economic cost of damage at $235 billion!

Once the shaking subsided, the following happened:



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=270

Learning Outcomes

- Investigate the causes and common locations of earthquakes
- Compare and contrast properties and mechanics of different types of waves
- Define and compare magnitude versus intensity.
- Understand the hazards of earthquakes and recognize our limited ability to predict seismic activity.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

All rights reserved content

- JAPAN - The Earthquake - 15 Minutes Live-Cam. **Authored by**: zSpaceTV. **Located at**: https://youtu.be/jBdvvXyS-r4. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License
- Incredible footage of Incoming Tsunami Japan. **Authored by**: TimC. **Located at**: https://youtu.be/yiENf1f1tIA. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License
- Huge Landslide and Hill Collapse after Massive Earthquake in Nepal (2015). **Authored by**: viralTV. **Located at**: https://youtu.be/Say2HiVwqTU. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 8.1: Why It Matters- Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.2: Outcome- Causes and Location of Earthquakes

Investigate the causes and common locations of earthquakes

In this section, you will learn what causes earthquakes and why. You will also learn the locations of common earthquakes.

What You'll Learn to Do

- Describe earthquakes and their features
- Identify the causes of earthquakes
- Identify where earthquakes commonly occur

Learning Activities

- Reading: The Nature of Earthquakes
- Reading: Causes of Earthquakes
- Reading: Common Locations of Earthquakes
- Reading: The Ring of Fire

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.2: Outcome- Causes and Location of Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.3: Reading- The Nature of Earthquakes

Seismology

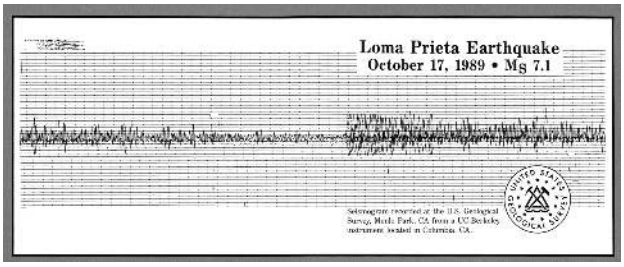
Seismology is the study of seismic waves. Seismology is also the study of earthquakes, mainly through the waves they produce. By measuring and analyzing seismic waves, seismologists can derive such information as:

- The epicenter of an earthquake
- The depth of an earthquake focus
- The magnitude (power) of an earthquake
- The type of fault movement that produced an earthquake
- Whether an earthquake beneath the ocean is likely to have generated a tsunami (a set of giant ocean waves)

In addition to information about earthquakes and faults, seismology gives us knowledge of the layers of the earth. Much of what we know about the crust, lithosphere, asthenosphere, mantle, and core comes from seismology. See the Earth's interior Basics page.

Seismology also gives us information about underground nuclear testing that takes place anywhere on earth, allows possible oil reservoirs to be located within the earth's crust, and helps us predict when a volcano is about to erupt.

Seismographs and seismometers are the instruments used to measure seismic waves. The traditional analog seismograph utilizes a pen (stylus) embedded in a heavy weight, which is suspended on springs. When the earth moves during an earthquake, a piece of paper rolling beneath the stylus moves with the earth, but the stylus, with its weight suspended on springs, remains stationary, drawing lines on the sheet of paper that show the seismic motions of the earth. The USGS photo below shows a seismogram from a seismograph located in Columbia, California that recorded the 1989 Loma Prieta Earthquake.



With modern technology, seismographs with pens and rolling sheets of paper are being replaced by seismometers with electronic sensors and computer screens. Seismographs and seismometers both produce a seismogram, which is a graphic record of the seismic waves, viewed either on paper or on a computer monitor.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Earthquakes. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 8.3: Reading- The Nature of Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.4: Reading- Causes of Earthquakes

The following video explains the cause of earthquakes.

A link to an interactive elements can be found at the bottom of this page.

Overview of Elastic Rebound Theory

In an earthquake, the initial point where the rocks rupture in the crust is called the **focus**. The epicenter is the point on the land surface that is directly above the focus. In about 75% of earthquakes, the focus is in the top 10 to 15 kilometers (6 to 9 miles) of the crust. Shallow earthquakes cause the most damage because the focus is near where people live. However, it is the epicenter of an earthquake that is reported by scientists and the media (figure 1).

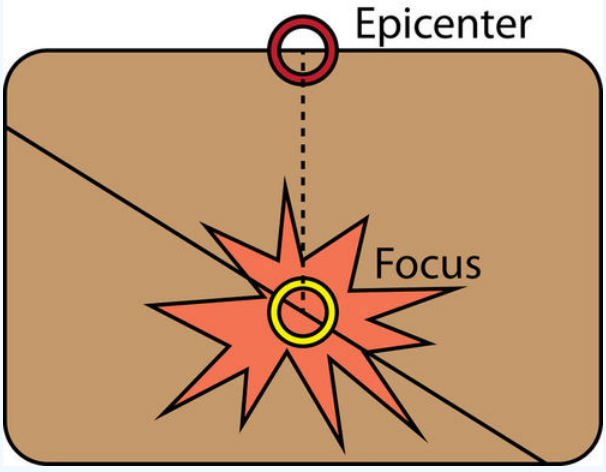


Figure 1. In the vertical cross section of crust, there are two features labeled—the focus and the epicenter, which is directly above the focus.

Watch this animation summarizing elastic rebound theory.

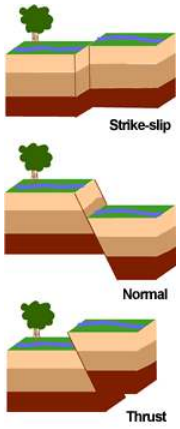


Figure 2. Fault types

Tectonic earthquakes occur anywhere in the earth where there is sufficient stored elastic strain energy to drive fracture propagation along a **fault plane**. The sides of a fault move past each other smoothly and aseismically only if there are no irregularities or asperities along the fault surface that increase the frictional resistance. Most fault surfaces do have such asperities and this leads to a form of stick-slip behavior. Once the fault has locked, continued relative motion between the plates leads to increasing stress and therefore, stored strain energy in the volume around the fault surface. This continues until the stress has risen sufficiently to break through the asperity, suddenly allowing sliding over the locked portion of the fault, releasing the stored energy.[1]

This energy is released as a combination of radiated elastic strain seismic waves, frictional heating of the fault surface, and cracking of the rock, thus causing an earthquake. This process of gradual build-up of strain and stress punctuated by occasional

sudden earthquake failure is referred to as the elastic-rebound theory. It is estimated that only 10 percent or less of an earthquake's total energy is radiated as seismic energy. Most of the earthquake's energy is used to power the earthquake fracture growth or is converted into heat generated by friction. Therefore, earthquakes lower the Earth's available elastic potential energy and raise its temperature, though these changes are negligible compared to the conductive and convective flow of heat out from the Earth's deep interior.[2]

Earthquake Fault Types

There are three main types of fault, all of which may cause an interplate earthquake: normal, reverse (thrust) and strike-slip. Normal and reverse faulting are examples of dip-slip, where the displacement along the fault is in the direction of dip and movement on them involves a vertical component. Normal faults occur mainly in areas where the crust is being extended such as a divergent boundary. Reverse faults occur in areas where the crust is being shortened such as at a convergent boundary. Strike-slip faults are steep structures where the two sides of the fault slip horizontally past each other; transform boundaries are a particular type of strike-slip fault. Many earthquakes are caused by movement on faults that have components of both dip-slip and strike-slip; this is known as oblique slip.

Reverse faults, particularly those along convergent plate boundaries are associated with the most powerful earthquakes, megathrust earthquakes, including almost all of those of magnitude 8 or more. Strike-slip faults, particularly continental transforms, can produce major earthquakes up to about magnitude 8. Earthquakes associated with normal faults are generally less than magnitude 7. For every unit increase in magnitude, there is a roughly thirtyfold increase in the energy released. For instance, an earthquake of magnitude 6.0 releases approximately 30 times more energy than a 5.0 magnitude earthquake and a 7.0 magnitude earthquake releases 900 times (30 × 30) more energy than a 5.0 magnitude of earthquake. An 8.6 magnitude earthquake releases the same amount of energy as 10,000 atomic bombs like those used in World War II.



Figure 3. Aerial photo of the San Andreas Fault in the Carrizo Plain, northwest of Los Angeles

This is so because the energy released in an earthquake, and thus its magnitude, is proportional to the area of the fault that ruptures2.0.CO;2." id="return-footnote-276-3" href="#footnote-276-3" aria-label="Footnote 3">[3] and the stress drop. Therefore, the longer the length and the wider the width of the faulted area, the larger the resulting magnitude. The topmost, brittle part of the Earth's crust, and the cool slabs of the tectonic plates that are descending down into the hot mantle, are the only parts of our planet which can store elastic energy and release it in fault ruptures. Rocks hotter than about 300 degrees Celsius flow in response to stress; they do not rupture in earthquakes.[4] The maximum observed lengths of ruptures and mapped faults (which may break in a single rupture) are approximately 1000 km. Examples are the earthquakes in Chile, 1960; Alaska, 1957; Sumatra, 2004, all in subduction zones. The longest earthquake ruptures on strike-slip faults, like the San Andreas Fault (1857, 1906), the North Anatolian Fault in Turkey (1939) and the Denali Fault in Alaska (2002), are about half to one third as long as the lengths along subducting plate margins, and those along normal faults are even shorter.

The most important parameter controlling the maximum earthquake magnitude on a fault is however not the maximum available length, but the available width because the latter varies by a factor of 20. Along converging plate margins, the dip angle of the rupture plane is very shallow, typically about 10 degrees.[5] Thus the width of the plane within the top brittle crust of the Earth can become 50 to 100 km (Japan, 2011; Alaska, 1964), making the most powerful earthquakes possible.

Strike-slip faults tend to be oriented near vertically, resulting in an approximate width of 10 km within the brittle crust,[6] thus earthquakes with magnitudes much larger than 8 are not possible. Maximum magnitudes along many normal faults are even more

limited because many of them are located along spreading centers, as in Iceland, where the thickness of the brittle layer is only about 6 km.[7]

In addition, there exists a hierarchy of stress level in the three fault types. Thrust faults are generated by the highest, strike slip by intermediate, and normal faults by the lowest stress levels.[8] This can easily be understood by considering the direction of the greatest principal stress, the direction of the force that "pushes" the rock mass during the faulting. In the case of normal faults, the rock mass is pushed down in a vertical direction, thus the pushing force (**greatest** principal stress) equals the weight of the rock mass itself. In the case of thrusting, the rock mass "escapes" in the direction of the **least** principal stress, namely upward, lifting the rock mass up, thus the overburden equals the least principal stress. Strike-slip faulting is intermediate between the other two types described above. This difference in stress regime in the three faulting environments can contribute to differences in stress drop during faulting, which contributes to differences in the radiated energy, regardless of fault dimensions.

Earthquakes away from Plate Boundaries

Where plate boundaries occur within the continental lithosphere, deformation is spread out over a much larger area than the plate boundary itself. In the case of the San Andreas fault continental transform, many earthquakes occur away from the plate boundary and are related to strains developed within the broader zone of deformation caused by major irregularities in the fault trace (e.g., the "Big bend" region). The Northridge earthquake was associated with movement on a blind thrust within such a zone. Another example is the strongly oblique convergent plate boundary between the Arabian and Eurasian plates where it runs through the northwestern part of the Zagros Mountains. The deformation associated with this plate boundary is partitioned into nearly pure thrust sense movements perpendicular to the boundary over a wide zone to the southwest and nearly pure strike-slip motion along the Main Recent Fault close to the actual plate boundary itself. This is demonstrated by earthquake focal mechanisms.[9]

All tectonic plates have internal stress fields caused by their interactions with neighboring plates and sedimentary loading or unloading (e.g. deglaciation).[10] These stresses may be sufficient to cause failure along existing fault planes, giving rise to intraplate earthquakes.[11]

Shallow-Focus and Deep-Focus Earthquakes



Figure 4. Collapsed Gran Hotel building in the San Salvador metropolis, after the shallow 1986 San Salvador earthquake.

The majority of tectonic earthquakes originate at the ring of fire in depths not exceeding tens of kilometers. Earthquakes occurring at a depth of less than 70 km are classified as **shallow-focus** earthquakes, while those with a focal-depth between 70 and 300 km are commonly termed **mid-focus** or **intermediate-depth** earthquakes. In subduction zones, where older and colder oceanic crust descends beneath another tectonic plate, **deep-focus** earthquakes may occur at much greater depths (ranging from 300 up to 700 kilometers).[12]

These seismically active areas of subduction are known as Wadati–Benioff zones. Deep-focus earthquakes occur at a depth where the subducted lithosphere should no longer be brittle, due to the high temperature and pressure. A possible mechanism for the generation of deep-focus earthquakes is faulting caused by olivine undergoing a phase transition into a spinel structure.[13]

Earthquakes and Volcanic Activity

Earthquakes often occur in volcanic regions and are caused there, both by tectonic faults and the movement of magma in volcanoes. Such earthquakes can serve as an early warning of volcanic eruptions, as during the 1980 eruption of Mount St. Helens.[14] Earthquake swarms can serve as markers for the location of the flowing magma throughout the volcanoes. These swarms can be recorded by seismometers and tiltmeters (a device that measures ground slope) and used as sensors to predict imminent or upcoming eruptions.[15]

Rupture Dynamics

A tectonic earthquake begins by an initial rupture at a point on the fault surface, a process known as nucleation. The scale of the nucleation zone is uncertain, with some evidence, such as the rupture dimensions of the smallest earthquakes, suggesting that it is smaller than 100 m while other evidence, such as a slow component revealed by low-frequency spectra of some earthquakes, suggest that it is larger. The possibility that the nucleation involves some sort of preparation process is supported by the observation that about 40% of earthquakes are preceded by foreshocks. Once the rupture has initiated, it begins to propagate along the fault surface. The mechanics of this process are poorly understood, partly because it is difficult to recreate the high sliding velocities in a laboratory. Also the effects of strong ground motion make it very difficult to record information close to a nucleation zone.[16]

Rupture propagation is generally modeled using a fracture mechanics approach, likening the rupture to a propagating mixed mode shear crack. The rupture velocity is a function of the fracture energy in the volume around the crack tip, increasing with decreasing fracture energy. The velocity of rupture propagation is orders of magnitude faster than the displacement velocity across the fault. Earthquake ruptures typically propagate at velocities that are in the range 70–90% of the S-wave velocity, and this is independent of earthquake size. A small subset of earthquake ruptures appear to have propagated at speeds greater than the S-wave velocity. These supershear earthquakes have all been observed during large strike-slip events. The unusually wide zone of coseismic damage caused by the 2001 Kunlun earthquake has been attributed to the effects of the sonic boom developed in such earthquakes. Some earthquake ruptures travel at unusually low velocities and are referred to as slow earthquakes. A particularly dangerous form of slow earthquake is the tsunami earthquake, observed where the relatively low felt intensities, caused by the slow propagation speed of some great earthquakes, fail to alert the population of the neighboring coast, as in the 1896 Sanriku earthquake.[17]

Earthquake Clusters

Most earthquakes form part of a sequence, related to each other in terms of location and time.[18] Most earthquake clusters consist of small tremors that cause little to no damage, but there is a theory that earthquakes can recur in a regular pattern.[19]

Aftershocks

An aftershock is an earthquake that occurs after a previous earthquake, the mainshock. An aftershock is in the same region of the main shock but always of a smaller magnitude. If an aftershock is larger than the main shock, the aftershock is redesignated as the main shock and the original main shock is redesignated as a foreshock. Aftershocks are formed as the crust around the displaced fault plane adjusts to the effects of the main shock.[20]

Earthquake Swarms

Earthquake swarms are sequences of earthquakes striking in a specific area within a short period of time. They are different from earthquakes followed by a series of aftershocks by the fact that no single earthquake in the sequence is obviously the main shock, therefore none have notable higher magnitudes than the other. An example of an earthquake swarm is the 2004 activity at Yellowstone National Park.[21] In August 2012, a swarm of earthquakes shook Southern California's Imperial Valley, showing the most recorded activity in the area since the 1970s.[22]

Sometimes a series of earthquakes occur in what has been called an earthquake storm, where the earthquakes strike a fault in clusters, each triggered by the shaking or stress redistribution of the previous earthquakes. Similar to aftershocks but on adjacent segments of fault, these storms occur over the course of years, and with some of the later earthquakes as damaging as the early ones. Such a pattern was observed in the sequence of about a dozen earthquakes that struck the North Anatolian Fault in Turkey in the 20th century and has been inferred for older anomalous clusters of large earthquakes in the Middle East.[23]

1. Ohnaka, M. (2013). *The Physics of Rock Failure and Earthquakes*. Cambridge University Press. p. 148. ↵

2. Spence, William; S. A. Sipkin; G. L. Choy (1989). "Measuring the Size of an Earthquake." United States Geological Survey. Retrieved 2006-11-03. ↵
3. Wyss, M. (1979). "Estimating expectable maximum magnitude of earthquakes from fault dimensions". *Geology***7** (7): 336–340 doi:10.1130/0091-7613(1979)7<336:EMEMOE>2.0.CO;2. ↵
4. Sibson R. H. (1982) "Fault Zone Models, Heat Flow, and the Depth Distribution of Earthquakes in the Continental Crust of the United States," *Bulletin of the Seismological Society of America*, Vol 72, No. 1, pp. 151–163. See also Sibson, R. H. (2002) "Geology of the crustal earthquake source," *International handbook of earthquake and engineering seismology*, Volume 1, Part 1, page 455, eds. W.H.K. Lee, H. Kanamori, P.C. Jennings, and C. Kisslinger, Academic Press. ↵
5. "Global Centroid Moment Tensor Catalog." Globalcmt.org. Retrieved 2011-07-24. ↵
6. "Instrumental California Earthquake Catalog." WGCEP. Retrieved 2011-07-24. ↵
7. Hjaltadóttir S., 2010, "Use of relatively located microearthquakes to map fault patterns and estimate the thickness of the brittle crust in Southwest Iceland." See also "Reports and publications | Seismicity | Icelandic Meteorological office." En.vedur.is. Retrieved 2011-07-24. ↵
8. Schorlemmer, D.; Wiemer, S.; Wyss, M. (2005). "Variations in earthquake-size distribution across different stress regimes." *Nature* **437** (7058): 539–542. doi:10.1038/nature04094. ↵
9. Talebian, M; Jackson, J (2004). "A reappraisal of earthquake focal mechanisms and active shortening in the Zagros mountains of Iran." *Geophysical Journal International***156** (3): 506–526. doi:10.1111/j.1365-246X.2004.02092.x. ↵
10. Nettles, M.; Ekström, G. (May 2010). "Glacial Earthquakes in Greenland and Antarctica." *Annual Review of Earth and Planetary Sciences***38** (1): 467–491. doi:10.1146/annurev-earth-040809-152414. ↵
11. Noson, Qamar, and Thorsen (1988). *Washington State Earthquake Hazards: Washington State Department of Natural Resources*. Washington Division of Geology and Earth Resources Information Circular 85. ↵
12. "M7.5 Northern Peru Earthquake of 26 September 2005" (PDF). National Earthquake Information Center. 17 October 2005. Retrieved2008-08-01. ↵
13. Greene II, H. W.; Burnley, P. C. (October 26, 1989). "A new self-organizing mechanism for deep-focus earthquakes." *Nature***341**(6244): 733–737. doi: 10.1038/341733a0. ↵
14. Foxworthy and Hill (1982). *Volcanic Eruptions of 1980 at Mount St. Helens, The First 100 Days: USGS Professional Paper 1249*. ↵
15. Watson, John; Watson, Kathie (January 7, 1998). "Volcanoes and Earthquakes." United States Geological Survey. Retrieved May 9,2009. ↵
16. National Research Council (U.S.). Committee on the Science of Earthquakes (2003). "5. Earthquake Physics and Fault-System Science." *Living on an Active Earth: Perspectives on Earthquake Science*. Washington D.C.: National Academies Press. p. 418. Retrieved 8 July 2010. ↵
17. *Ibid.* ↵
18. "What are Aftershocks, Foreshocks, and Earthquake Clusters?" ↵
19. "Repeating Earthquakes." United States Geological Survey. January 29, 2009. Retrieved May 11, 2009. ↵
20. "What are Aftershocks, Foreshocks, and Earthquake Clusters?" ↵
21. "Earthquake Swarms at Yellowstone." United States Geological Survey. Retrieved 2008-09-15. ↵
22. Duke, Alan. "Quake 'swarm' shakes Southern California." CNN. Retrieved 27 August 2012. ↵
23. Amos Nur; Cline, Eric H. (2000). "Poseidon's Horses: Plate Tectonics and Earthquake Storms in the Late Bronze Age Aegean and Eastern Mediterranean" (PDF). *Journal of Archaeological Science***27** (1): 43–63. See also "Earthquake Storms." *Horizon*. 1 April 2003. Retrieved 2007-05-02. ↵

Contributors and Attributions

CC licensed content, Shared previously

- 7.2: The Nature of Earthquakes. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/7.2/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Naturally occurring earthquakes. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Earthquake#Naturally_occurring_earthquakes. **License**: *CC BY-SA: Attribution-ShareAlike*

All rights reserved content

- Earthquakes 101. **Authored by**: National Geographic. **Located at**: https://youtu.be/VSgB1IWr6O4. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 8.4: Reading- Causes of Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.5: Reading- Common Locations of Earthquakes

Earthquakes and Plate Boundaries

Most, but not all, earthquakes occur at or near plate boundaries. A great deal of stress is concentrated and a great deal of strain, much of it in the form of rupture of the earth, takes place at locations where two plates diverge, transform, or converge relative to each other.

Tension is the dominant stress at divergent plate boundaries. Normal faults and rift valleys as the predominant earthquake-related structures at divergent plate boundaries. Earthquakes at divergent plate boundaries are usually relatively shallow, and, though they can be damaging, the most powerful earthquakes at divergent plate boundaries are not nearly as powerful as the most powerful earthquakes at convergent plate boundaries.

Transform plate boundaries are zones dominated by horizontal shear, with strike-slip faults the most characteristic fault type. Most transform plate boundaries cut through relatively thin oceanic crust, part of the structure of the ocean floor, and produce relatively shallow earthquakes that are only rarely of major magnitude. However, where transform plate boundaries and their strike-slip faults cut through the thicker crust of islands or the even thicker crust of continents, more stress may need to build up before the thicker masses of rock will rupture, and so the magnitudes of earthquakes can be higher than in transform plate boundary zones confined to thin oceanic crust. This is evident in such places as the San Andreas fault zone of California, where a transform fault cuts through continental crust and earthquakes there sometimes exceed 7.0 in magnitude.

Convergent plate boundaries are dominated by compression. The major faults found in convergent plate boundaries are usually reverse or thrust faults, including a master thrust fault at the boundary between the two plates and typically several more major thrust faults running roughly parallel to the plate boundary. The most powerful earthquakes that have been measured are subduction earthquakes, up to greater than 9.0 in magnitude. All subduction zones in the world are at risk of subduction earthquakes with magnitudes up to or even greater than 9.0 in extreme cases, and are likely to produce tsunamis. This includes the Cascadia subduction zone of northern California and coastal Oregon and Washington, the Aleutian subduction zone of southern Alaska, the Kamchatka subduction zone of Pacific Russia, the Acapulco subduction zone of southern Pacific Mexico, the Central American subduction zone, the Andean subduction zone, the West Indian or Caribbean subduction zone, and subduction zones of Indonesia, Japan, the Phillipines, and several more subduction zones in the western and southwestern Pacific Ocean.

Intraplate Earthquakes

Some earthquakes take place far away from plate boundaries. Earthquakes can occur wherever there is sufficient stress in the earth’s crust to drive rocks to rupture.

For example, Hawaii is thousands of km (thousands of miles) from any plate boundary, but the volcanoes that compose the islands have built up so rapidly that they are still undergoing gravitational stabilization. Sectors of the Hawaiian islands occasionally slump along normal faults, producing intraplate earthquakes. Most of the earthquakes occur on the big island of Hawaii, which is composed of the youngest, most recently built volcanoes. The geologic record shows that parts of the older islands have undergone major collapses in the last few million years, with sections of the islands sliding out to the seafloor in landslides floored on shallow normal faults.

Another example is the Basin and Range region of the western United States, including Nevada and eastern Utah, where the crust is subjected to tension. Earthquakes occur there on normal faults, far inland from the plate boundaries on the West Coast. The tension in the crust of the Basin and Range province may be partly due to a mid-ocean ridge system that subducted beneath California and is now located beneath the Basin and Range, causing tension in the lithosphere.

The region around Yellowstone National Park also undergoes occasional major earthquakes on normal faults. Earthquakes in that area may be due to the Yellowstone hot spot causing differential thermal expansion of the lithosphere in a broad zone round the hot spot center.

Several East Coast cities, including Boston, New York, and Charleston in South Carolina, have experienced damaging earthquakes in the last two centuries. The faults beneath these cities may date back to the rifting of Pangea and the opening up of the Atlantic Ocean beginning around 200 million years ago.

In the area of the town of New Madrid, along the Mississippi River in southeastern Missouri and western Tennessee, great earthquakes occurred in 1811-1812. Minor to moderate earthquakes continue to occur there, keeping active the possibility of damaging earthquakes occurring there again in the future. The fault system beneath that area may date from times of continental collision and continental rifting in the distant geologic past, and recent stress in the crust around New Madrid may be from the massive build-up of sediment in the Mississippi River delta region, which spreads out to the south of that area.

Earthquakes and Volcanoes

The connections between earthquakes and volcanoes are not always obvious. However, when magma is moving up beneath a volcano, and when a volcano is erupting, it produces earthquakes. Volcanic earthquakes are distinct from the more common type of earthquakes that occur by elastic rebound along faults.

Seismologists can use the patterns and signals of earthquakes coming from beneath volcanoes to predict that the volcano is about to erupt, and can use seismic waves to see that a volcano is undergoing an eruption even if the volcano is at a remote location, hidden in darkness, or hidden in storm clouds.

Volcanic vents, and volcanoes in general, are commonly located along faults, or at the intersection of several faults. Major faults that already exist in the crust may be natural paths to channel rising magma. However, on major volcanic edifices, shallower faults are a product of the development of the volcano. There are feedback effects between the upward pressure of magma buoyancy in the crust, the growth of faults in volcanic zones, and the venting of volcanoes, which is not yet completely understood.

As was noted at the beginning of this section, not quite all earthquakes are due to the slippage of solid blocks of rock along faults. When a volcano undergoes a powerful pyroclastic eruption – in other words, when a volcano explodes – it causes the earth to shake. Earthquakes caused by an explosive volcanic eruptions produce a different seismic signal than earthquakes caused by slippage along faults.

Another example of earthquakes that are caused at least in part by magma movement, rather than by slippage of entirely solid rock along faults, is earthquakes set off by the movement of magma upward beneath a volcano, or up to higher levels in the crust whether or not there is a volcano on top. Such upward movement of magma within the crust is sometimes called magma injection. Seismologists are still researching the interactions between movement of magma in the crust, and related slippage along faults that may be caused by the pressure and movement of the magma.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Earthquakes. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 8.5: Reading- Common Locations of Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.6: Reading- The Ring of Fire

The **Ring of Fire** is an area where a large number of earthquakes and volcanic eruptions occur in the basin of the Pacific Ocean. In a 40,000 km (25,000 mi) horseshoe shape, it is associated with a nearly continuous series of oceanic trenches, volcanic arcs, and volcanic belts and/or plate movements. It has 452 volcanoes and is home to over 75% of the world's active and dormant volcanoes. It is sometimes called the **circum-Pacific belt**.

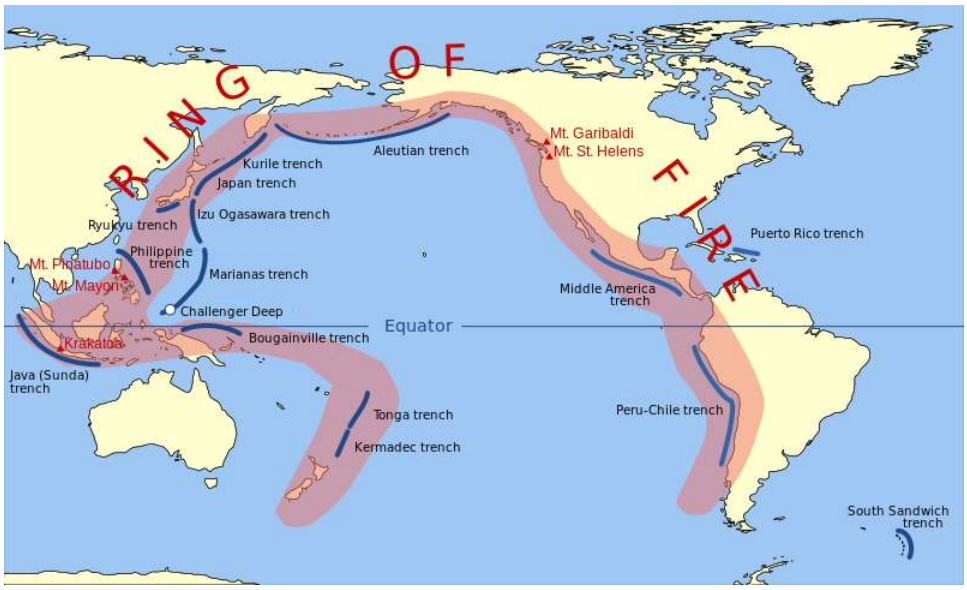


Figure 1. The Pacific Ring of Fire

About 90% of the world's earthquakes and 81% of the world's largest earthquakes occur along the Ring of Fire. The next most seismically active region (5–6% of earthquakes and 17% of the world's largest earthquakes) is the Alpide belt, which extends from Java to Sumatra through the Himalayas, theMediterranean, and out into the Atlantic. The Mid-Atlantic Ridge is the third most prominent earthquake belt.

The Ring of Fire is a direct result of plate tectonics and the movement and collisions of lithospheric plates. The eastern section of the ring is the result of the Nazca Plate and the Cocos Plate being subducted beneath the westward moving South American Plate. The Cocos Plate is being subducted beneath theCaribbean Plate, in Central America. A portion of the Pacific Plate along with the small Juan de Fuca Plate are being subducted beneath the North American Plate. Along the northern portion, the northwestward-moving Pacific plate is being subducted beneath the Aleutian Islands arc. Farther west, the Pacific plate is being subducted along the Kamchatka Peninsula arcs on south past Japan. The southern portion is more complex, with a number of smaller tectonic plates in collision with the Pacific plate from the Mariana Islands, the Philippines,Bougainville, Tonga, and New Zealand; this portion excludes Australia, since it lies in the center of its tectonic plate. Indonesia lies between the *Ring of Fire* along the northeastern islands adjacent to and including New Guinea and the *Alpide belt* along the south and west from Sumatra, Java, Bali, Flores, and Timor. The famous and very active San Andreas Fault zone of California is a transform faultwhich offsets a portion of the East Pacific Rise under southwestern United Statesand Mexico. The motion of the fault generates numerous small earthquakes, at multiple times a day, most of which are too small to be felt. The active Queen Charlotte Fault on the west coast of the Haida Gwaii, British Columbia, Canada, has generated three large earthquakes during the 20th century: a magnitude 7 event in 1929; a magnitude 8.1 in 1949 (Canada's largest recorded earthquake); and a magnitude 7.4 in 1970.

Contributors and Attributions

CC licensed content, Shared previously

- Ring of Fire. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Ring_of_Fire. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 8.6: Reading- The Ring of Fire is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.7: Self Check- Causes and Location of Earthquakes

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1106

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.7: Self Check- Causes and Location of Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.8: Outcome- Types of Waves

Compare and contrast properties and mechanics of different types of waves

When an earthquake occurs, some of the energy it releases is turned into heat within the earth. Some of the energy is expended in breaking and permanently deforming the rocks and minerals along the fault. The rest of the energy, which is most of the energy, is radiated from the focus of the earthquake in the form of seismic waves.

Seismic waves fall into two general categories: body waves (P-waves and S-waves), which travel through the interior of the earth, and surface waves, which travel only at the earth's surface.

What You'll Learn to Do

- Identify P-wave characteristics and behavior
- Identify S-wave characteristics and behavior
- Identify surface wave characteristics and behavior

Learning Activities

The learning activities for this section include the following:

- Reading: Body Waves
- Reading: Surface Waves
- Self Check: Types of Waves

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Seismic waves. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html#waves. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 8.8: Outcome- Types of Waves is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.9: Reading- Body Waves

Body waves travel through the interior of the earth. There are two types of body waves: P-waves and S-waves.

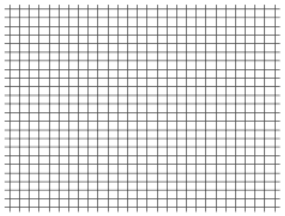
P-Waves

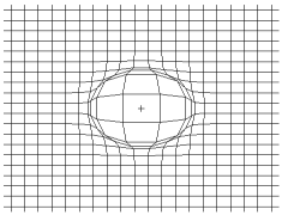
The P in P-waves stands for primary, because these are the fastest seismic waves and are the first to be detected once an earthquake has occurred. P-waves travel through the earth's interior many times faster than the speed of a jet airplane, taking only a few minutes to travel across the earth.

P-waves are predominantly compressional waves. As a P-wave passes, material compresses in the same direction the wave is moving, and then extends back to its original thickness once the wave has passed. The speed at which P-waves travel through material is determined by:

- rigidity—how strongly the material resists being bent sideways and is able to straighten itself out once the shearing force has passed – the more rigid the material, the faster the P-waves
- compressibility—how much the material can be compressed into a smaller volume and then recover its previous volume once the compressing force has passed; the more compressible the material, the faster the P-waves
- density—how much mass the material contains in a unit of volume; the greater the density of the material, the slower the P-waves

The animations below show P-waves propagating across a plane (left) and from a point source (right).





P-waves travel through liquids and gases as well as through solids. Although liquids and gases have zero rigidity, they have compressibility, which enables them to transmit P-waves. Sound waves are P-waves moving through the air.

Because the earth's mantle becomes more rigid and compressible as the depth below the asthenosphere increases, P-waves travel faster as they go deeper in the mantle. The density of the mantle also increases with depth below the asthenosphere. The higher density reduces the speed of seismic waves. However, the effects of increased rigidity and compressibility in the deep mantle are much greater than the effect of the increased density.

P-waves travel through materials with rigidity and/or compressiblity, and density	
greater rigidity	faster P-waves
greater compressibility	faster P-waves
greater density	slower P-waves

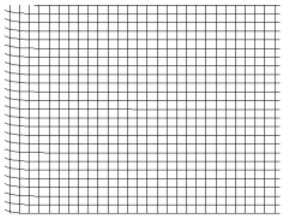
S-Waves

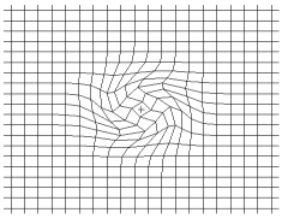
The S in S-waves stands for secondary, because they are the second-fastest seismic waves and the second type to be detected once an earthquake has occurred. Although S-waves are slower than P-waves, they still travel fast, over half the speed of P-waves, moving at thousands of kilometers per hour through the earth's crust and mantle.

S-waves are shear waves (though that is not what the S stands for). They move by material flexing or deforming sideways (shearing) from the direction of wave travel, and then returning to the original shape once the wave passes. The speed at which S-waves travel through material is determined only by:

- rigidity — how strongly the material resists being bent sideways and is able to straighten itself out once the shearing force has passed – the more rigid the material, the faster the S-waves
- density — how much mass the material contains in a unit of volume – the greater the density of the material, the slower the S-waves

The animations below show S-waves propogating across a plane (left) and from a point source (right):





S-waves can travel only through solids, because only solids have rigidity. S-waves cannot travel through liquids or gases.

Because the earth's mantle becomes more rigid as its depth below the asthenosphere increases, S-waves travel faster as they go deeper in the mantle. The density of the mantle also increases at greater depth, which has the effect of reducing the speed of seismic waves, but the increase in rigidity is much greater than the increase in density, so S-waves speed up as they get deeper in the mantle, in spite of the increased density.

S-waves travel through materials with rigidity and density	
greater rigidity	faster S-waves
greater density	slower S-waves

Contributors and Attributions

CC licensed content, Shared previously

- Seismic waves. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html#waves. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*
- Onde compression impulsion 1d (p-wave). **Authored by**: Christophe Dang Ngoc Chan. **Located at**: https://en.Wikipedia.org/wiki/File:Onde_compression_impulsion_1d_30_petit.gif. **License**: *CC BY-SA: Attribution-ShareAlike*
- Ondes compression 2d 20 (p-wave). **Authored by**: Christophe Dang Ngoc Chan. **Located at**: https://en.Wikipedia.org/wiki/File:Ondes_compression_2d_20_petit.gif. **License**: *CC BY-SA: Attribution-ShareAlike*
- Onde cisaillement impulsion 1d 30 (s-wave). **Authored by**: Christophe Dang Ngoc Chan. **Located at**: https://en.Wikipedia.org/wiki/File:Onde_cisaillement_impulsion_1d_30_petit.gif. **License**: *CC BY-SA: Attribution-ShareAlike*
- Ondes cisaillement 2d 20 (s-wave). **Authored by**: Christophe Dang Ngoc Chan. **Located at**: https://en.Wikipedia.org/wiki/File:Ondes_cisaillement_2d_20_petit.gif. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 8.9: Reading- Body Waves is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.10: Reading- Surface Waves

There are two types of surface waves, Rayleigh waves and Love waves. Rayleigh waves are named after Lord Rayleigh (John Strutt), an English aristocrat who, in his work as a scientist and mathematician, developed a detailed mathematical accounting of the type of surface wave named after him. Rayleigh waves are set off by the combined effect of P- and S-waves on the earth's surface. Rayleigh waves are sometimes called rolling waves. In Rayleigh waves the surface of the earth rises up and sinks down in crests and troughs, similar to waves on the surface of water. People who are outdoors during a major earthquake commonly see Rayleigh waves moving across the surface of the earth, and can feel the ground rising and falling as the waves pass beneath them.

Love waves, sometimes called L-waves, are named after Augustus Love, an English mathematician and physicist who first modeled them mathematically. Love waves involve the surface shearing sideways and then returning to its original form as each wave passes.

All surface waves travel slower than body waves and Rayleigh waves are slower than Love waves.

Contributors and Attributions

CC licensed content, Shared previously

- Seismic waves. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html#waves. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 8.10: Reading- Surface Waves is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.11: Self Check- Types of Waves

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1107

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.11: Self Check- Types of Waves is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.12: Outcome- Magnitude and Intensity

Define and compare magnitude versus intensity

This section introduces you to the magnitude and intensity of earthquakes. You will learn how the two are similar and how they are different.

What You'll Learn to Do

- Define earthquake magnitude.
- Define earthquake intensity.

Learning Activities

The learning activities for this section include the following:

- Reading: Measuring Earthquakes
- Reading: Magnitude versus Intensity
- Self Check: Magnitude and Intensity

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.12: Outcome- Magnitude and Intensity is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.13: Reading- Measuring Earthquakes

People have always tried to quantify the size of and damage done by earthquakes. Since early in the 20th century, there have been three methods. What are the strengths and weaknesses of each?

- Mercalli Intensity Scale. Earthquakes are described in terms of what nearby residents felt and the damage that was done to nearby structures.
- Richter magnitude scale. Developed in 1935 by Charles Richter, this scale uses a seismometer to measure the magnitude of the largest jolt of energy released by an earthquake.
- Moment magnitude scale. Measures the total energy released by an earthquake. Moment magnitude is calculated from the area of the fault that is ruptured and the distance the ground moved along the fault.

The Richter scale and the moment magnitude scale are logarithmic.

- The amplitude of the largest wave increases ten times from one integer to the next.
- An increase in one integer means that thirty times more energy was released.
- These two scales often give very similar measurements.

How does the amplitude of the largest seismic wave of a magnitude 5 earthquake compare with the largest wave of a magnitude 4 earthquake? How does it compare with a magnitude 3 quake? The amplitude of the largest seismic wave of a magnitude 5 quake is 10 times that of a magnitude 4 quake and 100 times that of a magnitude 3 quake.

How does an increase in two integers on the moment magnitude scale compare in terms of the amount of energy released? Two integers equals a 900-fold increase in released energy.

Which scale do you think is best? With the Richter scale, a single sharp jolt measures higher than a very long intense earthquake that releases more energy. The moment magnitude scale more accurately reflects the energy released and the damage caused. Most seismologists now use the moment magnitude scale.

The way scientists measure earthquake intensity and the two most common scales, Richter and moment magnitude, are described along with a discussion of the 1906 San Francisco earthquake in *Measuring Earthquakes* video:

A link to an interactive elements can be found at the bottom of this page.

Contributors and Attributions

CC licensed content, Shared previously

- 7.3: Measuring and Predicting Earthquakes. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/7.3/. **License**: *CC BY-NC: Attribution-NonCommercial*

All rights reserved content

- Measuring Earthquakes. **Authored by**: NASASciFiles's channel. **Located at**: https://youtu.be/wtlu_aDteCA. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 8.13: Reading- Measuring Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.14: Reading- Magnitude versus Intensity

Magnitude and Intensity measure different characteristics of earthquakes. Magnitude measures the energy released at the source of the earthquake. **Magnitude** is determined from measurements on seismographs. **Intensity** measures the strength of shaking produced by the earthquake at a certain location. Intensity is determined from effects on people, human structures, and the natural environment.

Calculating Earthquake Magnitude

The magnitude of an earthquake is a number that allows earthquakes to be compared with each other in terms of their relative power. For several decades, earthquake magnitudes were calculated based on a method first developed by Charles Richter, a seismologist based in California. Richter used seismograms of earthquakes that occurred in the San Andreas fault zone to calibrate his magnitude scale.

Two measurements are factored together to determine the Richter magnitude of an earthquake: the amplitude of the largest waves recorded on a seismogram of the earthquake, and the distance to the epicenter of the earthquake. The maximum amplitude seismic wave – the height of the tallest one – is measured in mm on a seismogram. The distance to the epicenter must also be taken into account because the greater the distance from the earthquake, the smaller the waves get. The effect of distance is factored out of the calculation. There is no upper limit defined for the Richter scale, but after a century of seismograph measurements, it appears that rocks in the earth release their stress before building up enough energy to reach magnitude 10.

The Richter scale was found to not transfer very well from the San Andreas fault zone, a transform plate boundary, to the much more powerful earthquakes that occur at convergent plate boundaries, particularly subduction zone earthquakes. Therefore, the Richter scale has been replaced by the moment magnitude scale, symbolized as $\mathbf{M_w}$.

The moment magnitude scale is broadly similar to the Richter scale, but it takes more factors into account, including the total area of the fault that moves during the earthquake, and how much it moves. This produces a magnitude number that is a better indicator of the total amount of energy released by the earthquake. Because the moment magnitude scale has replaced the Richter scale, we will assume from here on that we are referring to moment magnitude, not Richter magnitude, when we speak of earthquake magnitude.

The magnitude scale portrays energy logarithmically to approximately base 32. For example, a magnitude 6.0 earthquake releases about 32 times as much energy as a magnitude 5.0 earthquake. A magnitude 7.0 releases about $32 \times 32 = 1024$ times as much energy as a magnitude 5.0 earthquake. A magnitude 9.0 earthquake, which rarely occurs, releases over a million times as much energy as a magnitude 5.0 earthquake.

Ranking Earthquake Intensity

Earthquake intensity is very different from earthquake magnitude. Earthquake intensity is a ranking based on the observed effects of an earthquake in each particular place. Therefore, each earthquake produces a range of intensity values, ranging from highest in the epicenter area to zero at a distance from the epicenter. The most commonly used earthquake intensity scale is the Modified Mercalli earthquake intensity scale. Refer to the Modified Mercalli Intensity Scale page on the US Geological Survey Earthquake Hazards Program website for an abbreviated version.

The table below shows approximately how many earthquakes occur each year in each magnitude range and what the intensity might be at the epicenter for each magnitude range.

Magnitude	Average number per year	Modified Mercalli Intensity	Description
0 – 1.9	>1 million	—	micro – not felt
2.0 – 2.9	>1 million	I	minor – rarely felt
3.0 – 3.9	about 100,000	II – III	minor – noticed by a few people
4.0 – 4.9	about 10,000	IV – V	light – felt by many people, minor damage possible
5.0 – 5.9	about 1,000	VI – VII	moderate – felt by most people, possible broken plaster and chimneys
6.0 – 6.9	about 130	VII – IX	strong – damage variable depending on building construction and substrate
7.0 – 7.9	about 15	IX – X	major – extensive damage, some buildings destroyed
8.0 – 8.9	about 1	X – XII	great – extensive damage over broad areas, many buildings destroyed
9.0 and above	< 1	XI – XII	great – extensive damage over broad areas, most buildings destroyed

Magnitude / Intensity Comparison

The following table gives intensities that are typically observed at locations near the epicenter of earthquakes of different magnitudes.

Magnitude	Typical Maximum Modified Mercalli Intensity
1.0 – 3.0	**I**
3.0 – 3.9	**II – III**
4.0 – 4.9	**IV – V**
5.0 – 5.9	**VI – VII**
6.0 – 6.9	**VII – IX**
7.0 and higher	**VIII** or higher

Abbreviated Modified Mercalli Intensity Scale

I. Not felt except by a very few under especially favorable conditions.
II. Felt only by a few persons at rest, especially on upper floors of buildings.
III. 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. 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. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII. 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. 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. 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. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII. Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Earthquakes. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html#seismlgy. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

Public domain content

- Magnitude / Intensity Comparison. **Provided by**: USGS. **Located at**: http://earthquake.usgs.gov/learn/topics/mag_vs_int.php. **License**: *Public Domain: No Known Copyright*

This page titled 8.14: Reading- Magnitude versus Intensity is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.15: Self Check- Magnitude and Intensity

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1108

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.15: Self Check- Magnitude and Intensity is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.16: Outcome- Earthquake Hazards and Prediction

Investigate the causes, common locations and hazards of earthquakes

You will examine some of the hazards associated with earthquakes.

What You'll Learn to Do

- Identify common hazards associated with earthquakes.
- Recognize our limited ability to predict earthquakes.

Learning Activities

The learning activities for this section include the following:

- Reading: Earthquake Hazards
- Reading: Earthquake Prediction
- Reading: Seismicity and Earthquake Prediction
- Self Check: Earthquake Hazards and Prediction

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.16: Outcome- Earthquake Hazards and Prediction is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.17: Reading- Earthquake Hazards

Earthquakes can be hazardous to humans and property in a variety of ways. Earthquake hazards arise from a combination of factors such as the size of the earthquake, distance to the epicenter, the underlying material and geologic structures, and building construction.

Potential Hazards

Ground Shaking

Ground shaking is caused by seismic waves During a significant earthquake, a particular location, and any building at that location, will be shaken by body waves (P- and S-) and surface waves (Rayleigh and Love. Each type of wave will have a different frequency (different number of waves passing by each second), and can shear or move a building in a different way, sometimes simultaneously. Adjacent neighborhoods or towns may experience very different intensities from the same earthquake, based on how far they are from the epicenter and what sort of rocks or sediments are in the ground beneath each area. Places underlain by thick deposits of unconsolidated sediments will experience a higher amplitude of shaking, at the same distance from the same earthquake, than places underlain by solid bedrock all the way to the surface. If unconsolidated sediments are fine-grained and wet, they may undergo liquefaction, increasing the damage to buildings and infrastructure and therefore increasing the intensity of the earthquake there. If unconsolidated sediments are overlain by a layer of artificial fill, the area is likely to experience more intense shaking and undergo more ground settling, and liquefaction if wet, than places that have not had a layer of artificial fill added.

Mexico City, one of the most populated cities in the world, is in a basin in the mountains of Mexico. Much of the city is built on artificial fill on top of fine-grained sediments from an extensive lake and wetlands that were drained and filled in as the city grew. As a result of how seismic waves are amplified in soft sediments, the shaking of the ground in Mexico City during an earthquake is greater than it is in areas outside the basin, which have bedrock close to the surface. During the 1985 earthquake, which originated offshore of Acapulco on the Pacific coast, 300 km (200 miles) away, many buildings in Mexico City collapsed and more than 20,000 people died.

The Marina District in northern San Francisco is built on artificial fill on wet bayshore sediments. Rubble and debris from buildings that collapsed or burned in that district as a result of the 1906 earthquake was used as artificial fill beneath structures built during the reconstruction of that area. In 1989, the Loma Prieta earthquake caused collapse of several buildings in the Marina District, and several people died there. Another example of a structure on wet ground covered by artificial fill that collapsed during the Loma Prieta earthquake is the Cypress viaduct in Oakland, CA. The USGS photo below shows the failed support columns.

Permanent Ground Displacement

During large earthquakes, the ground may permanently shift to a new position up, down, or sideways (up to 10 or more m, 30 or 40 ft, in extreme cases). This change in the location of the ground, which also tilts the ground, may cause disruption of roads and utilities and, in coastal cities, submergence or emergence of harbor facilities. Even ground shifts of less than a meter (a foot or two) can cause serious disruption to infrastructure.

Earth Rupture

During most earthquakes, some rupturing of the earth's surface takes place along the fault trace. This produces a fault scarp, which may have up to several m (up to 10 ft or more) of vertical displacement. This can disrupt roads and utilities, and any buildings on a fault that ruptures may undergo extensive damage.

Rupture of the earth during an earthquake may also occur on secondary faults. Earthquake-induced rupture of the earth's surface may also take place in weak zones of surface sediment that fracture and spread. If enough spreading of a ruptured surface layer takes place, it can be classified as a landslide. The NOAA photo below shows substantial damage in the Turnagain-By-The-Sea subdivision caused by the 1964 Great Alaskan Earthquake.

Landslides and Avalanches

On steep slopes and in mountainous areas, large earthquakes can set off many landslides, rockfalls, or avalanches. These can damage buildings, towns, or roads in the path of the landslides.

Liquefaction

If fine- or medium-grained, unconsolidated sediments are saturated with groundwater, the shaking that occurs during an earthquake may cause the sediment grains to lose contact with each other and become suspended in the water, temporarily turning what was solid ground into liquid ground. Building and other structures may sink, tilt, or slide a short distant in liquefied ground, causing serious damage.

Fires

Fires are a secondary rather than a primary effect of earthquakes. Broken electrical wires and natural gas pipes commonly set off fires during earthquakes. To compound the problem, the water supply may also be disrupted by earthquake damage, making it impossible to put the fire out with water from fire hydrants. The fire that broke out as a result of the great San Francisco earthquake of 1906 burned much of the city to the ground, causing more extensive damage to buildings than the shaking of the ground did during the earthquake.

Tsunamis

A tsunami is a set of waves in the ocean (or a large lake) with an extremely long wavelength, typically over 100 km long. Tsunamis move at many 100s of km per hour in deep water. Tsunamis can be set off by violent volcanic eruptions originating just below sea level, by giant landslides that either occur underwater or tumble into the sea from coastal mountains, by large meteorite impacts, and, most commonly, by earthquakes that greatly shake the ocean floor, which commonly happens at subduction zones.

The amplitude, or crest height, of an individual tsunami wave may be only about 1 m (roughly 3 feet high) in the open ocean. It is common for a tsunami to pass ships at sea without being noticed. However, as the wave approaches shore where the bottom grows shallower, the crest builds up to a height of up to several tens of meters (over 30 feet in some cases). The wave crest may wash ashore for several minutes before subsiding. Even a tsunami wave of no higher than 3 m (10 feet) coming ashore can cause extensive damage in harbors and to shores, as the long-wavelength wave keeps pouring in for several minutes.

Tsunamis consist of more than one wave, so a second wave crest may climb ashore several minutes later. Some tsunamis lead with the wave trough, so the first thing noticed as that type of tsunami approaches a shore is a dramatic drawback, or retreat, of the sea, like the tide suddenly going out. Such a drawback will inevitably be followed by a rising tsunami wave crest.

The tsunamis from the Sumatra earthquake of 2004 killed over 100,000 people in coastal areas of the Indian Ocean, some on shores several thousand km (several thousand miles) away from the epicenter of the earthquake. The great southeast Alaska earthquake of 1964 generated a tsunami that killed 16 people on the coast of Oregon and northern California, over 1,000 km (600 miles) away. Tsunamis have been known to cross the entire Pacific Ocean and cause fatalities a third of the way around the world. Hawaii, in the middle of the Pacific Ocean, has been damaged by tsunamis, originating from subduction earthquakes on the Pacific Rim, several times in the last few centuries. Japan, with its complex set of subduction zones and its eastern shoreline open to the Pacific Ocean, has experienced over 100 tsunamis in its recorded history, most recently as a result of a great subduction earthquake off the northern island in 2011 which resulted in several coastal towns being destroyed and thousands of people dying. The last great tsunami generated by the Cascadia subduction zone along the coast of the Pacific Northwest flooded coastal areas of Washington, Oregon northern California, and Vancouver Island in Canada. It occurred in 1701, long before the region was as populated as it is now. Subduction continues in the Cascadia subduction zone and more tsunamis can be expected to be generated by earthquakes there in the future.

Mitigating Earthquake Damage

Much can be done to reduce the risk of fatalities during earthquakes, and to reduce the damage to buildings and infrastructure; in other words, to mitigate the effects of earthquakes.

In many cases, it is collapsed buildings that cause the most harm during an earthquake. Buildings should be constructed in ways that make them unlikely to collapse during an earthquake. The strategies that engineers have developed include having sufficient flexibility in the structure to absorb shaking during an earthquake. Bricks, mortar, and concrete are rigid and brittle. However, bricks and mortar, and concrete, can be reinforced with steel to make them better able to survive an earthquake. Wood and steel are more flexible than bricks, mortar, and concrete, and lend themselves to the type of building that, properly designed and built according to code, is likely to survive an earthquake without collapsing.

The way a building is attached to its foundation, and how the foundation is anchored in the earth, are important considerations in earthquake design. Many houses built in the the early and mid-1900s in California were not attached to their foundations, based on the assumption that the weight of a house would keep it on its foundation. It turned out to be a bad assumption. Earthquakes caused houses to slide off their foundations. Many home-owners in the state have taken steps to make sure that their houses are now attached to their foundations; if a home-owner buys earthquake insurance, it is usually required by the insurance company that they do so. A large building or skyscraper built in an earthquake-prone area will normally have a great deal of flexibility built into it, including some sort of elastic strain absorption mechanism focused on points where the building attaches to its foundation.

Infrastructure—roads, bridges, utilities—can be built with margins of safety for the event of an earthquake. This includes gas pipelines designed to slide back and forth on their supports and having built-in shutoff valves that may be activated by automatic sensors, electric lines and grids with similar flexibility and shut-off capabilities, and roads, overpasses, and bridges built to withstand shaking during an earthquake.

Development and enforcement of building codes aimed at reducing risk from earthquakes often requires resources that are not available in impoverished regions. This leads to a higher likelihood that buildings will collapse from the same size earthquake in some areas of the world than in other areas.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Earthquakes. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 8.17: Reading- Earthquake Hazards is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.18: Reading- Earthquake Prediction

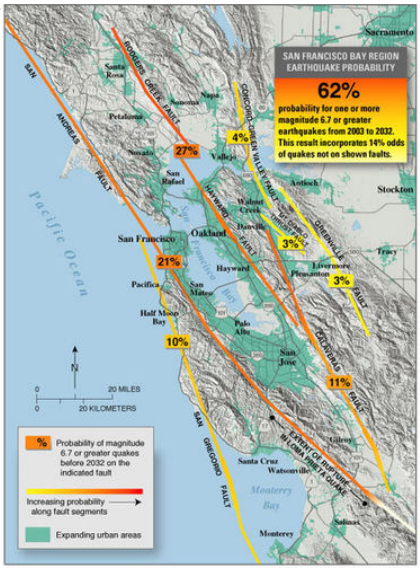


Figure 1. The probabilities of earthquakes striking along various faults in the San Francisco area between 2003 (when the work was done) and 2032.

Scientists are a long way from being able to predict earthquakes. A good prediction must be accurate as to where an earthquake will occur, when it will occur, and at what magnitude it will be so that people can evacuate. An unnecessary evacuation is expensive and causes people not to believe authorities the next time an evacuation is ordered.

Where an earthquake will occur is the easiest feature to predict. Scientists know that earthquakes take place at plate boundaries and tend to happen where they've occurred before (figure 1). Earthquake-prone communities should always be prepared for an earthquake. These communities can implement building codes to make structures earthquake safe.

When an earthquake will occur is much more difficult to predict. Since stress on a fault builds up at the same rate over time, earthquakes should occur at regular intervals (figure 2). But so far scientists cannot predict when quakes will occur even to within a few years.

Signs sometimes come before a large earthquake. Small quakes, called foreshocks, sometimes occur a few seconds to a few weeks before a major quake. However, many earthquakes do not have foreshocks and small earthquakes are not necessarily followed by a large earthquake. Often, the rocks around a fault will dilate as microfractures form. Ground tilting, caused by the buildup of stress in the rocks, may precede a large earthquake, but not always. Water levels in wells fluctuate as water moves into or out of fractures before an earthquake. This is also an uncertain predictor of large earthquakes. The relative arrival times of P-waves and S-waves also decreases just before an earthquake occurs.

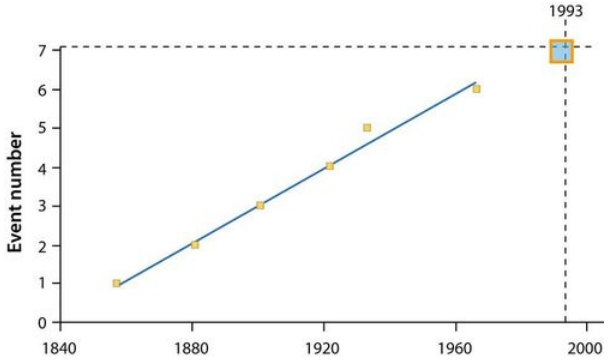


Figure 2. Around Parkfield, California, an earthquake of magnitude 6.0 or higher occurs about every 22 years. So seismologists predicted that one would strike in 1993, but that quake came in 2004—11 years late.

Folklore tells of animals behaving erratically just before an earthquake. Mostly these anecdotes are told after the earthquake. If indeed animals sense danger from earthquakes or tsunami, scientists do not know what it is they could be sensing, but they would

like to find out.

Contributors and Attributions

CC licensed content, Shared previously

- 7.3: Measuring and Predicting Earthquakes. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/7.3/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 8.18: Reading- Earthquake Prediction is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.19: Reading- Seismicity and Earthquake Prediction

Seismicity is the study of how often earthquakes occur in a particular area, which types of earthquakes occur there, and why.

In the United States, the areas that most frequently experience earthquakes are the coast of California, Oregon, and Washington, the southern coast and Aleutian Islands of Alaska, Hawaii, and the mountain west from the Rocky Mountains to the Pacific coast. The central and eastern United States rarely experience significant earthquakes.

Earthquake epicenters compiled on a map show that, on a global basis, most earthquakes occur around the rim of the Pacific Ocean, in the mountains of southern Asia from China to the Middle East, and in the Mediterranean Sea area. Earthquake epicenters also trace the mid-ocean ridges across the floors of the oceans.

Because nearly all earthquakes occur on faults, determining seismic risks on a finer scale largely consists of identifying, mapping, and studying active faults in each state or region. However, many active faults are hidden, either because any scarps they formed at the surface have been eroded or covered by sediments, soil, and vegetation, or because they are blind faults. A hidden fault is often not identified and located until one or more significant earthquakes has occurred on it and the seismic waves have been studied to determine its location and type of fault motion.

Information used to determine the seismicity of an area includes:

- frequency of earthquakes in the past, as deduced from:
  - historic records
  - geologic studies that examine evidence of the prehistoric earthquake record
- location of known active faults
- seismologic data collected on recent earthquakes that have occurred in the area
- tectonic setting of the area in terms of proximity to plate boundaries, and information about the plate boundary if one is nearby
- stress and strain being experienced by the crust in that area based on measurements from GPS equipment and from stress and strain measurements conducted in boreholes
- underground geologic layers and structures in that area based on cross-sections from geologic mapping, data from drilling, and remote imaging of deeper layers of the crust and mantle

Based on this information, the seismic risk of a particular area can be quantified statistically. For example, the odds of a major earthquake happening in the next century, or in the next 10 years, can be estimated for a specific seismic zone.

However, no scientific method has yet been developed that can predict precisely when the next earthquake in a specific region will happen, where it will happen, or what its magnitude will be. Scientists have looked into using such possible pre-earthquake indicators as ground tilting, changes in well water levels, changes in radon gas in groundwater near fault zones, changes in electrical conductivity in the earth around faults, changes or patterns in seismic activity that can be measured by seismometers even though it is not felt by humans, and strange animal behavior which, according to numerous, largely unconfirmed anecdotes, takes place before an earthquake. But, so far, none of these types of data have been found to lead to reliable earthquake predictions.

People have also looked into correlations between earthquakes and phases of the Moon, earthquakes and the time of day (such as dawn when the Sun is first shining on the ground), and so on. No connections have been found between earthquakes and these other types of phenomena.

As the study of seismicity stands now, we can identify which areas on earth will undergo major earthquakes in the coming decades and centuries, we can delineate which areas on earth are at risk for the most powerful types of earthquakes, and map the coastal areas that are most at risk of being inundated by a tsunami, but we cannot pinpoint in advance the date or location of the next major earthquake.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Earthquakes. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/earthquakes.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 8.19: Reading- Seismicity and Earthquake Prediction is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.20: Self Check- Earthquake Hazards and Prediction

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1109

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.20: Self Check- Earthquake Hazards and Prediction is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.21: Putting It Together- Earthquakes

Summary

Just to review, in the section we took an up close look at earthquakes. We made note of the following:

1. What seismic waves are and how they are generated
2. The different types of seismic waves and their characteristics
3. How seismic waves are used to give us a peak at the Earth's interior
4. What causes earthquakes and where they occur
5. The different ways earthquakes are measured
6. How different material responds to an earthquake
7. The inability of scientists to predict earthquakes with any accuracy

Synthesis

I'm sure at least some of the reasons to study earthquakes go without saying. Geologists study earthquakes so they can better understand the cause of earthquakes which can in turn help with future predictions. Right now, there is very little ability to predict an earthquake. Geologists are interested in how the ground and different materials move during the earthquake. All of this information helps scientists and engineers understand what is required to build structures to withstand earthquakes. The hazards associated with earthquakes are some of the most dangerous and deadly as you saw in the videos at the beginning of the section.

So, why do California and Japan have so many earthquakes? California is located on the San Andreas Fault (one of many), which is a part of a transform plate boundary that is constantly moving. In the case of Japan, if you look back at the plate tectonics map, you will see Japan sits on top of *three* different tectonic plates that all moving in different ways. We now know that this movement is the main cause of earthquakes. As we continue to learn more about earthquakes, perhaps the next 9.0 earthquake will not do so much damage or claim so many lives.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 8.21: Putting It Together- Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

8.22: Assignment- Earthquakes

In this assessment, you will read and interpret various seismograms to determine the location of an earthquake. You will also determine the magnitude of the earthquake. When you are finished you will be presented with a Certificate of Completion making you a Virtual Seismologist. Remember to access the tips and hits at the bottom of the page.

Basic Requirements (assignment criteria):

1. Go to the Virtual Earthquate (Links to an external site.) site from Geology Labs online.
2. Choose a location to “experience” your earthquake.
3. Read over the next page on how to determine the P-S wave time interval from a seismogram.
4. On the next page you will view three different seismograms. Determine the time difference from the P wave to the arrival of the S wave on each seismogram and enter it into the box.
5. Click on the convert button to go to the next page.
6. Use the bottom graph to get the epicenter distance. For example, if you have stated that the S-P interval is 35 seconds, you will find 35 seconds on the vertical (y-axis) and follow it across until it intersects the diagonal line. Then draw your line straight down to the horizontal line (x-axis) to get the distance. In this case, 35 seconds translates to 340 Km. Another example, 51 seconds is 500 Km. You will enter these values in the box on the right.
7. Click on find epicenter. Depending on well you did, you can either re-enter your data to try again or click View True Epicenter if you are close.
8. When you get close, go click on the View True Epicenter, look at how close you came to the true epicenter. Take a screenshot of the two pictures and save them for later.
9. Click on Compute Richter Magnitude. Read the explanation of magnitude, then go to the next page. Read about the nomogram and how to use it.
10. Go to the next page and complete the questions on magnitude. Click submit and proceed to the nomogram of your data.
11. Answer the magnitude estimate and then click on confirm magnitude. If you were successful you will have a screen congratulating you.
12. Fill in the necessary information to get your certificate, make sure you DO NOT email a copy to me. Click get certificate and you will see a green certificate and chart.
13. Take a screen shot and save this for later.
14. Open up a word document and insert both the picture of your earthquake location (the two side-by-side pictures) and the picture of your completion certificate and chart. Adjust them to fit on one page.

Answer the following questions on the same page:

1. Based on the location and magnitude of your earthquake, speculate on the type of damages your earthquake might have caused.
2. Now compare this to the Mercalli Intensity scale. What classification is your earthquake based on this scale?
3. How did the different waves (P, S & Surface Waves) assist you in determining the epicenter and the amount of damage caused?
4. Was your location in an area prone to earthquakes? Speculate on what might have caused this earthquake (be specific).
5. Why is it so difficult for geologists to predict when and where an earthquake will occur?
6. What connections can you make between the behavior of the seismic waves and the Earth’s interior?
7. Make sure your name is ON your document before submitting.

Tips and hints can be found here (Links to an external site.) .

This assessment is adapted from “Virtual Earthquake” by Gary Novack, originally foundhere (Links to an external site.).

Contributors and Attributions

CC licensed content, Original

- Earthquakes Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 8.22: Assignment- Earthquakes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

9: Volcanoes

Learning Objectives

Explain the origin of volcanic features and landforms; as well as the causes and hazards associated with volcanic activity.

- Describe and compare different volcano types.
- Describe the processes that form volcanoes.
- Classify and identify igneous features.
- Describe major volcanic hazards and their potential effects.
- Identify the various methods used to monitor volcanic activity.

9.1: Why It Matters- Volcanoes
9.2: Outcome- Volcano Types
9.3: Reading- Types of Volcanoes
9.4: Reading- Types of Eruptions
9.5: Reading- Supervolcanoes
9.6: Self Check- Volcano Types
9.7: Outcome- The Formation of Volcanoes
9.8: Reading- Volcanoes at Plate Boundaries
9.9: Reading- Volcanoes Hotspots
9.10: Self Check- The Formation of Volcanoes
9.11: Outcome- Igneous Features
9.12: Reading- Pyroclastic Deposits
9.13: Reading- Dikes and Sills
9.14: Reading- Volcanic Landforms
9.15: Self Check- Igneous Features
9.16: Outcome- Volcanic Hazards
9.17: Reading- Volcanic Gases, Pyroclastic Flow, and Tephra
9.18: Reading- Lahars, Landslides, and Lavaflow
9.19: Self Check- Volcanic Hazards
9.20: Outcome- Monitoring Volcanoes
9.21: Reading- Signs of an Eruption
9.22: Reading- Tools to Monitor Volcanoes
9.23: Self Check- Monitoring Volcanoes
9.24: Putting It Together- Volcanoes

This page titled 9: Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.1: Why It Matters- Volcanoes

Explain the origin of volcanic features and landforms; as well as the causes and hazards associated with volcanic activity.

Volcanoes are one of the most dynamic, powerful and destructive forces on the Earth. While they are majestic in appearance, they are often sleeping giants just waiting to wake up and make us take notice. Some of you may have seen volcanic eruptions in person or on TV. Volcanoes are the geologists' window into the Earth's interior. If you recall from the previous section, plate tectonics directly influences the location and types of volcanoes we find across the globe. Now we understand why the west coast of America as a chain of volcanoes in the Cascade Mountains and why Japan has so many active volcanoes.

? Occupation Focus: Volcanologists

Volcanologists have one of the most exciting yet dangerous jobs of all scientists. Please watch this video on the eruption of Mt. St. Helens in 1980 to learn more about volcanic eruptions, how scientists study the volcanoes and why volcanologists are important to society.



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=316

This video shows the most destructive eruption ever that happen to also be the loudest sound ever recorded on earth. This eruption actually blew the volcanoes out of existence, until recently as a new active volcano is currently forming in its place.



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=316

Learning Outcomes

- Describe and compare different volcano types.
- Describe the processes that form volcanoes.
- Classify and identify igneous features.
- Describe major volcanic hazards and their potential effects.
- Identify the various methods used to monitor volcanic activity

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

All rights reserved content

- Mount St. Helens May 18, 1980. **Provided by**: USGS. **Located at**: https://youtu.be/Ec30uU0G56U. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License
- THE LOUDEST SOUND IN HISTORY. **Authored by**: Second Thought. **Located at**: https://youtu.be/opWwfRS7HZU. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 9.1: Why It Matters- Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.2: Outcome- Volcano Types

Describe and compare different volcano types and the processes that form them

In this section, you will learn the different types of volcanoes, how they are formed and where they are commonly located.

What You'll Learn to Do

- Recognize the different types of volcanoes as well as their physical characteristics: composite, shield and cinder cone
- Recognize the different types of volcanic eruptions
- Discuss the occurance of supervolcanoes

Learning Activities

The learning activities for this section include the following:

- Reading: Types of Volcanoes
- Reading: Types of Eruptions
- Reading: Supervolcanoes
- Self Check: Volcano Types

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 9.2: Outcome- Volcano Types is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.3: Reading- Types of Volcanoes

A volcano is a vent through which molten rock and gas escape from a magma chamber. Volcanoes differ in many features such as height, shape, and slope steepness. Some volcanoes are tall cones and others are just cracks in the ground (figure 1). As you might expect, the shape of a volcano is related to the composition of its magma.



Figure 1. Mount St. Helens was a beautiful, classic, cone-shaped volcano. The volcano's 1980 eruption blew more than 400 meters (1,300 feet) off the top of the mountain.

Composite Volcanoes

Composite volcanoes are made of felsic to intermediate rock. The viscosity of the lava means that eruptions at these volcanoes are often explosive (figure 2).



Figure 2. Mt. Fuji, the highest mountain in Japan, is a dormant composite volcano.

The viscous lava cannot travel far down the sides of the volcano before it solidifies, which creates the steep slopes of a composite volcano. Viscosity also causes some eruptions to explode as ash and small rocks. The volcano is constructed layer by layer, as ash and lava solidify, one upon the other (figure 3). The result is the classic cone shape of composite volcanoes.

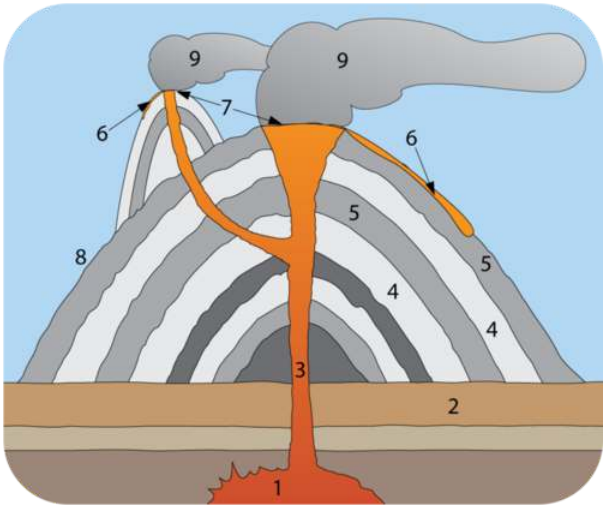


Figure 3. A cross section of a composite volcano reveals alternating layers of rock and ash: (1) magma chamber, (2) bedrock, (3) pipe, (4) ash layers, (5) lava layers, (6) lava flow, (7) vent, (8) lava, (9) ash cloud. Frequently there is a large crater at the top from the last eruption.

Shield Volcanoes

Shield volcanoes get their name from their shape. Although shield volcanoes are not steep, they may be very large. Shield volcanoes are common at spreading centers or intraplate hot spots (figure 4).



Figure 4. Mauna Loa Volcano in Hawaii (in the background) is the largest shield volcano on Earth with a diameter of more than 112 kilometers (70 miles). The volcano forms a significant part of the island of Hawaii.

The lava that creates shield volcanoes is fluid and flows easily. The spreading lava creates the shield shape. Shield volcanoes are built by many layers over time and the layers are usually of very similar composition. The low viscosity also means that shield eruptions are non-explosive.

This *Volcanoes 101* video from National Geographic discusses where volcanoes are found and what their properties come from:

A link to an interactive elements can be found at the bottom of this page.

Cinder Cones



Figure 5. In 1943, a Mexican farmer first witnessed a cinder cone erupting in his field. In a year, Paricutín was 336 meters high. By 1952, it reached 424 meters and then stopped erupting.

Cinder cones are the most common type of volcano. A cinder cone has a cone shape, but is much smaller than a composite volcano. Cinder cones rarely reach 300 meters in height but they have steep sides. Cinder cones grow rapidly, usually from a single eruption cycle (figure 5). Cinder cones are composed of small fragments of rock, such as pumice, piled on top of one another. The

rock shoots up in the air and doesn't fall far from the vent. The exact composition of a cinder cone depends on the composition of the lava ejected from the volcano. Cinder cones usually have a crater at the summit.

Cinder cones are often found near larger volcanoes (figure 6).

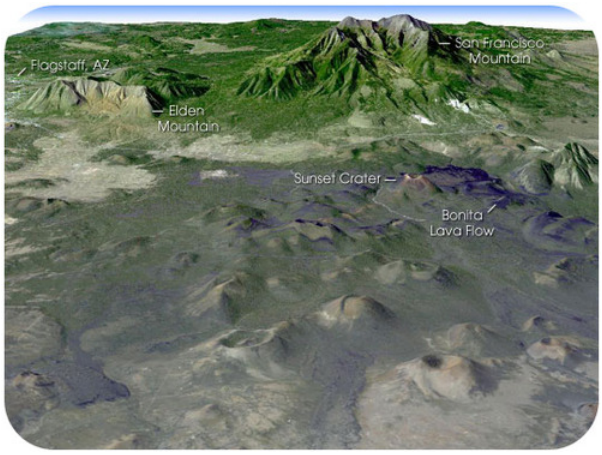


Figure 6. This Landsat image shows the topography of San Francisco Mountain, an extinct volcano, with many cinder cones near it in northern Arizona. Sunset crater is a cinder cone that erupted about 1,000 years ago.

Lesson Summary

- Composite, shield, cinder cones, and supervolcanoes are the main types of volcanoes.
- Composite volcanoes are tall, steep cones that produce explosive eruptions.
- Shield volcanoes form very large, gently sloped mounds from effusive eruptions.
- Cinder cones are the smallest volcanoes and result from accumulation of many small fragments of ejected material.
- An explosive eruption may create a caldera, a large hole into which the mountain collapses.

Contributors and Attributions

CC licensed content, Shared previously

- 8.3: Types of Volcanoes. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/8.3/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 9.3: Reading- Types of Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.4: Reading- Types of Eruptions



Figure 1. Some of the eruptive structures formed during volcanic activity: a Plinian eruption column, Hawaiian pahoehoe flows, and a lava arc from a Strombolian eruption.

Several **types ofvolcanic eruptions**—during which lava, tephra (ash, lapilli, volcanic bombs and blocks), and assorted gases are expelled from a volcanic vent or fissure—have been distinguished by volcanologists. These are often named after famous volcanoes where that type of behavior has been observed. Some volcanoes may exhibit only one characteristic type of eruption during a period of activity, while others may display an entire sequence of types all in one eruptive series.

There are three different types of eruptions. The most well-observed are magmatic eruptions, which involve the decompression of gas within magma that propels it forward. Phreatomagmatic eruptions are another type of volcanic eruption, driven by the compression of gas within magma, the direct opposite of the process powering magmatic activity. The third eruptive type is the phreatic eruption, which is driven by the superheating of steam via contact with magma; these eruptive types often exhibit no magmatic release, instead causing the granulation of existing rock.

Within these wide-defining eruptive types are several subtypes. The weakest are Hawaiian and submarine, then Strombolian, followed by Vulcanian and Surtseyan. The stronger eruptive types are Pelean eruptions, followed by Plinian eruptions; the strongest eruptions are called “Ultra-Plinian.” Subglacial and phreatic eruptions are defined by their eruptive mechanism, and vary in strength. An important measure of eruptive strength is Volcanic Explosivity Index (VEI), an order of magnitude scale ranging from 0 to 8 that often correlates to eruptive types.

Eruption Mechanisms

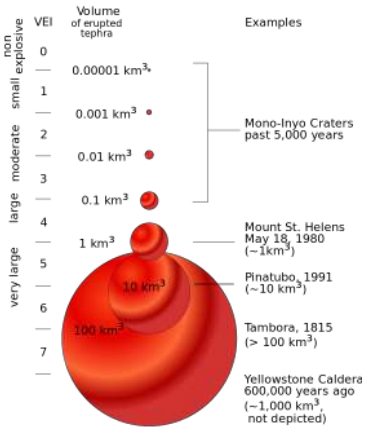


Figure 2. Diagram showing the scale of VEI correlation with total ejecta volume.

Volcanic eruptions arise through three main mechanisms:[1]

- Gas release under decompression causing magmatic eruptions
- Thermal contraction from chilling on contact with water causing phreatomagmatic eruptions
- Ejection of entrained particles during steam eruptions causing phreatic eruptions

There are two types of eruptions in terms of activity, explosive eruptions and effusive eruptions. Explosive eruptions are characterized by gas-driven explosions that propels magma and tephra.[2] Effusive eruptions, meanwhile, are characterized by the outpouring of lava without significant explosive eruption.[3]

Volcanic eruptions vary widely in strength. On the one extreme there are effusive Hawaiian eruptions, which are characterized by lava fountains and fluid lava flows, which are typically not very dangerous. On the other extreme, Plinian eruptions are large, violent, and highly dangerous explosive events. Volcanoes are not bound to one eruptive style, and frequently display many different types, both passive and explosive, even the span of a single eruptive cycle.[4] Volcanoes do not always erupt vertically from a single crater near their peak, either. Some volcanoes exhibit lateral and fissure eruptions. Notably, many Hawaiian eruptions start from rift zones,[5] and some of the strongest Surtseyan eruptions develop along fracture zones.[6] Scientists believed that pulses of magma mixed together in the chamber before climbing upward—a process estimated to take several thousands of years. But Columbia University volcanologists found that the eruption of Costa Rica’s Irazú Volcano in 1963 was likely triggered by magma that took a nonstop route from the mantle over just a few months.[7]

Volcano Explosivity Index

The volcanic explosivity index (commonly shortened to VEI) is a scale, from 0 to 8, for measuring the strength of eruptions. It is used by the Smithsonian Institution’s Global Volcanism Program in assessing the impact of historic and prehistoric lava flows. It operates in a way similar to the Richter scale for earthquakes, in that each interval in value represents a tenfold increasing in magnitude (it is logarithmic).[8] The vast majority of volcanic eruptions are of VEIs between 0 and 2.[9]

Volcanic eruptions by VEI index[10]					
VEI	Plume height	Eruptive volume*	Eruption type	Frequency**	Example
0	<100 m (330 ft)	1,000 m^3 (35,300 cu ft)	Hawaiian	Continuous	Kilauea
1	100–1,000 m (300–3,300 ft)	10,000 m^3 (353,000 cu ft)	Hawaiian/Strombolian	Fortnightly	Stromboli
2	1–5 km (1–3 mi)	1,000,000 m^3 (35,300,000 cu ft)†	Strombolian/Vulcanian	Monthly	Galeras (1992)
3	3–15 km (2–9 mi)	10,000,000 m^3 (353,000,000 cu ft)	Vulcanian	3 monthly	Nevado del Ruiz (1985)
4	10–25 km (6–16 mi)	100,000,000 m^3 (0.024 cu mi)	Vulcanian/Peléan	18 months	Eyjafjallajökull (2010)
5	>25 km (16 mi)	1 km^3 (0.24 cu mi)	Plinian	10–15 years	Mount St. Helens (1980)
6	>25 km (16 mi)	10 km^3 (2 cu mi)	Plinian/Ultra-Plinian	50–100 years	Krakatoa (1883)
7	>25 km (16 mi)	100 km^3 (20 cu mi)	Ultra-Plinian	500–1000 years	Tambora (1815)
8	>25 km (16 mi)	1,000 km^3 (200 cu mi)	Supervolcanic	50,000+ years[11]	Lake Toba (74 ka)

* This is the minimum eruptive volume necessary for the eruption to be considered within the category.

** Values are a rough estimate. They indicate the frequencies for volcanoes of that magnitude OR HIGHER

† There is a discontinuity between the 1st and 2nd VEI level; instead of increasing by a magnitude of 10, the value increases by a magnitude of 100 (from 10,000 to 1,000,000).

Magmatic Eruptions

Magmatic eruptions produce juvenile clasts during explosive decompression from gas release. They range in intensity from the relatively small lava fountains on Hawaii to catastrophic Ultra-Plinian eruption columns more than 30 km (19 mi) high, bigger than the eruption of Mount Vesuvius in 79 that buried Pompeii.[12]

Hawaiian

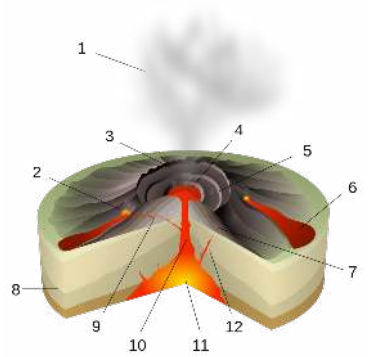


Figure 3. Diagram of a Hawaiian eruption. (key: 1. Ash plume 2. Lava fountain 3. Crater 4. Lava lake 5. Fumaroles 6. Lava flow 7. Layers of lava and ash 8. Stratum 9. Sill 10. Magma conduit 11. Magma chamber 12. Dike) Click for larger version.

Hawaiian eruptions are a type of volcanic eruption, named after the Hawaiian volcanoes with which this eruptive type is hallmark. Hawaiian eruptions are the calmest types of volcanic events, characterized by the effusive eruption of very fluid basalt-type lavas with low gaseous content. The volume of ejected material from Hawaiian eruptions is less than half of that found in other eruptive types. Steady production of small amounts of lava builds up the large, broad form of a shield volcano. Eruptions are not centralized at the main summit as with other volcanic types, and often occur at vents around the summit and from fissure vents radiating out of the center.[13]

Hawaiian eruptions often begin as a line of vent eruptions along a fissure vent, a so-called “curtain of fire.” These die down as the lava begins to concentrate at a few of the vents. Central-vent eruptions, meanwhile, often take the form of large lava fountains (both continuous and sporadic), which can reach heights of hundreds of meters or more. The particles from lava fountains usually cool in the air before hitting the ground, resulting in the accumulation of cindery scoria fragments; however, when the air is especially thick with clasts, they cannot cool off fast enough due to the surrounding heat, and hit the ground still hot, the accumulation of which forms spatter cones. If eruptive rates are high enough, they may even form splatter-fed lava flows. Hawaiian eruptions are often extremely long lived; Puʻu ʻŌʻō, a cinder cone of Kilauea, has been erupting continuously since 1983. Another Hawaiian volcanic feature is the formation of active lava lakes, self-maintaining pools of raw lava with a thin crust of semi-cooled rock; there are currently only 5 such lakes in the world, and the one at Kīlauea’s Kupaianaha vent is one of them.[14]



Figure 4. Ropey pahoehoe lava from Kilauea, Hawaiʻi.

Flows from Hawaiian eruptions are basaltic, and can be divided into two types by their structural characteristics. Pahoehoe lava is a relatively smooth lava flow that can be billowy or ropey. They can move as one sheet, by the advancement of “toes,” or as a snaking lava column. A’a lava flows are denser and more viscous then pahoehoe, and tend to move slower. Flows can measure 2 to 20

m (7 to 66 ft) thick. A'a flows are so thick that the outside layers cools into a rubble-like mass, insulating the still-hot interior and preventing it from cooling. A'a lava moves in a peculiar way—the front of the flow steepens due to pressure from behind until it breaks off, after which the general mass behind it moves forward. Pahoehoe lava can sometimes become A'a lava due to increasing viscosity or increasing rate of shear, but A'a lava never turns into pahoehoe flow.[15]

Volcanoes known to have Hawaiian activity include:[16]

- Puʻu ʻŌʻō, a parasitic cinder cone located on Kilauea on the island of Hawaiʻi which has been erupting continuously since 1983. The eruptions began with a 6 km (4 mi)-longfissure-based "curtain of fire" on 3 January. These gave way to centralized eruptions on the site of Kilauea's east rift, eventually building up the still active cone.
- For a list of all of the volcanoes of Hawaii, see List of volcanoes in the Hawaiian–Emperor seamount chain.
- Mount Etna, Italy.
- Mount Mihara in 1986 (see above paragraph)

Strombolian

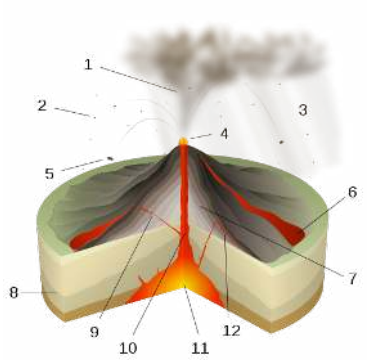


Figure 5. Diagram of a Strombolian eruption. (key: 1. Ash plume 2. Lapilli 3. Volcanic ash rain 4. Lava fountain 5. Volcanic bomb 6. Lava flow 7. Layers of lava and ash 8. Stratum 9. Dike 10. Magma conduit 11. Magma chamber 12. Sill) Click for larger version.

Strombolian eruptions are a type of volcanic eruption, named after the volcano Stromboli, which has been erupting continuously for centuries.[17] Strombolian eruptions are driven by the bursting of gas bubbles within the magma. These gas bubbles within the magma accumulate and coalesce into large bubbles, called gas slugs. These grow large enough to rise through the lava column.[18] Upon reaching the surface, the difference in air pressure causes the bubble to burst with a loud pop,[19] throwing magma in the air in a way similar to a soap bubble. Because of the high gas pressures associated with the lavas, continued activity is generally in the form of episodic explosive eruptions accompanied by the distinctive loud blasts.[20] During eruptions, these blasts occur as often as every few minutes.[21]

The term "Strombolian" has been used indiscriminately to describe a wide variety of volcanic eruptions, varying from small volcanic blasts to large eruptive columns. In reality, true Strombolian eruptions are characterized by short-lived and explosive eruptions of lavas with intermediate viscosity, often ejected high into the air. Columns can measure hundreds of meters in height. The lavas formed by Strombolian eruptions are a form of relatively viscous basaltic lava, and its end product is mostly scoria.[22] The relative passivity of Strombolian eruptions, and its non-damaging nature to its source vent allow Strombolian eruptions to continue unabated for thousands of years, and also makes it one of the least dangerous eruptive types.[23]

Figure 6. An example of the lava arcs formed during Strombolian activity. This image is of Stromboli itself.

Strombolian eruptions eject volcanic bombs and lapilli fragments that travel in parabolic paths before landing around their source vent. The steady accumulation of small fragments builds cinder cones composed completely of basaltic pyroclasts. This form of accumulation tends to result in well-ordered rings of tephra.[24]

Strombolian eruptions are similar to Hawaiian eruptions, but there are differences. Strombolian eruptions are noisier, produce no sustained eruptive columns, do not produce some volcanic products associated with Hawaiian volcanism (specifically Pele's tears and Pele's hair), and produce fewer molten lava flows (although the eruptive material does tend to form small rivulets).[25]

Volcanoes known to have Strombolian activity include:

- Parícutin, Mexico, which erupted from a fissure in a cornfield in 1943. Two years into its life, pyroclastic activity began to wane, and the outpouring of lava from its base became its primary mode of activity. Eruptions ceased in 1952, and the final height was 424 m (1,391 ft). This was the first time that scientists are able to observe the complete life cycle of a volcano.[26]
- Mount Etna, Italy, which has displayed Strombolian activity in recent eruptions, for example in 1981, 1999,[27] 2002-2003, and 2009.[28]
- Mount Erebus in Antarctica, the southernmost active volcano in the world, having been observed erupting since 1972.[29] Eruptive activity at Erebus consists of frequent Strombolian activity.[30]
- Stromboli itself. The namesake of the mild explosive activity that it possesses has been active throughout historical time; essentially continuous Strombolian eruptions, occasionally accompanied by lava flows, have been recorded at Stromboli for more than a millennium.[31]

Vulcanian

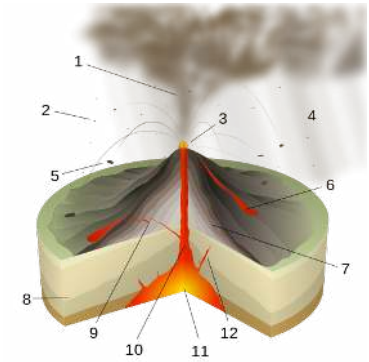


Figure 7. Diagram of a Vulcanian eruption. (key: 1. Ash plume 2. Lapilli 3. Lava fountain 4. Volcanic ash rain 5. Volcanic bomb 6. Lava flow 7. Layers of lava and ash 8. Stratum 9. Sill 10. Magma conduit 11. Magma chamber 12. Dike)

Vulcanian eruptions are a type of volcanic eruption, named after the volcano Vulcano.[32] It was named so following Giuseppe Mercalli's observations of its 1888-1890 eruptions.[33] In Vulcanian eruptions, highly viscous magma within the volcano make it difficult for vesiculate gases to escape. Similar to Strombolian eruptions, this leads to the buildup of high gas pressure, eventually popping the cap holding the magma down and resulting in an explosive eruption. However, unlike Strombolian eruptions, ejected lava fragments are not aerodynamic; this is due to the higher viscosity of Vulcanian magma and the greater incorporation of crystalline material broken off from the former cap. They are also more explosive than their Strombolian counterparts, with eruptive columns often reaching between 5 and 10 km (3 and 6 mi) high. Lastly, Vulcanian deposits are andesitic to dacitic rather than basaltic.[34]



Figure 8. Tavurvur in Papua New Guinea erupting.

Volcanoes that have exhibited Vulcanian activity include:

- Sakurajima, Japan has been the site of Vulcanian activity near-continuously since 1955.[35]
- Tavurvur, Papua New Guinea, one of several volcanoes in the Rabaul Caldera.[36]
- Irazú Volcano in Costa Rica exhibited Vulcanian activity in its 1965 eruption.[37]

Peléan

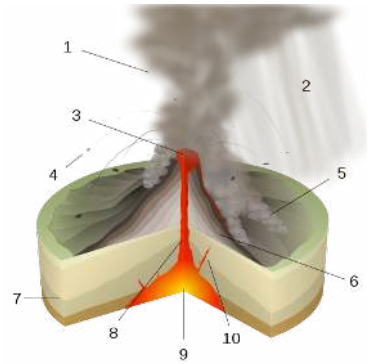


Figure 9. Diagram of Peléan eruption. (key: 1. Ash plume 2. Volcanic ash rain 3. Lava dome 4. Volcanic bomb 5. Pyroclastic flow 6. Layers of lava and ash 7. Stratum 8. Magma conduit 9. Magma chamber 10. Dike)

Peléan eruptions (or nuée ardente) are a type of volcanic eruption, named after the volcano Mount Pelée in Martinique, the site of a massive Peléan eruption in 1902 that is one of the worst natural disasters in history. In Peléan eruptions, a large amount of gas, dust, ash, and lava fragments are blown out the volcano's central crater,[38] driven by the collapse of rhyolite, dacite, and andesite lava dome collapses that often create large eruptive columns. An early sign of a coming eruption is the growth of a so-called Peléan or lava spine, a bulge in the volcano's summit preempting its total collapse.[39] The material collapses upon itself, forming a fast-moving pyroclastic flow[40] (known as a block-and-ash flow)[41] that moves down the side of the mountain at tremendous speeds, often over 150 km (93 mi) per hour. These massive landslides make Peléan eruptions one of the most dangerous in the world, capable of tearing through populated areas and causing massive loss of life. The 1902 eruption of Mount Pelée caused tremendous destruction, killing more than 30,000 people and competely destroying the town of St. Pierre, the worst volcanic event in the 20th century.[42]

Peléan eruptions are characterized most prominently by the incandescent pyroclastic flows that they drive. The mechanics of a Peléan eruption are very similar to that of a Vulcanian eruption, except that in Peléan eruptions the volcano's structure is able to withstand more pressure, hence the eruption occurs as one large explosion rather than several smaller ones.[43]

Volcanoes known to have Peléan activity include:

- Mount Pelée, Martinique. The 1902 eruption of Mount Pelée completely devastated the island, destroying the town of St. Pierre and leaving only 3 survivors.[44] The eruption was directly preceded by lava dome growth.[45]

- Mayon Volcano, the Philippines most active volcano. It has been the site of many different types of eruptions, Peléan included. Approximately 40 ravines radiate from the summit and provide pathways for frequent pyroclastic flows and mudslides to the lowlands below. Mayon's most violent eruption occurred in 1814 and was responsible for over 1200 deaths.[46]
- The 1951 Peléan eruption of Mount Lamington. Prior to this eruption the peak had not even been recognized as a volcano. Over 3,000 people were killed, and it has become a benchmark for studying large Peléan eruptions.[47]



Figure 10. (a) Mount Lamington following the devastating 1951 eruption. (b) The lava spine that developed after the 1902 eruption of Mount Pelée. (c) Pyroclastic flows at Mayon Volcano, Philippines, 1984.

Plinian

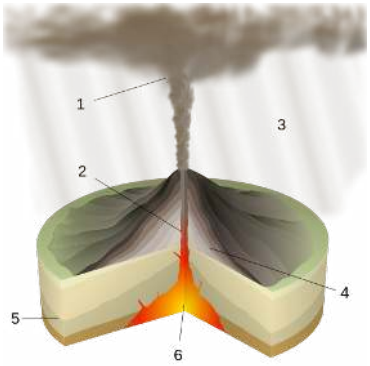


Figure 11. Diagram of a Plinian eruption. (key: 1. Ash plume 2. Magma conduit 3. Volcanic ash rain 4. Layers of lava and ash 5. Stratum 6. Magma chamber)

Plinian eruptions (or Vesuvian) are a type of volcanic eruption, named for the historical eruption of Mount Vesuvius in 79 of Mount Vesuvius that buried the Roman towns of Pompeii and Herculaneum and, specifically, for its chronicler Pliny the Younger.[48] The process powering Plinian eruptions starts in the magma chamber, where dissolved volatile gases are stored in the magma. The gases vesiculate and accumulate as they rise through the magma conduit. These bubbles agglutinate and once they reach a certain size (about 75% of the total volume of the magma conduit) they explode. The narrow confines of the conduit force the gases and associated magma up, forming an eruptive column. Eruption velocity is controlled by the gas contents of the column, and low-strength surface rocks commonly crack under the pressure of the eruption, forming a flared outgoing structure that pushes the gases even faster.[49]

These massive eruptive columns are the distinctive feature of a Plinian eruption, and reach up 2 to 45 km (1 to 28 mi) into the atmosphere. The densest part of the plume, directly above the volcano, is driven internally by gas expansion. As it reaches higher into the air the plume expands and becomes less dense, convection and thermal expansion of volcanic ash drive it even further up into the stratosphere. At the top of the plume, powerful prevailing winds drive the plume in a direction away from the volcano.[50]



Figure 12. 21 April 1990 eruptive column from Redoubt Volcano, as viewed to the west from the Kenai Peninsula.

These highly explosive eruptions are associated with volatile-rich dacitic to rhyolitic lavas, and occur most typically at stratovolcanoes. Eruptions can last anywhere from hours to days, with longer eruptions being associated with more felsic volcanoes. Although they are associated with felsic magma, Plinian eruptions can just as well occur at basaltic volcanoes, given that the magma chamber differentiates and has a structure rich in silicon dioxide.[51]

Plinian eruptions are similar to both Vulcanian and Strombolian eruptions, except that rather than creating discrete explosive events, Plinian eruptions form sustained eruptive columns. They are also similar to Hawaiian lava fountains in that both eruptive types produce sustained eruption columns maintained by the growth of bubbles that move up at about the same speed as the magma surrounding them.[52]



Figure 13. Lahar flows from the 1985 eruption of Nevado del Ruiz, which totally destroyed the town of Armero in Colombia.

Major Plinian eruptive events include:

- The AD 79 eruption of Mount Vesuvius buried the Roman towns of Pompeii and Herculaneum under a layer of ash and tephra. It is the model Plinian eruption. Mount Vesuvius has erupted several times since then. Its last eruption was in 1944 and caused problems for the allied armies as they advanced through Italy.[53] It was the report by Pliny that Younger that lead scientists to refer to vesuvian eruptions as "Plinian."
- The 1980 eruption of Mount St. Helens in Washington, which ripped apart the volcano's summit, was a Plinian eruption of Volcanic Explosivity Index (**VEI**) 5.[54]
- The strongest types of eruptions, with a VEI of 8, are so-called "Ultra-Plinian" eruptions, such as the most recent one at Lake Toba 74 thousand years ago, which put out 2800 times the material erupted by Mount St. Helens in 1980.[55]

- Hekla in Iceland, an example of basaltic Plinian volcanism being its 1947-48 eruption. The past 800 years have been a pattern of violent initial eruptions of pumice followed by prolonged extrusion of basaltic lava from the lower part of the volcano.[56]
- Pinatubo in the Philippines on 15 June 1991, which produced 5 km^3 (1 cu mi) of dacitic magma, a 40 km (25 mi) high eruption column, and released 17 megatons of sulfur dioxide.[57]

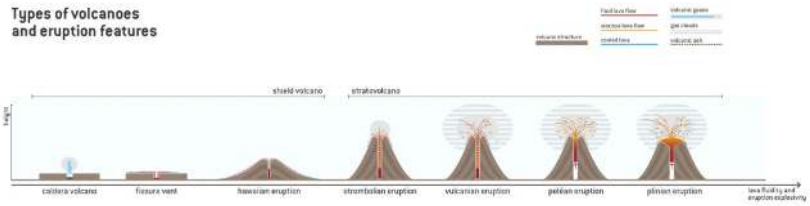


Figure 14. The image correlates types of volcanoes with their respective eruption, highlighting the differences. Click to view a larger version.

Phreatomagmatic Eruptions

Phreatomagmatic eruptions are eruptions that arise from interactions between water and magma. They are driven from thermal contraction (as opposed to magmatic eruptions, which are driven by thermal expansion) of magma when it comes in contact with water. This temperature difference between the two causes violent water-lava interactions that make up the eruption. The products of phreatomagmatic eruptions are believed to be more regular in shape and finer grained than the products of magmatic eruptions because of the differences in eruptive mechanisms.[58]

There is debate about the exact nature of phreatomagmatic eruptions, and some scientists believe that fuel-coolant reactions may be more critical to the explosive nature than thermal contraction.[59] Fuel coolant reactions may fragment the volcanic material by propagating stress waves, widening cracks and increasing surface area that ultimetly lead to rapid cooling and explosive contraction-driven eruptions.[60]

Surtseyan

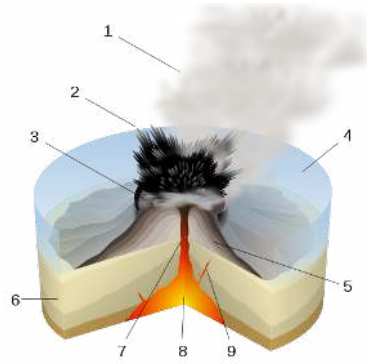


Figure 15. Diagram of a Surtseyan eruption. (key: 1. Water vapor cloud 2. Compressed ash 3. Crater 4. Water 5. Layers of lava and ash 6. Stratum 7. Magma conduit 8. Magma chamber 9. Dike)

A Surtseyan eruption (or hydrovolcanic) is a type of volcanic eruption caused by shallow-water interactions between water and lava, named so after its most famous example, the eruption and formation of the island of Surtsey off the coast of Iceland in 1963. Surtseyan eruptions are the “wet” equivalent of ground-based Strombolian eruptions, but because of where they are taking place they are much more explosive. This is because as water is heated by lava, it flashes in steam and expands violently, fragmenting the magma it is in contact with into fine-grained ash. Surtseyan eruptions are the hallmark of shallow-water volcanic oceanic islands, however they are not specifically confined to them. Surtseyan eruptions can happen on land as well, and are caused by rising magma that comes into contact with an aquifer (water-bearing rock formation) at shallow levels under the volcano.[61] The products of Surtseyan eruptions are generally oxidized palagonite basalts (though andesitic eruptions do occur, albeit rarely), and like Strombolian eruptions Surtseyan eruptions are generally continuous or otherwise rhythmic.[62]

Volcanoes known to have Surtseyan activity include:[63]

- Surtsey, Iceland. The volcano built itself up from depth and emerged above the Atlantic Ocean off the coast of Iceland in 1963. Initial hydrovolcanics were highly explosive, but as the volcano grew out rising lava started to interact less with the water and more with the air, until finally Surtseyan activity waned and became more Strombolian in character.
- Ukinrek Maars in Alaska, 1977, and Capelinhos in the Azores, 1957, both examples of above-water Surtseyan activity.
- Mount Tarawera in New Zealand erupted along a rift zone in 1886, killing 150 people.



Figure 16. (a) Surtsey, erupting 13 days after breaching the water. A tuff ring surrounds the vent. (b) The fissure formed by the 1886 eruption of Mount Tarawera, an example of a fracture zone eruption.

Submarine

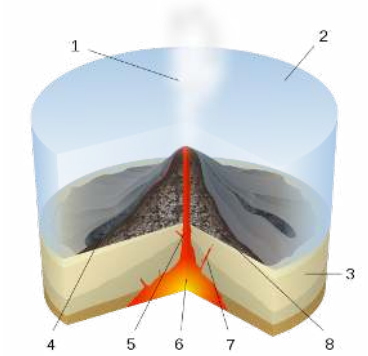


Figure 17. Diagram of a Submarine eruption. (key: 1. Water vapor cloud 2. Water 3. Stratum 4. Lava flow 5. Magma conduit 6. Magma chamber 7. Dike 8. Pillow lava)

Submarine eruptions are a type of volcanic eruption that occurs underwater. An estimated 75% of the total volcanic eruptive volume is generated by submarine eruptions near mid ocean ridges alone, however because of the problems associated with detecting deep sea volcanics, they remained virtually unknown until advances in the 1990s made it possible to observe them.[64]

Submarine eruptions may produce seamounts which may break the surface to form volcanic islands and island chains.

Submarine volcanism is driven by various processes. Volcanoes near plate boundaries and mid-ocean ridges are built by the decompression melting of mantle rock that rises on an upwelling portion of a convection cell to the crustal surface. Eruptions associated with subducting zones, meanwhile, are driven by subducting plates that add volatiles to the rising plate, lowering its melting point. Each process generates different rock; mid-ocean ridge volcanics are primarily basaltic, whereas subduction flows are mostly calc-alkaline, and more explosive and viscous.[65]

Subglacial

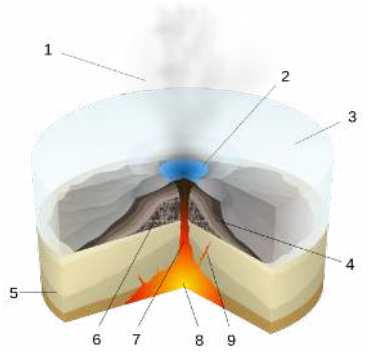


Figure 18. A diagram of a Subglacial eruption. (key: 1. Water vapor cloud 2. Crater lake 3. Ice 4. Layers of lava and ash 5. Stratum 6. Pillow lava 7. Magma conduit 8. Magma chamber 9. Dike)

Subglacial eruptions are a type of volcanic eruption characterized by interactions between lava and ice, often under a glacier. The nature of glaciovolcanism dictates that it occurs at areas of high latitude and high altitude.[66] It has been suggested that subglacial volcanoes that are not actively erupting often dump heat into the ice covering them, producing meltwater.[67] This meltwater mix means that subglacial eruptions often generate dangerous jökulhlaups (floods) and lahars.[68]

The study of glaciovolcanism is still a relatively new field. Early accounts described the unusual flat-topped steep-sided volcanoes (called tuyas) in Iceland that were suggested to have formed from eruptions below ice. The first English-language paper on the subject was published in 1947 by William Henry Mathews, describing the Tuya Butte field in northwest British Columbia, Canada. The eruptive process that builds these structures, originally inferred in the paper,[69] begins with volcanic growth below the glacier. At first the eruptions resemble those that occur in the deep sea, forming piles of pillow lava at the base of the volcanic structure. Some of the lava shatters when it comes in contact with the cold ice, forming a glassy breccia called hyaloclastite. After a while the ice finally melts into a lake, and the more explosive eruptions of Surtseyan activity begins, building up flanks made up of mostly hyaloclastite. Eventually the lake boils off from continued volcanism, and the lava flows become more effusive and thicken as the lava cools much more slowly, often forming columnar jointing. Well-preserved tuyas show all of these stages, for example Hjorleifshofdi in Iceland.[70]

Glaciovolcanic products have been identified in Iceland, the Canadian province of British Columbia, the U.S. states of Hawaii and Alaska, the Cascade Range of western North America, South America and even on the planet Mars.[71] Volcanoes known to have subglacial activity include:

- Mauna Kea in tropical Hawaii. There is evidence of past subglacial eruptive activity on the volcano in the form of a subglacial deposit on its summit. The eruptions originated about 10,000 years ago, during the last ice age, when the summit of Mauna Kea was covered in ice.[72]
- In 2008, the British Antarctic Survey reported a volcanic eruption under the Antarctica ice sheet 2,200 years ago. It is believed to be that this was the biggest eruption in Antarctica in the last 10,000 years. Volcanic ash deposits from the volcano were identified through an airborne radar survey, buried under later snowfalls in the Hudson Mountains, close to Pine Island Glacier.[73]
- Iceland, well known for both glaciers and volcanoes, is often a site of subglacial eruptions. An example an eruption under the Vatnajökull ice cap in 1996, which occurred under an estimated 2,500 ft (762 m) of ice.[74]
- As part of the search for life on Mars, scientists have suggested that there may be subglacial volcanoes on the red planet. Several potential sites of such volcanism have been reviewed, and compared extensively with similar features in Iceland:[75]
  - Viable microbial communities have been found living in deep (–2800 m) geothermal groundwater at 349 K and pressures >300 bar. Furthermore, microbes have been postulated to exist in basaltic rocks in rinds of altered volcanic glass. All of these conditions could exist in polar regions of Mars today where subglacial volcanism has occurred.



Figure 19. Herðubreið, a tuya in Iceland.

Phreatic eruptions

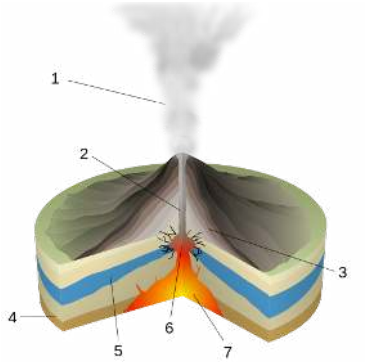


Figure 20. Diagram of a phreatic eruption. (key: 1. Water vapor cloud 2. Magma conduit 3. Layers of lava and ash 4. Stratum 5. Water table 6. Explosion 7. Magma chamber)

Phreatic eruptions (or steam-blast eruptions) are a type of eruption driven by the expansion of steam. When cold ground or surface water come into contact with hot rock or magma it superheats and explodes, fracturing the surrounding rock[76] and thrusting out a mixture of steam, water, ash, volcanic bombs, and volcanic blocks.[77] The distinguishing feature of phreatic explosions is that they only blast out fragments of pre-existing solid rock from the volcanic conduit; no new magma is erupted.[78] Because they are driven by the cracking of rock strata under pressure, phreatic activity does not always result in an eruption; if the rock face is strong enough to withstand the explosive force, outright eruptions may not occur, although cracks in the rock will probably develop and weaken it, furthering future eruptions.[79]

Volcanoes known to exhibit phreatic activity include:

- Mount St. Helens, which exhibited phreatic activity just prior to its catastrophic 1980 eruption (which was itself Plinian).[80]
- Taal Volcano, Philippines, 1965.[81]
- La Soufrière of Guadeloupe (Lesser Antilles), 1975-1976 activity.[82]
- Soufrière Hills volcano on Montserrat, West Indies, 1995–2012.
- Poás Volcano, has frequent geyser like phreatic eruptions from its crater lake.
- Mount Bulusan, well known for its sudden phreatic eruptions.
- Mount Ontake, all historical eruptions of this volcano have been phreatic including the deadly 2014 eruption.

---

1. Heiken, G. and Wohletz, K. *Volcanic Ash*. University of California Press. p. 246. ↵
2. *Ibid*. ↵
3. "VHP Photo Glossary: Effusive Eruption." USGS. 29 December 2009. Retrieved 3 August 2010. ↵
4. "Volcanoes of Canada: Volcanic eruptions." *Geological Survey of Canada*. Natural Resources Canada. 2 April 2009. Retrieved 3 August 2010. ↵
5. "How Volcanoes Work: Hawaiian Eruptions." San Diego State University. Retrieved 2 August 2010. ↵
6. "How Volcanoes Work: Hydrovolcic Eruptions." San Diego State University. Retrieved 4 August 2010. ↵
7. Ruprecht P, Plank T. Feeding andesitic eruptions with a high-speed connection from the mantle. *Nature*. 2013; 500(7460):68-72. ↵
8. "How Volcanoes Work: Eruption Variability." San Diego State University. Retrieved 3 August 2010. ↵
9. "Volcanoes of Canada: Volcanic eruptions." *Geological Survey of Canada*. Natural Resources Canada. 2 April 2009. Retrieved 3 August 2010. ↵
10. "How Volcanoes Work: Eruption Variability." San Diego State University. Retrieved 3 August 2010. ↵
11. Dosseto, A., Turner, S. P. and Van-Orman, J. A. (editors) (2011). *Timescales of Magmatic Processes: From Core to Atmosphere*. Wiley-Blackwell. See also Rothery, David A. (2010). *Volcanoes, Earthquakes and Tsunami*s. Teach Yourself. ↵
12. Heiken, G. and Wohletz, K. *Volcanic Ash*. University of California Press. p. 246. ↵
13. "How Volcanoes Work: Hawaiian Eruptions." San Diego State University. Retrieved 2 August 2010. ↵
14. *Ibid*. ↵
15. "How Volcanoes Work: Basaltic Lava." San Diego State University. Retrieved 2 August 2010. ↵
16. "How Volcanoes Work: Hawaiian Eruptions." San Diego State University. Retrieved 2 August 2010. ↵
17. "How Volcanoes Work: Strombolian Eruptions." San Diego State University. Retrieved 29 July 2010. ↵
18. Mike Burton, Patrick Allard, Filippo Muré, Alessandro La Spina (2007). "Magmatic Gas Composition Reveals the Source Depth of Slug-Driven Strombolian Explosive Activity." *Science* (American Association for the Advancement of Science) **317** (5835): 227–230. doi:10.1126/science.1141900. Retrieved 30 July 2010. ↵
19. "How Volcanoes Work: Strombolian Eruptions." San Diego State University. Retrieved 29 July 2010. ↵
20. *Ibid*. ↵
21. Cain, Fraser (22 April 2010). "Strombolian Eruption." *Universe Today*. Retrieved 30 July 2010. ↵
22. "How Volcanoes Work: Strombolian Eruptions." San Diego State University. Retrieved 29 July 2010. ↵
23. Cain, Fraser (22 April 2010). "Strombolian Eruption." *Universe Today*. Retrieved 30 July 2010. ↵

24. "How Volcanoes Work: Strombolian Eruptions." San Diego State University. Retrieved 29 July 2010. ↵
25. "How Volcanoes Work: Strombolian Eruptions." San Diego State University. Retrieved 29 July 2010. See also Cain, Fraser (22 April 2010). "Strombolian Eruption." *Universe Today*. Retrieved 30 July 2010. ↵
26. "How Volcanoes Work: Strombolian Eruptions." San Diego State University. Retrieved 29 July 2010. ↵
27. Seach, John. "Mt Etna Volcano Eruptions—John Seach." *Old eruptions*. Volcanolive. Retrieved 30 July 2010. ↵
28. Seach, John. "Mt Etna Volcano Eruptions—John Seach." *Recent eruptions*. Volcanolive. Retrieved 30 July 2010. ↵
29. "Erebus." *Global Volcanism Program*. Smithsonian National Museum of Natural History. Retrieved 31 July 2010. ↵
30. Kyle, P. R. (Ed.), Volcanological and Environmental Studies of Mount Erebus, Antarctica, Antarctic Research Series, American Geophysical Union, Washington DC, 1994. ↵
31. "Stromboli." *Global Volcanism Program*. Smithsonian National Museum of Natural History. Retrieved 31 July 2010. ↵
32. "How Volcanoes Work: Vulcanian Eruptions." San Diego State University. Retrieved 1 August 2010. ↵
33. Cain, Fraser. "Vulcanian Eruptions." Universe Today. Retrieved 1 August 2010. ↵
34. "How Volcanoes Work: Vulcanian Eruptions." San Diego State University. Retrieved 1 August 2010. ↵
35. "How Volcanoes Work: Sakurajima Volcano." San Diego State University. Retrieved 1 August 2010. ↵
36. "How Volcanoes Work: Vulcanian Eruptions." San Diego State University. Retrieved 1 August 2010. ↵
37. "VHP Photo Glossary: Vulcanian eruption." USGS. Retrieved 1 August 2010. ↵
38. Cain, Fraser. "Pelean Eruption." Universe Today. Retrieved 2 August 2010. ↵
39. Donald Hyndman and David Hyndman (April 2008). *Natural Hazards and Disasters*. Cengage Learning. pp. 134–135.↵
40. Cain, Fraser. "Pelean Eruption." Universe Today. Retrieved 2 August 2010. ↵
41. Nelson, Stephan A. (30 September 2007). "Volcanoes, Magma, and Volcanic Eruptions." Tulane University. Retrieved 2 August 2010. ↵
42. Cain, Fraser. "Pelean Eruption." Universe Today. Retrieved 2 August 2010. ↵
43. Richard V. Fisher and Grant Heiken (1982). "Mt. Pelée, Martinique: May 8 and 20 pyroclastic flows and surges." *Journal of Volcanology and Geothermal Research* **13** (3–4): 339–371. doi:10.1016/0377-0273(82)90056-7↵
44. "How Volcanoes Work: Mount Pelée Eruption (1902)."San Diego State University. Retrieved 1 August 2010. ↵
45. "How Volcanoes Work: Vulcanian Eruptions." San Diego State University. Retrieved 1 August 2010. ↵
46. "Mayon." *Global Volcanism Program*. Smithsonian National Museum of Natural History. Retrieved 2 August 2010. ↵
47. "Lamington: Photo Gallery." *Global Volcanism Program*. Smithsonian National Museum of Natural History. Retrieved2 August 2010. ↵
48. "How Volcanoes Work: Plinian Eruptions." San Diego State University. Retrieved 3 August 2010. ↵
49. "How Volcanoes Work: Eruption Model." San Diego State University. Retrieved 3 August 2010. ↵
50. *Ibid*. ↵
51. "How Volcanoes Work: Plinian Eruptions." San Diego State University. Retrieved 3 August 2010. ↵
52. *Ibid*. ↵
53. *Ibid*. ↵
54. "Volcanoes of Canada: Volcanic eruptions." *Geological Survey of Canada*. Natural Resources Canada. 2 April 2009. Retrieved 3 August 2010. ↵
55. "How Volcanoes Work: Eruption Variability." San Diego State University. Retrieved 3 August 2010. See also "How Volcanoes Work: Calderas." San Diego State University. Retrieved 3 August 2010. ↵
56. "How Volcanoes Work: Plinian Eruptions." San Diego State University. Retrieved 3 August 2010. ↵
57. Stephen Self, Jing-Xia Zhao, Rick E. Holasek, Ronnie C. Torres, and Alan J. King. "The Atmospheric Impact of the 1991 Mount Pinatubo Eruption." USGS. Retrieved 3 August 2010. ↵
58. Heiken, G. and Wohletz, K. *Volcanic Ash*. University of California Press. p. 246. See alsoA.B. Starostin, A.A. Barmin, and O.E. Melnik (May 2005). "A transient model for explosive and phreatomagmatic eruptions." *Journal of Volcanology and Geothermal Research*. Volcanic Eruption Mechanisms—Insights from intercomparison of models of conduit processes **143** (1–3): 133–151. doi: 10.1016/j.jvolgeores.2004.09.014. Retrieved 4 August 2010. ↵
59. A.B. Starostin, A.A. Barmin, and O.E. Melnik (May 2005). "A transient model for explosive and phreatomagmatic eruptions." *Journal of Volcanology and Geothermal Research*. Volcanic Eruption Mechanisms—Insights from intercomparison of models of conduit processes **143** (1–3): 133–151. doi: 10.1016/j.jvolgeores.2004.09.014. Retrieved 4 August 2010. ↵
60. Heiken, G. and Wohletz, K. *Volcanic Ash*. University of California Press. p. 246. ↵
61. "How Volcanoes Work: Hydrovolcic Eruptions." San Diego State University. Retrieved 4 August 2010. ↵
62. "X. Classification of Volcanic Eruptions: Surtseyan Eruptions." *Lecture Notes*. University of Alabama. Retrieved5 August 2010. ↵
63. "How Volcanoes Work: Hydrovolcic Eruptions." San Diego State University. Retrieved 4 August 2010. ↵
64. Chadwick, Bill (10 January 2006). "Recent Submarine Volcanic Eruptions." *Vents Program*. NOAA. Retrieved 5 August 2010. ↵
65. Hubert Straudigal and David A Clauge. "The Geological History of Deep-Sea Volcanoes: Biosphere, Hydrosphere, and Lithosphere Interactions" (PDF). *Oceanography*. Seamounts Special Issue (Oceanography Society) **32** (1). Retrieved 4 August 2010. ↵
66. "Glaciovolcanism—University of British Columbia." University of British Columbia. Retrieved 5 August 2010. ↵
67. Black, Richard (20 January 2008). "Ancient Antarctic eruption noted." BBC News. Retrieved 5 August 2010. ↵
68. "Glaciovolcanism—University of British Columbia." University of British Columbia. Retrieved 5 August 2010. ↵
69. *Ibid*. ↵
70. Alden, Andrew. "Tuya or Subglacial Volcano, Iceland." about.com. Retrieved 5 August 2010. ↵
71. *Ibid*. ↵
72. "Kinds of Volcanic Eruptions." *Volcano World*. Oregon State University. Retrieved 5 August 2010. ↵
73. Black, Richard (20 January 2008). "Ancient Antarctic eruption noted." BBC News. Retrieved 5 August 2010. ↵
74. "Iceland's subglacial eruption." *Hawaiian Volcano Observatory*. USGS. 11 October 1996. Retrieved 5 August 2010. ↵
75. "Subglacial Volcanoes On Mars." Space Daily. 27 June 2001. Retrieved 5 August 2010. ↵
76. Leonid N. Germanovich and Robert P. Lowell (1995). "The mechanism of phreatic eruptions." *Journal of Geophysical Research*. Solid Earth (American Geophysical Union) **100** (B5): 8417–8434. doi:10.1029/94JB03096. Retrieved 7 August 2010. ↵
77. "VHP Photo Glossary: Phreatic eruption." USGS. 17 July 2008. Retrieved 6 August 2010. ↵
78. Watson, John (5 February 1997). "Types of volcanic eruptions." USGS. Retrieved 7 August 2010. ↵
79. Leonid N. Germanovich and Robert P. Lowell (1995). "The mechanism of phreatic eruptions." *Journal of Geophysical Research*. Solid Earth (American Geophysical Union) **100** (B5): 8417–8434. doi:10.1029/94JB03096. Retrieved 7 August 2010. ↵
80. "VHP Photo Glossary: Phreatic eruption." USGS. 17 July 2008. Retrieved 6 August 2010. ↵
81. Watson, John (5 February 1997). "Types of volcanic eruptions." USGS. Retrieved 7 August 2010. ↵
82. *Ibid*. ↵

Contributors and Attributions

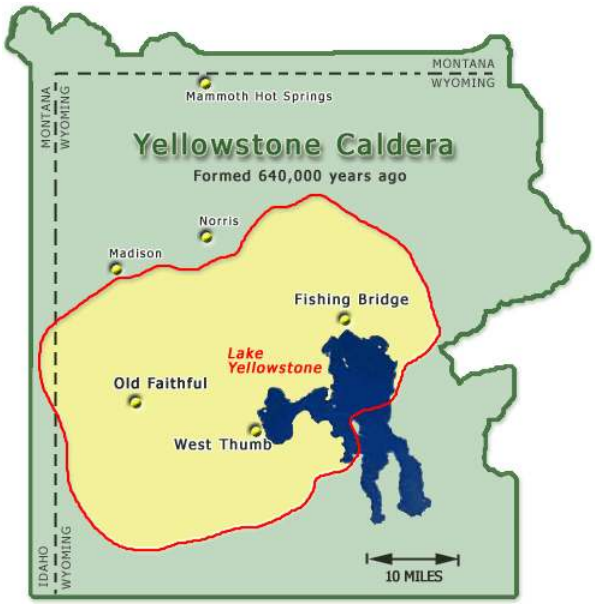
CC licensed content, Shared previously

- Types of volcanic eruptions. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Types_of_volcanic_eruptions. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 9.4: Reading- Types of Eruptions is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

https://geo.libretexts.org/@go/page/11529

9.5: Reading- Supervolcanoes



What would cause such a giant caldera?

You can stand on the rim and view the enormous Yellowstone Caldera, but it's hard to visualize a volcano or a set of eruptions that enormous. Supervolcanoes are a fairly new idea in volcanology. Although their eruptions are unbelievably massive, they are exceedingly rare. The power of Yellowstone, even 640,000 years after the most recent eruption, is seen in its fantastic geysers.

Supervolcano eruptions are extremely rare in Earth's history. It's a good thing because they are unimaginably large. A supervolcano must erupt more than 1,000 cubic km (240 cubic miles) of material, compared with 1.2 km^3 for Mount St. Helens or 25 km^3 for Mount Pinatubo, a large eruption in the Philippines in 1991. Not surprisingly, supervolcanoes are the most dangerous type of volcano.

Supervolcano Eruptions

The exact cause of supervolcano eruptions is still debated. However, scientists think that a very large magma chamber erupts entirely in one catastrophic explosion. This creates a huge hole or caldera into which the surface collapses (Figure 1).



Figure 1. The caldera at Santorini in Greece is so large that it can only be seen by satellite.

Yellowstone Caldera

The largest supervolcano in North America is beneath Yellowstone National Park in Wyoming. Yellowstone sits above a hotspot that has erupted catastrophically three times: 2.1 million, 1.3 million, and 640,000 years ago. Yellowstone has produced many smaller (but still enormous) eruptions more recently (Figure 2). Fortunately, current activity at Yellowstone is limited to the region's famous geysers.

The Old Faithful web cam shows periodic eruptions of Yellowstone's famous geyser in real time.

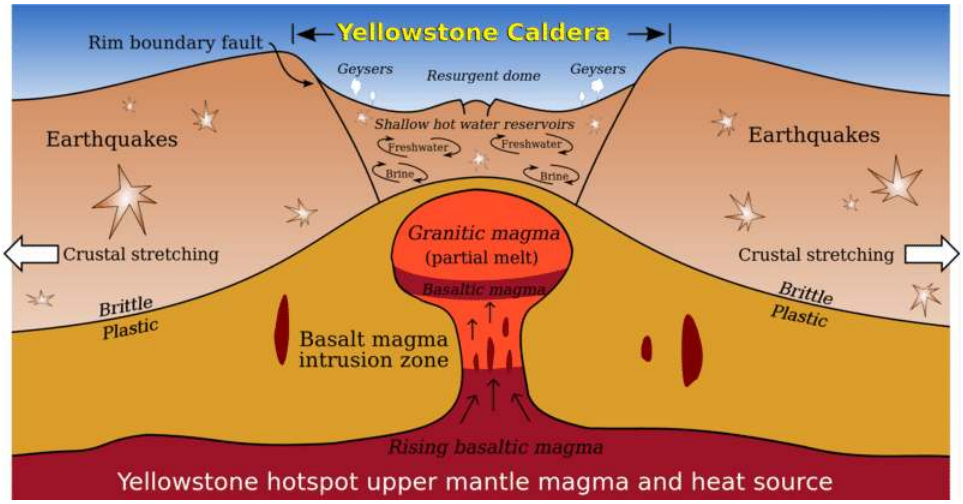


Figure 2. The Yellowstone hotspot has produced enormous felsic eruptions. The Yellowstone caldera collapsed in the most recent super eruption.

Supervolcano Eruptions and Life on Earth

A supervolcano could change life on Earth as we know it. Ash could block sunlight so much that photosynthesis would be reduced and global temperatures would plummet. Volcanic eruptions could have contributed to some of the mass extinctions in our planet's history. No one knows when the next super eruption will be.

Interesting volcano videos are seen on National Geographic Videos: Environment Video, Natural Disasters, Earthquakes. One interesting one is "Mammoth Mountain," which explores Hot Creek and the volcanic area it is a part of in California.

Summary

- Supervolcano eruptions are rare but massive and deadly.
- Yellowstone Caldera is a supervolcano that has erupted catastropically three times.
- Supervolcano eruptions can change the course of life on Earth.

Contributors and Attributions

CC licensed content, Shared previously

- Supervolcanoes. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Supervolcanoes/lesson/Supervolcanoes-HS-ES/?referrer=featured_content. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 9.5: Reading- Supervolcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.6: Self Check- Volcano Types

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1112

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 9.6: Self Check- Volcano Types is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.7: Outcome- The Formation of Volcanoes

Describe the processes that form volcanoes.

Volcanoes are a vibrant manifestation of plate tectonics processes. Volcanoes are common along convergent and divergent plate boundaries. Volcanoes are also found within lithospheric plates away from plate boundaries. Wherever mantle is able to melt, volcanoes may be the result.

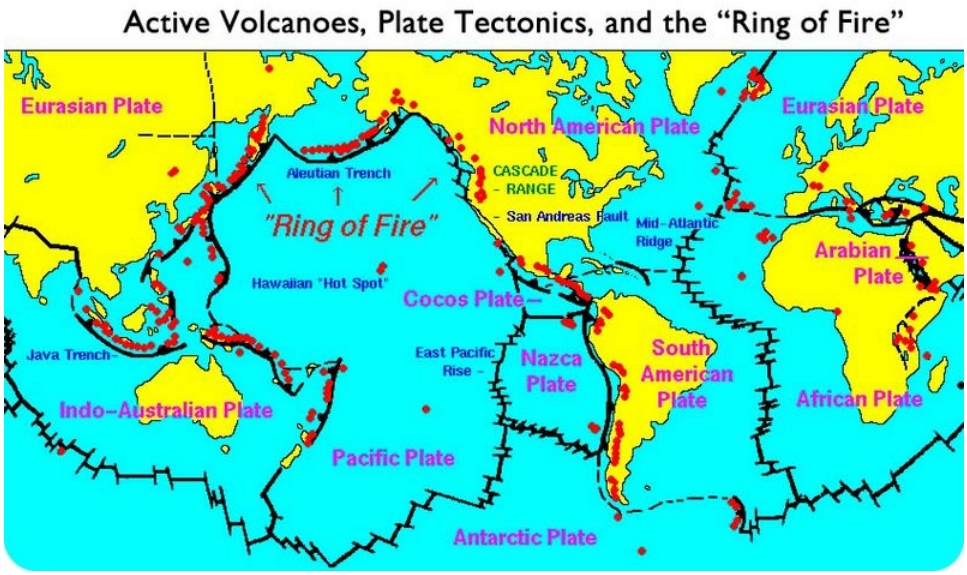


Figure 1. World map of active volcanoes.

See if you can give a geological explanation for the locations of all the volcanoes in figure 1. What is the Pacific Ring of Fire? Why are the Hawaiian volcanoes located away from any plate boundaries? What is the cause of the volcanoes along the mid-Atlantic ridge?

Volcanoes erupt because mantle rock melts. This is the first stage in creating a volcano. Remember from the chapter "Rocks" that mantle may melt if temperature rises, pressure lowers, or water is added. Be sure to think about how melting occurs in each of the following volcanic settings.

What You'll Learn to Do

- Describe various volcanic processess at plate boundaries
- Understand the development of hotspots and their common locations

Learning Activities

The learning activities for this section include the following:

- Reading: Volcanoes at Plate Boundaries
- Reading: Volcanoes Hotspots
- Reading: Volcano Formation
- Self Check: The Formation of Volcanoes

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Volcanoes. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/8.0/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 9.7: Outcome- The Formation of Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.8: Reading- Volcanoes at Plate Boundaries



Volcanoes are fun (and difficult) to climb. Climbing in the Cascades ranges in difficulty from a non-technical hike, like on South Sister, to a technical climb on Mount Baker in which an ice axe, crampons, and experience are needed.

Convergent Plate Boundaries

Converging plates can be oceanic, continental, or one of each. If both are continental they will smash together and form a mountain range. If at least one is oceanic, it will subduct. A subducting plate creates volcanoes. Locations with converging in which at least one plate is oceanic at the boundary have volcanoes.

Melting

Melting at convergent plate boundaries has many causes. The subducting plate heats up as it sinks into the mantle. Also, water is mixed in with the sediments lying on top of the subducting plate. As the sediments subduct, the water rises into the overlying mantle material and lowers its melting point. Melting in the mantle above the subducting plate leads to volcanoes within an island or continental arc.

Why does melting occur at convergent plate boundaries? The subducting plate heats up as it sinks into the mantle. Also, water is mixed in with the sediments lying on top of the subducting plate. This water lowers the melting point of the mantle material, which increases melting. Volcanoes at convergent plate boundaries are found all along the Pacific Ocean basin, primarily at the edges of the Pacific, Cocos, and Nazca plates. Trenches mark subduction zones, although only the Aleutian Trench and the Java Trench appear on the map in figure 1.

Remember your plate tectonics knowledge. Large earthquakes are extremely common along convergent plate boundaries. Since the Pacific Ocean is rimmed by convergent and transform boundaries, about 80% of all earthquakes strike around the Pacific Ocean basin (the ring of fire). Why are 75% of the world's volcanoes found around the Pacific basin? Of course, these volcanoes are caused by the abundance of convergent plate boundaries around the Pacific.



Figure 1. The Cascade Range is formed by volcanoes created from subduction of oceanic crust beneath the North American continent.

Pacific Rim

The Pacific Ring of Fire is where the majority of the volcanic activity on the Earth occurs. A description of the Pacific Ring of Fire along western North America is a description of the plate boundaries.

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

This incredible explosive eruption of Mount Vesuvius in Italy in A.D. 79 is an example of a composite volcano that forms as the result of a convergent plate boundary:

A link to an interactive elements can be found at the bottom of this page.

Volcanoes at convergent plate boundaries are found all along the Pacific Ocean basin, primarily at the edges of the Pacific, Cocos, and Nazca plates. Trenches mark subduction zones.

The Cascades are a chain of volcanoes at a convergent boundary where an oceanic plate is subducting beneath a continental plate. Specifically the volcanoes are the result of subduction of the Juan de Fuca, Gorda, and Explorer Plates beneath North America. The volcanoes are located just above where the subducting plate is at the right depth in the mantle for there to be melting (Figure 1).

The Cascades have been active for 27 million years, although the current peaks are no more than 2 million years old. The volcanoes are far enough north and are in a region where storms are common, so many are covered by glaciers.

The Cascades are shown on this interactive map with photos and descriptions of each of the volcanoes.



Figure 3. Mt. Baker, Washington.

Divergent plate boundaries

At divergent plate boundaries hot mantle rock rises into the space where the plates are moving apart. As the hot mantle rock convects upward it rises higher in the mantle. The rock is under lower pressure; this lowers the melting temperature of the rock and so it melts. Lava erupts through long cracks in the ground, or fissures.



Figure 4. A volcanic eruption at Surtsey, a small island near Iceland.

Why does melting occur at divergent plate boundaries? Hot mantle rock rises where the plates are moving apart. This releases pressure on the mantle, which lowers its melting temperature. Lava erupts through long cracks in the ground, or **fissures.**

Volcanoes erupt at mid-ocean ridges, such as the Mid-Atlantic ridge, where seafloor spreading creates new seafloor in the rift valleys. Where a hotspot is located along the ridge, such as at Iceland, volcanoes grow high enough to create islands (figure 4).

Mid-Ocean Ridges



Figure 5. Mount Gahinga in the East African Rift valley.

Volcanoes erupt at mid-ocean ridges, such as the Mid-Atlantic ridge, where seafloor spreading creates new seafloor in the rift valleys. Where a hotspot is located along the ridge, such as at Iceland, volcanoes grow high enough to create islands.

Continental Rifting

Eruptions are found at divergent plate boundaries as continents break apart. The volcanoes in Figure 5 are in the East African Rift between the African and Arabian plates. Remember from the chapter Plate Tectonics that Baja California is being broken apart from mainland Mexico as another example of continental rifting.

Summary

- Melting is common at convergent plate boundaries.
- Convergent plate boundaries line the Pacific Ocean basin so that volcanic arcs line the region.
- Melting at divergent plate boundaries is due to pressure release.
- At mid-ocean ridges seafloor is pulled apart and new seafloor is created.

? Explore More

Use this resource to answer the questions that follow.

A link to an interactive elements can be found at the bottom of this page.

(You can stop watching at 11:02.)

1. What percent of volcanoes and earthquakes occur on the Pacific Ring of Fire?
2. How long is the arc of volcanoes along the Pacific Rim?
3. How has Augustine built up so high? Does it have high or low silica?
4. What type of volcanoes are found along the ring of fire? What happens to the gas in the magma? what kills so many people?
5. What does water do in hot rock below the surface?
6. What does carbon-12 indicate?
7. What process brings the sediments and water into the mantle?

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Provided by**: Lumen Learning. **License**: *CC BY-NC: Attribution-NonCommercial*

CC licensed content, Shared previously

- Volcanoes at Plate Boundaries. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Volcanoes-at-Plate-Boundaries/lesson/Volcanoes-at-Plate-Boundaries-HS-ES/?referrer=featured_content#x-ck12-SFMtRVMtMDgtMDQtR2FoaW5nYU11aGFidXJh. **License**: *CC BY-NC: Attribution-NonCommercial*
- Volcanoes. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/8.0/. **License**: *CC BY-NC: Attribution-NonCommercial*

All rights reserved content

- Ring of Fire- Abbreviated. **Authored by**: Frank Gregorio. **Located at**: https://youtu.be/uw7Uq137YJQ. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 9.8: Reading- Volcanoes at Plate Boundaries is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.9: Reading- Volcanoes Hotspots

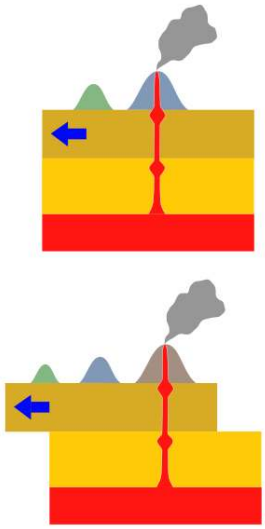


Figure 1. Diagram showing a cross section though the Earth's lithosphere (in yellow) with magma rising from the mantle (in red)

In geology, the places known as **hotspots** or **hot spots** are volcanic regions thought to be fed by underlying mantle that is anomalously hot compared with the surrounding mantle. They may be on, near to, or far from tectonic plate boundaries. Currently, there are two hypotheses that attempt to explain their origins. One suggests that they are due to hot mantle plumes that rise as thermal diapirs from the core–mantle boundary.[1] An alternative hypothesis postulates that it is not high temperature that causes the volcanism, but lithospheric extension that permits the passive rising of melt from shallow depths.[2] This hypothesis considers the term "hotspot" to be a misnomer, asserting that the mantle source beneath them is, in fact, not anomalously hot at all. Well known examples include Hawaii and Yellowstone.

Background

The origins of the concept of hotspots lie in the work of J. Tuzo Wilson, who postulated in 1963 that the Hawaiian Islands result from the slow movement of a tectonic plate across a hot region beneath the surface.[3] It was later postulated that hotspots are fed by narrow streams of hot mantle rising from the Earth's core–mantle boundary in a structure called a mantle plume.[4] Whether or not such mantle plumes exist is currently the subject of a major controversy in Earth science.[5] Estimates for the number of hotspots postulated to be fed by mantle plumes has ranged from about 20 to several thousands, over the years, with most geologists considering a few tens to exist. Hawaii, Réunion, Yellowstone, Galápagos, and Iceland are some of the currently most active volcanic regions to which the hypothesis is applied.

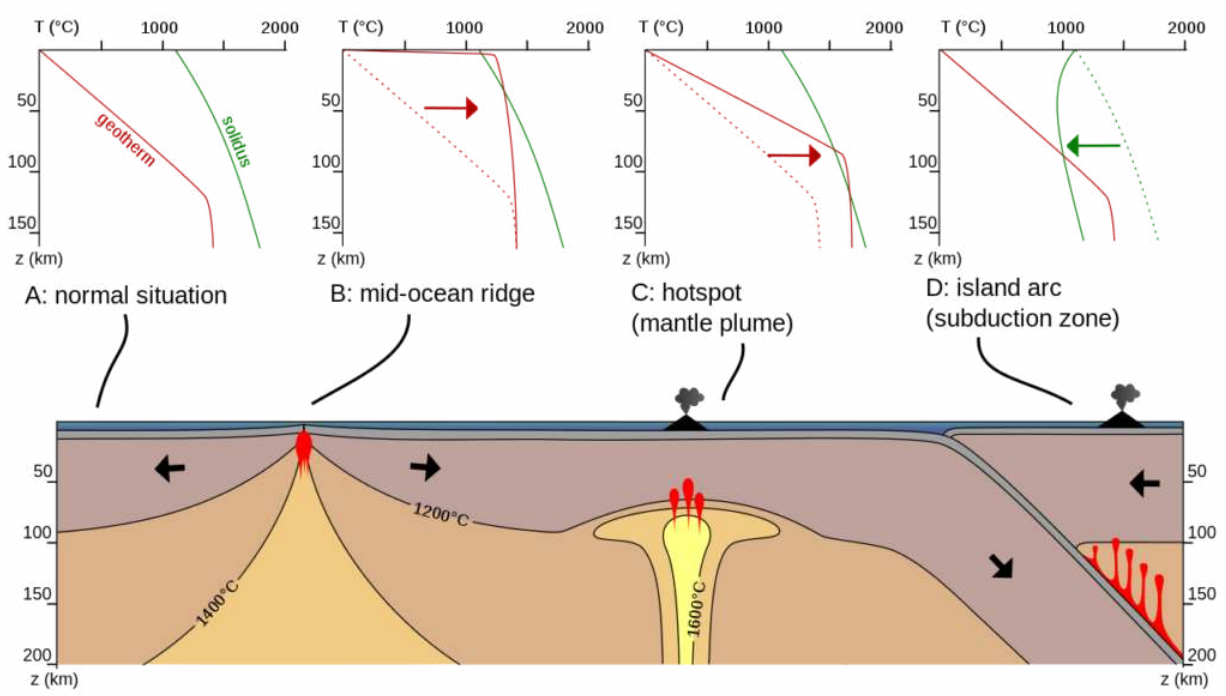


Figure 2. Schematic diagram showing the physical processes inside the Earth that lead to the generation of magma. Partial melting begins above the fusion point.

Most hotspot volcanoes are basaltic (e.g., Hawaii, Tahiti). As a result, they are less explosive than subduction zone volcanoes, in which water is trapped under the overriding plate. Where hotspots occur in continental regions, basaltic magma rises through the continental crust, which melts to form rhyolites. These rhyolites can form violent eruptions. For example, the Yellowstone Caldera was formed by some of the most powerful volcanic explosions in geologic history. However, when the rhyolite is completely erupted, it may be followed by eruptions of basaltic magma rising through the same lithospheric fissures (cracks in the lithosphere). An example of this activity is theIlgachuz Range in British Columbia, which was created by an early complex series of trachyte and rhyolite eruptions, and late extrusion of a sequence of basaltic lava flows.[6]

The hotspot hypothesis is now closely linked to the mantle plume hypothesis.

Comparison with island arc volcanoes

Hotspot volcanoes are considered to have a fundamentally different origin from island arc volcanoes. The latter form over subduction zones, at converging plate boundaries. When one oceanic plate meets another, the denser plate is forced downward into a deep ocean trench. This plate, as it is subducted, releases water into the base of the over-riding plate, and this water mixes with the rock, thus changing its composition causing some rock to melt and rise. It is this that fuels a chain of volcanoes, such as the Aleutian Islands, near Alaska.

Hotspot volcanic chains

The joint mantle plume/hotspot hypothesis envisages the feeder structures to be fixed relative to one another, with the continents and seafloor drifting overhead. The hypothesis thus predicts that time-progressive chains of volcanoes are developed on the surface. Examples are Yellowstone, which lies at the end of a chain of extinct calderas, which become progressively older to the west. Another example is the Hawaiian archipelago, where islands become progressively older and more deeply eroded to the northwest.

Geologists have tried to use hotspot volcanic chains to track the movement of the Earth's tectonic plates. This effort has been vexed by the lack of very long chains, by the fact that many are not time-progressive (e.g. the Galápagos) and by the fact that hotspots do not appear to be fixed relative to one another (e.g. Hawaii and Iceland[7]).

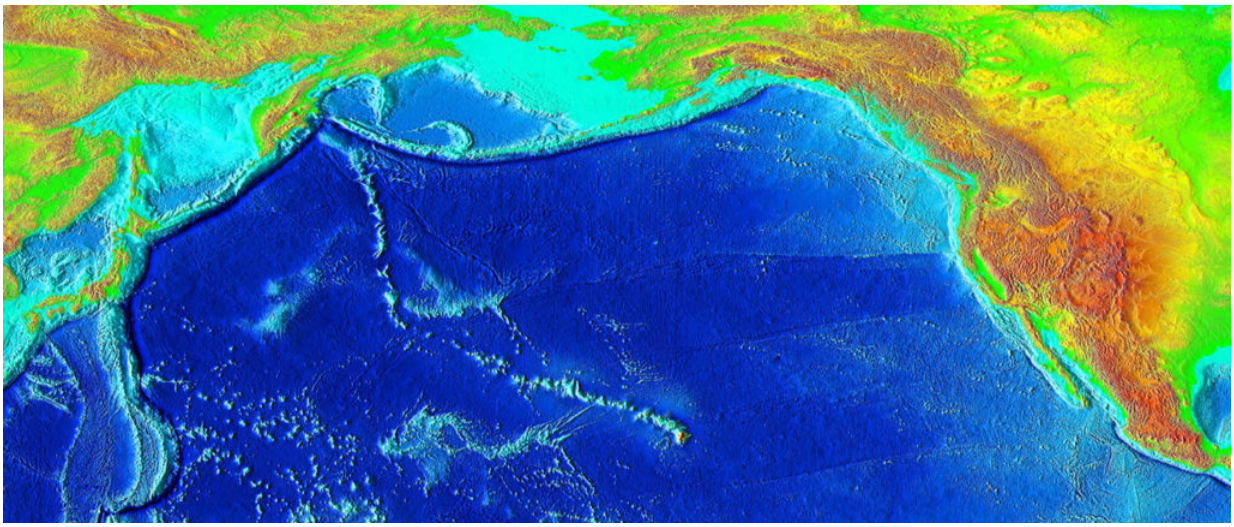


Figure 3. Over millions of years, the Pacific Plate has moved over the Hawaii hotspot, creating a trail of underwater mountains that stretch across the Pacific

1. W. J. Morgan (5 March 1971). "Convection Plumes in the Lower Mantle." *Nature***230** (5288): 42–43. doi: 10.1038/230042a0. ↵
2. "Do plumes exist?". Retrieved 2010-04-25. See also, Foulger, G.R. (2010). *Plates vs. Plumes: A Geological Controversy*. Wiley-Blackwell. ↵
3. Wilson, J. Tuzo (1963). "A possible origin of the Hawaiian Islands" (PDF). *Canadian Journal of Physics***41** (6): 863–870. doi:10.1139/p63-094. ↵
4. "Hotspots: Mantle thermal plumes." United States Geological Survey. 1999-05-05. Retrieved 2008-05-15. ↵
5. Foulger, G.R. (2010). *Plates vs. Plumes: A Geological Controversy*. Wiley-Blackwell. See also,Wright, Laura (November 2000). "Earth's interior: Raising hot spots." *Geotimes*. American Geological Institute. Retrieved 2008-06-15. ↵
6. Holbek, Peter (November 1983). "Report on Preliminary Geology and Geochemistry of the Ilga Claim Group" (PDF). Retrieved 2008-06-15. ↵
7. "What the hell is Hawaii?" Retrieved 2011-01-07. ↵

Contributors and Attributions

CC licensed content, Shared previously

- Hotspot (geology). **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Hotspot_%28geology%29. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 9.9: Reading- Volcanoes Hotspots is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.10: Self Check- The Formation of Volcanoes

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1113

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 9.10: Self Check- The Formation of Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.11: Outcome- Igneous Features

Classify and identify igneous features.

This section will introduce you to common volcanic features including types of deposits and lava associated with different volcano types.

What You'll Learn to Do

- Recognize pyroclastic deposit
- Differentiate between a dike and a sill
- Recognize different volcanic landforms
- Describe the development of continental and oceanic crusts.

Learning Activities

The learning activities for this section include the following:

- Reading: Pyroclastic Deposits
- Reading: Dikes and Sills
- Reading: Volcanic Landforms
- Self Check: Igneous Features

This page titled 9.11: Outcome- Igneous Features is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.12: Reading- Pyroclastic Deposits



Figure 1. USGS scientist examines pumice blocks at the edge of a pyroclastic flow from Mount St. Helens

Pyroclastic rocks or **pyroclastics** are clastic rocks composed solely or primarily of volcanic materials. Where the volcanic material has been transported and reworked through mechanical action, such as by wind or water, these rocks are termed ***volcaniclastic***. Commonly associated with unsieved volcanic activity—such as Plinian or krakatoan eruption styles, or phreatomagmatic eruptions—pyroclastic deposits are commonly formed from airborne ash, lapilli and bombs or blocks ejected from the volcano itself, mixed in with shatteredcountry rock.

Pyroclastic rocks may be a range of clast sizes, from the largest agglomerates, to very fine ashes and tuffs. Pyroclasts of different sizes are classified as volcanic bombs, lapilli, and volcanic ash. Ash is considered to be pyroclastic because it is a fine dust made up of volcanic rock. One of the most spectacular forms of pyroclastic deposit are the ignimbrites, deposits formed by the high-temperature gas-and-ash mix of a pyroclastic flow event.

Classification

Types of Pyroclasts[1]

Clast size	Pyroclast	Mainly unconsolidated: Tephra	Mainly consolidated: Pyroclastic rock
> 64 mm	Block, bomb	Agglomerate	Agglomerate, pyroclastic breccia
< 64 mm	Lapillus	Layer, lapilli tephra	Lapilli tuff, lapillistone
< 2 mm	Coarse ash	Coarse ash	Coarse (ash) tuff
< 0.063 mm	Fine ash	Fine ash	Fine (ash) tuff



Figure 2. Rocks from the Bishop Tuff, uncompressed with pumice on left; compressed with fiamme on right.

Three modes of transport can be distinguished: pyroclastic flow, pyroclastic surge, and pyroclastic fall. During Plinian eruptions, pumice and ash are formed when silicic magma is fragmented in the volcanic conduit, because of decompression and the growth of bubbles. Pyroclasts are then entrained in a buoyant eruption plume which can rise several kilometers into the air and cause aviation hazards. Particles falling from the eruption clouds form layers on the ground (this is pyroclastic fall or tephra). Pyroclastic density currents, which are referred to as “flows” or “surges” depending on particle concentration and the level turbulence, are sometimes called *glowing avalanches*. The deposits of pumice-rich pyroclastic flows can be called ignimbrites.

A pyroclastic eruption entails spitting or “fountaining” lava, where the lava will be thrown into the air along with ash, pyroclastic materials, and other volcanic byproducts. Hawaiian eruptions such as those at Kīlauea can eject clots of magma suspended into gas; this is called a “fire fountain”. The magma clots, if hot enough may coalesce upon landing to form a lava flow.

Pyroclastic deposits consist of pyroclasts which are not cemented together. Pyroclastic rocks (tuff) are pyroclastic deposits which have been lithified.

References

Blatt, Harvey and Robert J. Tracy (1996) *Petrology: Igneous, Sedimentary, and Metamorphic*, W.H.W. Freeman & Company; 2nd ed., pp. 26–29.

---

1. Heiken, G. and Wohletz, K., 1985 *Volcanic Ash*, University of California Press;, pp. 246. ↵

Contributors and Attributions

CC licensed content, Shared previously

- Pyroclastic rock. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Pyroclastic_rock#cite_ref-1. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 9.12: Reading- Pyroclastic Deposits is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.13: Reading- Dikes and Sills

Dikes

A **dike** is a sheet of rock that formed in a fracture in a pre-existing rock body. Dikes can be either magmatic or sedimentary in origin. Magmatic dikes form when magma intrudes into a crack then crystallizes as a sheet intrusion, either cutting across layers of rock or through an unlayered mass of rock. Clastic dikes are formed when sediment fills a pre-existing crack.[1]



Figure 1. A magmatic dike cross-cutting horizontal layers of sedimentary rock, in Makhtesh Ramon, Israel

Magmatic Dikes

An intrusive dike is an igneous body with a very high aspect ratio, which means that its thickness is usually much smaller than the other two dimensions. Thickness can vary from sub-centimeter scale to many meters, and the lateral dimensions can extend over many kilometres. A dike is an intrusion into an opening cross-cutting fissure, shouldering aside other pre-existing layers or bodies of rock; this implies that a dike is always younger than the rocks that contain it. Dikes are usually high-angle to near-vertical in orientation, but subsequent tectonic deformation may rotate the sequence of strata through which the dike propagates so that the dike becomes horizontal. Near-horizontal, or conformable intrusions, along bedding planes between strata are called intrusive sills.

Sometimes dikes appear in swarms, consisting of several to hundreds of dikes emplaced more or less contemporaneously during a single intrusive event. The world's largest dike swarm is the Mackenzie dike swarm in the Northwest Territories, Canada.[2]

Dikes often form as either radial or concentric swarms around plutonic intrusives, volcanic necks or feeder vents in volcanic cones. The latter are known as ring dikes.

Dikes can vary in texture and their composition can range from diabase or basaltic to granitic or rhyolitic, but on a global perspective the basaltic composition prevails, manifesting ascent of vast volumes of mantle-derived magmas through fractured lithosphere throughout Earth history. Pegmatite dikes comprise extremely coarse crystalline granitic rocks—often associated with late-stage granite intrusions or metamorphic segregations. Aplite dikes are fine-grained or sugary-textured intrusives of granitic composition.



Figure 2. A small dike on the Baranof Cross-Island Trail, Alaska

Sedimentary Dikes



Figure 3. Clastic dike (left of notebook) in the Chinle Formation in Canyonlands National Park, Utah

Sedimentary dikes or clastic dikes are vertical bodies of sedimentary rock that cut off other rock layers. They can form in two ways:

- When a shallow unconsolidated sediment is composed of alternating coarse grained andimpermeable clay layers the fluid pressure inside the coarser layers may reach a critical value due to lithostatic overburden. Driven by the fluid pressure the sediment breaks through overlying layers and forms a dike.
- When a soil is under permafrost conditions the pore water is totally frozen. When cracks are formed in such rocks, they may fill up with sediments that fall in from above. The result is a vertical body of sediment that cuts through horizontal layers: a dike.

Sills

In geology, a **sill** is a tabular sheet intrusion that has intruded between older layers of sedimentary rock, beds of volcanic lava or tuff, or even along the direction of foliation in metamorphic rock. The term sill is synonymous with concordant intrusive sheet. This means that the sill does not cut across preexisting rocks, in contrast to dikes, discordant intrusive sheets which do cut across older rocks. Sills are fed by dikes, except in unusual locations where they form in nearly vertical beds attached directly to a magma source. The rocks must be brittle and fracture to create the planes along which the magma intrudes the parent rock bodies, whether this occurs along preexisting planes between sedimentary or volcanic beds or weakened planes related to foliation in metamorphic rock. These planes or weakened areas allow the intrusion of a thin sheet-like body of magma paralleling the existing bedding planes, concordant fracture zone, or foliations.

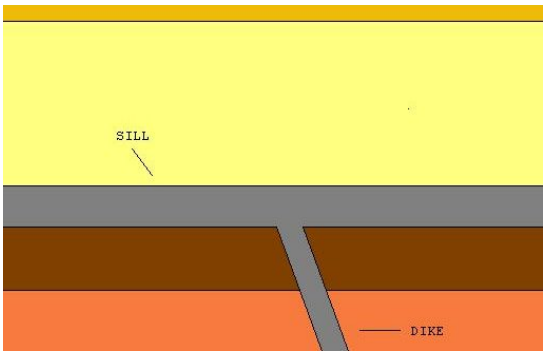


Figure 4. Illustration showing the difference between a dike and a sill.

Sills parallel beds (layers) and foliations in the surrounding country rock. They can be originally emplaced in a horizontal orientation, although tectonic processes may cause subsequent rotation of horizontal sills into near vertical orientations. Sills can be confused with solidified lava flows; however, there are several differences between them. Intruded sills will show partial melting and incorporation of the surrounding country rock. On both contact surfaces of the country rock into which the sill has intruded, evidence of heating will be observed (contact metamorphism). Lava flows will show this evidence only on the lower side of the flow. In addition, lava flows will typically show evidence of vesicles (bubbles) where gases escaped into the atmosphere. Because sills generally form at shallow depths (up to many kilometers) below the surface, the pressure of overlying rock prevents this from happening much, if at all. Lava flows will also typically show evidence of weathering on their upper surface, whereas sills, if still covered by country rock, typically do not.

Associated Ore Deposits


Figure 5. Mid-Carboniferous dolerite sill cutting Lower Carboniferous shales and sandstones, Horton Bluff, Minas Basin South Shore, Nova Scotia

Certain layered intrusions are a variety of sill that often contain important ore deposits. Precambrian examples include the Bushveld, Insizwa and the Great Dyke complexes of southern Africa, the Duluth intrusive complex of the Superior District, and the Stillwater igneous complex of the United States. Phanerozoic examples are usually smaller and include the Rùm peridotite complex of Scotland and the Skaergaard igneous complex of east Greenland. These intrusions often contain concentrations of gold, platinum, chromium and other rare elements.

Transgressive Sills

Despite their concordant nature, many large sills change stratigraphic level within the intruded sequence, with each concordant part of the intrusion linked by relatively short dike-like segments. Such sills are known as transgressive, examples include the Whin Sill and sills within the Karoo basin.[3] The geometry of large sill complexes in sedimentary basins has become clearer with the availability of 3D seismic reflection data.[4] Such data has shown that many sills have an overall saucer shape and that many others are at least in part transgressive.[5]

Other Meanings

"Sill" may also refer to the rise in depth near the mouth of a fjord caused by the terminal moraine of the previous glacier.

---

1. Essentials of Geology, 3rd Ed, Stephen Marshak ↵
2. Pilkington, Mark and Walter R. Roest; *Removing varying directional trends in aeromagnetic data*, Geophysics, vol. 63 no. 2 (1998), pp. 446–453. abstract↵
3. Holmes, A. 1978. *Principles of Physical Geology*, Van Nostrand Reinhold (UK) Co.Ltd., 720 pp. See also, Polteau, S., Mazzini, A., Galland, O., Planke, S. & Malthe-Sørenssen, A. 2008. Saucer-shaped intrusions: Occurrences, emplacement and implications, *Earth and Planetary Science Letters* 266, 195–204. ↵
4. Thomson, K. & Hutton, D. 2004. Geometry and growth of sill complexes: insights using 3D seismic from the North Rockall Trough, *Bulletin of Volcanology, 66*, 364–375. ↵
5. Planke, S., Rasmussen, T., Rey, S.S. & Myklebust, R. 2005. Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins, In: Doré, A. G. & Vining, B. A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives — Proceedings of the 6th Petroleum Geology Conference*, 833–844. Petroleum Geology Conferences Ltd. Published by the Geological Society, London. ↵

Contributors and Attributions

CC licensed content, Shared previously

- Dike (geology). **Provided by**: Wikipedi. **Located at**: https://en.Wikipedia.org/wiki/Dike_%28geology%29. **License**: *CC BY-SA: Attribution-ShareAlike*
- Sill (geology). **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Sill_%28geology%29. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 9.13: Reading- Dikes and Sills is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.14: Reading- Volcanic Landforms



Why is the Republic of Indonesia made of 17,508 islands?

Around the Pacific Rim is Indonesia, a nation built from the dotted volcanoes of an island arc. Indonesia is distinctive for its rich volcanic soil, tropical climate, tremendous biodiversity, and volcanoes. These volcanoes are in Java, Indonesia.

Landforms from Lava

Volcanoes and Vents

The most obvious landforms created by lava are volcanoes, most commonly as cinder cones, composite volcanoes, and shield volcanoes. Eruptions also take place through other types of vents, commonly from fissures (Figure 1). The eruptions that created the entire ocean floor are essentially fissure eruptions.



Figure 1. A fissure eruption on Mauna Loa in Hawaii travels toward Mauna Kea on the Big Island.

Lava Domes

Viscous lava flows slowly. If there is not enough magma or enough pressure to create an explosive eruption, the magma may form a lava dome. Because it is so thick, the lava does not flow far from the vent. (Figure 2).



Figure 2. Lava domes are large, round landforms created by thick lava that does not travel far from the vent.

Lava flows often make mounds right in the middle of craters at the top of volcanoes, as seen in the Figure 3.



Figure 3. Lava domes may form in the crater of composite volcanoes as at Mount St. Helens.

Lava Plateaus

A lava plateau forms when large amounts of fluid lava flow over an extensive area (Figure 4). When the lava solidifies, it creates a large, flat surface of igneous rock.



Figure 4. Layer upon layer of basalt have created the Columbia Plateau, which covers more than 161,000 square kilometers (63,000 square miles) in Washington, Oregon, and Idaho.

Land

Lava creates new land as it solidifies on the coast or emerges from beneath the water (Figure 5).



Figure 5. Lava flowing into the sea creates new land in Hawaii.

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 (Figure 6).



Figure 6. The island of Hawaii was created by hotspot volcanism. You can see some of the volcanoes (both active and extinct) in this mosaic of false-color composite satellite images.

Landforms from Magma

Magma intrusions can create landforms. Shiprock in New Mexico is the neck of an old volcano that has eroded away (Figure 7). The volcanic neck is the remnant of the conduit the magma traveled up to feed an eruption.



Figure 7. The aptly named Shiprock in New Mexico.

Summary

- Landforms created by lava include volcanoes, domes, and plateaus.
- New land can be created by volcanic eruptions.
- Landforms created by magma include volcanic necks and domes.

Contributors and Attributions

CC licensed content, Shared previously

- Volcanic Landforms. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Volcanic-Landforms/lesson/Volcanic-Landforms-HS-ES. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 9.14: Reading- Volcanic Landforms is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.15: Self Check- Igneous Features

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1114

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 9.15: Self Check- Igneous Features is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.16: Outcome- Volcanic Hazards

Describe major volcanic hazards and their potential effects.

Volcanic eruptions are one of Earth's most dramatic and violent agents of change. Not only can powerful explosive eruptions drastically alter land and water for tens of kilometers around a volcano, but tiny liquid droplets of sulfuric acid erupted into the stratosphere can change our planet's climate temporarily. Eruptions often force people living near volcanoes to abandon their land and homes, sometimes forever. Those living farther away are likely to avoid complete destruction, but their cities and towns, crops, industrial plants, transportation systems, and electrical grids can still be damaged by tephra, ash, lahars, and flooding.

What You'll Learn to Do

- Recognize and describe the impact of volcanic hazards associated with active eruptions.
- Recognize and describe the impact of volcanic hazards associated with the aftermath of eruptions.

Learning Activities

The learning activities for this section include the following:

- Reading: Volcanic Gases, Pyroclastic Flow, and Tephra
- Reading: Lahars, Landslides, and Lavaflow
- Self Check: Volcanic Hazards

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

Public domain content

- Types of Volcano Hazards. **Provided by**: USGS. **Located at**: http://volcanoes.usgs.gov/hazards/. **License**: *Public Domain: No Known Copyright*

This page titled 9.16: Outcome- Volcanic Hazards is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.17: Reading- Volcanic Gases, Pyroclastic Flow, and Tephra

Volcanic Gases and Their Effects

Magma contains dissolved gases that are released into the atmosphere during eruptions. Gases are also released from magma that either remains below ground (for example, as an intrusion) or is rising toward the surface. In such cases, gases may escape continuously into the atmosphere from the soil, volcanic vents, fumaroles, and hydrothermal systems.

At high pressures deep beneath the earth's surface, volcanic gases are dissolved in molten rock. But as magma rises toward the surface where the pressure is lower, gases held in the melt begin to form tiny bubbles. The increasing volume taken up by gas bubbles makes the magma less dense than the surrounding rock, which may allow the magma to continue its upward journey. Closer to the surface, the bubbles increase in number and size so that the gas volume may exceed the melt volume in the magma, creating a magma foam. The rapidly expanding gas bubbles of the foam can lead to explosive eruptions in which the melt is fragmented into pieces of volcanic rock, known as tephra. If the molten rock is not fragmented by explosive activity, a lava flow will be generated.

Together with the tephra and entrained air, volcanic gases can rise tens of kilometers into Earth's atmosphere during large explosive eruptions. Once airborne, the prevailing winds may blow the eruption cloud hundreds to thousands of kilometers from a volcano. The gases spread from an erupting vent primarily as acid aerosols (tiny acid droplets), compounds attached to tephra particles, and microscopic salt particles.

Volcanic gases undergo a tremendous increase in volume when magma rises to the Earth's surface and erupts. For example, consider what happens if one cubic meter of 900°C rhyolite magma containing five percent by weight of dissolved water were suddenly brought from depth to the surface. The one cubic meter of magma now would occupy a volume of 670 m^3 as a mixture of water vapor and magma at atmospheric pressure (Sparks et. al., 1997)! The one meter cube at depth would increase to 8.75 m on each side at the surface. Such enormous expansion of volcanic gases, primarily water, is the main driving force of explosive eruptions.

The most abundant gas typically released into the atmosphere from volcanic systems is water vapor (H_2O), followed by carbon dioxide (CO_2) and sulfur dioxide (SO_2). Volcanoes also release smaller amounts of others gases, including hydrogen sulfide (H_2S), hydrogen (H_2), carbon monoxide (CO), hydrogen chloride (HCL), hydrogen fluoride (HF), and helium (He).

Examples of volcanic gas compositions, in volume percent concentrations
(from Symonds et. al., 1994)

Volcano Tectonic Style Temperature	**Kilauea Summit** Hot Spot 1170°C	**Erta` Ale** Divergent Plate 1130°C	**Momotombo** Convergent Plate 820°C
H_20	37.1	77.2	97.1
$C0_2$	48.9	11.3	1.44
$S0_2$	11.8	8.34	0.50
H_2	0.49	1.39	0.70
CO	1.51	0.44	0.01
H_2S	0.04	0.68	0.23
HCl	0.08	0.42	2.89
HF	—	—	0.26

The volcanic gases that pose the greatest potential hazard to people, animals, agriculture, and property are sulfur dioxide, carbon dioxide, and hydrogen fluoride. Locally, sulfur dioxide gas can lead to acid rain and air pollution downwind from a volcano. Globally, large explosive eruptions that inject a tremendous volume of sulfur aerosols into the stratosphere can lead to lower

surface temperatures and promote depletion of the Earth's ozone layer. Because carbon dioxide gas is heavier than air, the gas may flow into in low-lying areas and collect in the soil. The concentration of carbon dioxide gas in these areas can be lethal to people, animals, and vegetation. A few historic eruptions have released sufficient fluorine-compounds to deform or kill animals that grazed on vegetation coated with volcanic ash; fluorine compounds tend to become concentrated on fine-grained ash particles, which can be ingested by animals.

Sulfur dioxide (SO_2)

The effects of SO_2 on people and the environment vary widely depending on (1) the amount of gas a volcano emits into the atmosphere; (2) whether the gas is injected into the troposphere or stratosphere; and (3) the regional or global wind and weather pattern that disperses the gas. Sulfur dioxide (SO_2) is a colorless gas with a pungent odor that irritates skin and the tissues and mucous membranes of the eyes, nose, and throat. Sulfur dioxide chiefly affects upper respiratory tract and bronchi. The World Health Organization recommends a concentration of no greater than 0.5 ppm over 24 hours for maximum exposure. A concentration of 6-12 ppm can cause immediate irritation of the nose and throat; 20 ppm can cause eye irritation; 10,000 ppm will irritate moist skin within minutes.

Emission rates of SO_2 from an active volcano range from <20 tonnes/day to >10 million tonnes/day according to the style of volcanic activity and type and volume of magma involved. For example, the large explosive eruption of Mount Pinatubo on 15 June 1991 expelled 3-5 km^3 of dacite magma and injected about 20 million metric tons of SO_2 into the stratosphere. The sulfur aerosols resulted in a 0.5-0.6°C cooling of the Earth's surface in the Northern Hemisphere. The sulfate aerosols also accelerated chemical reactions that, together with the increased stratospheric chlorine levels from human-made chlorofluorocarbon (CFC) pollution, destroyed ozone and led to some of the lowest ozone levels ever observed in the atmosphere.

At Kilauea Volcano, the recent effusive eruption of about 0.0005 km^3/day (500,000 m^3) of basalt magma releases about 2,000 tonnes of SO_2 into the lower troposphere. Downwind from the vent, acid rain and air pollution is a persistent health problem when the volcano is erupting.

- **SO_2 causes air pollutionVolcanic smog.** Eruptions of Kilauea Volcano release large quantities of sulfur dioxide gas into the atmosphere that can lead to volcanic air pollution on the Island of Hawai`i. Sulfur dioxide gas reacts chemically with sunlight, oxygen, dust particles, and water to form volcanic smog known as vog.
- **SO_2 effects Earth's surface temperatureGlobal cooling and ozone depletion.** Measurements from recent eruptions such as Mount St. Helens, Washington (1980), El Chichon, Mexico (1982), and Mount Pinatubo, Philippines (1991), clearly show the importance of sulfur aerosols in modifying climate, warming the stratosphere, and cooling the troposphere. Research has also shown that the liquid drops of sulfuric acid promote the destruction of the Earth's ozone layer.

Hydrogen sulfide (H_2S)

Hydrogen sulfide (H_2S) is a colorless, flammable gas with a strong offensive odor. It is sometimes referred to as sewer gas. At low concentrations it can irritate the eyes and acts as a depressant; at high concentrations it can cause irritation of the upper respiratory tract and, during long exposure, pulmonary edema. A 30-minute exposure to 500 ppm results in headache, dizziness, excitement, staggering gait, and diarrhea, followed sometimes by bronchitis or bronchopneumonia.

Carbon dioxide (CO_2)

Volcanoes release more than 130 million tonnes of CO_2 into the atmosphere every year. This colorless, odorless gas usually does not pose a direct hazard to life because it typically becomes diluted to low concentrations very quickly whether it is released continuously from the ground or during episodic eruptions. But in certain circumstances, CO_2 may become concentrated at levels lethal to people and animals. Carbon dioxide gas is heavier than air and the gas can flow into in low-lying areas; breathing air with more than 30% CO_2 can quickly induce unconsciousness and cause death. In volcanic or other areas where CO_2 emissions occur, it is important to avoid small depressions and low areas that might be CO_2 traps. The boundary between air and lethal gas can be extremely sharp; even a single step upslope may be adequate to escape death.

CO_2 trapped in depressions can be lethal to people and animals. When a burning piece of cloth is lowered into a hole that has a high concentration of CO_2, the fire goes out. Such a condition can be lethal to people and animals.

Air with 5% CO_2 causes perceptible increased respiration; 6-10% results in shortness of breath, headaches, dizziness, sweating, and general restlessness; 10-15% causes impaired coordination and abrupt muscle contractions; 20-30% causes loss of consciousness and convulsions; over 30% can cause death (Hathaway et. al., 1991).

Please see the web article, "Volcanic Gases and Climate Change Overview" for more information on Volcanic versus anthropogenic CO_2emissions.

Here is a historical example of the effects of carbon dioxide gas: Mammoth Mountain in Long Valley Caldera, California kills trees near Mammoth Mountain, California

Hydrogen Chloride (HCl)

Chlorine gas is emitted from volcanoes in the form of hydrochloric acid (HCl). Exposure to the gas irritates mucous membranes of the eyes and respiratory tract. Concentrations over 35 ppm cause irritation of the throat after short exposure; >100 ppm results in pulmonary edema, and often laryngeal spasm. It also causes acid rain downwind from volcanoes because HCl is extremely soluble in condensing water droplets and it is a very "strong acid" (it dissociates extensively to give H^+ ions in the droplets).

Hydrogen Fluoride (HF)

Fluorine is a pale yellow gas that attaches to fine ash particles, coats grass, and pollutes streams and lakes. Exposure to this powerful caustic irritant can cause conjunctivitis, skin irritation, bone degeneration and mottling of teeth. Excess fluorine results in a significant cause of death and injury in livestock during ash eruptions. Even in areas that receive just a millimeter of ash, poisoning can occur where the fluorine content of dried grass exceeds 250 ppm. Animals that eat grass coated with fluorine-tainted ash are poisoned. Small amounts of fluorine can be beneficial, but excess fluorine causes fluorosis, an affliction that eventually kills animals by destroying their bones. It also promotes acid rain effects downwind of volcanoes, like HCl.

Secondary Gas Emissions

Another type of gas release occurs when lava flows reach the ocean. Extreme heat from molten lava boils and vaporizes seawater, leading to a series of chemical reactions. The boiling and reactions produce a large white plume, locally known as lava haze or laze, containing a mixture of hydrochloric acid and concentrated seawater.

- **Laze plumes are very acidic.** Extreme heat from lava entering the sea rapidly boils and vaporizes seawater, leading to a series of chemical reactions. The boiling and reactions produce a large white plume, locally known as lava haze or laze, which contains a mixture of hydrochloric acid (HCl) and concentrated seawater. This is a short-lived local phenomenon that only affects people or vegetation directly under the plume.
  The hydrochloric acid (HCl) comes from the breakdown of seawater-derived chlorides during sudden boiling. Because the lava is largely degassed by the time it reaches the sea, any HCL coming from it is insignificant by comparison. Analyzed samples of the plume show that is is a brine with a salinity of about 2.3 times that of seawater and a pH of 1.5-2.0.
- **Key seawater chloride breakdown reactions that produce HCl gas**
  - $MgCl_2$ (sea salt) + H_2O (steam) = MgO (periclase) + 2HCl (HCl gas)
  - 2 NaCl (sea salt) + H_2O (steam) = Na_2O (sodium oxide) + 2 HCL (HCl gas)
  - $CaCl_2$ (sea salt) + H_2O (steam) = CaO (lime) + 2 HCL (HCl gas)
- **Avoid standing beneath a laze plume.** Dense laze plumes, such as that shown here (Photograph by C.C. Heliker, February 10, 1994) contain as much as 10-15 parts per million of hydrochloric acid. These values drop off sharply as the plume moves away from the lava entry areas. During along-shore or on-shore winds, this plume produces acid rain that may fall on people and land along the coast. This rain (pH 1.5 to 2), often more acidic that lime juice or stomach acid, is very corrosive to the skin and clothing. Visitors to the lava entry areas should avoid standing directly in, under, or downwind of the laze plume.

Pyroclastic Flows and Their Effects

About Pyroclastic Flows

Pyroclastic flows are high-density mixtures of hot, dry rock fragments and hot gases that move away from the vent that erupted them at high speeds. They may result from the explosive eruption of molten or solid rock fragments, or both. They may also result from the nonexplosive eruption of lava when parts of dome or a thick lava flow collapses down a steep slope. Most pyroclastic

flows consist of two parts: a basal flow of coarse fragments that moves along the ground, and a turbulent cloud of ash that rises above the basal flow. Ash may fall from this cloud over a wide area downwind from the pyroclastic flow.



Figure 1. Pyroclastic Flows destroy by direct impact.

Figure 1 shows a remnant of a building in Francisco Leon that was destroyed by pyroclastic flows and surges during the eruption of El Chichon volcano in southeastern Mexico between March 29 and April 4, 1982. Francisco Leon was located about 5 km SSE of the volcano. The reinforcement rods in the concrete wall are bent in the direction of flow (right to left).

Several pyroclastic surges swept down all sides of the volcano, reaching as far as 2 to 8 km from the volcano; pyroclastic flows represent only about 30 percent of the total combined mass of surges and flows. In addition to Francisco Leon, eight other villages were destroyed, claiming the lives of up to 2,000 people.



Figure 2. Pyroclastic Flows bury sites with hot rock debris.

Pyroclastic flows erupted by Mount Pinatubo on June 15, 1991, buried the Marella River valley (SW of Pinatubo) with pumice, ash, and other volcanic rocks to depths of between 50 and 200 m (as shown in figure 2). This eruption was one of the largest in the 20th century, depositing about 5.5 km^3 of rock debris over nearly 400 km^2. The pyroclastic flows traveled as far as 12 to 16 km from the volcano in all directions. Unlike river valleys, the steep slopes around the volcano were veneered with very thin, discontinuous pyroclastic-flow deposits.

A series of pyroclastic flows from Redoubt Volcano in Alaska between December 1989 and April 1990 rapidly melted snow and ice that generated lahars in Drift River (valley in figure 3).



Figure 3. Pyroclastic Flows melt snow and ice to form lahars.

The lahars swept 40 km to Cook Inlet. Most of the pyroclastic flows were caused by the repeated collapse of a lava dome growing high on the volcano's north flank.

This view across the upper Drift River valley is to the SW; the north flank is on the right side of the volcano, but the dome is not visible. As each pyroclastic flow swept down the volcano's snow- and glacier-covered north flank, the hot lava-dome fragments eroded and mixed with the snow and ice to form a torrent of water that swept into Drift River. The sudden surges of water eroded loose sediment on the valley floor and transformed into lahars.

In this part of the Drift River valley, many of the lahars covered the entire valley floor, but they were generally no more than a few meters thick. The lahars provided an excellent opportunity to test a new lahar detection system.



Figure 4. Pyroclastic Flows burn forests, crops, and buildings.

A small but highly fluidized pyroclastic flow traveled down the narrow Belham stream channel as far as 5 to 6 km from a lava dome growing at the summit of Soufriere Hills volcano in Montserrat (shown in figure 4). The basal part of the pyroclastic flow was confined to the channel bottom, but the overriding hot ash cloud burned and killed vegetation along the channel. The pyroclastic flow was triggered by a partial collapse of the dome. With initial temperatures higher than 900°C, the rock debris and gas carried by a pyroclastic flow or surge easily remain hot enough to burn or singe combustible material even when they travel more than 20 km from a vent.

Effects of Pyroclastic Flows

A pyroclastic flow will destroy nearly everything in its path. With rock fragments ranging in size from ash to boulders traveling across the ground at speeds typically greater than 80 km per hour, pyroclastic flows knock down, shatter, bury or carry away nearly all objects and structures in their way. The extreme temperatures of rocks and gas inside pyroclastic flows, generally between 200°C and 700°C, can cause combustible material to burn, especially petroleum products, wood, vegetation, and houses.

Pyroclastic flows vary considerably in size and speed, but even relatively small flows that move less than 5 km from a volcano can destroy buildings, forests, and farmland. And on the margins of pyroclastic flows, death and serious injury to people and animals may result from burns and inhalation of hot ash and gases.

Pyroclastic flows generally follow valleys or other low-lying areas and, depending on the volume of rock debris carried by the flow, they can deposit layers of loose rock fragments to depths ranging from less than one meter to more than 200 m. Such loose layers of ash and volcanic rock debris in valleys and on hillslopes can lead to lahars indirectly by:

1. Damming or blocking tributary streams, which may cause water to form a lake behind the blockage, overtop and erode the blockage, and mix with the rock fragments as it rushes downstream (for example, see this case study at Pinatubo Volcano, Philippines)
2. Increasing the rate of stream runoff and erosion during subsequent rainstorms. Hot pyroclastic flows and surges can also directly generate lahars by eroding and mixing with snow and ice on a volcano's flanks, thereby sending a sudden torrent of water surging down adjacent valleys (see case study from Nevado del Ruiz volcano, Colombia).

Tephra and Their Effects

Tephra is a general term for fragments of volcanic rock and lava regardless of size that are blasted into the air by explosions or carried upward by hot gases in eruption columns or lava fountains. Such fragments range in size from less than 2 mm (ash) to more than 1 m in diameter. Large-sized tephra typically falls back to the ground on or close to the volcano and progressively smaller fragments are carried away from the vent by wind. Volcanic ash, the smallest tephra fragments, can travel hundreds to thousands of kilometers downwind from a volcano.

Tephra consists of a wide range of rock particles (size, shape, density, and chemical composition), including combinations of pumice, glass shards, crystals from different types of minerals, and shattered rocks of all types (igneous, sedimentary, and

metamorphic). A great variety of terms are used to describe the range of rock fragments thrown into the air by volcanoes. The terms classify the fragments according to size, shape, or the way in which they form and travel.

Mount St. Helens Tephra: block	Mount St. Helens Tephra: ash & pumice	Kilauea Tephra: reticulite	Kilauea Tephra: Pele's hair
			

Volcanic Ash

How far will it fall downwind from an erupting volcano?

Ash usually covers a much larger area and disrupts the lives of far more people than the other more lethal types of volcano hazards. Unfortunately, the size of ash particles that fall to the ground and the thickness of ashfall downwind from an erupting volcano are difficult to predict in advance. Not only is there a wide range in the size of an eruption that might occur and the amount of tephra injected into the atmosphere, but the direction and strength of the prevailing wind can vary widely.

Case Histories: Tephra Distribution Downwind from Eruption

- Tephra Falls of the 1991 Eruptions of Mount Pinatubo
  online report from Fire and Mud: eruptions and lahars of Mount Pinatubo, Philippines.
- Tephra fall from Mount St. Helens, Washington, on May 18, 1980
  graph, ash thickness and particle size downwind from volcano

Potential Effects of Volcanic Ash

Volcanic ash is highly disruptive to economic activity because it covers just about everything, infiltrates most openings, and is highly abrasive. Airborne ash can obscure sunlight to cause temporary darkness and reduce visibility to zero. Ash is slippery, especially when wet; roads, highways, and airport runways may become impassable. Automobile and jet engines may stall from ash-clogged air filters and moving parts can be damaged from abrasion, including bearings, brakes, and transmissions.

More effects include the following:

- Daylight turns into darkness.
- Roofs may collapse from added weight.
- Machinery and vehicles will be abraded.
- Farmland will be covered.
- Roads will be slippery, blocked, or blocked.
- Power systems may shut down.
- Waste-water systems may clog.
- Gutters may fill and collapse.

Contributors and Attributions

Public domain content

- Types of Volcano Hazards. **Provided by**: USGS. **Located at**: http://volcanoes.usgs.gov/hazards/. **License**: *Public Domain: No Known Copyright*

This page titled 9.17: Reading- Volcanic Gases, Pyroclastic Flow, and Tephra is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.18: Reading- Lahars, Landslides, and Lavaflow

Lahars and Their Effects



Figure 1. Gualí River valley. Photograph by R. Janda on December 18, 1985

Lahar is an Indonesian term that describes a hot or cold mixture of water and rock fragments flowing down the slopes of a volcano and (or) river valleys. When moving, a lahar looks like a mass of wet concrete that carries rock debris ranging in size from clay to boulders more than 10 m in diameter. Lahars vary in size and speed. Small lahars less than a few meters wide and several centimeters deep may flow a few meters per second. Large lahars hundreds of meters wide and tens of meters deep can flow several tens of meters per second–much too fast for people to outrun.

As a lahar rushes downstream from a volcano, its size, speed, and the amount of water and rock debris it carries constantly change. The beginning surge of water and rock debris often erodes rocks and vegetation from the side of a volcano and along the river valley it enters. This initial flow can also incorporate water from melting snow and ice (if present) and the river it overruns. By eroding rock debris and incorporating additional water, lahars can easily grow to more than 10 times their initial size. But as a lahar moves farther away from a volcano, it will eventually begin to lose its heavy load of sediment and decrease in size.

Eruptions may trigger one or more lahars directly by quickly melting snow and ice on a volcano or ejecting water from a crater lake. More often, lahars are formed by intense rainfall during or after an eruption–rainwater can easily erode loose volcanic rock and soil on hillsides and in river valleys. Some of the largest lahars begin as landslides of saturated and hydrothermally altered rock on the flank of a volcano or adjacent hillslopes. Landslides are triggered by eruptions, earthquakes, precipitation, or the unceasing pull of gravity on the volcano.

Lahars almost always occur on or near stratovolcanoes because these volcanoes tend to erupt explosively and their tall, steep cones are either snow covered, topped with a crater lake, constructed of weakly consolidated rock debris that is easily eroded, or internally weakened by hot hydrothermal fluids. Lahars are also common from the snow- and ice-covered shield volcanoes in Iceland where eruptions of fluid basalt lava frequently occur beneath huge glaciers.

The scenarios listed below illustrate most of the mechanisms by which lahars are generated. For convenience, we've grouped the mechanisms according to whether a volcano is erupting, has erupted, or is quiet. Each mechanism is illustrated with one or more case studies.

Volcano Landslides and Their Effects

Landslides are large masses of rock and soil that fall, slide, or flow very rapidly under the force of gravity. These mixtures of debris move in a wet or dry state, or both. Landslides commonly originate as massive rockslides or avalanches which disintegrate during movement into fragments ranging in size from small particles to enormous blocks hundreds of meters across. If the moving rock debris is large enough and contains a large content of water and fine material (typically, >3-5 percent of clay-sized particles), the landslide may transform into a lahar and flow downvalley more than 100 km from a volcano!

Volcano landslides range in size from less than 1 km3 to more than 100 km3. The high velocity (>100 km/hr) and great momentum of landslides allows them to run up slopes and to cross valley divides up to several hundred meters high. For example, the landslide at Mount St. Helens on May 18, 1980, had a volume of 2.5 km3, reached speeds of 50-80 m/s (180-288 km/hr), and surged up and over a 400 m tall ridge located about 5 km from the volcano!

Landslides are common on volcanoes because their massive cones (1) typically rise hundreds to thousands of meters above the surrounding terrain; and (2) are often weakened by the very process that created them–the rise and eruption of molten rock. Each

time magma moves toward the surface, overlying rocks are shouldered aside as the molten rock makes room for itself, often creating internal shear zones or oversteepening one or more sides of the cone. Magma that remains within the cone releases volcanic gases that partially dissolve in groundwater, resulting in a hot acidic hydrothermal system that weakens rock by altering rock minerals to clay. Furthermore, the tremendous mass of thousands of layers lava and loose fragmented rock debris can lead to internal faults and fault zones that move frequently as the cone "settles" under the downward pull of gravity.

These conditions permit a number of factors to trigger a landslide or to allow part of a volcano's cone to simply collapse under the influence of gravity:

- intrusion of magma into a volcano
- explosive eruptions (magmatic or phreatic–steam-driven explosions)
- large earthquake directly beneath a volcano or nearby (typically >M5)
- intense rainfall that saturates a volcano or adjacent tephra-covered hillslopes with water, especially before or during a large earthquake.

A landslide typically destroys everything in its path and may generate a variety of related activity. Historically, landslides have caused explosive eruptions, buried river valleys with tens of meters of rock debris, generated lahars, triggered waves and tsunami, and created deep horseshoe-shaped craters.

By removing a large part of a volcano's cone, a landslide may abruptly decrease pressure on the shallow magmatic and hydrothermal systems, which can generate explosions ranging from a small steam explosion to large steam- and magma-driven directed blasts. A large landslide often buries valleys with tens to hundreds of meters of rock debris, forming a chaotic landscape marked by dozens of small hills and closed depressions. If the deposit is thick enough, it may dam tributary streams to form lakes in the subsequent days to months; the lakes may eventually drain catastrophically and generate lahars and floods downstream.

Landslides also generate some of the largest and most deadly lahars, either by transforming directly into a lahar or, after it stops moving, from dewatering of the deposit. Historically, however, the most deadly volcano landslide occurred in 1792 when sliding debris from Mt. Mayuyama near Unzen Volcano in Japan slammed into the Ariaka Sea and generated a wave on the opposite side that killed nearly 15,000 people.

On a volcano, landslides typically carve deep gashes into its cone or create large horseshoe-shaped craters hundreds of meters deep and more than a kilometer in width.

Volcanic landslides can do the following:

- Trigger volcanic explosions
- Generate lahars that travel far downstream
- Cause waves and tsunamis in a lake or ocean
- Bury river valleys with rock debris
- Dam tributary streams to form lakes
- Create a crater or scar on the volcano

Lava Flows and Their Effects

Lava flows are streams of molten rock that pour or ooze from an erupting vent. Lava is erupted during either nonexplosive activity or explosive lava fountains. Lava flows destroy everything in their path, but most move slowly enough that people can move out of the way. The speed at which lava moves across the ground depends on several factors, including (1) type of lava erupted and its viscosity; (2) steepness of the ground over which it travels; (3) whether the lava flows as a broad sheet, through a confined channel, or down a lava tube; and (4) rate of lava production at the vent.

Fluid basalt flows can extend tens of kilometers from an erupting vent. The leading edges of basalt flows can travel as fast as 10 km/hour on steep slopes but they typically advance less than 1 km/hour on gentle slopes. But when basalt lava flows are confined within a channel or lava tube on a steep slope, the main body of the flow can reach velocities >30 km/hour.

Viscous andesite flows move only a few kilometers per hour and rarely extend more than 8 km from their vents. Viscous dacite and rhyolite flows often form steep-sided mounds called lava domes over an erupting vent. Lava domes often grow by the extrusion of

many individual flows >30 m thick over a period of several months or years. Such flows will overlap one another and typically move less than a few meters per hour.



Figure 2. `A`a lava flow moves through an intersection in the Royal Garderns subdivision on the south flank of Kilauea Volcano, Hawai`i. Photograph by J.D. Griggs in 1984.

Everything in the path of an advancing lava flow will be knocked over, surrounded, or buried by lava, or ignited by the extremely hot temperature of lava. When lava erupts beneath a glacier or flows over snow and ice, meltwater from the ice and snow can result in far-reaching lahars. If lava enters a body of water or water enters a lava tube, the water may boil violently and cause an explosive shower of molten spatter over a wide area. Methane gas, produced as lava buries vegetation, can migrate in subsurface voids and explode when heated. Thick viscous lava flows, especially those that build a dome, can collapse to form fast-moving pyroclastic flows.

Deaths caused directly by lava flows are uncommon because most move slowly enough that people can move out the way easily and flows usually don’t travel far from the vent. Death and injury can result when onlookers approach an advancing lava flow too closely or their retreat is cut off by other flows. Deaths attributed to lava flows are often due to related causes, such as explosions when lava interacts with water, the collapse of an active lava delta, asphyxiation due to accompanying toxic gases, pyroclastic flows from a collapsing dome, and lahars from meltwater.

Other natural phenomena such as hurricanes, tornadoes, tsunami, fires, and earthquakes often destroy buildings, agricultural crops, and homes, but the owner(s) can usually rebuild or repair structures and their businesses in the same location. Lava flows, however, can bury homes and agricultural land under tens of meters of hardened black rock; landmarks and property lines become obscured by a vast, new hummocky landscape. People are rarely able to use land buried by lava flows or sell it for more than a small fraction of its previous worth.



Figure 3. Lava buries or surrounds everything.

Lava erupted from Kilauea Volcano covers part of Highway 130 on the southeast coast of the Island of Hawai`i (see figure 3). By the end of 1998, lava from the Pu’u’ ‘O’o-Kupaianaha eruption covered about 13 km of the highway to depths as great as 25 m. Between 1983 and 1998, lava flows covered an area of 99.7 km^2 (38.5 mi^2).

Because lava flows can completely block roads and highways that may serve as the only evacuation route for people threatened by an advancing flow, it is vital for communities that could be inundated with lava to develop emergency-response plans.

One of the chief threats of lava flows to property owners is that the flows may burn buildings and homes even if the flow doesn’t reach the structure. This house caught fire from the intense heat of an advancing `a`a flow (note red glow of flow left of the house).

Basalt has the highest temperature of any lava, typically between about 1170-1100°C (~2140-2000°F). The other lava types (andesite, dacite, and rhyolite) form cooler flows with temperatures between about 1000-800°C (~1800-1500°F); some flows can still move slowly at temperatures as low as about 600°C (~1100°F).



Figure 4. View of eruption crater and ash-covered Vatnajökull glacier about 36 hours after the eruption had broken through the ice.

Lava melts snow and ice to form jökulhlaups and lahars. By this time, the area of subsidence had grown to about 9 km long and 2-3 km wide. The eruption continued for about another 10 days, and meltwater from the glacier flowed into the Grímsvötn caldera. On October 1, water level in the caldera's subglacial lake was about 1410 m; by October 16, the water level had risen to 1504 m, an increase of 94 m! According to scientists monitoring the activity, lava erupting from the fissure was piled up on the ground beneath the glacier, "forming a mountain ridge which in places is expected to be 200 m high."

On October 16, scientists stated that the meltwater, which had been accumulating under the ice shelf in the Grímsvötn caldera lake, could begin draining at any time to trigger a jökulhlaup (glacial outburst flood). On November 5 the expected jökulhlaup began.

Collapsing lava flows trigger pyroclastic flows. The fast-moving pyroclastic flow was caused by the collapse of a thick lava flow that was extruding from the summit area and oozing down the volcano's steep upper cone. When the lava flow collapsed, the hot lava broke apart into fragments ranging in size from boulders to tiny ash particles and swept down the volcano under the influence of gravity to form the pyroclastic flow; the flow reached a maximum distance of 4.5 km from the summit.

Contributors and Attributions

Public domain content

- Types of Volcano Hazards. **Provided by**: USGS. **Located at**: http://volcanoes.usgs.gov/hazards/. **License**: *Public Domain: No Known Copyright*

This page titled 9.18: Reading- Lahars, Landslides, and Lavaflow is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.19: Self Check- Volcanic Hazards

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1115

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 9.19: Self Check- Volcanic Hazards is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.20: Outcome- Monitoring Volcanoes

Identify the various methods used to monitor volcanic activity

There are several different ways to monitor volcanoes. Let’s take a look at some of these different methods.

What You’ll Learn to Do

- Identify the six most important signs of an imminent volcanic eruption.
- Identify tools that can aid in monitoring volcanoes and actions that should be taken.

Learning Activities

The learning activities for this section include the following:

- Reading:Signs of an Eruption
- Reading: Tools to Monitor Volcanoes
- Self Check: Monitoring Volcanoes

This page titled 9.20: Outcome- Monitoring Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.21: Reading- Signs of an Eruption

In 2005 USGS geologist Chris Newhall made a list of the six most important signs of an imminent volcanic eruption. They are as follows:

1. *Gas leaks* — the release of gases (mostly H_2O, CO_2, and SO_2) from the magma into the atmosphere through cracks in the overlying rock
2. *Bit of a bulge* — the deformation of part of the volcano, indicating that a magma chamber at depth is swelling or becoming more pressurized
3. *Getting shaky* — many (hundreds to thousands) of small earthquakes, indicating that magma is on the move. The quakes may be the result of the magma forcing the surrounding rocks to crack, or a harmonic vibration that is evidence of magmatic fluids moving underground.
4. *Dropping fast* — a sudden decrease in the rate of seismicity, which may indicate that magma has stalled, which could mean that something is about to give way
5. *Big bump* — a pronounced bulge on the side of the volcano (like the one at Mt. St. Helens in 1980), which may indicate that magma has moved close to surface
6. *Blowing off steam* — steam eruptions (a.k.a. **phreaticeruptions**) that happen when magma near the surface heats groundwater to the boiling point. The water eventually explodes, sending fragments of the overlying rock far into the air.

Contributors and Attributions

CC licensed content, Shared previously

- 4.5 Monitoring Volcanoes and Predicting Eruptions. **Authored by**: Steven Earle. **Provided by**: BC Campus. **Located at**: https://opentextbc.ca/geology/chapter/4-5-monitoring-volcanoes-and-predicting-eruptions/. **Project**: Physical Geology. **License**: *CC BY: Attribution*

This page titled 9.21: Reading- Signs of an Eruption is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.22: Reading- Tools to Monitor Volcanoes

Here is a list of the equipment we should have and the actions we can take to monitor a volcano and predict when it might erupt.

Assessing Seismicity



Figure 1. A seismometer installed in 2007 in the vicinity of the Nazco Cone, B.C. [photo Cathie Hickson, used with permission]

The simplest and cheapest way to monitor a volcano is with seismometers. In an area with several volcanoes that have the potential to erupt (e.g., the Squamish-Pemberton area), a few well-placed seismometers can provide us with an early warning that something is changing beneath one of the volcanoes, and that we need to take a closer look. There are currently enough seismometers in the Lower Mainland and on Vancouver Island to provide this information.[1]

If there is seismic evidence that a volcano is coming to life, more seismometers should be placed in locations within a few tens of kilometers of the source of the activity (Figure 1). This will allow geologists to determine the exact location and depth of the seismic activity so that they can see where the magma is moving.

Detecting Gases

Water vapor quickly turns into clouds of liquid water droplets and is relatively easy to detect just by looking, but CO_2 and SO_2 are not as obvious. It's important to be able to monitor changes in the composition of volcanic gases, and we need instruments to do that. Some can be monitored from a distance (from the ground or even from the air) using infrared devices, but to obtain more accurate data, we need to sample the air and do chemical analysis. This can be achieved with instruments placed on the ground close to the source of the gases, or by collecting samples of the air and analyzing them in a lab.

Measuring Deformation



Figure 2. A GPS unit installed at Hualalai volcano, Hawaii. The dish-shaped antenna on the right is the GPS receiver. The antenna on the left is for communication with a base station. [from USGS at: http://hvo.wr.usgs.gov/volcanowatch/view.php?id=173]

There are two main ways to measure ground deformation at a volcano. One is known as a **tiltmeter**, which is a sensitive three-directional level that can sense small changes in the tilt of the ground at a specific location. Another is through the use of GPS (global positioning system) technology (Figure 2). GPS is more effective than a tiltmeter because it provides information on how far the ground has actually moved — east-west, north-south, and up-down.

By combining information from these types of sources, along with careful observations made on the ground and from the air, and a thorough knowledge of how volcanoes work, geologists can get a good idea of the potential for a volcano to erupt in the near future (months to weeks, but not days). They can then make recommendations to authorities about the need for evacuations and restricting transportation corridors. Our ability to predict volcanic eruptions has increased dramatically in recent decades because of advances in our understanding of how volcanoes behave and in monitoring technology. Providing that careful work is done, there is no longer a large risk of surprise eruptions, and providing that public warnings are issued and heeded, it is less and less likely that thousands will die from sector collapse, pyroclastic flows, ash falls, or lahars. Indirect hazards are still very real, however, and we can expect the next eruption like the one at Laki in 1783 to take an even greater toll than it did then, especially since there are now roughly eight times as many people on Earth.

? Think about It: Volcano Alert!

You're the chief volcanologist for the Geological Survey of Canada (GSC), based in Vancouver. At 10:30 a.m. on a Tuesday, you receive a report from a seismologist at the GSC in Sidney saying that there has been a sudden increase in the number of small earthquakes in the vicinity of Mt. Garibaldi. You have two technicians available, access to some monitoring equipment, and a four-wheel-drive vehicle. At noon, you meet with your technicians and a couple of other geologists. By the end of the day, you need to have a plan to implement, starting tomorrow morning, and a statement to release to the press. What should your first day's fieldwork include? What should you say later today in your press release?

1. See: http://www.earthquakescanada.nrcan.gc.ca↵

Contributors and Attributions

CC licensed content, Shared previously

- 4.5 Monitoring Volcanoes and Predicting Eruptions. **Authored by**: Steven Earle. **Provided by**: BC Campus. **Located at**: https://opentextbc.ca/geology/chapter/4-5-monitoring-volcanoes-and-predicting-eruptions/. **Project**: Physical Geology. **License**: *CC BY: Attribution*

This page titled 9.22: Reading- Tools to Monitor Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.23: Self Check- Monitoring Volcanoes

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1116

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: lule. **License**: *CC BY: Attribution*

This page titled 9.23: Self Check- Monitoring Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

9.24: Putting It Together- Volcanoes

Summary

In this section, you learned the following:

1. What the different types of volcanoes are
2. How the different types of volcanoes form and erupt
3. The different products of volcanic activity including pyroclastic flows, lahars, and the different types of lava
4. The hazards associated with volcanic eruptions

Synthesis

As you saw in the videos and readings, volcanoes can be beautiful but very deadly. It is important for those studying these dynamic forces to understand how they form, why they form where they do, what to expect when they erupt, and how often they will erupt —with at least some accuracy (which is not always easy to do). Knowing when an eruption is going to occur and how big the eruption will be can help save lives.

However, volcanic eruptions do have a positive side. Besides being spectacular to watch, the eruptions allow scientists to study the newly erupted material from inside the Earth. This is as close as we can get to knowing what the interior of the Earth looks like. Eruptions also help increase the fertility of the soil by adding essential nutrients. It doesn't take long for nature to bounce back after these huge eruptions.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 9.24: Putting It Together- Volcanoes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

10: Mass Movement

Learning Objectives

Define and interpret the causes, types, effects and hazards of mass movement and land subsidence.

- Identify and describe types of mass movement.
- Identify the various causes of mass movement, as well as ways to diminish the damage caused.

10.1: Why It Matters- Mass Movement
10.2: Outcome- Types of Mass Movement
10.3: Reading- Slides
10.4: Reading- Falls
10.5: Reading- Slump and Creep
10.6: Self Check- Types of Mass Movement
10.7: Outcome- Driving and Resisting Forces
10.8: Reading- Natural Mass Wasting
10.9: Reading- Human Impact on Mass Wasting
10.10: Self Check- Driving and Resisting Forces
10.11: Putting It Together- Mass Wasting
10.12: Assignment- Mass Movement

This page titled 10: Mass Movement is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.1: Why It Matters- Mass Movement

Define and interpret the causes, types, effects and hazards of mass movement and land subsidence.

Introduction

Mass movement can be devastating and costly. About 10 years ago, a friend was looking to purchase a new home in San Diego. She found a great neighborhood being built on the side of a mountain overlooking the town. They loved the area, the view and the home so they purchased the home site. The cost was $1.5 million.

Since this was not the first home she purchased, she knew the questions to ask and the various test that needed to be performed. One of the inspectors made note of elevated methane in the area. They thought it was temporary and would not cause any problems. However, as more people purchased homes in the area, the problem became more prominent. She contacted a geologist and asked what it could be. The geologist was from the area and was familiar with the location. They did a little research and ruled out numerous possible causes. They were stumped until one day a core sample revealed the neighborhood was being built on an old landslide area. The buried trees and vegetation were decomposing, which was causing them to give off various gases including methane. Building on the site was stopped and never proceeded due to the conditions. The time, effort, and money spent was wasted. While the homeowners did get their money back, the property owner was completed bankrupted.

Landslides and avalanches may not be something we really think about unless we live in an area prone to them, but mass wasting can occur just about anywhere. If you recall from when we learned about the rock cycle, erosion is a powerful and continuous process.

Watch a clip from this video to see remarkable earthflow in Italy (note there is background noise but no actual audio).

A link to an interactive elements can be found at the bottom of this page.

Wasn't that amazing?

Mass wasting can be very fast or slow. What do you make of this picture?



Do you notice anything strange about the trees? Would you want to live in an area like this?

Let's see what mass wasting is and what it can tell us about the video and picture.

Learning Outcomes

- Identify and describe types of mass movement.
- Identify the various causes of mass movement, as well as ways to diminish the damage caused.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- creep. **Authored by**: Curtis Abert. **Located at**: https://flic.kr/p/p5ASvB. **License**: *CC BY: Attribution*

All rights reserved content

- The Ground Is Moving Like Water in Italy. **Authored by**: Sai Sai. **Located at**: https://youtu.be/RGP6LzS_D5k. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 10.1: Why It Matters- Mass Movement is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.2: Outcome- Types of Mass Movement

Identify and describe types of mass movement.

In this section, you will learn the term mass wasting. You will also be exposed to the various types of mass wasting, their causes and their effects.

What You'll Learn to Do

- Describe slides as a type of mass movement
- Describe falls as a type of mass movement
- Describe slumps as a type of mass movement
- Describe creep as a type of mass movement

Learning Activities

The learning activities for this section include the following:

- Reading: Slides
- Reading: Falls
- Reading: Slump and Creep
- Self Check: Types of Mass Movement

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 10.2: Outcome- Types of Mass Movement is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.3: Reading- Slides

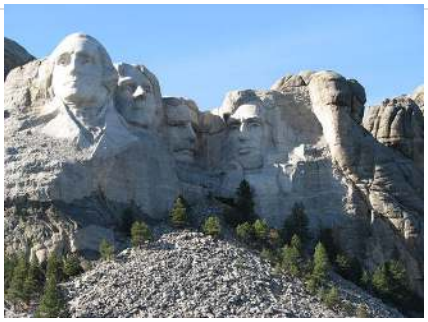


Figure 1. Pieces of rock regularly fall to the base of cliffs to form talus slopes.

Rocks that fall to the base of a cliff make a **talus slope** (figure 1). Sometimes as one rock falls, it hits another rock, which hits another rock, and begins a landslide.

Landslides and **avalanches** are the most dramatic, sudden, and dangerous examples of earth materials moved by gravity. Landslides are sudden falls of rock, whereas avalanches are sudden falls of snow.

- Here is a video of a snow avalanche.

Landslides

Although many types of mass movements are included in the general term “landslide,” the more restrictive use of the term refers only to mass movements, where there is a distinct zone of weakness that separates the slide material from more stable underlying material. The two major types of slides are rotational slides and translational slides. Rotational slide: This is a slide in which the surface of rupture is curved concavely upward and the slide movement is roughly rotational about an axis that is parallel to the ground surface and transverse across the slide (figure 2a). Translational slide: In this type of slide, the landslide mass moves along a roughly planar surface with little rotation or backward tilting (figure 2b). A block slide is a translational slide in which the moving mass consists of a single unit or a few closely related units that move downslope as a relatively coherent mass (figure 2c).

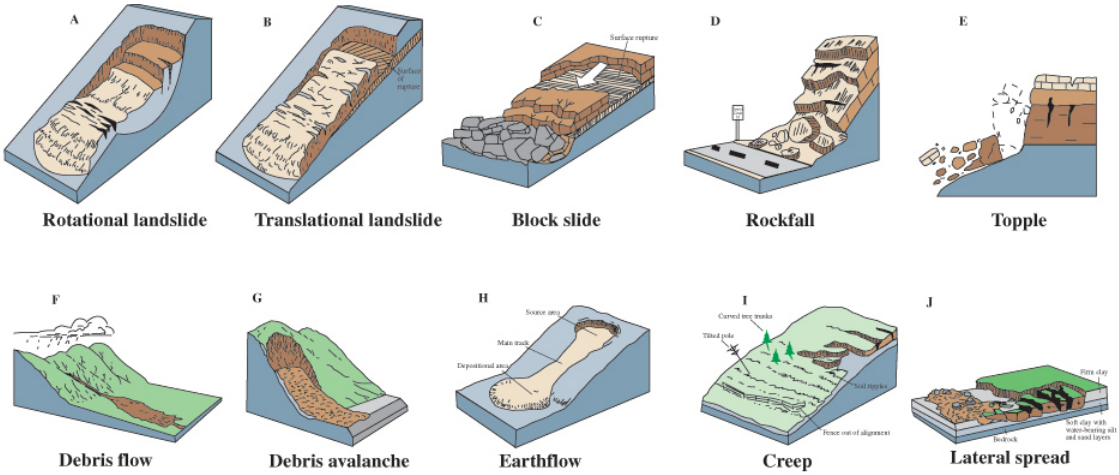


Figure 1. These schematics illustrate the major types of landslide movement.

When large amounts of rock suddenly break loose from a cliff or mountainside, they move quickly and with tremendous force (figure 2). Air trapped under the falling rocks acts as a cushion that keeps the rock from slowing down. Landslides and avalanches can move as fast as 200 to 300 km/hour.

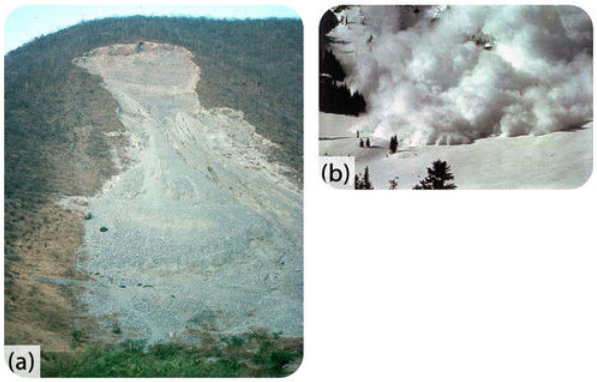


Figure 2. (a) Landslides are called rock slides by geologists. (b) A snow avalanche moves quickly down slope, burying everything in its path.

Landslides are exceptionally destructive. Homes may be destroyed as hillsides collapse. Landslides can even bury entire villages. Landslides may create lakes when the rocky material dams a stream. If a landslide flows into a lake or bay, they can trigger a tsunami (figure 3).



Figure 3. The 1958 landslide into Lituya Bay, Alaska, created a 524m tsunami that knocked down trees at elevations higher than the Empire State Building (light gray).

Landslides often occur on steep slopes in dry or semi-arid climates. The California coastline, with its steep cliffs and years of drought punctuated by seasons of abundant rainfall, is prone to landslides. At-risk communities have developed landslide warning systems. Around San Francisco Bay, the National Weather Service and the U.S. Geological Survey use rain gauges to monitor soil moisture. If soil becomes saturated, the weather service issues a warning. Earthquakes, which may occur on California's abundant faults, can also trigger landslides.

- Here is a video of rapid downslope movement of material.

? KQED: Landslide Detectives

Hillside properties in the San Francisco Bay Area and elsewhere may be prone to damage from landslides. Geologists are studying the warning signs and progress of local landslides to help reduce risks and give people adequate warnings of these looming threats. You can learn more here.

Contributors and Attributions

CC licensed content, Shared previously

- 10.5: Erosion and Deposition by Gravity. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/10.5/. **License**: *CC BY-NC: Attribution-NonCommercial*

Public domain content

- Landslide Types and Processes. **Provided by**: USGS. **Located at**: http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html. **License**: *Public Domain: No Known Copyright*

This page titled 10.3: Reading- Slides is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.4: Reading- Falls



Figure 1. The white areas on green hillsides mark scars from numerous mudflows.

Falls are abrupt movements of masses of geologic materials, such as rocks and boulders, that become detached from steep slopes or cliffs. Separation occurs along discontinuities such as fractures, joints, and bedding planes, and movement occurs by free-fall, bouncing, and rolling. Falls are strongly influenced by gravity, mechanical weathering, and the presence of interstitial water.

Lahars and Mudflow

Added water creates natural hazards produced by gravity (figure 1). On hillsides with soils rich in clay, little rain, and not much vegetation to hold the soil in place, a time of high precipitation will create a **mudflow**. Mudflows follow river channels, washing out bridges, trees, and homes that are in their path.

- This video shows a debris flow.

A lahar is mudflow that flows down a composite volcano (figure 2). Ash mixes with snow and ice melted by the eruption to produce hot, fast-moving flows. The lahar caused by the eruption of Nevado del Ruiz in Columbia in 1985 killed more than 23,000 people.



Figure 2. A lahar is a mudflow that forms from volcanic ash and debris.

Contributors and Attributions

CC licensed content, Shared previously

- 10.5: Erosion and Deposition by Gravity. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/10.5/. **License**: *CC BY-NC: Attribution-NonCommercial*

Public domain content

- Landslide Types and Processes. **Provided by**: USGS. **Located at**: http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html. **License**: *Public Domain: No Known Copyright*

This page titled 10.4: Reading- Falls is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.5: Reading- Slump and Creep

Less dramatic types of downslope movement move earth materials slowly down a hillside. **Slump** moves materials as a large block along a curved surface (figure 1). Slumps often happen when a slope is undercut, with no support for the overlying materials, or when too much weight is added to an unstable slope.



Figure 1. Slump material moves as a whole unit, leaving behind a crescent shaped scar.



Figure 2. Trees with curved trunks are often signs that the hillside is slowly creeping downhill.

Creep is the imperceptibly slow, steady, downward movement of slope-forming soil or rock. Movement is caused by shear stress sufficient to produce permanent deformation, but too small to produce shear failure. There are generally three types of creep:

1. Seasonal, where movement is within the depth of soil affected by seasonal changes in soil moisture and soil temperature
2. Continuous, where shear stress continuously exceeds the strength of the material
3. Progressive, where slopes are reaching the point of failure as other types of mass movements. Creep is indicated by curved tree trunks, bent fences or retaining walls, tilted poles or fences, and small soil ripples or ridges

Curves in tree trunks indicate creep because the base of the tree is moving downslope while the top is trying to grow straight up (figure 2). Tilted telephone or power company poles are also signs of creep.

Contributors and Attributions

CC licensed content, Shared previously

- 10.5: Erosion and Deposition by Gravity. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/10.5/. **License**: *CC BY-NC: Attribution-NonCommercial*

Public domain content

- Landslide Types and Processes. **Provided by**: USGS. **Located at**: http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html. **License**: *Public Domain: No Known Copyright*

This page titled 10.5: Reading- Slump and Creep is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.6: Self Check- Types of Mass Movement

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1119

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 10.6: Self Check- Types of Mass Movement is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.7: Outcome- Driving and Resisting Forces

Identify the various causes of mass movement, as well as ways to diminish the damage caused.

This section explains the various causes of mass wasting. It will illustrate what controls mass wasting and how to reduce the risk of occurrence.

What You'll Learn to Do

- Identify geologic-caused changes that can affect mass wasting.
- Identify human impact on mass wasting.

Learning Activities

The learning activities for this section include the following:

- Reading: Natural Mass Wasting
- Reading: Human Impact on Mass Wasting
- Self Check: Driving and Resisting Forces

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 10.7: Outcome- Driving and Resisting Forces is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.8: Reading- Natural Mass Wasting

Contributing Factors

There are several factors that increase the chance that a landslide will occur. Some of these we can prevent and some we cannot.

Water

A little bit of water helps to hold grains of sand or soil together. For example, you can build a larger sand castle with slightly wet sand than with dry sand. However too much water causes the sand to flow quickly away. Rapid snow melt or rainfall adds extra water to the soil, which increases the weight of the slope and makes sediment grains lose contact with each other, allowing flow.

Rock Type

Layers of weak rock, such as clay, also allow more landslides. Wet clay is very slippery, which provides an easy surface for materials to slide over.

Undercutting

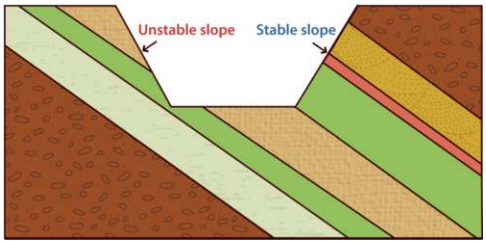


Figure 8. The slope of underlying materials must be considered when making road cuts.

If people dig into the base of a slope to create a road or a homesite, the slope may become unstable and move downhill. This is particularly dangerous when the underlying rock layers slope towards the area (figure 8).

- Ocean waves undercut cliffs and cause landslides on beaches as in this video.

When construction workers cut into slopes for homes or roads, they must stabilize the slope to help prevent a landslide (figure 9). Trees roots or even grasses can bind soil together. It is also a good idea to provide drainage so that the slope does not become saturated with water.



Figure 9. A rock wall stabilizes a slope that has been cut away to make a road.

Ground shaking

An earthquake, volcanic eruption, or even just a truck going by can shake unstable ground loose and cause a slide. Skiers and hikers may disturb the snow they travel over and set off an avalanche.

A very good introduction to the topic, "Landslide 101," is a video seen on National Geographic Videos, Environment Video, Natural Disasters, Landslides, and more.

Landslides

Although there are multiple types of causes of landslides, the three that cause most of the damaging landslides around the world are these:

Landslides and Water

Slope saturation by water is a primary cause of landslides. This effect can occur in the form of intense rainfall, snowmelt, changes in ground-water levels, and water-level changes along coastlines, earth dams, and the banks of lakes, reservoirs, canals, and rivers.

Landsliding and flooding are closely allied because both are related to precipitation, runoff, and the saturation of ground by water. In addition, debris flows and mudflows usually occur in small, steep stream channels and often are mistaken for floods; in fact, these two events often occur simultaneously in the same area.

Landslides can cause flooding by forming landslide dams that block valleys and stream channels, allowing large amounts of water to back up. This causes backwater flooding and, if the dam fails, subsequent downstream flooding. Also, solid landslide debris can "bulk" or add volume and density to otherwise normal streamflow or cause channel blockages and diversions creating flood conditions or localized erosion. Landslides can also cause overtopping of reservoirs and/or reduced capacity of reservoirs to store water.

Landslides and Seismic Activity

Many mountainous areas that are vulnerable to landslides have also experienced at least moderate rates of earthquake occurrence in recorded times. The occurrence of earthquakes in steep landslide-prone areas greatly increases the likelihood that landslides will occur, due to ground shaking alone or shaking-caused dilation of soil materials, which allows rapid infiltration of water. The 1964 Great Alaska Earthquake caused widespread landsliding and other ground failure, which caused most of the monetary loss due to the earthquake. Other areas of the United States, such as California and the Puget Sound region in Washington, have experienced slides, lateral spreading, and other types of ground failure due to moderate to large earthquakes. Widespread rockfalls also are caused by loosening of rocks as a result of ground shaking. Worldwide, landslides caused by earthquakes kill people and damage structures at higher rates than in the United States.

Landslides and Volcanic Activity

Landslides due to volcanic activity are some of the most devastating types. Volcanic lava may melt snow at a rapid rate, causing a deluge of rock, soil, ash, and water that accelerates rapidly on the steep slopes of volcanoes, devastating anything in its path. These volcanic debris flows (also known as lahars) reach great distances, once they leave the flanks of the volcano, and can damage structures in flat areas surrounding the volcanoes. The 1980 eruption of Mount St. Helens, in Washington triggered a massive landslide on the north flank of the volcano, the largest landslide in recorded times.

? Geological and Morphological Causes

Geological Causes

1. Weak or sensitive materials
2. Weathered materials
3. Sheared, jointed, or fissured materials
4. Adversely oriented discontinuity (bedding, schistosity, fault, unconformity, contact, and so forth)
5. Contrast in permeability and/or stiffness of materials

Morphological Causes

1. Tectonic or volcanic uplift
2. Glacial rebound
3. Fluvial, wave, or glacial erosion of slope toe or lateral margins
4. Subterranean erosion (solution, piping)
5. Deposition loading slope or its crest
6. Vegetation removal (by fire, drought)
7. Thawing

8. Freeze-and-thaw weathering
9. Shrink-and-swell weathering

Contributors and Attributions

CC licensed content, Shared previously

- 10.5: Erosion and Deposition by Gravity. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/10.5/. **License**: *CC BY: Attribution*

Public domain content

- Landslide Types and Processes. **Provided by**: USGS. **Located at**: http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html. **License**: *Public Domain: No Known Copyright*

This page titled 10.8: Reading- Natural Mass Wasting is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.9: Reading- Human Impact on Mass Wasting

Causing Mass Wasting

Humans can contribute to mass wasting in a few different ways:

1. Excavation of slope or its toe
2. Loading of slope or its crest
3. Drawdown (of reservoirs)
4. Deforestation
5. Irrigation
6. Mining
7. Artificial vibration
8. Water leakage from utilities

Prevention and Awareness

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.



Figure 1. Site of the 2008 rock slide at Porteau Cove. Notice the prominent fracture set parallel to the surface of the slope. The slope has been stabilized with rock bolts (top) and holes have been drilled into the rock to improve drainage (one is visible in the lower right). Risk to passing vehicles from rock fall has been reduced by hanging mesh curtains (background). [SE photo 2012]

It is comforting to think that we can prevent some effects of mass wasting by mechanical means, such as the rock bolts in the road cut at Porteau Cove (Figure 1), or the drill holes used to drain water out of a slope, as was done at the Downie Slide, or the building of physical barriers, such as retaining walls. What we have to remember is that the works of humans are limited compared to the works of nature. The rock bolts in the road cut at Porteau Cove will slowly start to corrode after a few years, and within a few decades, many of them will begin to lose their strength. Unless they are replaced, they will no longer support that slope. Likewise, drainage holes at the Downie Slide will eventually become plugged with sediment and chemical precipitates, and unless they are periodically unplugged, their effectiveness will decrease. Eventually, unless new holes are drilled, the drainage will be so compromised that the slide will start to move again. This is why careful slope monitoring by geological and geotechnical engineers is important at these sites. The point here is that our efforts to “prevent” mass wasting are only as good as our resolve to maintain those preventive measures.

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 wasting is road construction, and this applies both to 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 (Figure 2). 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, over-saturating fill of materials can result.

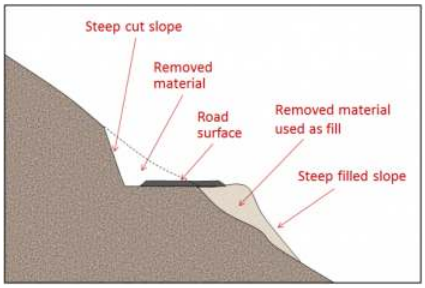
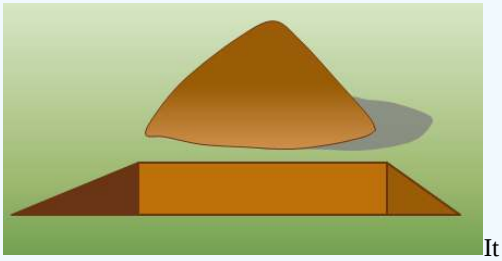


Figure 2. An example of a road constructed by cutting into a steep slope and the use of the cut material as fill. [SE]

Apart from water issues, engineers building roads and other infrastructure on bedrock slopes have to be acutely aware of the geology, and especially of any weaknesses or discontinuities in the rock related to bedding, fracturing, or foliation. If possible, situations like that at Porteau Cove (Figure 1) should be avoided — by building somewhere else — rather than trying to stitch the slope back together with rock bolts.

It is widely believed that 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. As you'll see by completing the exercise below, a typical house isn't usually heavier than the fill that was removed from the hole in the ground made to build it. A more likely contributor to instability of the slope around a building is the effect that it and the changes made to the surrounding area have on drainage.

? Exercise: How Much Does a House Weigh and Can It Contribute to a Slope Failure?



It is commonly believed that building a house (or some other building) at the top of a slope will add a lot of extra weight to the slope, which could contribute to slope failure. But what does a house actually weigh? A typical 150 m^2 (approximately 1,600 ft^2) wood-frame house with a basement and a concrete foundation weighs about 145 t (metric tonnes). But most houses are built on foundations that are excavated into the ground. This involves digging a hole and taking some material away, so we need to subtract what that excavated material weighs. Assuming our 150 m2 house required an excavation that was 15 m by 11 m by 1 m deep, that's 165 m^3 of "dirt," which typically has a density of about 1.6 t per m^3.

Calculate the weight of the soil that was removed and compare that with the weight of the house and its foundation.

If you're thinking that building a bigger building is going to add more weight, consider that bigger buildings need bigger and deeper excavations, and in many cases the excavations will be into solid rock, which is much heavier than surficial materials.

You may wish to consider how a building might change the drainage on a slope. There are a number ways. Water can be collected by roofs, go into downspouts, and form concentrated flows that are directed onto or into the slope. Likewise drainage from nearby access roads, lawn irrigation, leaking pools, and septic systems can all alter the surface and groundwater flow in a slope.



Figure 3. Part of a motion-monitoring device at the Checkerboard Slide near Revelstoke, B.C. The lower end of the cable is attached to a block of rock that is unstable. Any incremental motion of that block will move the cable, which will be detectable on this device. [SE]

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. The Downie Slide above the Revelstoke Resevoir is monitored 24/7 with a range of devices, such as inclinometers (slope-change detectors), bore-hole motion sensors, and GPS survey instruments. A simple mechanical device for monitoring the nearby Checkerboard Slide (which is also above the Revelstoke Reservoir) is shown in Figure 3. Both of these are very slow-moving rock slides, but it's very important to be able to detect changes in their rates of motion because at both of these locations a rapid failure would result in large bodies of rock plunging into the reservoir and sending a wall of water over the Revelstoke Dam, potentially destroying the nearby town of Revelstoke.

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 (Figure 4). 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.



Figure 4. Mt. Rainier, Washington, from Tacoma

Mitigating the Impacts of Mass Wasting

In situations where we can't predict, prevent, or delay mass-wasting hazards, some effective measures can be taken to minimize the associated risk. For example, many highways in B.C. and western Alberta have avalanche shelters like that shown in Figure 5. In some parts of the world, similar features have been built to protect infrastructure from other types of mass wasting.

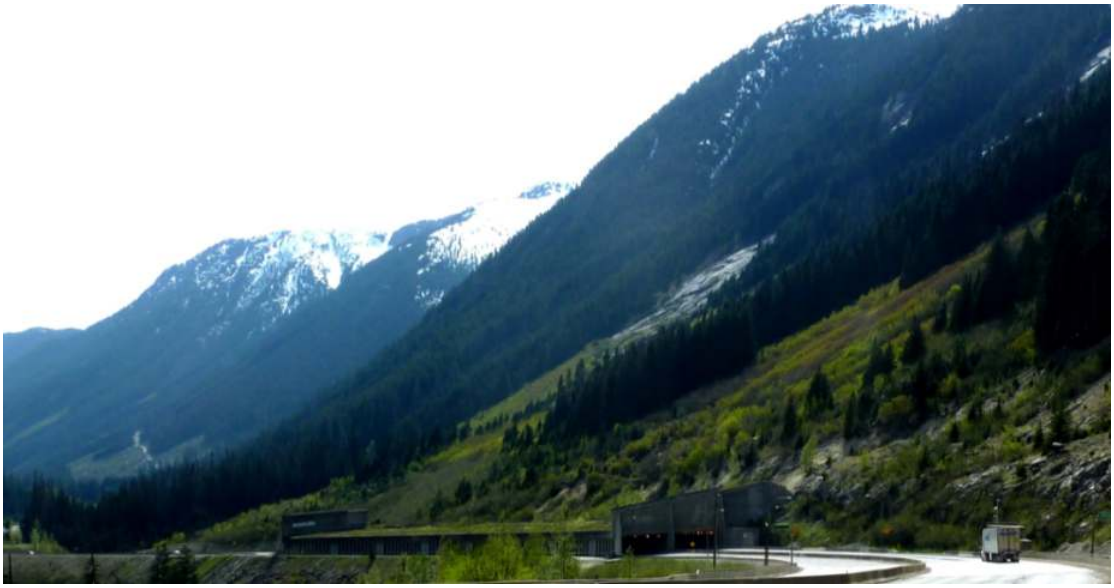


Figure 5. A snow avalanche shelter on the Coquihalla Highway. The expected path of the avalanche is the steep untreed slope above. [SE]

Debris flows are inevitable, unpreventable, and unpredictable in many parts of B.C., but nowhere more so than along the Sea-to-Sky Highway between Horseshoe Bay and Squamish. The results have been deadly and expensive many times in the past. It would be very expensive 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, as shown in Figure 6. 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.



Figure 6. Two strategies for mitigating debris flows on the Sea-to-Sky Highway. Left: A concrete –lined channel on Alberta Creek allows debris to flow quickly through to the ocean. Right: A debris-flow catchment basin on Charles Creek. In 2010, a debris flow filled the basin to the level of the dotted white line. [SE]

? Landslide Mitigation—How to Reduce the Effects of Landslides

Vulnerability to landslide hazards is a function of location, type of human activity, use, and frequency of landslide events. The effects of landslides on people and structures can be lessened by total avoidance of landslide hazard areas or by restricting, prohibiting, or imposing conditions on hazard-zone activity. Local governments can reduce landslide effects through land-use policies and regulations. Individuals can reduce their exposure to hazards by educating themselves on the past hazard history of a site and by making inquiries to planning and engineering departments of local governments. They can also obtain the

professional services of an engineering geologist, a geotechnical engineer, or a civil engineer, who can properly evaluate the hazard potential of a site, built or unbuilt.

The hazard from landslides can be reduced by avoiding construction on steep slopes and existing landslides, or by stabilizing the slopes. Stability increases when ground water is prevented from rising in the landslide mass by (1) covering the landslide with an impermeable membrane, (2) directing surface water away from the landslide, (3) draining ground water away from the landslide, and (4) minimizing surface irrigation. Slope stability is also increased when a retaining structure and/or the weight of a soil/rock berm are placed at the toe of the landslide or when mass is removed from the top of the slope.



Figure 7. The Barrier, south of Whistler, B.C., was the site of a huge rock avalanche in 1855, which extended from the cliff visible here 4 km down the valley and across the current location of the Sea-to-Sky Highway and the Cheakamus River. [SE]

Finally, in situations where we can't do anything to delay, predict, contain, or mitigate slope failures, we simply have to have the sense to stay away. There is a famous example of this in B.C. at a site known as Garibaldi, 25 km south of Whistler. In the early 1980s the village of Garibaldi had a population of about 100, with construction underway on some new homes, and plans for many more.

In the months that followed the deadly 1980 eruption of Mt. St. Helens in Washington State, the B.C. Ministry of Transportation commissioned a geological study that revealed that a steep cliff known as The Barrier (Figure 7) had collapsed in 1855, leading to a large rock avalanche, and that it was likely to collapse again unpredictably, putting the village of Garibaldi at extreme risk. In an ensuing court case, it was ruled that the Garibaldi site was not a safe place for people to live. Those who already had homes there were compensated, and everyone else was ordered to leave.

Contributors and Attributions

CC licensed content, Original

- Revision, adaption, and original content. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Preventing, Delaying, Monitoring, and Mitigating Mass Wasting. **Authored by**: Steven Earle. **Provided by**: BC Campus. **Located at**: https://opentextbc.ca/geology/chapter/15-3-preventing-delaying-monitoring-and-mitigating-mass-wasting/. **Project**: Physical Geology. **License**: *CC BY: Attribution*

Public domain content

- Landslide Types and Processes. **Provided by**: USGS. **Located at**: http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html. **License**: *Public Domain: No Known Copyright*
- Mount Rainier over Tacoma. **Authored by**: Lyn Topinka. **Provided by**: USGS. **Located at**: http://vulcan.wr.usgs.gov/Imgs/Jpg/Rainier/Images/Rainier84_mount_rainier_and_tacoma_08-20-84.jpg. **License**: *Public Domain: No Known Copyright*

This page titled 10.9: Reading- Human Impact on Mass Wasting is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.10: Self Check- Driving and Resisting Forces

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1120

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 10.10: Self Check- Driving and Resisting Forces is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.11: Putting It Together- Mass Wasting

Summary

In this section we were able to learn what implication erosion has on a grand scale. We learned the following:

1. The definition of mass wasting
2. The various types of mass wasting
3. The forces behind mass wasting
4. What humans are doing to aggravate the occurrence of mass wasting

Synthesis

In the opening section, we saw a video of an earthflow in Italy and the damage it caused. Can you imagine that coming down a mountain side towards a major city like this?



Figure 1. Damage from the debris flow on the Caraballeda fan. The main channel (at left) avulsed to a new course that led it through the houses to the right. These avulsion deposits are up to 6 meters (20 ft) thick and total about 1.8 million cubic meters of boulders and other material.

What about this?



Figure 2. The Mameyes mudflow disaster, in barrio Tibes, Ponce, Puerto Rico, was caused by heavy rainfall from Tropical Storm Isabel in 1985. The mudflow destroyed more than 100 homes and claimed an estimated 300 lives.

Back to the picture from the opening—did you notice anything odd about the trees in the picture? They were definitely shaped strangely at the base. Their trunks were curved. These trees are the result of mass wasting, specifically creep. Creep is the slowest form of mass wasting, but imagine what would happen if you had a house there!

Once again, we have seen strong forces we are dealing with in geology. By understanding how the various types of mass wasting occur, geologists can save not only money but lives as well.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

Public domain content

- Caraballeda 1999 Deposits and Damage. **Provided by**: USGS. **Located at**: http://pubs.usgs.gov/of/2001/ofr-01-0144/Venezuela/image031.jpg. **License**: *Public Domain: No Known Copyright*
- Mameyes. **Authored by**: R.W. Jibson. **Provided by**: USGS. **Located at**: http://www.ngdc.noaa.gov/hazardimages/picture/show/1549. **License**: *Public Domain: No Known Copyright*

This page titled 10.11: Putting It Together- Mass Wasting is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

10.12: Assignment- Mass Movement

In this assessment you will interpret and compare two mass wasting events. You will use Google Earth to complete the assignment. Remember to access the tips and hints at the bottom of the page.

Basic Requirements (assignment criteria):

1. Open Google Earth.
2. Type into “Earthquake Lake, WY” into the location search box.
3. Google Earth will fly you to the location. You will need to zoom out just a bit. To the southwest is a mass wasting event that dammed up a river and created the lake. If you move to the south and spin around using the tool in the top right you can actually see the scarp from the event. Make notes and take screen shots of the area and the event.
4. Now type “Lake San Cristobal, CO” into the search box. Again you will need to zoom out momentarily. Look to the northeast and you will notice the source of the event. Make notes and take screen shots of the area and the event.
5. Compare and contrast the two events, making sure you identify the type of mass wasting at each location. Do a little snooping around the areas to learn about the locations of each.
6. Insert your pictures into the document.
7. Make sure your name is on the document before saving.

Tips and hints can be found here.

Contributors and Attributions

CC licensed content, Original

- Mass Movement Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 10.12: Assignment- Mass Movement is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

11: Hydrology

Learning Objectives

Understand the roles, processes and effects of streams and groundwater.

- Describe and model processes involved throughout Earth's hydrologic cycle.
- Identify and describe channel types and sedimentary loads formed and carried by rivers and streams.
- Describe critical components of groundwater.
- Identify various geologic features associated with groundwater.
- Recognize features associated with oceans and shorelines.

11.1: Why It Matters- Hydrology
11.2: Outcome- The Hydrologic Cycle
11.3: Reading- Phases of the Hydrologic Cycle
11.4: Self Check- The Hydrologic Cycle
11.5: Outcome- Rivers and Streams
11.6: Reading- Types of Streams and Rivers
11.7: Reading- Drainage Basins
11.8: Reading- Geologic Processes and Flowing Water
11.9: Self Check- Rivers and Streams
11.10: Outcome- Components of Groundwater
11.11: Reading- Groundwater
11.12: Reading- Porosity and Permeability
11.13: Reading- Aquifers and Well-Potential
11.14: Reading- Groundwater Withdrawal
11.15: Reading- Quality of Groundwater
11.16: Self Check- Components of Groundwater
11.17: Outcome- Geologic Features
11.18: Reading- Karst Topography
11.19: Reading- Geysers
11.20: Reading- Springs
11.21: Self Check- Geologic Features
11.22: Outcome- Oceans and Shorelines
11.23: Reading- Ocean Movement
11.24: Reading- Shorelines
11.25: Reading- Coastal Hazards
11.26: Reading- Human Modifications of Coastal Processes
11.27: Self Check- Oceans and Shorelines
11.28: Putting It Together- Hydrology
11.29: Assignment- Hydrology

This page titled 11: Hydrology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.1: Why It Matters- Hydrology

Understand roles, processes, and effects of streams and groundwater

Introduction

This section focuses on hydrology. It goes without saying how important water is to all life on the planet. We simply cannot survive without it. Water is what sets the Earth apart from the other planets in our solar system. While the oceans cover roughly 74% of the Earth's surface and are the driving force behind the hydrologic cycle, it is the availability of freshwater that is of most concern today.

Currently, California is experiencing severe drought while the Midwest is currently undergoing extreme flooding. While these variations are a normal part of the complex dynamic of climate, they impact us in major ways. California is currently scrambling to find a solution as it is currently estimated that in just over a year they will no longer have enough freshwater to meet their needs. With flooding in the Midwest, the loss of life and property damage is steadily increasing. Droughts and floods are a normal part of the hydrologic cycle, the issue is how to be prepared for them and how to best adapt to them in order to survive.

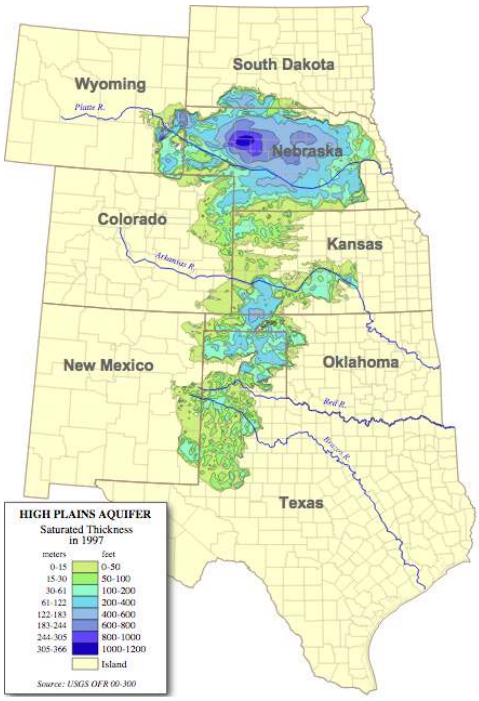


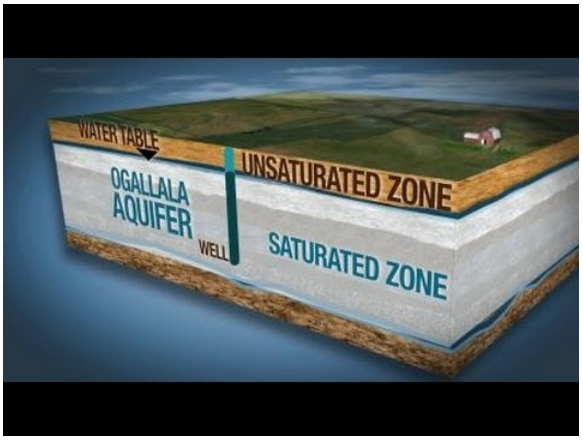
Figure 1. Saturated thickness of the Ogallala Aquifer in 1997 after several decades of intensive withdrawals. The breadth and depth of the aquifer generally decrease from north to south.

Freshwater consists of glaciers, groundwater, surface water (such as ponds and lakes) as well as water stored in the biosphere and the atmosphere. The vast majority of freshwater is used in agriculture for irrigation purposes. Again, without this freshwater our food production would suffer. Most people associate mining with metals, fuel resources and gems. However, would it surprise you to learn that we actually mine water? Mining means withdrawing or removing something from within the Earth. Groundwater is found within the Earth and is our second largest store of freshwater. Currently, groundwater use in the US is centered on the Ogallala Aquifer.

The Ogallala Aquifer is located in the central portion of the United States. It is located beneath 8 states: Texas, Oklahoma, Colorado, Kansas, Nebraska, New Mexico, South Dakota and Wyoming. It is approximately 174,000 square miles in area and is more than 10,000,000 years old (Kromm, n.d.). It is the freshwater source for over 13,600,000 acres of farming and ranch lands. This aquifer formed, in part, due to melting glaciers and took over 64,000 years to fill (Overmann, n.d.). It is the largest aquifer in North America and one of the largest freshwater sources in the world. Initially, farmers only had to drill down anywhere from 25 to 50 feet before they would hit the water table. However, in the 1940's this began to change. With the technology boom associated with the war and the post war period, numerous devices such as high capacity pumps allowed easier and greater access to the

aquifer. In some places, farmers now have to drill over 500 feet before they hit the water table. The Ogallala was originally over 500 feet in thickness but now that has diminished and varies by location. The issue with this particular aquifer is that is being used at a much greater rate than it is recharged. In fact, the Ogallala is considered to be a “fossil aquifer” which means once it is gone, it is gone. What does this mean for us? How does this translate into affecting you or your family?

Here is a short video that shows you some of the ways farmers are adapting the rapid depletion of the aquifer.



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=392

Learning Outcomes

- Describe and model processes involved throughout Earth’s hydrologic cycle.
- Identify and describe channel types and sedimentary loads formed and carried by rivers and streams.
- Describe critical components of groundwater
- Identify various geologic features associated with groundwater
- Recognize features associated with oceans and shorelines

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- Ogallala saturated thickness 1997-sattk97-v2. **Located at**: http://commons.wikimedia.org/wiki/File:Ogallala_saturated_thickness_1997-sattk97-v2.svg. **License**: *CC BY-SA: Attribution-ShareAlike*

All rights reserved content

- The Ogallala Aquifer. **Authored by**: National Science Foundation. **Located at**: https://youtu.be/XXFsS94HF08. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 11.1: Why It Matters- Hydrology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.2: Outcome- The Hydrologic Cycle

Describe and model processes involved throughout Earth's hydrologic cycle.

Water is simply two atoms of hydrogen and one atom of oxygen bonded together. Despite its simplicity, water has remarkable properties. Water expands when it freezes, has high surface tension (because of the polar nature of the molecules, they tend to stick together), and others. Without water, life might not be able to exist on Earth and it certainly would not have the tremendous complexity and diversity that we see.

This section illustrates how water moves in, on, and above the Earth.

What You'll Learn to Do

- Understand the basic outcomes of the hydrologic cycle.
- Describe the processes involved the hydrologic cycle.

Learning Activities

The learning activities for this section include the following:

- Reading: Phases of the Hydrologic Cycle
- Self Check: The Hydrologic Cycle

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- The Water Cycle. **Provided by**: CK-12. **Located at**: http://www.ck12.org/student/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 11.2: Outcome- The Hydrologic Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.3: Reading- Phases of the Hydrologic Cycle

Because of the unique properties of water, water molecules can cycle through almost anywhere on Earth. The water molecule found in your 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. Where will that water molecule go next?

Three States of Water

Water is the only substance on Earth that is present in all three states of matter—as a solid, liquid or gas. (And 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 single location or in a region. The three phases are solid (ice or snow), liquid (water), and gas (**water vapor**). See ice, water, and clouds (figure 2).



Figure 2. Can you find all three phases of water in this image? (a) Ice floating in the sea. (b) Liquid water. (c) Water vapor is invisible, but clouds that form when water vapor condenses are not.

The Water Cycle

Because Earth's water is present in all three states, it can get into a variety of environments around the planet. The movement of water around Earth's surface is the **hydrologic (water) cycle** (figure 3).

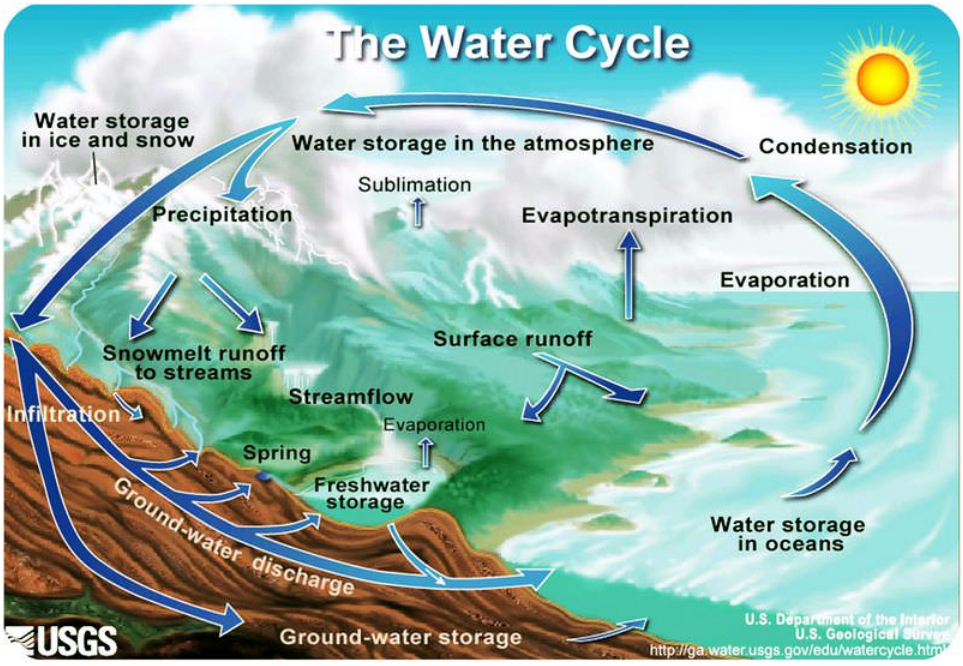


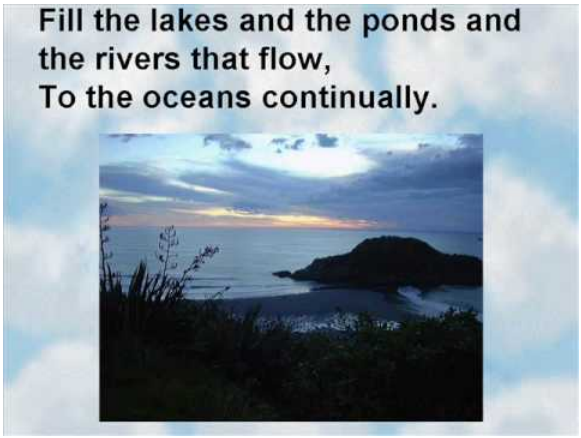
Figure 3. Because it is a cycle, the water cycle has no beginning and no end.

Most of Earth's water is stored in the oceans where it can remain for hundreds or thousands of years. The oceans are discussed in detail in the chapter Earth's Oceans.

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 from lakes, streams, or puddles on land. Only the water molecules evaporate; the salts remain in the ocean or a fresh water reservoir.

The water vapor remains 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 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.

For a little fun, watch this video. This water cycle song focuses on the role of the sun in moving H_2O from one reservoir to another. The movement of all sorts of matter between reservoirs depends on Earth's internal or external sources of energy:



A YouTube element has been excluded from this version of the text. You can view it online here: http://pb.libretexts.org/geo/?p=396

This animation shows the annual cycle of monthly mean precipitation around the world.

When water falls from the sky as rain it may enter streams and rivers that flow downward 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 you probably have not seen water vapor sublimating from a glacier, you may have seen dry ice sublimate in air.

Snow and ice slowly melt over time to become liquid water, which provides a steady flow of fresh water 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.

A significant amount of water infiltrates into the ground. Soil moisture is an important reservoir for water (figure 4). Water trapped in soil is important for plants to grow.

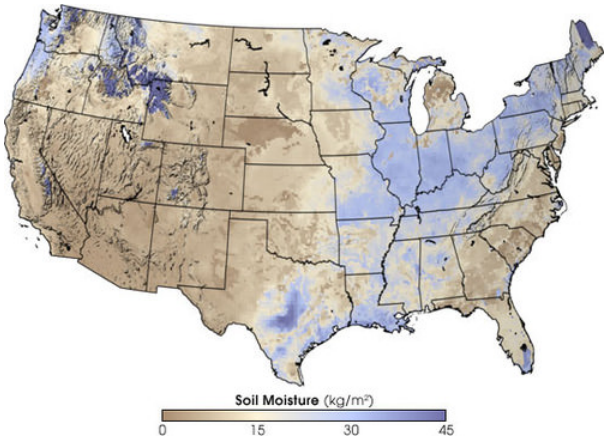


Figure 4. The moisture content of soil in the United States varies greatly.

Water may seep through dirt and rock below the soil through pores infiltrating the ground to go into Earth's groundwater system. Groundwater enters aquifers that may store fresh water 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 up water from the soil and release large amounts of water vapor into the air through their leaves (figure 5), a process known as **transpiration**.

An online guide to the hydrologic cycle from the University of Illinois is found here.

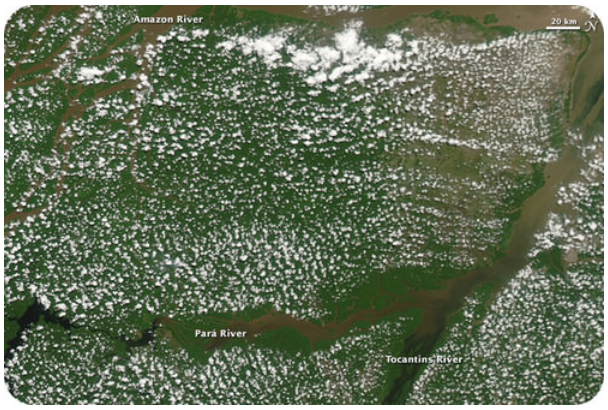


Figure 5. Clouds form above the Amazon Rainforest even in the dry season because of moisture from plant transpiration.

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 (figure 6).



Figure 6. The Pont du Gard aqueduct in France was constructed during the Roman Empire.

Table 1. Water Use in the United States and Globally

Use	United States	Global
Agriculture	34%	70%
Domestic (drinking, bathing)	12%	10%
Industry	5%	20%
Power plant cooling	49%	small

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.

? KQED: Tracking Raindrops

How the water cycle works and how rising global temperatures will affect the water cycle, especially in California, are the topics of this Quest video. Learn more here.

Contributors and Attributions

CC licensed content, Shared previously

- The Water Cycle. **Provided by**: CK-12. **Located at**: http://www.ck12.org/student/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 11.3: Reading- Phases of the Hydrologic Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.4: Self Check- The Hydrologic Cycle

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1123

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 11.4: Self Check- The Hydrologic Cycle is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.5: Outcome- Rivers and Streams

Identify and describe channel types and sedimentary loads formed and carried by rivers and streams.

In this section, you will learn the different types of streams. You will also learn the different types of stream loads.

What You'll Learn to Do

- Understand the different types of rivers and streams, as well as processes associated with them.
- Understand the processes of erosion and sediment transport and deposition

Learning Activities

The learning activities for this section include the following:

- Reading: Types of Streams and Rivers
- Reading: Drainage Basins
- Reading: Geologic Processes and Flowing Water
- Self Check: Rivers and Streams

This page titled 11.5: Outcome- Rivers and Streams is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.6: Reading- Types of Streams and Rivers

Introduction

Streams have a major role in geology. Streams sculpt and shape the earth's surface by eroding, transporting, and depositing sediment. By eroding sediment from uplifted areas and creating landforms made of deposited sediment in lower areas, streams shape the earth's surface more than glaciers do, more than waves on a beach do, and far more than wind does.

What Are Streams?

A stream is flow of water, driven by gravity, in a natural channel, on land. A small brook in a meadow and the Amazon River are both streams. It is interesting to watch water on a recently bulldozed construction site with a slope. At first the water saturates the ground and begins to flow downhill across the surface of the slope in a thin sheet. Soon, the water excavates small channels, known as rills, in the dirt. Rills coalesce to form larger channels. A network of streams, including tributaries, has formed. If not prevented, the channels may continue to deepen and erode soil from the construction site.

Over longer intervals of time the same processes we've imagined on the construction site have built systems of streams and stream valleys on the surface of the earth. Most valleys on earth are the product of streams. Streams erode dirt and rocks, transport the sediment, and redeposit it in new locations, shaping the earth's surface into a system of stream valleys.

Streams flow downhill due to the force of gravity. The higher the hill, the more gravitational energy there is to drive the stream. Where the slopes are steepest and the hills the highest, the streams will be the most energetic and the rate of erosion will be fastest.

Drainage Area

The drainage area of a stream encompasses all the land from which surface runoff flows into that stream. A stream drainage area is also called a watershed. Boundaries between stream drainage areas are called drainage divides. What stream drainage do you live in?

Stream Order

It is common for one stream to flow into another. The smaller of the two streams is a tributary of the larger stream. A stream with no tributaries is a first order stream. A stream with only first-order tributaries is a second order stream. A stream that has any second-order tributaries and none higher is a third-order stream, and so on. The Mississippi River is a tenth order stream, one of the highest order streams on earth. As more and more tributaries join together a larger stream network is formed and the master stream, the highest order stream in the system has a discharge that is the sum of all the tributary discharges. When flooding occurs, higher order streams take longer to build up to flood stage than lower order streams and longer for the flood to subside.

Drainage Patterns

A stream system that includes multiple tributaries exhibits a distinct drainage pattern as seen on a map. The drainage pattern depends on the rock types and geologic structures underlying the stream system. Some types of rock are harder and more resistant to erosion than others. If the geology underlying a stream system is fairly uniform—rocks equally resistant to erosion in all directions—a dendritic drainage pattern will develop, as shown in figure 1. A dendritic drainage pattern is the most common type.

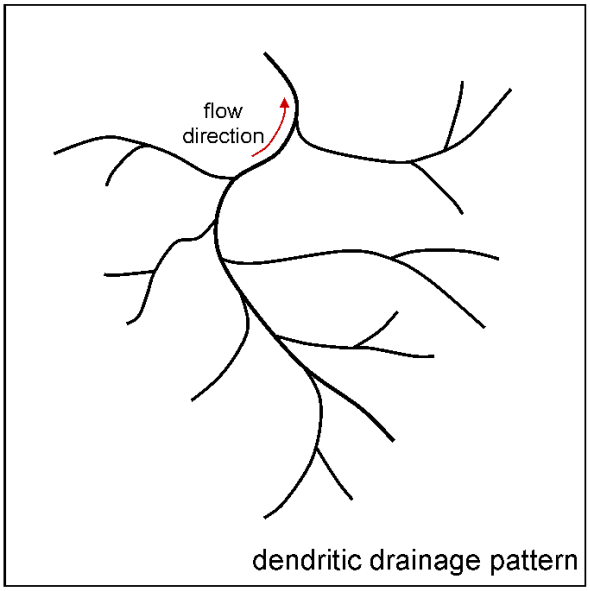


Figure 1

If a region is underlain by layered formations of rock that have been folded, and the layers have different degrees of resistance to erosion, the stream valleys will tend to follow the layers of less resistant rock, and the layers of harder rock will become ridges. This results in a trellis drainage pattern, as show in figure 2.

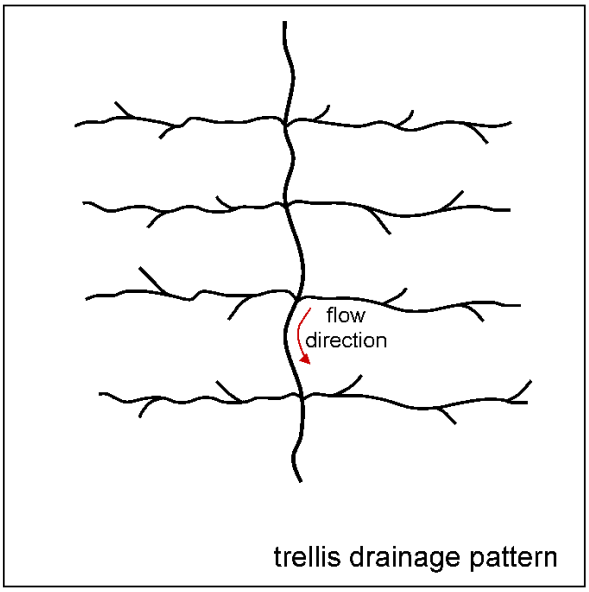


Figure 2.

In some places the geology consists of a single type of rock that is resistant to erosion but the rock contains sets of parallel joints where it erodes more easily. The sets of joints typically intersect each other at high angles. As stream valleys develop in the joint system a rectangular drainage pattern develops, as shown in figure 3. The stream valleys will bend sharply where they switch from following one joint set to another.

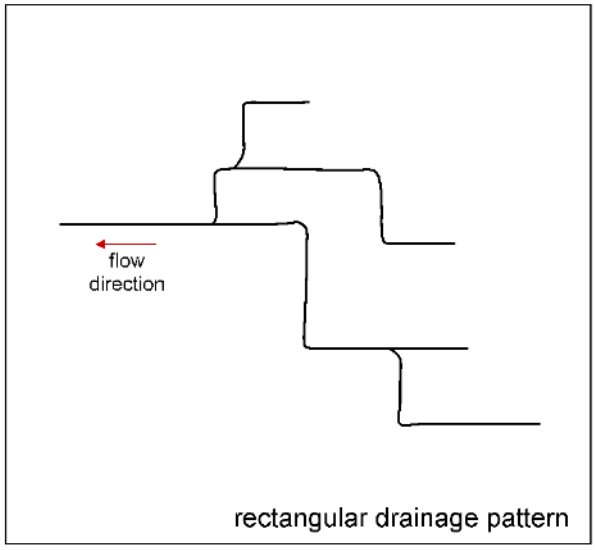


Figure 3.

Streams will radiate in all directions from the center of a broad, high-elevation area, such as a composite cone. This is known as a radial drainage pattern.

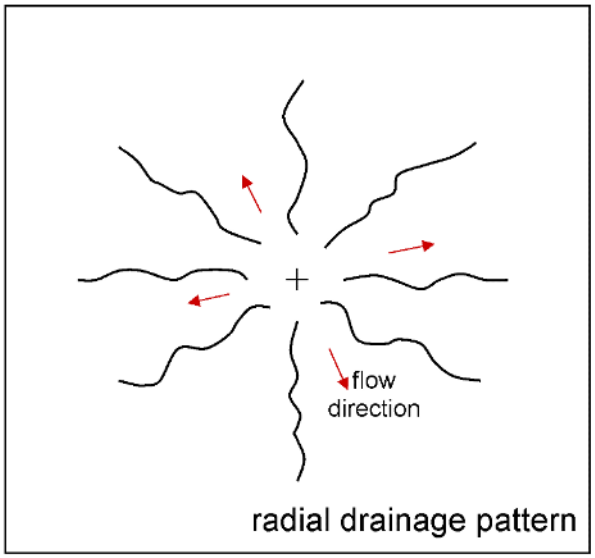


Figure 4.

Graded Profile

Because streams erode more and remove more sediment where the stream gradient is higher, and deposit more sediment where the stream gradient is lower, a stream will develop a graded profile as shown. The graded profile shows how the elevation of the stream changes along the length of the stream, from its beginning at the highest elevation to its base level where it ends at the lowest elevation it reaches.

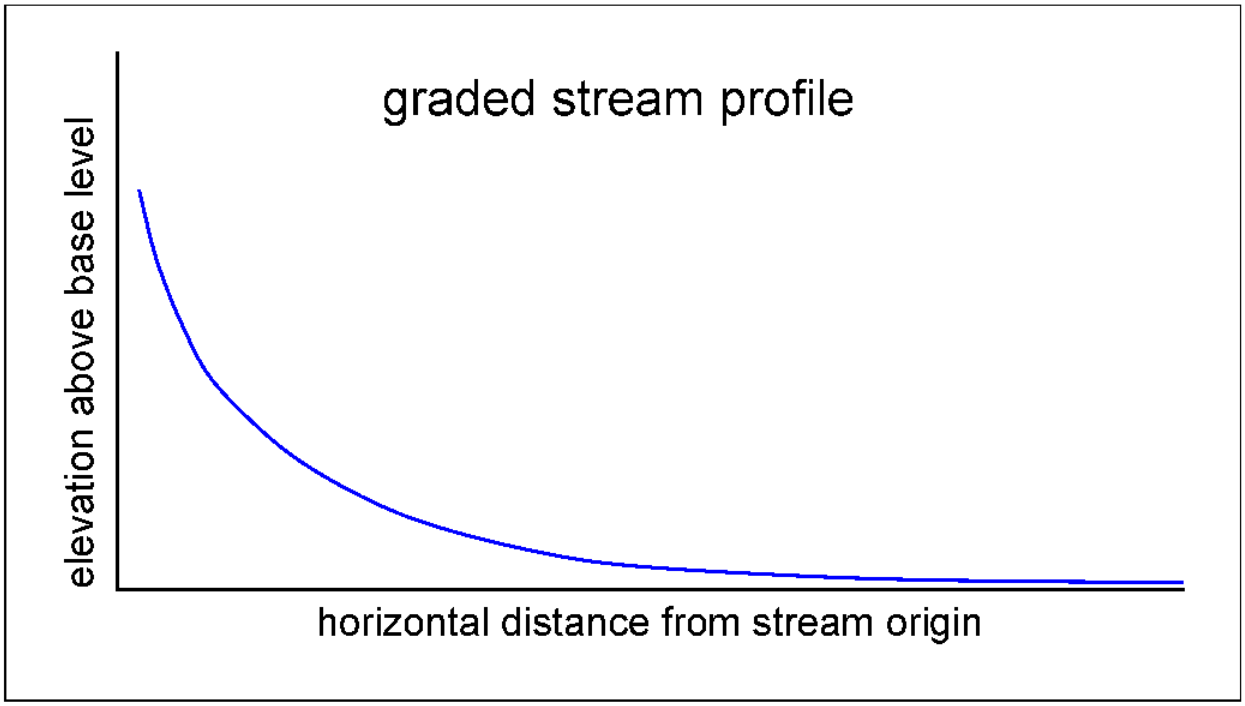


Figure 5.

A graded profile starts with a steep slope at the beginning of the stream and tapers to a gentle slope at the base level of the stream. Imagine a hiker following a stream up to its beginning and tracking her progress on a topographic map. She starts out where the stream valley is low and wide and the gradient is gentle so the hiking is easy. As the day goes on, the going gets steeper as she approaches the stream source. Checking the topographic map, she sees that the contour lines are much closer together than they were earlier in the day and farther down the valley. As she approaches the small lake on the side of the mountain where the stream begins, the slope is so steep that nearly loses her footing. She has experienced for herself a typical stream profile that steepens from near the base-level to the origin of the stream.

Lakes and waterfalls are temporary features in a stream drainage. If a lake forms the stream feeding it will slow down and deposit sediment until the lake has been filled with sediment. Where a waterfall forms the energy of the stream going over the waterfall is high will erode the base of the waterfall, causing the waterfall to retreat upstream until a graded profile is established.

Stream Discharge

The amount of water flowing through a stream and speed at which it is moving is expressed as the discharge of the stream. Discharge is measured by multiplying the cross-sectional area of a stream by the average speed of water through that cross-section. Multiplying the area of the cross-section by the average speed of the water results in units of volume/time. For example, if a stream has a cross-sectional area of 150 square feet (ft^2) and is moving at an average speed of 10 feet per second (ft/s), multiplying the area and the speed results in a discharge of 1,500 cubic feet per second (ft^3/s).

Sediment Load

The water flowing in streams erodes, transports, and deposits sediment. Most rocks and minerals are much denser than water. Sufficient energy in the stream is required to dislodge rocks from the earth and move them. The faster a stream flows, the more energy it has and the larger pieces of sediment it can transport. The *competence* of a stream refers to the maximum size of the pieces of sediment it can move. Faster-moving water has greater competence and can move larger pieces of sediment.

The *capacity* of a stream is the total amount of sediment it can move. Capacity depends on how fast the stream is moving and its total discharge. As a stream slows down, its competence and capacity are reduced. The stream starts to deposit sediment, beginning with the largest pieces. Several factors cause a stream to slow down, including the stream channel widening, the stream overflowing its banks and spreading into a floodplain, the stream gradient (downhill slope) diminishing, and the stream emptying into a larger, slower moving body of water.

Streams transport clastic sediment in two ways depending on the size of the particles. The coarser sediment is called bed load and consists of particles too large to be suspended in the moving current of water for an extended length of time. The bed load particles, the largest particles of sediment transported by a stream, spend most of their time on the bottom of the stream channel, rolling, sliding, or bouncing downstream in fits and starts. The finer sediment is called suspended load and consists of particles small enough to be suspended in the moving current of water. Suspended load moves at about the same rate as the flowing water. In a muddy river, the mud is suspended load

Floodplains

Streams build floodplains through a combination of erosion and deposition at lower gradient stretches of stream valleys. Although a floodplain has a general downhill slope consistent with the overall stream gradient, a floodplain is relatively flat.

Floodplains are filled with sediments spread by the stream. These sediments are known as alluvium. Because alluvium is loose material that is easy for the stream to erode and redeposit, the location of a stream channel in a floodplain changes frequently.

Meanders

A stream running down a slope, even the gentle slope of a floodplain, will seldom follow a straight path for very long. Depending on the distribution of sediments and turbulence of the stream, one side of the channel may erode more easily than the other. The stream will migrate toward the area undergoing erosion, developing a curve in that direction. Once the stream channel has begun to curve, the energy of the water is concentrated on the outside of the curve.

The diagram shows a stretch of stream channel with a significant bend, also known as meander. The blue line shows how erosive energy is concentrated along the outside of each bend in the stream. As erosion occurs on the outside bank of a meander, deposition occurs on the inside bank where the water slows and drops sediment.

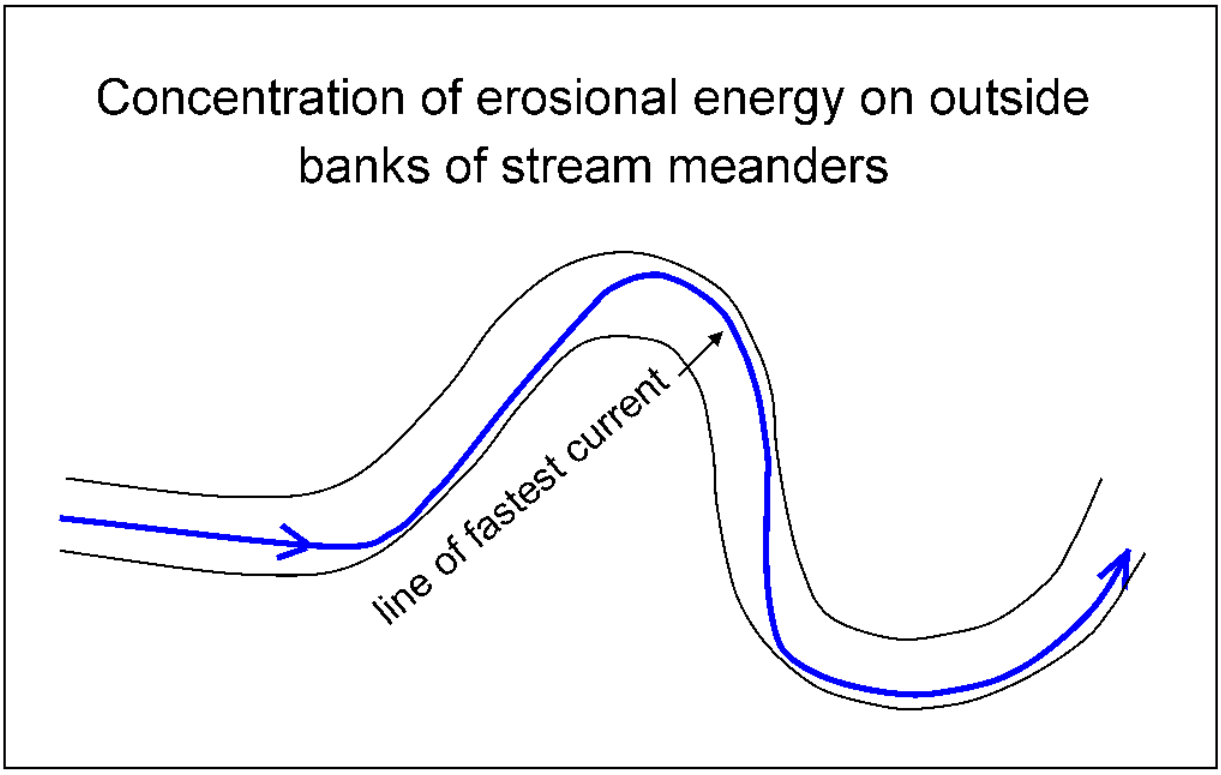


Figure 6.

The diagram below shows two well-developed meanders that have formed in a stream. Along each meander, the outer stream bank that is being cut into by erosion is called a cut bank. The inner bank, which has grown by accretion of deposited sediment, is called a point bar.

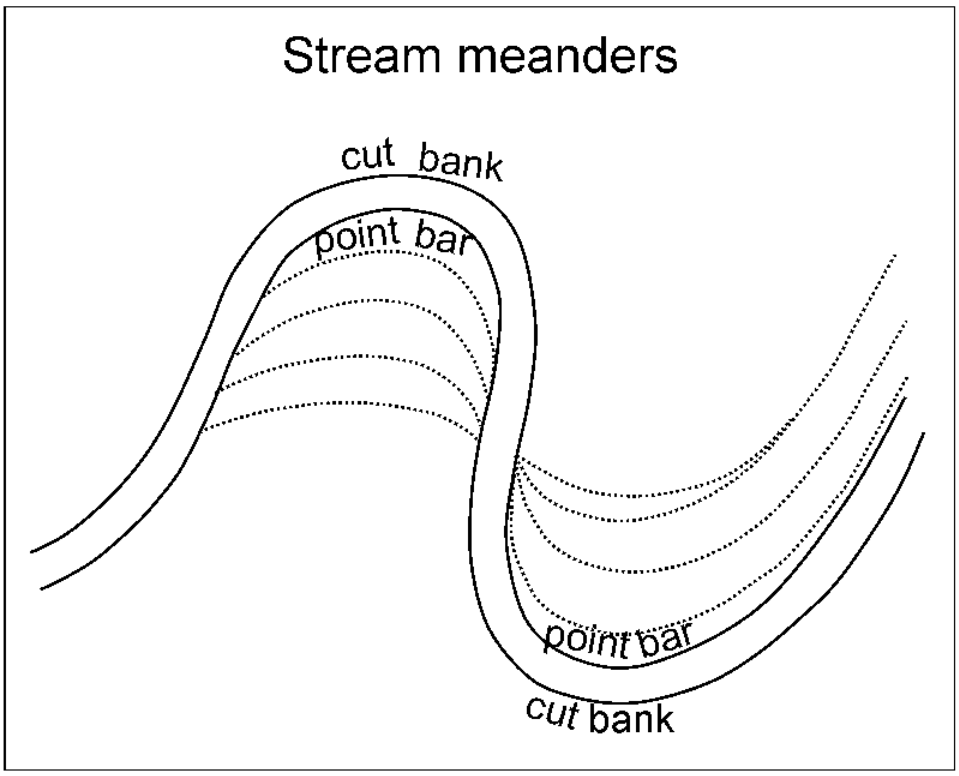


Figure 7.

In a stream, meanders enlarge and migrate downstream because the stream continually erodes its cut banks and grows its point bars. The diagram below shows the enlargement and downstream migration of a meander in a stream channel. As the meander is enlarged, its neck gets narrower. Eventually, the stream may cut through the neck of the meander, either as a result of gradual erosion and channel migration, or abruptly during high water and flooding. Once the stream has cut through the neck of the meander, the openings get filled with sediment dropped by water that slows down as it enters from the main stream. The sediment deposits will separate the cut off meander from the river channel and turn it into an oxbow lake. As the years go by, the oxbow lake will eventually be completely filled in with sediment because it is a low spot on the floodplain where any water that enters, such as during flooding, will come to a standstill and deposit its sediment load.

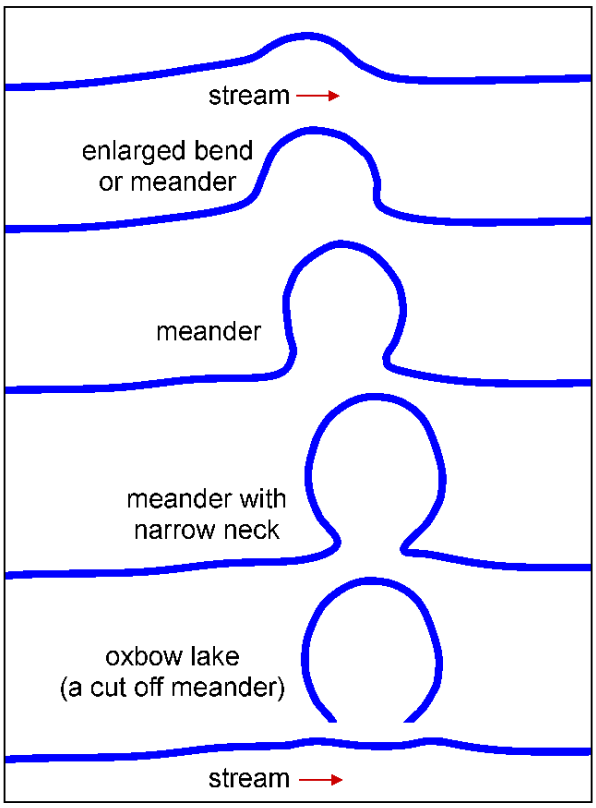


Figure 8.

Entrenched Meanders

Typical meandering stream channels flow through broad flood plains full of alluvial sediment. However, in some situations meanders may cut directly into bedrock. A meander that has cut into bedrock is known as an incised or entrenched meander. In contrast to meanders in alluvium that erode and migrate rapidly or get cut off at the neck abruptly, entrenched meanders are relatively fixed. This is because entrenched meanders are walled in by bedrock on both sides and have little floodplain to easily erode and redeposit.

Entrenched meanders form as a result of tectonic uplift of the stream drainage area. The uplift increases the gravity-driven energy of the stream causing it to incise rapidly down through the flood plain alluvium into the bedrock beneath. Entrenched meanders are striking landscape features because they are unusual and they provide strong evidence of tectonic activity in a region. Classic examples of entrenched meanders include the Goosenecks of the San Juan River, which are incised in the Colorado Plateau east of the Grand Canyon, and a stretch of the Yakima River with entrenched meanders, which are incised in a recently uplifted ridge of basalt in the Columbia Plateau of eastern Washington state.

Braided Streams

Rather than a single channel, some streams have multiple channels that weave in and out of each other forming what is known as a braided stream. Braided streams are associated with excessive amounts of sediment entering a stream system. Valleys draining alpine glaciers are common settings for braided streams. The glaciers deposit more sediment into the meltwater stream system than a stream of that discharge has capacity to transport in a single channel system. Braided stream systems are indicators that there is an additional source of sediment in the system besides the stream itself. Sources of excess sediment that lead to braided streams include glaciers, eruptions of pyroclastic material by volcanoes and landslides.

Flooding and Flood Frequency

Streams flood. Flooding is a normal part of stream behavior. The rate at which streams erode, transport, and deposit sediments greatly increases during flooding. A flood occurs when the water depth in a stream exceeds the depth of the stream channel and spreads beyond the stream channel onto the surrounding land. When a stream completely fills its channel it is said to be at bankfull

stage. When a stream surpasses bankfull stage it is said to be in flood. When the flood spreads widely enough to cause property damage, a stream is said to be at flood stage.

Different streams have different flood behaviors. Some rivers tend to have an annual flood associated with a rainy season or snowmelt season in the higher part of the drainage area. Some streams only flood sporadically, often with years between floods. In the United States all the larger streams have their flow measured at gaging stations that are installed and monitored by the US Geological Survey. Records of stream flow must be kept for at least 30 years to be statistically valid. The likelihood of a flood of a specified magnitude occurring on a stream in a given year can be calculated from the stream flow data. The magnitude of a flood that has a 1 out of 100 chance of happening in a given year—also known as the 100-year flood—is calculated for a stream from it record of stream flow. The 100-year flood magnitude, and maps that show what would be covered by a 100-year flood, are key elements in granting permits for land use and building construction in floodplains.

Low order streams may flood rapidly during or immediately after heavy rainfall. Such rapid floods are called flash floods. Flash floods are often unpredictable. If a river drains through a canyon from a high elevation area, people may be walking along a stream in the canyon in the sunshine and not realize that a thunderstorm is occurring at the stream's source. They may be surprised by a flash flood sweeping through the canyon. A slow building flood on a higher order stream can usually be predicted because major streams are monitored and it takes longer for water from heavy rainfall or rapidly melting snow to move through the higher order stream system. Floods on the highest order streams, such as the Mississippi River, may take several weeks to crest and subside.

Changes to the land in the drainage area of a stream, such as the addition of buildings and roads, can change how a stream floods. Buildings and pavement that cover the ground prevent infiltration and cause increased surface run off. Increased stream runoff means smaller amount of rain will cause the stream to reach flood stage than before the alterations to the land. The stream will flood more frequently. For the same amount and rate of rainfall that caused flooding prior to building, the stream will reach flood stage quicker and the flood will be deeper. The diagram below shows the flood response of a stream to a given amount of rainfall before and after the stream drainage area was urbanized by removal of forest and addition of buildings and roads. After urbanization, the stream reaches its peak flood level quicker and rises to a higher level than before urbanization. Unless countermeasures are engineered and installed, an urbanized area will flood more frequently and severely than the same area when it was forested.

Figure 9.

Alluvial Fans



Figure 10.

At the location where a stream reaches its base level, it slows down and deposits nearly all of the sediment it is carrying. A stream that comes down a canyon and enters a flat valley or plain builds a fan shaped deposit of sediment known as an alluvial fan. Alluvial fans are built mostly during flash floods. Alluvial fans are easy to recognize in arid areas but they form in wetter climates as well.

The diagram in figure 11 shows in cross-section how an alluvial fan develops over time as sediment is eroded from higher elevation and deposited on the adjacent lower elevation plain.

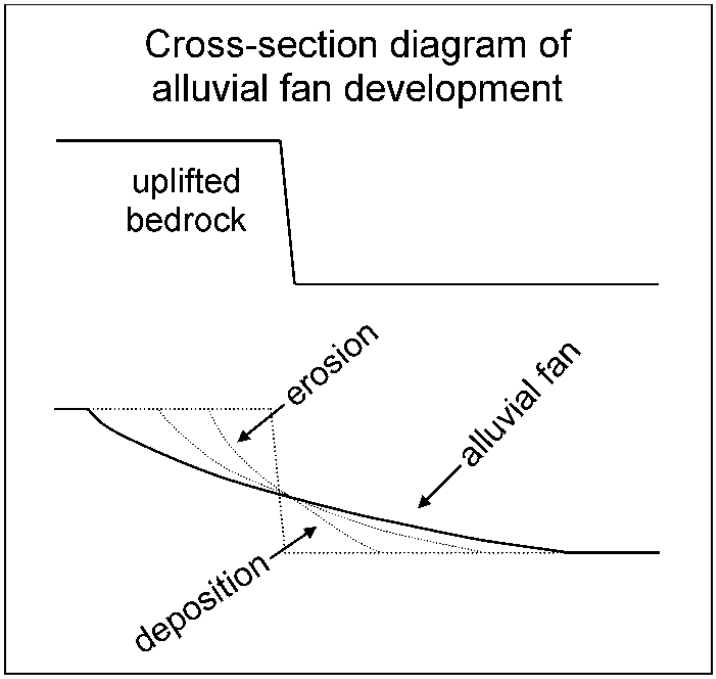


Figure 11.

Deltas

Deltas are important landforms to civilization. They provide fertile soils, flat land, and water for agriculture, as well as river channels for transportation.

A delta is a landform composed of sediment deposited where a stream enters a larger, slower moving body of water, such as an ocean, a lake, or a larger river. The term delta comes from the triangular shape of the Greek letter delta (Δ). Ancient Greek geographers recognized the triangular shape of the land created by the Nile River where it emptied into the Mediterranean Sea and gave the name delta to that landform. The Nile River delta is one of several types of deltas that are defined by the predominate processes that shape them. The Nile delta is a wave-dominated delta. Waves of the Mediterranean Sea have pushed and distributed sediment along the coast, flattening the seaward side of delta.

The Mississippi River delta is an example of a stream dominated delta. Deposition of sediments has built the delta into the Gulf of Mexico faster than waves or tides could redistribute the sediment. As commonly occurs in a delta, the Mississippi River splits in the downstream direction into several branches that discharge across the delta into the Gulf of Mexico. These branches are known as distributaries. The mouth of each distributary has built part of the delta farther out into the Gulf of Mexico forming what is known as a bird's foot delta, another name for a stream dominated delta based on the way it looks on a map.

The Ganges River delta is a tide dominated delta formed from sediment eroded from the Himalaya Mountains, the largest mountain range in the world. The mouth of the Ganges River is at the northern end of the Bay of Bengal, a large embayment of the Indian Ocean. The shape of this large bay has a magnifying effect on the tides. The combination of strong tides and the consistently high discharge from a river caring a large sediment load create a branching pattern of distributaries, in effect a braided stream system across the delta.

Deltas are lowlands that lie barely above sea level and are at high risk of being submerged under water. There are several ways in which deltas can be inundated by rising water. Floods coming down the river can cover a delta. Marine deltas can be subject to storm surges when extreme winds raise sea level along the coast and push ocean water inland. In the last several decades a new risk of submergence has arisen for marine deltas. Many marine deltas are undergoing gradual submergence as global sea level rises.

Contributors and Attributions

CC licensed content, Shared previously

- Basics -- Streams. **Authored by**: Ralph L. Dawes and Cheryl D. Dawes. **Provided by**: Wenatchee Valley College. **Located at**: http://commons.wvc.edu/rdawes/G101OCL/Basics/streams.html. **Project**: Geology 101 - Introduction to Physical Geology. **License**: *CC BY: Attribution*

This page titled 11.6: Reading- Types of Streams and Rivers is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.7: Reading- Drainage Basins

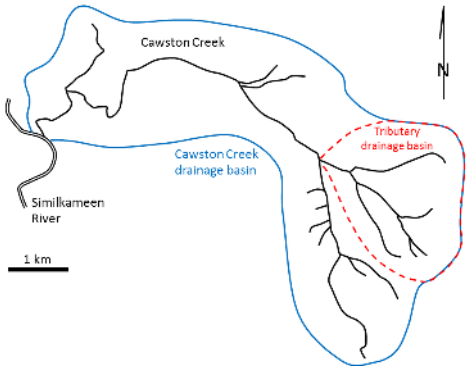


Figure 1. Cawston Creek near Keremeos, B.C. The blue line shows the extent of the drainage basin. The dashed red line is the drainage basin of one of its tributaries. [SE]

A **stream** is a body of flowing surface water of any size, ranging from a tiny trickle to a mighty river. The area from which the water flows to form a stream is known as its **drainage basin**. All of the precipitation (rain or snow) that falls within a drainage basin eventually flows into its stream, unless some of that water is able to cross into an adjacent drainage basin via groundwater flow. An example of a drainage basin is shown in Figure 1.

Cawston Creek is a typical small drainage basin (approximately 25 km^2) within a very steep glaciated valley. As shown in Figure 2, the upper and middle parts of the creek have steep **gradients** (averaging about 200 m/km but ranging from 100 to 350 m/km), and the lower part, within the valley of the Similkameen River, is relatively flat (<5 m/km). The shape of the valley has been controlled first by tectonic uplift (related to plate convergence), then by pre-glacial stream erosion and mass wasting, then by several episodes of glacial erosion, and finally by post-glacial stream erosion. The lowest elevation of Cawston Creek (275 m at the Similkameen River) is its **base level**. Cawston Creek cannot erode below that level unless the Similkameen River erodes deeper into its flood plain (the area that is inundated during a flood).

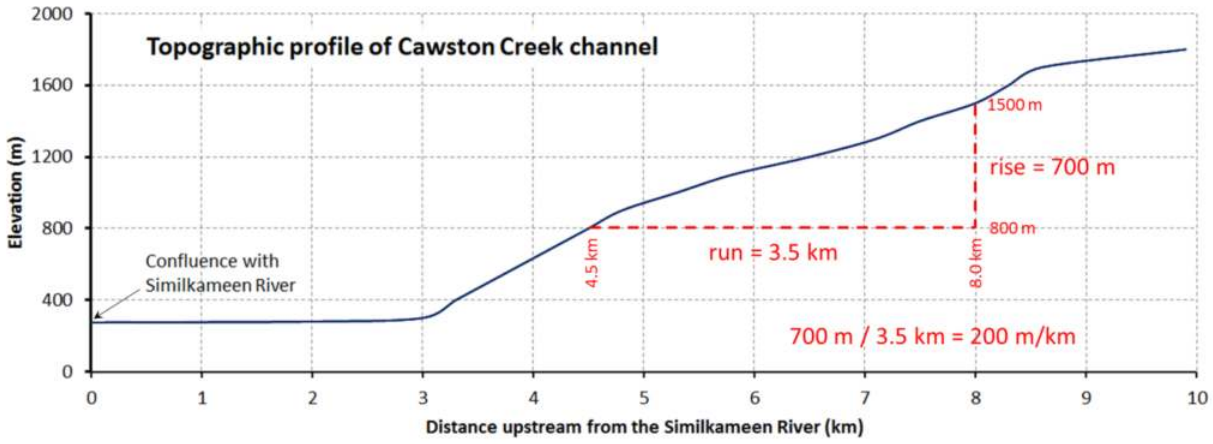


Figure 2. Profile of the main stem of Cawston Creek near Keremeos, B.C. The maximum elevation of the drainage basin is about 1,840 m, near Mount Kobau. The base level is 275 m, at the Similkameen River. As shown, the gradient of the stream can be determined by dividing the change in elevation between any two points (rise) by the distance between those two points (run). [SE]

Metro Vancouver's water supply comes from three large drainage basins on the north shore of Burrard Inlet. The boundary between two drainage basins is the height of land between them. A drop of water falling on the boundary between the Capilano and Seymour drainage basins (a.k.a., watersheds), for example, could flow into either one of them.

The pattern of tributaries within a drainage basin depends largely on the type of rock beneath, and on structures within that rock (folds, fractures, faults, etc.). The three main types of drainage patterns are illustrated in Figure 3. **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. Most areas of British Columbia have dendritic patterns, as do most areas of the prairies and the Canadian

Shield. **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 a good example of this, and many of the drainage systems within the Rockies have trellis patterns. **Rectangular** patterns develop in areas that have very little topography and a system of bedding planes, fractures, or faults that form a rectangular network. Rectangular drainage patterns are rare in Canada.

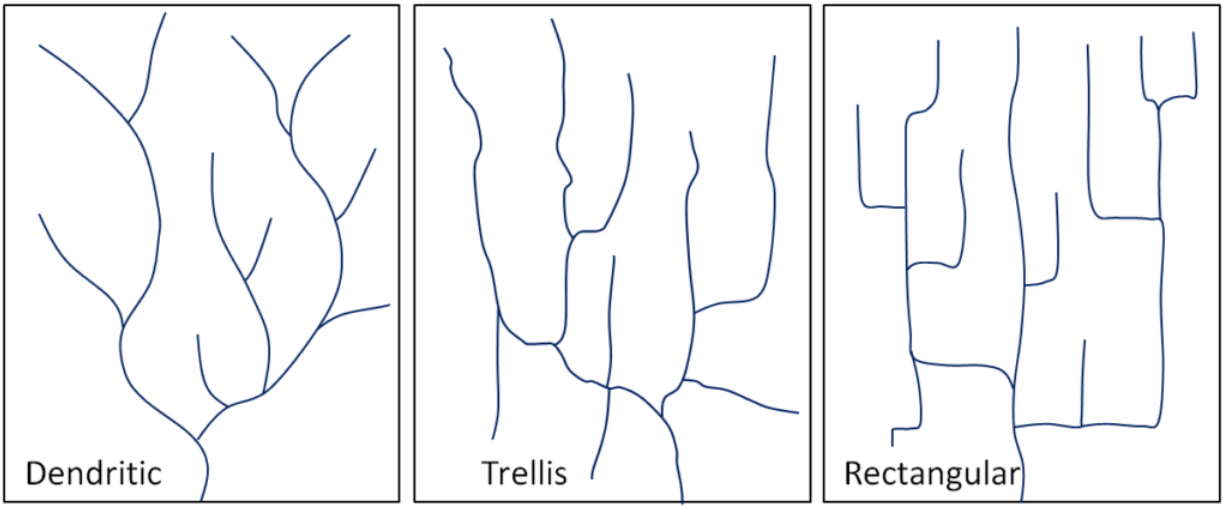


Figure 3. Typical dendritic, trellis, and rectangular stream drainage patterns. [SE]

In many parts of Canada, especially relatively flat areas with thick glacial sediments, and throughout much of Canadian Shield in eastern and central Canada, drainage patterns are chaotic, or what is known as **deranged** (Figure 4, left). Lakes and wetlands are common in this type of environment. A fourth type of drainage pattern, which is not specific to a drainage basin, is known as **radial** (Figure 4, right). Radial patterns form around isolated mountains (such as volcanoes) or hills, and the individual streams typically have dendritic drainage patterns.

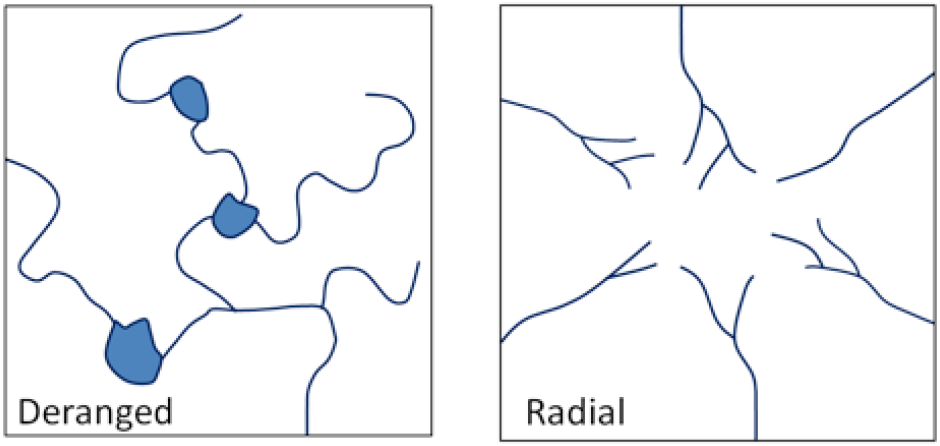


Figure 4. Left: a typical deranged pattern; right: a typical radial drainage pattern developed around a mountain or hill. [SE]

Over geological time, a stream will erode its drainage basin into a smooth profile similar to that shown in Figure 5. If we compare this with an ungraded stream like Cawston Creek (Figure 1), 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.

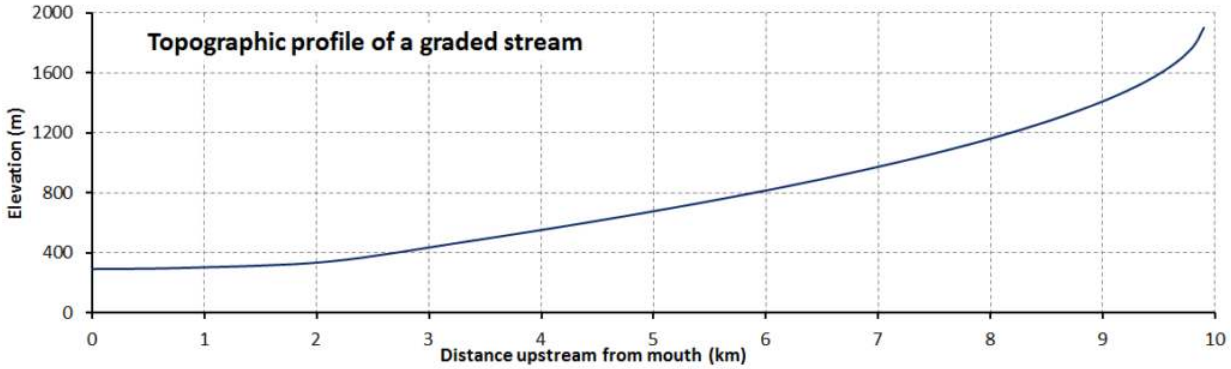


Figure 5. The topographic profile of a typical graded stream. [SE]



Figure 6. An example of a change in the base level of a small stream that flows into the Similkameen river near Keremeos. The previous base level was near the top of the sandy bank. The current base level is the river. [SE]

A graded stream can become ungraded if there is renewed tectonic uplift, or if there is a change in the base level, either because of tectonic uplift or some other reason. As stated earlier, the base level of Cawston Creek is defined by the level of the Similkameen River, but this can change, and has done so in the past. Figure 6 shows the valley of the Similkameen River in the Keremeos area. The river channel is just beyond the row of trees. The green field in the distance is underlain by material eroded from the hills behind and deposited by a small creek (not Cawston Creek) adjacent to the Similkameen River when its level was higher than it is now. Sometime in the past several centuries, the Similkameen River eroded down through these deposits (forming the steep bank on the other side of the river), and the base level of the small creek was lowered by about 10 m. Over the next few centuries, this creek will seek to become graded again by eroding down through its own alluvial fan.

Another example of a change in base level can be seen along the Juan de Fuca Trail on southwestern Vancouver Island. As shown in Figure 7, many of the small streams along this part of the coast flow into the ocean as waterfalls. It is evident that the land in this area has risen by about 5 m in the past few thousand years, probably in response to deglaciation. The streams that used to flow directly into the ocean now have a lot of down-cutting to do to become regraded.



Figure 7. Two streams with a lowered base level on the Juan de Fuca Trail, southwestern Vancouver Island. [SE]

The ocean is the ultimate base level, but lakes and other rivers act as base levels for many smaller streams. We can create an artificial base level on a stream by constructing a dam.

? Exercise: **The Effect of a Dam on Base Level**



Figure 8. Revelstoke Dam and Revelstoke Lake on the Columbia River at Revelstoke, BC [SE]

When a dam is built on a stream, a reservoir (artificial lake) forms behind the dam, and this temporarily (for many decades at least) creates a new base level for the part of the stream above the reservoir.

- How does the formation of a reservoir affect the stream where it enters the reservoir, and what happens to the sediment it was carrying?
- The water leaving the dam has no sediment in it. How does this affect the stream below the dam?

Take a moment to think about your answers to these questions. You can record them in the space below, if you'd like:

[practice-area rows="4"][/practice-area]



Figure 9. Terraces on the Fraser River at High Bar. [Marie Betcher photo, used with permission]

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. A terrace on the Similkameen River is shown in Figure 6 and some on the Fraser River are shown in Figure 9. The Fraser River photo shows at least two levels of terraces.

In the late nineteenth century, American geologist William Davis proposed that streams and the surrounding terrain develop in a cycle of erosion (Figure 10). Following tectonic uplift, streams erode quickly, developing deep V-shaped valleys that tend to follow relatively straight paths. Gradients are high, and profiles are ungraded. Rapids and waterfalls are common. During the mature stage, streams erode wider 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 wide sediment-filled valleys. Meandering patterns are common.

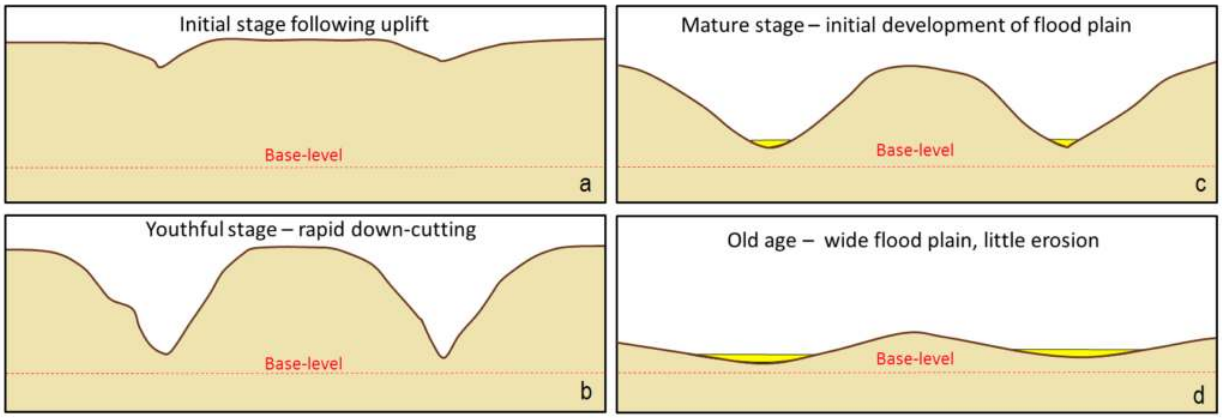


Figure 10. A depiction of the Davis cycle of erosion: a: initial stage, b: youthful stage, c: mature stage, and d: old age. [SE]

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.

Contributors and Attributions

CC licensed content, Shared previously

- Drainage Basins. **Authored by**: Steven Earle. **Provided by**: BC Campus. **Located at**: https://opentextbc.ca/geology/chapter/13-2-drainage-basins/. **Project**: Physical Geology. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 11.7: Reading- Drainage Basins is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.8: Reading- Geologic Processes and Flowing Water

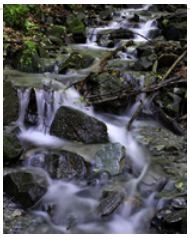


Figure 1. As streams flow towards the ocean, they carry weathered materials.

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 (figure 1). 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.

Erosion and Deposition by Streams

Erosion by Streams

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:

- **Dissolved load**: Dissolved load is composed of ions in solution. These ions are usually carried in the water all the way to the ocean.
- **Suspended load**: Sediments carried as solids as the stream flows are suspended load. The size of particles that can be carried is determined by the stream's velocity (figure 2). 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.



Figure 2. Rivers carry sand, silt and clay as suspended load. During flood stage, the suspended load greatly increases as stream velocity increases.

- **Bed load**: Particles that are too large to be carried as suspended load are bumped and pushed along the stream bed as bed load. Bed load sediments do not move continuously. This intermittent movement is 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.
- Here is a video of bedload transport.

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 (figure 3). The stream moves fast and does lots of work eroding the stream bed.



Figure 3. This stream begins as snow melt from the mountains.

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** (figure 4).



Figure 4. (a) At a meander, a stream actively erodes its outer banks and deposits material along the inside curves. This causes these meanders to migrate laterally over time. (b) This stream has deposited larger materials such as gravel and pebbles along the inside curve of a meander. (c) This image is a topographic map. The San Juan River eroded the land surface as the Colorado Plateau uplifted. The river's meanders were preserved as a feature called incised meanders.

As the river moves onto flatter ground, the stream erodes the outer edges of its banks to carve a **floodplain**, which is a flat level area surrounding the stream channel (figure 5).



Figure 5. The Vistula River in Poland flows onto its floodplain.

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 farther the stream is from where it will reach base level and the more cutting it has to do.

Stream Deposition

As a stream gets closer to base level, its gradient lowers and it deposits more material than it erodes. On flatter ground, streams deposit material on the inside of meanders. Placer mineral deposits, described in the Earth's Minerals chapter, are often deposited there. 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 (figure 6).

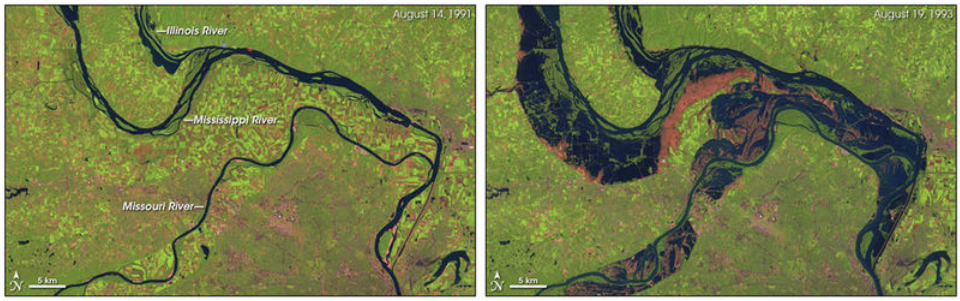


Figure 6. The Mississippi floodplain is heavily farmed. Flooding can wipe out farms and towns, but the stream also deposits nutrient-rich sediments that enrich the floodplain.

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** (figure 7).

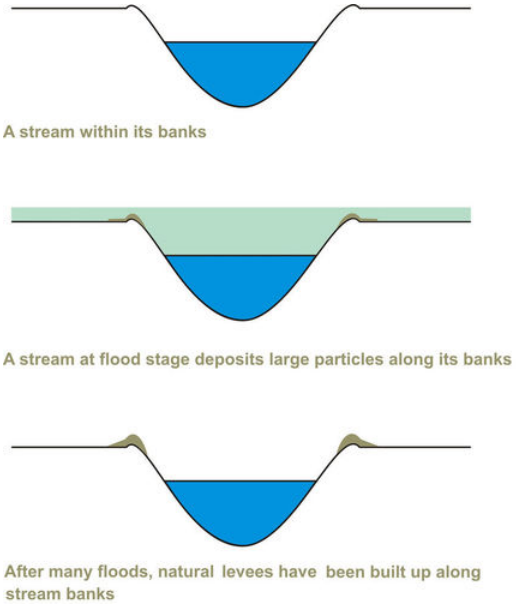


Figure 7. After many floods, a stream builds natural levees along its banks.

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 a wide triangular-shaped deposit called a **delta** (figure 8).



Figure 8. (a) The Nile River delta has a classic triangular shape, like the capital Greek letter delta. (b) Sediment in the Yellow River delta. The main stream channel splits into many smaller distributaries.

If a stream falls down a steep slope onto a broad flat valley, an **alluvial fan** develops (figure 9). Alluvial fans generally form in arid regions.



Figure 9. An alluvial fan in Iran. The mountains are in the lower right corner of the photograph.

Contributors and Attributions

CC licensed content, Shared previously

- 10.1: Water Erosion and Deposition. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/10.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 11.8: Reading- Geologic Processes and Flowing Water is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.9: Self Check- Rivers and Streams

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1124

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 11.9: Self Check- Rivers and Streams is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.10: Outcome- Components of Groundwater

Describe critical components of groundwater

What You'll Learn to Do

- Differentiate between groundwater and the water table
- Describe how groundwater is affected by porosity and permeability of geologic materials with respect to different types of aquifers.
- Compare and contrast potential well use within various types of aquifers.
- Identify issues with groundwater withdrawal
- Describe issues with the quality of groundwater and keeping water clean

Learning Activities

The learning activities for this section include the following:

- Reading: Groundwater
- Reading: Porosity and Permeability
- Reading: Aquifers and Well-Potential
- Reading: Groundwater Withdrawal
- Reading: Quality of Groundwater
- Self Check: Components of Groundwater

This page titled 11.10: Outcome- Components of Groundwater is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.11: Reading- Groundwater

Introduction

Although this may seem surprising, water beneath the ground is commonplace. Usually groundwater travels slowly and silently beneath the surface, but in some locations it bubbles to the surface at springs. The products of erosion and deposition by groundwater were described in the Erosion and Deposition chapter.

Groundwater

Groundwater is the largest reservoir of liquid fresh water on Earth and is found in **aquifers**, porous rock and sediment with water in between. Water is attracted to the soil particles and **capillary action**, which describes how water moves through a porous media, moves water from wet soil to dry areas.

Aquifers are found at different depths. Some are just below the surface and some are found much deeper below the land surface. A region may have more than one aquifer beneath it and even most deserts are above aquifers. The source region for an aquifer beneath a desert is likely to be far from where the aquifer is located; for example, it may be in a mountain area.

The amount of water that is available to enter groundwater in a region is influenced by the local climate, the slope of the land, the type of rock found at the surface, the vegetation cover, land use in the area, and water retention, which is the amount of water that remains in the ground. More water goes into the ground where there is a lot of rain, flat land, porous rock, exposed soil, and where water is not already filling the soil and rock.

The residence time of water in a groundwater aquifer can be from minutes to thousands of years. Groundwater is often called “fossil water” because it has remained in the ground for so long, often since the end of the ice ages.

Aquifers

Features of an Aquifer

To be a good aquifer, the rock in the aquifer must have good:

- **porosity**: small spaces between grains
- **permeability**: connections between pores

This animation shows porosity and permeability. The water droplets are found in the pores between the sediment grains, which is porosity. When the water can travel between ores, that’s permeability.

To reach an aquifer, surface water infiltrates downward into the ground through tiny spaces or pores in the rock. The water travels down through the permeable rock until it reaches a layer that does not have pores; this rock is **impermeable** (figure 1). This impermeable rock layer forms the base of the aquifer. The upper surface where the groundwater reaches is the **water table**.

Figure 1. Groundwater is found beneath the solid surface. Notice that the water table roughly mirrors the slope of the land's surface. A well penetrates the water table.

The Water Table

For a groundwater aquifer to contain the same amount of water, the amount of recharge must equal the amount of discharge. What are the likely sources of recharge? What are the likely sources of discharge?

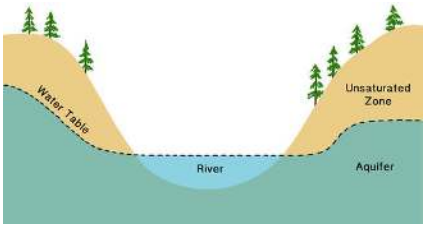


Figure 2. The top of the stream is the top of the water table. The stream feeds the aquifer.

In wet regions, streams are fed by groundwater; the surface of the stream is the top of the water table (figure 2). In dry regions, water seeps down from the stream into the aquifer. These streams are often dry much of the year. Water leaves a groundwater reservoir in streams or springs. People take water from aquifers, too.

What happens to the water table when there is a lot of rainfall? What happens when there is a drought? 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 is found in Florida. Although aquifers are very rarely underground rivers, in Florida water has dissolved the limestone so that streams travel underground and above ground (figure 3).

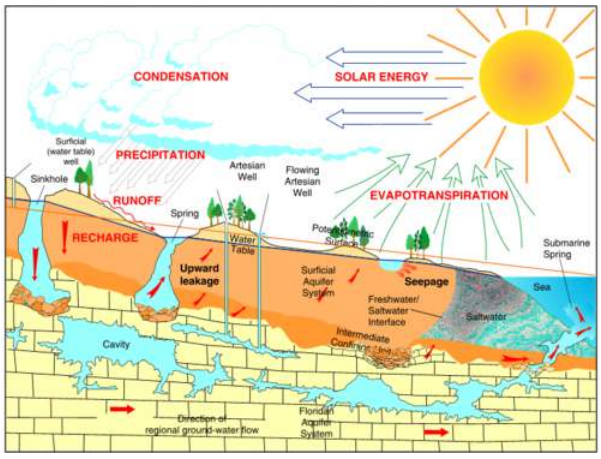


Figure 3. In Florida, groundwater is sometimes not underground.

Contributors and Attributions

CC licensed content, Shared previously

- 13.3: Groundwater. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/13.3/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 11.11: Reading- Groundwater is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.12: Reading- Porosity and Permeability

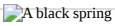


Figure 1. A spring coming out of the shale near Red Creek. Yes, that water is black! (Photo: Matt Herod)

As we've learned, groundwater is simply water that exists underground. However, there are still lots of misconceptions about how people envision groundwater. Many envision large underground lakes and rivers, and while those do exist, they represent an infinitesimally small percentage of all groundwater. Generally speaking groundwater exists in the pore spaces between grains of soil and rocks. Imagine a water filled sponge. All of the holes in that sponge are water-filled. By squeezing that sponge we force the water out, similarly, by pumping an aquifer we force the water out of pore spaces.

There are lots of terms in hydrogeology, most of which are very simple, but essential. Here are a few of the big ones and their meanings.

Porosity

Porosity is an intrinsic property of every material. It refers to the amount of empty space within a given material. In a soil or rock the porosity (empty space) exists between the grains of minerals. In a material like gravel the grains are large and there is lots of empty space between them since they don't fit together very well. However, in a material like a gravel, sand and clay mixture the porosity is much less as the smaller grains fill the spaces. The amount of water a material can hold is directly related to the porosity since water will try and fill the empty spaces in a material. We measure porosity by the percentage of empty space that exists within a particular porous media.

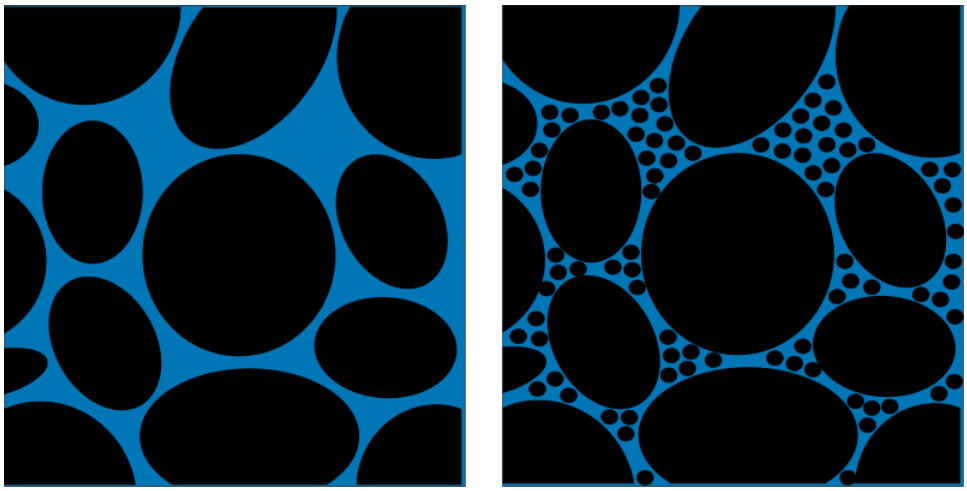


Figure 2. Porosity in two different media. The image on the left is analagous to gravel whereas on the right smaller particles are filling some of the pores and displacing water. Therefore, the water content of the material on the right is less. (Source: Wikipedia)

Permeability

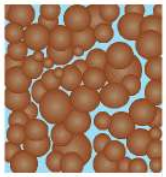


Figure 3. Video showing how connected pores have high permeability and can transport water easily. Note that some pores are isolated and cannot transport water trapped within them.

Permeability is another intrinsic property of all materials and is closely related to porosity. Permeability refers to how connected pore spaces are to one another. If the material has high permeability than pore spaces are connected to one another allowing water to flow from one to another, however, if there is low permeability then the pore spaces are isolated and water is trapped within them. For example, in a gravel all of the pores well connected one another allowing water to flow through it, however, in a clay most of the pore spaces are blocked, meaning water cannot flow through it easily.

Aquifer

An aquifer is a term for a type of soil or rock that can hold and transfer water that is completely saturated with water. That means that all it is simply a layer of soil or rock that has a reasonably high porosity and permeability that allows it to contain water and transfer it from pore to pore relatively quickly and all of the pore spaces are filled with water. Good examples of aquifers are glacial till or sandy soils which have both high porosity and high permeability. Aquifers allows us to recover groundwater by pumping quickly and easily. However, overpumping can easily reduce the amount of water in an aquifer and cause it to dry up. Aquifers are replenished when surface water infiltrates through the ground and refills the pore spaces in the aquifer. This process is called recharge. It is especially important to ensure that recharge is clean and uncontaminated or the entire aquifer could become polluted. There are two main types of aquifer. An unconfined aquifer is one that does not have an aquitard above it but usually does below it.

When a water-bearing rock readily transmits water to wells and springs, it is called an aquifer. Wells can be drilled into the aquifers and water can be pumped out. Precipitation eventually adds water (recharge) into the porous rock of the aquifer. The rate of recharge is not the same for all aquifers, though, and that must be considered when pumping water from a well. Pumping too much water too fast draws down the water in the aquifer and eventually causes a well to yield less and less water and even run dry. In fact, pumping your well too fast can even cause your neighbor's well to run dry if you both are pumping from the same aquifer.

In the diagram below, you can see how the ground below the water table (the blue area) is saturated with water. The "unsaturated zone" above the water table (the greenish area) still contains water (after all, plants' roots live in this area), but it is not totally saturated with water. You can see this in the two drawings at the bottom of the diagram, which show a close-up of how water is stored in between underground rock particles.

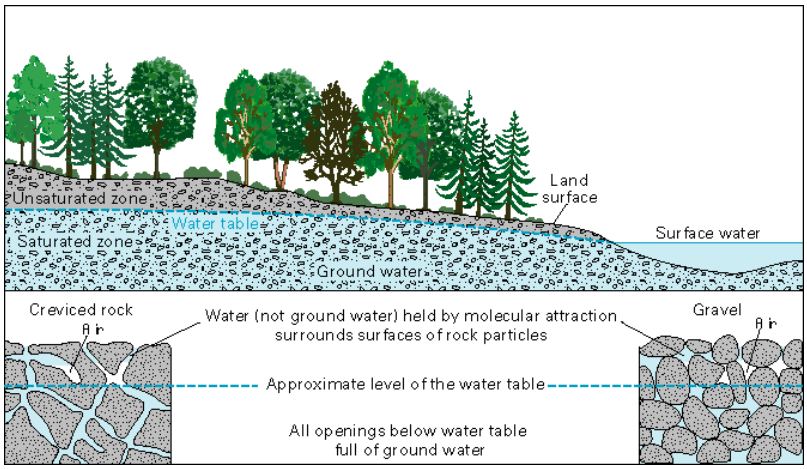


Figure 2.

Sometimes the porous rock layers become tilted in the earth. There might be a confining layer of less porous rock both above and below the porous layer. This is an example of a confined aquifer. In this case, the rocks surrounding the aquifer confines the pressure in the porous rock and its water. If a well is drilled into this "pressurized" aquifer, the internal pressure might (depending on the ability of the rock to transport water) be enough to push the water up the well and up to the surface without the aid of a pump, sometimes completely out of the well. This type of well is called artesian. The pressure of water from an artesian well can be quite dramatic.

A relationship does not necessarily exist between the water-bearing capacity of rocks and the depth at which they are found. A very dense granite that will yield little or no water to a well may be exposed at the land surface. Conversely, a porous sandstone, such as the Dakota Sandstone mentioned previously, may lie hundreds or thousands of feet below the land surface and may yield hundreds of gallons per minute of water. Rocks that yield freshwater have been found at depths of more than 6,000 feet, and salty water has

come from oil wells at depths of more than 30,000 feet. On the average, however, the porosity and permeability of rocks decrease as their depth below land surface increases; the pores and cracks in rocks at great depths are closed or greatly reduced in size because of the weight of overlying rocks.

Water Movement in Aquifers

Water movement in aquifers is highly dependent of the permeability of the aquifer material. Permeable material contains interconnected cracks or spaces that are both numerous enough and large enough to allow water to move freely. In some permeable materials groundwater may move several metres in a day; in other places, it moves only a few centimeters in a century. Groundwater moves very slowly through relatively impermeable materials such as clay and shale.

After entering an aquifer, water moves slowly toward lower lying places and eventually is discharged from the aquifer from springs, seeps into streams, or is withdrawn from the ground by wells. Groundwater in aquifers between layers of poorly permeable rock, such as clay or shale, may be confined under pressure. If such a confined aquifer is tapped by a well, water will rise above the top of the aquifer and may even flow from the well onto the land surface. Water confined in this way is said to be under artesian pressure, and the aquifer is called an artesian aquifer.

Visualizing Artesian Pressure

Here's a little experiment to show you how artesian pressure works. Fill a plastic sandwich baggie with water, put a straw in through the opening, tape the opening around the straw closed, do *not* point the straw towards your teacher or parents, and then squeeze the baggie. Artesian water is pushed out through the straw.

Aquitard

The other type is a confined aquifer that has an aquitard above and below it. An aquitard is basically the opposite of an aquifer with one key exception. Aquitards have very low permeability and do not transfer water well at all. In fact, in the ground they often act as a barrier to water flow and separate two aquifers. The one key exception is that aquitards can have high porosity and hold lots of water however, due to the their low permeability they are unable to transmit it from pore to pore and therefore water cannot flow within an aquitard very well. A good example of an aquitard is a layer of clay. Clay often has high porosity but almost no permeability meaning it is essentially a barrier which water cannot flow through and the water within it is trapped. However, there is still limited water flow within aquitards due to other processes that I won't get into now.

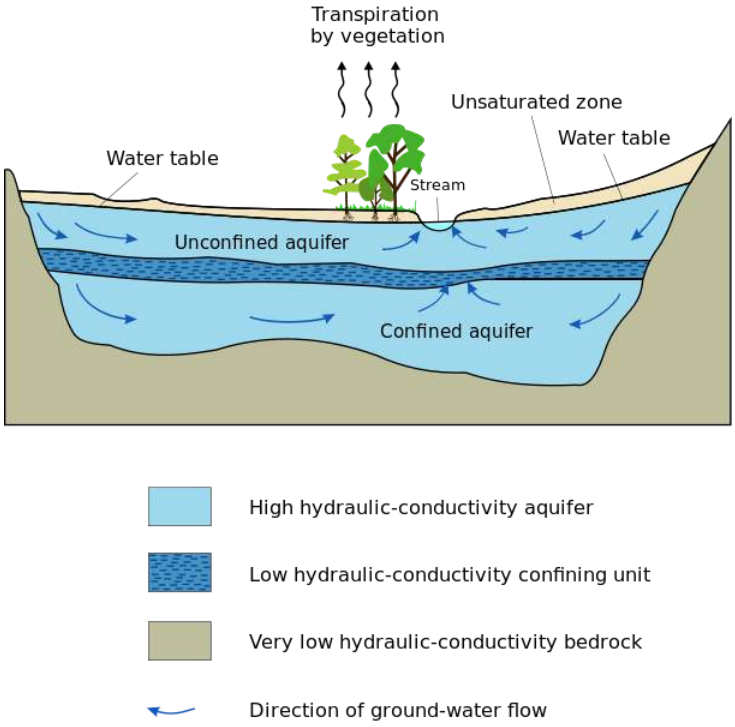


Figure 4.

Contributors and Attributions

CC licensed content, Shared previously

- Back to Basics on Groundwater. **Authored by**: Matt Herod. **Provided by**: European Geosciences Union. **Located at**: http://blogs.egu.eu/network/geosphere/2013/09/17/back-to-basics-on-groundwater/. **License**: *CC BY: Attribution*

Public domain content

- Aquifers. **Provided by**: USGS. **Located at**: http://water.usgs.gov/edu/earthgwaquifer.html. **License**: *Public Domain: No Known Copyright*

This page titled 11.12: Reading- Porosity and Permeability is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.13: Reading- Aquifers and Well-Potential

There's a good chance that the average Joe who had to dig a well in ancient Egypt probably did the work with his hands, a shovel, and a bucket. He would have kept digging until he reached the water table and water filled the bottom of the hole. Some wells are still dug by hand today, but more modern methods are available. It's still a dirty job, though!

Wells are extremely important to all societies. In many places wells provide a reliable and ample supply of water for home uses, irrigation, and industries. Where surface water is scarce, such as in deserts,people couldn't survive and thrive without groundwater.

Types of Wells

Digging a well by hand is becoming outdated today (would YOU want to do it?). Modern wells are more often drilled by a truck-mounted drill rig. Still, there are many ways to put in a well—here are some of the common methods.

Dug Wells

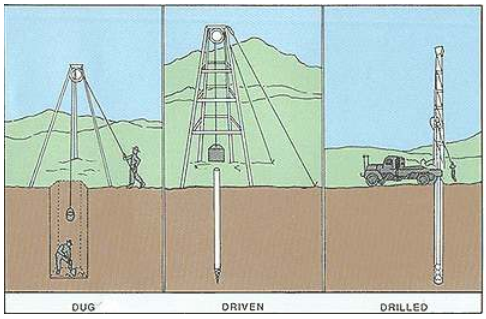


Figure 1. Well Types

Hacking at the ground with a pick and shovel is one way to dig a well. If the ground is soft and the water table is shallow,then dug wells can work. Historically, dug wells were excavated by hand shovel to below the water table until incoming water exceeded the digger's bailing rate . The well was lined with stones, brick, tile, or other material to prevent collapse, and was covered with a cap of wood, stone, or concrete. They cannot be dug much deeper than the water table — just as you cannot dig a hole very deep when you are at the beach… it keeps filling up with water!

Driven Wells

Driven wells are still common today. They are built by driving a small-diameter pipe into soft earth, such as sand or gravel. A screen is usually attached to the bottom of the pipe to filter out sand and other particles. Problems? They can only tap shallow water, and because the source of the water is so close to the surface, contamination from surface pollutants can occur.

Drilled Wells

Most modern wells are drilled, which requires a fairly complicated and expensive drill rig. Drill rigs are often mounted on big trucks. They use rotary drill bits that chew away at the rock, percussion bits that smash the rock, or, if the ground is soft,large auger bits. Drilled wells can be drilled more than 1,000 feet deep. Often a pump is placed at the bottom to push water up to the surface.

Water Levels in Wells

Ground-water users would find life easier if the water level in the aquifer that supplied their well always stayed the same. Seasonal variations in rainfall and the occasional drought affect the "height" of the underground water level. If a well is pumped at a faster rate than the aquifer around it is recharged by precipitation or other underground flow, then water levels around the well can be lowered. The water level in a well can also be lowered if other wells near it are withdrawing too much water. When water levels drop below the levels of the pump intakes, then wells will begin to pump air—they will "go dry."

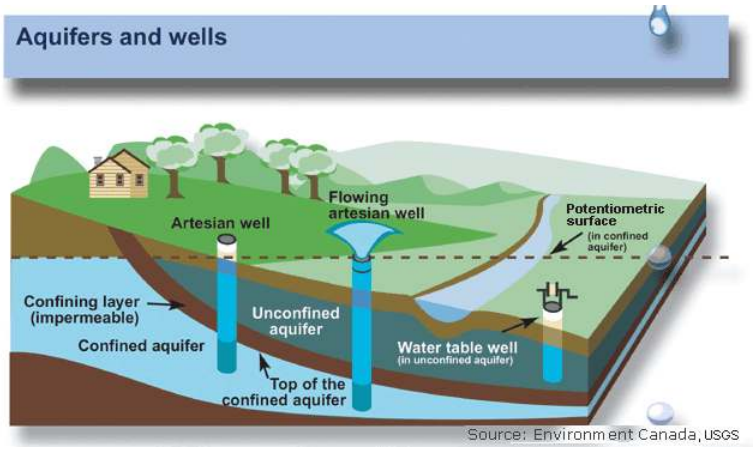


Figure 2. Aquifers and Wells

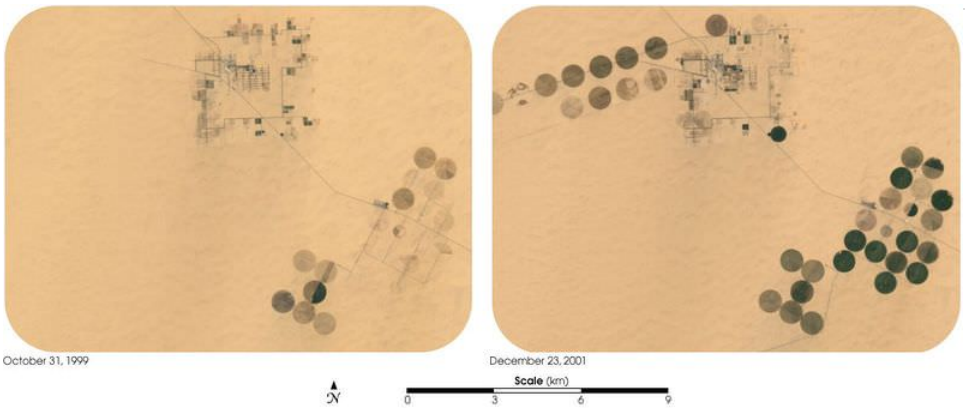
Contributors and Attributions

Public domain content

- Groundwater: Wells. **Authored by**: Roger M. Waller. **Provided by**: USGS. **Located at**: http://water.usgs.gov/edu/earthgwwells.html. **Project**: Ground Water and the Rural Homeowner. **License**: *Public Domain: No Known Copyright*

This page titled 11.13: Reading- Aquifers and Well-Potential is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.14: Reading- Groundwater Withdrawal



Is it good to make the desert bloom?

Many sunny, arid regions are good for growing crops as long as water can be added. Some of the increase in productivity is due to farming in regions that are technically too dry. Groundwater can be used to make the desert bloom, but at what cost? And for how long? Eventually the wells will run dry.

Groundwater Overuse

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.

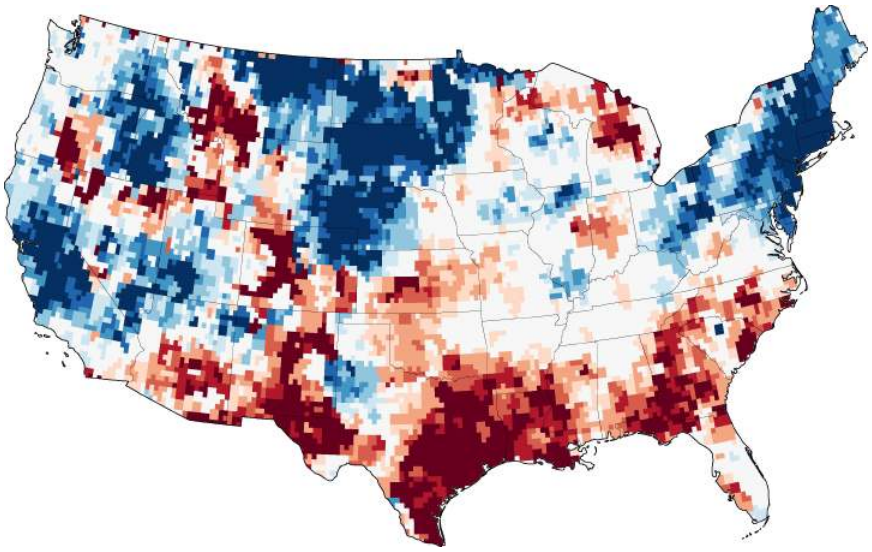


Figure 1. Intense drought has reduced groundwater levels in the southern U.S., particularly in Texas and New Mexico.

Other problems may stem from groundwater overuse. Subsidence and saltwater intrusion are two of them.

Ogallala Aquifer

The Ogallala Aquifer supplies about one-third of the irrigation water in the United States. The Ogallala Aquifer is widely used by people for municipal and agricultural needs. (Figure 2). The aquifer is found from 30 to 100 meters deep over an area of about 440,000 square kilometers!

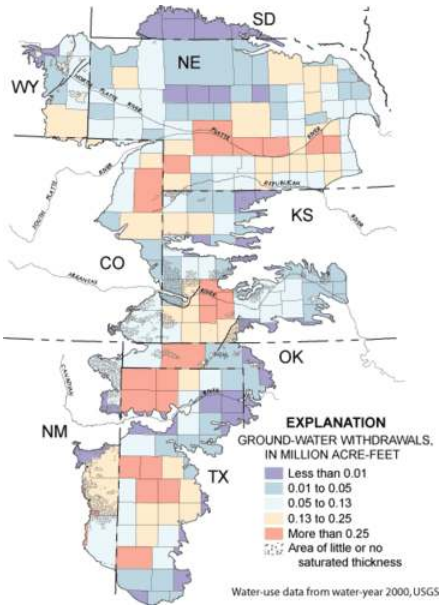


Figure 2. The Ogallala Aquifer is found beneath eight states and is heavily used.

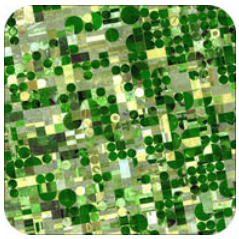


Figure 3. Farms in Kansas

The water in the aquifer is mostly from the last ice age. About eight times more water is taken from the Ogallala Aquifer each year than is replenished. Much of the water is used for irrigation .Farms in Kansas use central pivot irrigation (Figure 3), which is more efficient since water falls directly on the crops instead of being shot in the air. These fields are between 800 and 1600 meters (0.5 and 1 mile) in diameter.

Subsidence

Lowering the water table may cause the ground surface to sink. Subsidence may occur beneath houses and other structures. The San Joaquin Valley of California is one of the world's major agricultural areas. So much groundwater has been pumped that the land has subsided many tens of feet.

Salt Water Intrusion

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. Salt water incursion is a problem in developed coastal regions, such as on Hawaii.

Summary

- When water is pumped from an aquifer, the water table declines and wells must be drilled deeper.
- The Ogallala Aquifer was filled in the ice age but is being used to irrigate the farms of the Midwestern U.S. at a rate far greater than it is being replenished.
- Ground subsidence and saltwater intrusion are two possible consequences of groundwater overuse.

? Practice

Use this resource to answer the questions that follow.

A link to an interactive elements can be found at the bottom of this page.

1. How has irrigation changed farming?
2. What is leading to people's demands for additional water?
3. What do scientists need to see to better plan for future water use?
4. What is the GRACE satellite doing?
5. How does GRACE find groundwater aquifers?
6. How people know the aquifers are being depleted?
7. What is happening in India? what will happen if the water continues to decline?
8. What is the future of water?

Contributors and Attributions

CC licensed content, Shared previously

- Groundwater Depletion. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Groundwater-Depletion/lesson/Groundwater-Depletion-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

All rights reserved content

- NASA | Science for a Hungry World: Part 5. **Authored by**: NASA Goddard. **Located at**: https://youtu.be/o1QsCa7RmmU. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

This page titled 11.14: Reading- Groundwater Withdrawal is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.15: Reading- Quality of Groundwater

As was noted at the very beginning of this chapter, one of the good things about groundwater as a source of water is that it is not as easily contaminated as surface water is. But 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.

Natural Contamination of Groundwater

Groundwater moves slowly through an aquifer, and unlike the surface water of a stream, it has a lot of contact 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 more and more material dissolved within it as it remains in contact with the aquifer. In some areas, that rock or sediment includes some minerals that could potentially 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 particularly high levels of the element in question. In other cases, the aquifer material is just normal rock or sediment, but some particular feature of the water or the aquifer allows the contaminant to build up to significant levels.

An example of natural contamination takes place in the bedrock aquifers of the east coast of Vancouver Island and the adjacent Gulf Islands. The aquifer is the Cretaceous (90 Ma to 65 Ma) Nanaimo Group, which is made up of sandstone, mudstone, and conglomerate (Figure 1).



Figure 1. Cretaceous Nanaimo Group sandstone exposed in a Nanaimo parking lot [SE]

The rocks of the Nanaimo Group are not particularly enriched in any trace elements, but the submarine-fan sandstone that makes up much of the group is a lithic wacke, and therefore has relatively high levels of clay (for a sandstone). This clay is good at adsorbing[1] some elements from the water and desorbing others, and in the process, its pH goes up (it becomes alkaline). At high pH levels (some as high as 9 in the Nanaimo Group), the element fluorine that is present naturally in the rock (as it is in almost any rock) has an increased tendency to dissolve in the water. In some areas, groundwater in the Nanaimo Group has fluorine levels that are well above recommended levels for drinking water. The World Health Organization (WHO) maximum acceptable concentration (MAC) for fluorine is 1.5 mg/L (milligrams per litre). Between 5% and 10% of the domestic wells around Nanaimo and adjacent Gabriola Island have more than that, some as much as 10 mg/L. A small amount of fluorine in the human diet is considered important for maintaining dental health, but high levels can lead to malformation and discolouration of teeth, and long-term exposure can lead to other more serious health effects such as skeletal problems.

Nanaimo Group groundwater can also have elevated levels of boron, again related to pH and adsorption from clay minerals. While boron at the levels found there is not toxic to humans, there is enough boron in some wells to be toxic to plants, and the water cannot be used for irrigation.



Figure 2. The distribution of arsenic in groundwater in Bangladesh. The WHO recommended safe level for arsenic is 10 µg/L. All of the green, orange, and red areas on the map exceed that limit. [From: BGS and DPHE. 2001. Arsenic contamination of groundwater in Bangladesh. Kinniburgh, D G and Smedley, P L, http://www.bgs.ac.uk/arsenic/bangladesh/.]

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 (Figure 2).

Most of the wells in the affected areas are drilled into relatively 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 in them 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 final 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.

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 permeability of the aquifer, 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.

Studies of groundwater vulnerability have been completed for various regions of British Columbia. A groundwater vulnerability map for southern Vancouver Island is shown in Figure 3. The yellow to red areas are considered to have high vulnerability to pollution from surface sources, and most of these are where the aquifers are unconfined in quite permeable unconsolidated sediments of either glacial or fluvial origin, where the water table is relatively shallow and the terrain is relatively flat.

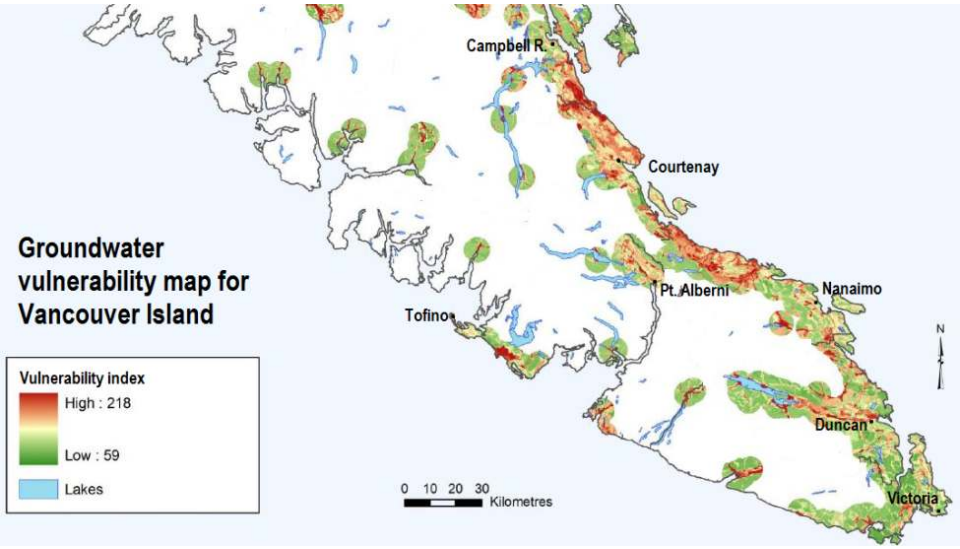


Figure 3. The vulnerability to anthropogenic contamination of aquifers on southern Vancouver Island. Much of the island is not mapped (shown as white) because of a lack of aquifer information in areas without wells. [From: Newton, P. and Gilchrist, A. 2010. Technical summary of intrinsic vulnerability mapping methods of Vancouver Island, Vancouver Island Water Resources Vulnerability Mapping Project, Vancouver Island University, 45pp. Used with permission. https://web.viu.ca/groundwater/PDF/VI_DRASTIC_Summary_Phase2_2010.pdf]

The important sources of anthropogenic groundwater contamination include the following:

- Chemicals and animal waste related to agriculture, and chemicals applied to golf courses and domestic gardens
- 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

Agriculture

Intensive agricultural operations and golf courses can have a significant impact on the environment, especially where chemicals and other materials are used to enhance growth or control pests. An example of agricultural contamination is in the Abbotsford area of the Fraser Valley, where nitrate levels above the 44 mg/L maximum acceptable level (expressed as nitrate) in the Abbotsford-Sumas aquifer have been observed since the 1950s; however, the problem became much worse as agriculture intensity increased in the 1980s. By 2004, groundwater with nitrate levels in excess of 44 mg/L was reported over an area of about 75 km2 around Abbotsford, and the problem extended across the border into the Sumas area of Washington State.

This region is intensively used for berry crops (especially raspberries and blueberries) and large poultry operations, as well as lesser amounts of grazing and forage crops. Chicken manure is typically stored in fields adjacent to chicken barns, and may release nitrogen to the environment from runoff water, and from releases of ammonia gas. Over decades, both chemical fertilizers and chicken manure and other manures have been applied to the berry crops to provide extra nitrogen to help maximize berry growth. If the fertilizer added is in excess of what the plants need, or is poorly timed compared to when it is needed, then the extra nitrogen may be leached into the groundwater below. Berry crops are irrigated over the summer to help the crops grow. Summer irrigation and winter rainfall may carry excess nitrate from the near surface to the aquifer below.

Since the 1990s, agricultural practices have been tightened up to reduce the rate of groundwater contamination, but it will take decades for nitrate levels to drop in the Abbotsford-Sumas aquifer. Agriculture and Agri-Food Canada and many others are conducting research on better irrigation and nitrate management techniques to reduce the amount of nitrogen that leaches to groundwater.

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 important 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 (Figure 4). Once 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 normal sewage treatment plant.

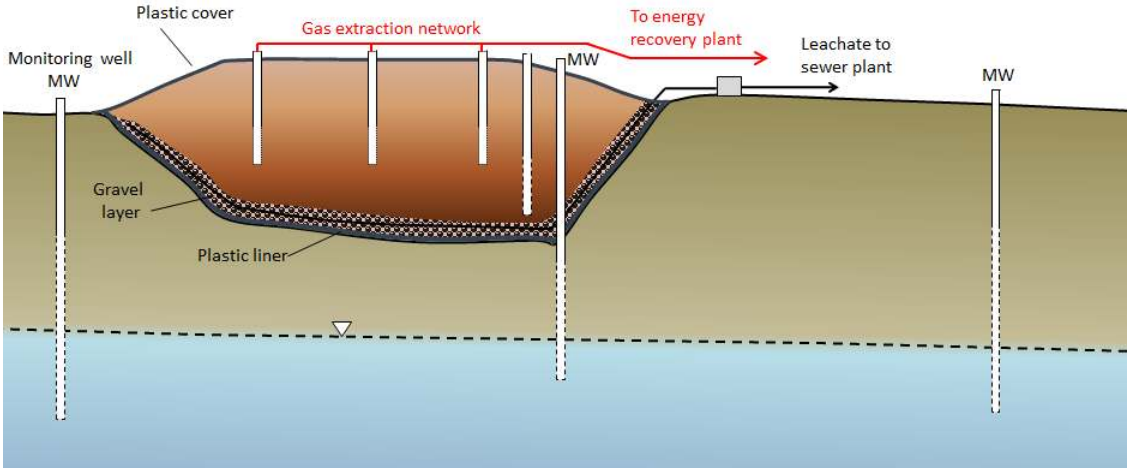


Figure 4 A cross-section of a typical modern landfill [SE]

The monitoring wells are used to assess the level of the water table around the landfill and to 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 metres if possible) and where the aquifer material is relatively impermeable. Landfills should also be situated far from streams, lakes, or wetlands so that contamination of aquatic habitats can be avoided.

Today there are hundreds of abandoned dumps 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’s unlikely that we’ll be able to do so.

? Exercises: What Goes on at Your Landfill?



Figure 5. A landfill [SE photo]

Unless you live in a remote rural area, there’s a good chance that the refuse you can’t recycle is picked up at the curb and taken to a landfill. Most landfills are operated by cities or regional districts, and you should be able to find information about yours on the appropriate local government website. See if you can answer some the following questions:

1. Which government body operates your landfill?

2. Where is the landfill situated?
3. Is your waste all placed in a landfill, or are there other processes in use (e.g., incineration or composting)?
4. Are landfill gases captured, and, if so, what is done with them?
5. What could be changed to improve the waste disposal situation in your community (e.g., more recycling, compost collection, waste-to-energy technology)?

Industrial Operations

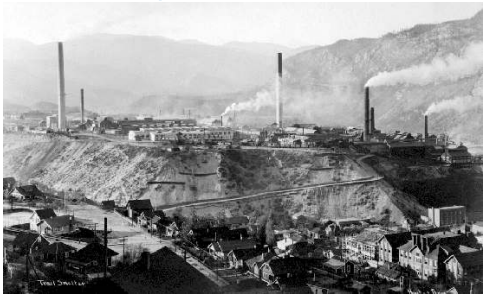


Figure 6. The Trail lead-zinc smelter in 1929
[http://upload.wikimedia.org /Wikipedia/commons/2/20
/Trail_Smelter_in_Year_1929.png]

Although western Canada doesn't have the same extent of industrial pollution as other parts of the country, there are still seriously contaminated sites in the west, most with the potential to contaminate groundwater. One example is the lead and zinc smelter at Trail, B.C. The largest in the world, it has been operating for over 100 years and has left a residue of metal contamination around the region (Figure 6). In some parts of Trail, the contamination is serious enough that existing soil has been removed from residential properties and replaced with clean soil brought in from elsewhere. This contaminated soil has contributed to contamination of groundwater in the Trail area. Groundwater beneath the actual smelter site is contaminated, and the operator (Teck Resources) is currently working on plans to prevent that water from reaching the nearby Columbia River.

Mines, Quarries, and Rock Excavations



Figure 7. Acidic runoff at the abandoned Mt. Washington Mine near Courtenay, B.C. [SE]

Mines and other operations that involve the excavation of large amounts of rock (e.g., highway construction) have the potential to create serious environmental damage. The exposure of rock that has previously not been exposed to air and water can lead to the oxidation of sulphide-bearing minerals, such a pyrite (FeS_2), within the rock. The combination of pyrite, water, oxygen, and a special 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 has the property of increasing 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 sulphide-bearing rocks are near the surface. The issue of ARD is a major environmental concern at both operating mines and abandoned mines. In streams around the Mt. Washington Mine on Vancouver Island (Figure 7), copper levels are high enough to be toxic to fish. Groundwater adjacent to the contaminated streams in the area is very likely contaminated as well.



Figure 8. A closed and fenced gas station site in Nanaimo, B.C. The white pipes in the background are wells for monitoring groundwater contamination on the site. [SE]

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 particular problem at older gas stations — although it may also become a future problem at newer gas stations. You may have noticed gas stations that have been closed and then surrounded by chain-link fence (Figure 8). In virtually all such cases the closure has been triggered by the discovery of leaking USTs and the requirement 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 (Figure 9). 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.

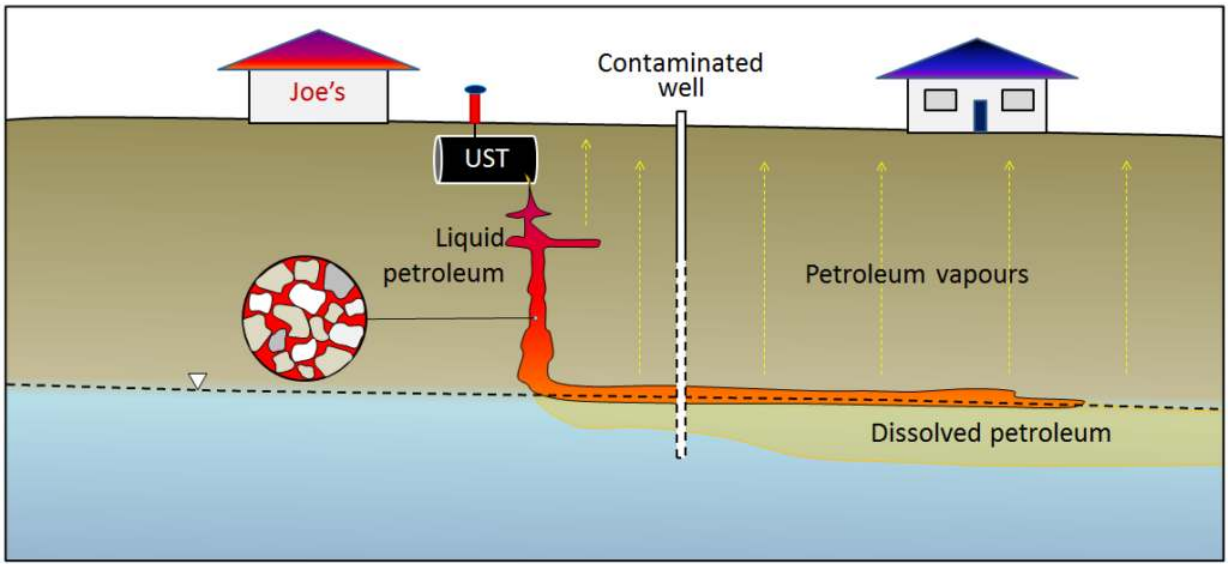


Figure 9. A depiction of the fate of different components of a petroleum spill from an underground storage tank. [SE]

? Exercises: Find a Leaking UST in Your Community

There is almost certainly a leaking UST at a former gas station near you. Look for an empty property that is surrounded by a chain-link fence with “No Trespassing” signs. You might see evidence of monitoring wells (like those shown in Figure 9), and there could be some petroleum barrels around that are being used to store contaminated water. Once you’ve identified one of these, you’ll probably start seeing them everywhere!

Septic Systems

In areas that are not served by sewage networks leading to a central sewage treatment plant, most homeowners rely on **septic systems** for disposal of sewage. There are two primary components to a simple septic system, the septic tank and the drainage field (Figure 10). A typical septic tank is constructed of either concrete or plastic and has a volume of 5,000 L to 10,000 L (5 m3 to 10 m3). This forms the first treatment and is designed to be **anaerobic** (without oxygen). That promotes the activity of certain bacteria that help break down the waste. As the waste is degraded, some portions tend to sink to form sludge at the base of the tank, and

others float to the surface, forming a scum layer. A septic tank may be divided into two parts to keep the sludge at the bottom and the scum on the top from draining out. The water then moves to the drainage field, which provides the right conditions for a different set of bacteria that operate in **aerobic** conditions. The drainage field includes an array of plastic pipes that are perforated to allow the effluent to drain out over a large area and seep slowly into the ground. In order to install a drainage field, it is first necessary to test the soil below, as it must be sufficiently permeable to allow the effluent to percolate away, but not so permeable that it flows too quickly and the soil is not able to filter out the pathogenic bacteria.

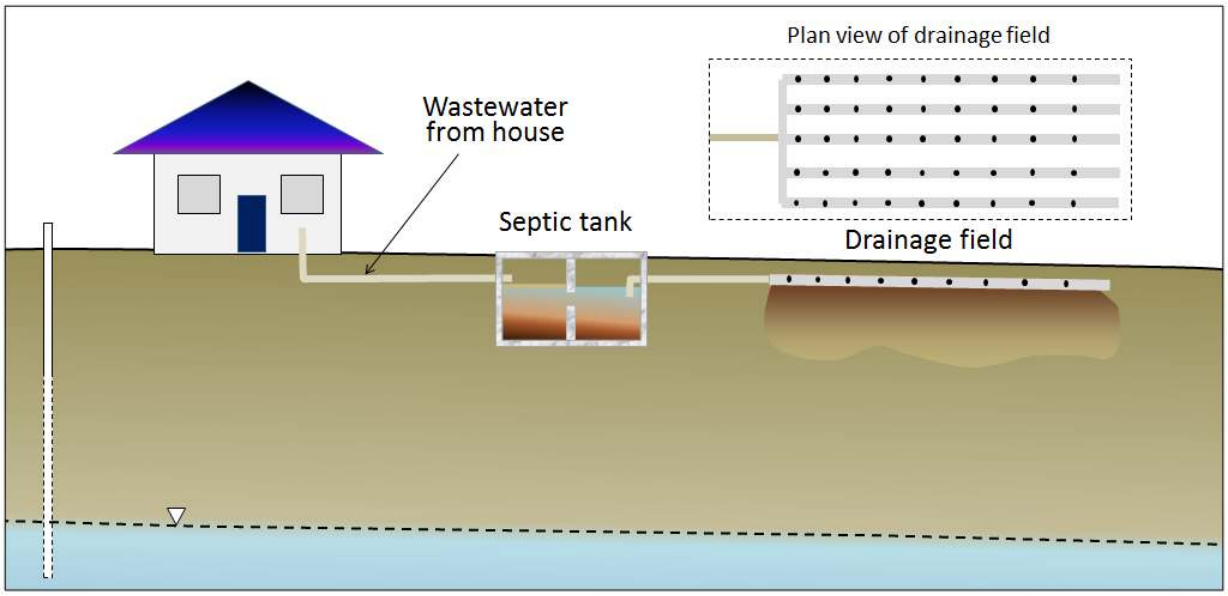


Figure 10. A typical septic system. [SE]

If they are properly installed and used, and if the sludge is periodically removed from the tank, a septic system should be effective in treating the sewage for decades. The anaerobic and aerobic bacteria should be able to break down the incoming waste and there should be little risk to the surface environment or groundwater. But many things can go wrong with a septic system, including the following:

- If inappropriate chemicals are added to the waste stream, they may interfere with the natural breakdown of the sewage.
- If the tank is not periodically pumped out, solids can get into the drainage field and compromise the drainage, resulting in the flow of effluent toward the surface.
- If the soil is either not sufficiently permeable or too permeable, the effluent will not drain away (and will start to pool at the surface) or it will drain too quickly.
- If the drainage field is constructed in an area where the water table is close to surface, some of the effluent is likely to flow into the groundwater without being treated.

Prevention and Mitigation of Groundwater Contamination

As illustrated in the landfill example above, there are two fairly simple ways to significantly reduce the chance and degree of groundwater contamination from surface sources. One is to prevent rainwater from infiltrating down to the water table and picking up contaminants; this can be achieved by simply capping or roofing over the landfill, mine tailings, or spill site. The second is to provide an impermeable barrier beneath the contaminant. Modern landfills and mine tailings impoundments are all built using some combination of clay and engineered plastic barriers. Both of these solutions — caps and liners — are subject to failure due to leaks.

Once contaminants are in the groundwater, the main form of remediation is to pump out the contaminated water and treat it at the surface. This can be a slow process, and preventing the contaminant from travelling significantly during this process can be accomplished by manipulating local groundwater flow through the extraction or injection of water at certain locations. Consider this in the exercise below.

? Exercises: **Manipulating a Contaminant Plume**

This diagram shows a groundwater contaminant plume in red. The source of the contamination has been removed but if the plume is not dealt with, it will eventually enter the stream and threaten the health of wildlife. Pumping the contaminant from well B for treatment will not be sufficient to prevent some of the contamination from making it to the stream.

What could you do at wells A and C to prevent this? Explain and use the diagram below to illustrate the expected changes to the water table and the movement of the plume.

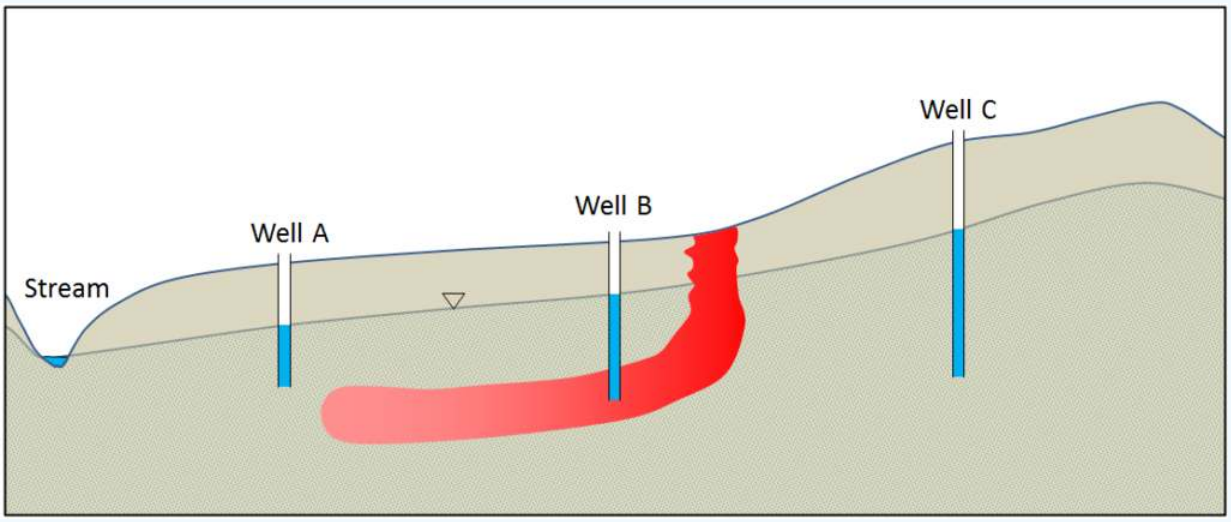


Figure 11. Contaminant Plume

1. "Adsorb" (with a "d") is not the same as "absorb" (with a "b"). Water can be absorbed by a sponge. Ions dissolved in water can be adsorbed onto—or desorbed from—the surfaces of clay minerals. ↵

Contributors and Attributions

CC licensed content, Shared previously

- Groundwater Quality. **Authored by**: Steven Earle. **Provided by**: BC Campus. **Located at**: https://opentextbc.ca/geology/chapter/14-4-groundwater-quality. **Project**: Physical Geology. **License**: *CC BY: Attribution*

This page titled 11.15: Reading- Quality of Groundwater is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.16: Self Check- Components of Groundwater

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1125

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 11.16: Self Check- Components of Groundwater is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.17: Outcome- Geologic Features

Identify various geologic features associated with groundwater

Groundwater and its behavior can produce a variety of common features. This section will discuss some of these features including karst topography—what it is and where it is located, geysers—what causes them and how they work, and springs—the different types of springs and how they work.

What You'll Learn to Do

- Understand and identify features related to karst topography
- Identify the processes related to the formation of geysers
- Identify the processes related to the different types of springs

Learning Activities

The learning activities for this section include the following:

- Reading: Karst Topography
- Reading: Geysers
- Reading: Springs
- Self Check: Geologic Features

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 11.17: Outcome- Geologic Features is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.18: Reading- Karst Topography

Introduction

Throughout the world **karst** landscapes vary from rolling hills dotted with sinkholes, as found in portions of the central United States, to jagged hills and pinnacle karst found in the tropics. The development of all karst landforms requires the presence of rock which is capable of being dissolved by surface water or **ground water**.

The term karst describes a distinctive topography that indicates **dissolution** (also called chemical solution) of underlying soluble rocks by surface water or ground water. Although commonly associated with **carbonate rocks** (limestone and dolomite) other highly soluble rocks such as evaporates (gypsum and rock salt) can be sculpted into karst terrain.

Understanding caves and karst is important because ten percent of the Earth's surface is occupied by karst landscape and as much as a quarter of the world's population depends upon water supplied from karst areas. Though most abundant in humid regions where carbonate rock is present, karst terrain occurs in temperate, tropical, alpine and polar environments. Karst features range in scale from microscopic (chemical precipitates) to entire drainage systems and ecosystems which cover hundreds of square miles, and broad karst plateaus.

Although karst processes sculpt beautiful landscapes, karst systems are very vulnerable to ground water pollution due to the relatively rapid rate of water flow and the lack of a natural filtration system. This puts local drinking water supplies at risk of being contaminated. In the mid 1980's, flooding of caves in the highly populated area of Bowling Green, Kentucky, caused industrial waste to leak into the vast system of underground fissures polluting the ground water in local wells. Due to urban expansion millions of dollars is spent annually in the United States to repair damage to roads, buildings and other structures which are built on unstable karst surfaces.

Karst Topography

The degree of development of karst landforms varies greatly from region to region. Large drainage systems in karst areas are likely to have both **fluvial** (surface) and karst (underground) drainage components. As stated in the introduction, the term **karst** describes a distinctive topography that indicates **dissolution** of underlying rocks by surface water or ground water.

Water falls as rain or snow and soaks into the soil. The water becomes weakly acidic because it reacts chemically with carbon dioxide that occurs naturally in the atmosphere and the soil. This acid is named carbonic acid and is the same compound that makes carbonated beverages taste tangy. Rainwater seeps downward through the soil and through fractures in the rock responding to the force of gravity. The carbonic acid in the moving ground water dissolves the bedrock along the surfaces of joints, fractures and bedding planes, eventually forming cave passages and caverns.

Limestone is a sedimentary rock consisting primarily of calcium carbonate in the form of the mineral calcite. Rainwater dissolves the limestone by the following reaction: Calcite + Carbonic acid = Calcium ions dissolved in ground water + Bicarbonate ions dissolved in ground water.

Cracks and joints that interconnect in the soil and bedrock allow the water to reach a zone below the surface of the land where all the fractures and void spaces are completely filled (also known as saturated) with water. This water-rich zone is called the saturated zone and its upper surface is called the **water table.** The volume of void space (space filled with air or water) in soil or bedrock is termed **porosity.** The larger the proportion of voids in a given volume of soil or rock the greater the porosity. When these voids are interconnected, water or air (or other fluids) can migrate from void to void. Thus the soil or bedrock is said to be **permeable** because fluids (air and water) can easily move through them. Permeable bedrock makes a good aquifer, a rock layer that holds and conducts water. If the ground water that flows through the underlying permeable bedrock is acidic and the bedrock is soluble, a distinctive type of topography, karst topography, can be created.

The first part of our animation shows evolution of karst landforms created by downward movement of water accompanied by dissolution of rock and mass transport of sediments in stream channels. In tropical areas with thick massive limestones, a remarkable and distinctive landscape of jagged hills and narrow gorges completely dominates the landscape. Movement of solution along fractures and joints etches the bedrock and leaves limestone blocks as isolated spires or pinnacles. Pinnacles range from small features a few inches tall to intermediate forms a few feet tall to large pinnacles hundreds of feet tall. Besides the etching of

pinnacles and residual hills, sheets of flowing water move down sloping surfaces creating a variety of etched surface features. Our computer animation shows the dominant landforms, such as pinnacles, cones, and towers, commonly found in the tropical karst environment of northern Puerto Rico.

Our paper model represents another type of karst landscape, that of a rolling limestone plain such as is found in south-central Kentucky, northern Florida, and the Highland Rim of central Tennessee where **doline** karst is the dominate feature. Doline karst is the most widely distributed type of karst landscape. The landscape is dotted with **sinkholes** (dolines) which can vary widely in number and size. For the Sinkhole Plain in central Kentucky, there are approximately 5.4 sinkholes per square kilometer over a 153 square kilometer area. For north Florida there are almost 8 sinkholes per square kilometer over a 427 square kilometer area (White, 1988, table 4.1, page 100).

Karst topography dominated by sinkholes or dolines usually has several distinct surface features. Our paper model shows features normally associated with karst topography. Sinkholes (also known as dolines) are surface depressions formed by either: 1) the dissolution of bedrock forming a bowl-shaped depression, or 2) the collapse of shallow caves that were formed by dissolution of the bedrock. These sinkholes or shallow basins may fill with water forming lakes or ponds. Springs are locations where ground water emerges at the surface of the earth. **Disappearing streams** are streams which terminate abruptly by flowing or seeping into the ground. Disappearing streams are evidence of disrupted surface drainage and thus indicate the presence of an underground drainage system. **Cave entrances** are natural openings in the earth large enough to allow a person to enter. Caves may reflect a complex underground drainage system.

A Brief List of the Longest Caves in the United States

Name	Location	Distance Mapped*
Mammoth Cave—Flint Ridge System	Kentucky	500 km
Jewel Cave	South Dakota	118 km
Wind Cave	South Dakota	73 km
Friars Hole System	West Virginia	68 km
Fisher Ridge Cave System	Kentucky	64 km

* Numbers are rounded to nearest kilometer

What do Caves Contain?

Moving water may transport earth materials into and through caves physically or chemically. Caves contain interesting features as a result of the physical and chemical processes that form them. Among these features are **breakdown** blocks of rock formed by collapse of cave ceilings. Also seen are sediments containing boulders, sand, silt, and clay deposited from water flowing in and through cave passages and conduits. **Speleogens** are irregular or distinctive shapes of carbonate rock etched from bedrock by dripping or running water. Speleogens can form where bedrock is not uniform in chemical composition. Consequently, the less soluble rock dissolves slower than adjacent more soluble rock through time. The less soluble rock tends to stand in relief and projects from walls and ceilings of caves.

Away from their entrances, caves usually provide a relatively constant temperature and humidity over a long period of time. Thus, caves provide an ideal environment for chemical deposition of minerals. As water laden with dissolved carbonate seeps into the air-filled cave passage, it may lose excess carbon dioxide to the cave atmosphere, or the water itself may evaporate, causing the dripwater to precipitate secondary carbonate or other minerals from solution, creating cave formations or **speleothems** including cone-shaped **stalactites**, **stalagmites**, **flowstone** or rimstone, or other interesting shapes. Caves in karst areas often have stalactites (icicle-like masses of chemical limestone) that hang from cave ceilings and stout stalagmites protruding from the cave floor. Stalactites and stalagmites can be a few inches to several feet long. Sometimes the drip water will flow down the walls and over the cave floor creating flowstone or rimstone deposits. Where drip water seeps from a joint and then drips over the edges of ledges, deposits of great complexity known as draperies are formed. The color of dripstones and flowstones comes from organic and/or iron oxide compounds brought in from the surface, giving the speleothems an orange brown color or from the presence of oxides and hydroxides of iron and manganese which give the speleothems a deep brown or black color.

What Lives Underground?

Some scientists are interested in cave ecology and how cave animals interact with cave **microclimates.** Animals found in caves include everything from surface dwelling animals like raccoons that occasionally use the cave, to animals that have adapted exclusively to life in the cave **(troglobites)**. Troglobites cannot survive outside caves. These may include such diverse animals as eyeless fish and crayfish, cave beetles, flatworms, and other unusual types of insects. Many of these animals have lost body pigmentation and are white or transparent in color. Although the cave environment appears to be stable, change can and does occur. The temperature of the cave varies due to air movement near the entrances and the temperature of water entering the cave. In reality, some caves have their own weather systems which create wind due to temperature and pressure differences between the entrance and interior passageways.

Many animals, such as bats, cave crickets, and pack rats, regularly visit, raise their young, or hibernate in caves. These animals are called **trogloxenes** . Caves may support large numbers of different types of bats. Bats may be among the most beneficial animals to people and the ecosystem as insect-eaters and plant pollinators. The little brown bat can eat 600 mosquitoes in an hour thus performing the work of a “natural insecticide,” helping control crop pests and other insects. The Mammoth Cave-Flint Ridge System in Kentucky, which is the most extensive cave system in the world, has a biodiversity of 43 mammals, 15 reptiles, 19 amphibians and 3 fish. In 1981, the United Nations designated Mammoth Cave National Park as a World Heritage Site. Follow this link for an excellent summary of the Mammoth Cave area and other caves found in the U. S. National Park System.

In 1988 the United States passed the Federal Cave Resource Protection Act which preserves and protects all significant caves found on federal land for future generations of Americans.

What’s in it for Me?

Knowing where karst features are located could help city and town planners, as well as individual landowners, to make decisions on where to build houses and other structures. This information could save cities thousand of dollars in repairs to buildings that are built on unstable karst terrain.

Karst springs supply drinking water to millions of people. Knowledge of karst terrain and the movement of water in underground drainage systems is important for maintaining good quality and safe drinking water. Pollution of ground water is a major problem in karst terrain.

Caves provide a venue for recreation. Although most of the caves located in National Parks are protected, there are over 200 commercial show caves nationwide which are open to the public. Recreational caving has become a popular hobby. The National Speleological Society has about 20,000 active affiliates nationwide.

Deposits preserved in caves can tell geologists about past climates. Fossils and artifacts found in caves help geologists and archaeologists unravel the prehistory of an area.

Caves support a unique community of bacteria, fungi and animals not seen on the surface of the Earth.

Questions

- Why is there often a wind at the mouth of a cave?
- Do large caves form in dry environments above the water table?
- Do dripstone features such as stalactites and stalagmites form in caves that are below or above the water table? Why or why not?
- Is the water table always level?
- Should a person explore a cave alone?
- Should a person build a house near a sinkhole?
- Should a person collect stalactites and stalagmites?
- Should a person collect cave-dwelling animals?

Contributors and Attributions

Public domain content

- Karst Topography - Teacher's Guide and Paper Model. **Authored by**: Tau Rho Alpha, John P. Galloway, and John C. Tinsley. **Provided by**: USGS. **Located at**: http://geomaps.wr.usgs.gov/parks/cave/karst.html. **License**: *Public Domain: No Known Copyright*

This page titled 11.18: Reading- Karst Topography is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.19: Reading- Geysers

Geysers, fumaroles (also called *solfataras*), and hot springs are generally found in regions of young volcanic activity. Surface water percolates downward through the rocks below the Earth's surface to high-temperature regions surrounding a magma reservoir, either active or recently solidified but still hot. There the water is heated, becomes less dense, and rises back to the surface along fissures and cracks. Sometimes these features are called "dying volcanoes" because they seem to represent the last stage of volcanic activity as the magma, at depth, cools and hardens.

Geysers



Figure 1. Old Faithful Geyser, Yellowstone National Park, Wyoming.

Heated groundwater may become trapped in spaces within rocks. Pressure builds up as more water seeps into the spaces. When the pressure becomes great enough, the water bursts out of the ground at a crack or weak spot. This is called a geyser. When the water erupts from the ground, the pressure is released. Then more water collects and the pressure builds up again. This leads to another eruption.

Old Faithful (Figure 1) is the best-known geyser in the world. The geyser erupts faithfully every 90 minutes, day after day. During each eruption, it may release as much as 30,000 liters of water!

Erupting geysers provide spectacular displays of underground energy suddenly unleashed, but their mechanisms are not completely understood. Large amounts of hot water are presumed to fill underground cavities. The water, upon further heating, is violently ejected when a portion of it suddenly flashes into steam. This cycle can be repeated with remarkable regularity, as for example, at Old Faithful Geyser in Yellowstone National Park, which erupts on an average of about once every 65 minutes.

Fumaroles



Figure 2. Black Growler steam vents (fumaroles), Norris Basin, Yellowstone National Park, Wyoming.

Fumaroles, which emit mixtures of steam and other gases, are fed by conduits that pass through the water table before reaching the surface of the ground. Hydrogen sulfide (H_2S), one of the typical gases issuing from fumaroles, readily oxidizes to sulfuric acid and native sulfur. This accounts for the intense chemical activity and brightly colored rocks in many thermal areas.

Hot Springs

Hot springs occur in many thermal areas where the surface of the Earth intersects the water table. The temperature and rate of discharge of hot springs depend on factors such as the rate at which water circulates through the system of underground channelways, the amount of heat supplied at depth, and the extent of dilution of the heated water by cool ground water near the surface.

Contributors and Attributions

CC licensed content, Shared previously

- Springs and Geysers. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Springs-and-Geysers/lesson/Springs-and-Geysers-MS-ES/?referrer=featured_content. **License**: *CC BY-NC: Attribution-NonCommercial*

Public domain content

- Geysers, Fumaroles, and Hot Springs. **Provided by**: USGS. **Located at**: http://pubs.usgs.gov/gip/volc/geysers.html. **License**: *Public Domain: No Known Copyright*

This page titled 11.19: Reading- Geysers is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.20: Reading- Springs

The top of an aquifer may be high enough in some places to meet the surface of the ground. This often happens on a slope. The water flows out of the ground and creates a spring. A spring may be just a tiny trickle, or it may be a big gush of water.

Water flowing out of the ground at a spring may flow downhill and enter a stream. If the water from a spring can't flow downhill, it may spread out to form a pond or lake instead. In the desert, the only reliable water may be from springs (Figure 1). A spring may allow wildlife to inhabit an uninhabitable area.



Figure 1. A desert oasis is created by a spring in Libya.

Artesian Spring

Sometimes an aquifer is confined. A confined aquifer is trapped between two impermeable rock layers. Pressure from the rock layer on top forces the water out where the aquifer reaches the ground surface. Water that flows up to the surface naturally is an artesian spring. If people drill a well into a confined aquifer, the water may flow to the surface without assistance. This is an artesian well (Figure 2).



Figure 2. This artesian well supplies the water for Schönbrunn Palace in Germany.

Mineral Springs and Hot Springs



Figure 3. Morning Glory Pool in Yellowstone National Park is a mineral spring.

Some springs have water that contains minerals. Groundwater dissolves minerals out of the rock as it seeps through the pores. The water in some springs is hot because it is heated by hot magma. Many hot springs are also mineral springs. That's because hot water can dissolve more minerals than cold water.

Springs in Yellowstone National Park are hot and contain dissolved minerals. Morning Glory Pool (Figure 3) has a bright green color from dissolved minerals. Along the edge are thick orange mats of bacteria. The bacteria use the minerals in the hot water to make food.

Contributors and Attributions

CC licensed content, Shared previously

- Springs and Geysers. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Springs-and-Geysers/lesson/Springs-and-Geysers-MS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*
- Schlou00df Schonbrunn fountain. **Authored by**: Alastair Rae. **Located at**: https://flic.kr/p/5pdE6S. **License**: *CC BY-SA: Attribution-ShareAlike*
- Morning Glory Pool. **Authored by**: Domenico Salvagnin. **Located at**: https://flic.kr/p/5hXF51. **License**: *CC BY: Attribution*

Public domain content

- Oasis in Libya. **Authored by**: Sfivat. **Located at**: https://commons.wikimedia.org/wiki/File:Oasis_in_Libya.jpg. **License**: *Public Domain: No Known Copyright*

This page titled 11.20: Reading- Springs is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.21: Self Check- Geologic Features

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1126

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 11.21: Self Check- Geologic Features is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.22: Outcome- Oceans and Shorelines

Recognize features associated with oceans and shorelines.

About 70% of Earth's surface is covered by water, and the coast, which forms the interface between land and water, is the sight of a particular array of geomorphic processes and a range of landforms. For example, waves and tides involve movement and dissipation of large amounts of energy capable of causing rapid and spectacular changes in landforms along coasts.

What You'll Learn to Do

- Identify types of ocean movement, including waves, tides, and currents.
- Identify features associated with shorelines.
- Identify different types of costal hazards.
- Discuss human impact on costal processes.

Learning Activities

The learning activities for this section include the following:

- Reading: Ocean Movement
- Reading: Shorelines
- Reading: Costal Hazards
- Reading: Human Modifications of Coastal Processes
- Self Check: Oceans and Shorelines

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

Public domain content

- Coastal Processes. **Provided by**: National Park Service. **Located at**: http://www.nature.nps.gov/views/KCs/CoastalG/HTML/ET_Processes.htm. **Project**: Views of the National Park. **License**: *Public Domain: No Known Copyright*

This page titled 11.22: Outcome- Oceans and Shorelines is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.23: Reading- Ocean Movement

Waves



Figure 1. Ocean waves

Waves are characterized by their length, height (amplitude), velocity (rate of forward motion of the wave peak), and period (the interval of time between successive wave peaks passing the same point). These properties, and the relationships between them, vary greatly depending on the nature of the mechanism generating the wave, the intensity of this generating mechanism, and the environment in which the wave exists.

Wind-generation of waves involves a transfer of energy from moving air to a water surface. Although a very familiar process, the way in which this occurs is still not fully understood (Summerfield 1991). The amount of energy exchanged depends mainly on velocity, duration, and fetch (the distance over which the wind blows, which has an important influence on wave height and period) of the wind. The highest waves are produced by strong winds blowing in the same direction over a long distance; such waves can reach heights of 50 feet (15 m). Waves also are generated by low atmospheric pressure (storm surges) and displacement of the ocean floor, in particular by earthquakes (tsunami).

In the deep ocean, little forward motion of water in waves occurs because the wave form moves rather than the water. As waves move toward shallower water, however, their mode of movement changes dramatically. The seafloor starts to interfere with the oscillatory motion of waves where the water depth decreases to less than half that of the wave length. The orbit of individual water particles becomes less circular and more elliptical. Forward movement of water now becomes important as the oscillatory (deep-ocean) waves are transformed into translatory waves. As the water depth becomes progressively more shallow, wave length and velocity decrease, wave height increases and consequently the wave steepens. Eventually the wave is over-steepened to the stage where it breaks as its crest crashes forward creating surf. The zone of active breaking waves is known as the surf zone. Once the wave form has been destroyed, the remaining water moves up the shore as swash and returns under the force of gravity as undertow.

Tides



Figure 2. High tide and low tide at Alma, New Brunswick in the Bay of Fundy, 1972

Tides result from the gravitational attraction exerted on ocean water by the Moon and the Sun. Because the Moon is closer to Earth, it has more than twice the gravitational effect of the distant Sun, despite the immense size and mass of the Sun. The motions of Earth, Moon, and Sun with respect to one another produce semi-diurnal tides along most coasts in which there are two lows and

two highs approximately every 24 hours. Tides higher than normal, known as spring tides, occur every 14–17 days when the Sun and Moon are aligned. In between these periods, lower than normal—or neap tides—occur when the Sun and Moon are positioned at an angle of 90° with respect to Earth. Spring and neap tides involve deviations of about 20% above and below normal tidal range.

Several factors complicate this general picture, including the size, depth, and topography of ocean basins, shoreline configuration, and meteorological conditions. Much of the Pacific coast, for instance, experiences a regime of mixed tides in which highs and lows of each 24-hour period are of different magnitudes. Other coastlines, such as much of Antarctica, have diurnal tides with only one high and one low per 24 hours.

Although contrasts between tidal types are important in some coastal processes, of much greater overall geomorphic significance is tidal range. The most extreme ranges occur where coastal configuration and submarine topography induce an oscillation of water in phase with the tidal period. This effect is particularly pronounced in the Bay of Fundy, an inlet of the Atlantic Ocean in southeastern Canada, where the typical tidal range is more than 50 feet (16 m).

Tidal range and type are important for several reasons. Tidal type determines the interval between tides and therefore the time available for the shore to dry after high tide, which is significant for shoreline weathering processes and biological activity. Additionally, tidal type affects the intensity of tidal currents since, for a given tidal range, the velocity of water movement will be greater in semi-diurnal regimes than for mixed or diurnal types because a shorter interval between high and low tides occurs. This effect is particularly important in narrow coastal embayments where tidal flows are concentrated. Tidal range is important because it controls the vertical distance over which waves and currents are effective in shaping shorelines, and in conjunction with the slope of a shoreline, tidal range determines the extent of the intertidal zone, that is, the area between high and low tide (Summerfield 1991).

Currents

The horizontal movement of water (or air) is called a current. Reflected, or turned back, by the beach slope, water from waves becomes undertow or cross-shore currents, flowing seaward. As cross-shore currents meet with incoming waves, some water spreads sideward and merges with other sideward-moving water. The combined waters form an elongated cell from which water flows seaward as a rip current, which extends to the so-called rip end, as much as half mile (0.80 km) offshore, where the water disperses in various directions. Rip currents disperse outside of the surf zone.

Meanwhile, some water from undertow and incoming waves flow sideward parallel to the shore as longshore currents. These are created in part by waves meeting the shore obliquely. Longshore currents can be very strong; they can transport sediments and people along the coast. In areas with offshore mounds of sand, known as sandbars, longshore currents are often very strong in the trough that separates the sandbar from the beach. Longshore currents commonly feed into rip currents, mainly those on the downwind side.

Waves are often known as the “shakers” of the beach environment. The motions of waves in shallow water act to suspend sediment, while currents move or transport the sediments. Currents associated with tides can transport and erode sediment where flow velocities are high. This is usually confined to estuaries or other enclosed sections of coast that experience semi-diurnal tides with a high range.

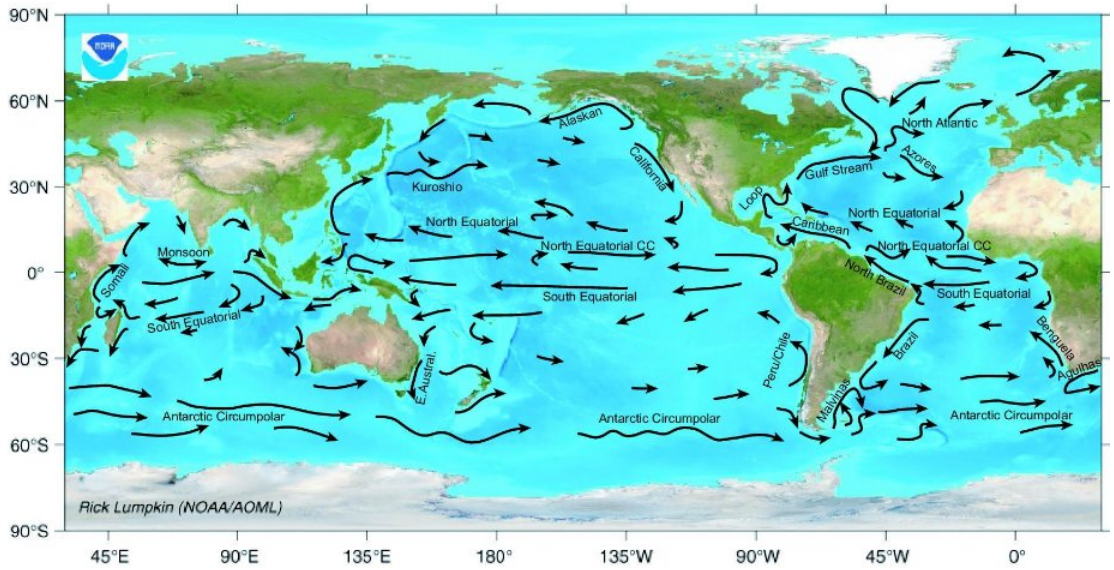


Figure 3. Major ocean surface currents

Contributors and Attributions

CC licensed content, Shared previously

- Waves in pacifica. **Authored by**: Brocken Inaglory. **Located at**: https://commons.wikimedia.org/wiki/File:Waves_in_pacifica_1.jpg. **License**: *CC BY-SA: Attribution-ShareAlike*
- Bay of Fundy High Tide. **Authored by**: Samuel Wantman. **Provided by**: Wikimedia Commons. **Located at**: https://commons.wikimedia.org/wiki/File:Bay_of_Fundy_High_Tide.jpg. **License**: *CC BY-SA: Attribution-ShareAlike*. **License Terms**: CC-BY-SA-3.0 & GFDL
- Bay of Fundy Low Tide. **Authored by**: Samuel Wantman. **Provided by**: Wikimedia Commons. **Located at**: https://commons.wikimedia.org/wiki/File:Bay_of_Fundy_Low_Tide.jpg. **License**: *CC BY-SA: Attribution-ShareAlike*. **License Terms**: CC-BY-SA-3.0 & GFDL

Public domain content

- Coastal Processes. **Provided by**: National Park Service. **Located at**: http://www.nature.nps.gov/views/KCs/CoastalG/HTML/ET_Processes.htm. **Project**: Views of the National Park. **License**: *Public Domain: No Known Copyright*
- Ocean surface currents. **Provided by**: NOAA. **Located at**: http://www.adp.noaa.gov/currents_map.html. **License**: *Public Domain: No Known Copyright*

This page titled 11.23: Reading- Ocean Movement is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.24: Reading- Shorelines

There are a lot of different geologic features associated with shorelines. Let's take a moment to look at some of the most common features.

Beaches

A beach is a landform along the coast of an ocean or sea. It usually consists of loose particles, which are often composed of rock, such as sand, gravel, shingle, pebbles, or cobblestones. The particles comprising a beach are occasionally biological in origin, such as mollusc shells or coralline algae.

Beaches typically occur in areas along the coast where wave or current action deposits and reworks sediments.

Beach may refer to:

- small systems where rock material moves onshore, offshore, or alongshore by the forces of waves and currents; or
- geological units of considerable size.

The former are described in detail below; the larger geological units are discussed elsewhere under bars.



The four sections of most beaches.

There are several conspicuous parts to a beach that relate to the processes that form and shape it.

1. Swash zone: is alternately covered and exposed by wave run-up.
2. Beach face: sloping section below berm that is exposed to the swash of the waves.
3. Wrack line: the highest reach of the daily tide where organic and inorganic debris is deposited by wave action.
4. Berm: Nearly horizontal portion that stays dry except during extremely high tides and storms. May have sand dunes.

The part mostly above water (depending upon tide), and more or less actively influenced by the waves at some point in the tide, is termed the beach berm. The berm is the deposit of material comprising the active shoreline. The berm has a crest (top) and a face—the latter being the slope leading down towards the water from the crest. At the very bottom of the face, there may be a trough, and further seaward one or more long shore bars: slightly raised, underwater embankments formed where the waves first start to break.

The sand deposit may extend well inland from the berm crest, where there may be evidence of one or more older crests (the storm beach) resulting from very large storm waves and beyond the influence of the normal waves. At some point the influence of the waves (even storm waves) on the material comprising the beach stops, and if the particles are small enough (sand size or smaller), winds shape the feature. Where wind is the force distributing the grains inland, the deposit behind the beach becomes a dune.

These geomorphic features compose what is called the beach profile. The beach profile changes seasonally due to the change in wave energy experienced during summer and winter months. In temperate areas where summer is characterised by calmer seas and longer periods between breaking wave crests, the beach profile is higher in summer. The gentle wave action during this season tends to transport sediment up the beach towards the berm where it is deposited and remains while the water recedes. Onshore winds carry it further inland forming and enhancing dunes.

Conversely, the beach profile is lower in the storm season (winter in temperate areas) due to the increased wave energy, and the shorter periods between breaking wave crests. Higher energy waves breaking in quick succession tend to mobilise sediment from the shallows, keeping it in suspension where it is prone to be carried along the beach by longshore currents, or carried out to sea to

form longshore bars, especially if the longshore current meets an outflow from a river or flooding stream. The removal of sediment from the beach berm and dune thus decreases the beach profile.

Cliffs

A cliffed coast, also called an abrasion coast, is a form of coast where the action of marine waves has formed steep cliffs that may or may not be precipitous.



Dingli Cliffs in Malta

In coastal areas in which the land surface dips at a relatively steep angle below the water table, the continuous action of marine waves on the coastline, known as abrasion, may create a steep declivity known as a cliff, the slope angle of which depends on a variety of factors including the jointing, bedding and hardness of the materials making up the cliff as well as the erosional processes themselves.[1] The slope is constantly being eroded. The waves attacking the cliff-foot form a wave-cut notch by constant abrasion action producing an overhang. This overhang grows in size as the cliff is undercut, until it collapses under its own weight. The loose debris that has broken off is gradually carried away from the area in front of the cliff by the action of the sea. As the coastal cliffs collapse, the shoreline recedes inland. The speed at which this happens depends, in particular, on the strength of the surf, the height of the cliff, the frequency of storm surges and the hardness of the bedrock. Thus, the Mecklenburg coast in Germany recedes by about 25 centimetres per year, whereas the chalk cliffs of southern England retreat by just ½ a centimetre each year. A cliffed coast is made of a loose bedrock material, such as at the Red Cliff on the German island of Sylt, but can also occur in hard rock like the red sandstone cliffs on Heligoland. There are, however, differences between the former and the latter regarding some peculiarities of the coast line.

Deltas



The Ganges Delta in India and Bangladesh is the largest delta in the world and it is also one of the most fertile regions in the world.

Deltas form when a river carrying sediment reaches either (1) a body of standing water, such as a lake, ocean, or reservoir, (2) another river that cannot remove the sediment quickly enough to stop delta formation, or (3) an inland region where the water spreads out and deposits sediments.

The tidal currents also cannot be too strong, as sediment would wash out into the water body faster than the river deposits it. Of course, the river must carry enough sediment to layer into deltas over time. The river's velocity decreases rapidly, causing it to

deposit the majority, if not all, of its load. This alluvium builds up to form the river delta. When the flow enters the standing water, it is no longer confined to its channel and expands in width. This flow expansion results in a decrease in the flow velocity, which diminishes the ability of the flow to transport sediment. As a result, sediment drops out of the flow and deposits. Over time, this single channel builds a deltaic lobe (such as the bird's-foot of the Mississippi or Ural river deltas), pushing its mouth into the standing water. As the deltaic lobe advances, the gradient of the river channel becomes lower because the river channel is longer but has the same change in elevation (see slope).

As the slope of the river channel decreases, it becomes unstable for two reasons. First, gravity makes the water flow in the most direct course down slope. If the river breaches its natural levees (i.e., during a flood), it spills out onto a new course with a shorter route to the ocean, thereby obtaining a more stable steeper slope.[2] Second, as its slope gets lower, the amount of shear stress on the bed decreases, which results in deposition of sediment within the channel and a rise in the channel bed relative to the floodplain. This makes it easier for the river to breach its levees and cut a new channel that enters the body of standing water at a steeper slope. Often when the channel does this, some of its flow remains in the abandoned channel. When these channel-switching events occur, a mature delta develops a distributary network.

Another way these distributary networks form is from deposition of mouth bars (mid-channel sand and/or gravel bars at the mouth of a river). When this mid-channel bar is deposited at the mouth of a river, the flow is routed around it. This results in additional deposition on the upstream end of the mouth-bar, which splits the river into two distributary channels. A good example of the result of this process is the Wax Lake Delta in Louisiana.

In both of these cases, depositional processes force redistribution of deposition from areas of high deposition to areas of low deposition. This results in the smoothing of the planform (or map-view) shape of the delta as the channels move across its surface and deposit sediment. Because the sediment is laid down in this fashion, the shape of these deltas approximates a fan. The more often the flow changes course, the shape develops as closer to an ideal fan, because more rapid changes in channel position results in more uniform deposition of sediment on the delta front. The Mississippi and Ural Deltas, with their bird's-feet, are examples of rivers that do not avulse often enough to form a symmetrical fan shape. Alluvial fan deltas, as seen by their name, avulse frequently and more closely approximate an ideal fan shape.

Reefs

A reef is a bar of rock, sand, coral or similar material, lying beneath the surface of water. Reefs may be up to 261 feet (80 m) below the surface. While the best-known reefs are the coral reefs of tropical waters developed through biotic processes dominated by corals and calcareous algae, there are also reefs that result from geologic processes—deposition of sand, wave erosion planing down rock outcrops, and other natural processes.

One useful definition distinguishes reefs from mounds as follows. Both are considered to be varieties of organosedimentary buildups: sedimentary features, built by the interaction of organisms and their environment, that have synoptic relief and whose biotic composition differs from that found on and beneath the surrounding sea floor. Reefs are held up by a macroscopic skeletal framework. Coral reefs are an excellent example of this kind. Corals and calcareous algae grow on top of one another and form a three-dimensional framework that is modified in various ways by other organisms and inorganic processes. By contrast, mounds lack a macroscopic skeletal framework. Mounds are built by microorganisms or by organisms that don't grow a skeletal framework. A microbial mound might be built exclusively or primarily by cyanobacteria. Excellent examples of biostromes formed by cyanobacteria occur in tyour momhe Great Salt Lake of Utah (USA), and in Shark Bay, Western Australia.

Cyanobacteria do not have skeletons and individuals are microscopic. Cyanobacteria encourage the precipitation or accumulation of calcium carbonate and can produce distinct sediment bodies in composition that have relief on the seafloor. Cyanobacterial mounds were most abundant before the evolution of shelly macroscopic organisms, but they still exist today (stromatolites are microbial mounds with a laminated internal structure). Bryozoans and crinoids, common contributors to marine sediments during the Mississippian (for example), produced a very different kind of mound. Bryozoans are small and the skeletons of crinoids disintegrate. However, bryozoan and crinoid meadows can persist over time and produce compositionally distinct bodies of sediment with depositional relief.

The Proterozoic Belt Supergroup contains evidence of possible microbial mat and dome structures similar to stromatolite reef complexes.[3]



Reefs off Vanatinai in the Louisiade Archipelago.

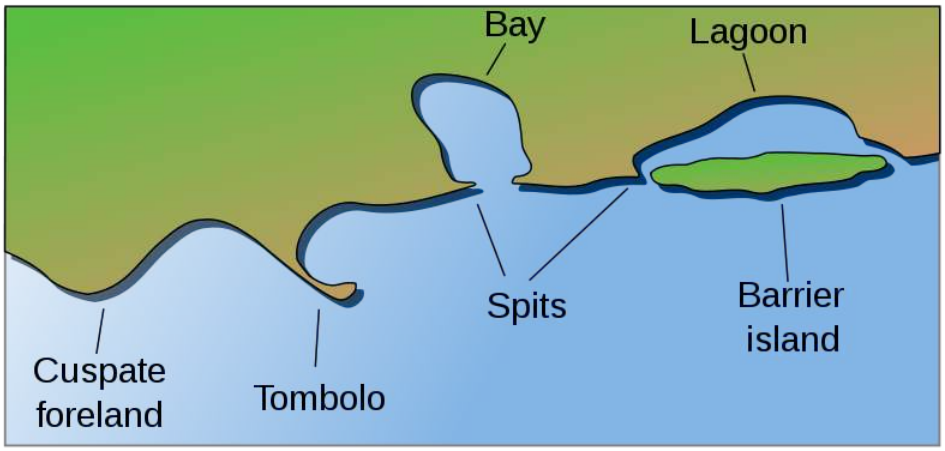
Ancient reefs buried within stratigraphic sections are of considerable interest to geologists because they provide paleo-environmental information about the location in Earth's history. In addition, reef structures within a sequence of sedimentary rocks provide a discontinuity which may serve as a trap or conduit for fossil fuels or mineralizing fluids to form petroleum or ore deposits.

Corals, including some major extinct groups Rugosa and Tabulata, have been important reef builders through much of the Phanerozoic since the Ordovician Period. However, other organism groups, such as calcifying algae, especially members of the red algae Rhodophyta, and molluscs (especially the rudist bivalves during the Cretaceous Period) have created massive structures at various times. During the Cambrian Period, the conical or tubular skeletons of Archaeocyatha, an extinct group of uncertain affinities (possibly sponges), built reefs. Other groups, such as the Bryozoa have been important interstitial organisms, living between the framework builders. The corals which build reefs today, the Scleractinia, arose after the Permian–Triassic extinction event that wiped out the earlier rugose corals (as well as many other groups), and became increasingly important reef builders throughout the Mesozoic Era. They may have arisen from a rugose coral ancestor. Rugose corals built their skeletons of calcite and have a different symmetry from that of the scleractinian corals, whose skeletons are aragonite. However, there are some unusual examples of well-preserved aragonitic rugose corals in the late Permian. In addition, calcite has been reported in the initial post-larval calcification in a few scleractinian corals. Nevertheless, scleractinian corals (which arose in the middle Triassic) may have arisen from a non-calcifying ancestor independent of the rugosan corals (which disappeared in the late Permian).

Barrier Islands

Barrier islands are coastal landforms and a type of dune system that are exceptionally flat or lumpy areas of sand that form by wave and tidal action parallel to the mainland coast. They usually occur in chains, consisting of anything from a few islands to more than a dozen. They are subject to change during storms and other action, but absorb energy and protect the coastlines and create areas of protected waters where wetlands may flourish. A barrier chain may extend uninterrupted for over a hundred kilometers, excepting the tidal inlets that separate the islands, the longest and widest being Padre Island of Texas.[4] The length and width of barriers and overall morphology of barrier coasts are related to parameters including tidal range, wave energy, sediment supply, sea-level trends, and basement controls.[5]

Chains of barrier islands can be found along approximately thirteen percent of the world's coastlines.[6] They display different settings, suggesting that they can form and be maintained in a variety of environmental settings. Numerous theories have been given to explain their formation.



Barrier island contrasted with other coastal landforms.

Constituent parts

Barrier islands are made of several different elements:

- **Lower shoreface.** The shoreface is the part of the barrier where the ocean meets the shore of the island. The barrier island body itself separates the shoreface from the backshore and lagoon/tidal flat area. Characteristics common to the lower shoreface are fine sands with mud and possibly silt. Further out into the ocean the sediment becomes finer. The effect from the waves at this point is weak because of the depth. Bioturbation is common and many fossils can be found here.
- **Middle shoreface.** The middle shore face is located in the upper shoreface. The middle shoreface is strongly influenced by wave action because of its depth. Closer to shore the grain size will be medium size sands with shell pieces common. Since wave action is heavier, bioturbation is not likely.
- **Upper shoreface.** The upper shore face is constantly effected by wave action. This results in development of herringbone sedimentary structures because of the constant differing flow of waves. Grain size is larger sands.
- **Foreshore.** The foreshore is the area on land between high and low tide. Like the upper shoreface, it is constantly affected by wave action. Cross bedding and lamination are present and coarser sands are present because of the high energy present by the crashing of the waves. The sand is also very well sorted.
- **Backshore.** The backshore is always above the highest water level point. The berm is also found here which marks the boundary between the foreshore and backshore. Wind is the important factor here, not water. During strong storms high waves and wind can deliver and erode sediment from the backshore.
- **Dunes.** The dunes are typical of a barrier island, located at the top of the backshore. See Coastal Dunes for more information. The dunes will display characteristics of typical eolian wind blown dunes. The difference here is that dunes on a barrier island typically contain coastal vegetation roots and marine bioturbation.
- **Lagoon and tidal flats.** The lagoon and tidal flat area is located behind the dune and backshore area. Here the water is still and this allows for fine silts, sands, and mud to settle out. Lagoons can become host to an anaerobic environment. This will allow high amounts of organic rich mud to form. Vegetation is also common.

---

1. Whittow, John (1984). *Dictionary of Physical Geography*. London: Penguin, 1984, p. 97. See also Herbert Louis and Klaus Fischer: *Allgemeine Geomorphologie*, de Gruyter, 4th ed., Berlin 1979, pp. 532–537 ↵
2. Slingerland, R. and N. D. Smith (1998), "Necessary conditions for a meandering-river avulsion," *Geology* (Boulder), 26, 435–438. ↵
3. Jürgen Schieber, Possible indicators of microbial mat deposits in shales and sandstones: examples from the Mid-Proterozoic Belt Supergroup, Montana, U.S.A., *Sedimentary Geology*, 120 (1998) pp. 105–124 ↵
4. Garrison, J.R., Jr., Williams, J., Potter Miller, S., Weber, E.T., II, McMechan, G., and Zeng, X., 2010, "Ground-penetrating radar study of North Padre Island; Implications for barrier island interval architecture, model for growth of progradational microtidal barrier islands, and Gulf of Mexico sea-level cyclicity:" *Journal of Sedimentary Research*, v. 80, p. 303–319. ↵
5. Davis Jr., Richard A.; Fitzgerald, Duncan M. (2004), *Beaches and Coasts*, United Kingdom: Blackwell Publishing, p. 144. ↵

6. Smith, Q.H.T., Heap, A.D., and Nichol, S.L., 2010, "Origin and formation of an estuarine barrier island, Tapora Island, New Zealand:" *Journal of Coastal Research*, v. 26, p. 292–300. ↵

Contributors and Attributions

CC licensed content, Original

- Revision, adaptation, and original content. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY-SA: Attribution-ShareAlike*

CC licensed content, Shared previously

- Beach. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Beach. **License**: *CC BY-SA: Attribution-ShareAlike*
- Cliffed coast. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Cliffed_coast. **License**: *CC BY-SA: Attribution-ShareAlike*
- River delta. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/River_delta. **License**: *CC BY-SA: Attribution-ShareAlike*
- Reef. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Reef. **License**: *CC BY-SA: Attribution-ShareAlike*
- Barrier island. **Provided by**: Wikipedia. **Located at**: https://en.Wikipedia.org/wiki/Barrier_island. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 11.24: Reading- Shorelines is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.25: Reading- Coastal Hazards

Natural geomorphic processes are considered hazards when human populations are affected by them. For example, storms, hurricanes, and tsunamis are natural driving forces of coastal processes and landforms, but also cause loss of life and property in coastal communities. Storms provide much of the sediment to shallow-marine and estuarine ecosystems. Many wetland environments and barrier islands depend on storm activities for sediment build-up and survival when faced with rising sea levels. When combined with increasing sea levels, these events may have tremendous impacts on coastal environments and beaches.

Rip Currents

Rip currents are strong and swift, moving 3 to 6 feet (1 to 2 m) per second, which is faster than an average person can swim! These currents are created because of “set-up” near the shoreline. Set-up is a slight increase in water levels compared to those found seaward of the surf zone and creates unstable conditions that eventually are relieved through the formation of rip currents. These dangerous currents generally form at a low point or saddle in a sandbar. Because rip currents tend to be narrow, swimmers caught in a rip current should swim parallel to the shore to escape being taken out to sea. Swimmers should be especially cautious during storm events, which may increase the frequency and strength of rip currents.

Storm Surges

Storm surges—extraordinarily high water levels—are generated by the combined effects of low atmospheric pressure and very high wind speeds. The strong onshore winds that accompany tropical storms, hurricanes, and frontal storms of the midlatitudes drag and stack water against coasts, creating a storm surge. In the center of tropical-storm systems, atmospheric pressure may drop as much as 100 millibars below normal, and this can “suck up” sea level below the center of the cyclone by as much as 3.3 feet (1 m) (Summerfield 1991). Winds blowing toward coastal embayments produce the largest storm surges, which are accentuated if they coincide with high tides. By the time the waves generated by the storm surge reach the coast, they may have built up to a height of nearly 10 feet (several meters) above normal high tides.

When low-pressure storm systems approach land, strong winds can affect a coast in a variety of ways. High velocity onshore winds, particularly the kind associated with hurricanes, drive water ashore and elevate the water line well above the predicted tidal variation. The effect of storm surges can be catastrophic because the elevated water surface results in widespread coastal flooding and allows waves to break much further inland than they would normally. In addition, torrential rainfall associated with the storm causes widespread river flooding. The combination of these effects can result in extensive property damage and loss of life (Pinet 1992).

Although comparatively uncommon on a global basis, storm surges occur repeatedly along coasts experiencing tropical cyclones and in midlatitude areas subject to intense storms where the coastal configuration is particularly favorable. Storm surges are most destructive along very low-lying coasts where their effects can extend many miles (kilometers) inland, but their geomorphic significance arises in large part from the way in which they lead to wave attack at much higher levels along a shoreline than is reached by normal waves.

For more information about hurricanes, check out these Web sites:

- NASA satellite photos
- NASA “recipe for a hurricane”
- NASA information on Hurricane Isabel
- Story and photos of Hurricane Isabel by Hurricane Hunters
- Listing of more Web sites on hurricanes
- Hurricane Hunters home page

Tsunamis

Tsunamis are very large seismic ocean waves that are radially generated from volcanic eruptions, earthquakes, or subaqueous slumping. In the open ocean, these waves may travel at speeds in excess of 493 miles per hour (793 kph)! Strangely, sailors on deep ocean vessels may not notice the passing of these waves on account of the waves’ flat, low propagation. In contrast, when tsunamis reach shallow water, they slow down considerably and may reach great heights [up to 33 ft (10 m)]. Tsunamis have caused great

destruction and loss of life because of abrupt changes in water levels above the normal high water mark. Numerous areas in the United States have experienced tsunamis including Hawaii, the Pacific Northwest, and Alaska. A new system, the International Tsunami Warning System, is used now to alert the public to impending tsunamis.

Use these Web links for more information about tsunamis: where they occur, why they occur, and what happens in a tsunami.

- Local tsunamis of the Pacific Northwest—USGS
- Tsunami and Earthquake Links—USGS
- Backgrounder: Tsunami—FEMA
- Tsunami: the Great Waves—NOAA

Contributors and Attributions

Public domain content

- Coastal Processes. **Provided by**: National Park Service. **Located at**: http://www.nature.nps.gov/views/KCs/CoastalG/HTML/ET_Processes.htm. **Project**: Views of the National Park. **License**: *Public Domain: No Known Copyright*

This page titled 11.25: Reading- Coastal Hazards is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.26: Reading- Human Modifications of Coastal Processes

People love living near the beach. More than 50% of the U.S. population lives within 50 miles (80 km) of a shoreline. Once developed, communities make an effort to protect their beach homes and coastal businesses. Throughout history, humans have attempted to slow or alter the dynamic coastal zone. The anthropogenic (human-influenced) changes to coastal environments may take many forms: creation or stabilization of inlets, beach nourishment and sediment bypassing, creation of dunes for property protection, dredging of waterways for shipping and commerce, and introduction of hard structures such as jetties, groins, and seawalls. These modifications change coastal features and have far-reaching effects on coastal processes and ecosystems. An understanding of how human changes alter shoreline environments and park resources is vital for the protection and preservation of coastal areas.

Variations in sea levels are natural responses to climate change, geodetic variations, movements of the sea floor, and other Earth processes. Human actions, including drainage of wetlands, withdrawal of groundwater (which eventually flows to the sea), and deforestation (which reduces terrestrial water-storage capacity), may also contribute to global rise in sea level. Additionally, human-induced climate change, primarily through the burning of fossil fuels, is also of importance. Local changes may be caused by large engineering works nearby, such as river channeling or dam construction that influence sediment delivery and deposition in deltaic areas.

The National Park Service allows natural coastal processes to continue without interference. However, when natural processes, including coastal erosion and storm events, interfere with the preservation of cultural resources and park infrastructure, modifications to coastal dynamics may be necessary. How coastal modifications will affect natural park resources (biological and physical) must be investigated thoroughly in order that wise decisions are made. Park managers in coastal parks strive to achieve a balance between preservation of historic landmarks (e.g., forts and lighthouses) and the protection of natural ecosystems. In addition, a history of long-term human alteration, combined with a lack of historical documentation, makes defining a natural coastal system difficult. An understanding of how anthropogenic modifications will alter shoreline environments and park resources is vital for effective coastal management.

Soft Structures

Dredging

Dredging, the removal of sediment, including sand, silt, rock, and other subaqueous materials from our coastal waterways is a hotly debated topic in coastal management. The effects of dredging waterways and ports to benefit shipping, transport, and recreation are not fully understood. Opponents claim that coastal dredging may have detrimental environmental impacts and may interfere with sediment transport and flow dynamics in coastal and marine systems.

Dredged sediments may include harmful contaminants and pollutants. After dredging, these sediments are often redeposited offshore or used for the creation of dredge spoil islands adjacent to the scoured waterways. In addition, dredged sediment may be incorporated into beach nourishment projects; however, the sediment grain size of dredged materials may not be compatible with native beach sediment. Grain-size alterations and contamination may exceed flora and fauna tolerances, negatively impacting native ecosystem functions.

Proponents of dredging cite that this method of removal is necessary for commerce, recreation, and national defense. Interagency partnerships, such as the Nature Conservancy and the U.S. Army Corps of Engineers, have been established to promote a better understanding of how dredging could impact coastal environments.

For more information about dredging, check out the Web sites:

- Information on dredging research, benefits, and resources; Dredging Operations Technical Support (DOTS) provides direct environmental and engineering support to the U.S. Army Corps of Engineers' Operations and Maintenance (O&M) dredging missions
- Overview of dredging by the Monterey Bay National Marine Sanctuary (NOAA)

Beach Nourishment

Beach nourishment is the process of placing additional sediment on a beach. This material is obtained from another source that either lies inland or is dredged offshore. Nourishment entails the removal of sediment from “borrow sites,” and the subsequent transport of the sediment to beach areas. Borrow sites may alter sediment transport, hydrodynamic patterns, marine ecosystems, and sediment transport, such as creating erosional “hot spots” on adjacent shorelines.

Subaqueous nourishment is an alternative form of replenishment. The creation of offshore berms (mounds) may be utilized for the subsequent landward migration of sediments, often leading to sediment accretion on adjacent beaches. Although still a fairly new replenishment method, and not documented as fully effective, subaqueous nourishment may be substituted on account of cost limitations or biotic complications (e.g., migration and preserving endangered species) resulting from direct beach nourishment.

Often, beach nourishment is needed to counteract the effects of the hard-structure stabilization of coastlines. These structures (e.g., jetties, groins, and seawalls) typically increase downdrift erosion rates, promoting a need for continued coastal modifications through nourishment. The need for beach nourishment after human alteration is quite evident at Assateague Island National Seashore (Maryland). In the mid-1930s, the U.S. Army Corps of Engineers established a jetty system to stabilize the Ocean City inlet. While sediment transported by north-to-south longshore currents increased sediment accretion updrift of the jetties at Ocean City, excessive erosion and barrier island migration have occurred on the island to the south of the jetties. That is, Assateague Island has migrated westward more than 1,148 feet (350 m) since 1933! The deterrence of longshore sediment transport to Assateague Island National Park has had numerous detrimental impacts on biological, geologic, and cultural resources. Both short-term and long-term beach nourishment plans are in place to mitigate the destructive effects of jetty placement.

For more information about Assateague Island National Seashore, check out these Web sites:

- Ocean City–Assateague Island, Maryland, studies by Gregory Bass, U.S. Army Corps of Engineers
- Report by the U.S. Geological Survey on coastal conflicts that highlights Ocean City jetty construction and Assateague Island migration
- Article in Maryland Newsline that describes nourishment efforts by the U.S. Army Corps of Engineers on Assateague Island

For more information about methods, environmental impacts, and costs of beach nourishment, check out these Web sites:

- Overview of NOAA dredging activities, including legal and political constraints, sand resources for beach nourishment, and potential impacts of nourishment projects
- NOAA Web site containing a national overview of state, territory, and commonwealth beach nourishment programs
- Environmental review of beach nourishing projects by the U.S. Army Corps of Engineers

Beach Scraping

Beach scraping (i.e., grading and bulldozing) is the process of reshaping beach and dune landforms with heavy machinery. Usually a layer of sand from the lower beach is moved to the upper beach. Beach scraping creates dunes, which are used to give property owners some security from beach erosion, severe storms, and winter washover events. During the summers, the created sandbanks may be bulldozed flat, providing water views to property owners. However, the effects of beach scraping on coastal environments are little known, and this procedure may be harmful to coastal biota and habitats. Proponents claim that beach scraping is a time and cost-effective method to ensure shoreline protection, while opponents state that this method may be the most ecologically destructive form of coastal manipulation to date.

Please see this Web site for more information on beach scraping:

- Brief summary of how beach scraping affects biology and turbidity in North Carolina

Hard Structures

Hard structures are often placed in marine environments to counteract erosion in sediment-deficient areas, or to deter accretion in sediment-rich areas such as inlets. Unfortunately, these anthropogenic modifications may accelerate erosion in adjacent downdrift areas, increasing the need for additional hard structures. The creation of new hard structures is currently banned in many states, or strongly discouraged as coastal management practice.

Groins are shore-perpendicular structures, used to maintain updrift beaches or to restrict longshore sediment transport. Permeable groins are becoming popular, and may negate some of the negative effects of impermeable groins. Another type of shore-perpendicular hard structure are jetties, which are normally placed adjacent to tidal inlets to control inlet migration and to minimize sediment deposition within the inlet.

Shore parallel structures include seawalls, bulkheads, and revetments. These structures are designed to protect coastal property. Development permits are relatively easy to obtain in many states because seawalls may be built above the high-water mark on private property, and they are relatively inexpensive, compared to beach nourishment. Ironically, seawalls usually accelerate erosion on beaches they are intended to protect. Wave energy is reflected off seawalls, increasing erosion in front of them. The placement of a seawall will decrease the sediment supply near seawalls, increasing erosion on adjacent beaches. In many areas, beaches have completely eroded and disappeared on account of seawalls.

Other anthropogenic structures that are used to stop or alter natural coastal changes include breakwaters, headlands, sills, and reefs. These structures are composed of either natural or artificial materials, and are designed to alter the effects of waves and slow coastline erosion and change. Submerged reefs and sills dampen wave energy and may create new habitat, which is significant for local fisheries. However, the long-term effects of these structures, on both physical and biological processes, are not understood and require thorough examination.

For more information concerning these and other anthropogenic modifications, check out these Web sites:

- Wilmington Morning Star article concerning the construction of hard structures on North Carolina shores; contains links to other articles discussing coastal management issues, Dr. Orrin Pilkey, and barrier-island geomorphology
- Associated Press article “Development-protecting seawalls debated”

Contributors and Attributions

Public domain content

- Coastal Processes. **Provided by**: National Park Service. **Located at**: http://www.nature.nps.gov/views/KCs/CoastalG/HTML/ET_Processes.htm. **Project**: Views of the National Park. **License**: *Public Domain: No Known Copyright*

This page titled 11.26: Reading- Human Modifications of Coastal Processes is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.27: Self Check- Oceans and Shorelines

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1127

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 11.27: Self Check- Oceans and Shorelines is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.28: Putting It Together- Hydrology

Summary

The hydrologic cycle is anything but a simple straight forward loop. As you saw in the lesson, it is a very complex and ever changing dynamic. In this section you learned:

1. What the hydrologic cycle is and the various steps within the cycle
2. How important the hydrologic cycle is to life on earth
3. About streams and stream loads
4. What an aquifer is and the various types of aquifers
5. Why permeability and porosity are an important component of aquifers
6. The issues associated with groundwater withdrawal
7. The various types of features groundwater can produce

Synthesis

In the opening of this section, we discussed the Ogallala Aquifer. Now that we understand more about hydrology in general, we know that even though we may not live in one of the states overlying the Ogallala we will all be affected by its continued depletion. Not only will those states suffer from not enough drinking water or water for irrigation, but the rest of the country will suffer as well. We will see an increase in prices of goods as farmers have to adapt to using crops that require less water. We will see a decline in certain crops and livestock production. This could make some products very scarce. Not only this but we will also need to figure out a way to get water to these deprived areas, exactly as California is having to do today.

We also talked about the flooding in the Midwest. Do you now see any advantages of flooding? Floods, like fires, are a normal and natural part of the Earth's cycles. They become an issue when humans are involved. One of the advantages of the flooding in the Midwest is that the flood water will in fact help recharge the Ogallala Aquifer. This is a good example of how the Earth maintains a balance. The question for us is how to best adapt and manage this balance.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 11.28: Putting It Together- Hydrology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

11.29: Assignment- Hydrology

This assessment consists of two parts: a virtual lab with lab report and a list of questions on groundwater and related features.

In the Virtual Lab, you will investigate how different types of soil hold water and which ones would make the best aquifer. You will collect data and use it to make observations about the relationship of soil porosity to soil permeability.

The list of questions follows the lab activity.

Basic Requirements (assignment criteria):

Visit the following website

1. To select a type of soil, change the percentages of sand, silt, and clay by sliding the bars on the Soil Meter.
2. Click the Test This Soil button to move 100 mL of the soil mixture to the funnel.
3. Click the Pour Water button to begin pouring water on the soil. The water will automatically stop when the first drop of water begins to form at the bottom of the funnel.
4. Observe the readout that displays how much water was poured. This is the volume of water the soil held.
5. To find the porosity of the soil, divide the volume of water the soil held by the total volume of the soil. Multiply the decimal by 100 and type this percentage in the Table. In the formula below, V w stands for the volume of water and V s stands for the volume of soil. V w V s x 100 = % Porosity
6. Click Reset and repeat steps 1 through 5 for at least 10 of the 13 soil types.
7. Please enter your values in a table (you can use the one provided on the website by clicking on the icon at the bottom).
8. Save this table for your lab report (you can print it by clicking on the print button or take a screen shot or create your own table in word or excel).

For the lab report, use the data and procedures you have completed so far. Make sure you include ALL components that are necessary. The graph can simple be a bar graph showing the type of soil and its porosity.

The following are components must be included:

1. Cover page with name, date & lab title
2. Introduction
3. Data Section
4. Calculations and Interpretations
5. Discussion—make sure you include a discussion on the role of the water cycle (including processes), how permeability and porosity are affected by soil types and the role of different aquifers (are there specific types of aquifers that are more suited to pumping for example)?
6. Conclusion
7. Reference page should include all resources cited.

In addition to the above virtual lab, please complete the following questions on groundwater and groundwater related features.

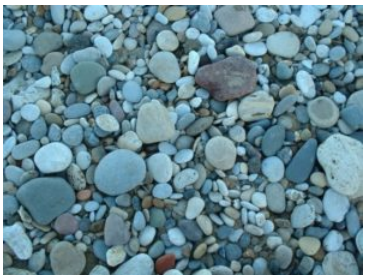
1. If channel shape and water volumes are the same, which river below would have the greater transport velocity?





A B

2. If you looked at the bottom of stream A, you would see:




A B




C D

3. Which of the above would you see at the bottom of River B?

4. The greater the velocity the greater the energy. The greater the energy, the _____ the particle size that can be carried.
a) smaller b) larger c) will be the same d) can't tell this way

5. Shale is mostly made of clay. In which depositional environment would you expect it to form:
a) mountain streams b) braided rivers c) lake bottoms d) fast moving rivers

6. With time, sediment transport by a fluvial system:
a) becomes rounded b) becomes smaller c) becomes rounded and smaller d) becomes angular e) none of the above




A B

7. In which of the above pictures of rock, has the sediment been carried the shortest distance?

8. Groundwater often produces some pretty spectacular features. Please provide a brief description for each of the following: geyser, sinkhole, karst topography, springs and disappearing streams.

Tips and hints can be found here.

The virtual assessment is adapted from "Virtual Lab" by M. Poarch, originally found here.

The question assessment is adapted from "Sediment Transport" by Austin Boyd, originally found here.

Contributors and Attributions

CC licensed content, Original

- Hydrology Assessment. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 11.29: Assignment- Hydrology is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

CHAPTER OVERVIEW

12: Geological Resources

Learning Objectives

Identify common geological resources and discuss how people use them.

- Learn common processes of geologic formation of rock and mineral resources.
- Describe some of the extraction methods and identify different types of mining.
- Describe geologic materials as current or potential energy resources and categorize sources as renewable or nonrenewable.

12.1: Why It Matters- Geological Resources
12.2: Outcome- Rock and Mineral Resources
12.3: Reading- Ore Genesis
12.4: Reading- Petroleum
12.5: Reading- Natural Gas
12.6: Reading- Coal
12.7: Self Check- Rock and Mineral Resources
12.8: Outcome- Extraction of Resources
12.9: Reading- Mining
12.10: Reading- Effects of Mining
12.11: Self Check- Extraction of Resources
12.12: Outcome- Getting Energy from Resources
12.13: Reading- Earth's Energy
12.14: Reading- Energy Consumption on Earth
12.15: Reading- Use and Conservation of Resources
12.16: Self Check- Getting Energy from Resources
12.17: Putting It Together- Geological Resources
12.18: Assignment- Geological Resources

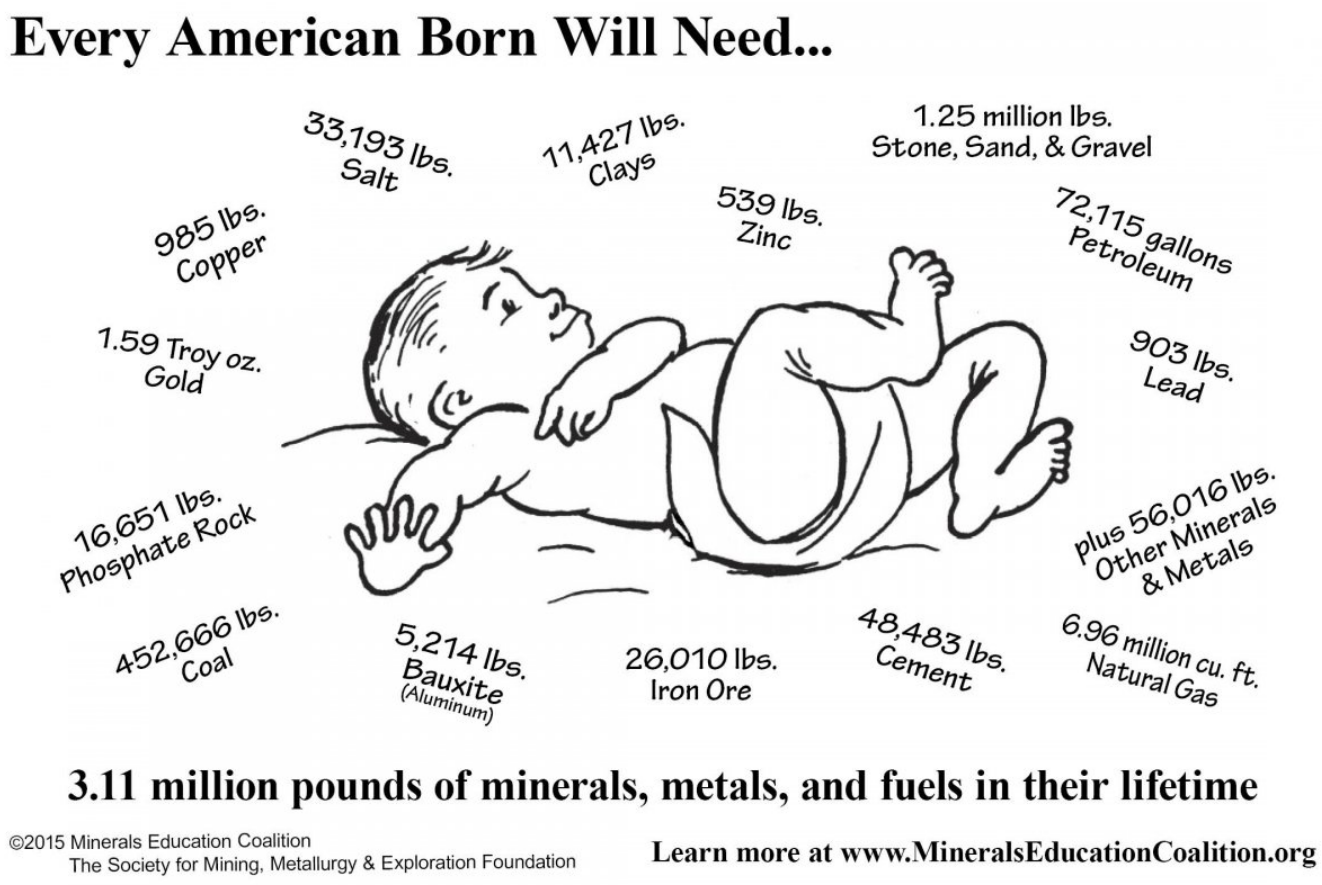
This page titled 12: Geological Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.1: Why It Matters- Geological Resources

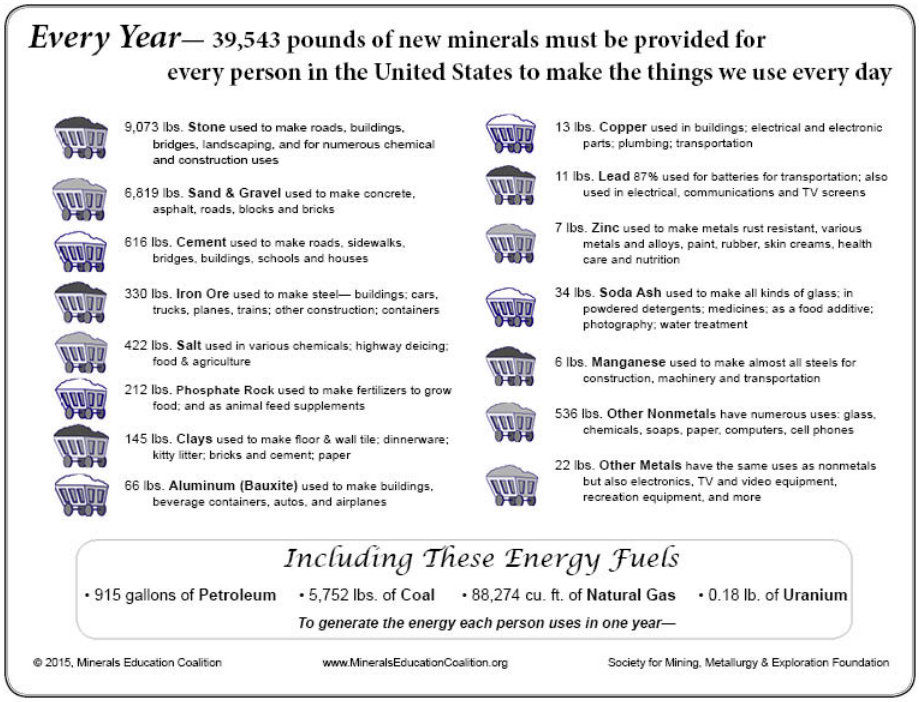
Identify common geological resources and discuss how people use them.

Introduction

This section takes into consideration everything we have discussed so far. We will take a glance back at the formation of rocks and minerals, concentrating on mineral and energy resources. These resources focus mainly on our fossil fuels—oil, natural gas and coal. However, we use a variety of other material as well. Most of the resources we use are done so indirectly. For example, each person will use over 450,000 pounds of coal in their lifetime. While you may not go to the store and purchase coal to use like you would gasoline for your car, you do it in other indirect ways—for instance, most electricity in the US is generated by coal burning. The following graphic illustrates the type and amount of resources each American will need and use throughout their lives.



This chart provides us with some staggering statistics on the amount of resources we use:



Were you surprised see some of the items listed? How about the quantities—3.11 million pounds of resources per person?!

One item not shown on the figure is tantalum. If you have a cell phone, tablet, computer, camera or gaming system you own some tantalum. This resource is used because it has many desirable properties including high heat capacity, ductile and the ability to conduct electricity (Tantalum, 2015). However, tantalum is considered to be a "conflict resource." This means that it is mined in an area where a dispute or conflict is occurring. It could also mean that the resource is used to perpetuate the conflict. In the case of tantalum, it is mined in an area of the Congo where it is believed to have played a role in helping finance war in the area. This conflict is believed to have caused the death of 5,400,000 since 1998 (Tantalum, 2015)!

These resources are collected in a variety of ways from drilling to mining. Depending on the resource and its location, different mining methods may be used. And these resources are mined on every continent (except Antarctica).

Unfortunately not all of our resources will be around forever. Our nonrenewable resources are in jeopardy of depletion. Alternative or renewable resources will play a bigger role in meeting our energy needs in the future.

Learning Outcomes

- Learn common processes of geologic formation of rock and mineral resources.
- Describe some of the extraction methods and identify different types of mining.
- Describe geologic materials as current or potential energy resources and categorize sources as renewable or nonrenewable.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

CC licensed content, Shared previously

- 2015 Per Capita Use of Minerals. **Authored by**: Minerals Education Coalition. **Located at**: https://www.mineralseducationcoalition.org/sites/default/files/uploads/2015percapita.jpg. **License**: *All Rights Reserved*. **License Terms**: Unless otherwise noted, MEC materials may be used unaltered and in their entirety for educational purposes. This includes, but is not limited to individual educators in a classroom setting and Science Teacher Workshops. Materials may be downloaded, printed and copied at no charge when used for educational purposes.

CC licensed content, Specific attribution

- 2015 Mineral Baby. **Authored by**: Minerals Education Coalition. **Located at**: https://www.mineralseducationcoalition.org/sites/default/files/uploads/2015baby.jpg. **License**: *All Rights Reserved*. **License Terms**: Unless otherwise noted, MEC materials may be used unaltered and in their entirety for educational purposes. This includes, but is not limited to individual educators in a classroom setting and Science Teacher Workshops. Materials may be downloaded, printed and copied at no charge when used for educational purposes.

This page titled 12.1: Why It Matters- Geological Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.2: Outcome- Rock and Mineral Resources

Learn common processes of geologic formation of rock and mineral resources.

This section introduces you to the processes leading to the formation of common rock and mineral resources. You will learn how and why these processes work and how they are different.

What You'll Learn to Do

- Describe the different processes that lead to various ore formation
- Describe the processes that lead to the formation of all fossil fuels: petroleum, natural gas, and coal

Learning Activities

The learning activities for this section include the following:

- Reading: Ore Genesis
- Reading: Petroleum
- Reading: Natural Gas
- Reading: Coal
- Self Check: Rock and Mineral Resources

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 12.2: Outcome- Rock and Mineral Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.3: Reading- Ore Genesis

The various theories of **ore genesis** explain how the various types of mineral deposits form within the Earth's crust. Ore genesis theories are dependent on the mineral or commodity.

Ore genesis theories generally involve three components: source, transport or conduit, and trap. This also applies to the petroleum industry, which was first to use this methodology.

- Source is required because metal must come from somewhere, and be liberated by some process
- Transport is required first to move the metal bearing fluids or solid minerals into the right position, and refers to the act of physically moving the metal, as well as chemical or physical phenomenon which encourage movement
- Trapping is required to concentrate the metal via some physical, chemical or geological mechanism into a concentration which forms mineable ore

The biggest deposits are formed when the source is large, the transport mechanism is efficient, and the trap is active and ready at the right time.

Ore Genesis Processes

Endogenous

Magmatic Processes

- Fractional crystallization: separates ore and non-ore minerals according to their crystallization temperature. As early crystallizing minerals form, they incorporate certain elements, some of which are metals. These crystals may settle onto the bottom of the intrusion, concentrating ore minerals there. Chromite and magnetite are ore minerals that form in this way.
- Liquid immiscibility: sulfide ores containing copper, nickel or platinum may form from this process. As a magma changes, parts of it may separate from the main body of magma. Two liquids that will not mix are called immiscible; oil and water are an example. In magmas, sulfides may separate and sink below the silicate-rich part of the intrusion or be injected into the rock surrounding it. These deposits are found in mafic and ultramafic rocks.

Hydrothermal Processes

These processes are the physicochemical phenomena and reactions caused by movement of hydrothermal water within the crust, often as a consequence of magmatic intrusion or tectonic upheavals. The foundations of hydrothermal processes are the source-transport-trap mechanism.

Sources of hydrothermal solutions include seawater and meteoric water circulating through fractured rock, formational brines (water trapped within sediments at deposition) and metamorphic fluids created by dehydration of hydrous minerals during metamorphism.

Metal sources may include a plethora of rocks. However most metals of economic importance are carried as trace elements within rock-forming minerals, and so may be liberated by hydrothermal processes. This happens because of:

- incompatibility of the metal with its host mineral, for example zinc in calcite, which favours aqueous fluids in contact with the host mineral during diagenesis.
- solubility of the host mineral within nascent hydrothermal solutions in the source rocks, for example mineral salts (halite), carbonates (cerussite), phosphates (monazite and thorianite) and sulfates (barite)
- elevated temperatures causing decomposition reactions of minerals

Transport by hydrothermal solutions usually requires a salt or other soluble species which can form a metal-bearing complex. These metal-bearing complexes facilitate transport of metals within aqueous solutions, generally as hydroxides, but also by processes similar to chelation.

This process is especially well understood in gold metallogeny where various thiosulfate, chloride and other gold-carrying chemical complexes (notably tellurium-chloride/sulfate or antimony-chloride/sulfate). The majority of metal deposits formed by hydrothermal processes include sulfide minerals, indicating sulfur is an important metal-carrying complex.

Sulfide deposition: Sulfide deposition within the *trap* zone occurs when metal-carrying sulfate, sulfide or other complexes become chemically unstable due to one or more of the following processes;

- falling temperature, which renders the complex unstable or metal insoluble
- loss of pressure, which has the same effect
- reaction with chemically reactive wall rocks, usually of reduced oxidation state, such as iron bearing rocks, mafic or ultramafic rocks or carbonate rocks
- degassing of the hydrothermal fluid into a gas and water system, or boiling, which alters the metal carrying capacity of the solution and even destroys metal-carrying chemical complexes

Metal can also become precipitated when temperature and pressure or oxidation state favour different ionic complexes in the water, for instance the change from sulfide to sulfate, oxygen fugacity, exchange of metals between sulfide and chloride complexes, et cetera.

Metamorphic Processes

Lateral secretion: Ore deposits formed by lateral secretion are formed by metamorphic reactions during shearing, which liberate mineral constituents such as quartz, sulfides, gold, carbonates and oxides from deforming rocks and focus these constituents into zones of reduced pressure or dilation such as faults. This may occur without much hydrothermal fluid flow, and this is typical of podiform chromite deposits.

Metamorphic processes also control many physical processes which form the source of hydrothermal fluids, outlined above.

Surficial Processes (Exogenous)

Surficial processes are the physical and chemical phenomena which cause concentration of ore material within the regolith, generally by the action of the environment. This includes placerdeposits, laterite deposits and residual or eluvial deposits. The physical processes of ore deposit formation in the surficial realm include;

- erosion
- deposition by sedimentary processes, including winnowing, density separation (e.g.; gold placers)
- weathering via oxidation or chemical attack of a rock, either liberating rock fragments or creating chemically deposited clays, laterites or supergene enrichment
- Deposition in low-energy environments in beach environments

Classification of Ore Deposits

Ore deposits are usually classified by ore formation processes and geological setting. For example, SEDEX deposits, literally meaning “sedimentary exhalative” are a class of ore deposit formed on the sea floor (sedimentary) by exhalation of brines into seawater (exhalative), causing chemical precipitation of ore minerals when the brine cools, mixes with sea water and loses its metal carrying capacity.

Ore deposits rarely fit snugly into the boxes in which geologists wish to place them. Many may be formed by one or more of the basic genesis processes above, creating ambiguous classifications and much argument and conjecture. Often ore deposits are classified after examples of their type, for instance Broken Hill type lead-zinc-silver deposits or Carlin–type gold deposits.

Classification of hydrothermal ore deposits is also achieved by classifying according to the temperature of formation, which roughly also correlates with particular mineralising fluids, mineral associations and structural styles. This scheme, proposed by Waldemar Lindgren (1933) classified hydrothermal deposits as *hypothermal*, *mesothermal*, *epithermal* and *telethermal*.

Genesis of Common Ores

As they require the conjunction of specific environmental conditions to form, particular mineral deposit types tend to occupy specific geodynamic niches,[1] therefore, this page has been organised by metal commodity. It is also possible to organise theories the other way, namely according to geological criteria of formation. Often ores of the same metal can be formed by multiple processes, and this is described here under each metal or metal complex.

Iron

Iron ores are overwhelmingly derived from ancient sediments known as *banded iron formations* (BIFs). These sediments are composed of iron oxide minerals deposited on the sea floor. Particular environmental conditions are needed to transport enough iron in sea water to form these deposits, such as acidic and oxygen-poor atmospheres within the Proterozoic Era.

Often, more recent weathering is required to convert the usual magnetite minerals into more easily processed hematite. Some iron deposits within the Pilbara of West Australia are *placer deposits*, formed by accumulation of hematite gravels called *pisolites* which form channel-iron deposits. These are preferred because they are cheap to mine.

Lead Zinc Silver

Lead-zinc deposits are generally accompanied by silver, hosted within the lead sulfide mineral galena or within the zinc sulfide mineral sphalerite.

Lead and zinc deposits are formed by discharge of deep sedimentary brine onto the sea floor (termed *sedimentary exhalative* or SEDEX), or by replacement of limestone, in skarn deposits, some associated with submarine volcanoes (called volcanogenic massive sulfide ore deposits or VMS) or in the aureole of subvolcanic intrusions of granite. The vast majority of SEDEX lead and zinc deposits are Proterozoic in age, although there are significant Jurassic examples in Canada and Alaska.

The carbonate replacement type deposit is exemplified by the Mississippi valley type (MVT) ore deposits. MVT and similar styles occur by replacement and degradation of carbonate sequences byhydrocarbons, which are thought important for transporting lead.

Gold



Figure 1. High-grade (bonanza) gold ore, brecciated quartz-adularia rhyolite. Native gold (Au) occurs in this rock as colloform bands, partially replaces breccia clasts, and is also disseminated in the matrix. Published research indicates that Sleeper Mine rocks represent an ancient epithermal gold deposit (hot springs gold deposit), formed by volcanism during Basin & Range extensional tectonics. Sleeper Mine, Humboldt County, Nevada.

Gold deposits are formed via a very wide variety of geological processes. Deposits are classified as primary, alluvial or placerdeposits, or residual or laterite deposits. Often a deposit will contain a mixture of all three types of ore.

Plate tectonics is the underlying mechanism for generating gold deposits. The majority of primary gold deposits fall into two main categories: lode gold deposits or intrusion-related deposits.

Lode gold deposits are generally high-grade, thin, vein and fault hosted. They are primarily made up of quartz veins also known as lodes or *reefs*, which contain either native gold or gold sulfides and tellurides. Lode gold deposits are usually hosted in basalt or in sediments known as turbidite, although when in faults, they may occupy intrusive igneous rocks such as granite.

Lode-gold deposits are intimately associated with orogeny and other plate collision events within geologic history. Most lode gold deposits *sourced* from metamorphic rocks because it is thought that the majority are formed by dehydration of basalt during metamorphism. The gold is transported up faults by hydrothermal waters and deposited when the water cools too much to retain gold in solution.

Intrusive related gold is generally hosted in granites, porphyry or rarely dikes. Intrusive related gold usually also contains copper, and is often associated with tin and tungsten, and rarely molybdenum, antimony and uranium. Intrusive-related gold deposits rely on gold existing in the fluids associated with the magma (White, 2001), and the inevitable discharge of thesehydrothermal fluids into the wall-rocks (Lowenstern, 2001). Skarn deposits are another manifestation of intrusive-related deposits.

Placer deposits are sourced from pre-existing gold deposits and are secondary deposits. Placer deposits are formed by alluvialprocesses within rivers, streams and on beaches. Placer gold deposits form via gravity, with the density of gold causing it to

sink into trap sites within the river bed, or where water velocity drops, such as bends in rivers and behind boulders. Often placer deposits are found within sedimentary rocks and can be billions of years old, for instance the Witwatersrand deposits in South Africa. Sedimentary placer deposits are known as “leads” or “deep leads.”

Placer deposits are often worked by fossicking, and panning for gold is a popular pastime.

Laterite gold deposits are formed from pre-existing gold deposits (including some placer deposits) during prolonged weathering of the bedrock. Gold is deposited within iron oxides in the weathered rock or regolith, and may be further enriched by reworking by erosion. Some laterite deposits are formed by wind erosion of the bedrock leaving a residuum of native gold metal at surface.

A bacterium, Cupriavidus metallidurans plays a vital role in the formation of gold nuggets, by precipitating metallic gold from a solution of gold (III) tetrachloride, a compound highly toxic to most other microorganisms. Similarly, Delftia acidovorans can form gold nuggets.

Platinum

Platinum and palladium are precious metals generally found in ultramafic rocks. The source of platinum and palladium deposits is ultramafic rocks which have enough sulfur to form a sulfide mineral while the magma is still liquid. This sulfide mineral (usually pentlandite, pyrite, chalcopyrite or pyrrhotite) gains platinum by mixing with the bulk of the magma because platinum is chalcophile and is concentrated in sulfides. Alternatively, platinum occurs in association with chromite either within the chromite mineral itself or within sulfides associated with it.

Sulfide phases only form in ultramafic magmas when the magma reaches sulfur saturation. This is generally thought to be nearly impossible by pure fractional crystallisation, so other processes are usually required in ore genesis models to explain sulfur saturation. These include contamination of the magma with crustal material, especially sulfur-rich wall-rocks or sediments; magma mixing; volatile gain or loss.

Often platinum is associated with nickel, copper, chromium, and cobalt deposits.

Nickel

Nickel deposits are generally found in two forms, either as sulfide or laterite.

Sulfide type nickel deposits are formed in essentially the same manner as platinum deposits. Nickel is a chalcophile element which prefers sulfides, so an ultramafic or mafic rock which has a sulfide phase in the magma may form nickel sulfides. The best nickel deposits are formed where sulfide accumulates in the base of lava tubes or volcanic flows—especially komatiite lavas.

Komatiitic nickel-copper sulfide deposits are considered to be formed by a mixture of sulfide segregation, immiscibility, and thermal erosion of sulfidic sediments. The sediments are considered to be necessary to promote sulfur saturation.

Some subvolcanic sills in the Thompson Belt of Canada host nickel sulfide deposits formed by deposition of sulfides near the feeder vent. Sulfide was accumulated near the vent due to the loss of magma velocity at the vent interface. The massive Voisey’s Bay nickel deposit is considered to have formed via a similar process.

The process of forming *nickel laterite* deposits is essentially similar to the formation of gold laterite deposits, except that ultramafic or mafic rocks are required. Generally nickel laterites require very large olivine-bearing ultramafic intrusions. Minerals formed in laterite nickel deposits include gibbsite.

Copper

Copper is found in association with many other metals and deposit styles. Commonly, copper is either formed within sedimentary rocks, or associated with igneous rocks.

The world’s major copper deposits are formed within the granitic porphyry copper style. Copper is enriched by processes during crystallisation of the granite and forms as chalcopyrite—a sulfide mineral, which is carried up with the granite.

Sometimes granites erupt to surface as volcanoes, and copper mineralisation forms during this phase when the granite and volcanic rocks cool via hydrothermal circulation.

Sedimentary copper forms within ocean basins in sedimentary rocks. Generally this forms by brine from deeply buried sediments discharging into the deep sea, and precipitating copper and oftenlead and zinc sulfides directly onto the sea floor. This is then

buried by further sediment. This is a process similar to SEDEX zinc and lead, although some carbonate-hosted examples exist.

Often copper is associated with gold, lead, zinc and nickel deposits.

Uranium

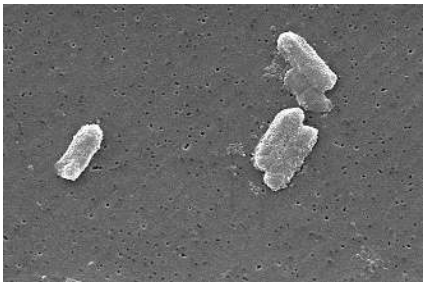


Figure 2. Citrobacter species can have concentrations of uranium in their bodies 300 times higher than in the surrounding environment.

Uranium deposits are usually *sourced* from radioactive granites, where certain minerals such as monazite are leached during hydrothermal activity or during circulation of groundwater. The uranium is brought into solution by acidic conditions and is deposited when this acidity is neutralised. Generally this occurs in certain carbon-bearing sediments, within an unconformity in sedimentary strata. The majority of the world's nuclear power is sourced from uranium in such deposits.

Uranium is also found in nearly all coal at several parts per million, and in all granites. Radon is a common problem during mining of uranium as it is a radioactive gas.

Uranium is also found associated with certain igneous rocks, such as granite and porphyry. The Olympic Dam deposit in Australia is an example of this type of uranium deposit. It contains 70% of Australia's share of 40% of the known global low-cost recoverable uranium inventory.

Titanium and Zirconium

Mineral sands are the predominant type of titanium, zirconium and thorium deposit. They are formed by accumulation of such heavy minerals within beach systems, and are a type of *placer deposits*. The minerals which contain titanium are ilmenite, rutile and leucoxene, zirconium is contained within zircon, and thorium is generally contained within monazite. These minerals are sourced from primarily granite bedrock by erosion and transported to the sea by rivers where they accumulate within beach sands. Rarely, but importantly, gold, tin and platinum deposits can form in beach placer deposits.

Tin, Tungsten, and Molybdenum

These three metals generally form in a certain type of granite, via a similar mechanism to intrusive-related gold and copper. They are considered together because the process of forming these deposits is essentially the same. Skarn type mineralisation related to these granites is a very important type of tin, tungsten and molybdenum deposit. Skarn deposits form by reaction of mineralised fluids from the granite reacting with wall rocks such as limestone. Skarn mineralisation is also important in lead, zinc, copper, gold and occasionally uranium mineralisation.

Greisen granite is another related tin-molybdenum and topaz mineralisation style.

Rare Earth Elements, Niobium, Tantalum, Lithium

The overwhelming majority of rare earth elements, tantalum and lithium are found within pegmatite. Ore genesis theories for these ores are wide and varied, but most involve metamorphism and igneous activity. Lithium is present as spodumene or lepidolite within pegmatite.

Carbonatite intrusions are an important source of these elements. Ore minerals are essentially part of the unusual mineralogy of carbonatite.

Phosphate

Phosphate is used in fertilisers. Immense quantities of *phosphate rock* or phosphorite occur in sedimentary shelf deposits, ranging in age from the Proterozoic to currently forming environments. Phosphate deposits are thought to be sourced from the skeletons of

dead sea creatures which accumulated on the seafloor. Similar to iron ore deposits and oil, particular conditions in the ocean and environment are thought to have contributed to these deposits within the geological past.



Figure 3. Tunicates such as this bluebell tunicate contain vanadium as vanabin.

Phosphate deposits are also formed from alkaline igneous rocks such as nepheline syenites, carbonatites and associated rock types. The phosphate is, in this case, contained within magmaticapatite, monazite or other rare-earth phosphates.

Vanadium

Due to the presence of vanabins, concentration of vanadium found in the blood cells of *Ascidia gemmata* belonging to the suborder Phlebobranchia is 10,000,000 times higher than that in the surrounding seawater. A similar biological process might have played a role in the formation of vanadium ores. Vanadium is also present in fossil fuel deposits such as crude oil, coal, oil shale and oil sands. In crude oil, concentrations up to 1200 ppm have been reported.

Contributors and Attributions

CC licensed content, Shared previously

- Ore genesis. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Ore_genesis. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 12.3: Reading- Ore Genesis is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.4: Reading- Petroleum



Figure 1. Pumpjack pumping an oil well near Lubbock, Texas

Petroleum is a naturally occurring, yellow-to-black liquid found in geological formations beneath the Earth's surface, which is commonly refined into various types of fuels.

It consists of hydrocarbons of various molecular weights and other organic compounds. The name *petroleum* covers both naturally occurring unprocessed **crude oil** and petroleum products that are made up of refined crude oil. A fossil fuel, petroleum is formed when large quantities of dead organisms, usually zooplankton and algae, are buried underneath sedimentary rock and subjected to intense heat and pressure.

Petroleum is recovered mostly through oil drilling (natural petroleum springs are rare). This comes after the studies of structural geology (at the reservoir scale), sedimentary basin analysis, reservoir characterization (mainly in terms of the porosity and permeability of geologic reservoir structures). It is refined and separated, most easily by distillation, into a large number of consumer products, from gasoline (petrol) and kerosene to asphalt and chemical reagents used to make plastics and pharmaceuticals. Petroleum is used in manufacturing a wide variety of materials, and it is estimated that the world consumes about 90 million barrels each day.

Concern over the depletion of the earth's finite reserves of oil, and the effect this would have on a society dependent on it, is a concept known as peak oil. The use of fossil fuels, such as petroleum, has a negative impact on Earth's biosphere, damaging ecosystems through events such as oil spills and releasing a range of pollutants into the air including ground-level ozone and sulfur dioxide from sulfur impurities in fossil fuels.

Composition

In its strictest sense, petroleum includes only crude oil, but in common usage it includes all liquid, gaseous, and solid hydrocarbons. Under surface pressure and temperature conditions, lighter hydrocarbons methane, ethane, propane and butane occur as gases, while pentane and heavier ones are in the form of liquids or solids. However, in an underground oil reservoir the proportions of gas, liquid, and solid depend on subsurface conditions and on the phase diagram of the petroleum mixture.

An oil well produces predominantly crude oil, with some natural gas dissolved in it. Because the pressure is lower at the surface than underground, some of the gas will come out of solution and be recovered (or burned) as *associated gas* or *solution gas*. A gas well produces predominantly natural gas. However, because the underground temperature and pressure are higher than at the surface, the gas may contain heavier hydrocarbons such as pentane, hexane, and heptane in the gaseous state. At surface conditions these will condense out of the gas to form natural gas condensate, often shortened to *condensate.* Condensate resembles gasoline in appearance and is similar in composition to some volatile light crude oils.

The proportion of light hydrocarbons in the petroleum mixture varies greatly among different oil fields, ranging from as much as 97 percent by weight in the lighter oils to as little as 50 percent in the heavier oils and bitumens.

The hydrocarbons in crude oil are mostly alkanes, cycloalkanes and various aromatic hydrocarbons while the other organic compounds contain nitrogen, oxygen and sulfur, and trace amounts of metals such as iron, nickel, copper and vanadium. Many oil reservoirs contain live bacteria. The exact molecular composition varies widely from formation to formation but the proportion of chemical elements vary over fairly narrow limits as follows:

Composition by weight

Element	Percent range
Carbon	83 to 85%
Hydrogen	10 to 14%
Nitrogen	0.1 to 2%
Oxygen	0.05 to 1.5%
Sulfur	0.05 to 6.0%
Metals	< 0.1%

Four different types of hydrocarbon molecules appear in crude oil. The relative percentage of each varies from oil to oil, determining the properties of each oil.

Composition by weight

Hydrocarbon	Average	Range
Alkanes (paraffins)	30%	15 to 60%
Naphthenes	49%	30 to 60%
Aromatics	15%	3 to 30%
Asphaltics	6%	remainder

Crude oil varies greatly in appearance depending on its composition. It is usually black or dark brown (although it may be yellowish, reddish, or even greenish). In the reservoir it is usually found in association with natural gas, which being lighter forms a gas cap over the petroleum, and saline water which, being heavier than most forms of crude oil, generally sinks beneath it. Crude oil may also be found in semi-solid form mixed with sand and water, as in the Athabasca oil sands in Canada, where it is usually referred to as crude bitumen. In Canada, bitumen is considered a sticky, black, tar-like form of crude oil which is so thick and heavy that it must be heated or diluted before it will flow. Venezuela also has large amounts of oil in the Orinoco oil sands, although the hydrocarbons trapped in them are more fluid than in Canada and are usually called extra heavy oil. These oil sands resources are called unconventional oil to distinguish them from oil which can be extracted using traditional oil well methods. Between them, Canada and Venezuela contain an estimated 3.6 trillion barrels (570×10^9 m^3) of bitumen and extra-heavy oil, about twice the volume of the world's reserves of conventional oil.

Petroleum is used mostly, by volume, for producing fuel oil and gasoline, both important *"primary energy"* sources. 84 percent by volume of the hydrocarbons present in petroleum is converted into energy-rich fuels (petroleum-based fuels), including gasoline, diesel, jet, heating, and other fuel oils, and liquefied petroleum gas. The lighter grades of crude oil produce the best yields of these products, but as the world's reserves of light and medium oil are depleted, oil refineries are increasingly having to process heavy oil and bitumen, and use more complex and expensive methods to produce the products required. Because heavier crude oils have too much carbon and not enough hydrogen, these processes generally involve removing carbon from or adding hydrogen to the molecules, and using fluid catalytic cracking to convert the longer, more complex molecules in the oil to the shorter, simpler ones in the fuels.

Due to its high energy density, easy transportability and relative abundance, oil has become the world's most important source of energy since the mid-1950s. Petroleum is also the raw material for many chemical products, including pharmaceuticals, solvents, fertilizers, pesticides, and plastics; the 16 percent not used for energy production is converted into these other materials. Petroleum is found in porous rock formations in the upper strata of some areas of the Earth's crust. There is also petroleum in oil sands (tar sands). Known oil reserves are typically estimated at around 190 km^3(1.2 trillion (short scale) barrels) without oil sands, or 595 km^3 (3.74 trillion barrels) with oil sands. Consumption is currently around 84 million barrels (13.4×10^6 m^3) per day, or 4.9 km^3 per year. Which in turn yields a remaining oil supply of only about 120 years, if current demand remain static.

Formation



Figure 2. Natural petroleum spring in Korňa, Slovakia

Petroleum is a fossil fuel derived from ancient fossilized organic materials, such as zooplankton and algae. Vast quantities of these remains settled to sea or lake bottoms, mixing with sediments and being buried under anoxic conditions. As further layers settled to the sea or lake bed, intense heat and pressure build up in the lower regions. This process caused the organic matter to change, first into a waxy material known as kerogen, which is found in various oil shales around the world, and then with more heat into liquid and gaseous hydrocarbons via a process known as catagenesis. Formation of petroleum occurs from hydrocarbon pyrolysis in a variety of mainly endothermic reactions at high temperature and/or pressure.

There were certain warm nutrient-rich environments such as the Gulf of Mexico and the ancient Tethys Sea where the large amounts of organic material falling to the ocean floor exceeded the rate at which it could decompose. This resulted in large masses of organic material being buried under subsequent deposits such as shale formed from mud. This massive organic deposit later became heated and transformed under pressure into oil.

Geologists often refer to the temperature range in which oil forms as an “oil window”—below the minimum temperature oil remains trapped in the form of kerogen, and above the maximum temperature the oil is converted to natural gas through the process of thermal cracking. Sometimes, oil formed at extreme depths may migrate and become trapped at a much shallower level. The Athabasca Oil Sands are one example of this.

An alternative mechanism was proposed by Russian scientists in the mid-1850s, the Abiogenic petroleum origin, but this is contradicted by the geological and geochemical evidence.

Reservoirs

Crude Oil Reservoirs

Three conditions must be present for oil reservoirs to form: a source rock rich in hydrocarbon material buried deep enough for subterranean heat to cook it into oil, a porous and permeable reservoir rock for it to accumulate in, and a cap rock (seal) or other mechanism that prevents it from escaping to the surface. Within these reservoirs, fluids will typically organize themselves like a three-layer cake with a layer of water below the oil layer and a layer of gas above it, although the different layers vary in size between reservoirs. Because most hydrocarbons are less dense than rock or water, they often migrate upward through adjacent rock layers until either reaching the surface or becoming trapped within porous rocks (known as reservoirs) by impermeable rocks above. However, the process is influenced by underground water flows, causing oil to migrate hundreds of kilometres horizontally or even short distances downward before becoming trapped in a reservoir. When hydrocarbons are concentrated in a trap, an oil field forms, from which the liquid can be extracted by drilling and pumping.

The reactions that produce oil and natural gas are often modeled as first order breakdown reactions, where hydrocarbons are broken down to oil and natural gas by a set of parallel reactions, and oil eventually breaks down to natural gas by another set of reactions. The latter set is regularly used in petrochemical plants and oil refineries.

Wells are drilled into oil reservoirs to extract the crude oil. “Natural lift” production methods that rely on the natural reservoir pressure to force the oil to the surface are usually sufficient for a while after reservoirs are first tapped. In some reservoirs, such as in the Middle East, the natural pressure is sufficient over a long time. The natural pressure in most reservoirs, however, eventually dissipates. Then the oil must be extracted using “artificial lift” means. Over time, these “primary” methods become less effective and “secondary” production methods may be used. A common secondary method is “waterflood” or injection of water into the

reservoir to increase pressure and force the oil to the drilled shaft or “wellbore.” Eventually “tertiary” or “enhanced” oil recovery methods may be used to increase the oil’s flow characteristics by injecting steam, carbon dioxide and other gases or chemicals into the reservoir. In the United States, primary production methods account for less than 40 percent of the oil produced on a daily basis, secondary methods account for about half, and tertiary recovery the remaining 10 percent. Extracting oil (or “bitumen”) from oil/tar sand and oil shale deposits requires mining the sand or shale and heating it in a vessel or retort, or using “in-situ” methods of injecting heated liquids into the deposit and then pumping out the oil-saturated liquid.

Unconventional oil reservoirs

Oil-eating bacteria biodegrade oil that has escaped to the surface. Oil sands are reservoirs of partially biodegraded oil still in the process of escaping and being biodegraded, but they contain so much migrating oil that, although most of it has escaped, vast amounts are still present—more than can be found in conventional oil reservoirs. The lighter fractions of the crude oil are destroyed first, resulting in reservoirs containing an extremely heavy form of crude oil, called crude bitumen in Canada, or extra-heavy crude oil in Venezuela. These two countries have the world’s largest deposits of oil sands.

On the other hand, oil shales are source rocks that have not been exposed to heat or pressure long enough to convert their trapped hydrocarbons into crude oil. Technically speaking, oil shales are not always shales and do not contain oil, but are fined-grain sedimentary rocks containing an insoluble organic solid called kerogen. The kerogen in the rock can be converted into crude oil using heat and pressure to simulate natural processes. The method has been known for centuries and was patented in 1694 under British Crown Patent No. 330 covering, “A way to extract and make great quantities of pitch, tar, and oil out of a sort of stone.” Although oil shales are found in many countries, the United States has the world’s largest deposits.

Contributors and Attributions

CC licensed content, Shared previously

- Petroleum. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Petroleum. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 12.4: Reading- Petroleum is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.5: Reading- Natural Gas

Natural gas is a fossil fuel formed when layers of buried plants, gases, and animals are exposed to intense heat and pressure over thousands of years. The energy that the plants originally obtained from the sun is stored in the form of chemical bonds in natural gas. Natural gas is a nonrenewable resource because it cannot be replenished on a human time frame. Natural gas is a hydrocarbon gas mixture consisting primarily of methane, but commonly includes varying amounts of other higher alkanes and sometimes a usually lesser percentage of carbon dioxide, nitrogen, and/or hydrogen sulfide. Natural gas is an energy source often used for heating, cooking, and electricity generation. It is also used as fuel for vehicles and as a chemical feedstock in the manufacture of plastics and other commercially important organic chemicals.

Natural gas is found in deep underground rock formations or associated with other hydrocarbon reservoirs in coal beds and as methane clathrates. Petroleum is another resource and fossil fuel found in close proximity to, and with natural gas. Most natural gas was created over time by two mechanisms: biogenic and thermogenic. Biogenic gas is created by methanogenic organisms in marshes, bogs, landfills, and shallow sediments. Deeper in the earth, at greater temperature and pressure, thermogenic gas is created from buried organic material.

Before natural gas can be used as a fuel, it must be processed to remove impurities, including water, to meet the specifications of marketable natural gas. The by-products of this processing include: ethane, propane, butanes, pentanes, and higher molecular weight hydrocarbons, hydrogen sulfide (which may be converted into pure sulfur), carbon dioxide, water vapor, and sometimes helium and nitrogen.

Natural gas is often informally referred to simply as “gas,” especially when compared to other energy sources such as oil or coal. However, it is not to be confused with gasoline, especially in North America, where the term gasoline is often shortened in colloquial usage to *gas*.

Natural gas was used by the Chinese in about 500 BC. They discovered a way to transport gas seeping from the ground in crude pipelines of bamboo to where it was used to boil salt water to extract the salt, in the Ziliujing District of Sichuan. The world’s first industrial extraction of natural gas started at Fredonia, New York, USA in 1825. By 2009, 66 trillion cubic meters (or 8%) had been used out of the total 850 trillion cubic meters of estimated remaining recoverable reserves of natural gas. Based on an estimated 2015 world consumption rate of about 3.4 trillion cubic meters of gas per year, the total estimated remaining economically recoverable reserves of natural gas would last 250 years at current consumption rates. An annual increase in usage of 2–3% could result in currently recoverable reserves lasting significantly less, perhaps as few as 80 to 100 years.

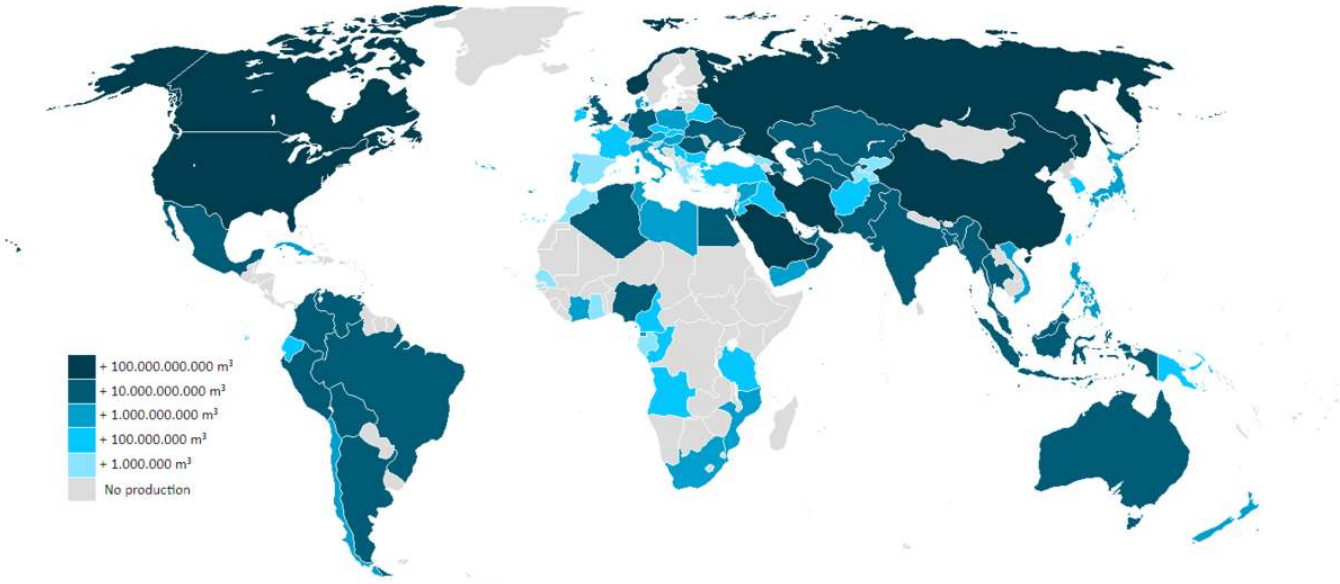


Figure 1. Natural gas extraction by countries in cubic meters per year.



Figure 2. Natural gas drilling rig in Texas.

In the 19th century, natural gas was usually obtained as a by-product of producing oil, since the small, light gas carbon chains came out of solution as the extracted fluids underwent pressure reduction from the reservoir to the surface, similar to uncapping a soft drink bottle where the carbon dioxide effervesces. Unwanted natural gas was a disposal problem in the active oil fields. If there was not a market for natural gas near the wellhead it was virtually valueless since it had to be piped to the end user.

In the 19th century and early 20th century, such unwanted gas was usually burned off at oil fields. Today, unwanted gas (or stranded gas without a market) associated with oil extraction often is returned to the reservoir with 'injection' wells while awaiting a possible future market or to repressurize the formation, which can enhance extraction rates from other wells. In regions with a high natural gas demand (such as the US), pipelines are constructed when it is economically feasible to transport gas from a wellsite to an end consumer.

In addition to transporting gas via pipelines for use in power generation, other end uses for natural gas include export as liquefied natural gas (LNG) or conversion of natural gas into other liquid products via gas-to-liquids (GTL) technologies. GTL technologies can convert natural gas into liquids products such as gasoline, diesel or jet fuel. A variety of GTL technologies have been developed, including Fischer–Tropsch (F–T), methanol to gasoline (MTG) and STG+. F–T produces a synthetic crude that can be further refined into finished products, while MTG can produce synthetic gasoline from natural gas. STG+ can produce drop-in gasoline, diesel, jet fuel and aromatic chemicals directly from natural gas via a single-loop process. In 2011, Royal Dutch Shell's 140,000 barrel per day F–T plant went into operation in Qatar.

Natural gas can be "associated" (found in oil fields), or "non-associated" (isolated in natural gas fields), and is also found in coal beds (as coalbed methane). It sometimes contains a significant amount of ethane, propane, butane, and pentane—heavier hydrocarbons removed for commercial use prior to the methane being sold as a consumer fuel or chemical plant feedstock. Non-hydrocarbons such as carbon dioxide, nitrogen, helium (rarely), andhydrogen sulfide must also be removed before the natural gas can be transported.

Natural gas extracted from oil wells is called casinghead gas (whether or not truly produced up the annulus and through a casinghead outlet) or associated gas. The natural gas industry is extracting an increasing quantity of gas from challenging resource types: sour gas, tight gas, shale gas, and coalbed methane.

There is some disagreement on which country has the largest proven gas reserves. Sources that consider that Russia has by far the largest proven reserves include the US CIA (47.6 trillion cubic meters), the US Energy Information Administration (47.8 tcm), and OPEC (48.7 tcm). However, BP credits Russia with only 32.9 tcm, which would place it in second place, slightly behind Iran (33.1 to 33.8 tcm, depending on the source). With Gazprom, Russia is frequently the world's largest natural gas extractor. Major proven resources (in billion cubic meters) are world 187,300 (2013), Iran 33,600 (2013), Russia 32,900 (2013), Qatar 25,100 (2013), Turkmenistan 17,500 (2013) and the United States 8,500 (2013).

It is estimated that there are about 900 trillion cubic meters of “unconventional” gas such as shale gas, of which 180 trillion may be recoverable. In turn, many studies from MIT, Black & Veatchand the DOE predict that natural gas will account for a larger portion of electricity generation and heat in the future.

The world’s largest gas field is the offshore South Pars / North Dome Gas-Condensate field, shared between Iran and Qatar. It is estimated to have 51 trillion cubic meters of natural gas and 50 billion barrels of natural gas condensates.

Because natural gas is not a pure product, as the reservoir pressure drops when non-associated gas is extracted from a field under supercritical (pressure/temperature) conditions, the higher molecular weight components may partially condense upon isothermic depressurizing—an effect called retrograde condensation. The liquid thus formed may get trapped as the pores of the gas reservoir get depleted. One method to deal with this problem is to re-inject dried gas free of condensate to maintain the underground pressure and to allow re-evaporation and extraction of condensates. More frequently, the liquid condenses at the surface, and one of the tasks of the gas plant is to collect this condensate. The resulting liquid is called natural gas liquid (NGL) and has commercial value.

Shale gas

Shale gas is natural gas produced from shale. Because shale has matrix permeability too low to allow gas to flow in economical quantities, shale gas wells depend on fractures to allow the gas to flow. Early shale gas wells depended on natural fractures through which gas flowed; almost all shale gas wells today require fractures artificially created by hydraulic fracturing. Since 2000, shale gas has become a major source of natural gas in the United States and Canada. Following the success in the United States, shale gas exploration is beginning in countries such as Poland, China, and South Africa. With the increase of shale production it has caused the United States to become the number one natural gas producer in the world.

Town Gas

Town gas is a flammable gaseous fuel made by the destructive distillation of coal and contains a variety of calorific gases including hydrogen, carbon monoxide, methane, and other volatile hydrocarbons, together with small quantities of non-calorific gases such as carbon dioxide and nitrogen, and is used in a similar way to natural gas. This is a historical technology, not usually economically competitive with other sources of fuel gas today. But there are still some specific cases where it is the best option and it may be so into the future.

Most town “gashouses” located in the eastern US in the late 19th and early 20th centuries were simple by-product coke ovens that heated bituminous coal in air-tight chambers. The gas driven off from the coal was collected and distributed through networks of pipes to residences and other buildings where it was used for cooking and lighting. (Gas heating did not come into widespread use until the last half of the 20th century.) The coal tar (or asphalt) that collected in the bottoms of the gashouse ovens was often used for roofing and other waterproofing purposes, and when mixed with sand and gravel was used for paving streets.

Biogas

Methanogenic archaea are responsible for all biological sources of methane. Some live in symbiotic relationships with other life forms, including termites, ruminants, and cultivated crops. Other sources of methane, the principal component of natural gas, include landfill gas, biogas, and methane hydrate. When methane-rich gases are produced by the anaerobic decay of non-fossilorganic matter (biomass), these are referred to as biogas (or natural biogas). Sources of biogas include swamps, marshes, and landfills (see landfill gas), as well as agricultural waste materials such as sewage sludge and manure by way of anaerobic digesters, in addition to enteric fermentation, particularly in cattle. Landfill gas is created by decomposition of waste in landfill sites. Excluding water vapor, about half of landfill gas is methane and most of the rest is carbon dioxide, with small amounts of nitrogen, oxygen, and hydrogen, and variable trace amounts of hydrogen sulfide and siloxanes. If the gas is not removed, the pressure may get so high that it works its way to the surface, causing damage to the landfill structure, unpleasant odor, vegetation die-off, and an explosion hazard. The gas can be vented to the atmosphere, flared or burned to produce electricity or heat. Biogas can also be produced by separating organic materials from waste that otherwise goes to landfills. This method is more efficient than just capturing the landfill gas it produces. Anaerobic lagoons produce biogas from manure, while biogas reactors can be used for manure or plant parts. Like landfill gas, biogas is mostly methane and carbon dioxide, with small amounts of nitrogen, oxygen and hydrogen. However, with the exception of pesticides, there are usually lower levels of contaminants.

Landfill gas cannot be distributed through utility natural gas pipelines unless it is cleaned up to less than 3 per cent CO_2, and a few parts per million H_2S, because CO_2 and H_2S corrode the pipelines. The presence of CO_2 will lower the energy level of the gas

below requirements for the pipeline. Siloxanes in the gas will form deposits in gas burners and need to be removed prior to entry into any gas distribution or transmission system. Consequently it may be more economical to burn the gas on site or within a short distance of the landfill using a dedicated pipeline. Water vapor is often removed, even if the gas is burned on site. If low temperatures condense water out of the gas, siloxanes can be lowered as well because they tend to condense out with the water vapor. Other non-methane components may also be removed to meet emission standards, to prevent fouling of the equipment or for environmental considerations. Co-firing landfill gas with natural gas improves combustion, which lowers emissions.

Biogas, and especially landfill gas, are already used in some areas, but their use could be greatly expanded. Experimental systems were being proposed for use in parts of Hertfordshire, UK, and Lyon in France. Using materials that would otherwise generate no income, or even cost money to get rid of, improves the profitability and energy balance of biogas production. Gas generated in sewage treatment plants is commonly used to generate electricity. For example, the Hyperion sewage plant in Los Angeles burns 8 million cubic feet (230,000 m^3) of gas per day to generate power New York City utilizes gas to run equipment in the sewage plants, to generate electricity, and in boilers. Using sewage gas to make electricity is not limited to large cities. The city of Bakersfield, California, uses cogeneration at its sewer plants. California has 242 sewage wastewater treatment plants, 74 of which have installed anaerobic digesters. The total biopower generation from the 74 plants is about 66 MW.

Crystallized Natural Gas—Hydrates



Figure 3. The McMahon natural gas processing plant in Taylor, British Columbia, Canada.

Huge quantities of natural gas (primarily methane) exist in the form of hydrates under sediment on offshore continental shelves and on land in arctic regions that experience permafrost, such as those in Siberia. Hydrates require a combination of high pressure and low temperature to form.

In 2010, the cost of extracting natural gas from crystallized natural gas was estimated to 100–200 per cent the cost of extracting natural gas from conventional sources, and even higher from offshore deposits.

In 2013, Japan Oil, Gas and Metals National Corporation (JOGMEC) announced that they had recovered commercially relevant quantities of natural gas from methane hydrate.

Depletion

Natural gas production in the U.S. reached a peak in 1973, and went over a second lower peak in 2001, but recently has peaked again and is continuing to rise.

Uses

Mid-Stream Natural Gas

Natural gas flowing in the distribution lines and at the natural gas well head are often used to power natural gas powered engines. These engines rotate compressors to facilitate the natural gas transmission. These compressors are required in the mid-stream line to pressurize and to re-pressurize the natural gas in the transmission line as the gas travels. The natural gas transmission lines extend to the natural gas processing plant or unit which removes the higher molecular weighted natural gas hydrocarbons to produce a British thermal unit (BTU) value between 950 and 1050 BTUs. The processed natural gas may then be used for residential, commercial and industrial uses.

Often mid-stream and well head gases require removal of many of the various hydrocarbon species contained within the natural gas. Some of these gases include heptane, pentane, propane and other hydrocarbons with molecular weights above Methane (CH4) to produce a natural gas fuel which is used to operate the natural gas engines for further pressurized transmission. Typically, natural gas compressors require 950 to 1050 BTU per cubic foot to operate at the natural gas engines rotational name plate specifications.

Several methods are used to remove these higher molecular weighted gases for use at the natural gas engine. A few technologies are as follows:

- Joule–Thomson skid
- Cryogenic or chiller system
- Chemical enzymology system

Power Generation

Natural gas is a major source of electricity generation through the use of cogeneration, gas turbines and steam turbines. Natural gas is also well suited for a combined use in association with renewable energy sources such as wind or solar and for alimenting peak-load power stations functioning in tandem with hydroelectric plants. Most grid peaking power plants and some off-grid engine-generators use natural gas. Particularly high efficiencies can be achieved through combining gas turbines with a steam turbine in combined cycle mode. Natural gas burns more cleanly than other hydrocarbon fuels, such as oil and coal, and produces less carbon dioxide per unit of energy released. For transportation, burning natural gas produces about 30 per cent less carbon dioxide than burning petroleum. For an equivalent amount of heat, burning natural gas produces about 45 per cent less than burning coal for power. The US Energy Information Administration reports the following emissions in million metric tons of carbon dioxide in the world for 2012:

- Natural gas: 6,799
- Petroleum: 11,695
- Coal: 13,787

Coal-fired electric power generation emits around 2,000 pounds of carbon dioxide for every megawatt hour generated, which is almost double the carbon dioxide released by a natural gas-fired electric plant per megawatt hour generated. Because of this higher carbon efficiency of natural gas generation, as the fuel mix in the United States has changed to reduce coal and increase natural gas generation, carbon dioxide emissions have unexpectedly fallen. Those measured in the first quarter of 2012 were the lowest of any recorded for the first quarter of any year since 1992.

Combined cycle power generation using natural gas is currently the cleanest available source of power using hydrocarbon fuels, and this technology is widely and increasingly used as natural gas can be obtained at increasingly reasonable costs. Fuel cell technology may eventually provide cleaner options for converting natural gas into electricity, but as yet it is not price-competitive. Locally produced electricity and heat using natural gas powered Combined Heat and Power plant (CHP or Cogeneration plant) is considered energy efficient and a rapid way to cut carbon emissions. Natural gas power plants are increasing in popularity and generate 22% of the worlds total electricity. Approximately half as much as generated with coal.

Domestic Use

Natural gas dispensed from a simple stovetop can generate temperatures in excess of 1100 °C (2000 °F) making it a powerful domestic cooking and heating fuel. In much of the developed world it is supplied through pipes to homes, where it is used for many purposes including ranges and ovens, gas-heated clothes dryers, heating/cooling, and central heating. Heaters in homes and other buildings may include boilers, furnaces, and water heaters.

Compressed natural gas (CNG) is used in rural homes without connections to piped-in public utility services, or with portable grills. Natural gas is also supplied by independent natural gas suppliers through Natural Gas Choice programs throughout the United States. However, as CNG costs more than LPG, LPG (propane) is the dominant source of rural gas.



Figure 4. A Washington, D.C. Metrobus, which runs on natural gas.

CNG is a cleaner and also cheaper alternative to other automobile fuels such as gasoline (petrol) and diesel. By the end of 2012 there were 17.25 millionnatural gas vehicles worldwide, led by Iran (3.3 million), Pakistan (3.1 million), Argentina (2.18 million), Brazil (1.73 million), India (1.5 million), and China(1.5 million). The energy efficiency is generally equal to that of gasoline engines, but lower compared with modern diesel engines. Gasoline/petrol vehicles converted to run on natural gas suffer because of the low compression ratio of their engines, resulting in a cropping of delivered power while running on natural gas (10%–15%). CNG-specific engines, however, use a higher compression ratio due to this fuel's higher octane number of 120–130.

Contributors and Attributions

CC licensed content, Shared previously

- Natural gas. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Natural_gas. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 12.5: Reading- Natural Gas is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.6: Reading- Coal



Figure 1. Bituminous coal

Coal (from the Old English term *col*, which has meant “mineral of fossilized carbon” since the thirteent century)is a combustible black or brownish-black sedimentary rock usually occurring in rock strata in layers or veins called **coal beds** or **coal seams**. The harder forms, such as anthracite coal, can be regarded as metamorphic rock because of later exposure to elevated temperature and pressure. Coal is composed primarily of carbon along with variable quantities of other elements, chiefly hydrogen, sulfur, oxygen, and nitrogen.

Throughout history, coal has been used as an energy resource, primarily burned for the production of electricity and/or heat, and is also used for industrial purposes, such as refining metals. A fossil fuel, coal forms when dead plant matter is converted into peat, which in turn is converted into lignite, then sub-bituminous coal, after that bituminous coal, and lastly anthracite. This involves biological and geological processes that take place over a long period. The United States Energy Information Administration estimates coal reserves at 948×10^9 short tons (860 Gt). One estimate for resources is 18 000 Gt.

Coal is the largest source of energy for the generation of electricity worldwide, as well as one of the largest worldwide anthropogenic sources ofcarbon dioxide releases. In 1999, world gross carbon dioxide emissions from coal usage were 8,666 million tonnes of carbon dioxide. In 2011, world gross emissions from coal usage were 14,416 million tonnes. Coal-fired electric power generation emits around 2,000 pounds of carbon dioxide for every megawatt-hour generated, which is almost double the approximately 1100 pounds of carbon dioxide released by a natural gas-fired electric plant per megawatt-hour generated. Because of this higher carbon efficiency of natural gas generation, as the market in the United States has changed to reduce coal and increase natural gas generation, carbon dioxide emissions have fallen. Those measured in the first quarter of 2012 were the lowest of any recorded for the first quarter of any year since 1992 In 2013, the head of the UN climate agency advised that most of the world’s coal reserves should be left in the ground to avoid catastrophic global warming.

Coal is extracted from the ground by coal mining, either underground by shaft mining, or at ground level by open pit mining extraction. Since 1983 the world top coal producer has been China. In 2011 China produced 3,520 million tonnes of coal – 49.5% of 7,695 million tonnes world coal production. In 2011 other large producers were United States (993 million tonnes), India (589), European Union (576) and Australia (416). In 2010 the largest exporters were Australia with 328 million tonnes (27.1% of world coal export) and Indonesia with 316 million tonnes (26.1%), while the largest importers were Japan with 207 million tonnes (17.5% of world coal import), China with 195 million tonnes (16.6%) and South Korea with 126 million tonnes (10.7%).

Formation



Figure 2. Coastal exposure of the Point Aconi Seam (Nova Scotia)

At various times in the geologic past, the Earth had dense forests in low-lying wetland areas. Due to natural processes such as flooding, these forests were buried underneath soil. As more and more soil deposited over them, they were compressed. The temperature also rose as they sank deeper and deeper. As the process continued the plant matter was protected from biodegradation and oxidation, usually by mud or acidic water. This trapped the carbon in immense peat bogs that were eventually covered and deeply buried by sediments. Under high pressure and high temperature, dead vegetation was slowly converted to coal. As coal contains mainly carbon, the conversion of dead vegetation into coal is called carbonization.

The wide, shallow seas of the Carboniferous Period provided ideal conditions for coal formation, although coal is known from most geological periods. The exception is the coal gap in the Permian–Triassic extinction event, where coal is rare. Coal is known from Precambrian strata, which predate land plants—this coal is presumed to have originated from residues of algae.

Ranks

As geological processes apply pressure to dead biotic material over time, under suitable conditions, its metamorphic grade increases successively into:

- **Peat**, considered to be a precursor of coal, has industrial importance as a fuel in some regions, for example, Ireland and Finland. In its dehydrated form, peat is a highly effective absorbent for fuel and oil spills on land and water. It is also used as a conditioner for soil to make it more able to retain and slowly release water.
- **Lignite**, or brown coal, is the lowest rank of coal and used almost exclusively as fuel for electric power generation. Jet, a compact form of lignite, is sometimes polished and has been used as an ornamental stone since the Upper Palaeolithic.
- **Sub-bituminous coal**, whose properties range from those of lignite to those of bituminous coal, is used primarily as fuel for steam-electric power generation and is an important source of light aromatic hydrocarbons for the chemical synthesis industry.
- **Bituminous coal** is a dense sedimentary rock, usually black, but sometimes dark brown, often with well-defined bands of bright and dull material; it is used primarily as fuel in steam-electric power generation, with substantial quantities used for heat and power applications in manufacturing and to make coke.
- "**Steam coal**" is a grade between bituminous coal and anthracite, once widely used as a fuel for steam locomotives. In this specialized use, it is sometimes known as "sea-coal" in the United States. Small steam coal (dry small steam nuts or DSSN) was used as a fuel for domestic water heating.
- **Anthracite**, the highest rank of coal, is a harder, glossy black coal used primarily for residential and commercial space heating. It may be divided further into metamorphically altered bituminous coal and "petrified oil," as from the deposits in Pennsylvania.
- **Graphite**, technically the highest rank, is difficult to ignite and is not commonly used as fuel—it is mostly used in pencils and, when powdered, as a lubricant.

The classification of coal is generally based on the content of volatiles. However, the exact classification varies between countries. According to the German classification, coal is classified as follows:

German Classification	English Designation	Volatiles %	C Carbon %	H Hydrogen %	O Oxygen %	S Sulfur %	Heat content kJ/kg
Braunkohle	Lignite (brown coal)	45–65	60–75	6.0–5.8	34-17	0.5-3	<28,470
Flammkohle	Flame coal	40-45	75-82	6.0-5.8	>9.8	~1	<32,870
Gasflammkohle	Gas flame coal	35-40	82-85	5.8-5.6	9.8-7.3	~1	<33,910
Gaskohle	Gas coal	28-35	85-87.5	5.6-5.0	7.3-4.5	~1	<34,960
Fettkohle	Fat coal	19-28	87.5-89.5	5.0-4.5	4.5-3.2	~1	<35,380
Esskohle	Forge coal	14-19	89.5-90.5	4.5-4.0	3.2-2.8	~1	<35,380
Magerkohle	Nonbaking coal	10-14	90.5-91.5	4.0-3.75	2.8-3.5	~1	35,380
Anthrazit	Anthracite	7-12	>91.5	<3.75	<2.5	~1	<35,300
Note, the percentages are percent by mass of the indicated elements							

The middle six grades in the table represent a progressive transition from the English-language sub-bituminous to bituminous coal, while the last class is an approximate equivalent to anthracite, but more inclusive (US anthracite has < 6% volatiles).

Cannel coal (sometimes called “candle coal”) is a variety of fine-grained, high-rank coal with significant hydrogen content. It consists primarily of “exinite” macerals, now termed “liptinite.”

Hilt’s law

Hilt’s law is a geological term that states that, in a small area, the deeper the coal, the higher its rank (grade). The law holds true if the thermal gradient is entirely vertical, but metamorphism may cause lateral changes of rank, irrespective of depth.

Content

Average content

Substance	Content
Mercury (Hg)	0.10±0.01 ppm
Arsenic (As)	1.4 – 71 ppm
Selenium (Se)	3 ppm

Uses Today

Coal as Fuel



Figure 3. Castle Gate Power Plant near Helper, Utah, USA

Coal is primarily used as a solid fuel to produce electricity and heat through combustion. World coal consumption was about 7.25 billion tonnes in 2010 (7.99 billion short tons) and is expected to increase 48% to 9.05 billion tonnes (9.98 billion short tons) by

2030.

China produced 3.47 billion tonnes (3.83 billion short tons) in 2011. India produced about 578 million tonnes (637.1 million short tons) in 2011. 68.7% of China's electricity comes from coal. The USA consumed about 13% of the world total in 2010, i.e. 951 million tonnes (1.05 billion short tons), using 93% of it for generation of electricity. 46% of total power generated in the USA was done using coal.



Figure 4. Coal rail cars

When coal is used for electricity generation, it is usually pulverized and then combusted (burned) in a furnace with a boiler. The furnace heat converts boiler water to steam, which is then used to spin turbines which turn generators and create electricity. The thermodynamic efficiency of this process has been improved over time; some older coal-fired power stations have thermal efficiencies in the vicinity of 25% whereas the newest supercritical and "ultra-supercritical" steam cycle turbines, operating at temperatures over 600 °C and pressures over 27 MPa (over 3900 psi), can practically achieve thermal efficiencies in excess of 45% (LHV basis) using anthracite fuel, or around 43% (LHV basis) even when using lower-grade lignite fuel. Further thermal efficiency improvements are also achievable by improved pre-drying (especially relevant with high-moisture fuel such as lignite or biomass) and cooling technologies.

An alternative approach of using coal for electricity generation with improved efficiency is the integrated gasification combined cycle (IGCC) power plant. Instead of pulverizing the coal and burning it directly as fuel in the steam-generating boiler, the coal can be first gasified (see coal gasification) to create syngas, which is burned in a gas turbine to produce electricity (just like natural gas is burned in a turbine). Hot exhaust gases from the turbine are used to raise steam in a heat recovery steam generator which powers a supplemental steam turbine. Thermal efficiencies of current IGCC power plants range from 39-42% (HHV basis) or ~42-45% (LHV basis) for bituminous coal and assuming utilization of mainstream gasification technologies (Shell, GE Gasifier, CB&I). IGCC power plants outperform conventional pulverized coal-fueled plants in terms of pollutant emissions, and allow for relatively easy carbon capture.

At least 40% of the world's electricity comes from coal, and in 2012, about one-third of the United States' electricity came from coal, down from approximately 49% in 2008. As of 2012 in the United States, use of coal to generate electricity was declining, as plentiful supplies of natural gas obtained by hydraulic fracturing of tight shale formations became available at low prices.

In Denmark, a net electric efficiency of > 47% has been obtained at the coal-fired Nordjyllandsværket CHP Plant and an overall plant efficiency of up to 91% with cogeneration of electricity and district heating. The multifuel-fired Avedøreværket CHP Plant just outside Copenhagen can achieve a net electric efficiency as high as 49%. The overall plant efficiency with cogeneration of electricity and district heating can reach as much as 94%.

An alternative form of coal combustion is as coal-water slurry fuel (CWS), which was developed in the Soviet Union. CWS significantly reduces emissions, improving the heating value of coal. Other ways to use coal are combined heat and power cogeneration and an MHD topping cycle.

The total known deposits recoverable by current technologies, including highly polluting, low-energy content types of coal (i.e., lignite, bituminous), is sufficient for many years. However, consumption is increasing and maximal production could be reached within decades (see world coal reserves, below). On the other hand much may have to be left in the ground to avoid climate change.

Gasification

Coal gasification can be used to produce syngas, a mixture of carbon monoxide (CO) and hydrogen (H_2) gas. Often syngas is used to fire gas turbines to produce electricity, but the versatility of syngas also allows it to be converted into transportation fuels, such as gasoline and diesel, through the Fischer-Tropsch process; alternatively, syngas can be converted into methanol, which can be blended into fuel directly or converted to gasoline via the methanol to gasoline process.[59] Gasification combined with Fischer-Tropsch technology is currently used by the Sasol chemical company of South Africa to make motor vehicle fuels from coal and natural gas. Alternatively, the hydrogen obtained from gasification can be used for various purposes, such as powering ahydrogen economy, making ammonia, or upgrading fossil fuels.

During gasification, the coal is mixed with oxygen and steam while also being heated and pressurized. During the reaction, oxygen and water molecules oxidize the coal into carbon monoxide (CO), while also releasing hydrogen gas (H_2). This process has been conducted in both underground coal mines and in the production of town gas.

$$C\ (as\ Coal) + O_2 + H_2O \rightarrow H_2 + CO$$

If the refiner wants to produce gasoline, the syngas is collected at this state and routed into a Fischer-Tropsch reaction. If hydrogen is the desired end-product, however, the syngas is fed into thewater gas shift reaction, where more hydrogen is liberated.

$$CO + H_2O \rightarrow CO_2 + H_2$$

In the past, coal was converted to make coal gas (town gas), which was piped to customers to burn for illumination, heating, and cooking.

Liquefaction

Coal can also be converted into synthetic fuels equivalent to gasoline or diesel by several different direct processes (which do not intrinsically require gasification or indirect conversion). In the direct liquefaction processes, the coal is either hydrogenated or carbonized. Hydrogenation processes are the Bergius process, the SRC-I and SRC-II (Solvent Refined Coal) processes, the NUS Corporation hydrogenation process and several other single-stage and two-stage processes. In the process of low-temperature carbonization, coal is coked at temperatures between 360 and 750 °C (680 and 1,380 °F). These temperatures optimize the production of coal tars richer in lighter hydrocarbons than normal coal tar. The coal tar is then further processed into fuels. An overview of coal liquefaction and its future potential is available.

Coal liquefaction methods involve carbon dioxide (CO_2) emissions in the conversion process. If coal liquefaction is done without employing either carbon capture and storage (CCS) technologies or biomass blending, the result is lifecycle greenhouse gas footprints that are generally greater than those released in the extraction and refinement of liquid fuel production from crude oil. If CCS technologies are employed, reductions of 5–12% can be achieved in Coal to Liquid (CTL) plants and up to a 75% reduction is achievable when co-gasifying coal with commercially demonstrated levels of biomass (30% biomass by weight) in coal/biomass-to-liquids plants. For future synthetic fuel projects, carbon dioxide sequestration is proposed to avoid releasing CO_2 into the atmosphere. Sequestration adds to the cost of production.

Refined Coal

Refined coal is the product of a coal-upgrading technology that removes moisture and certain pollutants from lower-rank coals such as sub-bituminous and lignite (brown) coals. It is one form of several precombustion treatments and processes for coal that alter coal's characteristics before it is burned. The goals of precombustion coal technologies are to increase efficiency and reduce emissions when the coal is burned. Depending on the situation, precombustion technology can be used in place of or as a supplement to postcombustion technologies to control emissions from coal-fueled boilers.

Industrial Processes

Finely ground bituminous coal, known in this application as sea coal, is a constituent of foundry sand. While the molten metal is in the mould, the coal burns slowly, releasing reducing gases at pressure, and so preventing the metal from penetrating the pores of the sand. It is also contained in "mould wash," a paste or liquid with the same function applied to the mould before casting. Sea coal

can be mixed with the clay lining (the “bod”) used for the bottom of a cupola furnace. When heated, the coal decomposes and the bod becomes slightly friable, easing the process of breaking open holes for tapping the molten metal.

Production of Chemicals

Coal is an important feedstock in production of a wide range of chemical fertilizers and other chemical products. The main route to these products is coal gasification to produce syngas. Primary chemicals that are produced directly from the syngas include methanol, hydrogen and carbon monoxide, which are the chemical building blocks from which a whole spectrum of derivative chemicals are manufactured, including olefins, acetic acid, formaldehyde, ammonia,urea and others. The versatility of syngas as a precursor to primary chemicals and high-value derivative products provides the option of using relatively inexpensive coal to produce a wide range of valuable commodities.

Historically, production of chemicals from coal has been used since the 1950s and has become established in the market. According to the 2010 Worldwide Gasification Database, a survey of current and planned gasifiers, from 2004 to 2007 chemical production increased its gasification product share from 37% to 45%. From 2008 to 2010, 22% of new gasifier additions were to be for chemical production.

Because the slate of chemical products that can be made via coal gasification can in general also use feedstocks derived from natural gas and petroleum, the chemical industry tends to use whatever feedstocks are most cost-effective. Therefore, interest in using coal tends to increase for higher oil and natural gas prices and during periods of high global economic growth that may strain oil and gas production. Also, production of chemicals from coal is of much higher interest in countries like South Africa, China, India and the United States where there are abundant coal resources. The abundance of coal combined with lack of natural gas resources in China is strong inducement for the coal to chemicals industry pursued there. In the United States, the best example of the industry is Eastman Chemical Company which has been successfully operating a coal-to-chemicals plant at its Kingsport, Tennessee, site since 1983. Similarly, Sasol has built and operated coal-to-chemicals facilities in South Africa.

Coal to chemical processes do require substantial quantities of water. As of 2013 much of the coal to chemical production was in the People’s Republic of China where environmental regulation and water management was weak.

World Coal Reserves

The 948 billion short tons of recoverable coal reserves estimated by the Energy Information Administration are equal to about 4,196 BBOE (billion barrels of oil equivalent). The amount of coal burned during 2007 was estimated at 7.075 billion short tons, or 133.179 quadrillion BTU’s. This is an average of 18.8 million BTU per short ton. In terms of heat content, this is about 57,000,000 barrels (9,100,000 m^3) of oil equivalent per day. By comparison in 2007, natural gas provided 51,000,000 barrels (8,100,000 m^3) of oil equivalent per day, while oil provided 85,800,000 barrels (13,640,000 m^3) per day.



Figure 5. A coal mine in Wyoming, United States. The United States has the world’s largest coal reserves.

British Petroleum, in its 2007 report, estimated at 2006 end that there were 147 years reserves-to-production ratio based on *proven* coal reserves worldwide. This figure only includes reserves classified as “proven”; exploration drilling programs by mining companies, particularly in under-explored areas, are continually providing new reserves. In many cases, companies are aware of coal deposits that have not been sufficiently drilled to qualify as “proven.” However, some nations haven’t updated their information and assume reserves remain at the same levels even with withdrawals.

Of the three fossil fuels, coal has the most widely distributed reserves; coal is mined in over 100 countries, and on all continents except Antarctica. The largest reserves are found in the United States, Russia, China, Australia and India.

Contributors and Attributions

CC licensed content, Shared previously

- Coal. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Coal. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 12.6: Reading- Coal is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.7: Self Check- Rock and Mineral Resources

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1130

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 12.7: Self Check- Rock and Mineral Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.8: Outcome- Extraction of Resources

Describe some of the extraction methods and identify different types of mining.

In order to use the resources at our disposal, we need to be able to get to them. This section introduces the different techniques used to extract or remove these resources.

What You'll Learn to Do

- Describe the processes involved in mining.
- Identify the effects of different types of mining: surface mining, underground mining and open pit mining.

Learning Activities

The learning activities for this section include the following:

- Reading: Mining
- Reading: Effects of Mining
- Self Check: Extraction Methods

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 12.8: Outcome- Extraction of Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.9: Reading- Mining



Figure 1. Surface coal mining

Mining is the extraction of valuable minerals or other geological materials from the earth from an orebody, lode, vein, seam, or reef, which forms the mineralized package of economic interest to the miner.

Ores recovered by mining include metals, coal, oil shale, gemstones, limestone, dimension stone, rock salt, potash, gravel, and clay. Mining is required to obtain any material that cannot be grown through agricultural processes, or created artificially in a laboratory or factory. Mining in a wider sense includes extraction of any non-renewable resource such as petroleum, natural gas, or even water.

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

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

Mine Development and Lifecycle

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

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

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

To gain access to the mineral deposit within an area it is often necessary to mine through or remove waste material which is not of immediate interest to the miner. The total movement of ore and waste constitutes the mining process. Often more waste than ore is mined during the life of a mine, depending on the nature and location of the ore body. Waste removal and placement is a major cost to the mining operator, so a detailed characterization of the waste material forms an essential part of the geological exploration program for a mining operation.

Once the analysis determines a given ore body is worth recovering, development begins to create access to the ore body. The mine buildings and processing plants are built, and any necessary equipment is obtained. The operation of the mine to recover the ore

begins and continues as long as the company operating the mine finds it economical to do so. Once all the ore that the mine can produce profitably is recovered, reclamation begins to make the land used by the mine suitable for future use.

Mining Techniques

Mining techniques can be divided into two common excavation types: surface mining and sub-surface (underground) mining. Today, surface mining is much more common, and produces, for example, 85% of minerals (excluding petroleum and natural gas) in the United States, including 98% of metallic ores.

Targets are divided into two general categories of materials: *placer deposits*, consisting of valuable minerals contained within river gravels, beach sands, and other unconsolidated materials; and *lode deposits*, where valuable minerals are found in veins, in layers, or in mineral grains generally distributed throughout a mass of actual rock. Both types of ore deposit, placer or lode, are mined by both surface and underground methods.

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

Surface Mining

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



Figure 2. Garzweiler surface mine, Germany

Open-Pit Mining

Open-pit mining, or **open-cast mining** is a surface mining technique of extracting rock or minerals from the earth by their removal from an open pit or borrow.

This form of mining differs from extractive methods that require tunneling into the earth, such as long wall mining. Open-pit mines are used when deposits of commercially useful minerals or rocks are found near the surface; that is, where the overburden (surface material covering the valuable deposit) is relatively thin or the material of interest is structurally unsuitable for tunneling (as would be the case for sand, cinder, and gravel). For minerals that occur deep below the surface—where the overburden is thick or the mineral occurs as veins in hard rock—underground mining methods extract the valued material.

Open-pit mines that produce building materials and dimension stone are commonly referred to as “quarries.”

Open-pit mines are typically enlarged until either the mineral resource is exhausted, or an increasing ratio of overburden to ore makes further mining uneconomic. When this occurs, the exhausted mines are sometimes converted to landfills for disposal of solid wastes. However, some form of water control is usually required to keep the mine pit from becoming a lake, if the mine is situated in a climate of considerable precipitation or if any layers of the pit forming the mine border productive aquifers.



Figure 3. Note the angled and stepped sides of the Sunrise Dam Gold Mine, Australia.

Open-cast mines are dug on benches, which describe vertical levels of the hole. These benches are usually on four to sixty meter intervals, depending on the size of the machinery that is being used. Many quarries do not use benches, as they are usually shallow.

Most walls of the pit are generally dug on an angle less than vertical, to prevent and minimize damage and danger from rock falls. This depends on how weathered the rocks are, and the type of rock, and also how many structural weaknesses occur within the rocks, such as a faults, shears, joints orfoliations.

The walls are stepped. The inclined section of the wall is known as the batter, and the flat part of the step is known as the bench or berm. The steps in the walls help prevent rock falls continuing down the entire face of the wall. In some instances additional ground support is required and rock bolts, cable bolts and shotcrete are used. De-watering bores may be used to relieve water pressure by drilling horizontally into the wall, which is often enough to cause failures in the wall by itself.

A haul road is usually situated at the side of the pit, forming a ramp up which trucks can drive, carrying ore and waste rock.

Waste rock is piled up at the surface, near the edge of the open pit. This is known as the waste dump. The waste dump is also tiered and stepped, to minimize degradation.

Ore which has been processed is known as tailings, and is generally a slurry. This is pumped to a tailings dam or settling pond, where the water evaporates. Tailings dams can often be toxic due to the presence of unextracted sulfide minerals, some forms of toxic minerals in the gangue, and often cyanide which is used to treat gold ore via the cyanide leach process. This toxicity can harm the surrounding environment.

Typical Open Cut Grades

Gold is generally extracted in open-pit mines at 1 to 2 ppm (parts per million) but in certain cases, 0.75 ppm gold is economical. This was achieved by bulk heap leaching at the Peak Hill mine in western New South Wales, near Dubbo, Australia.

Nickel, generally as laterite, is extracted via open-pit down to 0.2%. Copper is extracted at grades as low as 0.15% to 0.2%, generally in massive open-pit mines in Chile, where the size of the resources and favorable metallurgy allows economies of scale.

Materials typically extracted from open-pit mines include:

- Bitumen
- Clay
- Coal
- Copper
- Coquina
- Diamonds
- Gravel and stone (stone refers to bedrock, while gravel is unconsolidated material)
- Granite
- Gritstone
- Gypsum
- Limestone
- Marble
- Metal ores, such as Copper, Iron, Gold, Silver and Molybdenum
- Uranium
- Phosphate



Figure 4. Mantrip used for transporting miners within an underground mine

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

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

Machines

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

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



Figure 5. The Bagger 288 is a bucket-wheel excavator used in strip mining. It is also the largest land vehicle of all time.

Processing

Once the mineral is extracted, it is often then processed. The science of extractive metallurgy is a specialized area in the science of metallurgy that studies the extraction of valuable metals from their ores, especially through chemical or mechanical means.

Mineral processing (or mineral dressing) is a specialized area in the science of metallurgy that studies the mechanical means of crushing, grinding, and washing that enable the separation (extractive metallurgy) of valuable metals or minerals from their gangue (waste material). Processing of placer ore material consists of gravity-dependent methods of separation, such as sluice boxes. Only minor shaking or washing may be necessary to disaggregate (unclump) the sands or gravels before processing. Processing of ore from a lode mine, whether it is a surface or subsurface mine, requires that the rock ore be crushed and pulverized before extraction of the valuable minerals begins. After lode ore is crushed, recovery of the valuable minerals is done by one, or a combination of several, mechanical and chemical techniques.

Since most metals are present in ores as oxides or sulfides, the metal needs to be reduced to its metallic form. This can be accomplished through chemical means such as smelting or through electrolytic reduction, as in the case of aluminium. Geometallurgy combines the geologic sciences with extractive metallurgy and mining.

Mining Industry

Mining exists in many countries. London is known as the capital of global “mining houses” such as Rio Tinto Group, BHP Billiton, and Anglo American PLC. The US mining industry is also large, but it is dominated by the coal and other nonmetal minerals (e.g., rock and sand), and various regulations have worked to reduce the significance of mining in the United States. In 2007 the totalmarket capitalization of mining companies was reported at US$962 billion, which compares to a total global market cap of publicly traded companies of about US$50 trillion in 2007. In 2002, Chile and Peru were reportedly the major mining countries of South America. The mineral industry of Africa includes the mining of various minerals; it produces relatively little of the industrial metals copper, lead, and zinc, but according to one estimate has as a percent of world reserves 40% of gold, 60% of cobalt, and 90% of the world’s platinum group metals. Mining in India is a significant part of that country’s economy. In the developed world, mining in Australia, with BHP Billiton founded and headquartered in the country, and mining in Canada are particularly significant. For rare earth minerals mining, China reportedly controlled 95% of production in 2013.

Mining operations can be grouped into five major categories in terms of their respective resources. These are oil and gas extraction, coal mining, metal ore mining, nonmetallic mineral mining and quarrying, and mining support activities. Of all of these categories, oil and gas extraction remains one of the largest in terms of its global economic importance. Prospecting potential mining sites, a vital area of concern for the mining industry, is now done using sophisticated new technologies such as seismic prospecting and remote-sensing satellites. Mining is heavily affected by the prices of the commodity minerals, which are often volatile. The 2000s commodities boom (“commodities supercycle”) increased the prices of commodities, driving aggressive mining. In addition, the price of gold increased dramatically in the 2000s, which increased gold mining; for example, one study found that conversion of forest in the Amazon increased six-fold from the period 2003–2006 (292 ha/yr) to the period 2006–2009 (1,915 ha/yr), largely due to artisanal mining.

Safety

Safety has long been a concern in the mining business especially in sub-surface mining. The Courrières mine disaster, Europe’s worst mining accident, involved the death of 1,099 miners in Northern France on March 10, 1906. This disaster was surpassed only by the Benxihu Colliery accident in China on April 26, 1942, which killed 1,549 miners. While mining today is substantially safer than it was in previous decades, mining accidents still occur. Government figures indicate that 5,000 Chinese miners die in accidents each year, while other reports have suggested a figure as high as 20,000. Mining accidents continue worldwide, including accidents causing dozens of fatalities at a time such as the 2007 Ulyanovskaya Mine disaster in Russia, the 2009 Heilongjiang mine explosion in China, and the 2010 Upper Big Branch Mine disaster in the United States.

Mining ventilation is a significant safety concern for many miners. Poor ventilation inside sub-surface mines causes exposure to harmful gases, heat, and dust, which can cause illness, injury, and death. The concentration of methane and other airborne contaminants underground can generally be controlled by dilution (ventilation), capture before entering the host air stream (methane drainage), or isolation (seals and stoppings). Rock dusts, including coal dust and silicon dust, can cause long-term lung problems including silicosis, asbestosis, and pneumoconiosis (also known as miners lung or black lungdisease). A ventilation

system is set up to force a stream of air through the working areas of the mine. The air circulation necessary for effective ventilation of a mine is generated by one or more large mine fans, usually located above ground. Air flows in one direction only, making circuits through the mine such that each main work area constantly receives a supply of fresh air. Watering down in coal mines also helps to keep dust levels down: by spraying the machine with water and filtering the dust-laden water with a scrubber fan, miners can successfully trap the dust.

Gases in mines can poison the workers or displace the oxygen in the mine, causing asphyxiation. For this reason, the U.S. Mine Safety and Health Administration requires that groups of miners in the United States carry gas detection equipment that can detect common gases, such as CO, O_2, H_2S, CH_4, as well as calculate % Lower Explosive Limit. Regulation requires that all production stop if there is a concentration of 1.4% of flammable gas present. Additionally, further regulation is being requested for more gas detection as newer technology such as nanotechnology is introduced.

Ignited methane gas is a common source of explosions in coal mines, which in turn can initiate more extensive coal dust explosions. For this reason, rock dusts such as limestone dust are spread throughout coal mines to diminish the chances of coal dust explosions as well as to limit the extent of potential explosions, in a process known as rock dusting. Coal dust explosions can also begin independently of methane gas explosions. Frictional heat and sparks generated by mining equipment can ignite both methane gas and coal dust. For this reason, water is often used to cool rock-cutting sites.

Miners utilize equipment strong enough to break through extremely hard layers of the Earth's crust. This equipment, combined with the closed work space in which underground miners work, can cause hearing loss. For example, a roof bolter (commonly used by mine roof bolter operators) can reach sound power levels of up to 115 dB. Combined with the reverberant effects of underground mines, a miner without proper hearing protection is at a high risk forhearing loss. By age 50, nearly 90% of U.S. coal miners have some hearing loss, compared to only 10% among workers not exposed to loud noises. Roof bolters are among the loudest machines, but auger miners, bulldozers, continuous mining machines, front end loaders, and shuttle cars and trucks are also among those machines most responsible for excessive noise in mine work.

Since mining entails removing dirt and rock from its natural location, thereby creating large empty pits, rooms, and tunnels, cave-ins as well as ground and rock falls are a major concern within mines. Modern techniques for timbering and bracing walls and ceilings within sub-surface mines have reduced the number of fatalities due to cave-ins, but ground falls continue to represent up to 50% of mining fatalities. Even in cases where mine collapses are not instantly fatal, they can trap mine workers deep underground. Cases such as these often lead to high-profile rescue efforts, such as when 33 Chilean miners were trapped deep underground for 69 days in 2010.

High temperatures and humidity may result in heat-related illnesses, including heat stroke, which can be fatal. The presence of heavy equipment in confined spaces also poses a risk to miners. To improve the safety of mine workers, modern mines use automation and remote operation including, for example, such equipment as automated loaders and remotely operated rockbreakers. However, despite modern improvements to safety practices, mining remains a dangerous occupation throughout the world.

Contributors and Attributions

CC licensed content, Original

- Revision and adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY-SA: Attribution-ShareAlike*

CC licensed content, Shared previously

- Mining. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Mining. **License**: *CC BY-SA: Attribution-ShareAlike*
- Open-pit mining. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Open-pit_mining. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 12.9: Reading- Mining is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.10: Reading- Effects of Mining

Environmental Effects

Environmental issues can include erosion, formation of sinkholes, loss of biodiversity, and contamination of soil, groundwater and surface water by chemicals from mining processes. In some cases, additional forest logging is done in the vicinity of mines to create space for the storage of the created debris and soil. Contamination resulting from leakage of chemicals can also affect the health of the local population if not properly controlled. Extreme examples of pollution from mining activities include coal fires, which can last for years or even decades, producing massive amounts of environmental damage.

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

Waste

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

The waste is classified as either sterile or mineralised, with acid generating potential, and the movement and storage of this material forms a major part of the mine planning process. When the mineralised package is determined by an economic cut-off, the near-grade mineralised waste is usually dumped separately with view to later treatment should market conditions change and it becomes economically viable. Civil engineering design parameters are used in the design of the waste dumps, and special conditions apply to high-rainfall areas and to seismically active areas. Waste dump designs must meet all regulatory requirements of the country in whose jurisdiction the mine is located. It is also common practice to rehabilitate dumps to an internationally acceptable standard, which in some cases means that higher standards than the local regulatory standard are applied.

Open-Pit Mining



Figure 1. Opencut coal mine loadout station and reclaimed land at the North Antelope Rochelle coal mine in Wyoming, United States.

After mining finishes, the mine area must undergo rehabilitation. Waste dumps are contoured to flatten them out, to further stabilise them. If the ore contains sulfides it is usually covered with a layer of clay to prevent access of rain and oxygen from the air, which can oxidise the sulfides to produce sulfuric acid, a phenomenon known as acid mine drainage. This is then generally covered with soil, and vegetation is planted to help consolidate the material. Eventually this layer will erode, but it is generally hoped that the rate of leaching or acid will be slowed by the cover such that the environment can handle the load of acid and associated heavy metals. There are no long term studies on the success of these covers due to the relatively short time in which large scale open pit mining has existed. It may take hundreds to thousands of years for some waste dumps to become “acid neutral” and stop leaching

to the environment. The dumps are usually fenced off to prevent livestock denuding them of vegetation. The open pit is then surrounded with afence, to prevent access, and it generally eventually fills up with ground water. In arid areas it may not fill due to deep groundwater levels.



Figure 2. An open-pit sulfur mine at Tarnobrzeg, Poland undergoing land rehabilitation

Metal Reserves and Recycling

During the twentieth century, the variety of metals used in society grew rapidly. Today, the development of major nations such as China and India and advances in technologies are fueling an ever greater demand. The result is that metal mining activities are expanding and more and more of the world's metal stocks are above ground in use rather than below ground as unused reserves. An example is the in-use stock of copper. Between 1932 and 1999, copper in use in the USA rose from 73 kilograms (161 lb) to 238 kilograms (525 lb) per person.

95% of the energy used to make aluminum from bauxite ore is saved by using recycled material. However, levels of metals recycling are generally low. In 2010, the International Resource Panel, hosted by the United Nations Environment Programme (UNEP), published reports on metal stocks that exist within society and their recycling rates.

The report's authors observed that the metal stocks in society can serve as huge mines above ground. However, they warned that the recycling rates of some rare metals used in applications such as mobile phones, battery packs for hybrid cars, and fuel cells are so low that unless future end-of-life recycling rates are dramatically stepped up these critical metals will become unavailable for use in modern technology.

Contributors and Attributions

CC licensed content, Original

- Revision and Adaptation. **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY-SA: Attribution-ShareAlike*

CC licensed content, Shared previously

- Open-pit mining. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Open-pit_mining. **License**: *CC BY-SA: Attribution-ShareAlike*
- Mining. **Provided by**: Wikipedia. **Located at**: http://en.Wikipedia.org/wiki/Mining. **License**: *CC BY-SA: Attribution-ShareAlike*

This page titled 12.10: Reading- Effects of Mining is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.11: Self Check- Extraction of Resources

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1131

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 12.11: Self Check- Extraction of Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.12: Outcome- Getting Energy from Resources

Describe geologic materials as current or potential energy resources and categorize sources as renewable or nonrenewable.

This section discusses the importance of both non-renewable and renewable resources. It also stresses the importance of resource conservation.

What You'll Learn to Do

- Identify available resources current or potential resources and as renewable or nonrenewable.
- Identify the type of energy currently consumed.
- Describe various ways to conserve resources and recognize alternative fuels options.

Learning Activities

The learning activities for this section include the following:

- Reading: Earth's Energy
- Reading: Energy Consumption on Earth
- Reading: Use and Conservation of Resources
- Self Check: Geologic Materials as Energy Sources

This page titled 12.12: Outcome- Getting Energy from Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.13: Reading- Earth's Energy

Much of Earth's energy comes from the Sun. Nearly all life on Earth depends on solar energy since plants use sunlight to make food through the process of photosynthesis. Photosynthesis was the process that fed plants and animals, which in turn, over the course of millions of years, became fossil fuels. The Sun heats some areas of Earth more than other areas, which causes wind. The Sun's energy also drives the water cycle, which moves water over the surface of the Earth. Some of these types of energy can be harnessed for use by people.

The other main source of energy is Earth's internal heat. This heat has two origins: the breakdown of chemical elements by radioactivity, and the heat that is left over from when the planet came together. These two sources will be described in more detail in later chapters.

Energy Resources

Everything requires energy. Even when you are sitting as still as you possibly can, your body is using energy to breathe, circulate blood, digest food, and perform many other functions. Producing light or heat requires energy. Making something requires energy. Plants and animals all require energy to function. To repeat, everything requires energy!

The Need for Energy



Figure 1. Electrical transmission towers like the one shown in this picture help deliver the electricity people use for energy every day.

Energy is the ability to do work or produce change. Every living thing needs energy to perform its daily functions and even more energy to grow. Plants get energy from the "food" they make by photosynthesis, and animals get energy directly or indirectly from that food. People also use energy for many things, such as cooking food, keeping ice cream cold in the freezer, heating a house, constructing a skyscraper, or lighting their homes. Because billions of people all around the world use energy, there is a huge need for energy resources (figure 1). Energy conservation is something everyone can do now to help reduce the strain on energy resources.

The **law of conservation of energy** says that energy cannot be created or destroyed. This means that even though energy changes form, the total amount of energy always stays the same. How does energy get converted from one type to another when you kick a soccer ball? When your body breaks down the food you eat, it stores the energy from the food as **chemical energy**. Chemical energy is stored within chemical bonds. But some of this stored energy has to be released to make your leg muscles move. The chemical energy is converted to another form of energy called **kinetic energy**. Kinetic energy is the energy of anything in motion. Your muscles move your leg, your foot kicks the ball, and the ball gains kinetic energy from the kick. So you can think of the action of kicking the ball as a story of energy changing forms.

To learn the quadratic equations related to getting a rapidly moving car to overcome its kinetic energy and come to a stop, watch this video:

A link to an interactive elements can be found at the bottom of this page.

Potential energy is energy that is stored. Potential energy has the potential to do work or the potential to be converted into other forms of energy. If a ball is sitting on the very edge at the top of the hill, it is not moving, but it has a lot of potential energy.

Animations showing the conversion of potential energy to kinetic energy can be seen at the following sites:

- Energy Transformation for Downhill Skiing

- Energy Transformation on a Roller Coaster
- Energy Transformation for a Dart

Energy, Fuel, and Heat

If you read a book beneath a lit lamp, that lamp has energy from electricity. The energy to make the electricity comes from **fuel.** Fuel has energy that it releases. A fuel is any material that can release energy in a chemical change.

What are some examples of fuel, and what are they used for?

1. Food is fuel for your body.
2. Sunlight is the energy plants need to make food by photosynthesis.
3. Gasoline is fuel for cars.
4. Hydrogen is fuel for the Sun.



Figure 2. A controlled fire.

For a fuel to be useful, its energy must be released in a way that can be controlled. Controlling the release of energy makes it possible for the energy to be used to do work. When fuel is used for its energy, it is usually burned, and most of the energy is released as **heat** (figure 2). The heat may then be used to do work. Think of a person striking a match to set some small twigs on fire. After the twigs burn for a while, they get hot enough to make some larger sticks burn. The fire keeps getting hotter, and soon it is hot enough to burn whole logs. Pretty soon the fire is roaring, and a pot of water placed on the fire starts to boil. Some of the liquid water evaporates.

What is the source of energy for boiling and evaporating the water? Although some chemical energy from the match was put into starting the fire, the heat to boil and evaporate the water comes from the energy that was stored in the wood. The wood is the fuel for the fire.

Types of Energy Resources



Figure 3. Anthracite coal is a non-renewable energy resource.

Energy resources are either renewable or non-renewable. **Non-renewable resources** are used faster than they can be replaced,so the supply available to society is limited (see example in figure 3). **Renewable resources** will not run out because they are replaced as quickly as they are used. Can you think of some renewable and non-renewable energy sources?

Non-renewable Resources

Fossil fuels—coal, oil, and natural gas—are the most common example of non-renewable energy resources. Fossil fuels are formed from fossils, the partially decomposed remains of once living plants and animals. These fossils took millions of years to form. When fossil fuels are burned for energy, they release pollutants into the atmosphere. Fossil fuels also release carbon dioxide and other greenhouse gases, which are causing global temperatures to rise. The environmental effects of fossil fuel use are discussed in the “Climate” and “Human Actions and the Atmosphere” chapters.

Renewable Resources

Renewable energy resources include solar, water, wind, biomass, and geothermal. These resources are either virtually limitless like the Sun, which will continue to shine for billions of years, or will be replaced faster than we can use them. Amounts of falling water or wind will change over the course of time, but they are quite abundant. Biomass energy, like wood for fire, can be replaced quickly.

The use of renewable resources may also cause problems. Some are expensive, while some, such as trees, have other uses. Some cause environmental problems. As the technology improves and more people use renewable energy, the prices may come down. At the same time, as we use up fossil fuels, coal, oil, and natural gas, these non-renewable resources will become more expensive. At some point, even if renewable energy costs are high, non-renewable energy will be even more expensive. Ultimately, we will have to use renewable sources.

Important Things to Consider about Energy Resources

With both renewable and non-renewable resources, there are at least two important things to consider. One is that we have to have a practical way to turn the resource into a useful form of energy. The other is that we have to consider what happens when we turn the resource into energy.

For example, if we get much less energy from burning a fuel than we put into making it, then that fuel is probably not a practical energy resource. On the other hand, if another fuel gives us large amounts of energy but creates large amounts of pollution, that fuel also may not be the best choice for an energy resource.

Today we rely on electricity more than ever, but the resources that currently supply our power are finite. The race is on to harness more renewable resources, but getting all that clean energy from production sites to homes and businesses is proving to be a major challenge.

A link to an interactive elements can be found at the bottom of this page.

Non-renewable Energy Resources

Millions of years ago, plants used energy from the Sun to form sugars, carbohydrates, and other energy-rich carbon compounds that were later transformed into coal, oil, or natural gas. The solar energy stored in these fuels is a rich source of energy. Although fossil fuels provide very high quality energy, they are non-renewable.

In large part, non-renewable energy sources are responsible for the world's lights seen in this animation.

Formation of Fossil Fuels



Figure 4. This wetland may look something like an ancient coal-forming swamp.

Can you name some fossils? How about dinosaur bones or dinosaur footprints? Animal skeletons, teeth, shells, coprolites (otherwise known as feces), or any other remains or trace from a living creature that becomes a rock is a **fossil**.

The same processes that formed these fossils also created some of our most important energy resources, **fossil fuels**. Coal, oil, and natural gas are fossil fuels. Fossil fuels come from living matter starting about 500 million years ago. As plants and animals died, their remains settled on the ground on land and in swamps, lakes, and seas (figure 4).

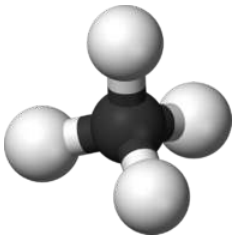


Figure 5. Hydrocarbons are made of carbon and hydrogen atoms. This molecule with one carbon and four hydrogen atoms is methane.

Over time, layer upon layer of these remains accumulated. Eventually, the layers were buried so deeply that they were crushed by an enormous mass of earth. The weight of this earth pressing down on these plant and animal remains created intense heat and pressure. After millions of years of heat and pressure, the material in these layers turned into chemicals called **hydrocarbons** (figure 5). Here is an animated view of a hydrocarbon.

Hydrocarbons can be solid, liquid, or gaseous. The solid form is what we know as coal. The liquid form is petroleum, or crude oil. Natural gas is the gaseous form.

Coal

Coal, a solid fossil fuel formed from the partially decomposed remains of ancient forests, is burned primarily to produce electricity. Coal use is undergoing enormous growth as the availability of oil and natural gas decreases and cost increases. This increase in coal use is happening particularly in developing nations, such as China, where coal is cheap and plentiful.

Coal Formation

Coal forms from dead plants that settled at the bottom of ancient swamps. Lush coal swamps were common in the tropics during the Carboniferous period, which took place more than 300 million years ago (figure 6). The climate was warmer then.

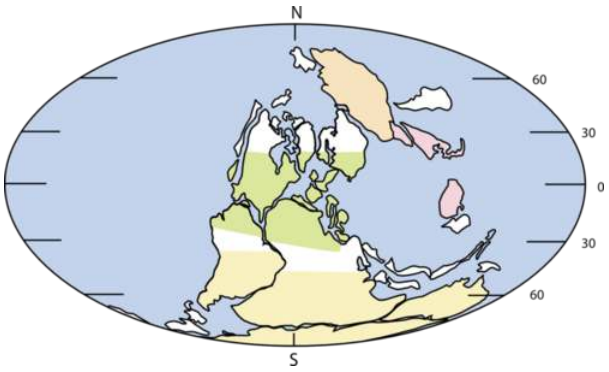


Figure 6. The location of the continents during the Carboniferous period. Notice that quite a lot of land area is in the region of the tropics.



Figure 7. Bituminous coal is a sedimentary rock.

Mud and other dead plants buried the organic material in the swamp, and burial kept oxygen away. When plants are buried without oxygen, the organic material can be preserved or fossilized. Sand and clay settling on top of the decaying plants squeezed out the water and other substances. Millions of years later, what remains is a carbon-containing rock that we know as coal.

Coal is black or brownish-black. The most common form of coal is bituminous, a sedimentary rock that contains impurities such as sulfur (figure 7). Anthracite coal, seen in figure 3, has been metamorphosed and is nearly all carbon. For this reason, anthracite coal burns more cleanly than bituminous coal.

Coal Use

Around the world, coal is the largest source of energy for electricity. The United States is rich in coal (figure 8). California once had a number of small coal mines, but the state no longer produces coal. To turn coal into electricity, the rock is crushed into powder, which is then burned in a furnace that has a boiler. Like other fuels, coal releases its energy as heat when it burns. Heat from the burning coal boils the water in the boiler to make steam. The steam spins turbines, which turn generators to create electricity. In this way, the energy stored in the coal is converted to useful energy like electricity.

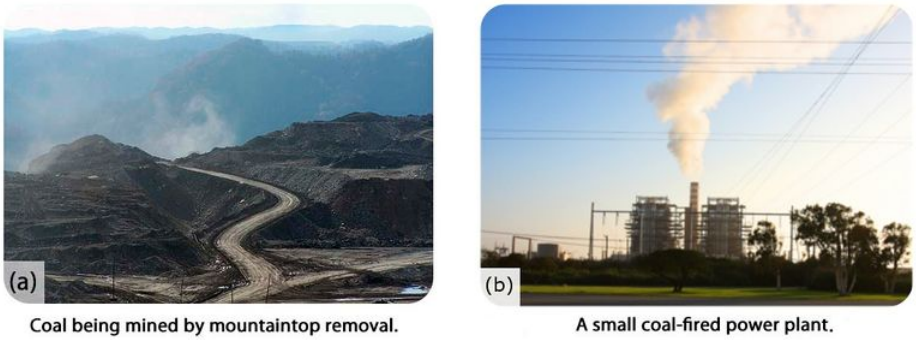


Figure 8. United States coal-producing regions in 1996. Orange is highest grade anthracite; red is low volatile bituminous; gray and gray-green is medium to high-volatile bituminous; green is subbituminous; and yellow is the lowest grade lignite

Coal that has been located but is not being used is part of our reserves. Reserves are important because if the price of the resource goes up or the cost of extracting it goes down, they may be useful.

Consequences of Coal Use

For coal to be used as an energy source, it must first be mined. Coal mining occurs at the surface or underground by methods that are described in the "Earth's Minerals" chapter (figure 9). Mining, especially underground mining, can be dangerous. In April 2010, twenty-nine miners were killed at a West Virginia coal mine when gas that had accumulated in the mine tunnels exploded and started a fire.



Coal being mined by mountaintop removal. A small coal-fired power plant.

Figure 9. The coal used in power plants must be mined. One method to mine coal is by mountaintop removal.

Some possible types of environmental damage from mining are discussed in the "Earth's Minerals" chapter. Coal mining exposes minerals and rocks from underground to air and water at the surface. Many of these minerals contain the element sulfur, which mixes with air and water to make sulfuric acid, a highly corrosive chemical. If the sulfuric acid gets into streams, it can kill fish, plants, and animals that live in or near the water.

Oil

Oil is a liquid fossil fuel that is extremely useful because it can be transported easily and can be used in cars and other vehicles. Oil is currently the single largest source of energy in the world.

Oil Formation

Oil from the ground is called **crude oil**, which is a mixture of many different hydrocarbons. Crude oil is a thick dark brown or black liquid hydrocarbon. Oil also forms from buried dead organisms, but these are tiny organisms that live on the sea surface and then sink to the seafloor when they die. The dead organisms are kept away from oxygen by layers of other dead creatures and sediments. As the layers pile up, heat and pressure increase. Over millions of years, the dead organisms turn into liquid oil.

Oil Production

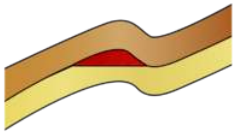


Figure 10. Oil (red) is found in the porous rock layer (yellow) and trapped by the impermeable layer (brown). The folded structure has allowed the oil to pool so a well can be drilled into the reservoir.

In order to be collected, the oil must be located between a porous rock layer and an impermeable layer (figure 10). Trapped above the porous rock layer and beneath the impermeable layer, the oil will remain between these layers until it is extracted from the rock.

- Here is an animation of an oil deposit forming.
- The oil pocket is then drilled into from the surface. Here is an animation of an oil deposit being drilled.
- Sideways drilling allows a deposit that lies beneath land that cannot be drilled to be mined for oil.

To separate the different types of hydrocarbons in crude oil for different uses, the crude oil must be refined in refineries like the one shown in figure 11. Refining is possible because each hydrocarbon in crude oil boils at a different temperature. When the oil is boiled in the refinery, separate equipment collects the different compounds.



Figure 11. Refineries like this one separate crude oil into many useful fuels and other chemicals.

Oil Use

Most of the compounds that come out of the refining process are fuels, such as gasoline, diesel, and heating oil. Because these fuels are rich sources of energy and can be easily transported, oil provides about 90% of the energy used for transportation around the world. The rest of the compounds from crude oil are used for waxes, plastics, fertilizers, and other products.

Gasoline is in a convenient form for use in cars and other transportation vehicles. In a car engine, the burned gasoline mostly turns into carbon dioxide and water vapor. The fuel releases most of its energy as heat, which causes the gases to expand. This creates enough force to move the pistons inside the engine and to power the car.

Consequences of Oil Use

The United States does produce oil, but the amount produced is only about one-quarter as much as the nation uses. The United States has only about 1.5% of the world's proven oil reserves, and so most of the oil used by Americans must be imported from other nations.

The main oil-producing regions in the United States are the Gulf of Mexico, Texas, Alaska, and California. Most offshore drilling occurs in the Gulf of Mexico, but there are offshore platforms in California as well (Figure 12). Here is an animation of the location of petroleum basins in the contiguous United States.

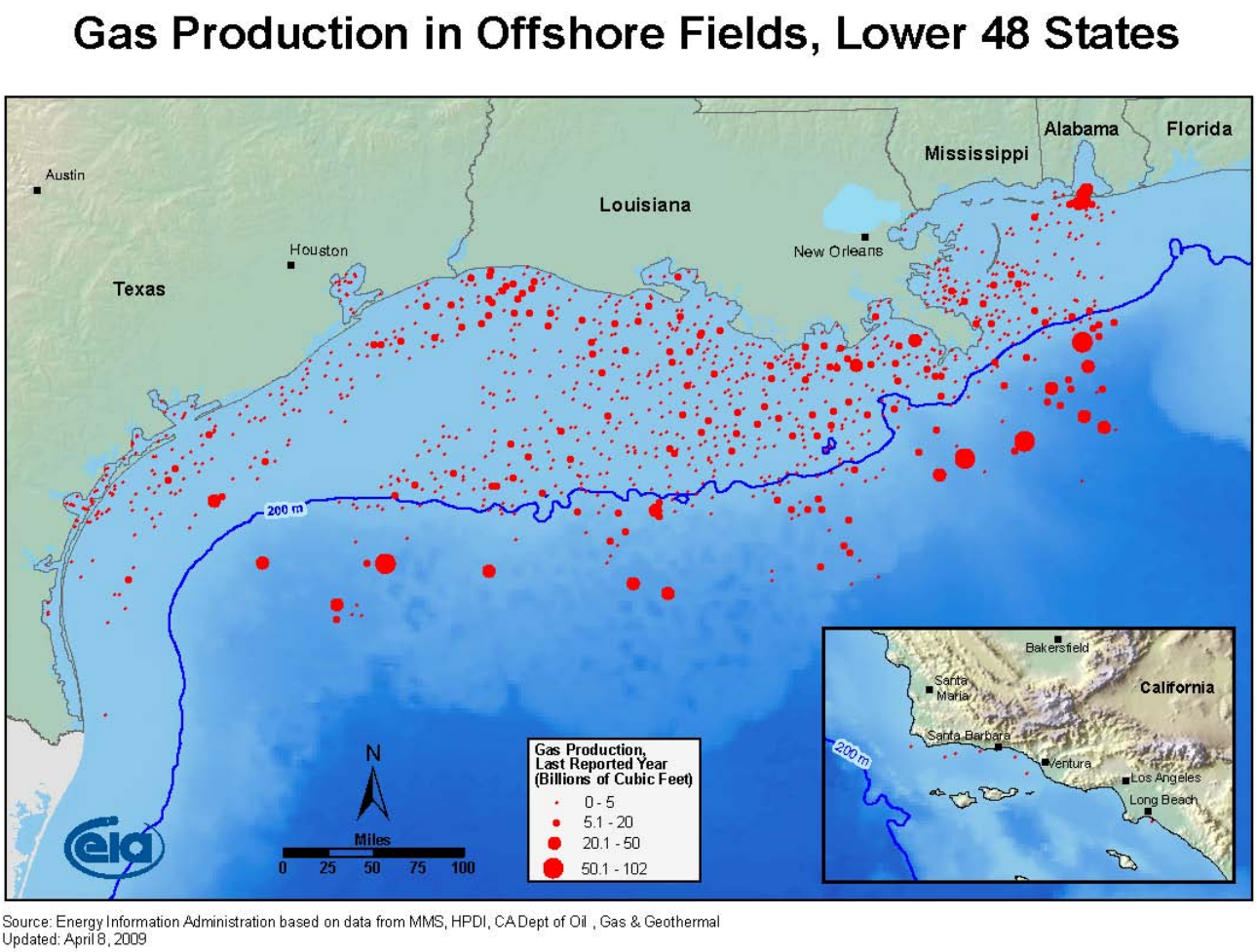
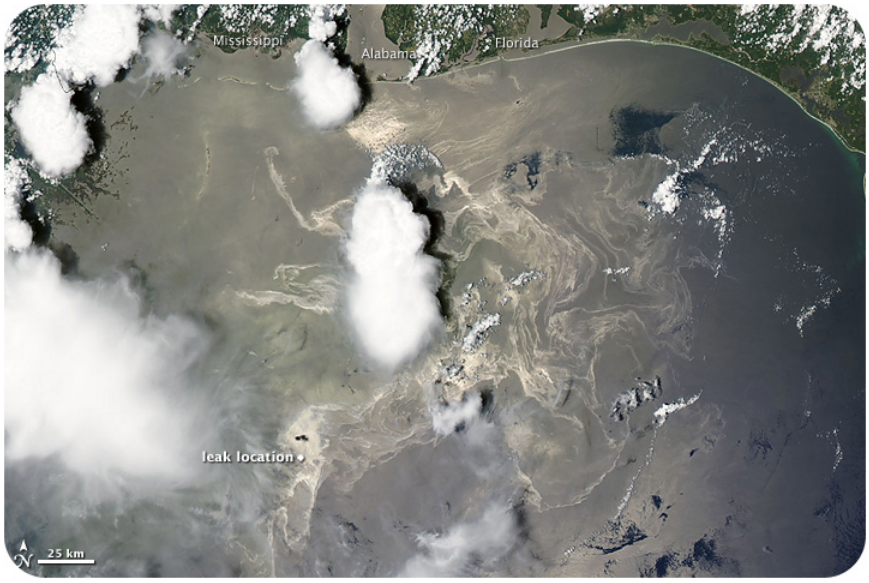


Figure 12. Offshore well locations in the Gulf of Mexico. Note that some wells are located in very deep water.

As in every type of mining, mining for oil has environmental consequences. Oil rigs are unsightly (figure 13), and spills are too common (figure 14).



Figure 13. Drill rigs at the San Ardo Oil Field in Monterey, California.



A deadly explosion on an oil rig in the Gulf of Mexico in April 2010 led to a massive oil spill. When this picture was taken in July 2010, oil was still spewing into the Gulf. The long-term consequences of the spill are being studied and are as yet unknown.

Natural Gas

Natural gas, often known simply as gas, is composed mostly of the hydrocarbon methane (refer to figure 5 for the structure).

Natural Gas Formation

Natural gas forms under the same conditions that create oil. Organic material buried in the sediments harden to become a shale formation that is the source of the gas. Although natural gas forms at higher temperatures than crude oil, the two are often found together. The formation of a minable oil and gas deposit is seen in this animation.

The largest natural gas reserves in the United States are in the Appalachian Basin, Texas, and the Gulf of Mexico region (Figure 15). California also has natural gas, found mostly in the Central Valley. In the northern Sacramento Valley and the Sacramento Delta, a sediment-filled trough formed along a location where crust was pushed together (an ancient convergent margin). Here is an animation of global natural gas reserves.



Figure 15. Gas production in the Lower 48 United States.

Natural Gas Use

Like crude oil, natural gas must be processed before it can be used as a fuel. Some of the chemicals in unprocessed natural gas are poisonous to humans. Other chemicals, such as water, make the gas less useful as a fuel. Processing natural gas removes almost

everything except the methane. Once the gas is processed, it is ready to be delivered and used. Natural gas is delivered to homes for uses such as cooking and heating. Like coal and oil, natural gas is also burned to generate heat for powering turbines. The spinning turbines turn generators, and the generators create electricity.

Consequences of Natural Gas Use



Figure 16. A natural gas drill rig.

Natural gas burns much cleaner than other fossil fuels, meaning that it causes less air pollution. Natural gas also produces less carbon dioxide than other fossil fuels do for the same amount of energy, so its global warming effects are less (figure 16). See the pollution created by a car burning gasoline and a car burning natural gas in this animation.

Unfortunately, drilling for natural gas can be environmentally destructive. One technique used is hydraulic fracturing, also called fracking, which increases the rate of recovery of natural gas. Fluids are pumped through a borehole to create fractures in the reservoir rock that contains the natural gas. Material is added to the fluid to prevent the fractures from closing. The damage comes primarily from chemicals in the fracturing fluids. Chemicals that have been found in the fluids may be carcinogens (cancer-causing), radioactive materials, or endocrine disruptors, which interrupt hormones in the bodies of humans and animals. The fluids may get into groundwater or may runoff into streams and other surface waters.

Fossil Fuel Reserves

Fossil fuels provide about 85% of the world's energy at this time. Worldwide fossil fuel usage has increased many times over in the past half century (coal: 2.6x, oil: 8x, natural gas: 14x) because of population increases, because of increases in the number of cars, televisions, and other fuel-consuming uses in the developed world, and because of lifestyle improvements in the developing world. Past and predicted use of different types of energy in the United States can be seen in this animation.

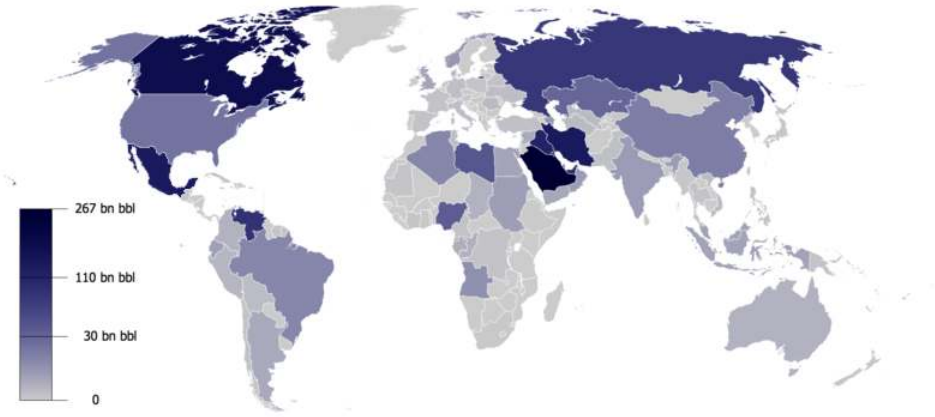


Figure 17. Worldwide oil reserves.

The amount of fossil fuels that remain untapped is unknown but can likely be measured in decades for oil and natural gas and in a few centuries for coal (figure 17). Alternative sources of fossil fuels, such as oil shales and tar sands, are increasingly being exploited (figure 18).



Figure 18. A satellite image of an oil-sands mine in Canada.

The environmental consequences of mining these fuels, and of fossil fuel use in general, along with the fact that these fuels do not have a limitless supply, are prompting the development of alternative energy sources.

Nuclear Energy

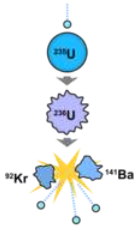


Figure 19. When struck by a tiny particle, Uranium-235 breaks apart and releases energy.

When the nucleus of an atom is split, it releases a huge amount of energy called **nuclear energy.** For nuclear energy to be used as a power source, scientists and engineers have learned to split nuclei and to control the release of energy (Figure 19).

Nuclear Energy Use

Nuclear power plants, such as the one seen in figure 20, use uranium, which is mined, processed, and then concentrated into fuel rods. When the uranium atoms in the fuel rods are hit by other extremely tiny particles, they split apart. The number of tiny particles allowed to hit the fuel rods needs to be controlled or they would cause a dangerous explosion. The energy from a nuclear power plant heats water, which creates steam and causes a turbine to spin. The spinning turbine turns a generator, which in turn produces electricity.



Figure 20. Nuclear power plants like this one provide France with almost 80% of its electricity.

Many countries around the world use nuclear energy as a source of electricity. In the United States, a little less than 20% of electricity comes from nuclear energy.

Consequences of Nuclear Power



Figure 21. Uranium mine in Kakadu National Park, Australia.

Nuclear power is clean. It does not pollute the air or release carbon dioxide. However, the use of nuclear energy does create other environmental problems. Uranium must be mined (figure 21). The process of splitting atoms creates radioactive waste, which remains dangerous for thousands or hundreds of thousands of years. As yet, there is no long-term solution for storing this waste.

The development of nuclear power plants has been on hold for three decades. Accidents at Three Mile Island and Chernobyl, Ukraine verified people's worst fears about the dangers of harnessing nuclear power (figure 22).



Figure 22. Damaged building near the site of the Chernobyl disaster.

Recently, nuclear power appeared to be making a comeback as society looked for alternatives to fossil fuels. But the 2011 disaster at the Fukushima Daiichi Nuclear Power Plant in Japan may have resulted in a new fear of nuclear power. The cause of the disaster was a 9.0 magnitude earthquake and subsequent tsunami, which compromised the plant. Although a total meltdown was averted, the plant experienced multiple partial meltdowns, core breaches, radiation releases, and cooling failures. The plant is scheduled for a complete cold shutdown before the end of 2011.

KQED: Nuclear Energy Use. Nuclear power is a controversial subject in California and most other places. Nuclear power has no pollutants including carbon emissions, but power plants are not always safe and the long-term disposal of wastes is a problem that has not yet been solved. The future of nuclear power is murky.

Renewable Energy Resources

Fossil fuels have the advantage of being cheap and transportable, but they cause environmental damage and will eventually run out. Renewable energy sources, by definition, will not run out, and most do not cause much pollution. But renewable energy sources do have a downside, too. Both the advantages and disadvantages of solar, water, wind, biomass, and geothermal energy will be described in this lesson.

Solar Power

The Sun is Earth's main source of energy, making the development of solar power a natural choice for an alternative energy source.

Solar Energy

Energy from the Sun comes from the lightest element, hydrogen, fusing together to create the second lightest element, helium. Nuclear fusion releases tremendous amounts of solar energy. The energy travels to the Earth, mostly as visible light. The light carries the energy through the empty space between the Sun and the Earth as **radiation**.

Solar Power Use

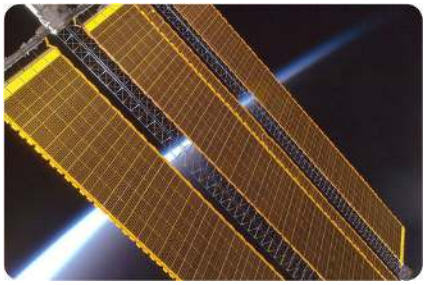


Figure 23. Solar panels supply power to the International Space Station.

Solar energy has been used for power on a small scale for hundreds of years, and plants have used it for billions of year. Unlike energy from fossil fuels, which almost always come from a central power plant or refinery, solar power can be harnessed locally (figure 23). A set of solar panels on a home's rooftop can be used to heat water for a swimming pool or can provide electricity to the house.

Society's use of solar power on a larger scale is just starting to increase. Scientists and engineers have very active, ongoing research into new ways to harness energy from the Sun more efficiently. Because of the tremendous amount of incoming sunlight, solar power is being developed in the United States in southeastern California, Nevada, and Arizona.

Solar power plants turn sunlight into electricity using a large group of mirrors to focus sunlight on one place, called a receiver (figure 24). A liquid, such as oil or water, flows through this receiver and is heated to a high temperature by the focused sunlight. The heated liquid transfers its heat to a nearby object that is at a lower temperature through a process called **conduction**. The energy conducted by the heated liquid is used to make electricity.



Figure 24. This solar power plant uses mirrors to focus sunlight on the tower in the center. The sunlight heats a liquid inside the tower to a very high temperature, producing energy to make electricity.

Here's a video of how solar energy can be concentrated so that it can be used for power.

Consequences of Solar Power Use



Figure 25. This experimental car is one example of the many uses that engineers have found for solar energy.

Solar energy has many benefits. It is extremely abundant, widespread, and will never run out. But there are problems with the widespread use of solar power.

- Sunlight must be present. Solar power is not useful in locations that are often cloudy or at night. However, storage technology is being developed.

- The technology needed for solar power is still expensive. An increase in interested customers will provide incentive for companies to research and develop new technologies and to figure out how to mass-produce existing technologies (figure 25).
- Solar panels require a lot of space. Fortunately, solar panels can be placed on any rooftop to supply at least some of the power required for a home or business.

Water Power

Water covers 70% of the planet's surface, and water power (hydroelectric power) is the most widely used form of renewable energy in the world. Hydroelectric power from streams provides almost one fifth of the world's electricity.

Hydroelectric Power

Remember that potential energy is the energy of an object waiting to fall. Water held behind a dam has a lot of potential energy. In a hydroelectric plant, a dam across a riverbed holds a stream to create a reservoir. Instead of flowing down its normal channel, the water is allowed to flow into a large turbine. As the water moves, it has kinetic energy, which makes the turbine spin. The turbine is connected to a generator, which makes electricity (figure 26).

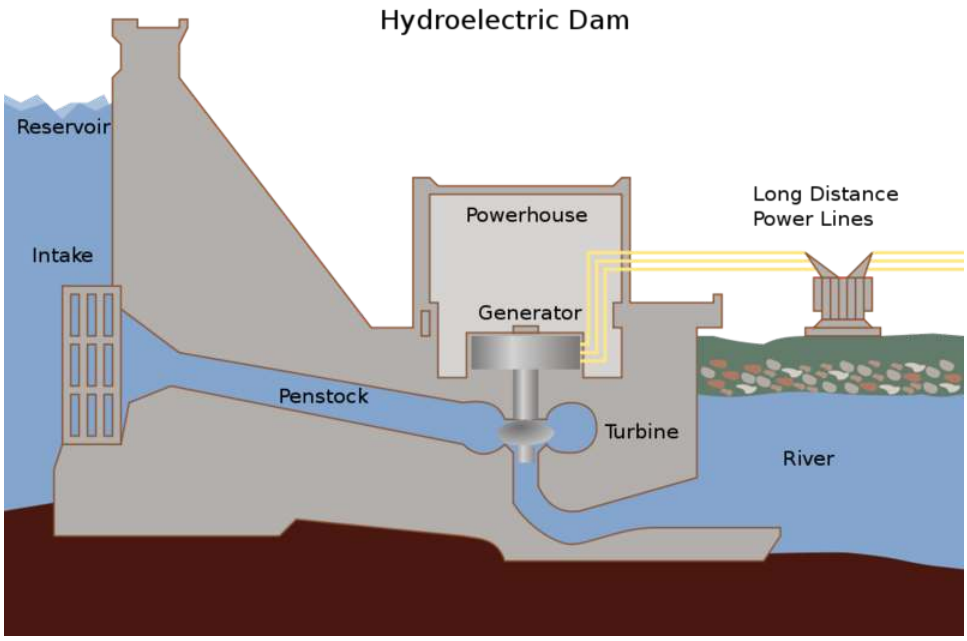


Figure 26. A cross-section of a hydroelectric plant.

Most of the streams in the United States and elsewhere in the developed world that are suitable for hydroelectric power have already been dammed (figure 27). In California, about 14.5% of the total electricity comes from hydropower. The state's nearly 400 hydropower plants are mostly located in the eastern mountain ranges where large streams descend down a steep grade.



Figure 27. Hydroelectric dams like this one use the power of moving water to create electricity.

Consequences of Water Power Use



Figure 28. Glen Canyon Dam in Arizona created Lake Powell. The dam was controversial because it flooded Glen Canyon, a beautiful desert canyon.

The major benefit of hydropower is that it generates power without releasing any pollution. Hydropower is also a renewable resource since the stream will keep on flowing. However, there are a limited number of suitable dam sites. Hydropower also has environmental problems. When a large dam disrupts a river's flow, it changes the ecosystem upstream. As the land is flooded by rising water, plants and animals are displaced or killed. Many beautiful landscapes, villages, and archeological sites have been drowned by the water in a reservoir (figure 28).

The dam and turbines also change the downstream environment for fish and other living things. Dams slow the release of silt so that downstream deltas retreat and seaside cities become dangerously exposed to storms and rising sea levels.

Ocean Water Power

The energy of waves and tides can be used to produce water power. Tidal power stations may need to close off a narrow bay or estuary. Wave power applications have to be able to withstand coastal storms and the corrosion of seawater. Because of the many problems with them, tide and wave power plants are not very common.

KQED: Harnessing Power from the Sea. Although not yet widely used, many believe tidal power has more potential than wind or solar power for meeting alternative energy needs. Quest radio looks at plans for harnessing power from the sea by San Francisco and along the northern California coast.

Wind Power

Wind power is the fastest growing renewable energy source in the world. Windmills are now seen in many locations, either individually or, more commonly, in large fields. Wind Powering America follows the development of wind power in the United States over the past several years.

Wind Energy

Energy from the sun also creates wind, which can be used as wind power. The sun heats different locations on Earth by different amounts. Air that becomes warm rises and then sucks cooler air into that spot. The movement of air from one spot to another along the ground creates wind. Since wind is moving, it has kinetic energy.

Wind Power Use



Figure 29. Wind turbines like the ones shown here turn wind into electricity without creating pollution.

Wind is the source of energy for wind power. Wind has been used for power for centuries. For example, windmills were used to grind grain and pump water. Sailing ships traveled by wind power long before ships were powered by fossil fuels. Wind can be

used to generate electricity, as the moving air spins a turbine to create electricity (figure 29). This animation shows how wind power works.

Consequences of Wind Power

Wind power has many advantages. It does not burn, so it does not release pollution or carbon dioxide. Also, wind is plentiful in many places. Wind, however, does not blow all of the time, even though power is needed all of the time. Just as with solar power, engineers are working on technologies that can store wind power for later use.

Windmills are expensive and wear out quickly. A lot of windmills are needed to power a region, so nearby residents may complain about the loss of a nice view if a wind farm is built. Coastlines typically receive a lot of wind, but wind farms built near beaches may cause unhappiness for local residents and tourists.

The Cape Wind Project off of Cape Cod has been approved but is generating much controversy. Opponents are in favor of green power but not at that location. Proponents say that clean energy is needed and the project would supply 75% of the electricity needed for Cape Cod and nearby islands (figure 30).



Figure 30. Cape Wind off of Cape Cod in Massachusetts receives a great deal of wind (red color) but is also popular with tourists for its beauty.

California was an early adopter of wind power. Windmills are found in mountain passes where the cooler Pacific Ocean air is sucked through on its way to warmer inland valleys. Large fields of windmills can be seen at Altamont pass in the eastern San Francisco Bay Area, San Gorgonio Pass east of Los Angeles, and Tehachapi Pass at the southern end of the San Joaquin Valley.

Geothermal Power

Geothermal energy comes from heat deep below the surface of the Earth. Nothing must be done to the geothermal energy. It is a resource that can be used without processing.

Geothermal Energy

The heat that is used for geothermal power may come to the surface naturally as hot springs or geysers, like The Geysers in northern California. Where water does not naturally come to the surface, engineers may pump cool water into the ground. The water is heated by the hot rock and then pumped back to the surface for use. The hot water or steam from a geothermal well spins a turbine to make electricity.



Figure 31. A geothermal energy plant in Iceland. Iceland gets about one fourth of its electricity from geothermal sources.

Geothermal energy is clean and safe. The energy source is renewable since hot rock is found everywhere in the Earth, although in many parts of the world the hot rock is not close enough to the surface for building geothermal power plants. In some areas, geothermal power is common (figure 31).

In the United States, California is a leader in producing geothermal energy. The largest geothermal power plant in the state is in the Geysers Geothermal Resource Area in Napa and Sonoma Counties, north of San Francisco. The source of heat is thought to be a large magma chamber lying beneath the area.

KQED: Geothermal Heats Up. Where Earth's internal heat gets close to the surface, geothermal power is a clean source of energy. In California, The Geysers supplies energy for many nearby homes and businesses.

A link to an interactive elements can be found at the bottom of this page.

Biomass



Figure 32. Biofuels, such as ethanol, are added to gasoline to cut down the amount of fossil fuels that are used.

Biomass is the material that comes from plants and animals that were recently living. Biomass can be burned directly, such as setting fire to wood. For as long as humans have had fire, people have used biomass for heating and cooking. People can also process biomass to make fuel, called **biofuel.** Biofuel can be created from crops, such as corn or algae, and processed for use in a car (figure 32). The advantage to biofuels is that they burn more cleanly than fossil fuels. As a result, they create less pollution and less carbon dioxide. Critics say, however, that the amount of energy, fertilizer, and land needed to produce the crops used make biofuels only a slightly better alternative than fossil fuels.

- KQED: How Green is Biomass Energy? Organic material, like almond shells, can be made into electricity. Biomass power is a great use of wastes and is more reliable than other renewable energy sources, but harvesting biomass energy uses energy and biomass plants produce pollutants including greenhouse gases.

- KQED: From Waste to Watts: Biofuel Bonanza. Cow manure can have a second life as a source of methane gas, which can be converted to electricity. Not only that food scraps can also be converted into green energy.
- KQED: Biofuels: Beyond Ethanol. To generate biomass energy, break down the cell walls of plants to release the sugars and then ferment those sugars to create fuel. Corn is a very inefficient source; scientists are looking for much better sources of biomass energy.
- Algae Power. Many people think that the best source of biomass energy for the future is algae. Compared to corn, algae is not a food crop, it can grow in many places, its much easier to convert to a usable fuel and its carbon neutral.
- Power Up with Leftovers. Food that is tossed out produces methane, a potent greenhouse gas. But that methane from leftovers can be harnessed and used as fuel. Sounds like a win-win situation.

Lesson Summary

- According to the law of conservation of energy, energy is neither created nor destroyed.
- Renewable resources can be replaced at the rate they are being used.
- Non-renewable resources are available in limited amounts or are being used faster than they can be replaced.
- Coal, oil, and natural gas are fossil fuels formed from the remains of living organisms.
- Coal is the largest source of energy for producing electricity.
- Oil and natural gas are important energy sources for vehicles and electricity generation.
- Nuclear energy is produced by splitting atoms. It also produces radioactive wastes that are very dangerous for many years.
- Solar energy, water power, wind power, geothermal energy, and biomass energy are renewable energy sources.
- Solar energy can be used either by passively storing and holding the Sun's heat, converting it to electricity, or concentrating it.
- There are many ways to use the energy of moving water, including hydroelectric dams and tidal and wave plants.
- Wind power uses the energy of moving air to turn turbines.
- Geothermal energy uses heat from deep within the earth to heat homes or produce steam that turns turbines.
- Biomass energy uses renewable materials such as wood or grains to produce energy.

Contributors and Attributions

CC licensed content, Shared previously

- Chapter 5: HS Earth's Energy. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/5.0/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 12.13: Reading- Earth's Energy is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.14: Reading- Energy Consumption on Earth



What resources are in those electronics?

Everyone may realize that we use resources like trees, copper, water, and gemstones, but how many of us realize the tremendous variety of elements we need to make a single electronic device? A tablet computer with a touch screen contains many common chemical elements and a variety of rare earth elements.

Common Materials We Use from the Earth

People depend on natural resources for just about everything that keeps us fed and sheltered, as well as for the things that keep us entertained. Every person in the United States uses about 20,000 kilograms (40,000 pounds) of minerals every year for a wide range of products, such as cell phones, TVs, jewelry, and cars. Table 1 shows some common objects, the materials they are made from, and whether they are renewable or non-renewable.

Table 1. Common Objects We Use from the Earth

Common Object	Natural Resources Uses	Renewable or Non-Renewable?
Cars	15 different metals, such as iron, lead, and chromium to make the body.	Non-renewable
Jewelry	Precious metals like gold, silver, and platinum. Gems like diamonds, rubies, emeralds, turquoise.	Non-renewable
Electronic Appliances (TV's, computers, DVD players, cell phones, etc.)	Many different metals, like copper, mercury, gold.	Non-renewable
Clothing	Soil to grow fibers such as cotton. Sunlight for the plants to grow. Animals for fur and leather.	Renewable
Food	Soil to grow plants. Wildlife and agricultural animals.	Renewable
Bottled Water	Water from streams or springs. Petroleum products to make plastic bottles.	Non-renewable and Renewable
Gasoline	Petroleum drilled from wells.	Non-renewable
Household Electricity	Coal, natural gas, solar power, wind power, hydroelectric power.	Non-renewable and Renewable
Paper	Trees Sunlight Soil	Renewable
Houses	Trees for timber. Rocks and minerals for construction materials, for example, granite, gravel, sand.	Non-renewable and Renewable

Summary

- Many objects, such as a car, contain many types of resources.
- Resources may be renewable or non-renewable, and an object may contain some of each.
- Rare earth elements and other unusual materials are used in some electronic devices.

? Practice

Use this resource to answer the questions that follow.

A link to an interactive elements can be found at the bottom of this page.

1. What do we use neodymium for?
2. What are rare earth elements used for in general?
3. Where do we get our REEs? Why are there signs that this can't continue?
4. Can we develop alternatives?
5. What is the problem with the deposit of REEs that is offshore of Japan?
6. What is the danger for the future?

Contributors and Attributions

CC licensed content, Shared previously

- Materials Humans Use. **Provided by**: CK-12. **Located at**: http://www.ck12.org/earth-science/Materials-Humans-Use/lesson/Materials-Humans-Use-HS-ES/. **License**: *CC BY-NC: Attribution-NonCommercial*

All rights reserved content

- Why We Need Rare Earth Elements. **Authored by**: DNews. **Located at**: https://youtu.be/xqoQfN9DgNs. **License**: *All Rights Reserved*. **License Terms**: Standard YouTube License

---

This page titled 12.14: Reading- Energy Consumption on Earth is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.15: Reading- Use and Conservation of Resources

Introduction

Natural resources may be living or non-living. Their value may be tangible, such as the price of an ounce of gold, or intangible, like the psychological value of being able to visit pristine natural areas. Some natural resources must be used and used wisely, but some must be preserved to maintain their value.

Mystery in the Forest

Like all forests, the Monongahela National Forest of West Virginia is an important natural resource. A forest is a resource in ways that are obvious and ways that are not so obvious. This forest is used for many things including:

- Recreation, such as hiking, camping, and picnicking.
- Habitat for many organisms, including nine endangered species and 50 species of rare plants.
- Streams [207 kilometers (129 miles)] for fishing, particularly trout fishing.
- Wildlife management areas for hunting deer, squirrels, turkeys, rabbits, mink, and foxes.
- Mineral and energy resources such as coal, gas, limestone, and gravel.
- Hardwood trees used for **timber**, which brings in over $7 million a year.



Figure 1. The Monongahela National Forest in West Virginia contains many natural resources. Notice the air pollution that obscures the view.

But Monongahela National Forest has a problem; for several years, trees in the forest have not grown well. What are some reasons that trees might not grow well (figure 1)?

Scientists have been working for several years to solve the mystery. The scientists suspected that the soil is missing nutrients that the trees and other plants need to grow. Can you design an experiment that scientists could do to test this hypothesis? (There is a clue in the caption for figure 1.)

The scientists sampled the soil and tested it for important nutrients. They discovered that the soil has very low levels of plant nutrients, such as magnesium and calcium. Can you develop a hypothesis for why these nutrients might be missing from the soil? The scientists thought that air pollution from nearby factories had released chemicals into the environment that removed the nutrients from the soil and carried them away. How would the scientists test that hypothesis?

Scientists in the Monongahela National Forest are still researching the missing plant nutrients. They are trying to learn what they can do to help keep the nutrients in the soil so the trees will grow better.



Figure 2. We use Earth's resources for many purposes, including recreation and natural beauty.

Like the Monongahela National Forest, people use parts of the Earth for many reasons, such as food, water, building materials, timber, recreation, and energy (figure 2). As you've already learned, human activities can degrade natural resources, just like air pollution from factories is speeding up the loss of soil nutrients in West Virginia.

For natural resources to continue to be available, they need to be protected. We also need to **conserve** natural resources so they will last longer. When we practice conservation, we make sure resources will be available in the future, both for ourselves and for other organisms.

Renewable versus Non-Renewable Resources

In the Earth's Energy chapter, energy resources were classified as renewable or non-renewable. How do you think other natural resources, such as minerals and forests, are classified? Like energy resources, all natural resources are divided into renewable and non-renewable. Can you define these terms?

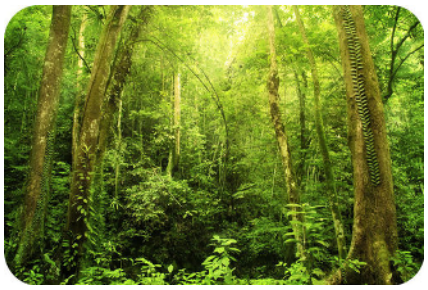


Figure 3. An old growth forest, like this tropical rainforest in Malaysia, is a complex ecosystem with many types of plants and animals. When a forest is destroyed by logging, it takes hundreds or thousands of years for the forest to regenerate.

Renewable resources can be regenerated or grown so rapidly that they reappear at the same rate or even faster as they are being used (figure 3). Are forests a renewable resource? Why are they a renewable resource? Why aren't they a renewable resource? Although new trees can grow to replace logged trees, their growth is often too slow for the trees to be of use for a long time. Loggers just move to a new area rather than wait for the forest to regenerate.

Other examples of resources that are renewable but not entirely renewable include soil, wildlife, and water. How do these resources fit in both categories? Soil has a very slow renewal rate, so they are often non-renewable. Fish and other wildlife can reproduce and so are a renewable resource, yet it is possible to take so many of these creatures that the populations are not able to rebound, making them a non-renewable resource (figure 4). Organisms can be over-hunted, over-fished or have populations decline because of habitat loss so that their numbers go so low they are no longer a renewable resource.



Figure 4. Chimpanzees are eaten and taken as pets so their numbers in the wild are declining.

Non-renewable resources are resources that cannot be regenerated on a useful timescale. Fossil fuels and most minerals are non-renewable resources. We can (and eventually will) run out of these resources.

Resource Availability

From the table on the previous page you can see that many of the resources we depend on are non-renewable. Non-renewable resources vary in their availability; some are very abundant and others are rare. Materials, such as gravel or sand are technically

non-renewable but are so abundant that running out is no issue. Some resources are truly limited in quantity: When they are gone, they are gone and something must be found that will replace them. There are even resources, such as diamonds and rubies, that are valuable in part because they are so rare.



Figure 5. Tampa Bay, Florida, has one of the few desalination plants in the United States.

Besides abundance, resource value is determined by how easy it is to locate and extract. If a resource is difficult to use, it will not be used until the price for that resource becomes so great that it is worth paying for. For example, the oceans are filled with an abundant supply of water, but desalination is costly, so it is used only where water is really limited (figure 5). As the cost of desalination plants comes down, more will likely be built.

Politics is also part of determining resource availability and cost. Nations that have a desired resource in abundance will often **export** that resource to other countries, while countries that need that resource must **import** it from one of the countries that produces it. This situation is a potential source of economic and political trouble.

Of course the greatest example of this is oil. Only 12 countries have approximately 80% of all of the world's oil (Figure 6). However, the biggest users of oil, the United States, China, and Japan, are all located outside this oil-rich region. This leads to a situation in which the availability and price of the oil is determined largely by one set of countries that have their own interests to look out for. The result has sometimes been war, which may have been attributed to all sorts of reasons, but at the bottom, the reason is oil.

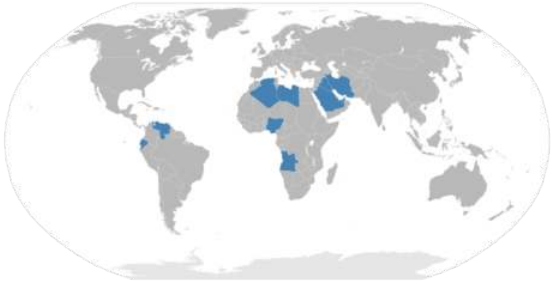


Figure 6. The nations in blue are the 12 biggest producers of oil; they are Algeria, Angola, Ecuador, Iran, Iraq, Kuwait, Libya, Nigeria, Qatar, Saudi Arabia, the United Arab Emirates, and Venezuela.



Figure 7. Pollution from discarded materials degrades the environment and reduces the availability of natural resources.

The topic of overconsumption was touched on in the Ecosystems and Human Populations chapter. Many people in developed countries, such as the United States and most of Europe, use many more natural resources than people in many other countries. We have many luxury and recreational items, and it is often cheaper for us to throw something away than to fix it or just hang on to it

for a while longer. This consumerism leads to greater resource use, but it also leads to more waste. Pollution from discarded materials degrades the land, air, and water (figure 7).

Natural resource use is generally lower in developing countries because people cannot afford many products. Some of these nations export natural resources to the developed world since their deposits may be richer and the cost of labor lower. Environmental regulations are often more lax, further lowering the cost of resource extraction.

Besides obtaining resources, we also dump waste on these nations. Many of our electronic wastes, which we think are being recycled, end up in developing countries where they pose a problem for human health and the environment. Electronic wastes are sent to developing nations where people pick through them for valuable materials. These wastes contain many toxic compounds and are hazardous.

Conserving Natural Resources



Figure 8. Recycling can help conserve natural resources.

So that people in developed nations maintain a good lifestyle and people in developing nations have the ability to improve their lifestyles, natural resources must be conserved and protected (figure 8). People are researching ways to find renewable alternatives to non-renewable resources. Here is a checklist of ways to conserve resources:

- Buy less stuff (use items as long as you can, and ask yourself if you really need something new).
- Reduce excess packaging (drink tap water instead of water from plastic bottles).
- Recycle materials such as metal cans, old cell phones, and plastic bottles.
- Purchase products made from recycled materials.
- Reduce pollution so that resources are maintained.
- Prevent soil erosion.
- Plant new trees to replace those that are cut down.
- Drive cars less, take public transportation, bicycle, or walk.
- Conserve energy at home (turn out lights when they are not needed).

National Geographic videos found on this site in Environment Videos, Environmental Threats, Deforestation.

- “Sustainable Logging”

Or Environment Videos, Habitats, Rainforest.

- “Mamirarua” is a sustainable development reserve that is protecting the Amazon
- “Vancouver Rain Forest” explores an alliance between conservationists and logging companies

Or find ways to go green from National Geographic videos, Environment Videos, Going Green.

- The problem with plastic bags is discussed in this Conservation in action, “Edward Norton: Bag the Bag”
- Trying to mitigate problems caused by intensive logging in Ecuador while helping the people who live there improve their standards of living is in “Ecuador Conservation”

Lesson Summary

- We use natural resources for many things. Natural resources give us food, water, recreation, energy, building materials, and luxury items.
- Many resources vary in their availability throughout the world. Some are rare, difficult to get, or in short supply.
- Natural resources must be preserved and protected from pollution and overuse.

- Buying fewer new products and recycling will help to conserve resources.

Contributors and Attributions

CC licensed content, Shared previously

- 20.1: Use and Conservation of Resources. **Provided by**: CK-12. **Located at**: http://www.ck12.org/book/CK-12-Earth-Science-For-High-School/section/20.1/. **License**: *CC BY-NC: Attribution-NonCommercial*

This page titled 12.15: Reading- Use and Conservation of Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.16: Self Check- Getting Energy from Resources

Check Your Understanding

Answer the question(s) below to see how well you understand the topics covered in the previous section. This short quiz does **not** count toward your grade in the class, and you can retake it an unlimited number of times.

Use this quiz to check your understanding and decide whether to (1) study the previous section further or (2) move on to the next section.

https://assessments.lumenlearning.co...sessments/1132

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 12.16: Self Check- Getting Energy from Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.17: Putting It Together- Geological Resources

Summary

In this section, we used almost all of the concepts we have learned so far. While plate tectonics may not have been mentioned directly, we know the role it plays in the formation of rock, minerals and mineral resources. In this section, we focused on these items:

1. How mineral resources and fossil fuels are formed
2. How these resources are mined
3. Nonrenewable and renewable resources
4. What type and amount of resources we use in our everyday life

Synthesis

Hopefully, having a better understanding of the material and resources we use will give you a better understanding of current issues including the importance of resource conservation, alternative resource use, and what it means to live sustainably.

Contributors and Attributions

CC licensed content, Original

- **Authored by**: Kimberly Schulte and Lumen Learning. **Provided by**: Lumen Learning. **License**: *CC BY: Attribution*

This page titled 12.17: Putting It Together- Geological Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

12.18: Assignment- Geological Resources

For this assessment, you will create a poster using the program of your choice (a single page Word or slide in PowerPoint is recommended). You will investigate a resource, how it is used and how it is mined. You will also discuss the impact this resource use has on society. Remember to access the tips and hints at the bottom of the page.

Basic Requirements (assignment criteria):

1. Choose from the following list of minerals and mineral resources that we currently mine:

Coal	Granite
Oil	Gold
Natural Gas	Copper
Limestone	Any metallic ore such as nickel

2. On your poster include the following:

- How the resource is currently used
- If the resource is renewable or non-renewable. If nonrenewable, state any renewable alternatives
- How the resource is typically mined
- The environmental and societal impacts or side effects of this techniques
- Any advances in mining to improve the technique(s) used for this resource

3. Make sure you cite any resources you may use in the appropriate format, including pictures. Remember to not only list references but cite WITHIN the text itself.

Please note—the text is cited within the body of the work and not just listed as references. It is important to remember to cite within the body of the text so it easy to tell what information came from what source. If you do not cite within the text, it is a form of plagiarism and will negatively impact your grade.

4. You can use a separate page or slide to list your references on so you don't take away space from your poster.

5. Make sure your name is on the document before saving.

Tips and hints can be found here.

Geological Implications Assessment

Criteria	Ratings		Pts
Learns common processes of geologic formation of rock and mineral resources.	Exceeded Expectations: Mastery with Distinction 5.0 pts	Met Expectations: Mastery AchievedMet expectation 4.0 pts	Fell below expectation 0.0 pts 5.0 pts
Describes some of the extraction methods and how extraction impacts society and our environment.	Exceeded Expectations: Mastery with Distinction 5.0 pts	Met Expectations: Mastery AchievedMet expectation 4.0 pts	Fell below expectation 0.0 pts 5.0 pts
Describes geologic materials as current or potential energy resources and categorize sources as renewable or nonrenewable.escription of criterion	Exceeded Expectations: Mastery with Distinction 5.0 pts	Met Expectations: Mastery AchievedMet expectation 4.0 pts	Fell below expectation 0.0 pts 5.0 pts
Total Points: 15.0			

Contributors and Attributions

CC licensed content, Original

- Geological Resources Assessments. **Authored by**: Kimberly Schulte. **Provided by**: SBCTC. **Located at**: http://www.columbiabasin.edu. **License**: *CC BY: Attribution*

This page titled 12.18: Assignment- Geological Resources is shared under a CC BY 4.0 license and was authored, remixed, and/or curated by Lumen Learning via source content that was edited to the style and standards of the LibreTexts platform.

Index

C

Causes and Location of Earthquakes
8: Earthquakes

Chemistry of Minerals
2: Rock Forming Minerals

Components of Groundwater
11: Hydrology

continental drift
5: Plate Tectonics

D

dike
9.13: Reading- Dikes and Sills

Driving and Resisting Forces
10: Mass Movement

E

Earthquake Hazards and Prediction
8: Earthquakes

G

Geologic Features
11: Hydrology

geologic structures
7: Crustal Deformation

geological processes
5: Plate Tectonics

I

Identifying Minerals
2: Rock Forming Minerals

Igneous Features
9: Volcanoes

igneous rocks
3: Rocks and the Rock Cycle

L

Layers of the Geosphere
6: Earth's Interior

M

Magnitude and Intensity
8: Earthquakes

metamorphic rocks
3: Rocks and the Rock Cycle

monitoring volcanoes
9: Volcanoes

Most Common Elements
2: Rock Forming Minerals

O

Oceans and Shorelines
11: Hydrology

R

Rivers and Streams
11: Hydrology

S

Scientific Processes in Geology
1: Science of Geology

Scientific Tools
1: Science of Geology

sedimentary rocks
3: Rocks and the Rock Cycle

soil conservation
4: Weathering and Soil Formation

Soil Profiles and Types
4: Weathering and Soil Formation

Stress and Strain
7: Crustal Deformation

T

The Formation of Volcanoes
9: Volcanoes

The Hydrologic Cycle
11: Hydrology

The Theory of Plate Tectonics
5: Plate Tectonics

Types of Mass Movement
10: Mass Movement

Types of Waves'
8: Earthquakes

U

Understanding the Earth's Interior
6: Earth's Interior

V

volcanic hazards
9: Volcanoes

Volcano Types
9: Volcanoes

W

Weathering and Erosion
4: Weathering and Soil Formation

What is Geology?
1: Science of Geology

Detailed Licensing

Overview

Title: Geology (Lumen)

Webpages: 236

All licenses found:

- CC BY 4.0: 98.7% (233 pages)
- Undeclared: 0.8% (2 pages)
- CC BY-SA 4.0: 0.4% (1 page)

By Page

- Geology (Lumen) - *CC BY 4.0*
  - Front Matter - *CC BY 4.0*
    - TitlePage - *CC BY 4.0*
    - InfoPage - *CC BY 4.0*
    - Table of Contents - *Undeclared*
    - Licensing - *CC BY 4.0*
    - 1.1: Assignments - *CC BY 4.0*
  - 1: Science of Geology - *CC BY 4.0*
    - 1.1: Why It Matters- Science of Geology - *CC BY 4.0*
    - 1.2: Outcome- What is Geology? - *CC BY 4.0*
    - 1.3: Reading- The Science of Geology - *CC BY 4.0*
    - 1.4: Reading- The Branches of Geology - *CC BY 4.0*
    - 1.5: Self Check- What is Geology? - *CC BY 4.0*
    - 1.6: Outcome- Scientific Processes in Geology - *CC BY 4.0*
    - 1.7: Reading- The Nature of Science - *CC BY 4.0*
    - 1.8: Self Check- Scientific Processes in Geology - *CC BY 4.0*
    - 1.9: Outcome- Scientific Tools - *CC BY 4.0*
    - 1.10: Reading- Geologic Tools - *CC BY 4.0*
    - 1.11: Reading- Maps - *CC BY 4.0*
    - 1.12: Video- Exploring Topographic Maps - *CC BY 4.0*
    - 1.13: Reading- Location and Direction - *CC BY 4.0*
    - 1.14: Reading- Scientific Models - *CC BY 4.0*
    - 1.15: Reading- Geologic Modelling - *CC BY 4.0*
    - 1.16: Self Check- Scientific Tools - *CC BY 4.0*
    - 1.17: Putting It Together- Science of Geology - *CC BY 4.0*
    - 1.18: Assignment- Science of Geology - *CC BY 4.0*
  - 2: Rock Forming Minerals - *CC BY 4.0*
    - 2.1: Why It Matters- Rock Forming Minerals - *CC BY 4.0*
    - 2.2: Outcome- Chemistry of Minerals - *CC BY 4.0*
    - 2.3: Reading- The Building Blocks of Matter - *CC BY 4.0*
    - 2.4: Reading- Atomic Bonds - *CC BY 4.0*
    - 2.5: Self Check- Chemistry of Minerals - *CC BY 4.0*
    - 2.6: Outcome- Identifying Minerals - *CC BY 4.0*
    - 2.7: Reading- Physical Characteristics of Minerals - *CC BY 4.0*
    - 2.8: Reading- Classifying Minerals - *CC BY 4.0*
    - 2.9: Self Check- Identifying Minerals - *CC BY 4.0*
    - 2.10: Outcome- Most Common Elements - *CC BY 4.0*
    - 2.11: Reading- Abundance of Elements in Earth's Crust - *CC BY 4.0*
    - 2.12: Reading- Silicate Minerals and the Silicate Tetrahedron - *CC BY 4.0*
    - 2.13: Self Check- Most Common Elements - *CC BY 4.0*
    - 2.14: Putting It Together- Rock Forming Minerals - *CC BY 4.0*
    - 2.15: Assignment- Rock Forming Minerals - *CC BY 4.0*
  - 3: Rocks and the Rock Cycle - *CC BY 4.0*
    - 3.1: Why It Matters- Rocks and the Rock Cycle - *CC BY 4.0*
    - 3.2: Outcome- Igneous Rocks - *CC BY 4.0*
    - 3.3: Reading- Characteristics of Igneous Rocks - *CC BY 4.0*
    - 3.4: Reading- How Are Igneous Rocks Classified? - *CC BY 4.0*
    - 3.5: Reading- Identifying Igneous Rocks - *CC BY 4.0*
    - 3.6: Reading- Uses of Igneous Rocks - *CC BY 4.0*
    - 3.7: Self Check- Igneous Rocks - *CC BY 4.0*
    - 3.8: Outcome- Sedimentary Rocks - *CC BY 4.0*
    - 3.9: Reading- Characteristics of Sedimentary Rocks - *CC BY 4.0*
    - 3.10: Self Check- Sedimentary Rocks - *CC BY 4.0*
    - 3.11: Outcome- Metamorphic Rocks - *CC BY 4.0*

- 3.12: Reading- Characteristics of Metamorphic Rocks - *CC BY 4.0*
- 3.13: Video- Identifying Metamorphic Rocks - *CC BY 4.0*
- 3.14: Self Check- Metamorphic Rocks - *CC BY 4.0*
- 3.15: Putting It Together- Rocks and the Rock Cycle - *CC BY 4.0*

- 4: Weathering and Soil Formation - *CC BY 4.0*
  - 4.1: Why It Matters- Weathering and Soil Formation - *CC BY 4.0*
  - 4.2: Outcome- Weathering and Erosion - *CC BY 4.0*
  - 4.3: Reading- What Is Weathering? - *CC BY 4.0*
  - 4.4: Reading- Mechanical Weathering - *CC BY 4.0*
  - 4.5: Reading- Chemical Weathering - *CC BY 4.0*
  - 4.6: Reading- Influences on Weathering - *CC BY 4.0*
  - 4.7: Self Check- Weathering and Erosion - *CC BY 4.0*
  - 4.8: Outcome- Soil Profiles and Types - *CC BY 4.0*
  - 4.9: Reading- Soil Texture and Composition - *CC BY 4.0*
  - 4.10: Reading- Soil Horizons and Profiles - *CC BY 4.0*
  - 4.11: Reading- Types of Soils - *CC BY 4.0*
  - 4.12: Self Check- Soil Profiles and Types - *CC BY 4.0*
  - 4.13: Outcome- Soil Conservation - *CC BY 4.0*
  - 4.14: Reading- Causes of Soil Erosion - *CC BY 4.0*
  - 4.15: Video- The Dust Bowl - *CC BY 4.0*
  - 4.16: Reading- Avoiding Soil Loss - *CC BY 4.0*
  - 4.17: Self Check- Soil Conservation - *CC BY 4.0*
  - 4.18: Putting It Together- Weathering and Soil Formation - *CC BY 4.0*
  - 4.19: Assignment- Weathering and Soil Formation - *CC BY 4.0*
- 5: Plate Tectonics - *CC BY 4.0*
  - 5.1: Why It Matters- Plate Tectonics - *CC BY 4.0*
  - 5.2: Outcome- Continental Drift - *CC BY 4.0*
  - 5.3: Reading- Continental Drift - *CC BY 4.0*
  - 5.4: Reading- Wegener and the Continental Drift Hypothesis - *CC BY 4.0*
  - 5.5: Self Check- Continental Drift - *CC BY 4.0*
  - 5.6: Outcome- The Theory of Plate Tectonics - *CC BY 4.0*
  - 5.7: Reading- Theory of Plate Tectonics - *CC BY 4.0*
  - 5.8: Reading- Developing the Theory - *CC BY 4.0*
  - 5.9: Self Check- The Theory of Plate Tectonics - *CC BY 4.0*
  - 5.10: Outcome- Geological Processes - *CC BY 4.0*
  - 5.11: Reading- Supercontinents - *CC BY 4.0*
  - 5.12: Reading- Volcanic Arcs - *CC BY 4.0*
  - 5.13: Video- Ocean Basins - *CC BY 4.0*
  - 5.14: Reading- Hot Spots - *CC BY 4.0*
  - 5.15: Self Check- Geological Processes - *CC BY 4.0*
  - 5.16: Putting It Together- Plate Tectonics - *CC BY 4.0*
  - 5.17: Assignment- Plate Tectonics - *CC BY 4.0*
- 6: Earth's Interior - *CC BY 4.0*
  - 6.1: Why It Matters- Earth's Interior - *CC BY 4.0*
  - 6.2: Outcome- Layers of the Geosphere - *CC BY 4.0*
  - 6.3: Reading- Characteristics of the Crust - *CC BY 4.0*
  - 6.4: Reading- Characteristics of the Mantle - *CC BY 4.0*
  - 6.5: Reading- Characteristics of the Inner and Outer Core - *CC BY 4.0*
  - 6.6: Reading- The Lithosphere and Asthenosphere - *CC BY 4.0*
  - 6.7: Self Check- Layers of the Geosphere - *CC BY 4.0*
  - 6.8: Outcome- Understanding the Earth's Interior - *CC BY 4.0*
  - 6.9: Reading- Studying the Earth's Interior - *CC BY 4.0*
  - 6.10: Self Check- Understanding the Earth's Interior - *CC BY 4.0*
  - 6.11: Putting It Together- Earth's Interior - *CC BY 4.0*
  - 6.12: Assignment- Earth's Interior - *CC BY 4.0*
- 7: Crustal Deformation - *CC BY 4.0*
  - 7.1: Why It Matters- Crustal Deformation - *CC BY 4.0*
  - 7.2: Outcome- Stress and Strain - *CC BY 4.0*
  - 7.3: Reading- Stress In Earth's Crust - *CC BY 4.0*
  - 7.4: Reading- Strain - *CC BY 4.0*
  - 7.5: Self Check- Stress and Strain - *CC BY 4.0*
  - 7.6: Outcome- Geologic Structures - *CC BY 4.0*
  - 7.7: Reading- Folds - *CC BY-SA 4.0*
  - 7.8: Reading- Faults - *CC BY 4.0*
  - 7.9: Reading- Mountains - *CC BY 4.0*
  - 7.10: Self Check- Geologic Structures - *CC BY 4.0*
  - 7.11: Putting It Together- Crustal Deformation - *CC BY 4.0*
- 8: Earthquakes - *CC BY 4.0*
  - 8.1: Why It Matters- Earthquakes - *CC BY 4.0*
  - 8.2: Outcome- Causes and Location of Earthquakes - *CC BY 4.0*
  - 8.3: Reading- The Nature of Earthquakes - *CC BY 4.0*
  - 8.4: Reading- Causes of Earthquakes - *CC BY 4.0*
  - 8.5: Reading- Common Locations of Earthquakes - *CC BY 4.0*
  - 8.6: Reading- The Ring of Fire - *CC BY 4.0*
  - 8.7: Self Check- Causes and Location of Earthquakes - *CC BY 4.0*

- 8.8: Outcome- Types of Waves - *CC BY 4.0*
- 8.9: Reading- Body Waves - *CC BY 4.0*
- 8.10: Reading- Surface Waves - *CC BY 4.0*
- 8.11: Self Check- Types of Waves - *CC BY 4.0*
- 8.12: Outcome- Magnitude and Intensity - *CC BY 4.0*
- 8.13: Reading- Measuring Earthquakes - *CC BY 4.0*
- 8.14: Reading- Magnitude versus Intensity - *CC BY 4.0*
- 8.15: Self Check- Magnitude and Intensity - *CC BY 4.0*
- 8.16: Outcome- Earthquake Hazards and Prediction - *CC BY 4.0*
- 8.17: Reading- Earthquake Hazards - *CC BY 4.0*
- 8.18: Reading- Earthquake Prediction - *CC BY 4.0*
- 8.19: Reading- Seismicity and Earthquake Prediction - *CC BY 4.0*
- 8.20: Self Check- Earthquake Hazards and Prediction - *CC BY 4.0*
- 8.21: Putting It Together- Earthquakes - *CC BY 4.0*
- 8.22: Assignment- Earthquakes - *CC BY 4.0*

- 9: Volcanoes - *CC BY 4.0*
  - 9.1: Why It Matters- Volcanoes - *CC BY 4.0*
  - 9.2: Outcome- Volcano Types - *CC BY 4.0*
  - 9.3: Reading- Types of Volcanoes - *CC BY 4.0*
  - 9.4: Reading- Types of Eruptions - *CC BY 4.0*
  - 9.5: Reading- Supervolcanoes - *CC BY 4.0*
  - 9.6: Self Check- Volcano Types - *CC BY 4.0*
  - 9.7: Outcome- The Formation of Volcanoes - *CC BY 4.0*
  - 9.8: Reading- Volcanoes at Plate Boundaries - *CC BY 4.0*
  - 9.9: Reading- Volcanoes Hotspots - *CC BY 4.0*
  - 9.10: Self Check- The Formation of Volcanoes - *CC BY 4.0*
  - 9.11: Outcome- Igneous Features - *CC BY 4.0*
  - 9.12: Reading- Pyroclastic Deposits - *CC BY 4.0*
  - 9.13: Reading- Dikes and Sills - *CC BY 4.0*
  - 9.14: Reading- Volcanic Landforms - *CC BY 4.0*
  - 9.15: Self Check- Igneous Features - *CC BY 4.0*
  - 9.16: Outcome- Volcanic Hazards - *CC BY 4.0*
  - 9.17: Reading- Volcanic Gases, Pyroclastic Flow, and Tephra - *CC BY 4.0*
  - 9.18: Reading- Lahars, Landslides, and Lavaflow - *CC BY 4.0*
  - 9.19: Self Check- Volcanic Hazards - *CC BY 4.0*
  - 9.20: Outcome- Monitoring Volcanoes - *CC BY 4.0*
  - 9.21: Reading- Signs of an Eruption - *CC BY 4.0*
  - 9.22: Reading- Tools to Monitor Volcanoes - *CC BY 4.0*
  - 9.23: Self Check- Monitoring Volcanoes - *CC BY 4.0*
  - 9.24: Putting It Together- Volcanoes - *CC BY 4.0*
- 10: Mass Movement - *CC BY 4.0*
  - 10.1: Why It Matters- Mass Movement - *CC BY 4.0*
  - 10.2: Outcome- Types of Mass Movement - *CC BY 4.0*
  - 10.3: Reading- Slides - *CC BY 4.0*
  - 10.4: Reading- Falls - *CC BY 4.0*
  - 10.5: Reading- Slump and Creep - *CC BY 4.0*
  - 10.6: Self Check- Types of Mass Movement - *CC BY 4.0*
  - 10.7: Outcome- Driving and Resisting Forces - *CC BY 4.0*
  - 10.8: Reading- Natural Mass Wasting - *CC BY 4.0*
  - 10.9: Reading- Human Impact on Mass Wasting - *CC BY 4.0*
  - 10.10: Self Check- Driving and Resisting Forces - *CC BY 4.0*
  - 10.11: Putting It Together- Mass Wasting - *CC BY 4.0*
  - 10.12: Assignment- Mass Movement - *CC BY 4.0*
- 11: Hydrology - *CC BY 4.0*
  - 11.1: Why It Matters- Hydrology - *CC BY 4.0*
  - 11.2: Outcome- The Hydrologic Cycle - *CC BY 4.0*
  - 11.3: Reading- Phases of the Hydrologic Cycle - *CC BY 4.0*
  - 11.4: Self Check- The Hydrologic Cycle - *CC BY 4.0*
  - 11.5: Outcome- Rivers and Streams - *CC BY 4.0*
  - 11.6: Reading- Types of Streams and Rivers - *CC BY 4.0*
  - 11.7: Reading- Drainage Basins - *CC BY 4.0*
  - 11.8: Reading- Geologic Processes and Flowing Water - *CC BY 4.0*
  - 11.9: Self Check- Rivers and Streams - *CC BY 4.0*
  - 11.10: Outcome- Components of Groundwater - *CC BY 4.0*
  - 11.11: Reading- Groundwater - *CC BY 4.0*
  - 11.12: Reading- Porosity and Permeability - *CC BY 4.0*
  - 11.13: Reading- Aquifers and Well-Potential - *CC BY 4.0*
  - 11.14: Reading- Groundwater Withdrawal - *CC BY 4.0*
  - 11.15: Reading- Quality of Groundwater - *CC BY 4.0*
  - 11.16: Self Check- Components of Groundwater - *CC BY 4.0*
  - 11.17: Outcome- Geologic Features - *CC BY 4.0*
  - 11.18: Reading- Karst Topography - *CC BY 4.0*
  - 11.19: Reading- Geysers - *CC BY 4.0*
  - 11.20: Reading- Springs - *CC BY 4.0*

- 11.21: Self Check- Geologic Features - *CC BY 4.0*
- 11.22: Outcome- Oceans and Shorelines - *CC BY 4.0*
- 11.23: Reading- Ocean Movement - *CC BY 4.0*
- 11.24: Reading- Shorelines - *CC BY 4.0*
- 11.25: Reading- Coastal Hazards - *CC BY 4.0*
- 11.26: Reading- Human Modifications of Coastal Processes - *CC BY 4.0*
- 11.27: Self Check- Oceans and Shorelines - *CC BY 4.0*
- 11.28: Putting It Together- Hydrology - *CC BY 4.0*
- 11.29: Assignment- Hydrology - *CC BY 4.0*

12: Geological Resources - *CC BY 4.0*

- 12.1: Why It Matters- Geological Resources - *CC BY 4.0*
- 12.2: Outcome- Rock and Mineral Resources - *CC BY 4.0*
- 12.3: Reading- Ore Genesis - *CC BY 4.0*
- 12.4: Reading- Petroleum - *CC BY 4.0*
- 12.5: Reading- Natural Gas - *CC BY 4.0*
- 12.6: Reading- Coal - *CC BY 4.0*
- 12.7: Self Check- Rock and Mineral Resources - *CC BY 4.0*
- 12.8: Outcome- Extraction of Resources - *CC BY 4.0*
- 12.9: Reading- Mining - *CC BY 4.0*
- 12.10: Reading- Effects of Mining - *CC BY 4.0*
- 12.11: Self Check- Extraction of Resources - *CC BY 4.0*
- 12.12: Outcome- Getting Energy from Resources - *CC BY 4.0*
- 12.13: Reading- Earth's Energy - *CC BY 4.0*
- 12.14: Reading- Energy Consumption on Earth - *CC BY 4.0*
- 12.15: Reading- Use and Conservation of Resources - *CC BY 4.0*
- 12.16: Self Check- Getting Energy from Resources - *CC BY 4.0*
- 12.17: Putting It Together- Geological Resources - *CC BY 4.0*
- 12.18: Assignment- Geological Resources - *CC BY 4.0*

Back Matter - *CC BY 4.0*

- Index - *CC BY 4.0*
- Glossary - *CC BY 4.0*
- Detailed Licensing - *CC BY 4.0*
- Detailed Licensing - *Undeclared*

Detailed Licensing

Overview

Title: Geology (Lumen)

Webpages: 236

All licenses found:

- CC BY 4.0: 98.7% (233 pages)
- Undeclared: 0.8% (2 pages)
- CC BY-SA 4.0: 0.4% (1 page)

By Page

- Geology (Lumen) - *CC BY 4.0*
  - Front Matter - *CC BY 4.0*
    - TitlePage - *CC BY 4.0*
    - InfoPage - *CC BY 4.0*
    - Table of Contents - *Undeclared*
    - Licensing - *CC BY 4.0*
    - 1.1: Assignments - *CC BY 4.0*
  - 1: Science of Geology - *CC BY 4.0*
    - 1.1: Why It Matters- Science of Geology - *CC BY 4.0*
    - 1.2: Outcome- What is Geology? - *CC BY 4.0*
    - 1.3: Reading- The Science of Geology - *CC BY 4.0*
    - 1.4: Reading- The Branches of Geology - *CC BY 4.0*
    - 1.5: Self Check- What is Geology? - *CC BY 4.0*
    - 1.6: Outcome- Scientific Processes in Geology - *CC BY 4.0*
    - 1.7: Reading- The Nature of Science - *CC BY 4.0*
    - 1.8: Self Check- Scientific Processes in Geology - *CC BY 4.0*
    - 1.9: Outcome- Scientific Tools - *CC BY 4.0*
    - 1.10: Reading- Geologic Tools - *CC BY 4.0*
    - 1.11: Reading- Maps - *CC BY 4.0*
    - 1.12: Video- Exploring Topographic Maps - *CC BY 4.0*
    - 1.13: Reading- Location and Direction - *CC BY 4.0*
    - 1.14: Reading- Scientific Models - *CC BY 4.0*
    - 1.15: Reading- Geologic Modelling - *CC BY 4.0*
    - 1.16: Self Check- Scientific Tools - *CC BY 4.0*
    - 1.17: Putting It Together- Science of Geology - *CC BY 4.0*
    - 1.18: Assignment- Science of Geology - *CC BY 4.0*
  - 2: Rock Forming Minerals - *CC BY 4.0*
    - 2.1: Why It Matters- Rock Forming Minerals - *CC BY 4.0*
    - 2.2: Outcome- Chemistry of Minerals - *CC BY 4.0*
    - 2.3: Reading- The Building Blocks of Matter - *CC BY 4.0*
    - 2.4: Reading- Atomic Bonds - *CC BY 4.0*
    - 2.5: Self Check- Chemistry of Minerals - *CC BY 4.0*
    - 2.6: Outcome- Identifying Minerals - *CC BY 4.0*
    - 2.7: Reading- Physical Characteristics of Minerals - *CC BY 4.0*
    - 2.8: Reading- Classifying Minerals - *CC BY 4.0*
    - 2.9: Self Check- Identifying Minerals - *CC BY 4.0*
    - 2.10: Outcome- Most Common Elements - *CC BY 4.0*
    - 2.11: Reading- Abundance of Elements in Earth's Crust - *CC BY 4.0*
    - 2.12: Reading- Silicate Minerals and the Silicate Tetrahedron - *CC BY 4.0*
    - 2.13: Self Check- Most Common Elements - *CC BY 4.0*
    - 2.14: Putting It Together- Rock Forming Minerals - *CC BY 4.0*
    - 2.15: Assignment- Rock Forming Minerals - *CC BY 4.0*
  - 3: Rocks and the Rock Cycle - *CC BY 4.0*
    - 3.1: Why It Matters- Rocks and the Rock Cycle - *CC BY 4.0*
    - 3.2: Outcome- Igneous Rocks - *CC BY 4.0*
    - 3.3: Reading- Characteristics of Igneous Rocks - *CC BY 4.0*
    - 3.4: Reading- How Are Igneous Rocks Classified? - *CC BY 4.0*
    - 3.5: Reading- Identifying Igneous Rocks - *CC BY 4.0*
    - 3.6: Reading- Uses of Igneous Rocks - *CC BY 4.0*
    - 3.7: Self Check- Igneous Rocks - *CC BY 4.0*
    - 3.8: Outcome- Sedimentary Rocks - *CC BY 4.0*
    - 3.9: Reading- Characteristics of Sedimentary Rocks - *CC BY 4.0*
    - 3.10: Self Check- Sedimentary Rocks - *CC BY 4.0*
    - 3.11: Outcome- Metamorphic Rocks - *CC BY 4.0*

- 3.12: Reading- Characteristics of Metamorphic Rocks - *CC BY 4.0*
- 3.13: Video- Identifying Metamorphic Rocks - *CC BY 4.0*
- 3.14: Self Check- Metamorphic Rocks - *CC BY 4.0*
- 3.15: Putting It Together- Rocks and the Rock Cycle - *CC BY 4.0*

- 4: Weathering and Soil Formation - *CC BY 4.0*
  - 4.1: Why It Matters- Weathering and Soil Formation - *CC BY 4.0*
  - 4.2: Outcome- Weathering and Erosion - *CC BY 4.0*
  - 4.3: Reading- What Is Weathering? - *CC BY 4.0*
  - 4.4: Reading- Mechanical Weathering - *CC BY 4.0*
  - 4.5: Reading- Chemical Weathering - *CC BY 4.0*
  - 4.6: Reading- Influences on Weathering - *CC BY 4.0*
  - 4.7: Self Check- Weathering and Erosion - *CC BY 4.0*
  - 4.8: Outcome- Soil Profiles and Types - *CC BY 4.0*
  - 4.9: Reading- Soil Texture and Composition - *CC BY 4.0*
  - 4.10: Reading- Soil Horizons and Profiles - *CC BY 4.0*
  - 4.11: Reading- Types of Soils - *CC BY 4.0*
  - 4.12: Self Check- Soil Profiles and Types - *CC BY 4.0*
  - 4.13: Outcome- Soil Conservation - *CC BY 4.0*
  - 4.14: Reading- Causes of Soil Erosion - *CC BY 4.0*
  - 4.15: Video- The Dust Bowl - *CC BY 4.0*
  - 4.16: Reading- Avoiding Soil Loss - *CC BY 4.0*
  - 4.17: Self Check- Soil Conservation - *CC BY 4.0*
  - 4.18: Putting It Together- Weathering and Soil Formation - *CC BY 4.0*
  - 4.19: Assignment- Weathering and Soil Formation - *CC BY 4.0*
- 5: Plate Tectonics - *CC BY 4.0*
  - 5.1: Why It Matters- Plate Tectonics - *CC BY 4.0*
  - 5.2: Outcome- Continental Drift - *CC BY 4.0*
  - 5.3: Reading- Continental Drift - *CC BY 4.0*
  - 5.4: Reading- Wegener and the Continental Drift Hypothesis - *CC BY 4.0*
  - 5.5: Self Check- Continental Drift - *CC BY 4.0*
  - 5.6: Outcome- The Theory of Plate Tectonics - *CC BY 4.0*
  - 5.7: Reading- Theory of Plate Tectonics - *CC BY 4.0*
  - 5.8: Reading- Developing the Theory - *CC BY 4.0*
  - 5.9: Self Check- The Theory of Plate Tectonics - *CC BY 4.0*
  - 5.10: Outcome- Geological Processes - *CC BY 4.0*
  - 5.11: Reading- Supercontinents - *CC BY 4.0*
  - 5.12: Reading- Volcanic Arcs - *CC BY 4.0*
  - 5.13: Video- Ocean Basins - *CC BY 4.0*
  - 5.14: Reading- Hot Spots - *CC BY 4.0*
  - 5.15: Self Check- Geological Processes - *CC BY 4.0*
  - 5.16: Putting It Together- Plate Tectonics - *CC BY 4.0*
  - 5.17: Assignment- Plate Tectonics - *CC BY 4.0*
- 6: Earth's Interior - *CC BY 4.0*
  - 6.1: Why It Matters- Earth's Interior - *CC BY 4.0*
  - 6.2: Outcome- Layers of the Geosphere - *CC BY 4.0*
  - 6.3: Reading- Characteristics of the Crust - *CC BY 4.0*
  - 6.4: Reading- Characteristics of the Mantle - *CC BY 4.0*
  - 6.5: Reading- Characteristics of the Inner and Outer Core - *CC BY 4.0*
  - 6.6: Reading- The Lithosphere and Asthenosphere - *CC BY 4.0*
  - 6.7: Self Check- Layers of the Geosphere - *CC BY 4.0*
  - 6.8: Outcome- Understanding the Earth's Interior - *CC BY 4.0*
  - 6.9: Reading- Studying the Earth's Interior - *CC BY 4.0*
  - 6.10: Self Check- Understanding the Earth's Interior - *CC BY 4.0*
  - 6.11: Putting It Together- Earth's Interior - *CC BY 4.0*
  - 6.12: Assignment- Earth's Interior - *CC BY 4.0*
- 7: Crustal Deformation - *CC BY 4.0*
  - 7.1: Why It Matters- Crustal Deformation - *CC BY 4.0*
  - 7.2: Outcome- Stress and Strain - *CC BY 4.0*
  - 7.3: Reading- Stress In Earth's Crust - *CC BY 4.0*
  - 7.4: Reading- Strain - *CC BY 4.0*
  - 7.5: Self Check- Stress and Strain - *CC BY 4.0*
  - 7.6: Outcome- Geologic Structures - *CC BY 4.0*
  - 7.7: Reading- Folds - *CC BY-SA 4.0*
  - 7.8: Reading- Faults - *CC BY 4.0*
  - 7.9: Reading- Mountains - *CC BY 4.0*
  - 7.10: Self Check- Geologic Structures - *CC BY 4.0*
  - 7.11: Putting It Together- Crustal Deformation - *CC BY 4.0*
- 8: Earthquakes - *CC BY 4.0*
  - 8.1: Why It Matters- Earthquakes - *CC BY 4.0*
  - 8.2: Outcome- Causes and Location of Earthquakes - *CC BY 4.0*
  - 8.3: Reading- The Nature of Earthquakes - *CC BY 4.0*
  - 8.4: Reading- Causes of Earthquakes - *CC BY 4.0*
  - 8.5: Reading- Common Locations of Earthquakes - *CC BY 4.0*
  - 8.6: Reading- The Ring of Fire - *CC BY 4.0*
  - 8.7: Self Check- Causes and Location of Earthquakes - *CC BY 4.0*

- 8.8: Outcome- Types of Waves - *CC BY 4.0*
- 8.9: Reading- Body Waves - *CC BY 4.0*
- 8.10: Reading- Surface Waves - *CC BY 4.0*
- 8.11: Self Check- Types of Waves - *CC BY 4.0*
- 8.12: Outcome- Magnitude and Intensity - *CC BY 4.0*
- 8.13: Reading- Measuring Earthquakes - *CC BY 4.0*
- 8.14: Reading- Magnitude versus Intensity - *CC BY 4.0*
- 8.15: Self Check- Magnitude and Intensity - *CC BY 4.0*
- 8.16: Outcome- Earthquake Hazards and Prediction - *CC BY 4.0*
- 8.17: Reading- Earthquake Hazards - *CC BY 4.0*
- 8.18: Reading- Earthquake Prediction - *CC BY 4.0*
- 8.19: Reading- Seismicity and Earthquake Prediction - *CC BY 4.0*
- 8.20: Self Check- Earthquake Hazards and Prediction - *CC BY 4.0*
- 8.21: Putting It Together- Earthquakes - *CC BY 4.0*
- 8.22: Assignment- Earthquakes - *CC BY 4.0*

- 9: Volcanoes - *CC BY 4.0*
  - 9.1: Why It Matters- Volcanoes - *CC BY 4.0*
  - 9.2: Outcome- Volcano Types - *CC BY 4.0*
  - 9.3: Reading- Types of Volcanoes - *CC BY 4.0*
  - 9.4: Reading- Types of Eruptions - *CC BY 4.0*
  - 9.5: Reading- Supervolcanoes - *CC BY 4.0*
  - 9.6: Self Check- Volcano Types - *CC BY 4.0*
  - 9.7: Outcome- The Formation of Volcanoes - *CC BY 4.0*
  - 9.8: Reading- Volcanoes at Plate Boundaries - *CC BY 4.0*
  - 9.9: Reading- Volcanoes Hotspots - *CC BY 4.0*
  - 9.10: Self Check- The Formation of Volcanoes - *CC BY 4.0*
  - 9.11: Outcome- Igneous Features - *CC BY 4.0*
  - 9.12: Reading- Pyroclastic Deposits - *CC BY 4.0*
  - 9.13: Reading- Dikes and Sills - *CC BY 4.0*
  - 9.14: Reading- Volcanic Landforms - *CC BY 4.0*
  - 9.15: Self Check- Igneous Features - *CC BY 4.0*
  - 9.16: Outcome- Volcanic Hazards - *CC BY 4.0*
  - 9.17: Reading- Volcanic Gases, Pyroclastic Flow, and Tephra - *CC BY 4.0*
  - 9.18: Reading- Lahars, Landslides, and Lavaflow - *CC BY 4.0*
  - 9.19: Self Check- Volcanic Hazards - *CC BY 4.0*
  - 9.20: Outcome- Monitoring Volcanoes - *CC BY 4.0*
  - 9.21: Reading- Signs of an Eruption - *CC BY 4.0*
  - 9.22: Reading- Tools to Monitor Volcanoes - *CC BY 4.0*
  - 9.23: Self Check- Monitoring Volcanoes - *CC BY 4.0*
  - 9.24: Putting It Together- Volcanoes - *CC BY 4.0*
- 10: Mass Movement - *CC BY 4.0*
  - 10.1: Why It Matters- Mass Movement - *CC BY 4.0*
  - 10.2: Outcome- Types of Mass Movement - *CC BY 4.0*
  - 10.3: Reading- Slides - *CC BY 4.0*
  - 10.4: Reading- Falls - *CC BY 4.0*
  - 10.5: Reading- Slump and Creep - *CC BY 4.0*
  - 10.6: Self Check- Types of Mass Movement - *CC BY 4.0*
  - 10.7: Outcome- Driving and Resisting Forces - *CC BY 4.0*
  - 10.8: Reading- Natural Mass Wasting - *CC BY 4.0*
  - 10.9: Reading- Human Impact on Mass Wasting - *CC BY 4.0*
  - 10.10: Self Check- Driving and Resisting Forces - *CC BY 4.0*
  - 10.11: Putting It Together- Mass Wasting - *CC BY 4.0*
  - 10.12: Assignment- Mass Movement - *CC BY 4.0*
- 11: Hydrology - *CC BY 4.0*
  - 11.1: Why It Matters- Hydrology - *CC BY 4.0*
  - 11.2: Outcome- The Hydrologic Cycle - *CC BY 4.0*
  - 11.3: Reading- Phases of the Hydrologic Cycle - *CC BY 4.0*
  - 11.4: Self Check- The Hydrologic Cycle - *CC BY 4.0*
  - 11.5: Outcome- Rivers and Streams - *CC BY 4.0*
  - 11.6: Reading- Types of Streams and Rivers - *CC BY 4.0*
  - 11.7: Reading- Drainage Basins - *CC BY 4.0*
  - 11.8: Reading- Geologic Processes and Flowing Water - *CC BY 4.0*
  - 11.9: Self Check- Rivers and Streams - *CC BY 4.0*
  - 11.10: Outcome- Components of Groundwater - *CC BY 4.0*
  - 11.11: Reading- Groundwater - *CC BY 4.0*
  - 11.12: Reading- Porosity and Permeability - *CC BY 4.0*
  - 11.13: Reading- Aquifers and Well-Potential - *CC BY 4.0*
  - 11.14: Reading- Groundwater Withdrawal - *CC BY 4.0*
  - 11.15: Reading- Quality of Groundwater - *CC BY 4.0*
  - 11.16: Self Check- Components of Groundwater - *CC BY 4.0*
  - 11.17: Outcome- Geologic Features - *CC BY 4.0*
  - 11.18: Reading- Karst Topography - *CC BY 4.0*
  - 11.19: Reading- Geysers - *CC BY 4.0*
  - 11.20: Reading- Springs - *CC BY 4.0*

- 11.21: Self Check- Geologic Features - *CC BY 4.0*
- 11.22: Outcome- Oceans and Shorelines - *CC BY 4.0*
- 11.23: Reading- Ocean Movement - *CC BY 4.0*
- 11.24: Reading- Shorelines - *CC BY 4.0*
- 11.25: Reading- Coastal Hazards - *CC BY 4.0*
- 11.26: Reading- Human Modifications of Coastal Processes - *CC BY 4.0*
- 11.27: Self Check- Oceans and Shorelines - *CC BY 4.0*
- 11.28: Putting It Together- Hydrology - *CC BY 4.0*
- 11.29: Assignment- Hydrology - *CC BY 4.0*

12: Geological Resources - *CC BY 4.0*

- 12.1: Why It Matters- Geological Resources - *CC BY 4.0*
- 12.2: Outcome- Rock and Mineral Resources - *CC BY 4.0*
- 12.3: Reading- Ore Genesis - *CC BY 4.0*
- 12.4: Reading- Petroleum - *CC BY 4.0*
- 12.5: Reading- Natural Gas - *CC BY 4.0*
- 12.6: Reading- Coal - *CC BY 4.0*
- 12.7: Self Check- Rock and Mineral Resources - *CC BY 4.0*
- 12.8: Outcome- Extraction of Resources - *CC BY 4.0*
- 12.9: Reading- Mining - *CC BY 4.0*
- 12.10: Reading- Effects of Mining - *CC BY 4.0*
- 12.11: Self Check- Extraction of Resources - *CC BY 4.0*
- 12.12: Outcome- Getting Energy from Resources - *CC BY 4.0*
- 12.13: Reading- Earth's Energy - *CC BY 4.0*
- 12.14: Reading- Energy Consumption on Earth - *CC BY 4.0*
- 12.15: Reading- Use and Conservation of Resources - *CC BY 4.0*
- 12.16: Self Check- Getting Energy from Resources - *CC BY 4.0*
- 12.17: Putting It Together- Geological Resources - *CC BY 4.0*
- 12.18: Assignment- Geological Resources - *CC BY 4.0*

Back Matter - *CC BY 4.0*

- Index - *CC BY 4.0*
- Glossary - *CC BY 4.0*
- Detailed Licensing - *CC BY 4.0*
- Detailed Licensing - *Undeclared*